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U.S. GLOBAL CHANGE RESEARCH PROGRAM CLIMATE SCIENCE SPECIAL REPORT (CSSR)

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U.S. GLOBAL CHANGE RESEARCH PROGRAM CLIMATE SCIENCE SPECIAL REPORT (CSSR)

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EXECUTIVE SUMMARY

Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, B. DeAngelo, S. Doherty, K. Hayhoe, R. Horton, J.P. Kossin, P.C. Taylor, A.M. Waple, and C.P. Weaver, 2017: Executive summary. In: *Climate Science Special Report: A Sustained Assessment Activity of the U.S. Global Change Research Program* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 12-37.

CHAPTERS

1. **Wuebbles**, D.J., D.R. Easterling, K. Hayhoe, T. Knutson, R.E. Kopp, J.P. Kossin, K.E. Kunkel, A.N. LeGrande, C. Mears, W.V. Sweet, P.C. Taylor, R.S. Vose, and M.F. Wehner, 2017: Our globally changing climate. In: *Climate Science Special Report: A Sustained Assessment Activity of the U.S. Global Change Research Program* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 38-97.
2. **Fahey**, D.W., S. Doherty, K.A. Hibbard, A. Romanou, and P.C. Taylor, 2017: Physical drivers of climate change. In: *Climate Science Special Report: A Sustained Assessment Activity of the U.S. Global Change Research Program* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 98-159.
3. **Knutson**, T., J.P. Kossin, C. Mears, J. Perlwitz, and M.F. Wehner, 2017: Detection and attribution of climate change. In: *Climate Science Special Report: A Sustained Assessment Activity of the U.S. Global Change Research Program* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 160-185.
4. **Hayhoe**, K., J. Edmonds, R.E. Kopp, A.N. LeGrande, B.M. Sanderson, M.F. Wehner, and D.J. Wuebbles, 2017: Climate models, scenarios, and projections. In: *Climate Science Special Report: A Sustained Assessment Activity of the U.S. Global Change Research Program* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 186-227.
5. **Perlwitz**, K., T. Knutson, and J.P. Kossin, 2017: Large-scale circulation and climate variability. In: *Climate Science Special Report: A Sustained Assessment Activity of the U.S. Global Change Research Program* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 228-266.
6. **Vose**, R.S., D.R. Easterling, K.E. Kunkel, and M.F. Wehner, 2017: Temperature changes in the United States. In: *Climate Science Special Report: A Sustained Assessment Activity of the U.S. Global Change Research Program* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 267-300.
7. **Easterling**, D.R., J.R. Arnold, T. Knutson, K.E. Kunkel, A.N. LeGrande, L.R. Leung, R.S. Vose, D.E. Waliser, and M.F. Wehner, 2017: Precipitation change in the United States. In: *Climate Science Special Report: A Sustained Assessment Activity of the U.S. Global Change Research Program* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 301-335.
8. **Wehner**, M.F., J.R. Arnold, T. Knutson, K.E. Kunkel, and A.N. LeGrande, 2017: Droughts, floods, and hydrology. In: *Climate Science Special Report: A Sustained Assessment Activity of the U.S. Global Change Research Program* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 336-374.

9. **Kossin**, J.P., T. Hall, T. Knutson, K.E. Kunkel, R.J. Trapp, D.E. Waliser, and M.F. Wehner, 2017: Extreme storms. In: *Climate Science Special Report: A Sustained Assessment Activity of the U.S. Global Change Research Program* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 375-404.
10. **Hibbard**, K.A., F.M. Hoffman, D. Huntzinger, and T.O. West, 2017: Changes in land cover and terrestrial biogeochemistry. In: *Climate Science Special Report: A Sustained Assessment Activity of the U.S. Global Change Research Program* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 405-442.
11. **Taylor**, P.C., W. Maslowski, J. Perlwitz, and D.J. Wuebbles, 2017: Arctic changes and their effects on Alaska and the rest of the United States. In: *Climate Science Special Report: A Sustained Assessment Activity of the U.S. Global Change Research Program* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 443-492.
12. **Sweet**, W.V., R. Horton, R.E. Kopp, and A. Romanou, 2017: Sea level rise. In: *Climate Science Special Report: A Sustained Assessment Activity of the U.S. Global Change Research Program* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 493-539.
13. **Jewett**, L. and A. Romanou, 2017: Ocean changes – warming, stratification, circulation, acidification, and deoxygenation. In: *Climate Science Special Report: A Sustained Assessment Activity of the U.S. Global Change Research Program* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 540-583.
14. **DeAngelo**, B., J. Edmonds, D.W. Fahey, and B.M. Sanderson, 2017: Perspectives on climate change mitigation. In: *Climate Science Special Report: A Sustained Assessment Activity of the U.S. Global Change Research Program* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 584-607.
15. **Kopp**, R.E., D.R. Easterling, T. Hall, K. Hayhoe, R. Horton, K.E. Kunkel, and A.N. LeGrande, 2017: Potential surprises – compound extremes and tipping elements. In: *Climate Science Special Report: A Sustained Assessment Activity of the U.S. Global Change Research Program* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 608-635.

APPENDICES

- A. **Wuebbles**, D.J., 2017: Observational datasets used in climate studies. In: *Climate Science Special Report: A Sustained Assessment Activity of the U.S. Global Change Research Program* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 636-641.
- B. **Sanderson**, B.M. and M.F. Wehner, 2017: Weighting strategy for the Fourth National Climate Assessment. In: *Climate Science Special Report: A Sustained Assessment Activity of the U.S. Global Change Research Program* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 642-651.
- C. **Knutson**, T., 2017: Detection and attribution methodologies overview. In: *Climate Science Special Report: A Sustained Assessment Activity of the U.S. Global Change Research Program* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 652-663.

1 **About This Report**

2 As a key input into the Fourth National Climate Assessment (NCA4), the U.S. Global Change
3 Research Program (USGCRP) oversaw the production of this special, stand-alone report of the
4 state of science relating to climate change and its physical impacts.

5 This report is designed to be an authoritative assessment of the science of climate change, with a
6 focus on the United States, to serve as the foundation for efforts to assess climate-related risks
7 and inform decision-making about responses. In accordance with this purpose, it does not
8 include an assessment of literature on climate change mitigation, adaptation, economic valuation,
9 or societal responses, nor does it include policy recommendations.

10 The Climate Science Special Report (CSSR) serves several purposes for NCA4, including
11 providing 1) an updated detailed analysis of the findings of how climate change is affecting
12 weather and climate across the United States; 2) an executive summary that will be used as the
13 basis for the science summary of NCA4; and 3) foundational information and projections for
14 climate change, including extremes, to improve “end-to-end” consistency in sectoral, regional,
15 and resilience analyses for NCA4. As an assessment and analysis of the science, this report
16 provides important input to the development of NCA4 and its primary focus on the human
17 welfare, societal, economic and environmental elements of climate change.

18 Much of this report is written at a level more appropriate for a scientific audience, though the
19 Executive Summary is designed to be accessible to a broader audience.

20 **Report Development, Review, and Approval Process**

21 The National Oceanic and Atmospheric Administration (NOAA) served as the administrative
22 lead agency for the preparation of this report. The Federal Science Steering Committee (SSC)¹
23 comprises representatives from four agencies (NOAA, the National Aeronautics and Space
24 Administration [NASA], the Department of Energy [DOE], and the Environmental Protection
25 Agency [EPA]), the U.S. Global Change Research Program (USGCRP),² and three Coordinating
26 Lead Authors, all of whom were Federal employees during the development of this report.
27 Following a public notice for author nominations in March 2016, the SSC selected the writing
28 team, consisting of scientists representing Federal agencies, national laboratories, universities,

¹ The Science Steering Committee is a federal advisory committee that oversees the production of the CSSR.

² The USGCRP is made up of 13 Federal departments and agencies that carry out research and support the Nation's response to global change. The USGCRP is overseen by the Subcommittee on Global Change Research (SGCR) of the National Science and Technology Council's Committee on Environment, Natural Resources, and Sustainability (CENRS), which in turn is overseen by the White House Office of Science and Technology Policy (OSTP). The agencies within USGCRP are the Department of Agriculture, the Department of Commerce (NOAA), the Department of Defense, the Department of Energy, the Department of Health and Human Services, the Department of the Interior, the Department of State, the Department of Transportation, the Environmental Protection Agency, the National Aeronautics and Space Administration, the National Science Foundation, the Smithsonian Institution, and the U.S. Agency for International Development.

1 and the private sector. Contributing Authors were requested to provide special input to the Lead
2 Authors to help with specific issues of the assessment.

3 The first Lead Author Meeting was held in Washington, DC in April 2016, to refine the outline
4 contained in the SSC-endorsed prospectus and to make writing assignments. Over the course of
5 16 months, 6 CSSR drafts were generated, with each successive iteration—from zero-order to
6 fifth-order drafts—undergoing additional expert review, as follows: (i) by the writing team itself
7 (13–20 June 2016); (ii) by the SSC convened to oversee report development (29 July–18 August
8 2016); (iii) by the technical agency representatives (and designees) comprising the
9 Subcommittee on Global Change Research (SGCR, 3–14 October 2016); (iv) by the SSC and
10 technical liaisons again (5–13 December 2016); (v) by the general public during the Public
11 Comment Period (15 December 2016–3 February 2017) and an expert panel convened by the
12 National Academies of Sciences (NAS, 21 December 2016–13 March 2017); and (vi) by the
13 SGCR again (3–24 May 2017) to confirm the Review Editor conclusions that all public and NAS
14 comments were adequately addressed. In October 2016, an 11-member core writing team was
15 tasked with capturing the most important CSSR key findings and generating an Executive
16 Summary. Two additional Lead Authors Meetings were held after major review milestones to
17 facilitate chapter team deliberations and consistency: 2–4 November 2016 (Boulder, CO) and
18 21–22 April 2017 (Asheville, NC). Literature cutoff dates were enforced, with all cited material
19 published by June 2017. The final (fifth-order) draft including the Executive Summary was
20 compiled in June 2017, and submitted to the Office of Science and Technology Policy (OSTP).
21 OSTP is responsible for the Federal clearance process prior to final report production and public
22 release.

23 **The Sustained National Climate Assessment**

24 The Climate Science Special Report has been developed as part of the USGCRP’s sustained
25 National Climate Assessment (NCA) process. This process facilitates continuous and transparent
26 participation of scientists and stakeholders across regions and sectors, enabling new information
27 and insights to be assessed as they emerge. The Climate Science Special Report is aimed at a
28 comprehensive assessment of the science underlying the changes occurring in Earth’s climate
29 system, with a special focus on the United States.

30 **Sources Used in this Report**

31 The findings in this report are based on a large body of scientific, peer-reviewed research, as well
32 as a number of other publicly available sources, including well-established and carefully
33 evaluated observational and modeling datasets. The team of authors carefully reviewed these
34 sources to ensure a reliable assessment of the state of scientific understanding. Each source of
35 information was determined to meet the four parts of the internal quality assurance guidance
36 provided to authors (following the approach from NCA3): 1) utility, 2) transparency and
37 traceability, 3) objectivity, and 4) integrity and security. Report authors assessed and synthesized

1 information from peer-reviewed journal articles, technical reports produced by Federal agencies,
2 scientific assessments (such as the rigorously-reviewed international assessments from the
3 Intergovernmental Panel on Climate Change; IPCC 2013), reports of the National Academy of
4 Sciences and its associated National Research Council, and various regional climate impact
5 assessments, conference proceedings, and government statistics (such as population census and
6 energy usage).

7

FINAL DRAFT

1 **Guide to the Report**

2 The following subsections describe the format of the Climate Science Special Report and the
3 overall structure and features of the chapters.

4 **Executive Summary**

5 The Executive Summary describes the major findings from the Climate Science Special Report.
6 It summarizes the overall findings and includes some key figures and additional bullet points
7 covering overarching and especially noteworthy conclusions. The Executive Summary and the
8 majority of the Key Findings are written to be accessible to a wide range of audiences.

9 **Chapters**

10 **Key Findings and Traceable Accounts**

11 Each topical chapter includes Key Findings, which are based on the authors' expert judgment of
12 the synthesis of the assessed literature. Each Key Finding includes a confidence statement and, as
13 appropriate, framing of key scientific uncertainties, so as to better support assessment of climate-
14 related risks. (See "Documenting Uncertainty" below).

15 Each Key Finding is also accompanied by a Traceable Account that documents the supporting
16 evidence, process, and rationale the authors used in reaching these conclusions and provides
17 additional information on sources of uncertainty through confidence and likelihood statements.
18 The Traceable Accounts can be found at the end of each chapter.

19 **Regional Analyses**

20 Throughout the report, the regional analyses of climate changes for the United States are based
21 on 10 different regions as shown in Figure 1. There are differences from the regions used in the
22 Third National Climate Assessment (Melillo et al. 2014): 1) the Great Plains are split into the
23 Northern Great Plains and Southern Great Plains; and 2) The U.S. islands in the Caribbean are
24 analyzed as a separate region apart from the Southeast.

25 **Chapter Text**

26 Each chapter assesses the state of the science for a particular aspect of the changing climate. The
27 first chapter gives a summary of the global changes occurring in the Earth's climate system. This
28 is followed in Chapter 2 by a summary of the scientific basis for climate change. Chapter 3 gives
29 an overview of the processes used in the detection and attribution of climate change and
30 associated studies using those techniques. Chapter 4 then discusses the scenarios for greenhouse
31 gases and particles and the modeling tools used to study future projections. Chapters 5 through 9
32 primarily focus on physical changes in climate occurring in the United States, including those
33 projected to occur in the future. Chapter 10 provides a focus on land use change and associated

1 feedbacks on climate. Chapter 11 addresses changes in Alaska in the Arctic, and how the latter
2 affects the United States. Chapters 12 and 13 discuss key issues connected with sea level rise and
3 ocean changes, including ocean acidification, and their potential effects on the United States.
4 Finally, Chapters 14 and 15 discuss some important perspectives on how mitigation activities
5 could affect future changes in climate and provide perspectives on what surprises could be in
6 store for the changing climate beyond the analyses already covered in the rest of the assessment.

7 Throughout the report, results are presented in American units (e.g., degree Fahrenheit) as well
8 as in the International System of Units (e.g., degrees Celsius).

9 **Reference time periods for graphics**

10 There are many different types of graphics in the Climate Science Special Report. Some of the
11 graphs in this report illustrate historical changes and future trends in climate compared to some
12 reference period, with the choice of this period determined by the purpose of the graph and the
13 availability of data. The scientific community does not have a standard set of reference time
14 periods for assessing the science, and these tend to be chosen differently for different reports and
15 assessments. Some graphics are pulled from other studies using different time periods.

16 Where graphs were generated for this report (those not based largely on prior publications), they
17 are mostly based on one of two reference periods. The 1901–1960 reference period is
18 particularly used for graphs that illustrate past changes in climate conditions, whether in
19 observations or in model simulations. This 60-year time period was also used for analyses in the
20 Third National Climate Assessment (NCA3; Melillo et al. 2014). The beginning date was chosen
21 because earlier historical observations are generally considered to be less reliable. Thus, a
22 number of the graphs in the report are able to highlight the recent, more rapid changes relative to
23 the early part of the century (the reference period) and also reveal how well the climate models
24 simulate observed changes. In this report, this time period is used as the base period in most
25 maps of observed trends and all time-varying, area-weighted averages that show both observed
26 and projected quantities. For the observed trends, 1986–2015 is generally chosen as the most
27 recent 30-year period (2016 data was not fully available until late in our development of the
28 assessment).

29 The other commonly used reference period in this report is 1976–2005. The choice of a 30-year
30 period is chosen to account for natural variations and to have a reasonable sampling in order to
31 estimate likelihoods of trends in extremes. This period is consistent with the World
32 Meteorological Organization’s recommendation for climate statistics. This period is used for
33 graphs that illustrate projected changes simulated by climate models. The purpose of these
34 graphs is to show projected changes compared to a period that allows stakeholders and decision
35 makers to base fundamental planning and decisions on average and extreme climate conditions
36 in a non-stationary climate; thus, a recent available 30-year period was chosen (Arguez and Vose
37 2011). The year 2005 was chosen as an end date because the historical period simulated by the

1 models used in this assessment ends in that year.

2 For future projections, 30-year periods are again used for consistency. Projections are centered
3 around 2030, 2050, and 2085 with an interval of plus and minus 15 years (for example, results
4 for 2030 cover the period 2015–2045); Most model runs used here only project out to 2100 for
5 future scenarios, but where possible, results beyond 2100 are shown. Note that these time periods
6 are different than those used in some of the graphics in NCA3. There are also exceptions for
7 graphics that are based on existing publications.

8 For global results that may be dependent on findings from other assessments (such as those
9 produced by the Intergovernmental Panel on Climate Change, or IPCC), and for other graphics
10 that depend on specific published work, the use of other time periods was also allowed, but an
11 attempt was made to keep them as similar to the selected periods as possible. For example, in the
12 discussion of radiative forcing, the report uses the standard analyses from IPCC for the industrial
13 era (1750 to 2011) (following IPCC 2013a). And, of course, the paleoclimatic discussion of past
14 climates goes back much further in time.

15 **Model Results: Past Trends and Projected Futures**

16 The NCA3 included global modeling results from both the CMIP3 (Coupled Model
17 Intercomparison Project, 3rd phase) models used in the 2007 international assessment (IPCC
18 2007) and the CMIP5 (Coupled Model Intercomparison Project, Phase 5) models used in the
19 more recent international assessment (IPCC 2013a). Here, the primary resource for this
20 assessment is the more recent global model results and associated downscaled products from
21 CMIP5. The CMIP5 models and the associated downscaled products are discussed in Chapter 4:
22 Projections.

23 **Treatment of Uncertainties: Likelihoods, Confidence, and Risk Framing**

24 Throughout this report's assessment of the scientific understanding of climate change, the
25 authors have assessed to the fullest extent possible the state-of-the-art understanding of the
26 science resulting from the information in the scientific literature to arrive at a series of findings
27 referred to as Key Findings. The approach used to represent the extent of understanding
28 represented in the Key Findings is done through two metrics:

- 29 • **Confidence** in the validity of a finding based on the type, amount, quality, strength, and
30 consistency of evidence (such as mechanistic understanding, theory, data, models, and expert
31 judgment); the skill, range, and consistency of model projections; and the degree of
32 agreement within the body of literature.
- 33 • **Likelihood**, or probability of an effect or impact occurring, is based on measures of
34 uncertainty expressed probabilistically (in other words, based on the degree of understanding
35 or knowledge, e.g., resulting from evaluating statistical analyses of observations or model

1 results or on expert judgment).

2 The terminology used in the report associated with these metrics is shown in Figure 2. This
3 language is based on that used in NCA3 (Melillo et al. 2014), the IPCC's Fifth Assessment
4 Report (IPCC 2013a), and most recently the USGCRP Climate and Health assessment (USGCRP
5 2016). Wherever used, the confidence and likelihood statements are italicized.

6 Assessments of confidence in the Key Findings are based on the expert judgment of the author
7 team. Authors provide supporting evidence for each of the chapter's Key Findings in the
8 Traceable Accounts. Confidence is expressed qualitatively and ranges from low confidence
9 (inconclusive evidence or disagreement among experts) to very high confidence (strong evidence
10 and high consensus) (see Figure 2). Confidence should not be interpreted probabilistically, as it
11 is distinct from statistical likelihood. See chapter 1 in IPCC (2013a) for further discussion of this
12 terminology.

13 In this report, likelihood is the chance of occurrence of an effect or impact based on measures of
14 uncertainty expressed probabilistically (in other words, based on statistical analysis of
15 observations or model results or on expert judgment). The authors used expert judgment based
16 on the synthesis of the literature assessed to arrive at an estimation of the likelihood that a
17 particular observed effect was related to human contributions to climate change or that a
18 particular impact will occur within the range of possible outcomes. Model uncertainty is an
19 important contributor to uncertainty in climate projections, and includes, but is not restricted to,
20 the uncertainties introduced by errors in the model's representation of the physical and bio-
21 geochemical processes affecting the climate system as well as in the model's response to external
22 forcing (IPCC 2013a).

23 Where it is considered justified to report the likelihood of particular impacts within the range of
24 possible outcomes, this report takes a plain-language approach to expressing the expert judgment
25 of the chapter team, based on the best available evidence. For example, an outcome termed
26 "likely" has at least a 66% chance of occurring (in other words, a likelihood greater than about 2
27 of 3 chances); an outcome termed "very likely," at least a 90% chance (or more than 9 out of 10
28 chances). See Figure 2 for a complete list of the likelihood terminology used in this report.

29 Traceable Accounts for each Key Finding 1) document the process and rationale the authors used
30 in reaching the conclusions in their Key Finding, 2) provide additional information to readers
31 about the quality of the information used, 3) allow traceability to resources and data, and 4)
32 describe the level of likelihood and confidence in the Key Finding. Thus, the Traceable Accounts
33 represent a synthesis of the chapter author team's judgment of the validity of findings, as
34 determined through evaluation of evidence and agreement in the scientific literature. The
35 Traceable Accounts also identify areas where data are limited or emerging. Each Traceable
36 Account includes 1) a description of the evidence base, 2) major uncertainties, and 3) an
37 assessment of confidence based on evidence.

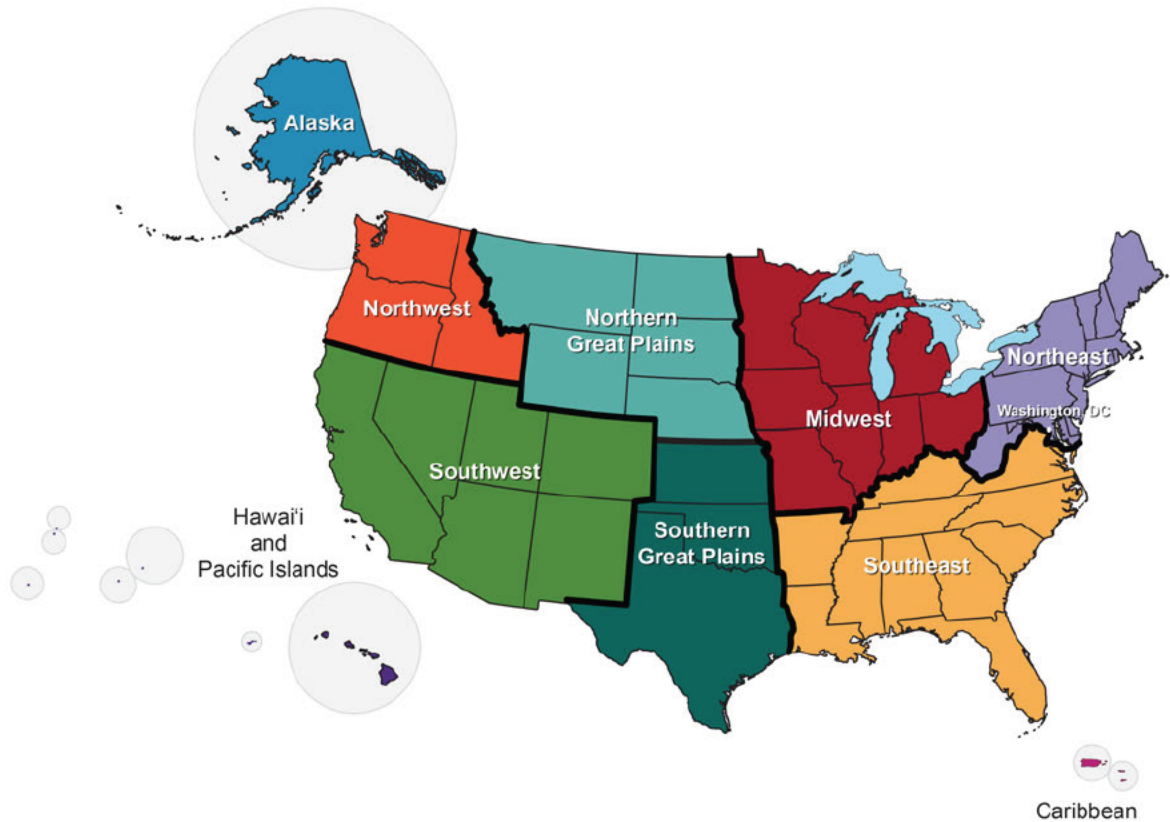
1 All Key Findings include a description of confidence. Where it is considered scientifically
2 justified to report the likelihood of particular impacts within the range of possible outcomes, Key
3 Findings also include a likelihood designation.

4 Confidence and likelihood levels are based on the expert judgment of the author team. They
5 determined the appropriate level of confidence or likelihood by assessing the available literature,
6 determining the quality and quantity of available evidence, and evaluating the level of agreement
7 across different studies. Often, the underlying studies provided their own estimates of uncertainty
8 and confidence intervals. When available, these confidence intervals were assessed by the
9 authors in making their own expert judgments. For specific descriptions of the process by which
10 the author team came to agreement on the Key Findings and the assessment of confidence and
11 likelihood, see the Traceable Accounts in each chapter.

12 In addition to the use of systematic language to convey confidence and likelihood information,
13 this report attempts to highlight aspects of the science that are most relevant for supporting the
14 assessment (for example, in the upcoming Fourth National Climate Assessment) of key societal
15 risks posed by climate change. This includes attention to trends and changes in the tails of the
16 probability distribution of future climate change and its proximate impacts (for example, on sea
17 level or temperature and precipitation extremes) and on defining plausible bounds for the
18 magnitude of future changes, since many key risks are disproportionately determined by
19 plausible low-probability, high-consequence outcomes. Therefore, in addition to presenting the
20 expert judgment on the “most likely” range of projected future climate outcomes, where
21 appropriate, this report also provides information on the outcomes lying outside this range which
22 nevertheless cannot be ruled out, and may therefore be relevant for assessing overall risk. In
23 some cases, this involves an evaluation of the full range of information contained in the
24 ensemble of climate models used for this report, and in other cases will involve the consideration
25 of additional lines of scientific evidence beyond the models.

26 Complementing this use of risk-focused language and presentation around specific scientific
27 findings in the report, Chapter 15: Potential Surprises provides an overview of potential low
28 probability/high consequence “surprises” resulting from climate change, including thresholds,
29 also called tipping points, in the climate system and the compounding effects of multiple,
30 interacting climate change impacts whose consequences may be much greater than the sum of
31 the individual impacts. Chapter 15 also highlights critical knowledge gaps that determine the
32 degree to which such high-risk tails and bounding scenarios can be precisely defined, including
33 missing processes and feedbacks that make it more likely than not that climate models currently
34 underestimate the potential for high-end changes, reinforcing the need to look beyond the central
35 tendencies of model projections to meaningfully assess climate change risk.

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Figure 1. Map of the ten regions of the United States used throughout the Climate Science Special Report. Regions are similar to that used in the Third National Climate Assessment except that 1) the Great Plains are split into the Northern Great Plains and Southern Great Plains, and 2) the Caribbean islands have been split from the Southeast region. (Figure source: adapted from Melillo et al. 2014).

Confidence Level	Likelihood
Very High	Virtually Certain
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus	99%–100%
High	Extremely Likely
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	95%–100%
Medium	Very Likely
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	90%–100%
Low	Likely
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts	66%–100%
	About as Likely as Not
	33%–66%
	Unlikely
	0%–33%
	Very Unlikely
	0%–10%
	Extremely Unlikely
	0%–5%
	Exceptionally Unlikely
	0%–1%

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Figure 2. Confidence levels and likelihood statements used in the report. (Figure source: adapted from USGCRP 2016 and IPCC 2013 (likelihoods use the broader range from the IPCC assessment). As an example, a 66%–100% probability can be interpreted as a likelihood of more than 2 out of 3 chances for this certainty.

1 Front Matter References

- 2 Arguez, A. and R.S. Vose, 2011: The definition of the standard WMO climate normal: The key
3 to deriving alternative climate normals. *Bulletin of the American Meteorological Society*, **92**,
4 699-704. <http://dx.doi.org/10.1175/2010BAMS2955.1>
- 5 IPCC, 2007: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group*
6 *I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.*
7 Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L.
8 Miller, Eds. Cambridge University Press, Cambridge. U.K, New York, NY, USA, 996 pp.
9 [www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1_repor](http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1_report_the_physical_science_basis.htm)
10 [t_the_physical_science_basis.htm](http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1_report_the_physical_science_basis.htm)
- 11 IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group*
12 *I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.*
13 Cambridge University Press, Cambridge, UK and New York, NY, 1535 pp.
14 <http://dx.doi.org/10.1017/CBO9781107415324> www.climatechange2013.org
- 15 Melillo, J.M., T.C. Richmond, and G.W. Yohe, eds. *Climate Change Impacts in the United*
16 *States: The Third National Climate Assessment.* 2014, U.S. Global Change Research
17 Program: Washington, D.C. 842. <http://dx.doi.org/10.7930/J0Z31WJ2>.
- 18 USGCRP, 2016: *The Impacts of Climate Change on Human Health in the United States: A*
19 *Scientific Assessment.* Crimmins, A., J. Balbus, J.L. Gamble, C.B. Beard, J.E. Bell, D.
20 Dodgen, R.J. Eisen, N. Fann, M.D. Hawkins, S.C. Herring, L. Jantarasami, D.M. Mills, S.
21 Saha, M.C. Sarofim, J. Trtanj, and L. Ziska, Eds. U.S. Global Change Research Program,
22 Washington, DC, 312 pp. <http://dx.doi.org/10.7930/J0R49NQX>

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1 **Executive Summary**

2 **Introduction**

3 New observations and new research have increased our understanding of past, current, and
4 future climate change since the Third U.S. National Climate Assessment (NCA3) was
5 published in May 2014. This Climate Science Special Report (CSSR) is designed to capture
6 that new information and build on the existing body of science in order to summarize the
7 current state of knowledge and provide the scientific foundation for the Fourth National
8 Climate Assessment (NCA4).

9 Since NCA3, stronger evidence has emerged for continuing, rapid, human-caused warming of
10 the global atmosphere and ocean. This report concludes that “it is *extremely likely* that human
11 influence has been the dominant cause of the observed warming since the mid-20th century.
12 For the warming over the last century, there is no convincing alternative explanation
13 supported by the extent of the observational evidence.”

14 The last few years have also seen record-breaking, climate-related weather extremes, the three
15 warmest years on record for the globe, and continued decline in arctic sea ice. These trends
16 are expected to continue in the future over climate (multidecadal) timescales. Significant
17 advances have also been made in our understanding of extreme weather events and how they
18 relate to increasing global temperatures and associated climate changes. Since 1980, the cost
19 of extreme events for the United States has exceeded \$1.1 trillion, therefore better
20 understanding of the frequency and severity of these events in the context of a changing
21 climate is warranted.

22 Periodically taking stock of the current state of knowledge about climate change and putting
23 new weather extremes, changes in sea ice, increases in ocean temperatures, and ocean
24 acidification into context ensures that rigorous, scientifically-based information is available to
25 inform dialogue and decisions at every level. Most of this special report is intended for those
26 who have a technical background in climate science and to provide input to the authors of
27 NCA4. In this Executive Summary, green boxes present highlights of the main report. These
28 are followed by related points and selected figures providing more scientific details. The
29 summary material on each topic presents the most salient points of chapter findings and
30 therefore represents only a subset of the report’s content. For more details, the reader is
31 referred to the individual chapters. This report discusses climate trends and findings at several
32 scales: global, nationwide for the United States, and for ten specific U.S. regions (shown in
33 Figure 1 in the Guide to the Report). A statement of scientific confidence also follows each
34 point in the Executive Summary. The confidence scale is described in the Guide to the Report.
35 At the end of the Executive Summary and in Chapter 1: Our Globally Changing Climate,
36 there is also a summary box highlighting the most notable advances and topics since NCA3
37 and since the 2013 Intergovernmental Panel on Climate Change (IPCC) report.

1 Global and U.S. Temperatures Continue to Rise

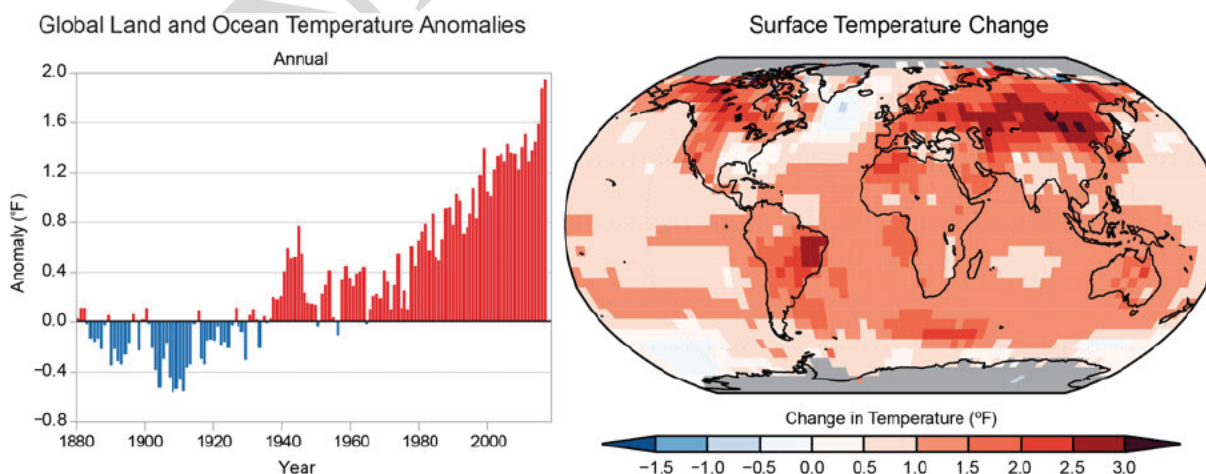
2 Long-term temperature observations are among the most consistent and widespread evidence
3 of a warming planet. Temperature (and, above all, its local averages and extremes) affects
4 agricultural productivity, energy use, human health, water resources, infrastructure, natural
5 ecosystems, and many other essential aspects of society and the natural environment. Recent
6 data adds to the weight of evidence for rapid global-scale warming, the dominance of human
7 causes, and the expected continuation of increasing temperatures, including more record-
8 setting extremes. (Ch.1)

9 Changes in Observed and Projected Global Temperature

The global, long-term, and unambiguous warming trend has continued during recent years. Since the last National Climate Assessment was published, 2014 became the warmest year on record globally; 2015 surpassed 2014 by a wide margin; and 2016 surpassed 2015. Sixteen of the last 17 years are the warmest years on record for the globe. (Ch.1; Fig ES.1)

13

- 14 • Global annual-average temperature (as calculated from instrumental records over both
15 land and oceans) has increased by more than 1.2°F (0.7°F) for the period 1986–2016
16 relative to 1901–1960; the linear regression change over the entire period from 1901–
17 2016 is 1.8°F (1.0°C) (*very high confidence*; Fig. ES.1). Longer-term climate records
18 over past centuries and millennia indicate that average temperatures in recent decades
19 over much of the world have been much higher, and have risen faster during this time
20 period, than at any time in the past 1,700 years or more, the time period for which the
21 global distribution of surface temperatures can be reconstructed (*high confidence*).
22 (Ch.1)



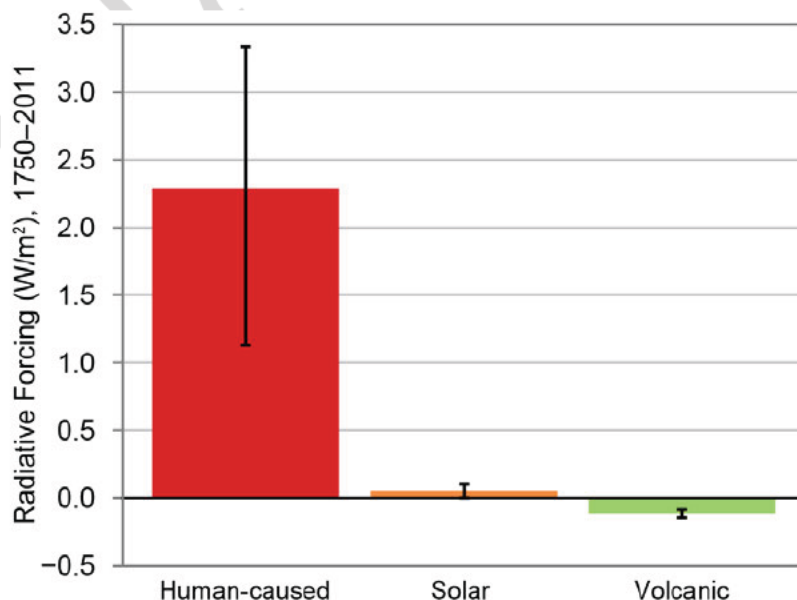
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1 **Figure ES.1 Global Temperatures Continue to Rise**

2 Left: Global annual average temperature has increased by more than 1.2°F (0.7°C) for the period
 3 1986–2016 relative to 1901–1960. Red bars show temperatures that were above the 1901–1960
 4 average, and blue bars indicate temperatures below the average. Right: Surface temperature change (in
 5 °F) for the period 1986–2016 relative to 1901–1960. Grey indicates missing data. *From Figures 1.2.*
 6 *and 1.3 in Ch.1.*

- 7
- 8 • Many lines of evidence demonstrate that it is *extremely likely* that human influence has
 9 been the dominant cause of the observed warming since the mid-20th century. Over
 10 the last century, there are no convincing alternative explanations supported by the
 11 extent of the observational evidence. Solar output changes and internal natural
 12 variability can only contribute marginally to the observed changes in climate over the
 13 last century, and we find no convincing evidence for natural cycles in the
 14 observational record that could explain the observed changes in climate. (*Very high*
confidence) (Ch.1)
 - 15 • The *likely* range of the human contribution to the global mean temperature increase
 16 over the period 1951–2010 is 1.1° to 1.4°F (0.6° to 0.8°C), and the central estimate of
 17 the observed warming of 1.2°F (0.65°C) lies within this range (*high confidence*). This
 18 translates to a *likely* human contribution of 92%–123% of the observed 1951–2010
 19 change. The *likely* contributions of natural forcing and internal variability to global
 20 temperature change over that period are minor (*high confidence*). (Ch.3; Fig ES.2)
 - 21 • Natural variability, including El Niño events and other recurring patterns of ocean–
 22 atmosphere interactions, impact temperature and precipitation, especially regionally,
 23 over timescales of months to years. The global influence of natural variability,
 24 however, is limited to a small fraction of observed climate trends over decades. (*Very*
 25 *high confidence*) (Ch.1)



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1 **Figure ES.2 Human Activities Are the Primary Driver of Recent Global Temperature** 2 **Rise**

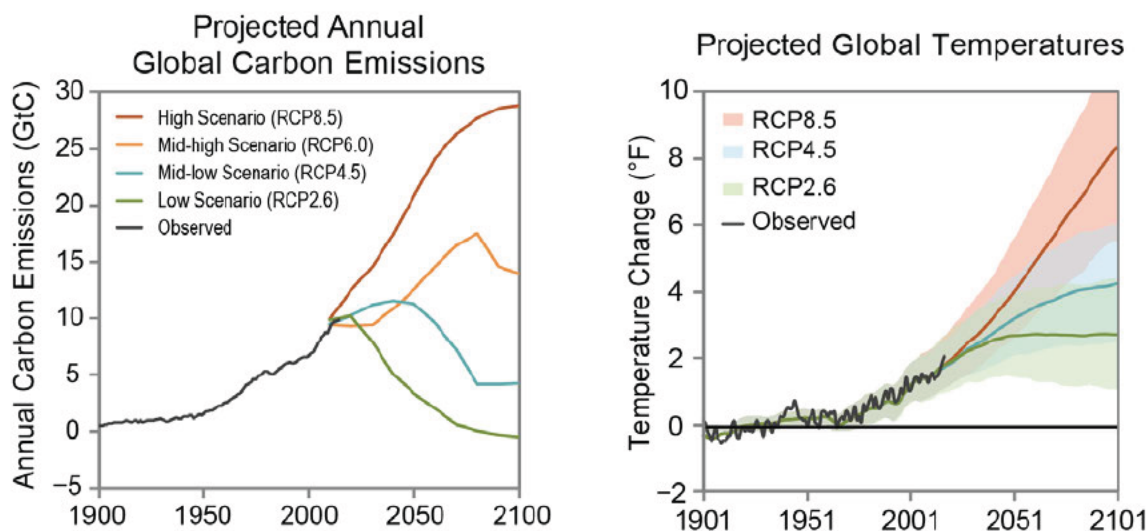
3 Global annual average radiative forcing change from 1750 to 2011 due to human activities, changes in
4 total solar irradiance, and volcanic emissions. Black bars indicate the uncertainty in each. Radiative
5 forcing is a measure of the influence a factor (such as greenhouse gas emissions) has in changing the
6 global balance of incoming and outgoing energy. Over this time period, solar forcing has oscillated on
7 approximately an 11-year cycle between -0.11 and $+0.19$ W/m^2 . Radiative forcing due to volcanic
8 emissions is always negative (cooling) and can be very large immediately following significant
9 eruptions but is short-lived. Over the industrial era, the largest volcanic forcing followed the eruption
10 of Mt. Tambora in 1815 (-11.6 W/m^2). This forcing declined to -4.5 W/m^2 in 1816, and to near-zero
11 by 1820. Forcing due to human activities, in contrast, has become increasingly positive (warming)
12 since about 1870, and has grown at an accelerated rate since about 1970. Radiative forcings greater
13 than zero (positive forcings) produce climate warming; forcings less than zero (negative forcings)
14 produce climate cooling. There are also natural variations in temperature and other climate variables
15 which operate on annual to decadal time-scales. This natural variability contributes very little to
16 climate trends over decades and longer. *Simplified from Figure 2.6 in Chapter 2. See Chapter 2 for*
17 *more details.*

- 18 • Global climate is projected to continue to change over this century and beyond. The
19 magnitude of climate change beyond the next few decades will depend primarily on
20 the amount of greenhouse (heat-trapping) gases emitted globally and on the remaining
21 uncertainty in the sensitivity of Earth's climate to those emissions (*very high*
22 *confidence*). With significant reductions in the emissions of greenhouse gases,
23 the global annually averaged temperature rise could be limited to 3.6°F (2°C) or less.
24 Without major reductions in these emissions, the increase in annual average global
25 temperatures relative to pre-industrial times could reach 9°F (5°C) or more by the end
26 of this century. (Ch.1; Fig ES.3)
- 27 • If greenhouse gas concentrations were stabilized at their current level, existing
28 concentrations would commit the world to at least an additional 1.1°F (0.6°C) of
29 warming over this century relative to the last few decades (*high confidence* in
30 continued warming, *medium confidence* in amount of warming). (Ch.4)

31 **Sidebar: Scenarios Used in this Assessment**

32 Projections of future climate conditions use a range of plausible future scenarios. Consistent
33 with previous practice, this assessment relies on scenarios generated for the
34 Intergovernmental Panel on Climate Change (IPCC). The IPCC completed its last assessment
35 in 2013–2014, and its projections were based on updated scenarios, namely four
36 “representative concentration pathways” (RCPs). The RCP scenarios are numbered according
37 to changes in radiative forcing in 2100 relative to preindustrial conditions: $+2.6$, $+4.5$, $+6.0$
38 and $+8.5$ watts per square meter (W/m^2). Radiative forcing is a measure of the influence a
39 factor (such as greenhouse gas emissions) has in changing the global balance of incoming and
40 outgoing energy. Greenhouse gases (GHGs) in the atmosphere absorb most of the outgoing

1 radiation, leading to a warming of the surface and atmosphere. Though multiple emissions
 2 pathways could lead to the same 2100 radiative forcing value, an associated pathway of
 3 CO₂ and other human-caused emissions of greenhouse gases, aerosols, and air pollutants has
 4 been selected for each RCP. RCP8.5 implies a future with continued high emissions growth,
 5 whereas the other RCPs represent different pathways of mitigating emissions. Figure ES.3
 6 shows these emission pathways and the corresponding projected changes in global
 7 temperature.



8

9 **Figure ES.3. Greater Emissions Lead to Significantly More Warming.**

10 The two panels above show annual historical and a range of plausible future carbon emissions in units
 11 of gigatons of carbon (GtC) per year (left) and the historical observed and future temperature change
 12 that would result for a range of future scenarios relative to the 1901–1960 average, based on the
 13 central estimate (lines) and a range (shaded areas, two standard deviations) as simulated by the full
 14 suite of CMIP5 global climate models (right). By 2081–2100, the projected range in global mean
 15 temperature change is 1.1°–4.3°F under the RCP2.6 scenario (0.6°–2.4°C, green), 2.4°–5.9°F under
 16 RCP4.5 (1.3°–3.3°C, blue), 3.0°–6.8°F under RCP6.0 (1.6°–3.8°C, not shown) and 5.0°–10.2°F under
 17 RCP8.5 (2.8°–5.7°C, orange). See the main report for more details on these scenarios and
 18 implications. *Based on Figure 4.1 in Chapter 4.*

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1 Changes in Observed and Projected U.S. Temperature

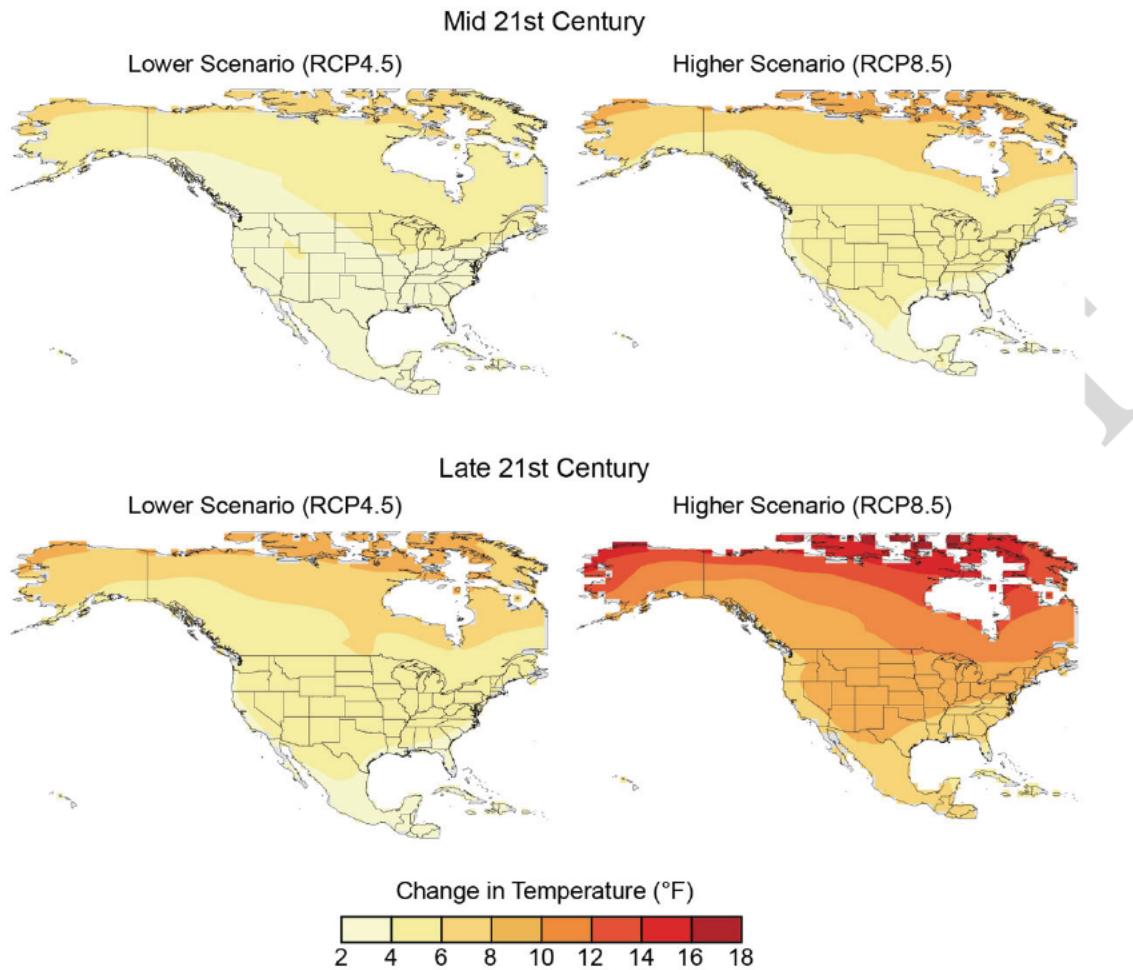
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Average annual temperature over the contiguous United States has increased by 1.8°F (1.0°C) for the period 1901–2016 and is projected to continue to rise. (*Very high confidence*). (Ch.6; Fig ES.4)

- 3 • Average annual temperature over the contiguous United States has increased by 1.2°F
4 (0.7°C) for the period 1986–2016 relative to 1901–1960 and by 1.8°F (1.0°C) based
5 on a linear regression for the period 1901–2016 (*very high confidence*). Surface and
6 satellite data are consistent in their depiction of rapid warming since 1979 (*high*
7 *confidence*). Paleo-temperature evidence shows that recent decades are the warmest of
8 the past 1,500 years (*medium confidence*) (Ch.6)
- 9 • Average annual temperature over the contiguous United States is projected to rise
10 (*very high confidence*). Increases of about 2.5°F (1.4°C), relative to the recent past
11 (average from 1976–2005) are projected for the next few decades in all emissions
12 scenarios, implying recent record-setting years may be “common” in the near future
13 (*high confidence*). Much larger rises are projected by late century: 2.8°–7.3°F (1.6°–
14 4.1°C) in a lower emissions scenario (RCP4.5) and 5.8°–11.9°F (3.2°–6.6°C) in a
15 higher emissions scenario (RCP8.5) (*high confidence*). (Ch.6; Fig ES.4)
- 16 • In the United States, the urban heat island effect results in daytime temperatures 0.9°–
17 7.2°F (0.5°–4.0°C) higher and nighttime temperatures 1.8°– 4.5°F (1.0°–2.5°C) higher
18 in urban areas, with larger temperature differences in humid regions (primarily in the
19 eastern United States) and in cities with larger and denser populations. The urban heat
20 island effect will strengthen in the future as the structure and spatial extent as well as
21 population density of urban areas change and grow (*high confidence*). (Ch.10)

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Projected Changes in Average Annual Temperature



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Figure ES.4 Significantly More Warming Occurs Under Higher Greenhouse Gas Concentration Scenarios

These maps show the projected changes in annual average temperatures for mid- and late-21st century for two future pathways. Changes are the differences between the average projected temperatures for mid-century (2036–2065; top), and late-century (2071–2100; bottom), and those observed for the near-present (1976–2005). See Figure 6.7 in Chapter 6 for more details.

1 **Many Temperature and Precipitation Extremes Are Becoming More** 2 **Common**

3 Temperature and precipitation extremes can affect water quality and availability, agricultural
4 productivity, human health, vital infrastructure, iconic ecosystems and species, and the
5 likelihood of disasters. Some extremes have already become more frequent, intense, or of
6 longer duration, and many extremes are expected to continue to increase or worsen,
7 presenting substantial challenges for built, agricultural, and natural systems. Some storm
8 types such as hurricanes, tornadoes, and winter storms are also exhibiting changes that have
9 been linked to climate change, although the current state of the science does not yet permit
10 detailed understanding.

11 **Observed Changes in Extremes**

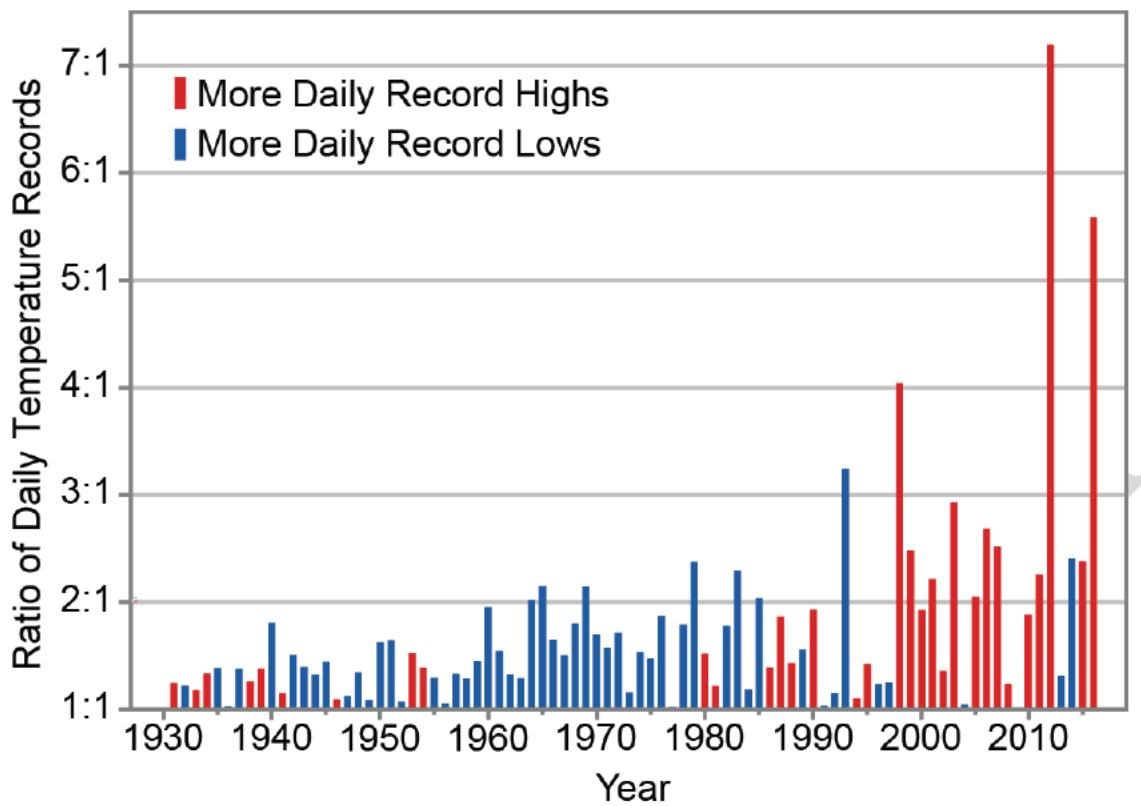
There have been marked changes in temperature extremes across the contiguous United States. The number of high temperature records set in the past two decades far exceeds the number of low temperature records. (*Very high confidence*) (Ch.6, Fig ES.5)

12

13 • The frequency of cold waves has decreased since the early 1900s, and the frequency of
14 heat waves has increased since the mid-1960s (the Dust Bowl remains the peak period
15 for extreme heat). (*Very high confidence*). (Ch.6)

16 • The frequency and intensity of extreme heat and heavy precipitation events are
17 increasing in most continental regions of the world (*very high confidence*). These
18 trends are consistent with expected physical responses to a warming climate. Climate
19 model studies are also consistent with these trends, although models tend to
20 underestimate the observed trends, especially for the increase in extreme precipitation
21 events (*very high confidence* for temperature, *high confidence* for extreme
22 precipitation). (Ch.1)

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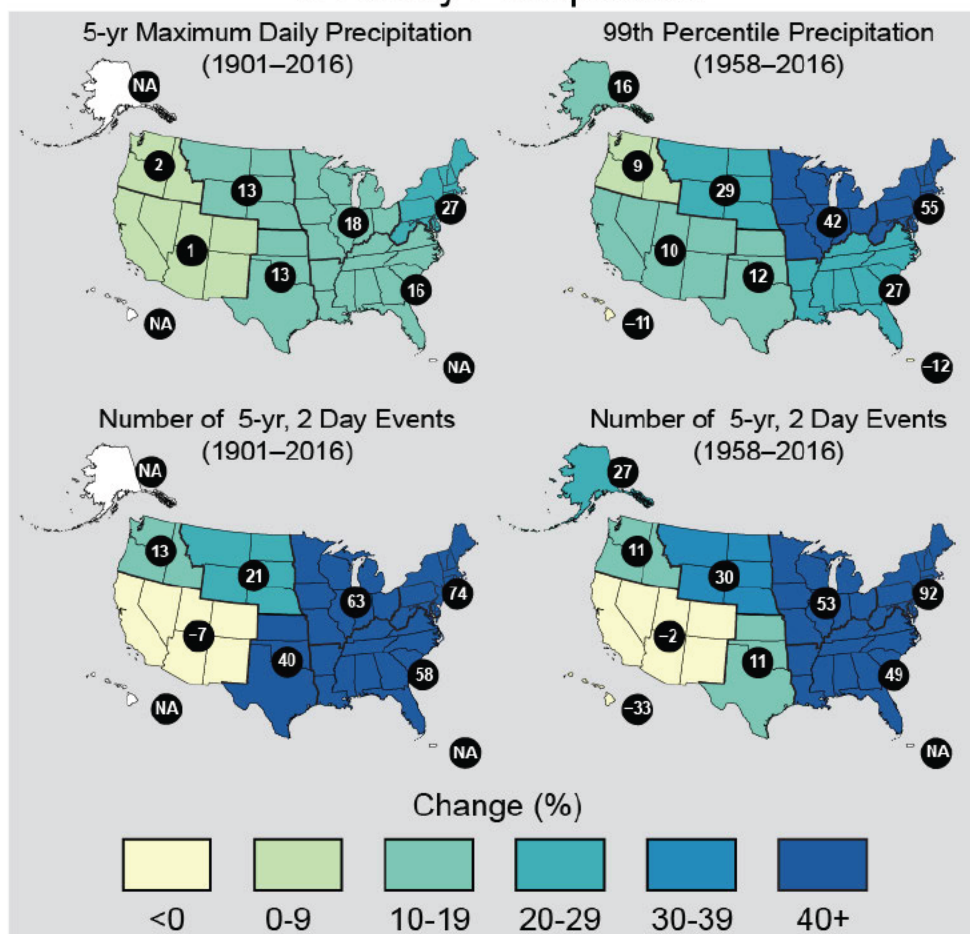


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Figure ES.5: Record Warm Daily Temperatures Are Occurring More Often. Observed changes in the occurrence of record-setting daily temperatures in the contiguous United States. Red bars indicate a year with more daily record highs than daily record lows, while blue bars indicate a year with more record lows than highs. The height of the bar indicates the ratio of record highs to lows (red) or of record lows to highs (blue). For example, a ratio of 2:1 for a blue bar means that there were twice as many record daily lows as daily record highs that year. (Figure source: NOAA/NCEI). (from Figure 6.5 in Chapter 6)

Heavy precipitation events in most parts of the United States have increased in both intensity and frequency since 1901 (*high confidence*). There are important regional differences in trends, with the largest increases occurring in the northeastern United States (*high confidence*). (Ch.7; Fig ES.6)

Observed Change in Heavy Precipitation



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2 **Figure ES.6: Extreme Precipitation Has Increased Across Much of the United States**
 3 These maps show the percentage change in several metrics of extreme precipitation by NCA4 region,
 4 including (upper left) the maximum daily precipitation in consecutive 5-year periods; (upper right) the
 5 amount of precipitation falling in daily events that exceed the 99th percentile of all non-zero
 6 precipitation days (top 1% of all daily precipitation events); (lower left) the number of 2-day events
 7 with a precipitation total exceeding the largest 2-day amount that is expected to occur, on average,
 8 only once every 5 years, as calculated over 1901-2016; and (lower right) the number of 2-day events
 9 with a precipitation total exceeding the largest 2-day amount that is expected to occur, on average,
 10 only once every 5 years, as calculated over 1958-2016. The number in each black circle is the percent
 11 change over the entire period, either 1901-2016 or 1958-2016. Note that Alaska and Hawai'i are not
 12 included in the 1901-2016 maps owing to a lack of observations in the earlier part of the 20th century.
 13 (Figure source: CICS-NC / NOAA NCEI). Based on figure 7.4 in Chapter 7.

- 14 • Recent droughts and associated heat waves have reached record intensity in some
 15 regions of the United States; however, by geographical scale and duration, the Dust
 16 Bowl era of the 1930s remains the benchmark drought and extreme heat event in the
 17 historical record. (Very high confidence) (Ch. 8)

- 1 • Northern Hemisphere spring snow cover extent, North America maximum snow
2 depth, snow water equivalent in the western United States, and extreme snowfall years
3 in the southern and western United States, have all declined, while extreme snowfall
4 years in parts of the northern United States have increased. (*Medium confidence*).
5 (Ch.7)
- 6 • There has been a trend toward earlier snowmelt and a decrease in snowstorm frequency
7 on the southern margins of climatologically snowy areas (*medium confidence*). Winter
8 storm tracks have shifted northward since 1950 over the Northern Hemisphere (*medium*
9 *confidence*). Potential linkages between the frequency and intensity of severe winter
10 storms in the United States and accelerated warming in the Arctic have been postulated,
11 but they are complex, and, to some extent, contested, and confidence in the connection
12 is currently *low*. (Ch.9)
- 13 • Tornado activity in the United States has become more variable, particularly over the
14 2000s, with a decrease in the number of days per year with tornadoes and an increase
15 in the number of tornadoes on these days (*medium confidence*). Confidence in past
16 trends for hail and severe thunderstorm winds, however, is *low* (Ch.9)

17 **Projected Changes in Extremes**

- 18 • The frequency and intensity of extreme temperature events are *virtually certain* to
19 increase in the future as global temperature increases (*high confidence*). Extreme
20 precipitation events will *very likely* continue to increase in frequency and intensity
21 throughout most of the world (*high confidence*). Observed and projected trends for
22 some other types of extreme events, such as floods, droughts, and severe storms, have
23 more variable regional characteristics. (Ch.1)

24

Extreme temperatures in the contiguous United States are projected to increase even more than average temperatures (*very high confidence*). (Ch.6)

- 27 • Both extremely cold days and extremely warm days are expected to become warmer.
28 Cold waves are predicted to become less intense while heat waves will become more
29 intense. The number of days below freezing is projected to decline while the number
30 above 90°F will rise. (*Very high confidence*) (Ch.6)
- 31 • The frequency and intensity of heavy precipitation events in the United States are
32 projected to continue to increase over the 21st century (*high confidence*). There are,
33 however, important regional and seasonal differences in projected changes in total
34 precipitation: the northern United States, including Alaska, is projected to receive
35 more precipitation in the winter and spring, and parts of the southwestern United

- 1 States are projected to receive less precipitation in the winter and spring (*medium*
2 *confidence*). (Ch.7)
- 3 • The frequency and severity of landfalling “atmospheric rivers” on the U.S. West Coast
4 (narrow streams of moisture that account for 30%–40% of precipitation and snowpack
5 in the region and are associated with severe flooding events) will increase as a result of
6 increasing evaporation and resulting higher atmospheric water vapor that occurs with
7 increasing temperature. (*Medium confidence*) (Ch.9)
- 8 • Projections indicate large declines in snowpack in the western United States and shifts
9 to more precipitation falling as rain than snow in the cold season in many parts of the
10 central and eastern United States (*high confidence*). (Ch.7)
- 11 • Substantial reductions in western U.S. winter and spring snowpack are projected as the
12 climate warms. Earlier spring melt and reduced snow water equivalent have been
13 formally attributed to human induced warming (*high confidence*) and will *very likely*
14 be exacerbated as the climate continues to warm (*very high confidence*). Under higher
15 emissions scenarios, and assuming no change to current water resources management,
16 chronic, long-duration hydrological drought is increasingly possible by the end of this
17 century (*very high confidence*). (Ch.8)

18

Future decreases in surface soil moisture from human activities over most of the United States are *likely* as the climate warms under the higher emissions scenarios. (*Medium confidence*) (Ch.8)

- 19 • The human effect on recent major U.S. droughts is complicated. Little evidence is
20 found for a human influence on observed precipitation deficits, but much evidence is
21 found for a human influence on surface soil moisture deficits due to increased
22 evapotranspiration caused by higher temperatures. (*High confidence*) (Ch.8)
- 23 • The incidence of large forest fires in the western United States and Alaska has
24 increased since the early 1980s (*high confidence*) and is projected to further increase
25 in those regions as the climate warms, with profound changes to certain ecosystems
26 (*medium confidence*). (Ch.8)
- 27 • Both physics and numerical modeling simulations (in general) indicate an increase in
28 tropical cyclone intensity in a warmer world, and the models generally show an
29 increase in the number of very intense tropical cyclones. For Atlantic and eastern
30 North Pacific hurricanes and western North Pacific typhoons, increases are projected
31 in precipitation rates (*high confidence*) and intensity (*medium confidence*). The
32 frequency of the most intense of these storms is projected to increase in the Atlantic

1 and western North Pacific (*low confidence*) and in the eastern North Pacific (*medium*
2 *confidence*). (Ch.9)

3 *****BOX ES.1*****

4 **The Connected Climate System: Distant Changes Affect the United States**

5 Weather conditions and the ways they vary across regions and over the course of the year are
6 influenced, in the United States as elsewhere, by a range of factors, including local conditions
7 (such as topography and urban heat islands), global trends (such as human-caused warming),
8 and global and regional circulation patterns, including cyclical and chaotic patterns of natural
9 variability within the climate system. For example, during an El Niño year, winters across the
10 southwestern United States are typically wetter than average, and global temperatures are
11 higher than average. During a La Niña year, conditions across the southwestern United States
12 are typically dry, and there tends to be a lowering of global temperatures (Fig. ES.7).

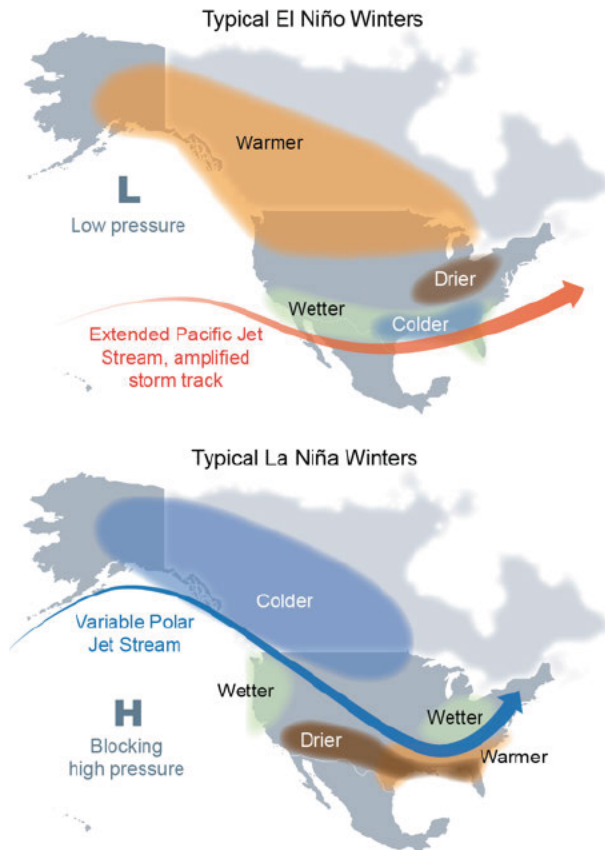
13 El Niño is not the only repeating pattern of natural variability in the climate system. Other
14 important patterns include the North Atlantic Oscillation (NAO)/Northern Annular Mode
15 (NAM) that particularly affects conditions on the U.S. East Coast, and the North Pacific
16 Oscillation (NPO) and Pacific North American Pattern (PNA) that especially affect conditions
17 in Alaska and the U.S. West Coast. These patterns are closely linked to other atmospheric
18 circulation phenomena like the position of the jet streams. Changes in the occurrence of these
19 patterns or their properties have contributed to recent U.S. temperature and precipitation
20 trends (*medium confidence*) although confidence is low regarding the size of the role of
21 human activities in these changes. (Ch.5)

22 Understanding the full scope of human impacts on climate requires a global focus because of
23 the interconnected nature of the climate system. For example, the climate of the Arctic and the
24 climate of the continental United States are connected through atmospheric circulation
25 patterns. While the Arctic may seem remote to most Americans, the climatic effects of
26 perturbations to arctic sea ice, land ice, surface temperature, snow cover, and permafrost
27 affect the amount of warming, sea level change, carbon cycle impacts, and potentially even
28 weather patterns in the lower 48 states. The Arctic is warming at a rate approximately twice as
29 fast as the global average and, if it continues to warm at the same rate, Septembers will be
30 nearly ice-free in the Arctic Ocean sometime between now and the 2040s (see ES.10). The
31 important influence of Arctic climate change on Alaska is apparent; the influence of Arctic
32 changes on U.S. weather over the coming decades remains an open question with the potential
33 for significant impact. (Ch.11)

34 Changes in the Tropics can also impact the rest of the globe, including the United States.
35 There is growing evidence that the Tropics have expanded poleward by about 70 to 200 miles
36 in each hemisphere over the period 1979–2009, with an accompanying shift of the subtropical
37 dry zones, midlatitude jets, and storm tracks (*medium to high confidence*). Human activities

1 have played a role in the change (*medium confidence*), although confidence is presently low
 2 regarding the magnitude of the human contribution relative to natural variability (Ch.5).

3



4

5

6 **Figure ES.7. Large-Scale Patterns of Natural Variability Affect U.S. Climate**

7 For example, this figure illustrates the typical January–March weather anomalies and atmospheric
 8 circulation during moderate to strong (top) El Niño and (bottom) La Niña. These influences over the
 9 United States often occur most strongly during the cold season. *From Figure 5.2 in Chapter 5.*

10 ******END BOX ES.1******

11 **Oceans Are Rising, Warming, and Becoming More Acidic**

12 Oceans occupy two-thirds of the planet’s surface and host unique ecosystems and species,
 13 including those important for global commercial and subsistence fishing. Understanding
 14 climate impacts on the ocean and the ocean’s feedbacks to the climate system is critical for a
 15 comprehensive understanding of current and future changes in climate.

16 **Global Ocean heat**

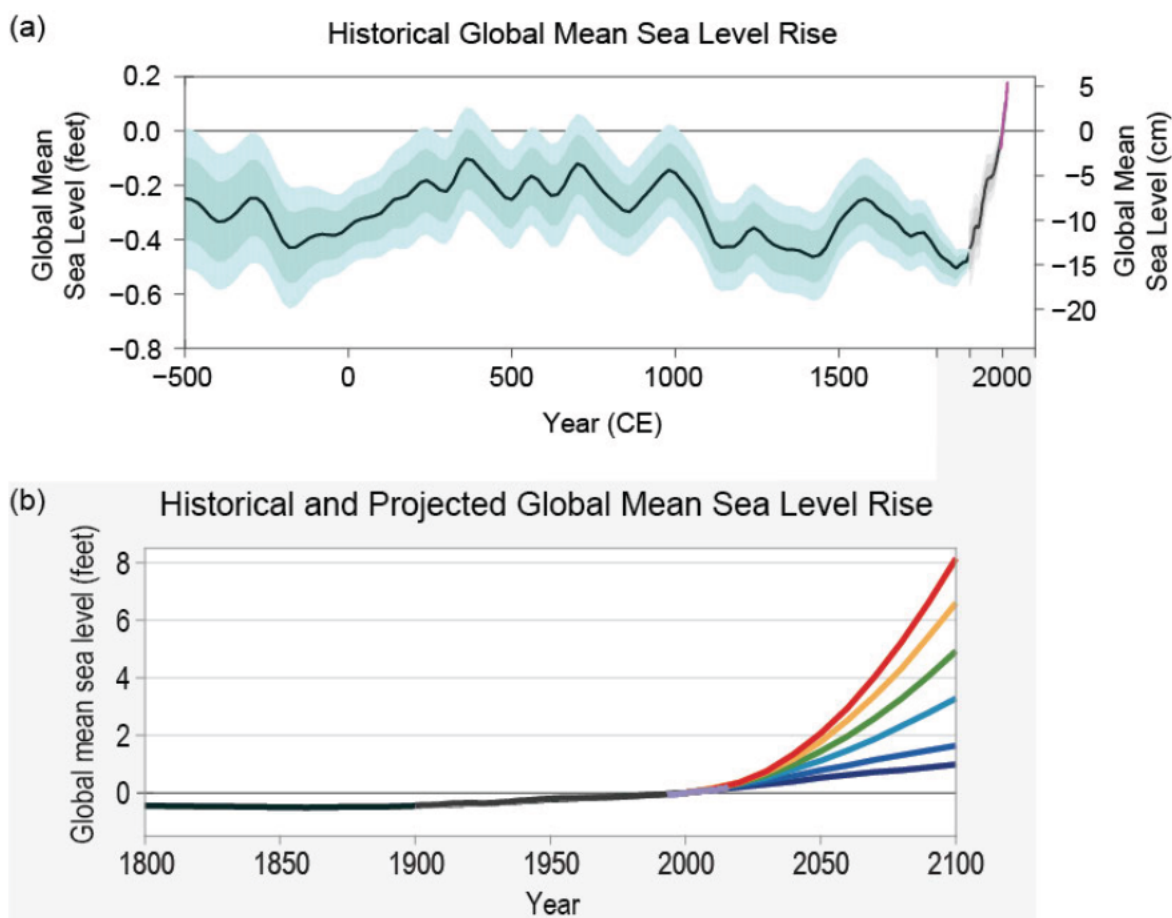
The world's oceans have absorbed about 93% of the excess heat caused by greenhouse gas warming since the mid-20th century, making them warmer and altering global and regional climate feedbacks. (*Very high confidence*) (Ch.13)

- 3 • Ocean heat content has increased at all depths since the 1960s and surface waters have
4 warmed by about $1.3^{\circ}\pm 0.1^{\circ}\text{F}$ ($0.7^{\circ}\pm 0.08^{\circ}\text{C}$) per century globally since 1900 to 2016.
5 Under high emissions scenarios, a global increase in average sea surface temperature
6 of $4.9^{\circ}\pm 1.3^{\circ}\text{F}$ ($2.7^{\circ}\pm 0.7^{\circ}\text{C}$) is projected by 2100. (*Very high confidence*). (Ch.13)

7 **Global and Regional Sea Level Rise**

Global mean sea level (GMSL) has risen by about 7–8 inches (about 16-21 cm) since 1900, with about 3 of those inches (about 7 cm) occurring since 1993 (*very high confidence*). (Ch.12)

- 12 • Human-caused climate change has made a substantial contribution to GMSL rise since
13 1900 (*high confidence*), contributing to a rate of rise that is greater than during any
14 preceding century in at least 2,800 years (*medium confidence*). (Ch.12; Fig ES.8)
- 15 • Relative to the year 2000, GMSL is *very likely* to rise by 0.3–0.6 feet (9–18 cm) by
16 2030, 0.5–1.2 feet (15–38 cm) by 2050, and 1–4 feet (30–130 cm) by 2100 (*very high*
17 *confidence* in lower bounds; *medium confidence* in upper bounds for 2030 and 2050;
18 *low confidence* in upper bounds for 2100). Future emissions pathways have little
19 effect on projected GMSL rise in the first half of the century, but significantly affect
20 projections for the second half of the century (*high confidence*). (Ch.12)



1

2 **Figure ES.8 Recent Sea Level Rise Fastest for Over 2,000 Years**

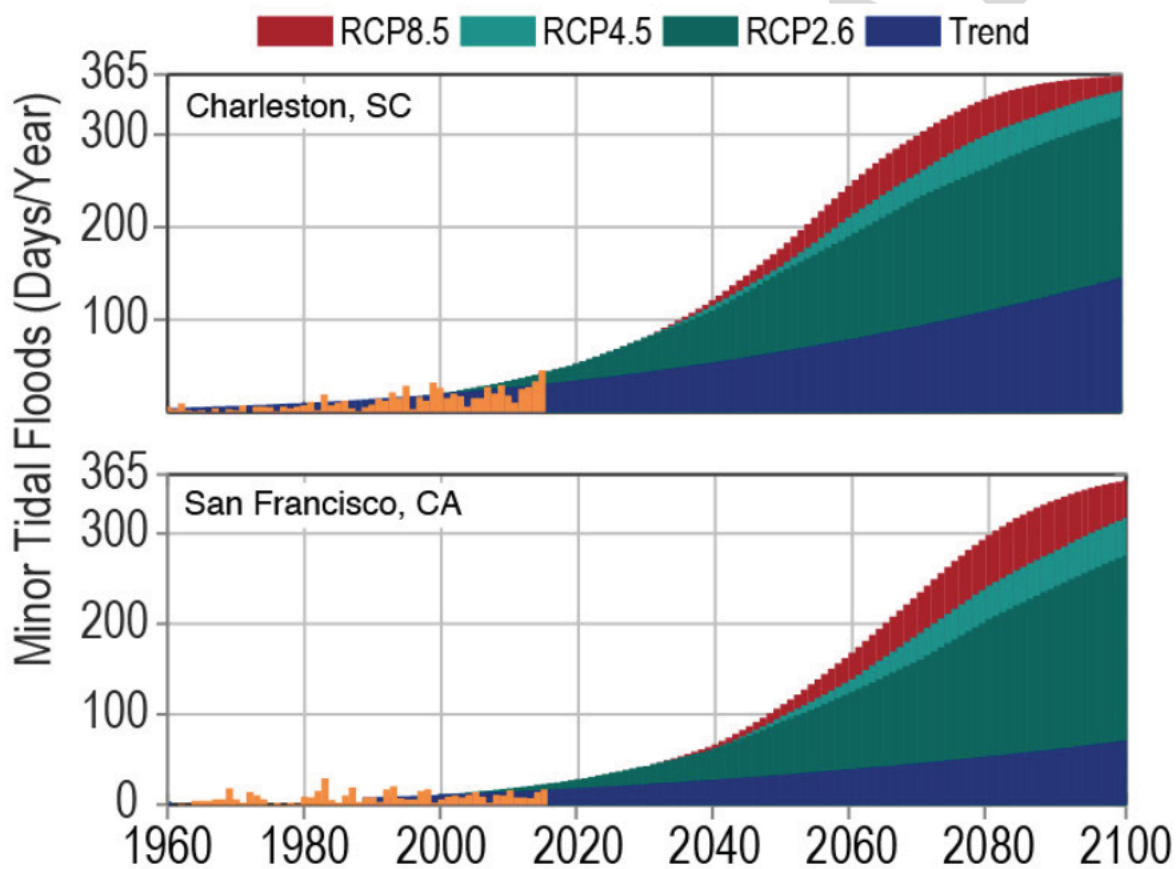
3 The top panel shows observed and reconstructed mean sea level for the last 2,500 years. The bottom
 4 panel shows projected mean sea level for six future scenarios. The six scenarios—spanning a range
 5 designed to inform a variety of decision makers—extend from a low scenario, consistent with
 6 continuation of the rate of sea level rise over the last quarter century, to an extreme scenario, assuming
 7 rapid mass loss from the Antarctic ice sheet. Note that the scale in the bottom graphic is three times
 8 greater than in the top graph. In both panels, the steep slope at the right of the graph depicts rapid sea
 9 level rise. *Based on Figure 12.2 and 12.4 in Chapter 12. See the main report for more details.*

- 10
- 11 • Emerging science regarding Antarctic ice sheet stability suggests that, for high
 12 emissions scenarios, a GMSL rise exceeding 8 feet (2.4 m) by 2100 is physically
 13 possible, although the probability of such an extreme outcome cannot currently be
 14 assessed. Regardless of emission pathway, it is *extremely likely* that GMSL rise will
 continue beyond 2100 (*high confidence*). (Ch.12)
 - 15 • Relative sea level rise in this century will vary along U.S. coastlines due, in part, to
 16 changes in Earth's gravitational field and rotation from melting of land ice, changes in
 17 ocean circulation, and vertical land motion (*very high confidence*). For almost all
 18 future GMSL rise scenarios, relative sea level rise is *likely* to be greater than the global
 19 average in the U.S. Northeast and the western Gulf of Mexico. In intermediate and low
 20 GMSL rise scenarios, relative sea level rise is *likely* to be less than the global average

1 in much of the Pacific Northwest and Alaska. For high GMSL rise scenarios, relative
 2 sea level rise is *likely* to be higher than the global average along all U.S. coastlines
 3 outside Alaska. Almost all U.S. coastlines experience more than global mean sea level
 4 rise in response to Antarctic ice loss, and thus would be particularly affected under
 5 extreme GMSL rise scenarios involving substantial Antarctic mass loss (*high*
 6 *confidence*). (Ch.12)

7 **Coastal Flooding**

- 8 • As sea levels have risen, the number of tidal floods each year that cause minor impacts
 9 (also called “nuisance floods”) have increased 5- to 10-fold since the 1960s in several
 10 U.S. coastal cities (*very high confidence*). Rates of increase are accelerating in over 25
 11 Atlantic and Gulf Coast cities (*very high confidence*). Tidal flooding will continue
 12 increasing in depth, frequency, and extent this century (*very high confidence*). (Ch.12)



13

14 **Figure ES. 9 “Nuisance Flooding” Increases Across the United States**

15 Annual occurrences of tidal floods (days per year), also called sunny-day or nuisance flooding, have
 16 increased for some U.S. coastal cities. Historical exceedances (orange bars) for two of the locations—
 17 Charleston, SC and San Francisco, CA—and future projections through 2100 based upon the
 18 continuation of the historical trend (blue) and under median RCP2.6, 4.5 and 8.5 conditions. (From
 19 *Figure 12.5, Chapter 12*).

1

- 2 • Assuming storm characteristics do not change, sea level rise will increase the
3 frequency and extent of extreme flooding associated with coastal storms, such as
4 hurricanes and nor'easters (*very high confidence*). A projected increase in the intensity
5 of hurricanes in the North Atlantic could increase the probability of extreme flooding
6 along most of the U.S. Atlantic and Gulf Coast states beyond what would be projected
7 based solely on RSL rise. However, there is *low confidence* in the magnitude of the
8 increase in intensity and the associated flood risk amplification, and these effects
9 could be offset or amplified by other factors, such as changes in storm frequency or
10 tracks. (Ch.12; ES. 9)

11 **Global Ocean Circulation**

- 12 • The potential slowing of the Atlantic Meridional Overturning Circulation (AMOC; of
13 which the Gulf Stream is one component)—as a result of increasing ocean heat
14 content and freshwater driven buoyancy changes—could have dramatic climate
15 feedbacks as the ocean absorbs less heat and CO₂ from the atmosphere. This slowing
16 would also affect the climates of North America and Europe. Any slowing
17 documented to date cannot be directly tied to human-caused forcing primarily due to
18 lack of adequate observational data and to challenges in modeling ocean circulation
19 changes. Under a high emissions scenario (RCP8.5), it is likely that the AMOC will
20 weaken over the 21st century by 12% to 54% (*low confidence*). (Ch.13)

21 **Global and Regional Ocean Acidification**

The world's oceans are currently absorbing more than a quarter of the CO₂ emitted to the atmosphere annually from human activities, making them more acidic (*very high confidence*), with potential detrimental impacts to marine ecosystems. (Ch.13)

22

- 23 • Higher-latitude systems typically have a lower buffering capacity against changing
24 acidity, exhibiting seasonally corrosive conditions sooner than low-latitude
25 systems. The rate of acidification is unparalleled in at least the past 66 million years
26 (*medium confidence*). Under RCP8.5, the global average surface ocean acidity is
27 projected to increase by 100% to 150% (*high confidence*). (Ch.13)
- 28 • Acidification is regionally greater than the global average along U.S. coastal systems
29 as a result of upwelling (e.g., in the Pacific Northwest) (*high confidence*), changes in
30 freshwater inputs (e.g., in the Gulf of Maine) (*medium confidence*), and nutrient input
31 (e.g., in urbanized estuaries) (*high confidence*). (Ch.13)

1

2 Ocean Oxygen

- 3 • Increasing sea surface temperatures, rising sea levels, and changing patterns of
4 precipitation, winds, nutrients, and ocean circulation are contributing to overall
5 declining oxygen concentrations at intermediate depths in various ocean locations and
6 in many coastal areas. Over the last half century, major oxygen losses have occurred
7 in inland seas, estuaries, and in the coastal and open ocean (*high confidence*). Ocean
8 oxygen levels are projected to decrease by as much as 3.5% under the RCP8.5
9 scenario by 2100 relative to preindustrial values (*high confidence*). (Ch.13)

**10 Climate Change in Alaska and across the Arctic Continues to Outpace
11 Global Climate Change**

12 Residents of Alaska are on the front lines of climate change. Crumbling buildings, roads, and
13 bridges and eroding shorelines are commonplace. Accelerated melting of multiyear sea ice
14 cover, mass loss from the Greenland Ice Sheet, reduced snow cover, and permafrost thawing
15 are stark examples of the rapid changes occurring in the Arctic. Furthermore, because
16 elements of the climate system are interconnected (see Box ES.1), changes in the Arctic
17 influence climate conditions outside the Arctic.

18 Arctic Temperature Increases

Annual average near-surface air temperatures across Alaska and the Arctic have increased over the last 50 years at a rate more than twice as fast as the global average temperature. (*Very high confidence*) (Ch.11)

19

- 20 • Rising Alaskan permafrost temperatures are causing permafrost to thaw and become
21 more discontinuous; this process releases additional carbon dioxide and methane
22 resulting in additional warming (*high confidence*). The overall magnitude of the
23 permafrost-carbon feedback is uncertain (Ch.2); however, it is clear that these
24 emissions have the potential to complicate the ability to meet policy goals for the
25 reduction of greenhouse gas concentrations. (Ch.11)
- 26 • Atmospheric circulation patterns connect the climates of the Arctic and the contiguous
27 United States. Evidenced by recent record warm temperatures in the Arctic and
28 emerging science, the midlatitude circulation has influenced observed arctic
29 temperatures and sea ice (*high confidence*). However, confidence is low regarding
30 whether or by what mechanisms observed arctic warming may have influenced the
31 midlatitude circulation and weather patterns over the continental United States. The

1 influence of arctic changes on U.S. weather over the coming decades remains an open
2 question with the potential for significant impact. (Ch.11)

3 **Arctic Land Ice Loss**

4 • Arctic land ice loss observed in the last three decades continues, in some cases
5 accelerating (*very high confidence*). It is *virtually certain* that Alaska glaciers have lost
6 mass over the last 50 years, with each year since 1984 showing an annual average ice
7 mass less than the previous year. Over the satellite record, average ice mass loss from
8 Greenland was -269 Gt per year between April 2002 and April 2016, accelerating in
9 recent years (*high confidence*). (Ch.11)

10 **Arctic Sea Ice Loss**

11

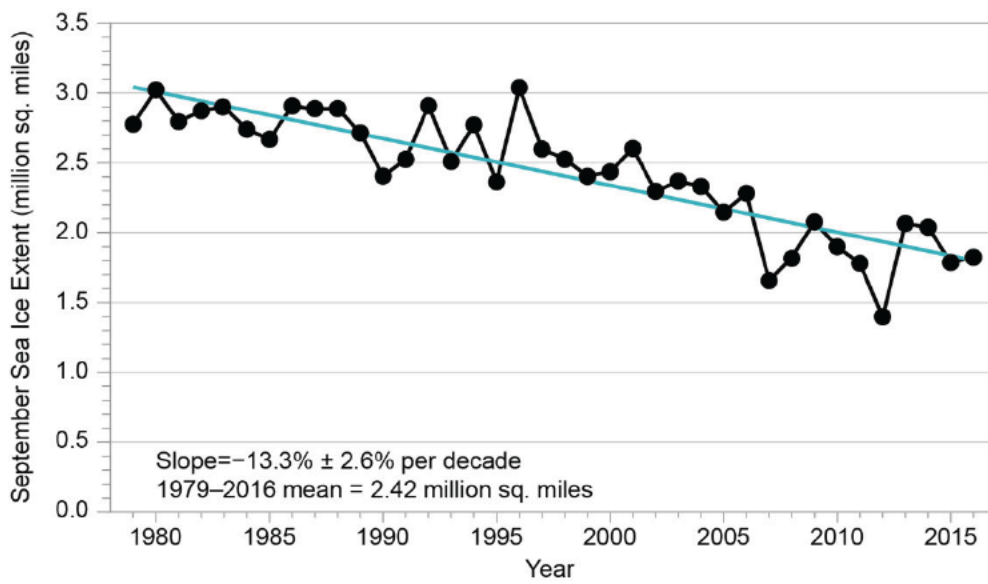
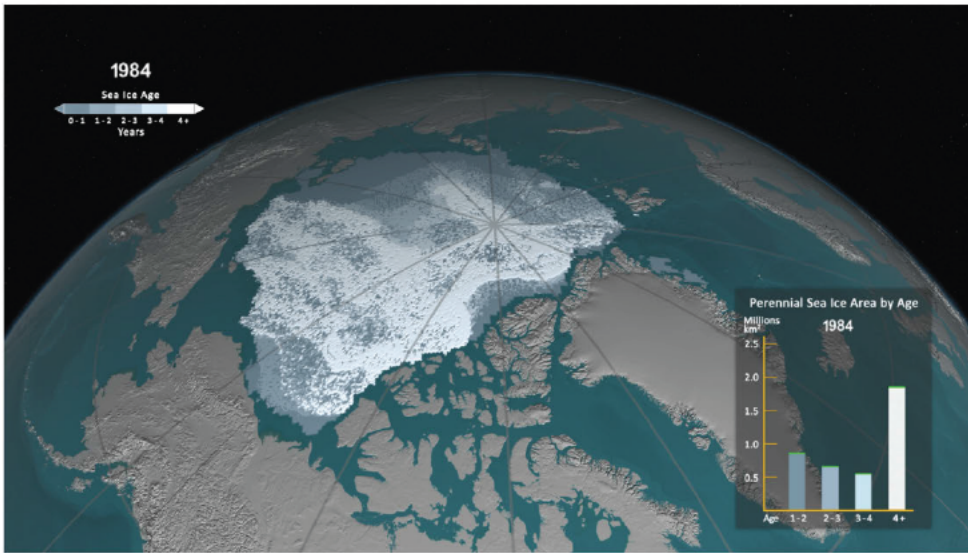
Since the early 1980s, annual average arctic sea ice has decreased in extent between 3.5% and 4.1% per decade, has become thinner by between 4.3 and 7.5 feet, and is melting at least 15 more days each year. September sea ice extent has decreased between 10.7% and 15.9% per decade. (*Very high confidence*) (Ch.11)

12

13 • Arctic sea ice loss is expected to continue through the 21st century, *very likely*
14 resulting in nearly sea ice-free late summers by the 2040s (*very high confidence*).
15 (Ch.11)

16 • It is *virtually certain* that human activities have contributed to Arctic surface
17 temperature warming, sea ice loss since 1979, glacier mass loss, and northern
18 hemisphere snow extent decline observed across the Arctic (*very high confidence*).
19 Human activities have *likely* contributed to more than half of the observed September
20 sea ice decline since 1979 (*high confidence*). (Ch.11)

21



1

1 **Figure ES.10 Multiyear Sea Ice Has Declined Dramatically**

2 September sea ice extent and age shown for (a) 1984 and (b) 2016, illustrating significant reductions
3 in sea ice extent and age (thickness). The bar graph in the lower right of each panel illustrates the sea
4 ice area (unit: million km²) covered within each age category (> 1 year), and the green bars represent
5 the maximum extent for each age range during the record. The year 1984 is representative of
6 September sea ice characteristics during the 1980s. The years 1984 and 2016 are selected as endpoints
7 in the time series; a movie of the complete time series is available at [http://svs.gsfc.nasa.gov/cgi-](http://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=4489)
8 [bin/details.cgi?aid=4489](http://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=4489). (c) Shows the satellite-era arctic sea ice areal extent trend from 1979 to 2016
9 for September (unit: million mi²)

10 *From Figure 11.1 in Chapter 11.*

11 **Limiting Globally Averaged Warming to 2°C (3.6°F) Will Require Major** 12 **Reductions in Emissions**

13 Human activities are now the dominant cause of the observed trends in climate. For that
14 reason, future climate projections are based on scenarios of how greenhouse gas emissions
15 will continue to affect the climate over the remainder of this century and beyond (see Sidebar:
16 Scenarios Used in this Assessment). There remains significant uncertainty about future
17 emissions due to changing economic, political, and demographic factors. For that reason, this
18 report quantifies possible climate changes for a broad set of plausible future scenarios through
19 the end of the century. (Ch.2, 4, 14)

The observed increase in global carbon emissions over the past 15–20 years has been consistent with higher scenarios (*very high confidence*). In 2014 and 2015, emission growth rates slowed as economic growth has become less carbon-intensive (*medium confidence*). Even if this slowing trend continues, however, it is not yet at a rate that would meet the long-term temperature goal of the Paris Agreement of holding the increase in the global average temperature to well below 3.6°F (2°C) above preindustrial levels (*high confidence*). (Ch.4)

- 20
21
- 22 • Global mean atmospheric carbon dioxide (CO₂) concentration has now passed 400
23 ppm, a level that last occurred about 3 million years ago, when global average
24 temperature and sea level were significantly higher than today (*high confidence*).
25 Continued growth in CO₂ emissions over this century and beyond would lead to an
26 atmospheric concentration not experienced in tens of millions of years (*medium*
27 *confidence*). The present-day emissions rate of nearly 10 GtC per year suggests that
28 there is no climate analog for this century any time in at least the last 50 million years
29 (*medium confidence*). (Ch.4)

- 1 • Warming and associated climate effects from CO₂ emissions persist for decades to
2 millennia. In the near-term, changes in climate are determined by past and present
3 greenhouse gas emissions modified by natural variability. Reducing the total
4 concentration of atmospheric CO₂ is necessary to limit near-term climate change and
5 stay below long-term warming targets (such as the oft-cited 3.6°F [2°C] goal). Other
6 greenhouse gases (e.g., methane) and black carbon aerosols exert stronger warming
7 effects than CO₂ on a per ton basis, but they do not persist as long in the atmosphere
8 (Ch.2); therefore, mitigation of non-CO₂ species contributes substantially to near-term
9 cooling benefits but cannot be relied upon for ultimate stabilization goals. (*Very high*
10 *confidence*) (Ch.14)
- 11 • Stabilizing global mean temperature below long-term warming targets requires an
12 upper limit on the accumulation of CO₂ in the atmosphere. The relationship between
13 cumulative CO₂ emissions and global temperature response is estimated to be nearly
14 linear. Nevertheless, in evaluating specific temperature targets, there are uncertainties
15 about the exact amount of compatible human-caused CO₂ emissions due to
16 uncertainties in climate sensitivity, the response of the carbon cycle including
17 feedbacks, the amount of past CO₂ emissions, and the influence of past and future
18 non-CO₂ species. (*Very high confidence*) (Ch.14)

19

Choices made today will determine the magnitude of climate change risks beyond the next few decades. (Chs. 4,14)

- 20 • Stabilizing global mean temperature below 3.6°F (2°C) or lower relative to
21 preindustrial levels requires significant reductions in net global CO₂ emissions relative
22 to present-day values before 2040 and likely requires net emissions to become zero or
23 possibly negative later in the century. Accounting for the temperature effects of non-
24 CO₂ species, cumulative CO₂ emissions are required to stay below about 800 GtC in
25 order to provide a two-thirds likelihood of preventing 3.6°F (2°C) of warming,
26 meaning approximately 230 GtC more could be emitted globally. Assuming global
27 emissions follow the range between the RCP8.5 and RCP4.5 scenarios, emissions
28 could continue for approximately two decades before this cumulative carbon threshold
29 is exceeded. (Ch.14)
- 30 • Successful implementation of the first round of Nationally Determined Contributions
31 associated with the Paris Agreement will provide some likelihood of meeting the long-
32 term temperature goal of limiting global warming to “well below” 3.6°F (2°C) above
33 preindustrial levels; the likelihood depends strongly on the magnitude of global
34 emission reductions after 2030. (*High confidence*) (Ch.14)

- 1 • Climate intervention or geoengineering strategies such as solar radiation management
2 are measures that attempt to limit or reduce global temperature increases. If interest in
3 geoengineering increases with observed impacts and/or projected risks of climate
4 change, interest will also increase in assessments of the technical feasibilities, costs,
5 risks, co-benefits, and governance challenges of these additional measures, which are
6 as yet unproven at scale. These assessments are a necessary step before judgments
7 about the benefits and risks of these approaches can be made with high confidence.
8 (*High confidence*) (Ch.14)
- 9 • As a whole, the terrestrial biosphere (soil and plants) is a net “sink” for carbon
10 (drawing down carbon from the atmosphere), and this sink has steadily increased since
11 1980 (*very high confidence*). Because of the uncertainty in the trajectory of land cover,
12 the possibility of the land becoming a net carbon source cannot be excluded (*very high*
13 *confidence*). (Ch.10)

14 **There is a Significant Possibility for Unanticipated Changes**

15 Humanity is conducting an unprecedented experiment with the Earth’s climate system
16 through emissions from large-scale fossil-fuel combustion, widespread deforestation, and
17 other changes to the atmosphere and landscape. While researchers and policymakers must rely
18 on climate model projections for a representative picture of the future Earth system under
19 these conditions, there are still elements of the Earth system that models do not capture well.
20 For this reason, there is significant potential for humankind’s planetary experiment to result in
21 unanticipated surprises—and the further and faster the Earth’s climate system is changed, the
22 greater the risk of such surprises.

23 There are at least two types of potential surprises: *compound events*, where multiple extreme
24 climate events occur simultaneously or sequentially (creating greater overall impact), and
25 *critical threshold or tipping point events*, where some threshold is crossed in the climate
26 system (that leads to large impacts). The probability of such surprises – some of which may
27 be abrupt and/or irreversible - as well as other more predictable but difficult-to-manage
28 impacts, increases as the influence of human activities on the climate system increases.
29 (Ch.15)

Unanticipated and difficult or impossible-to-manage changes in the climate system are possible throughout the next century as critical thresholds are crossed and/or multiple climate-related extreme events occur simultaneously. (Ch.15)

- 33 • Positive feedbacks (self-reinforcing cycles) within the climate system have the
34 potential to accelerate human-induced climate change and even shift the Earth’s
35 climate system, in part or in whole, into new states that are very different from those
36 experienced in the recent past (for example, ones with greatly diminished ice sheets or

1 different large-scale patterns of atmosphere or ocean circulation). Some feedbacks and
2 potential state shifts can be modeled and quantified; others can be modeled or
3 identified but not quantified; and some are probably still unknown. (*Very high*
4 *confidence* in the potential for state shifts and in the incompleteness of knowledge
5 about feedbacks and potential state shifts). (Ch.15)

- 6 • The physical and socioeconomic impacts of compound extreme events (such as
7 simultaneous heat and drought, wildfires associated with hot and dry conditions, or
8 flooding associated with high precipitation on top of snow or waterlogged ground) can
9 be greater than the sum of the parts (*very high confidence*). Few analyses consider the
10 spatial or temporal correlation between extreme events. (Ch.15)

- 11 • While climate models incorporate important climate processes that can be well
12 quantified, they do not include all of the processes that can contribute to feedbacks
13 (Ch. 2), compound extreme events, and abrupt and/or irreversible changes. For this
14 reason, future changes outside the range projected by climate models cannot be ruled
15 out (*very high confidence*). Moreover, the systematic tendency of climate models to
16 underestimate temperature change during warm paleoclimates suggests that climate
17 models are more likely to underestimate than to overestimate the amount of long-term
18 future change (*medium confidence*). (Ch.15)

19 ****BOX ES.2****

20 A Summary of Advances Since NCA3

21 Advances in scientific understanding and scientific approach, as well as developments in
22 global policy, have occurred since NCA3. A detailed summary of these advances can be
23 found at the end of Chapter 1: Our Globally Changing Climate. Highlights of what aspects are
24 either especially strengthened or are emerging in the current findings include:

- 25 • *Detection and attribution*: Significant advances have been made in the attribution of
26 the human influence for individual climate and weather extreme events since NCA3.
27 (Chapters 3,6,7,8).
- 28 • *Atmospheric circulation and extreme events*: The extent to which atmospheric
29 circulation in the midlatitudes is changing or is projected to change, possibly in ways
30 not captured by current climate models, is a new important area of research. (Chapters
31 5,6,7).
- 32 • *Increased understanding of specific types of extreme events*: How climate change may
33 affect specific types of extreme events in the United States is another key area where
34 scientific understanding has advanced. (Chapter 9).
- 35 • *High-resolution global climate model simulations*: As computing resources have
36 grown, multidecadal simulations of global climate models are now being conducted at
37 horizontal resolutions on the order of 15 miles (25 km) that provide more realistic

- 1 characterization of intense weather systems, including hurricanes. (Chapter 9).
- 2 • *Oceans and coastal waters*: Concern over ocean acidification, warming, and oxygen
3 loss is increasing as scientific understanding of the severity of their impacts grows.
4 Both oxygen loss and acidification may be magnified in some U.S. coastal waters
5 relative to the global average, raising the risk of serious ecological and economic
6 consequences. (Chapters 2, 13).
- 7 • *Local sea level change projections*: For the first time in the NCA process, sea level
8 rise projections incorporate geographic variation based on factors such as local land
9 subsidence, ocean currents, and changes in Earth’s gravitational field. (Chapter 12).
- 10 • *Accelerated ice-sheet loss and irreversibility*: New observations from many different
11 sources confirm that ice-sheet loss is accelerating. Combining observations with
12 simultaneous advances in the physical understanding of ice sheets, leads to the
13 conclusion that up to 8.5 feet of global sea level rise is possible by 2100 under a high
14 emissions scenario (RCP8.5), up from 6.6 feet in NCA3. (Chapter 12).
- 15 • *Slower regrowth in Arctic sea ice area extent in fall and winter 2016–2017*: The
16 annual Arctic sea ice extent minimum for 2016 relative to the long-term record was
17 the second lowest on record; since 1981, the sea ice minimum has decreased by 13.3%
18 per decade, more than 46% over the 35 years. In fall and winter 2016–2017, record-
19 setting slow seasonal ice regrowth was the lowest since observations began in 1981.
20 (Chapter 11).
- 21 • *Potential surprises*: Both large-scale state shifts in the climate system (sometimes
22 called “tipping points”) and compound extremes have the potential to generate
23 unanticipated climate surprises. The further the Earth system departs from historical
24 climate forcings, and the more the climate changes, the greater the potential for these
25 surprises. (Chapter 15).
- 26 • *The Paris Agreement*: The Paris Agreement, which entered into force in 2016,
27 provides a new framework for its parties for the mitigation of and adaption to climate
28 change. This report discusses some important aspects of climate science that are
29 relevant to the Agreement. (Chapters 4, 14).

30 ****End Box ES.2****

1. Our Globally Changing Climate

2. KEY FINDINGS

- 3 1. The global climate continues to change rapidly compared to the pace of the natural
4 variations in climate that have occurred throughout Earth's history. Trends in globally
5 averaged temperature, sea level rise, upper-ocean heat content, land-based ice melt,
6 Arctic sea ice, depth of seasonal permafrost thaw, and other climate variables provide
7 consistent evidence of a warming planet. These observed trends are robust and have been
8 confirmed by multiple independent research groups around the world. (*Very high*
9 *confidence*)
- 10 2. The frequency and intensity of extreme heat and heavy precipitation events are increasing
11 in most continental regions of the world (*very high confidence*). These trends are
12 consistent with expected physical responses to a warming climate. Climate model studies
13 are also consistent with these trends, although models tend to underestimate the observed
14 trends, especially for the increase in extreme precipitation events (*very high confidence*
15 for temperature, *high confidence* for extreme precipitation). The frequency and intensity
16 of extreme temperature events are *virtually certain* to increase in the future as global
17 temperature increases (*high confidence*). Extreme precipitation events will *very likely*
18 continue to increase in frequency and intensity throughout most of the world (*high*
19 *confidence*). Observed and projected trends for some other types of extreme events, such
20 as floods, droughts, and severe storms, have more variable regional characteristics.
- 21 3. Many lines of evidence demonstrate that it is *extremely likely* that human influence has
22 been the dominant cause of the observed warming since the mid-20th century. Formal
23 detection and attribution studies for the period 1951 to 2010 find that the observed global
24 mean surface temperature warming lies in the middle of the range of likely human
25 contributions to warming over that same period. We find no convincing evidence that
26 natural variability can account for the amount of global warming observed over the
27 industrial era. For the period extending over the last century, there are no convincing
28 alternative explanations supported by the extent of the observational evidence. Solar
29 output changes and internal variability can only contribute marginally to the observed
30 changes in climate over the last century, and we find no convincing evidence for natural
31 cycles in the observational record that could explain the observed changes in climate.
32 (*Very high confidence*)
- 33 4. Global climate is projected to continue to change over this century and beyond. The
34 magnitude of climate change beyond the next few decades will depend primarily on the
35 amount of greenhouse (heat-trapping) gases emitted globally and on the remaining
36 uncertainty in the sensitivity of Earth's climate to those emissions (*very high confidence*).
37 With significant reductions in the emissions of greenhouse gases, the global annually

1 averaged temperature rise could be limited to 3.6°F (2°C) or less. Without major
2 reductions in these emissions, the increase in annual average global temperatures relative
3 to preindustrial times could reach 9°F (5°C) or more by the end of this century (*high*
4 *confidence*).

5 5. Natural variability, including El Niño events and other recurring patterns of ocean–
6 atmosphere interactions, impact temperature and precipitation, especially regionally, over
7 months to years. The global influence of natural variability, however, is limited to a small
8 fraction of observed climate trends over decades. (*Very high confidence*)

9 6. Longer-term climate records over past centuries and millennia indicate that average
10 temperatures in recent decades over much of the world have been much higher, and have
11 risen faster during this time period, than at any time in the past 1,700 years or more, the
12 time period for which the global distribution of surface temperatures can be
13 reconstructed. (*High confidence*)

14 **1.1. Introduction**

15 Since the Third U.S. National Climate Assessment (NCA3) was published in May 2014, new
16 observations along multiple lines of evidence have strengthened the conclusion that Earth’s
17 climate is changing at a pace and in a pattern not explainable by natural influences. While this
18 report focuses especially on observed and projected future changes for the United States, it is
19 important to understand those changes in the global context (this chapter).

20 The world has warmed over the last 150 years, especially over the last six decades, and that
21 warming has triggered many other changes to Earth’s climate. Evidence for a changing climate
22 abounds, from the top of the atmosphere to the depths of the oceans. Thousands of studies
23 conducted by tens of thousands of scientists around the world have documented changes in
24 surface, atmospheric, and oceanic temperatures; melting glaciers; disappearing snow cover;
25 shrinking sea ice; rising sea level; and an increase in atmospheric water vapor. Rainfall patterns
26 and storms are changing and the occurrence of droughts is shifting.

27 Many lines of evidence demonstrate that human activities, especially emissions of greenhouse
28 gases, are primarily responsible for the observed climate changes in the industrial era, especially
29 over the last six decades (see attribution analysis in Ch. 3: Detection and Attribution). Formal
30 detection and attribution studies for the period 1951 to 2010 find that the observed global mean
31 surface temperature warming lies in the middle of the range of likely human contributions to
32 warming over that same period. The Intergovernmental Panel on Climate Change concluded that
33 it is extremely likely that human influence has been the dominant cause of the observed warming
34 since the mid-20th century (IPCC 2013). Over the last century, there are no alternative
35 explanations supported by the evidence that are either credible or that can contribute more than
36 marginally to the observed patterns. We find no convincing evidence that natural variability can

1 account for the amount of global warming observed over the industrial era. Solar flux variations
2 over the last six decades have been too small to explain the observed changes in climate (Bindoff
3 et al. 2013). There are no apparent natural cycles in the observational record that can explain the
4 recent changes in climate (e.g., PAGES 2K Consortium 2013; Marcott et al. 2013). In addition,
5 natural cycles within the Earth’s climate system can only redistribute heat; they cannot be
6 responsible for the observed increase in the overall heat content of the climate system (Church et
7 al. 2011). Any explanations for the observed changes in climate must be grounded in understood
8 physical mechanisms, appropriate in scale, and consistent in timing and direction with the long-
9 term observed trends. Known human activities quite reasonably explain what has happened
10 without the need for other factors. Internal variability and forcing factors other than human
11 activities cannot explain what is happening and there are no suggested factors, even speculative
12 ones, that can explain the timing or magnitude and that would somehow cancel out the role of
13 human factors (Anderson et al. 2012). The science underlying this evidence, along with the
14 observed and projected changes in climate, is discussed in later chapters, starting with the basis
15 for a human influence on climate in Chapter 2: Physical Drivers of Climate Change.

16 Throughout this report, we also analyze projections of future changes in climate. Predicting how
17 climate will change in future decades is a different scientific issue from predicting weather a few
18 weeks from now. Local weather is short term, with limited predictability, and is determined by
19 the complicated movement and interaction of high pressure and low pressure systems in the
20 atmosphere; thus, it is difficult to forecast day-to-day changes beyond about two weeks into the
21 future. Climate, on the other hand, is the statistics of weather—meaning not just average values
22 but also the prevalence and intensity of extremes—as observed over a period of decades. Climate
23 emerges from the interaction, over time, of rapidly changing local weather and more slowly
24 changing regional and global influences, such as the distribution of heat in the oceans, the
25 amount of energy reaching Earth from the sun, and the composition of the atmosphere. See
26 Chapter 4: Projections and later chapters for more on climate projections.

27 Throughout this report, we include many findings that further strengthen or add to the
28 understanding of climate change relative to those found in NCA3 and other assessments of the
29 science. Several of these are highlighted in an “Advances Since NCA3” box at the end of this
30 chapter.

31 **1.2. Indicators of a Globally Changing Climate**

32 Highly diverse types of direct measurements made on land, sea, and in the atmosphere over
33 many decades have allowed scientists to conclude with high confidence that global mean
34 temperature is increasing. Observational datasets for many other climate variables support the
35 conclusion with high confidence that the global climate is changing (Blunden and Arndt 2016;
36 Meehl et al. 2016a; also see EPA 2016). Figure 1.1 depicts several of the observational indicators
37 that demonstrate trends consistent with a warming planet over the last century. Temperatures in
38 the lower atmosphere and ocean have increased, as have near-surface humidity and sea level. Not

1 only has ocean heat content increased dramatically (Figure 1.1), but more than 90% of the
2 energy gained in the combined ocean–atmosphere system over recent decades has gone into the
3 ocean (Rhein et al. 2013; Johnson et al. 2015).

4 Basic physics tells us that a warmer atmosphere can hold more water vapor; this is exactly what
5 is measured from satellite data. At the same time, a warmer world means higher evaporation
6 rates and major changes to the hydrological cycle, including increases in the prevalence of
7 torrential downpours. In addition, Arctic sea ice, mountain glaciers, and Northern Hemisphere
8 spring snow cover have all decreased. The relatively small increase in Antarctic sea ice in the 15-
9 year period from 2000 through early 2016 appears to be best explained as being due to localized
10 natural variability (see e.g., Meehl et al. 2016a; Ramsayer 2014); while possibly also related to
11 natural variability, the 2017 Antarctic sea ice minimum reached in early March was the lowest
12 measured since reliable records began in 1979. The vast majority of the glaciers in the world are
13 losing mass at significant rates. The two largest ice sheets on our planet—on the land masses of
14 Greenland and Antarctica—are shrinking. Five different observational datasets show the heat
15 content of the oceans is increasing.

16 Many other indicators of the changing climate have been determined from other observations –
17 for example, changes in the growing season and the allergy season (see e.g., EPA 2016;
18 USGCRP 2017). In general, the indicators demonstrate continuing changes in climate since the
19 publication of NCA3. As with temperature, independent researchers have analyzed each of these
20 indicators and come to the same conclusion: all of these changes paint a consistent and
21 compelling picture of a warming planet.

22 **[INSERT FIGURE 1.1 HERE]**

23 **1.3. Trends in Global Temperatures**

24 Global annual-average temperature (as calculated from instrumental records over both land and
25 oceans; used interchangeably with global average temperature in the discussion below) has
26 increased by more than 1.2°F (0.7°C) for the period 1986–2016 relative to 1901–1960 (Figure
27 1.2); see Vose et al. (2012) for discussion on how global annual-average temperature is derived
28 by scientists. The linear regression change over the entire period from 1901–2016 is 1.8°F
29 (1.0°C). Global average temperature is not expected to increase smoothly over time in response
30 to the human warming influences, because the warming trend is superimposed on natural
31 variability associated with, for example, the El Niño/ La Niña ocean-heat oscillations and the
32 cooling effects of particles emitted by volcanic eruptions. Even so, 16 of the 17 warmest years in
33 the instrumental record (since the late 1800s) occurred in the period from 2001 to 2016 (1998
34 was the exception). Global average temperature for 2016 has now surpassed 2015 by a small
35 amount as the warmest year on record. The year 2015 far surpassed 2014 by 0.29°F (0.16°C),
36 four times greater than the difference between 2014 and the next warmest year, 2010 (NCEI

1 2016). Three of the four warmest years on record have occurred since the analyses through 2012
2 were reported in NCA3.

3 A strong El Niño contributed to 2015's record warmth (Blunden and Arndt 2016). Though an
4 even more powerful El Niño occurred in 1998, the global temperature in that year was
5 significantly lower (by 0.49°F [0.27°C]) than that in 2015. This suggests that human-induced
6 warming now has a stronger influence on the occurrence of record temperatures than El Niño
7 events. In addition, the El Niño/La Niña cycle may itself be affected by the human influence on
8 the Earth's climate system (Steinman et al. 2012; Trenberth 2015). It is the complex interaction
9 of natural sources of variability with the continuously growing human warming influence that is
10 now shaping the Earth's weather and, as a result, its climate.

11 Globally, the persistence of the warming over the past 60 years far exceeds what can be
12 accounted for by natural variability alone (IPCC 2013). That does not mean, of course, that
13 natural sources of variability have become insignificant. They can be expected to continue to
14 contribute a degree of "bumpiness" in the year-to-year global average temperature trajectory, as
15 well as exert influences on the average rate of warming that can last a decade or more (Deser et
16 al. 2012; Karl et al. 2015; Knutson et al. 2016) (see Box 1.1).

17 **[INSERT FIGURE 1.2 HERE]**

18 Warming during the first half of the 1900s occurred mostly in the Northern Hemisphere
19 (Delworth and Knutson 2000). Recent decades have seen greater warming in response to
20 accelerating increases in greenhouse gas concentrations, particularly at high northern latitudes,
21 and over land as compared to the ocean (see Figure 1.3). In general, winter is warming faster
22 than summer (especially in northern latitudes). Also, nights are warming faster than days
23 (Alexander et al. 2006; Davy et al. 2016). There is also some evidence of faster warming at
24 higher elevations (Mountain Research Initiative 2015).

25 Most ocean areas around the Earth are warming (see Ch. 13: Ocean Changes). Even in the
26 absence of significant ice melt, the ocean is expected to warm more slowly given its larger heat
27 capacity, leading to land-ocean differences in warming (as seen in Figure 1.3). As a result, the
28 climate for land areas often responds more rapidly than the ocean areas, even though the forcing
29 driving a change in climate occurs equally over land and the oceans (IPCC 2013). A few regions,
30 such as the North Atlantic Ocean, have experienced cooling over the last century, though these
31 areas have warmed over recent decades. Regional climate variability is important (e.g., Hurrell
32 and Deser 2009; Hoegh-Guldberg et al. 2014) as are the effects of the increasing freshwater in
33 the North Atlantic from melting of sea and land ice (Rahmstorf et al. 2015).

34 **[INSERT FIGURE 1.3 HERE]**

35 Figure 1.4 shows the projected changes in globally averaged temperature for a range of future
36 pathways that vary from assuming strong continued dependence on fossil fuels in energy and

1 transportation systems over the 21st century (the high scenario is Representative Concentration
2 Pathway 8.5, or RCP8.5) to assuming major emissions-reduction actions (the very low scenario,
3 RCP2.6). Chapter 4: Projections describes the future scenarios and the models of Earth's climate
4 system being used to quantify the impact of human choices and natural variability on future
5 climate. These analyses also suggest that global surface temperature increases for the end of the
6 21st century are *very likely* to exceed 1.5°C (2.7°F) relative to the 1850–1900 average for all
7 projections, with the exception of the lowest part of the uncertainty range for RCP2.6 (IPCC
8 2013).

9 **[INSERT FIGURE 1.4 HERE]**

10 ----- **START BOX 1.1 HERE** -----

11 **Box 1.1. Was there a “Hiatus” in Global Warming?**

12 Natural variability in the climate system leads to year-to-year and decade-to-decade changes in
13 global mean temperature. For short enough periods of time, this variability can lead to temporary
14 slowdowns or even reversals in the globally-averaged temperature increase. Over the past
15 decade, such a slowdown led to numerous assertions about a ‘hiatus’ (a period of zero or
16 negative temperature trend) in global warming. For longer periods, variability becomes less
17 important, and the long-term increase in global temperature is clearly revealed in both the
18 surface temperature data and in satellite measurements of tropospheric temperature (see Figure
19 1.5) (Santer et al. 2017a). Thus the surface and tropospheric temperature records do not support
20 the assertion that long-term (time periods of 25 years or longer) global warming has ceased or
21 substantially slowed (Lewandowsky et al. 2016; Santer et al. 2017b), a conclusion further
22 reinforced by recently updated and improved datasets (Karl et al. 2015; Mears and Wentz 2016;
23 Richardson et al. 2016; Hausfather et al. 2017).

24 **[INSERT FIGURE 1.5 HERE]**

25 For the 15 years following the 1997–1998 El Niño–Southern Oscillation (ENSO) event, the
26 observed rate of temperature increase was smaller than the underlying long-term increasing trend
27 on 30-year climate time scales (Fyfe et al. 2016), even as other measures of global warming such
28 as ocean heat content (see Ch. 13: Ocean Changes) and Arctic sea ice extent (see Ch. 12: Sea
29 Level Rise) continued to change (Benestad 2017). Variation in the rate of warming on this time
30 scale is not unexpected and can be the result of long-term internal variability in the climate
31 system, or short-term changes in climate forcings such as aerosols or solar irradiance. Temporary
32 periods similar or larger in magnitude to the current slowdown have occurred earlier in the
33 historical record (in addition, almost no increase occurred from the mid 1940s to the mid 1970s,
34 which is not well understood but may be related to an increase in anthropogenic and volcanic
35 aerosols and/or to ocean interactions (Meehl et al. 2016a)) during this period. Shorter-term
36 slowdowns also occur after major volcanic eruptions, such as Pinatubo’s eruption in 1991.

1 Temporary speedups have also occurred, most notably in the 1930s and early 1940s, and in the
2 late 1970s and early 1980s. Comparable slowdown and speedup events are also present in
3 climate simulations of both historical and future climate, even without decadal scale fluctuations
4 in forcing (Easterling and Wehner 2009; Knutson et al. 2016), and thus recent variations in short-
5 term temperature trend statistics are not particularly surprising.

6 Even though such slowdowns are not unexpected, the slowdown of the early 2000s has been
7 used as informal evidence to cast doubt on the accuracy of climate projections from CMIP5
8 models, since the measured rate of warming in all surface and tropospheric temperature datasets
9 from 2000 to 2014 was less than was expected given the results of the CMIP3 and CMIP5
10 historical climate simulations (Fyfe et al. 2016; Santer et al. 2017a). Thus, it is important to
11 explore a physical explanation of the recent slowdown and to identify the relative contributions
12 of different factors.

13 Numerous studies have investigated the role of natural modes of variability and how they
14 affected the flow of energy in the climate system of the post-2000 period (Balmaseda et al. 2013;
15 England et al. 2014; Meehl et al. 2011; Kosaka and Xie 2013; Meehl et al. 2016a). For the 2000–
16 2013 time period, they find

- 17 • In the Pacific Ocean, a number of interrelated features, including cooler than expected
18 tropical ocean surface temperatures, stronger than normal trade winds, and a shift to the
19 cool phase of the Pacific Decadal Oscillation (PDO) led to cooler than expected surface
20 temperatures in the Eastern Tropical Pacific, a region that has been shown to have an
21 influence on global-scale climate (Kosaka and Xie 2013).
- 22 • For most of the world's oceans, heat was transferred from the surface into the deeper
23 ocean (Balmaseda et al. 2013; Chen and Tung 2014; Nieves et al. 2015), causing a
24 reduction in surface warming worldwide.
- 25 • Other studies attributed part of the cause of the measurement/model discrepancy to
26 natural fluctuations in radiative forcings, such as volcanic aerosols, stratospheric water
27 vapor, or solar output (Solomon et al. 2010; Schmidt et al 2014; Huber and Knutti 2014;
28 Ridley et al. 2014; Santer et al. 2014).

29 When comparing model predictions with measurements, it is important to note that the CMIP5
30 runs used an assumed representation of these factors for time periods after 2000, possibly leading
31 to errors, especially in the year-to-year simulation of internal variability in the oceans. It is *very*
32 *likely* that the early 2000s slowdown was caused by a combination of short-term variations in
33 forcing and internal variability in the climate system, though the relative contribution of each is
34 still an area of active research (e.g., Trenberth 2015; Meehl et al. 2016a; Fyfe et al. 2016).

35 Although 2014 already set a new high in globally averaged temperature record up to that time, in
36 2015–2016, the situation changed dramatically. A switch of the PDO to the positive phase,

1 combined with a strong El Niño event during the fall and winter of 2015–2016, led to months of
2 record-breaking globally averaged temperatures in both the surface and satellite temperature
3 records (see Figure 1.5; Trenberth 2015), bringing observed temperature trends into better
4 agreement with model expectations (see Figure 1.6).

5 On longer time scales, observed temperature changes are more consistent with model simulations
6 and have been attributed to anthropogenic causes with high confidence (Bindoff et al. 2013; see
7 Ch. 3: Detection and Attribution for further discussion). The pronounced globally averaged
8 surface temperature record of 2015 and 2016 appear to make recent observed temperature
9 changes more consistent with model simulations—including with CMIP5 projections that were
10 (notably) developed in advance of occurrence of the 2015–2016 observed anomalies (Figure
11 1.6). A second important point illustrated by Figure 1.6 is the broad overall agreement between
12 observations and models on the century timescale, which is robust to the shorter-term variations
13 in trends in the past decade or so. Continued global warming and the frequent setting of new high
14 global mean temperature records or near-records is consistent with expectations based on model
15 projections of continued anthropogenic forcing toward warmer global mean conditions.

16 **[INSERT FIGURE 1.6 HERE]**

17 ----- **END BOX 1.1 HERE** -----

18 **1.4. Trends in Global Precipitation**

19 Annual averaged precipitation across global land areas exhibits a slight rise (that is not
20 statistically significant because of a lack of data coverage early in the record) over the past
21 century (see Figure 1.7) along with ongoing increases in atmospheric moisture levels.
22 Interannual and interdecadal variability is clearly found in all precipitation evaluations, owing to
23 factors such as the North Atlantic Oscillation (NAO) and ENSO—note that precipitation
24 reconstructions are updated operationally by NOAA NCEI on a monthly basis (Becker et al.
25 2013; Adler et al. 2003).

26 **[INSERT FIGURE 1.7 HERE]**

27 The hydrological cycle and the amount of global mean precipitation is primarily controlled by
28 the atmosphere's energy budget and its interactions with clouds (Allen and Ingram 2002). The
29 amount of global mean precipitation also changes as a result of a mix of fast and slow
30 atmospheric responses to the changing climate (Collins et al. 2013). In the long term, increases in
31 tropospheric radiative effects from increasing amounts of atmospheric CO₂ (i.e., increasing CO₂
32 leads to greater energy absorbed by the atmosphere and re-emitted to the surface, with the
33 additional transport to the atmosphere coming by convection) must be balanced by increased
34 latent heating, resulting in precipitation increases of approximately 0.55% to 0.72% per °F (1%
35 to 3% per °C) (IPCC 2013; Held and Soden 2006). Global atmospheric water vapor should
36 increase by about 6%–7% per °C of warming based on the Clausius–Clapeyron relationship (see

1 Ch. 2: Physical Drivers of Climate Change); satellite observations of changes in precipitable
2 water over oceans have been detected at about this rate and attributed to human-caused changes
3 in the atmosphere (Santer et al. 2007). Similar observed changes in land-based measurements
4 have also been attributed to the changes in climate from greenhouse gases (Willet et al. 2010).

5 Earlier studies suggested a climate change pattern of wet areas getting wetter and dry areas
6 getting drier (e.g., Greve et al. 2014). While Hadley Cell expansion should lead to more drying
7 in the subtropics, the poleward shift of storm tracks should lead to enhanced wet regions. While
8 this high/low rainfall behavior appears to be valid over ocean areas, changes over land are more
9 complicated. The wet versus dry pattern in observed precipitation has only been attributed for the
10 zonal mean (Zhang et al. 2007; Marvel and Bonfils 2013) and not regionally due to the large
11 amount of spatial variation in precipitation changes as well as significant natural variability. The
12 detected signal in zonal mean precipitation is largest in the Northern Hemisphere, with decreases
13 in the subtropics and increases at high latitudes. As a result, the observed increase (about 5%
14 since the 1950s [Walsh et al. 2011; Vihma et al. 2016]) in annual averaged Arctic precipitation
15 have been detected and attributed to human activities (Min et al. 2008).

16 **1.5. Trends in Global Extreme Weather Events**

17 A change in the frequency, duration, and/or magnitude of extreme weather events is one of the
18 most important consequences of a warming climate. In statistical terms, a small shift in the mean
19 of a weather variable, with or without this shift occurring in concert with a change in the shape
20 of its probability distribution, can cause a large change in the probability of a value relative to an
21 extreme threshold (Katz and Brown 1992; see Figure 1.8 in IPCC 2013). Examples include
22 extreme high temperature events and heavy precipitation events. Additionally, extreme events
23 such as intense tropical cyclones, midlatitude cyclones, and hail and tornadoes associated with
24 thunderstorms can occur as isolated events that are not generally studied in terms of extremes
25 within a probability distribution. Detecting trends in the frequency and intensity of extreme
26 weather events is challenging (Sardeshmukh et al. 2015). The most intense events are rare by
27 definition, and observations may be incomplete and suffer from reporting biases. Further
28 discussion on trends and projections of extreme events for the United States can be found in
29 Chapters 6–9 and 11.

30 An emerging area in the science of detection and attribution has been the attribution of extreme
31 weather and climate events. Extreme event attribution generally addresses the question of
32 whether climate change has altered the odds of occurrence of an extreme event like one just
33 experienced. Attribution of extreme weather events under a changing climate is now an
34 important and highly visible aspect of climate science. As discussed in a recent National
35 Academy of Sciences (NAS) report (NAS 2016), the science of event attribution is rapidly
36 advancing, including the understanding of the mechanisms that produce extreme events and the
37 development of methods that are used for event attribution. Several other reports and papers have
38 reviewed the topic of extreme event attribution (Hulme 2014; Stott 2016; Easterling et al. 2016).

1 This report briefly reviews extreme event attribution methodologies in practice (Ch. 3: Detection
2 and Attribution) and provides a number of examples within the chapters on various climate
3 phenomena (especially relating to the United States in Chapters 6–9).

4 **Extreme Heat and Cold**

5 The frequency of multiday heat waves and extreme high temperatures at both daytime and
6 nighttime hours is increasing over many of the global land areas (IPCC 2013). There are
7 increasing areas of land throughout our planet experiencing an excess number of daily highs
8 above given thresholds (for example, the 90th percentile), with an approximate doubling of the
9 world's land area since 1998 with 30 extreme heat days per year (Seneviratne et al. 2014). At the
10 same time, frequencies of cold waves and extremely low temperatures are decreasing over the
11 United States and much of the earth. In the United States, the number of record daily high
12 temperatures has been about double the number of record daily low temperatures in the 2000s
13 (Meehl et al. 2009), and much of the United States has experienced decreases of 5%–20% per
14 decade in cold wave frequency (IPCC 2013; Easterling et al. 2016).

15 The enhanced radiative forcing caused by greenhouse gases has a direct influence on heat
16 extremes by shifting distributions of daily temperature (Min et al. 2013). Recent work indicates
17 changes in atmospheric circulation may also play a significant role (see Ch. 5: Circulation and
18 Variability). For example, a recent study found that increasing anticyclonic circulations partially
19 explain observed trends in heat events over North America and Eurasia, among other effects
20 (Horton et al. 2015). Observed changes in circulation may also be the result of human influences
21 on climate, though this is still an area of active research.

22 **Extreme Precipitation**

23 A robust consequence of a warming climate is an increase in atmospheric water vapor, which
24 exacerbates precipitation events under similar meteorological conditions, meaning that when
25 rainfall occurs, the amount of rain falling in that event tends to be greater. As a result, what in the
26 past have been considered to be extreme precipitation events are becoming more frequent (IPCC
27 2013; Asadieh and Krakauer 2015; Kunkel and Frankson 2015; Donat et al. 2016). On a global
28 scale, the observational annual-maximum daily precipitation has increased by 8.5% over the last
29 110 years; global climate models also derive an increase in extreme precipitation globally but
30 tend to underestimate the rate of the observed increase (Asadieh and Krakauer 2015; Donat et al.
31 2016; Fischer and Knutti 2016). Extreme precipitation events are increasing globally in
32 frequency over both wet and dry regions (Donat et al. 2016). Although more spatially
33 heterogeneous than heat extremes, numerous studies have found increases in precipitation
34 extremes on many regions using a variety of methods and threshold definitions (Kunkel et al.
35 2013), and those increases can be attributed to human-caused changes to the atmosphere (Min et
36 al. 2011; Zhang et al. 2013). Finally, extreme precipitation associated with tropical cyclones

1 (TCs) is expected to increase in the future (Knutson et al. 2015), but current trends are not clear
2 (Kunkel et al. 2013).

3 The impact of extreme precipitation trends on flooding globally is complex because additional
4 factors like soil moisture and changes in land cover are important (Berghuijs et al. 2016).
5 Globally, due to limited data, there is low confidence for any significant current trends in river-
6 flooding associated with climate change (Kundzewicz et al. 2014), but the magnitude and
7 intensity of river flooding is projected to increase in the future (Arnell and Gosling 2016). More
8 on flooding trends in the United States is in Chapter 8: Droughts, Floods, and Wildfires.

9 **Tornadoes and Thunderstorms**

10 Increasing air temperature and moisture increase the risk of extreme convection, and there is
11 evidence for a global increase in severe thunderstorm conditions (Sander et al. 2013). Strong
12 convection, along with wind shear, represents favorable conditions for tornadoes. Thus, there is
13 reason to expect increased tornado frequency and intensity in a warming climate (Diffenbaugh et
14 al. 2013). Inferring current changes in tornado activity is hampered by changes in reporting
15 standards, and trends remain highly uncertain (Kunkel et al. 2013) (see Ch. 9: Extreme Storms).

16 **Winter Storms**

17 Winter storm tracks have shifted slightly northward (by about 0.4 degrees) in recent decades
18 over the Northern Hemisphere (Bender et al. 2012). More generally, extratropical cyclone
19 activity is projected to change in complex ways under future climate scenarios, with increases in
20 some regions and seasons and decreases in others. There are large model-to-model differences
21 among CMIP5 climate models, with some models underestimating the current cyclone track
22 density (Colle et al. 2013; Chang 2013).

23 Enhanced Arctic warming (arctic amplification), due in part to sea ice loss, reduces lower
24 tropospheric meridional temperature gradients, diminishing baroclinicity (a measure of how
25 misaligned the gradient of pressure is from the gradient of air density)—an important energy
26 source for extratropical cyclones. At the same time, upper-level meridional temperature gradients
27 will increase due to a warming tropical upper troposphere and a cooling high-latitude lower
28 stratosphere. While these two effects counteract each other with respect to a projected change in
29 midlatitude storm tracks, the simulations indicate that the magnitude of Arctic amplification may
30 modulate some aspects (e.g., jet position, wave extent, and blocking frequency) of the circulation
31 in the North Atlantic region in some seasons (Barnes and Polvani 2015).

32 **Tropical Cyclones**

33 Detection and attribution of trends in past tropical cyclone (TC) activity is hampered by
34 uncertainties in the data collected prior to the satellite era and by uncertainty in the relative
35 contributions of natural variability and anthropogenic influences. Theoretical arguments and

1 numerical modeling simulations support an expectation that radiative forcing by greenhouse
2 gases and anthropogenic aerosols can affect tropical cyclone activity in a variety of ways, but
3 robust formal detection and attribution for past observed changes has not yet been realized. Since
4 the IPCC AR5 (2013), there is new evidence that the locations where tropical cyclones reach
5 their peak intensity have migrated poleward in both the Northern and Southern Hemispheres, in
6 concert with the independently measured expansion of the tropics (Kossin et al. 2014). In the
7 western North Pacific, this migration has substantially changed the tropical cyclone hazard
8 exposure patterns in the region and appears to have occurred outside of the historically measured
9 modes of regional natural variability (Kossin et al. 2016).

10 Whether global trends in high-intensity tropical cyclones are already observable is a topic of
11 active debate. Some research suggests positive trends (Elsner et al. 2008; Kossin et al. 2013), but
12 significant uncertainties remain (Kossin et al. 2013; see Ch. 9: Extreme Storms). Other studies
13 have suggested that aerosol pollution has masked the increase in TC intensity expected otherwise
14 from enhanced greenhouse warming (Wang et al. 2014; Sobel et al. 2016).

15 TC intensities are expected to increase with warming, both on average and at the high end of the
16 scale, as the range of achievable intensities expands, so that the most intense storms will exceed
17 the intensity of any in the historical record (Sobel et al. 2016). Some studies have projected an
18 overall increase in tropical cyclone activity (Emanuel 2013). However, studies with high-
19 resolution models are giving a different result. For example, a high-resolution dynamical
20 downscaling study of global TC activity under the RCP4.5 scenario projects an increased
21 occurrence of the highest-intensity tropical cyclones (Saffir-Simpson Categories 4 and 5), along
22 with a reduced overall tropical cyclone frequency, though there are considerable basin-to-basin
23 differences (Knutson et al. 2015). Chapter 9: Extreme Storms covers more on extreme storms
24 affecting the United States.

25 **1.6. Global Changes in Land Processes**

26 Changes in regional land cover have had important effects on climate, while climate change also
27 has important effects on land cover (IPCC 2013; also see Ch. 10: Land Cover). In some cases,
28 there are changes in land cover that are both consequences of and influences on global climate
29 change (e.g., declines in land ice and snow cover, thawing permafrost, and insect damage to
30 forests).

31 Northern Hemisphere snow cover extent has decreased, especially in spring, primarily due to
32 earlier spring snowmelt (by about 0.2 million square miles [0.5 million square km]; NSIDC
33 2017; Kunkel et al. 2016), and this decrease since the 1970s is at least partially driven by
34 anthropogenic influences (Rupp et al. 2013). Snow cover reductions, especially in the Arctic
35 region in summer, have led to reduced seasonal albedo (Callaghan et al. 2011).

1 While global-scale trends in drought are uncertain due to insufficient observations, regional
2 trends indicate increased frequency and intensity of drought and aridification on land cover in the
3 Mediterranean (Sousa et al. 2011; Hoerling et al. 2013) and West Africa (Sheffield et al. 2012;
4 Dai 2013) and decreased frequency and intensity of droughts in central North America (Peterson
5 et al. 2013) and northwestern Australia (Jones et al. 2009; Sheffield et al. 2012; Dai 2013).

6 Anthropogenic land-use changes, such as deforestation and growing cropland extent, have
7 increased the global land surface albedo, resulting in a small cooling effect. Effects of other land-
8 use changes, including modifications of surface roughness, latent heat flux, river runoff, and
9 irrigation, are difficult to quantify, but may offset the direct land-use albedo changes (Bonan
10 2008; de Noblet-Ducoudré et al. 2012).

11 Globally, land-use change since 1750 has been typified by deforestation, driven by the growth in
12 intensive farming and urban development. Global land-use change is estimated to have released
13 190 ± 65 GtC (gigatonnes of carbon) through 2015 (Le Quéré et al. 2015, 2016). Over the same
14 period, cumulative fossil fuel and industrial emissions are estimated to have been 410 ± 20 GtC,
15 yielding total anthropogenic emissions of 600 ± 70 GtC, of which cumulative land-use change
16 emissions were about 32% (Le Quéré et al. 2015, 2016). Tropical deforestation is the dominant
17 driver of land-use change emissions, estimated at 0.1–1.7 GtC per year, primarily from biomass
18 burning. Global deforestation emissions of about 3 GtC per year are compensated by around 2
19 GtC per year of forest regrowth in some regions, mainly from abandoned agricultural land
20 (Houghton et al. 2012; Pan et al. 2011).

21 Natural terrestrial ecosystems are gaining carbon through uptake of CO₂ by enhanced
22 photosynthesis due to higher CO₂ levels, increased nitrogen deposition, and longer growing
23 seasons in mid- and high latitudes. Anthropogenic atmospheric CO₂ absorbed by land
24 ecosystems is stored as organic matter in live biomass (leaves, stems, and roots), dead biomass
25 (litter and woody debris), and soil carbon.

26 Many studies have documented a lengthening growing season, primarily due to the changing
27 climate (Myneni et al. 1997; Menzel et al. 2006; Schwartz et al. 2006; Kim et al. 2012), and
28 elevated CO₂ is expected to further lengthen the growing season in places where the length is
29 water limited (Reyes-Fox et al. 2014). In addition, a recent study has shown an overall increase
30 in greening of the Earth in vegetated regions (Zhu et al. 2016), while another has demonstrated
31 evidence that the greening of Northern Hemisphere extratropical vegetation is attributable to
32 anthropogenic forcings, particularly rising atmospheric greenhouse gas levels (Mao et al. 2016).
33 However, observations (Finzi et al. 2006; Palmroth et al. 2006; Norby et al. 2010) and models
34 (Sokolov et al. 2008; Thornton et al. 2009; Zaehle and Friend 2010) indicate that nutrient
35 limitations and land availability will constrain future land carbon sinks.

36 Modifications to the water, carbon, and biogeochemical cycles on land result in both positive and
37 negative feedbacks to temperature increases (Betts et al. 2007; Bonan 2008; Bernier et al. 2011).

1 Snow and ice albedo feedbacks are positive, leading to increased temperatures with loss of snow
2 and ice extent. While land ecosystems are expected to have a net positive feedback due to
3 reduced natural sinks of CO₂ in a warmer world, anthropogenically increased nitrogen deposition
4 may reduce the magnitude of the net feedback (Churkina et al. 2009; Zaehle et al. 2010;
5 Thornton et al. 2009). Increased temperature and reduced precipitation increase wildfire risk and
6 susceptibility of terrestrial ecosystems to pests and disease, with resulting feedbacks on carbon
7 storage. Increased temperature and precipitation, particularly at high latitudes, drives up soil
8 decomposition, which leads to increased CO₂ and CH₄ (methane) emissions (Page et al. 2002;
9 Ciais et al. 2005; Chambers et al. 2007; Kurz et al. 2008; Clark et al. 2010; van der Werf et al.
10 2010; Lewis et al. 2011). While some of these feedbacks are well known, others are not so well
11 quantified and yet others remain unknown; the potential for surprise is discussed further in
12 Chapter 15: Potential Surprises.

13 **1.7. Global Changes in Sea Ice, Glaciers, and Land Ice**

14 Since NCA3 (Melillo et al. 2014), there have been significant advances in the understanding of
15 changes in the cryosphere. Observations continue to show declines in Arctic sea ice extent and
16 thickness, Northern Hemisphere snow cover, and the volume of mountain glaciers and
17 continental ice sheets (Derksen and Brown 2012; IPCC 2013; Stroeve et al. 2014a,b; Comiso and
18 Hall 2014; Derksen et al. 2015). Evidence suggests in many cases that the net loss of mass from
19 the global cryosphere is accelerating indicating significant climate feedbacks and societal
20 consequences (Rignot et al. 2011, 2014; Williams et al. 2014; Zemp et al. 2015; Seo et al. 2015;
21 Harig and Simons 2016).

22 Arctic sea ice areal extent, thickness, and volume have declined since 1979 (IPCC 2013; Stroeve
23 et al. 2014a,b; Comiso and Hall 2014; Perovich et al. 2015). Annually-averaged Arctic sea ice
24 extent has decreased by 3.5%–4.1% per decade since 1979 with much larger reductions in
25 summer and fall (IPCC 2013; Stroeve et al. 2012b; Stroeve et al. 2014a; Comiso and Hall 2014).
26 For example, September sea ice extent decreased by 13.3% per decade between 1979 and 2016.
27 At the same time, September multi-year sea ice has melted faster than perennial sea ice (13.5% ±
28 2.5% and 11.5% ± 2.1% per decade, respectively, relative to the 1979–2012 average)
29 corresponding to 4–7.5 feet (1.3–2.3 meter) declines in winter sea ice thickness (IPCC 2013;
30 Perovich et al. 2015). October 2016 serves as a recent example of the observed lengthening of
31 the Arctic sea ice melt season marking the slowest recorded Arctic sea ice growth rate for that
32 month (Stroeve et al. 2014a; Parkinson 2014; NSIDC 2016). While current generation climate
33 models project a nearly ice-free Arctic Ocean in late summer by mid-century, they still simulate
34 weaker reductions in volume and extent than observed, suggesting that projected changes are too
35 conservative (IPCC 2013; Stroeve et al. 2012a; Stroeve et al. 2014b; Zhang and Knutson 2013).
36 See Chapter 11: Arctic Changes for further discussion of the implications of changes in the
37 Arctic.

1 In contrast to the Arctic, sea ice extent around Antarctica has increased since 1979 by 1.2% to
2 1.8% per decade (IPCC 2013). Strong regional differences in the sea ice growth rates are found
3 around Antarctica but most regions (about 75%) show increases over the last 30 years (Zunz et
4 al. 2013). The gain in Antarctic sea ice is much smaller than the decrease in Arctic sea ice.
5 Changes in wind patterns, ice–ocean feedbacks, and freshwater flux have contributed to
6 Antarctic sea ice growth (Zunz et al. 2013; Eisenman et al. 2014; Pauling et al. 2016; Meehl et
7 al. 2016b).

8 Since the NCA3 (Mellilo et al. 2014), the Gravity Recovery and Climate Experiment (GRACE)
9 constellation (e.g., Velicogna and Wahr 2013) has provided a record of gravimetric land ice
10 measurements, advancing knowledge of recent mass loss from the global cryosphere. These
11 measurements indicate that mass loss from the Antarctic Ice Sheet, Greenland Ice Sheet, and
12 mountain glaciers around the world continues accelerating in some cases (Rignot et al. 2014;
13 Joughin et al. 2014; Williams et al. 2014; Harig and Simons 2015; Seo et al. 2015; Harig and
14 Simons 2016). The annually averaged ice mass from 37 global reference glaciers has decreased
15 every year since 1984, a decline expected to continue even if climate were to stabilize (IPCC
16 2013; Pelto 2015; Zemp et al. 2015; Mengel et al. 2016).

17 Observed rapid mass loss from West Antarctica is attributed to increased glacial discharge rates
18 due to diminishing ice shelves from the surrounding ocean becoming warmer (Jenkins et al.
19 2010; Feldmann and Levermann 2015). Recent evidence suggests that the Amundsen Sea sector
20 is expected to disintegrate entirely (Rignot et al. 2014; Joughin et al. 2014; Feldmann and
21 Levermann 2015) raising sea level by at least 1.2 meters (about 4 feet) and potentially an
22 additional foot or more on top of current sea level rise projections during this century (DeConto
23 and Pollard 2016; see Section 1.2.7 and Ch. 12: Sea Level Rise for further details). The potential
24 for unanticipated rapid ice sheet melt and/or disintegration is discussed further in Chapter 15:
25 Potential Surprises.

26 Over the last decade, the Greenland Ice Sheet mass loss has accelerated, losing 244 ± 6 Gt per
27 year on average between January 2003 and May 2013 (Harig and Simons 2012; Jacob et al.
28 2012; IPCC 2013; Harig and Simons 2016). The portion of the Greenland Ice Sheet experiencing
29 annual melt has increased since 1980 including significant events (Tedesco et al. 2011; Fettweis
30 et al. 2011; IPCC 2013; Tedesco et al. 2015). A recent example, an unprecedented 98.6% of the
31 Greenland Ice Sheet surface experienced melt on a single day in July 2012 (Nghiem et al. 2012;
32 Tedesco et al. 2013). Encompassing this event, GRACE data indicate that Greenland lost 562 Gt
33 of mass between April 2012 and April 2013—more than double the average annual mass loss.

34 In addition, permafrost temperatures and active layer thicknesses have increased across much of
35 the Arctic (Shiklomanov et al. 2012; IPCC 2013; Romanovsky et al. 2015; also see Ch. 11:
36 Arctic Changes). Rising permafrost temperatures causing permafrost to thaw and become more
37 discontinuous raises concerns about potential emissions of carbon dioxide and methane (IPCC
38 2013). The potentially large contribution of carbon and methane emissions from permafrost and

1 the continental shelf in the Arctic to overall warming is discussed further in Chapter 15: Potential
2 Surprises).

3 **1.8. Global Changes in Sea Level**

4 Statistical analyses of tide gauge data indicate that global mean sea level has risen about 8–9
5 inches (20–23 cm) since 1880, with a rise rate of approximately 0.5–0.6 inches/decade from
6 1901 to 1990 (about 12–15 mm/decade; Church and White 2011; Hay et al. 2015; also see Ch.
7 12: Sea Level Rise). However, since the early 1990s, both tide gauges and satellite altimeters
8 have recorded a faster rate of sea level rise of about 1.2 inches/decade (approximately 3
9 cm/decade; Church and White 2011; Nerem et al. 2010; Hay et al. 2015), resulting in about 3
10 inches (about 8 cm) of the global rise since the early 1990s. Nearly two-thirds of the sea level
11 rise measured since 2005 has resulted from increases in ocean mass, primarily from land-based
12 ice melt; the remaining one-third of the rise is in response to changes in density from increasing
13 ocean temperatures (Merrifield et al. 2015).

14 Global sea level rise and its regional variability forced by climatic and ocean circulation patterns
15 are contributing to significant increases in annual tidal-flood frequencies, which are measured by
16 NOAA tide gauges and associated with minor infrastructure impacts to date; along some portions
17 of the U.S. coast, frequency of the impacts from such events appears to be accelerating (Ezer and
18 Atkinson 2014; Sweet and Park 2014; also see Ch. 12: Sea-Level Rise).

19 Future projections show that by 2100, global mean sea level is *very likely* to rise by 1.6–4.3 feet
20 (0.5–1.3 m) under RCP8.5, 1.1–3.1 feet (0.35–0.95 m) under RCP4.5, and 0.8–2.6 feet (0.24–
21 0.79 m) under RCP2.6 (see Ch. 4: Projections for a description of the scenarios) (Kopp et al.
22 2014). Sea level will not rise uniformly around the coasts of the United States and its oversea
23 territories. Local sea level rise is *likely* to be greater than the global average along the U.S.
24 Atlantic and Gulf Coasts and less than the global average in most of the Pacific Northwest.
25 Emerging science suggests these projections may be underestimates, particularly for higher
26 scenarios; a global mean sea level rise exceeding 8 feet (2.4 m) by 2100 cannot be excluded (see
27 Ch. 12: Sea Level Rise), and even higher amounts are possible as a result of marine ice sheet
28 instability (see Ch. 15: Potential Surprises). We have updated the global sea level rise scenarios
29 for 2100 of Parris et al. (2012) accordingly (Sweet et al. 2017), and also extended to year 2200 in
30 Chapter 12: Sea Level Rise. The scenarios are regionalized to better match the decision context
31 needed for local risk framing purposes.

32 **1.9. Recent Global Changes Relative to Paleoclimates**

33 Paleoclimate records demonstrate long-term natural variability in the climate and overlap the
34 records of the last two millennia, referred to here as the "Common Era". Before the emissions of
35 greenhouse gases from fossil fuels and other human-related activities became a major factor over
36 the last few centuries, the strongest drivers of climate during the last few thousand years had

1 been volcanoes and land-use change (which has both albedo and greenhouse gas emissions
2 effects) (Schmidt et al. 2011). Based on a number of proxies for temperature (for example, from
3 tree rings, fossil pollen, corals, ocean and lake sediments, and ice cores), temperature records are
4 available for the last 2,000 years on hemispherical and continental scales (Figures 1.8 and 1.9)
5 (Mann et al. 2008; PAGES 2K Consortium 2013). High-resolution temperature records for North
6 America extend back less than half of this period, with temperatures in the early parts of the
7 Common Era inferred from analyses of pollen and other archives. For this era, there is a general
8 cooling trend, with a relatively rapid increase in temperature over the last 150–200 years (Figure
9 1.9, PAGES 2k Consortium 2013). For context, global annual-averaged temperatures for 1986–
10 2015 are likely much higher, and appear to have risen at a more rapid rate during the last 3
11 decades, than any similar period possibly over the past 2,000 years or longer (IPCC [2013]
12 makes a similar statement, but for the last 1,400 years because of data quality issues before that
13 time).

14 **[INSERT FIGURES 1.8 AND 1.9 HERE]**

15 Global temperatures of the magnitude observed recently (and projected for the rest of this
16 century) are related to very different forcings than past climates, but studies of past climates
17 suggest that such global temperatures were *likely* last observed during the Eemian period—the
18 last interglacial—125,000 years ago; at that time, global temperatures were, at their peak, about
19 1.8°F–3.6°F (1°C–2°C) warmer than preindustrial temperatures (Turney and Jones 2010).
20 Coincident with these higher temperatures, sea levels during that period were about 16–30 feet
21 (6–9 meters) higher than modern levels (Kopp et al. 2009; Dutton and Lambeck 2012) (for
22 further discussion on sea levels in the past, see Ch. 12: Sea Level Rise).

23 Modeling studies suggest that the Eemian period warming can be explained in part by the
24 hemispheric changes in solar insolation from orbital forcing as a result of cyclic changes in the
25 shape of Earth's orbit around the sun (e.g., Kaspar et al. 2005), even though greenhouse gas
26 concentrations were similar to preindustrial levels. Equilibrium climate with modern greenhouse
27 gas concentrations (about 400 ppm CO₂) most recently occurred 3 million years ago during the
28 Pliocene. During the warmest parts of this period, global temperatures were 5.4°F–7.2°F (3°C–
29 4°C) higher than today, and sea levels were about 82 feet (25 meters) higher (Haywood et al.
30 2013).

31 ----- **START BOX 1.2 HERE** -----

32 **Box 1.2: Advances Since NCA3**

33 This assessment reflects both advances in scientific understanding and approach since NCA3, as
34 well as global policy developments. Highlights of what aspects are either especially strengthened
35 or are emerging in the findings include

- 1 • *Spatial downscaling*: Projections of climate changes are downscaled to a finer resolution
2 than the original global climate models using the Localized Constructed Analogs
3 (LOCA) empirical statistical downscaling model. The downscaling generates temperature
4 and precipitation on a 1/16th degree latitude/longitude grid for the contiguous United
5 States. LOCA, one of the best statistical downscaling approaches, produces downscaled
6 estimates using a multi-scale spatial matching scheme to pick appropriate analog days
7 from observations (Chapters 4,6,7).

- 8 • *Risk-based framing*: Highlighting aspects of climate science most relevant to assessment
9 of key societal risks are included more here than in prior national climate assessments.
10 This approach allows for emphasis of possible outcomes that, while relatively unlikely to
11 occur or characterized by high uncertainty, would be particularly consequential, and thus
12 associated with large risks (Chapters 6,7,8,9,12,15).

- 13 • *Detection and attribution*: Significant advances have been made in the attribution of the
14 human influence for individual climate and weather extreme events since NCA3. This
15 assessment contains extensive discussion of new and emerging findings in this area
16 (Chapters 3,6,7,8).

- 17 • *Atmospheric circulation and extreme events*: The extent to which atmospheric circulation
18 in the midlatitudes is changing or is projected to change, possibly in ways not captured by
19 current climate models, is a new important area of research. While still in its formative
20 stages, this research is critically important because of the implications of such changes
21 for climate extremes including extended cold air outbreaks, long-duration heat waves,
22 and changes in storms and drought patterns (Chapters 5,6,7).

- 23 • *Increased understanding of specific types of extreme events*: How climate change may
24 affect specific types of extreme events in the United States is another key area where
25 scientific understanding has advanced. For example, this report highlights how intense
26 flooding associated with atmospheric rivers could increase dramatically as the
27 atmosphere and oceans warm or how tornadoes could be concentrated into a smaller
28 number of high-impact days over the average severe weather season (Chapter 9).

- 29 • *Model weighting*: For the first time, maps and plots of climate projections will not show a
30 straight average of all available climate models. Rather, each model is given a weight
31 based on their 1) historical performance relative to observations and 2) independence
32 relative to other models. Although this is a more accurate way of representing model
33 output, it does not significantly alter the results: the weighting produces very similar
34 trends and spatial patterns to the equal-weighting-of-models approach used in prior
35 assessments (Chapters 4,6,7).

- 1 • *High-resolution global climate model simulations*: As computing resources have grown,
2 multidecadal simulations of global climate models are now being conducted at horizontal
3 resolutions on the order of 15 miles (25 km) that provide more realistic characterization
4 of intense weather systems, including hurricanes. Even the limited number of high-
5 resolution models currently available have increased confidence in projections of extreme
6 weather (Chapter 9).

- 7 • *The so-called “global warming hiatus”*: Since NCA3, many studies have investigated
8 causes for the reported slowdown in the rate of increase in near-surface global mean
9 temperature from roughly 2000 through 2013. The slowdown, which ended with the
10 record warmth in 2014–2016, is understood to have been caused by a combination of
11 internal variability, mostly in the heat exchange between the ocean and the atmosphere,
12 and short-term variations in external forcing factors, both human and natural. On longer
13 time scales, relevant to human-induced climate change, there is no hiatus and the planet
14 continues to warm at a steady pace as predicted by basic atmospheric physics and the
15 well-documented increase in heat-trapping gases (Chapter 1).

- 16 • *Oceans and coastal waters*: Concern over ocean acidification, warming, and oxygen loss
17 is increasing as scientific understanding of the severity of their impacts grows. Both
18 oxygen loss and acidification may be magnified in some U.S. coastal waters relative to
19 the global average, raising the risk of serious ecological and economic consequences.
20 There is some evidence, still highly uncertain, that the Atlantic Meridional Circulation
21 (AMOC), sometimes referred to as the ocean’s conveyor belt, may be slowing down
22 (Chapters 2, 13).

- 23 • *Local sea level change projections*: For the first time in the NCA process, sea level rise
24 projections incorporate geographic variation based on factors such as local land
25 subsidence, ocean currents, and changes in Earth’s gravitational field (Chapter 12).

- 26 • *Accelerated ice-sheet loss and irreversibility*: New observations from many different
27 sources confirm that ice-sheet loss is accelerating. Combining observations with
28 simultaneous advances in the physical understanding of ice sheets, scientists are now
29 concluding that up to 8.5 feet of global sea level rise is possible by 2100 under a high
30 emissions scenario, up from 6.6 feet in NCA3 (Chapter 12).

- 31 • *Slower Arctic sea-ice area extent regrowth in fall and winter 2016-2017*: The annual
32 Arctic sea ice extent minimum for 2016 relative to the long-term record was the second
33 lowest on record; since 1981, the sea ice minimum has decreased by 13.3% per decade,
34 more than 46% over the 35 years. In fall and winter 2016–2017, record-setting slow ice
35 regrowth was the lowest since observations began in 1981 (Chapter 11).

- 1 • *Potential surprises*: Both large-scale state shifts in the climate system (sometimes
2 called “tipping points”) and compound extremes have the potential to generate
3 unanticipated surprises. The further the Earth system departs from historical climate
4 forcings, and the more the climate changes, the greater the potential for these surprises.
5 For the first time in the NCA process we include an extended discussion of these
6 potential surprises (Chapter 15).
- 7 • *The Paris Agreement*: The Paris Agreement, which entered into force November 4, 2016,
8 provides a new framework for its parties for the mitigation of and adaptation to climate
9 change, and to periodically update and revisit their respective domestic commitments.
10 This report discusses some important aspects of climate science that are relevant to
11 meeting the objectives of the Agreement (Chapters 4, 14).

12 ----- **END BOX 1.2 HERE** -----

13

1 TRACEABLE ACCOUNTS

2 Key Finding 1

3 The global climate continues to change rapidly compared to the pace of the natural variations in
4 climate that have occurred throughout Earth's history. Trends in globally averaged temperature,
5 sea level rise, upper-ocean heat content, land-based ice melt, Arctic sea ice, depth of seasonal
6 permafrost thaw, and other climate variables provide consistent evidence of a warming planet.
7 These observed trends are robust and have been confirmed by multiple independent research
8 groups around the world.

9 Description of evidence base

10 The Key Finding and supporting text summarize extensive evidence documented in the climate
11 science literature. Similar to statements made in previous national (NCA3; Melillo et al. 2014)
12 and international (IPCC 2013) assessments.

13 Evidence for changes in global climate arises from multiple analyses of data from in-situ,
14 satellite, and other records undertaken by many groups over several decades. These observational
15 datasets are used throughout this chapter and are discussed further in Appendix 1 (e.g., updates
16 of prior uses of these datasets by Vose et al. 2012; Karl et al. 2015). Changes in the mean state
17 have been accompanied by changes in the frequency and nature of extreme events (e.g., Kunkel
18 and Frankson 2015; Donat et al. 2016). A substantial body of analysis comparing the observed
19 changes to a broad range of climate simulations consistently points to the necessity of invoking
20 human-caused changes to adequately explain the observed climate system behavior. The
21 influence of human impacts on the climate system has also been observed in a number of
22 individual climate variables (attribution studies are discussed in Ch. 3: Detection and Attribution
23 and in other chapters).

24 Major uncertainties

25 Key remaining uncertainties relate to the precise magnitude and nature of changes at global, and
26 particularly regional, scales, and especially for extreme events and our ability to observe these
27 changes at sufficient resolution and to simulate and attribute such changes using climate models.
28 Innovative new approaches to instigation and maintenance of reference quality observation
29 networks such as the U.S. Climate Reference Network (<http://www.ncei.noaa.gov/crn/>),
30 enhanced climate observational and data analysis capabilities, and continued improvements in
31 climate modeling all have the potential to reduce uncertainties.

32 Assessment of confidence based on evidence and agreement, including short description of 33 nature of evidence and level of agreement

34 There is *very high confidence* that global climate is changing and this change is apparent across a
35 wide range of observations, given the evidence base and remaining uncertainties. All

1 observational evidence is consistent with a warming climate since the late 1800s. There is *very*
2 *high confidence* that the global climate change of the past 50 years is primarily due to human
3 activities, given the evidence base and remaining uncertainties (IPCC 2013). Recent changes
4 have been consistently attributed in large part to human factors across a very broad range of
5 climate system characteristics.

6 **Summary sentence or paragraph that integrates the above information**

7 The key message and supporting text summarizes extensive evidence documented in the climate
8 science peer-reviewed literature. The trends described in NCA3 have continued and our
9 understanding of the observations related to climate and the ability to evaluate the many facets of
10 the climate system have increased substantially.

11

12 **Key Finding 2**

13 The frequency and intensity of extreme heat and heavy precipitation events are increasing in
14 most continental regions of the world (*very high confidence*). These trends are consistent with
15 expected physical responses to a warming climate. Climate model studies are also consistent
16 with these trends, although models tend to underestimate the observed trends, especially for the
17 increase in extreme precipitation events (*very high confidence* for temperature, *high confidence*
18 for extreme precipitation). The frequency and intensity of extreme temperature events are
19 *virtually certain* to increase in the future as global temperature increases (*high confidence*).
20 Extreme precipitation events will *very likely* continue to increase in frequency and intensity
21 throughout most of the world (*high confidence*). Observed and projected trends for some other
22 types of extreme events, such as floods, droughts, and severe storms, have more variable regional
23 characteristics.

24 **Description of evidence base**

25 The Key Finding and supporting text summarizes extensive evidence documented in the climate
26 science literature and are similar to statements made in previous national (NCA3; Melillo et al.,
27 2014) and international (IPCC 2013) assessments. The analyses of past trends and future
28 projections in extreme events and the fact that models tend to underestimate the observed trends
29 are also well substantiated through more recent peer-reviewed literature as well (Seneviratne et
30 al. 2014; Arnell and Gosling 2016; Wuebbles et al. 2014; Kunkel and Frankson 2015; Easterling
31 et al. 2016; Donat et al. 2016; Berghuijs et al. 2016; Fischer and Knutti 2016).

32 **Major uncertainties**

33 Key remaining uncertainties relate to the precise magnitude and nature of changes at global, and
34 particularly regional, scales, and especially for extreme events and our ability to simulate and
35 attribute such changes using climate models. Innovative new approaches to climate data analysis,

1 continued improvements in climate modeling, and instigation and maintenance of reference
2 quality observation networks such as the U.S. Climate Reference Network
3 (<http://www.ncei.noaa.gov/crn/>) all have the potential to reduce uncertainties.

4 **Assessment of confidence based on evidence and agreement, including short description of**
5 **nature of evidence and level of agreement**

6 There is *very high confidence* for the statements about past extreme changes in temperature and
7 precipitation and *high confidence* for future projections, based on the observational evidence and
8 physical understanding, that there are major trends in extreme events and significant projected
9 changes for the future.

10 **Summary sentence or paragraph that integrates the above information**

11 The Key Finding and supporting text summarizes extensive evidence documented in the climate
12 science peer-reviewed literature. The trends for extreme events that were described in the NCA3
13 and IPCC assessments have continued and our understanding of the data and ability to evaluate
14 the many facets of the climate system have increased substantially.

15

16 **Key Finding 3**

17 Many lines of evidence demonstrate that it is *extremely likely* that human influence has been the
18 dominant cause of the observed warming since the mid-20th century. Formal detection and
19 attribution studies for the period 1951 to 2010 find that the observed global mean surface
20 temperature warming lies in the middle of the range of likely human contributions to warming
21 over that same period. We find no convincing evidence that natural variability can account for
22 the amount of global warming observed over the industrial era. For the period extending over the
23 last century, there are no convincing alternative explanations supported by the extent of the
24 observational evidence. Solar output changes and internal variability can only contribute
25 marginally to the observed changes in climate over the last century, and we find no convincing
26 evidence for natural cycles in the observational record that could explain the observed changes in
27 climate. (*Very high confidence*)

28 **Description of evidence base**

29 The Key Finding and supporting text summarizes extensive evidence documented in the climate
30 science literature and are similar to statements made in previous national (NCA3; Melillo et al.
31 2014) and international (IPCC 2013) assessments. The human effects on climate have been well
32 documented through many papers in the peer reviewed scientific literature (e.g., see Ch. 2:
33 Physical Drivers of Climate Change and Ch. 3: Detection and Attribution for more discussion of
34 supporting evidence).

1 **Major uncertainties**

2 Key remaining uncertainties relate to the precise magnitude and nature of changes at global, and
3 particularly regional, scales, and especially for extreme events and our ability to simulate and
4 attribute such changes using climate models. The exact effects from land use changes relative to
5 the effects from greenhouse gas emissions needs to be better understood.

6 **Assessment of confidence based on evidence and agreement, including short description of** 7 **nature of evidence and level of agreement**

8 There is *very high confidence* for a major human influence on climate.

9 **Summary sentence or paragraph that integrates the above information**

10 The key message and supporting text summarizes extensive evidence documented in the climate
11 science peer reviewed literature. The analyses described in the NCA3 and IPCC assessments
12 support our findings and new observations and modeling studies have further substantiated these
13 conclusions.

14

15 **Key Finding 4**

16 Global climate is projected to continue to change over this century and beyond. The magnitude
17 of climate change beyond the next few decades will depend primarily on the amount of
18 greenhouse (heat-trapping) gases emitted globally and on the remaining uncertainty in the
19 sensitivity of Earth's climate to those emissions (*very high confidence*). With significant
20 reductions in the emissions of greenhouse gases, the global annually averaged temperature rise
21 could be limited to 3.6°F (2°C) or less. Without major reductions in these emissions, the increase
22 in annual average global temperatures relative to preindustrial times could reach 9°F (5°C) or
23 more by the end of this century (*high confidence*).

24 **Description of evidence base**

25 The Key Finding and supporting text summarizes extensive evidence documented in the climate
26 science literature and are similar to statements made in previous national (NCA3; Melillo et al.
27 2014) and international (IPCC 2013) assessments. The projections for future climate have been
28 well documented through many papers in the peer-reviewed scientific literature (e.g., see Ch. 4:
29 Projections for descriptions of the scenarios and the models used).

30 **Major uncertainties**

31 Key remaining uncertainties relate to the precise magnitude and nature of changes at global, and
32 particularly regional, scales, and especially for extreme events and our ability to simulate and
33 attribute such changes using climate models. Of particular importance are remaining

1 uncertainties in the understanding of feedbacks in the climate system, especially in ice-albedo
2 and cloud cover feedbacks. Continued improvements in climate modeling to represent the
3 physical processes affecting Earth's climate system are aimed at reducing uncertainties.
4 Monitoring and observation programs also can help improve the understanding needed to reduce
5 uncertainties.

6 **Assessment of confidence based on evidence and agreement, including short description of**
7 **nature of evidence and level of agreement**

8 There is *very high confidence* for continued changes in climate and *high confidence* for the levels
9 shown in the Key Finding.

10 **Summary sentence or paragraph that integrates the above information**

11 The Key Finding and supporting text summarizes extensive evidence documented in the climate
12 science peer-reviewed literature. The projections that were described in the NCA3 and IPCC
13 assessments support our findings and new modeling studies have further substantiated these
14 conclusions.

15

16 **Key Finding 5**

17 Natural variability, including El Niño events and other recurring patterns of ocean-atmosphere
18 interactions, impact temperature and precipitation, especially regionally, over months to years.
19 The global influence of natural variability, however, is limited to a small fraction of observed
20 climate trends over decades.

21 **Description of evidence base**

22 The Key Finding and supporting text summarizes extensive evidence documented in the climate
23 science literature and are similar to statements made in previous national (NCA3; Melillo et al.
24 2014) and international (IPCC 2013) assessments. The role of natural variability in climate
25 trends has been extensively discussed in the peer-reviewed literature (e.g., Karl et al. 2015;
26 Rahmstorf et al. 2015; Lewandowsky et al. 2016; Mears and Wentz 2016; Trenberth et al. 2014;
27 Santer et al. 2017a,b).

28 **Major uncertainties**

29 Uncertainties still exist in the precise magnitude and nature of the full effects of individual ocean
30 cycles and other aspects of natural variability on the climate system. Increased emphasis on
31 monitoring should reduce this uncertainty significantly over the next few decades.

32

1 **Assessment of confidence based on evidence and agreement, including short description of**
2 **nature of evidence and level of agreement**

3 There is *very high confidence*, affected to some degree by limitations in the observational record,
4 that the role of natural variability on future climate change is limited.

5 **Summary sentence or paragraph that integrates the above information**

6 The Key Finding and supporting text summarizes extensive evidence documented in the climate
7 science peer-reviewed literature. There has been an extensive increase in the understanding of
8 the role of natural variability on the climate system over the last few decades, including a
9 number of new findings since NCA3.

10

11 **Key Finding 6**

12 Longer-term climate records over past centuries and millennia indicate that average temperatures
13 in recent decades over much of the world have been much higher, and have risen faster during
14 this time period, than at any time in the past 1,700 years or more, the time period for which the
15 global distribution of surface temperatures can be reconstructed.

16 **Description of evidence base**

17 The Key Finding and supporting text summarizes extensive evidence documented in the climate
18 science literature and are similar to statements made in previous national (NCA3; Melillo et al.,
19 2014) and international (IPCC 2013) assessments. There are many recent studies of the
20 paleoclimate leading to this conclusion including those cited in the report (e.g., Mann et al. 2008;
21 PAGE 2K Consortium 2013).

22 **Major uncertainties**

23 Despite the extensive increase in knowledge in the last few decades, there are still many
24 uncertainties in understanding the hemispheric and global changes in climate over the Earth's
25 history, including that of the last few millennia. Additional research efforts in this direction can
26 help reduce those uncertainties.

27 **Assessment of confidence based on evidence and agreement, including short description of**
28 **nature of evidence and level of agreement**

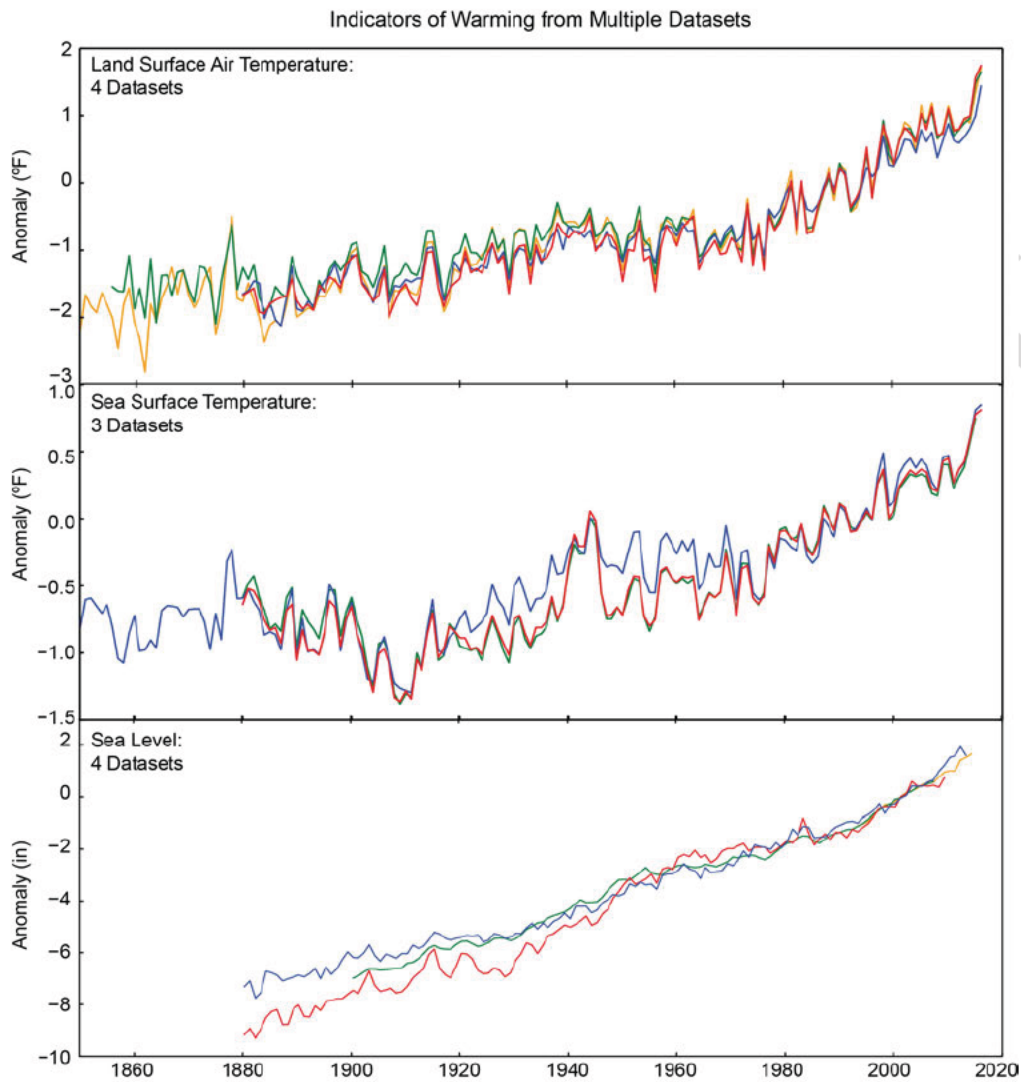
29 There is *high confidence* for current temperatures to be higher than they have been in at least
30 1,700 years and perhaps much longer.

31

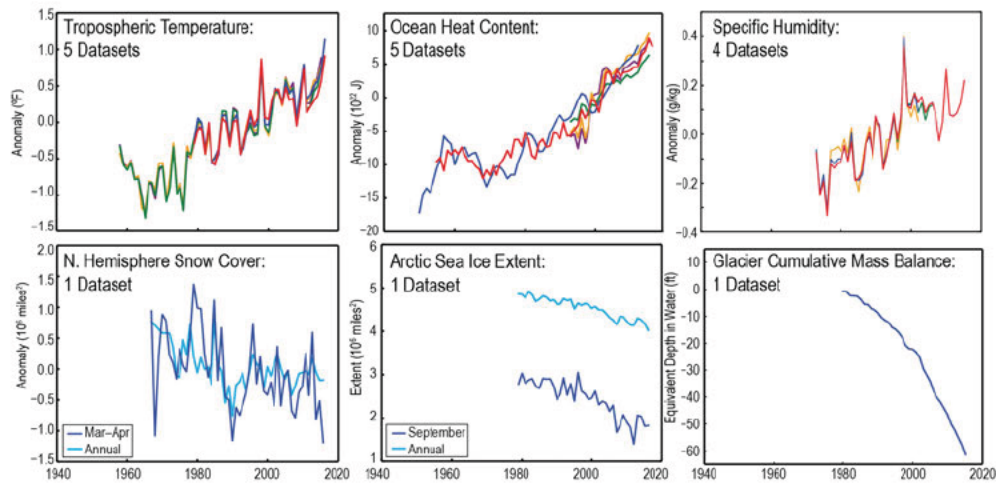
- 1 **Summary sentence or paragraph that integrates the above information**
- 2 The Key Finding and supporting text summarizes extensive evidence documented in the climate
- 3 science peer-reviewed literature. There has been an extensive increase in the understanding of
- 4 past climates on our planet, including a number of new findings since NCA3.
- 5

FINAL DRAFT

1 FIGURES



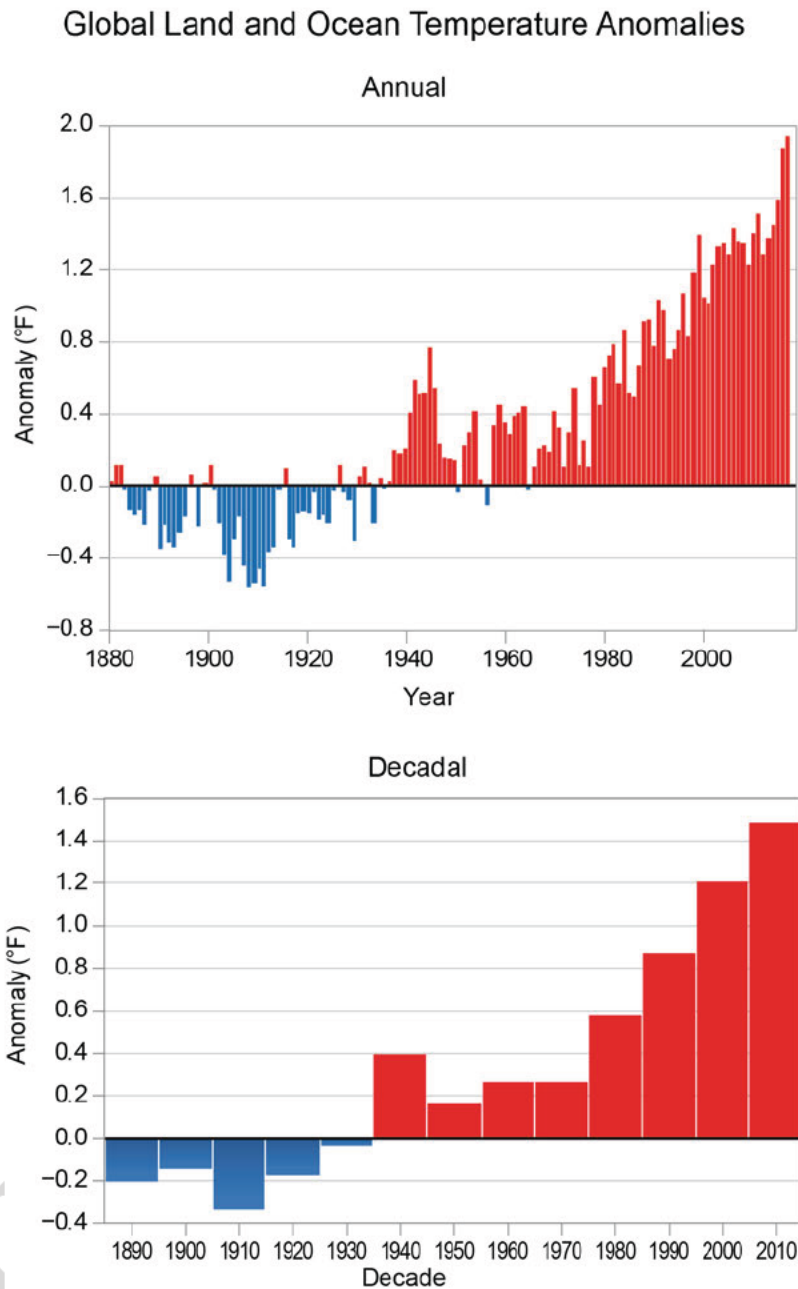
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1 **Figure 1.1.** This image shows observations globally from nine different variables that are key
2 indicators of a warming climate. The indicators (listed below) all show long-term trends that are
3 consistent with global warming. In parentheses are the number of datasets shown in each graph,
4 the length of time covered by the combined datasets and their anomaly reference period (where
5 applicable), and the direction of the trend: land surface air temperature (4 datasets, 1850–2016
6 relative to 1976–2005, increase); sea surface temperature (3 datasets, 1850–2016 relative to
7 1976–2005, increase); sea level (4 datasets, 1880–2014 relative to 1996–2005, increase);
8 tropospheric temperature (5 datasets, 1958–2016 relative to 1981–2005, increase); ocean heat
9 content, upper 700m (5 datasets, 1950–2016 relative to 1996–2005, increase); specific humidity
10 (4 datasets, 1973–2015 relative to 1986–2000, increase); Northern Hemisphere snow cover,
11 March–April and annual (1 dataset, 1967–2016 relative to 1976–2005, decrease); Arctic sea ice
12 extent, September and annual (1 dataset, 1979–2016, decrease); glacier cumulative mass balance
13 (1 dataset, 1980–2015, decrease). More information on the datasets can be found in the
14 accompanying metadata. (Figure source: NOAA NCEI/CICS-NC, updated from Melillo et al.
15 2014; Blunden and Arndt 2016).

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Figure 1.2. Top: Global annual average temperatures (as measured over both land and oceans) for 1880–2016 relative to the reference period of 1901–1960; red bars indicate temperatures above the average over 1901–1960, and blue bars indicate temperatures below the average. Global annual average temperature has increased by more than 1.2°F (0.7°C) for the period 1986–2016 relative to 1901–1960. While there is a clear long-term global warming trend, some years do not show a temperature increase relative to the previous year, and some years show greater changes than others. These year-to-year fluctuations in temperature are mainly due to natural sources of variability, such as the effects of El Niños, La Niñas, and volcanic eruptions. Based on the NCEI (NOAAGlobalTemp) dataset (updated from Vose et al. 2012). Bottom:

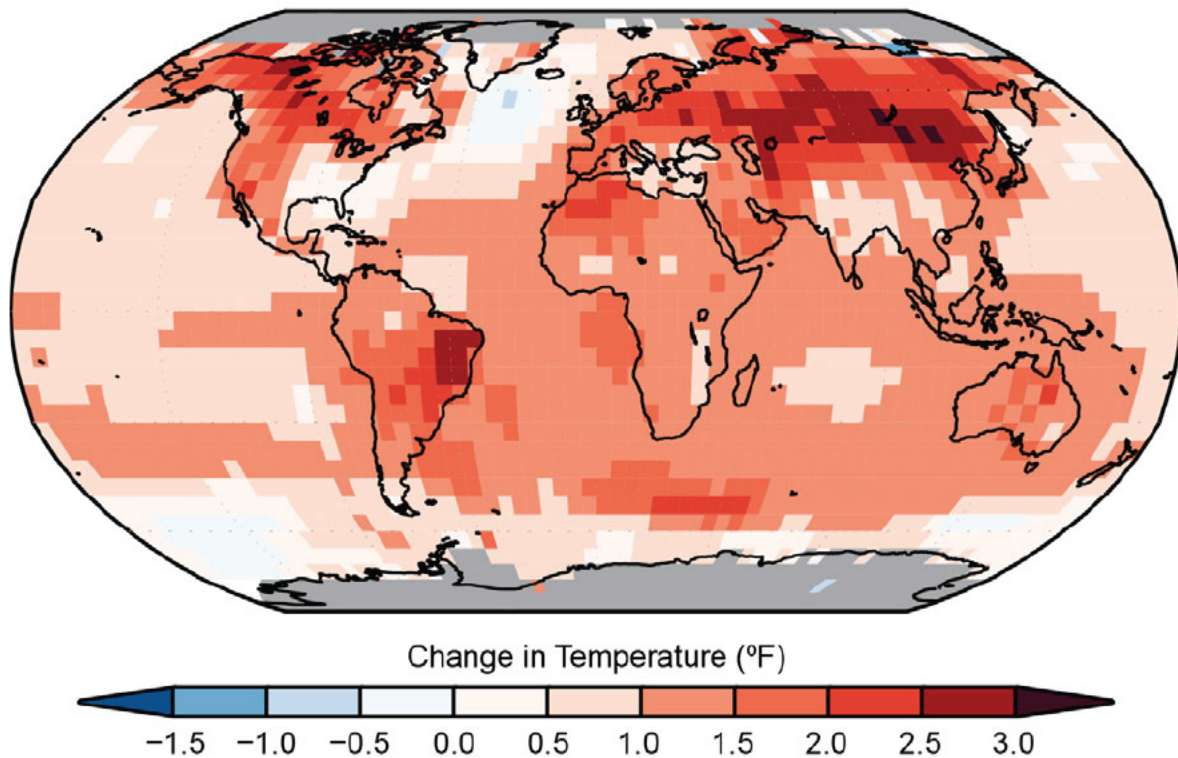
1 Global average temperature averaged over decadal periods (1886–1895, 1896–1905, ..., 1996–
2 2005, except for the 11 years in the last period, 2006–2016). Horizontal label indicates mid-point
3 year of decadal period. Every decade since 1966–1975 has been warmer than the previous
4 decade. (Figure source: [top] adapted from NCEI 2016, [bottom] NOAA NCEI / CICS-NC).

5

FINAL DRAFT

1

Surface Temperature Change

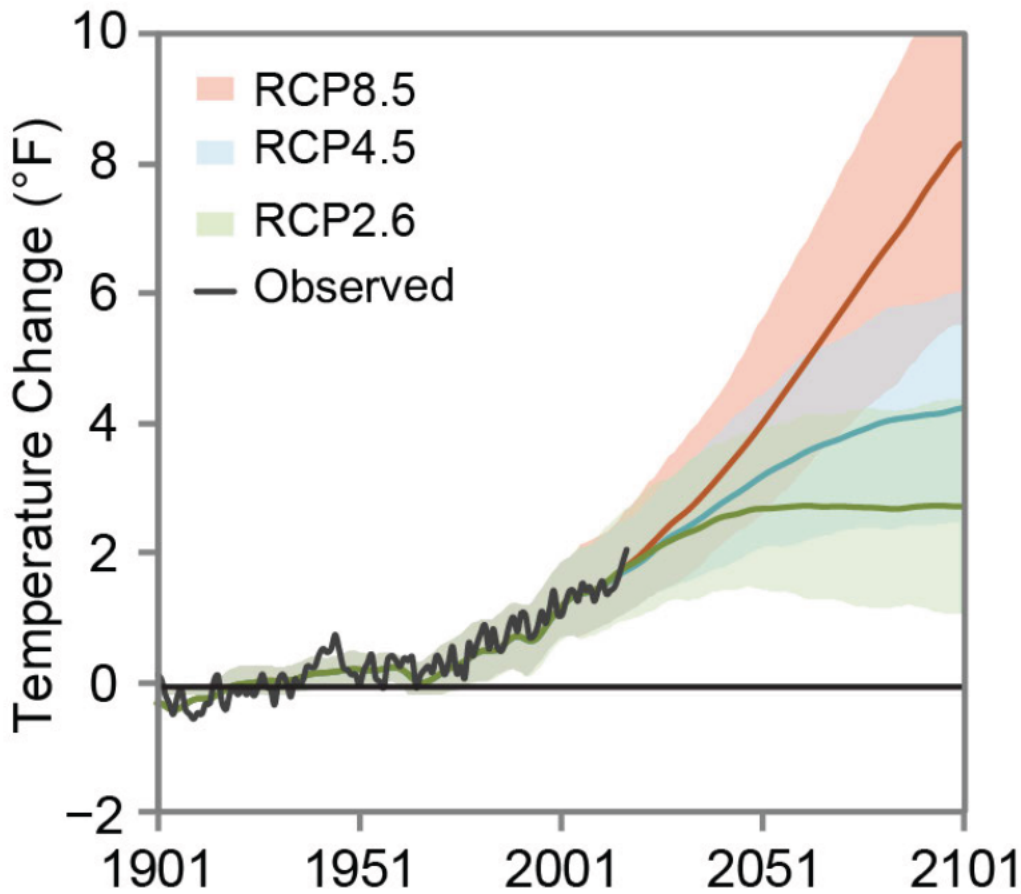


2

3 **Figure 1.3.** Surface temperature change (in °F) for the period 1986–2015 relative to 1901–1960
4 from the NOAA National Centers for Environmental Information’s (NCEI) surface temperature
5 product. For visual clarity, statistical significance is not depicted on this map. Changes are
6 generally significant (at the 90% level) over most land and ocean areas. Changes are not
7 significant in parts of the North Atlantic Ocean, the South Pacific Ocean, and the southeastern
8 United States. There is insufficient data in the Arctic Ocean and Antarctica for computing long-
9 term changes (those sections are shown in grey because no trend can be derived). The relatively
10 coarse resolution ($5.0^\circ \times 5.0^\circ$) of these maps does not capture the finer details associated with
11 mountains, coastlines, and other small-scale effects (see Ch. 6: Temperature Changes for a focus
12 on the United States). (Figure source: updated from Vose et al. 2012).

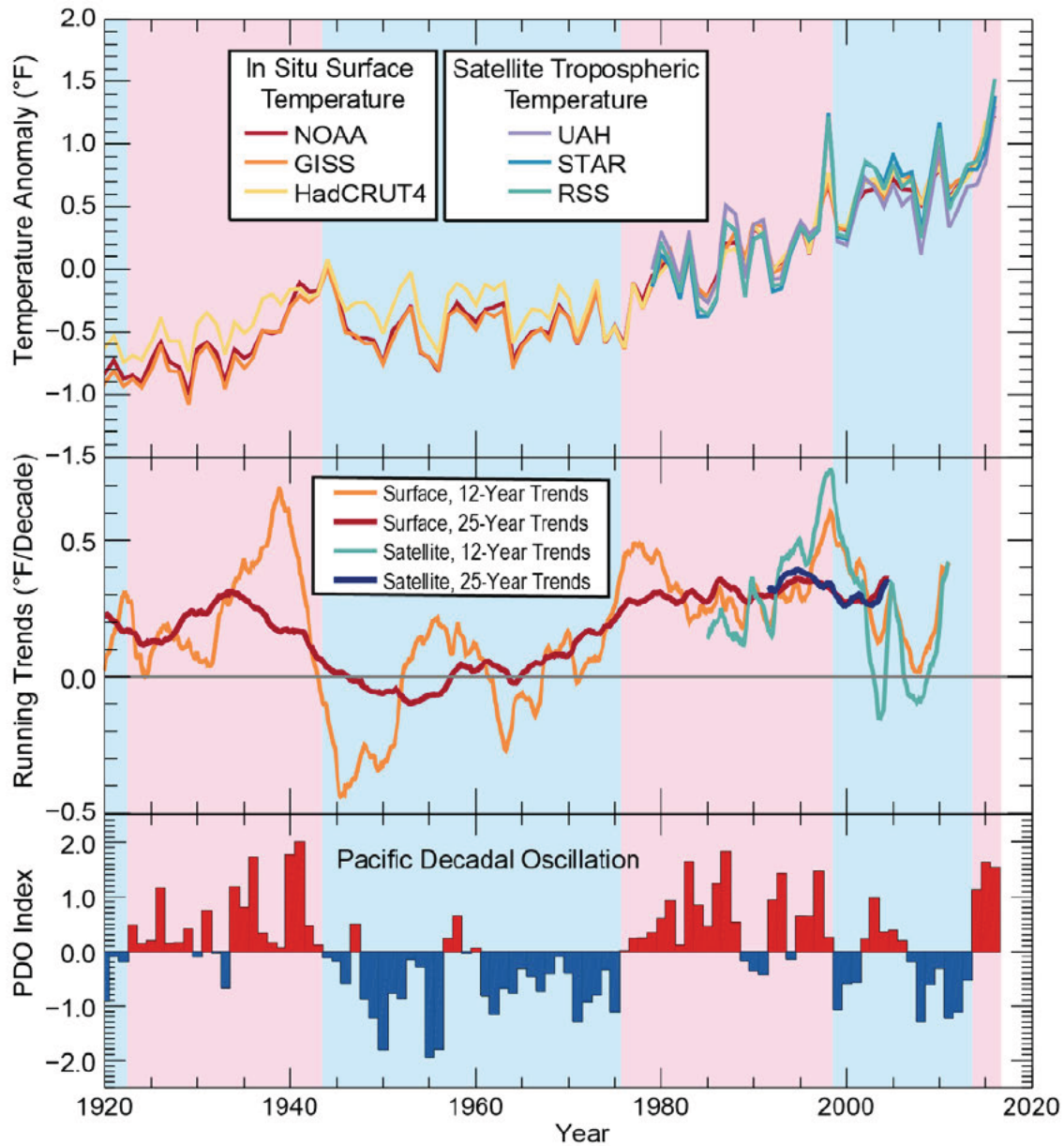
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Projected Global Temperatures



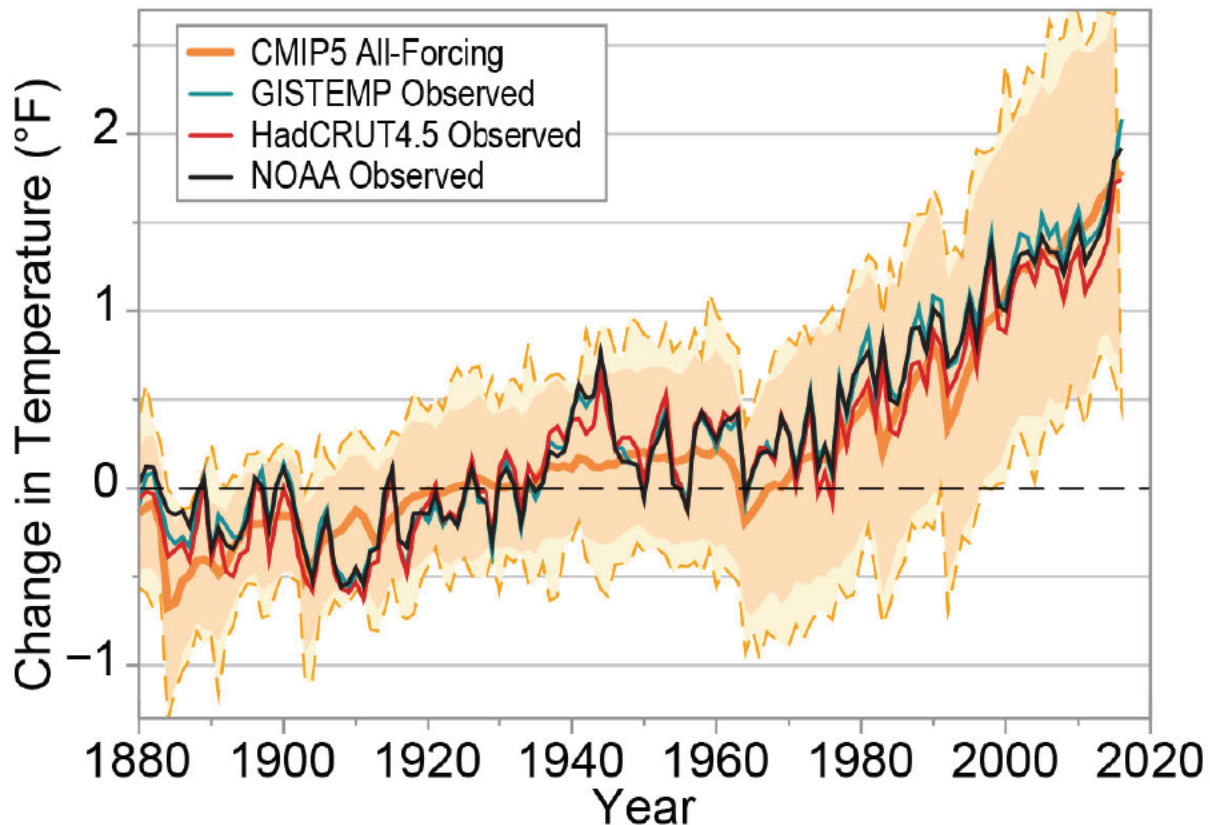
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Figure 1.4. Multimodel simulated time series from 1900 to 2100 for the change in global annual mean surface temperature relative to 1901–1960 for a range of the Representative Concentration Pathways (RCPs; see Ch. 4: Projections for more information). These scenarios account for the uncertainty in future emissions from human activities (as analyzed with the 20+ models from around the world used in the most recent international assessment [IPCC 2013]). The mean (solid lines) and associated uncertainties (shading, showing ± 2 standard deviations [5%–95%] across the distribution of individual models based on the average over 2081–2100) are given for all of the RCP scenarios as colored vertical bars. The numbers of models used to calculate the multimodel means are indicated. (Figure source: adapted from Walsh et al. 2014).



1
 2 **Figure 1.5.** Panel A shows the annual mean temperature anomalies relative to a 1901–1960
 3 baseline for global mean surface temperature and global mean tropospheric temperature. Short-
 4 term variability is superposed on a long-term warming signal, particularly since the 1960s. Panel
 5 B shows the linear trend of short (12-year) and longer (25-year) overlapping periods plotted at
 6 the time of the center of the trend period. For the longer period, trends are positive and nearly
 7 constant since about 1975. Panel C shows the annual mean Pacific Decadal Oscillation (PDO)
 8 index. Short-term temperature trends show a marked tendency to be lower during periods of
 9 generally negative PDO index, shown by the blue shading. (Figure source: adapted and updated
 10 from Trenberth 2015 and Santer et al. 2017a; Panel B, © American Meteorological Society.
 11 Used with permission.)

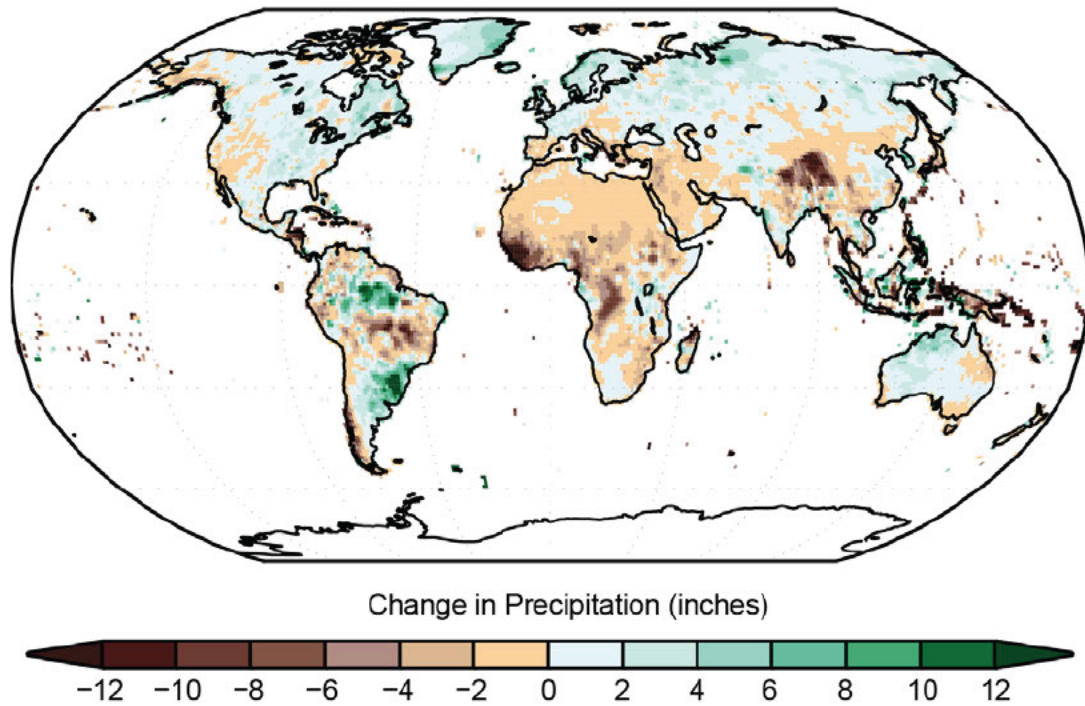
Global Mean Temperature Change



1

2 **Figure 1.6.** Comparison of global mean temperature anomalies (°F) from observations (through
 3 2016) and the CMIP5 multimodel ensemble (through 2016), using the reference period 1901-
 4 1960. The CMIP5 multimodel ensemble (black) is constructed from blended surface temperature
 5 (ocean regions) and surface air temperature (land regions) data from the models, masked where
 6 observations are not available in the GISTEMP dataset (Knutson et al. 2016). The importance of
 7 using blended model data is shown in Richardson et al. (2016). The thick solid orange curve is
 8 the model ensemble mean, formed from the ensemble across 36 models of the individual model
 9 ensemble means. The shaded region shows the +/- two standard deviation range of the individual
 10 ensemble member annual means from the 36 CMIP5 models. The dashed lines show the range
 11 from maximum to minimum values for each year among these ensemble members. The sources
 12 for the three observational indices are: HadCRUT4.5 (brown):
 13 <http://www.metoffice.gov.uk/hadobs/hadcrut4/data/current/download.html>; NOAA (black):
 14 <https://www.ncdc.noaa.gov/monitoring-references/faq/anomalies.php>; and GISTEMP (green):
 15 https://data.giss.nasa.gov/pub/gistemp/gistemp1200_ERSSTv4.nc. (NOAA and HadCRUT4
 16 downloaded on Feb. 15, 2017; GISTEMP downloaded on Feb. 10, 2017). (Figure source:
 17 adapted from Knutson et al. 2016)

1

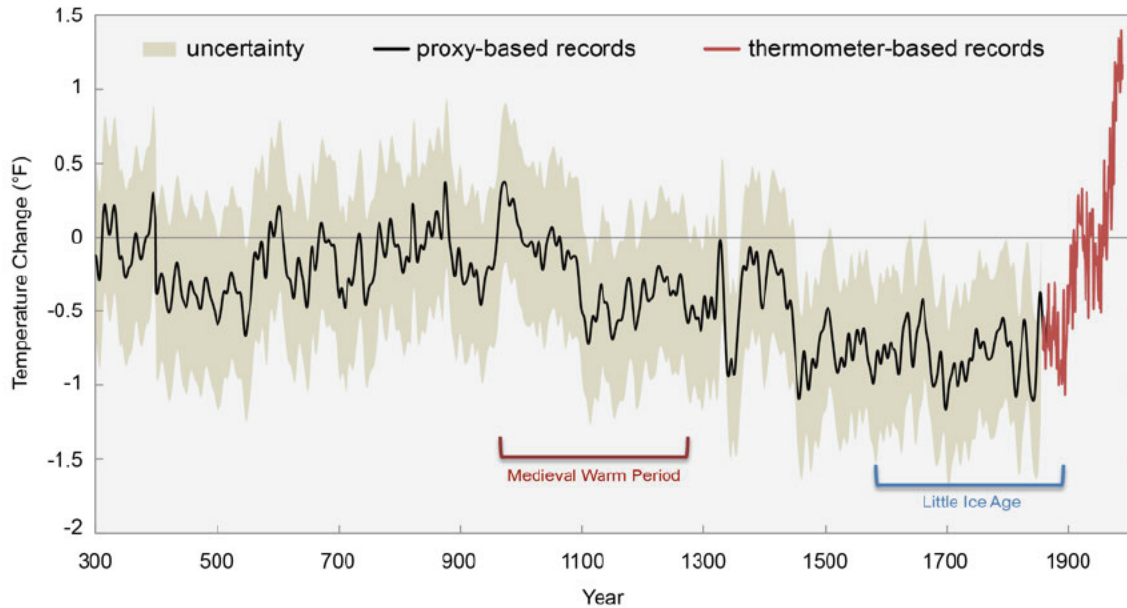


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4 **Figure 1.7.** Surface annually averaged precipitation change (in inches) for the period 1986–2015
5 relative to 1901–1960. The data is from long-term stations, so precipitation changes over the
6 ocean and Antarctica cannot be evaluated. The trends are not considered to be statistically
7 significant because of a lack of data coverage early in the record. The relatively coarse resolution
8 ($0.5^\circ \times 0.5^\circ$) of these maps does not capture the finer details associated with mountains,
9 coastlines, and other small-scale effects. (Figure source: NOAA NCEI / CICS-NC).

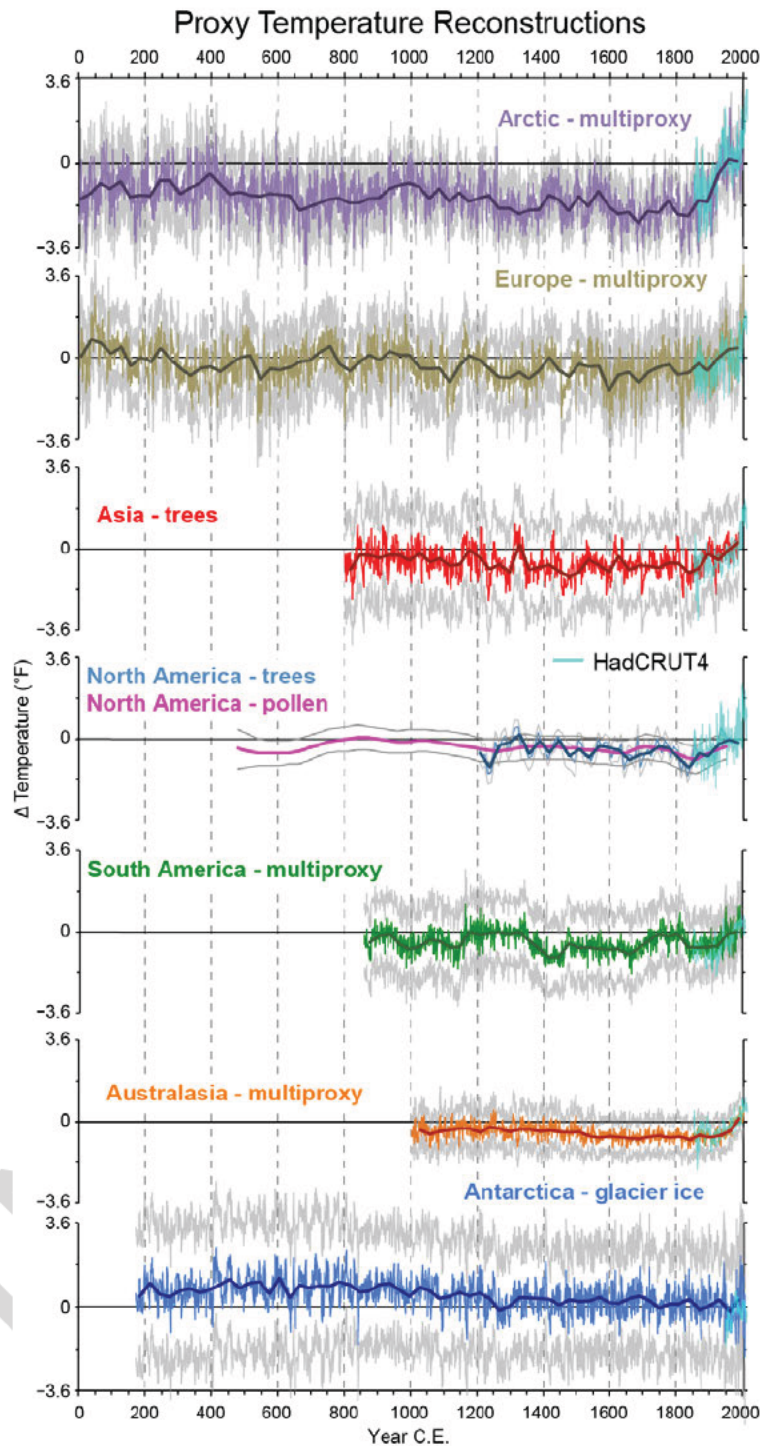
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2 **Figure 1.8.** Changes in the temperature of the northern hemisphere from surface observations (in
 3 red) and from proxies (in black; uncertainty range represented by shading) relative to 1961–1990
 4 average temperature. If this graph were plotted relative to 1901–1960 instead of 1961–1990, the
 5 temperature changes would be 0.47°F (0.26°C) higher. These analyses suggest that current
 6 temperatures are higher than seen in the Northern Hemisphere, and likely globally, in at least the
 7 last 1,700 years, and that the last decade (2006–2015) was the warmest decade on record. (Figure
 8 source: adapted from Mann et al. 2008).

9



1

2 **Figure 1.9.** Proxy temperatures reconstructions for the seven regions of the PAGES 2K
 3 Network. Temperature anomalies are relative to the 1961–1990 reference period. If this graph
 4 were plotted relative to 1901–1960 instead of 1961–1990, the temperature changes would 0.47°F
 5 (0.26°C) higher. Grey lines around expected-value estimates indicate uncertainty ranges as
 6 defined by each regional group (see PAGE 2K Consortium 2013 and related Supplementary
 7 Information). Note that the changes in temperature over the last century tend to occur at a much

1 faster rate than found in the previous time periods. The teal values are from the HadCRUT4
2 surface observation record for land and ocean for the 1800s to 2000 (Jones et al. 2012). (Figure
3 source: adapted from PAGES 2k Consortium 2013).

4

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1 **REFERENCES**

- 2 Adler, R.F., G.J. Huffman, A. Chang, R. Ferraro, P.-P. Xie, J. Janowiak, B. Rudolf, U.
3 Schneider, S. Curtis, D. Bolvin, A. Gruber, J. Susskind, P. Arkin, and E. Nelkin, 2003: The
4 version-2 Global Precipitation Climatology Project (GPCP) monthly precipitation analysis
5 (1979–present). *Journal of Hydrometeorology*, **4**, 1147-1167. [http://dx.doi.org/10.1175/1525-](http://dx.doi.org/10.1175/1525-7541(2003)004<1147:TVGPCP>2.0.CO;2)
6 [7541\(2003\)004<1147:TVGPCP>2.0.CO;2](http://dx.doi.org/10.1175/1525-7541(2003)004<1147:TVGPCP>2.0.CO;2)
- 7 Alexander, L.V., X. Zhang, T.C. Peterson, J. Caesar, B. Gleason, A.M.G. Klein Tank, M.
8 Haylock, D. Collins, B. Trewin, F. Rahimzadeh, A. Tagipour, K. Rupa Kumar, J. Revadekar,
9 G. Griffiths, L. Vincent, D.B. Stephenson, J. Burn, E. Aguilar, M. Brunet, M. Taylor, M.
10 New, P. Zhai, M. Rusticucci, and J.L. Vazquez-Aguirre, 2006: Global observed changes in
11 daily climate extremes of temperature and precipitation. *Journal of Geophysical Research*,
12 **111**, 22. <http://dx.doi.org/10.1029/2005JD006290>
- 13 Allen, M.R. and W.J. Ingram, 2002: Constraints on future changes in climate and the hydrologic
14 cycle. *Nature*, **419**, 224-232. <http://dx.doi.org/10.1038/nature01092>
- 15 Anderson, B.T., J.R. Knight, M.A. Ringer, J.-H. Yoon, and A. Cherchi, 2012: Testing for the
16 possible influence of unknown climate forcings upon global temperature increases from 1950
17 to 2000. *Journal of Climate*, **25**, 7163-7172. <http://dx.doi.org/10.1175/jcli-d-11-00645.1>
- 18 Arnell, N.W. and S.N. Gosling, 2016: The impacts of climate change on river flood risk at the
19 global scale. *Climatic Change*, **134**, 387-401. <http://dx.doi.org/10.1007/s10584-014-1084-5>
- 20 Asadieh, B. and N.Y. Krakauer, 2015: Global trends in extreme precipitation: climate models
21 versus observations. *Hydrology and Earth System Sciences*, **19**, 877-891.
22 <http://dx.doi.org/10.5194/hess-19-877-2015>
- 23 Balmaseda, M.A., K.E. Trenberth, and E. Källén, 2013: Distinctive climate signals in reanalysis
24 of global ocean heat content. *Geophysical Research Letters*, **40**, 1754-1759.
25 <http://dx.doi.org/10.1002/grl.50382>
- 26 Barnes, E.A. and L.M. Polvani, 2015: CMIP5 projections of arctic amplification, of the North
27 American/North Atlantic circulation, and of their relationship. *Journal of Climate*, **28**, 5254-
28 5271. <http://dx.doi.org/10.1175/JCLI-D-14-00589.1>
- 29 Becker, A., P. Finger, A. Meyer-Christoffer, B. Rudolf, K. Schamm, U. Schneider, and M. Ziese,
30 2013: A description of the global land-surface precipitation data products of the Global
31 Precipitation Climatology Centre with sample applications including centennial (trend)
32 analysis from 1901–present. *Earth System Science Data*, **5**, 71-99.
33 <http://dx.doi.org/10.5194/essd-5-71-2013>

- 1 Bender, F.A.-M., V. Ramanathan, and G. Tselioudis, 2012: Changes in extratropical storm track
2 cloudiness 1983–2008: Observational support for a poleward shift. *Climate Dynamics*, **38**,
3 2037-2053. <http://dx.doi.org/10.1007/s00382-011-1065-6>
- 4 Benestad, R.E., 2017: A mental picture of the greenhouse effect. *Theoretical and Applied*
5 *Climatology*, **128**, 679-688. <http://dx.doi.org/10.1007/s00704-016-1732-y>
- 6 Berghuijs, W.R., R.A. Woods, C.J. Hutton, and M. Sivapalan, 2016: Dominant flood generating
7 mechanisms across the United States. *Geophysical Research Letters*, **43**, 4382-4390.
8 <http://dx.doi.org/10.1002/2016GL068070>
- 9 Bernier, P.Y., R.L. Desjardins, Y. Karimi-Zindashty, D. Worth, A. Beaudoin, Y. Luo, and S.
10 Wang, 2011: Boreal lichen woodlands: A possible negative feedback to climate change in
11 eastern North America. *Agricultural and Forest Meteorology*, **151**, 521-528.
12 <http://dx.doi.org/10.1016/j.agrformet.2010.12.013>
- 13 Betts, R.A., O. Boucher, M. Collins, P.M. Cox, P.D. Falloon, N. Gedney, D.L. Hemming, C.
14 Huntingford, C.D. Jones, D.M.H. Sexton, and M.J. Webb, 2007: Projected increase in
15 continental runoff due to plant responses to increasing carbon dioxide. *Nature*, **448**, 1037-
16 1041. <http://dx.doi.org/10.1038/nature06045>
- 17 Bindoff, N.L., P.A. Stott, K.M. AchutaRao, M.R. Allen, N. Gillett, D. Gutzler, K. Hansingo, G.
18 Hegerl, Y. Hu, S. Jain, I.I. Mokhov, J. Overland, J. Perlwitz, R. Sebbari, and X. Zhang, 2013:
19 Detection and attribution of climate change: From global to regional. *Climate Change 2013:*
20 *The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report*
21 *of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M.
22 Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds.
23 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 867–
24 952. <http://www.climatechange2013.org/report/full-report/>
- 25 Blunden, J. and D.S. Arndt, 2016: State of the climate in 2015. *Bulletin of the American*
26 *Meteorological Society*, **97**, Si-S275.
27 <http://dx.doi.org/10.1175/2016BAMSSStateoftheClimate.1>
- 28 Bonan, G.B., 2008: Forests and climate change: Forcings, feedbacks, and the climate benefits of
29 forests. *Science*, **320**, 1444-1449. <http://dx.doi.org/10.1126/science.1155121>
- 30 Callaghan, T.V., M. Johansson, R.D. Brown, P.Y. Groisman, N. Labba, V. Radionov, R.S.
31 Bradley, S. Blangy, O.N. Bulygina, T.R. Christensen, J.E. Colman, R.L.H. Essery, B.C.
32 Forbes, M.C. Forchhammer, V.N. Golubev, R.E. Honrath, G.P. Juday, A.V. Meshcherskaya,
33 G.K. Phoenix, J. Pomeroy, A. Rautio, D.A. Robinson, N.M. Schmidt, M.C. Serreze, V.P.
34 Shevchenko, A.I. Shiklomanov, A.B. Shmakin, P. Sköld, M. Sturm, M.-k. Woo, and E.F.

- 1 Wood, 2011: Multiple effects of changes in Arctic snow cover. *Ambio*, **40**, 32-45.
2 <http://dx.doi.org/10.1007/s13280-011-0213-x>
- 3 Chambers, J.Q., J.I. Fisher, H. Zeng, E.L. Chapman, D.B. Baker, and G.C. Hurtt, 2007:
4 Hurricane Katrina's carbon footprint on U.S. Gulf Coast forests. *Science*, **318**, 1107-1107.
5 <http://dx.doi.org/10.1126/science.1148913>
- 6 Chang, E.K.M., 2013: CMIP5 projection of significant reduction in extratropical cyclone activity
7 over North America. *Journal of Climate*, **26**, 9903-9922. [http://dx.doi.org/10.1175/JCLI-D-](http://dx.doi.org/10.1175/JCLI-D-13-00209.1)
8 [13-00209.1](http://dx.doi.org/10.1175/JCLI-D-13-00209.1)
- 9 Chen, X. and K.-K. Tung, 2014: Varying planetary heat sink led to global-warming slowdown
10 and acceleration. *Science*, **345**, 897-903. <http://dx.doi.org/10.1126/science.1254937>
- 11 Church, J.A. and N.J. White, 2011: Sea-level rise from the late 19th to the early 21st century.
12 *Surveys in Geophysics*, **32**, 585-602. <http://dx.doi.org/10.1007/s10712-011-9119-1>
- 13 Church, J.A., N.J. White, L.F. Konikow, C.M. Domingues, J.G. Cogley, E. Rignot, J.M.
14 Gregory, M.R. van den Broeke, A.J. Monaghan, and I. Velicogna, 2011: Revisiting the
15 Earth's sea-level and energy budgets from 1961 to 2008. *Geophysical Research Letters*, **38**,
16 L18601. <http://dx.doi.org/10.1029/2011GL048794>
- 17 Churkina, G., V. Brovkin, W. von Bloh, K. Trusilova, M. Jung, and F. Dentener, 2009: Synergy
18 of rising nitrogen depositions and atmospheric CO₂ on land carbon uptake moderately offsets
19 global warming. *Global Biogeochemical Cycles*, **23**, n/a-n/a.
20 <http://dx.doi.org/10.1029/2008GB003291>
- 21 Ciais, P., M. Reichstein, N. Viovy, A. Granier, J. Ogee, V. Allard, M. Aubinet, N. Buchmann, C.
22 Bernhofer, A. Carrara, F. Chevallier, N. De Noblet, A.D. Friend, P. Friedlingstein, T.
23 Grunwald, B. Heinesch, P. Keronen, A. Knohl, G. Krinner, D. Loustau, G. Manca, G.
24 Matteucci, F. Miglietta, J.M. Ourcival, D. Papale, K. Pilegaard, S. Rambal, G. Seufert, J.F.
25 Soussana, M.J. Sanz, E.D. Schulze, T. Vesala, and R. Valentini, 2005: Europe-wide
26 reduction in primary productivity caused by the heat and drought in 2003. *Nature*, **437**, 529-
27 533. <http://dx.doi.org/10.1038/nature03972>
- 28 Clark, D.B., D.A. Clark, and S.F. Oberbauer, 2010: Annual wood production in a tropical rain
29 forest in NE Costa Rica linked to climatic variation but not to increasing CO₂. *Global*
30 *Change Biology*, **16**, 747-759. <http://dx.doi.org/10.1111/j.1365-2486.2009.02004.x>
- 31 Colle, B.A., Z. Zhang, K.A. Lombardo, E. Chang, P. Liu, and M. Zhang, 2013: Historical
32 evaluation and future prediction of eastern North American and western Atlantic
33 extratropical cyclones in the CMIP5 models during the cool season. *Journal of Climate*, **26**,
34 6882-6903. <http://dx.doi.org/10.1175/JCLI-D-12-00498.1>

- 1 Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J.
2 Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver, and M. Wehner,
3 2013: Long-term climate change: Projections, commitments and irreversibility. *Climate*
4 *Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth*
5 *Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D.
6 Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and
7 P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New
8 York, NY, USA, 1029–1136. <http://www.climatechange2013.org/report/full-report/>
- 9 Comiso, J.C. and D.K. Hall, 2014: Climate trends in the Arctic as observed from space. *Wiley*
10 *Interdisciplinary Reviews: Climate Change*, **5**, 389-409. <http://dx.doi.org/10.1002/wcc.277>
- 11 Dai, A., 2013: Increasing drought under global warming in observations and models. *Nature*
12 *Climate Change*, **3**, 52-58. <http://dx.doi.org/10.1038/nclimate1633>
- 13 Davy, R., I. Esau, A. Chernokulsky, S. Outten, and S. Zilitinkevich, 2016: Diurnal asymmetry to
14 the observed global warming. *International Journal of Climatology*, **37**, 79-93.
15 <http://dx.doi.org/10.1002/joc.4688>
- 16 de Noblet-Ducoudré, N., J.-P. Boisier, A. Pitman, G.B. Bonan, V. Brovkin, F. Cruz, C. Delire,
17 V. Gayler, B.J.J.M.v.d. Hurk, P.J. Lawrence, M.K.v.d. Molen, C. Müller, C.H. Reick, B.J.
18 Strengers, and A. Voldoire, 2012: Determining robust impacts of land-use-induced land
19 cover changes on surface climate over North America and Eurasia: Results from the first set
20 of LUCID experiments. *Journal of Climate*, **25**, 3261-3281. [http://dx.doi.org/10.1175/JCLI-](http://dx.doi.org/10.1175/JCLI-D-11-00338.1)
21 [D-11-00338.1](http://dx.doi.org/10.1175/JCLI-D-11-00338.1)
- 22 DeConto, R.M. and D. Pollard, 2016: Contribution of Antarctica to past and future sea-level rise.
23 *Nature*, **531**, 591-597. <http://dx.doi.org/10.1038/nature17145>
- 24 Delworth, T.L. and T.R. Knutson, 2000: Simulation of early 20th century global warming.
25 *Science*, **287**, 2246-2250. <http://dx.doi.org/10.1126/science.287.5461.2246>
- 26 Derksen, C. and R. Brown, 2012: Spring snow cover extent reductions in the 2008–2012 period
27 exceeding climate model projections. *Geophysical Research Letters*, **39**, L19504.
28 <http://dx.doi.org/10.1029/2012gl053387>
- 29 Derksen, D., R. Brown, L. Mudryk, and K. Loujus, 2015: [The Arctic] Terrestrial snow cover [in
30 “State of the Climate in 2014”]. *Bulletin of the American Meteorological Society*, **96** (12),
31 S133-S135. <http://dx.doi.org/10.1175/2015BAMSSStateoftheClimate.1>
- 32 Deser, C., R. Knutti, S. Solomon, and A.S. Phillips, 2012: Communication of the role of natural
33 variability in future North American climate. *Nature Climate Change*, **2**, 775-779.
34 <http://dx.doi.org/10.1038/nclimate1562>

- 1 Diffenbaugh, N.S., M. Scherer, and R.J. Trapp, 2013: Robust increases in severe thunderstorm
2 environments in response to greenhouse forcing. *Proceedings of the National Academy of*
3 *Sciences*, **110**, 16361-16366. <http://dx.doi.org/10.1073/pnas.1307758110>
- 4 Donat, M.G., A.L. Lowry, L.V. Alexander, P.A. Ogorman, and N. Maher, 2016: More extreme
5 precipitation in the world's dry and wet regions. *Nature Climate Change*, **6**, 508-513.
6 <http://dx.doi.org/10.1038/nclimate2941>
- 7 Dutton, A. and K. Lambeck, 2012: Ice volume and sea level during the Last Interglacial. *Science*,
8 **337**, 216-219. <http://dx.doi.org/10.1126/science.1205749>
- 9 Easterling, D.R. and M.F. Wehner, 2009: Is the climate warming or cooling? *Geophysical*
10 *Research Letters*, **36**, 3. <http://dx.doi.org/10.1029/2009GL037810>
- 11 Easterling, D.R., K.E. Kunkel, M.F. Wehner, and L. Sun, 2016: Detection and attribution of
12 climate extremes in the observed record. *Weather and Climate Extremes*, **11**, 17-27.
13 <http://dx.doi.org/10.1016/j.wace.2016.01.001>
- 14 Eisenman, I., W.N. Meier, and J.R. Norris, 2014: A spurious jump in the satellite record: Has
15 Antarctic sea ice expansion been overestimated? *The Cryosphere*, **8**, 1289-1296.
16 <http://dx.doi.org/10.5194/tc-8-1289-2014>
- 17 Elsner, J.B., J.P. Kossin, and T.H. Jagger, 2008: The increasing intensity of the strongest tropical
18 cyclones. *Nature*, **455**, 92-95. <http://dx.doi.org/10.1038/nature07234>
- 19 Emanuel, K.A., 2013: Downscaling CMIP5 climate models shows increased tropical cyclone
20 activity over the 21st century. *Proceedings of the National Academy of Sciences*, **110**, 12219-
21 12224. <http://dx.doi.org/10.1073/pnas.1301293110>
- 22 England, M.H., S. McGregor, P. Spence, G.A. Meehl, A. Timmermann, W. Cai, A.S. Gupta,
23 M.J. McPhaden, A. Purich, and A. Santoso, 2014: Recent intensification of wind-driven
24 circulation in the Pacific and the ongoing warming hiatus. *Nature Climate Change*, **4**, 222-
25 227. <http://dx.doi.org/10.1038/nclimate2106>
- 26 EPA, 2016: Climate change indicators in the United States, 2016. U.S. Environmental Protection
27 Agency, 92 pp.
- 28 Ezer, T. and L.P. Atkinson, 2014: Accelerated flooding along the U.S. East Coast: On the impact
29 of sea-level rise, tides, storms, the Gulf Stream, and the North Atlantic Oscillations. *Earth's*
30 *Future*, **2**, 362-382. <http://dx.doi.org/10.1002/2014EF000252>
- 31 Feldmann, J. and A. Levermann, 2015: Collapse of the West Antarctic Ice Sheet after local
32 destabilization of the Amundsen Basin. *Proceedings of the National Academy of Sciences*,
33 **112**, 14191-14196. <http://dx.doi.org/10.1073/pnas.1512482112>

- 1 Fettweis, X., M. Tedesco, M. van den Broeke, and J. Ettema, 2011: Melting trends over the
2 Greenland ice sheet (1958–2009) from spaceborne microwave data and regional climate
3 models. *The Cryosphere*, **5**, 359-375. <http://dx.doi.org/10.5194/tc-5-359-2011>
- 4 Finzi, A.C., D.J.P. Moore, E.H. DeLucia, J. Lichter, K.S. Hofmockel, R.B. Jackson, H.-S. Kim,
5 R. Matamala, H.R. McCarthy, R. Oren, J.S. Phippen, and W.H. Schlesinger, 2006: Progressive
6 nitrogen limitation of ecosystem processes under elevated CO₂ in a warm-temperate forest.
7 *Ecology*, **87**, 15-25. <http://dx.doi.org/10.1890/04-1748>
- 8 Fischer, E.M., and R. Knutti, 2016: Observed heavy precipitation increase confirms theory and
9 early models. *Nature Climate Change*, **6**, 986-992
- 10 Fyfe, J.C., G.A. Meehl, M.H. England, M.E. Mann, B.D. Santer, G.M. Flato, E. Hawkins, N.P.
11 Gillett, S.-P. Xie, Y. Kosaka, and N.C. Swart, 2016: Making sense of the early-2000s
12 warming slowdown. *Nature Climate Change*, **6**, 224-228.
13 <http://dx.doi.org/10.1038/nclimate2938>
- 14 Greve, P., B. Orlowsky, B. Mueller, J. Sheffield, M. Reichstein, and S.I. Seneviratne, 2014:
15 Global assessment of trends in wetting and drying over land. *Nature Geoscience*, **7**, 716-721.
16 <http://dx.doi.org/10.1038/ngeo2247>
- 17 Harig, C. and F.J. Simons, 2012: Mapping Greenland's mass loss in space and time. *Proceedings*
18 *of the National Academy of Sciences*, **109**, 19934-19937.
19 <http://dx.doi.org/10.1073/pnas.1206785109>
- 20 Harig, C. and F.J. Simons, 2015: Accelerated West Antarctic ice mass loss continues to outpace
21 East Antarctic gains. *Earth and Planetary Science Letters*, **415**, 134-141.
22 <http://dx.doi.org/10.1016/j.epsl.2015.01.029>
- 23 Harig, C. and F.J. Simons, 2016: Ice mass loss in Greenland, the Gulf of Alaska, and the
24 Canadian Archipelago: Seasonal cycles and decadal trends. *Geophysical Research Letters*,
25 **43**, 3150-3159. <http://dx.doi.org/10.1002/2016GL067759>
- 26 Hausfather, Z., K. Cowtan, D.C. Clarke, P. Jacobs, M. Richardson, and R. Rohde, 2017:
27 Assessing recent warming using instrumentally homogeneous sea surface temperature
28 records. *Science Advances*, **3**. <http://dx.doi.org/10.1126/sciadv.1601207>
- 29 Hay, C.C., E. Morrow, R.E. Kopp, and J.X. Mitrovica, 2015: Probabilistic reanalysis of
30 twentieth-century sea-level rise. *Nature*, **517**, 481-484. <http://dx.doi.org/10.1038/nature14093>
- 31 Haywood, A.M., D.J. Hill, A.M. Dolan, B.L. Otto-Bliesner, F. Bragg, W.L. Chan, M.A.
32 Chandler, C. Contoux, H.J. Dowsett, A. Jost, Y. Kamae, G. Lohmann, D.J. Lunt, A. Abe-
33 Ouchi, S.J. Pickering, G. Ramstein, N.A. Rosenbloom, U. Salzmann, L. Sohl, C. Stepanek,
34 H. Ueda, Q. Yan, and Z. Zhang, 2013: Large-scale features of Pliocene climate: Results from

- 1 the Pliocene Model Intercomparison Project. *Climate of the Past*, **9**, 191-209.
2 <http://dx.doi.org/10.5194/cp-9-191-2013>
- 3 Held, I.M. and B.J. Soden, 2006: Robust responses of the hydrological cycle to global warming.
4 *Journal of Climate*, **19**, 5686-5699. <http://dx.doi.org/10.1175/jcli3990.1>
- 5 Hoegh-Guldberg, O., R. Cai, E.S. Poloczanska, P.G. Brewer, S. Sundby, K. Hilmi, V.J. Fabry,
6 and S. Jung, 2014: The Ocean. *Climate Change 2014: Impacts, Adaptation, and*
7 *Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth*
8 *Assessment Report of the Intergovernmental Panel of Climate Change*. Barros, V.R., C.B.
9 Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O.
10 Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea,
11 and L.L. White, Eds. Cambridge University Press, Cambridge, United Kingdom and New
12 York, NY, USA, 1655-1731. <http://www.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5->
13 [Chap30_FINAL.pdf](http://www.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-Chap30_FINAL.pdf)
- 14 Hoerling, M., M. Chen, R. Dole, J. Eischeid, A. Kumar, J.W. Nielsen-Gammon, P. Pegion, J.
15 Perlwitz, X.-W. Quan, and T. Zhang, 2013: Anatomy of an extreme event. *Journal of*
16 *Climate*, **26**, 2811–2832. <http://dx.doi.org/10.1175/JCLI-D-12-00270.1>
- 17 Horton, D.E., N.C. Johnson, D. Singh, D.L. Swain, B. Rajaratnam, and N.S. Diffenbaugh, 2015:
18 Contribution of changes in atmospheric circulation patterns to extreme temperature trends.
19 *Nature*, **522**, 465-469. <http://dx.doi.org/10.1038/nature14550>
- 20 Houghton, R.A., J.I. House, J. Pongratz, G.R. van der Werf, R.S. DeFries, M.C. Hansen, C. Le
21 Quéré, and N. Ramankutty, 2012: Carbon emissions from land use and land-cover change.
22 *Biogeosciences*, **9**, 5125-5142. <http://dx.doi.org/10.5194/bg-9-5125-2012>
- 23 Huber, M. and R. Knutti, 2014: Natural variability, radiative forcing and climate response in the
24 recent hiatus reconciled. *Nature Geoscience*, **7**, 651-656. <http://dx.doi.org/10.1038/ngeo2228>
- 25 Hulme, M., 2014: Attributing weather extremes to ‘climate change’. *Progress in Physical*
26 *Geography*, **38**, 499-511. <http://dx.doi.org/10.1177/0309133314538644>
- 27 Hurrell, J.W. and C. Deser, 2009: North Atlantic climate variability: The role of the North
28 Atlantic oscillation. *Journal of Marine Systems*, **78**, 28-41.
29 <http://dx.doi.org/10.1016/j.jmarsys.2008.11.026>
- 30 IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group*
31 *I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.
32 Cambridge University Press, Cambridge, UK and New York, NY, 1535 pp.
33 <http://www.climatechange2013.org/report/>

- 1 Jacob, T., J. Wahr, W.T. Pfeffer, and S. Swenson, 2012: Recent contributions of glaciers and ice
2 caps to sea level rise. *Nature*, **482**, 514-518. <http://dx.doi.org/10.1038/nature10847>
- 3 Jenkins, A., P. Dutrieux, S.S. Jacobs, S.D. McPhail, J.R. Perrett, A.T. Webb, and D. White,
4 2010: Observations beneath Pine Island Glacier in West Antarctica and implications for its
5 retreat. *Nature Geoscience*, **3**, 468-472. <http://dx.doi.org/10.1038/ngeo890>
- 6 Johnson, G.C., J.M. Lyman, J. Antonov, N. Bindoff, T. Boyer, C.M. Domingues, S.A. Good, M.
7 Ishii, and J.K. Willis, 2015: [Global Oceans] Ocean Heat Content [in “State of the Climate in
8 2014”]. *Bulletin of the American Meteorological Society (BAMS)*, **96** (7), S64-S66
- 9 Jones, D.A., W. Wang, and R. Fawcett, 2009: High-quality spatial climate data-sets for
10 Australia. *Australian Meteorological and Oceanographic Journal*, **58**, 233-248.
11 <http://dx.doi.org/10.22499/2.5804.003>
- 12 Jones, P.D., D.H. Lister, T.J. Osborn, C. Harpham, M. Salmon, and C.P. Morice, 2012:
13 Hemispheric and large-scale land surface air temperature variations: An extensive revision
14 and an update to 2010. *Journal of Geophysical Research*, **117**.
15 <http://dx.doi.org/10.1029/2011JD017139>
- 16 Joughin, I., B.E. Smith, and B. Medley, 2014: Marine ice sheet collapse potentially under way
17 for the Thwaites Glacier Basin, West Antarctica. *Science*, **344**, 735-738.
18 <http://dx.doi.org/10.1126/science.1249055>
- 19 Karl, T.R., A. Arguez, B. Huang, J.H. Lawrimore, J.R. McMahon, M.J. Menne, T.C. Peterson,
20 R.S. Vose, and H.-M. Zhang, 2015: Possible artifacts of data biases in the recent global
21 surface warming hiatus. *Science*, **348**, 1469-1472. <http://dx.doi.org/10.1126/science.aaa5632>
- 22 Kaspar, F., N. Köhl, U. Cubasch, and T. Litt, 2005: A model-data comparison of European
23 temperatures in the Eemian interglacial. *Geophysical Research Letters*, **32**, n/a-n/a.
24 <http://dx.doi.org/10.1029/2005GL022456>
- 25 Katz, R.W. and B.G. Brown, 1992: Extreme events in a changing climate: Variability is more
26 important than averages. *Climatic Change*, **21**, 289-302.
27 <http://dx.doi.org/10.1007/bf00139728>
- 28 Kim, Y., J.S. Kimball, K. Zhang, and K.C. McDonald, 2012: Satellite detection of increasing
29 Northern Hemisphere non-frozen seasons from 1979 to 2008: Implications for regional
30 vegetation growth. *Remote Sensing of Environment*, **121**, 472-487.
31 <http://dx.doi.org/10.1016/j.rse.2012.02.014>
- 32 Knutson, T.R., J.J. Sirutis, M. Zhao, R.E. Tuleya, M. Bender, G.A. Vecchi, G. Villarini, and D.
33 Chavas, 2015: Global projections of intense tropical cyclone activity for the late twenty-first

- 1 century from dynamical downscaling of CMIP5/RCP4.5 scenarios. *Journal of Climate*, **28**,
2 7203-7224. <http://dx.doi.org/10.1175/JCLI-D-15-0129.1>
- 3 Knutson, T.R., R. Zhang, and L.W. Horowitz, 2016: Prospects for a prolonged slowdown in
4 global warming in the early 21st century. *Nature Communcations*, **7**, 13676.
5 <http://dx.doi.org/10.1038/ncomms13676>
- 6 Kopp, R.E., F.J. Simons, J.X. Mitrovica, A.C. Maloof, and M. Oppenheimer, 2009: Probabilistic
7 assessment of sea level during the last interglacial stage. *Nature*, **462**, 863-867.
8 <http://dx.doi.org/10.1038/nature08686>
- 9 Kopp, R.E., R.M. Horton, C.M. Little, J.X. Mitrovica, M. Oppenheimer, D.J. Rasmussen, B.H.
10 Strauss, and C. Tebaldi, 2014: Probabilistic 21st and 22nd century sea-level projections at a
11 global network of tide-gauge sites. *Earth's Future*, **2**, 383-406.
12 <http://dx.doi.org/10.1002/2014EF000239>
- 13 Kosaka, Y. and S.-P. Xie, 2013: Recent global-warming hiatus tied to equatorial Pacific surface
14 cooling. *Nature*, **501**, 403-407. <http://dx.doi.org/10.1038/nature12534>
- 15 Kossin, J.P., T.L. Olander, and K.R. Knapp, 2013: Trend analysis with a new global record of
16 tropical cyclone intensity. *Journal of Climate*, **26**, 9960-9976.
17 <http://dx.doi.org/10.1175/JCLI-D-13-00262.1>
- 18 Kossin, J.P., K.A. Emanuel, and G.A. Vecchi, 2014: The poleward migration of the location of
19 tropical cyclone maximum intensity. *Nature*, **509**, 349-352.
20 <http://dx.doi.org/10.1038/nature13278>
- 21 Kossin, J.P., K.A. Emanuel, and S.J. Camargo, 2016: Past and projected changes in western
22 North Pacific tropical cyclone exposure. *Journal of Climate*, **29**, 5725-5739.
23 <http://dx.doi.org/10.1175/JCLI-D-16-0076.1>
- 24 Kundzewicz, Z.W., S. Kanae, S.I. Seneviratne, J. Handmer, N. Nicholls, P. Peduzzi, R. Mechler,
25 L.M. Bouwer, N. Arnell, K. Mach, R. Muir-Wood, G.R. Brakenridge, W. Kron, G. Benito,
26 Y. Honda, K. Takahashi, and B. Sherstyukov, 2014: Flood risk and climate change: Global
27 and regional perspectives. *Hydrological Sciences Journal*, **59**, 1-28.
28 <http://dx.doi.org/10.1080/02626667.2013.857411>
- 29 Kunkel, K.E. and R.M. Frankson, 2015: Global land surface extremes of precipitation: Data
30 limitations and trends. *Journal of Extreme Events*, **02**, 1550004.
31 <http://dx.doi.org/10.1142/S2345737615500049>
- 32 Kunkel, K.E., T.R. Karl, H. Brooks, J. Kossin, J. Lawrimore, D. Arndt, L. Bosart, D. Changnon,
33 S.L. Cutter, N. Doesken, K. Emanuel, P.Y. Groisman, R.W. Katz, T. Knutson, J. O'Brien,
34 C.J. Paciorek, T.C. Peterson, K. Redmond, D. Robinson, J. Trapp, R. Vose, S. Weaver, M.

- 1 Wehner, K. Wolter, and D. Wuebbles, 2013: Monitoring and understanding trends in extreme
2 storms: State of knowledge. *Bulletin of the American Meteorological Society*, **94**.
3 <http://dx.doi.org/10.1175/BAMS-D-11-00262.1>
- 4 Kunkel, K.E., D.A. Robinson, S. Champion, X. Yin, T. Estilow, and R.M. Frankson, 2016:
5 Trends and extremes in Northern Hemisphere snow characteristics. *Current Climate Change*
6 *Reports*, **2**, 65-73. <http://dx.doi.org/10.1007/s40641-016-0036-8>
- 7 Kurz, W.A., G. Stinson, G.J. Rampley, C.C. Dymond, and E.T. Neilson, 2008: Risk of natural
8 disturbances makes future contribution of Canada's forests to the global carbon cycle highly
9 uncertain. *Proceedings of the National Academy of Sciences*, **105**, 1551-1555.
10 <http://dx.doi.org/10.1073/pnas.0708133105>
- 11 Le Quéré, C., R. Moriarty, R.M. Andrew, J.G. Canadell, S. Sitch, J.I. Korsbakken, P.
12 Friedlingstein, G.P. Peters, R.J. Andres, T.A. Boden, R.A. Houghton, J.I. House, R.F.
13 Keeling, P. Tans, A. Arneeth, D.C.E. Bakker, L. Barbero, L. Bopp, J. Chang, F. Chevallier,
14 L.P. Chini, P. Ciais, M. Fader, R.A. Feely, T. Gkritzalis, I. Harris, J. Hauck, T. Ilyina, A.K.
15 Jain, E. Kato, V. Kitidis, K. Klein Goldewijk, C. Koven, P. Landschützer, S.K. Lauvset, N.
16 Lefèvre, A. Lenton, I.D. Lima, N. Metzl, F. Millero, D.R. Munro, A. Murata, J.E.M.S. Nabel,
17 S. Nakaoka, Y. Nojiri, K. O'Brien, A. Olsen, T. Ono, F.F. Pérez, B. Pfeil, D. Pierrot, B.
18 Poulter, G. Rehder, C. Rödenbeck, S. Saito, U. Schuster, J. Schwinger, R. Séférian, T.
19 Steinhoff, B.D. Stocker, A.J. Sutton, T. Takahashi, B. Tilbrook, I.T. van der Laan-Luijkx,
20 G.R. van der Werf, S. van Heuven, D. Vandemark, N. Viovy, A. Wiltshire, S. Zaehle, and N.
21 Zeng, 2015: Global carbon budget 2015. *Earth System Science Data*, **7**, 349-396.
22 <http://dx.doi.org/10.5194/essd-7-349-2015>
- 23 Le Quéré, C., Andrew, R. M., Canadell, J. G., Sitch, S., Korsbakken, J. I., Peters, G. P.,
24 Manning, A. C., Boden, T. A., Tans, P. P., Houghton, R. A., Keeling, R. F., Alin, S.,
25 Andrews, O. D., Anthoni, P., Barbero, L., Bopp, L., Chevallier, F., Chini, L. P., Ciais, P.,
26 Currie, K., Delire, C., Doney, S. C., Friedlingstein, P., Gkritzalis, T., Harris, I., Hauck, J.,
27 Haverd, V., Hoppema, M., Klein Goldewijk, K., Jain, A. K., Kato, E., Körtzinger, A.,
28 Landschützer, P., Lefèvre, N., Lenton, A., Lienert, S., Lombardozi, D., Melton, J. R., Metzl,
29 N., Millero, F., Monteiro, P. M. S., Munro, D. R., Nabel, J. E. M. S., Nakaoka, S.-I., O'Brien,
30 K., Olsen, A., Omar, A. M., Ono, T., Pierrot, D., Poulter, B., Rödenbeck, C., Salisbury, J.,
31 Schuster, U., Schwinger, J., Séférian, R., Skjelvan, I., Stocker, B. D., Sutton, A. J.,
32 Takahashi, T., Tian, H., Tilbrook, B., van der Laan-Luijkx, I. T., van der Werf, G. R., Viovy,
33 N., Walker, A. P., Wiltshire, A. J., and Zaehle, S., 2016: Global Carbon Budget 2016, *Earth*
34 *Syst. Sci. Data*, **8**, 605-649, doi:10.5194/essd-8-605-2016.
- 35 Lewandowsky, S., J.S. Risbey, and N. Oreskes, 2016: The “pause” in global warming: Turning a
36 routine fluctuation into a problem for science. *Bulletin of the American Meteorological*
37 *Society*, **97**, 723-733. <http://dx.doi.org/10.1175/BAMS-D-14-00106.1>

- 1 Lewis, S.L., P.M. Brando, O.L. Phillips, G.M.F. van der Heijden, and D. Nepstad, 2011: The
2 2010 Amazon drought. *Science*, **331**, 554-554. <http://dx.doi.org/10.1126/science.1200807>
- 3 Mann, M.E., Z. Zhang, M.K. Hughes, R.S. Bradley, S.K. Miller, S. Rutherford, and F. Ni, 2008:
4 Proxy-based reconstructions of hemispheric and global surface temperature variations over
5 the past two millennia. *Proceedings of the National Academy of Sciences*, **105**, 13252-13257.
6 <http://dx.doi.org/10.1073/pnas.0805721105>
- 7 Mao, J., A. Ribes, B. Yan, X. Shi, P.E. Thornton, R. Seferian, P. Ciais, R.B. Myneni, H.
8 Douville, S. Piao, Z. Zhu, R.E. Dickinson, Y. Dai, D.M. Ricciuto, M. Jin, F.M. Hoffman, B.
9 Wang, M. Huang, and X. Lian, 2016: Human-induced greening of the northern extratropical
10 land surface. *Nature Climate Change*, **6**, 959-963. <http://dx.doi.org/10.1038/nclimate3056>
- 11 Marcott, S.A., J.D. Shakun, P.U. Clark, and A.C. Mix, 2013: A reconstruction of regional and
12 global temperature for the past 11,300 years. *Science*, **339**, 1198-1201.
13 <http://dx.doi.org/10.1126/science.1228026>
- 14 Marvel, K. and C. Bonfils, 2013: Identifying external influences on global precipitation.
15 *Proceedings of the National Academy of Sciences*, **110**, 19301-19306.
16 <http://dx.doi.org/10.1073/pnas.1314382110>
- 17 Mears, C.A. and F.J. Wentz, 2016: Sensitivity of satellite-derived tropospheric temperature
18 trends to the diurnal cycle adjustment. *Journal of Climate*, **29**, 3629-3646.
19 <http://dx.doi.org/10.1175/JCLI-D-15-0744.1>
- 20 Meehl, G.A., C. Tebaldi, G. Walton, D. Easterling, and L. McDaniel, 2009: Relative increase of
21 record high maximum temperatures compared to record low minimum temperatures in the
22 US. *Geophysical Research Letters*, **36**, L23701. <http://dx.doi.org/10.1029/2009GL040736>
- 23 Meehl, G.A., J.M. Arblaster, J.T. Fasullo, A. Hu, and K.E. Trenberth, 2011: Model-based
24 evidence of deep-ocean heat uptake during surface-temperature hiatus periods. *Nature*
25 *Climate Change*, **1**, 360-364. <http://dx.doi.org/10.1038/nclimate1229>
- 26 Meehl, G.A., A. Hu, B.D. Santer, and S.-P. Xie, 2016a: Contribution of the Interdecadal Pacific
27 Oscillation to twentieth-century global surface temperature trends. *Nature Climate Change*,
28 **6**, 1005-1008. <http://dx.doi.org/10.1038/nclimate3107>
- 29 Meehl, G.A., J.M. Arblaster, C.M. Bitz, C.T.Y. Chung, and H. Teng, 2016b: Antarctic sea-ice
30 expansion between 2000 and 2014 driven by tropical Pacific decadal climate variability.
31 *Nature Geoscience*, **9**, 590-595. <http://dx.doi.org/10.1038/ngeo2751>
- 32 Melillo, J.M., T.C. Richmond, and G.W. Yohe, eds., 2014: *Climate Change Impacts in the*
33 *United States: The Third National Climate Assessment*. U.S. Global Change Research
34 Program: Washington, D.C., 842 pp. <http://dx.doi.org/10.7930/J0Z31WJ2>

- 1 Mengel, M., A. Levermann, K. Frieler, A. Robinson, B. Marzeion, and R. Winkelmann, 2016:
2 Future sea level rise constrained by observations and long-term commitment. *Proceedings of*
3 *the National Academy of Sciences*, **113**, 2597-2602.
4 <http://dx.doi.org/10.1073/pnas.1500515113>
- 5 Menzel, A., T.H. Sparks, N. Estrella, E. Koch, A. Aasa, R. Ahas, K. Alm-Kübler, P. Bissolli,
6 O.G. Braslavská, A. Briede, F.M. Chmielewski, Z. Crepinsek, Y. Curnel, Å. Dahl, C. Defila,
7 A. Donnelly, Y. Filella, K. Jatzcak, F. Måge, A. Mestre, Ø. Nordli, J. Peñuelas, P. Pirinen, V.
8 Remišvá, H. Scheifinger, M. Striz, A. Susnik, A.J.H. Van Vliet, F.-E. Wielgolaski, S. Zach,
9 and A.N.A. Zust, 2006: European phenological response to climate change matches the
10 warming pattern. *Global Change Biology*, **12**, 1969-1976. [http://dx.doi.org/10.1111/j.1365-](http://dx.doi.org/10.1111/j.1365-2486.2006.01193.x)
11 [2486.2006.01193.x](http://dx.doi.org/10.1111/j.1365-2486.2006.01193.x)
- 12 Merrifield, M.A., P. Thompson, E. Leuliette, G.T. Mitchum, D.P. Chambers, S. Jevrejeva, R.S.
13 Nerem, M. Menéndez, W. Sweet, B. Hamlington, and J.J. Marra, 2015: [Global Oceans] Sea
14 level variability and change [in “State of the Climate in 2014”]. *Bulletin of the American*
15 *Meteorological Society*, **96 (12)**, S82-S85.
16 <http://dx.doi.org/10.1175/2015BAMSStateoftheClimate.1>
- 17 Min, S.-K., X. Zhang, and F. Zwiers, 2008: Human-induced Arctic moistening. *Science*, **320**,
18 518-520. <http://dx.doi.org/10.1126/science.1153468>
- 19 Min, S.K., X. Zhang, F.W. Zwiers, and G.C. Hegerl, 2011: Human contribution to more-intense
20 precipitation extremes. *Nature*, **470**, 378-381. <http://dx.doi.org/10.1038/nature09763>
- 21 Min, S.-K., X. Zhang, F. Zwiers, H. Shiogama, Y.-S. Tung, and M. Wehner, 2013: Multimodel
22 detection and attribution of extreme temperature changes. *Journal of Climate*, **26**, 7430-7451.
23 <http://dx.doi.org/10.1175/JCLI-D-12-00551.1>
- 24 Mountain Research Initiative, 2015: Elevation-dependent warming in mountain regions of the
25 world. *Nature Climate Change*, **5**, 424-430. <http://dx.doi.org/10.1038/nclimate2563>
- 26 Myneni, R.B., C.D. Keeling, C.J. Tucker, G. Asrar, and R.R. Nemani, 1997: Increased plant
27 growth in the northern high latitudes from 1981 to 1991. *Nature*, **386**, 698-702.
28 <http://dx.doi.org/10.1038/386698a0>
- 29 NAS, 2016: *Attribution of Extreme Weather Events in the Context of Climate Change*. The
30 National Academies Press, Washington, DC, 186 pp. <http://dx.doi.org/10.17226/21852>
- 31 NCEI, 2016: Climate at a Glance: Global Temperature Anomalies.
32 http://www.ncdc.noaa.gov/cag/time-series/global/globe/land_ocean/ytd/12/1880-2015

- 1 Nerem, R.S., D.P. Chambers, C. Choe, and G.T. Mitchum, 2010: Estimating mean sea level
2 change from the TOPEX and Jason altimeter missions. *Marine Geodesy*, **33**, 435-446.
3 <http://dx.doi.org/10.1080/01490419.2010.491031>
- 4 Nghiem, S.V., D.K. Hall, T.L. Mote, M. Tedesco, M.R. Albert, K. Keegan, C.A. Shuman, N.E.
5 DiGirolamo, and G. Neumann, 2012: The extreme melt across the Greenland ice sheet in
6 2012. *Geophysical Research Letters*, **39**, L20502. <http://dx.doi.org/10.1029/2012GL053611>
- 7 Nieves, V., J.K. Willis, and W.C. Patzert, 2015: Recent hiatus caused by decadal shift in Indo-
8 Pacific heating. *Science*, **349**, 532-535. <http://dx.doi.org/10.1126/science.aaa4521>
- 9 Norby, R.J., J.M. Warren, C.M. Iversen, B.E. Medlyn, and R.E. McMurtrie, 2010: CO₂
10 enhancement of forest productivity constrained by limited nitrogen availability. *Proceedings*
11 *of the National Academy of Sciences*, **107**, 19368-19373.
12 <http://dx.doi.org/10.1073/pnas.1006463107>
- 13 NSIDC, 2016: Sluggish Ice Growth in the Arctic. Arctic Sea Ice News and Analysis, National
14 Snow and Ice Data Center. [http://nsidc.org/arcticseaicenews/2016/11/sluggish-ice-growth-in-](http://nsidc.org/arcticseaicenews/2016/11/sluggish-ice-growth-in-the-arctic/)
15 [the-arctic/](http://nsidc.org/arcticseaicenews/2016/11/sluggish-ice-growth-in-the-arctic/)
- 16 NSIDC, 2017: SOTC (State of the Cryosphere): Northern Hemisphere Snow. National Snow and
17 Ice Data Center. https://nsidc.org/cryosphere/sotc/snow_extent.html
- 18 Page, S.E., F. Siegert, J.O. Rieley, H.-D.V. Boehm, A. Jaya, and S. Limin, 2002: The amount of
19 carbon released from peat and forest fires in Indonesia during 1997. *Nature*, **420**, 61-65.
20 <http://dx.doi.org/10.1038/nature01131>
- 21 PAGES 2K Consortium, 2013: Continental-scale temperature variability during the past two
22 millennia. *Nature Geoscience*, **6**, 339-346. <http://dx.doi.org/10.1038/ngeo1797>
- 23 Palmroth, S., R. Oren, H.R. McCarthy, K.H. Johnsen, A.C. Finzi, J.R. Butnor, M.G. Ryan, and
24 W.H. Schlesinger, 2006: Aboveground sink strength in forests controls the allocation of
25 carbon below ground and its [CO₂]-induced enhancement. *Proceedings of the National*
26 *Academy of Sciences*, **103**, 19362-19367. <http://dx.doi.org/10.1073/pnas.0609492103>
- 27 Pan, Y., R.A. Birdsey, J. Fang, R. Houghton, P.E. Kauppi, W.A. Kurz, O.L. Phillips, A.
28 Shvidenko, S.L. Lewis, J.G. Canadell, P. Ciais, R.B. Jackson, S.W. Pacala, A.D. McGuire, S.
29 Piao, A. Rautiainen, S. Sitch, and D. Hayes, 2011: A large and persistent carbon sink in the
30 world's forests. *Science*, **333**, 988-93. <http://dx.doi.org/10.1126/science.1201609>
- 31 Parkinson, C.L., 2014: Spatially mapped reductions in the length of the Arctic sea ice season.
32 *Geophysical Research Letters*, **41**, 4316-4322. <http://dx.doi.org/10.1002/2014GL060434>

- 1 Parris, A., P. Bromirski, V. Burkett, D. Cayan, M. Culver, J. Hall, R. Horton, K. Knuuti, R.
2 Moss, J. Obeysekera, A. Sallenger, and J. Weiss, 2012: Global Sea Level Rise Scenarios for
3 the United States National Climate Assessment. NOAA Tech Memo OAR CPO-1. National
4 Oceanic and Atmospheric Administration, Silver Spring, MD. 37 pp.
5 http://scenarios.globalchange.gov/sites/default/files/NOAA_SLR_r3_0.pdf
- 6 Pauling, A.G., C.M. Bitz, I.J. Smith, and P.J. Langhorne, 2016: The response of the Southern
7 Ocean and Antarctic sea ice to freshwater from ice shelves in an Earth system model. *Journal*
8 *of Climate*, **29**, 1655-1672. <http://dx.doi.org/10.1175/JCLI-D-15-0501.1>
- 9 Pelto, M.S., 2015: [Global Climate] Alpine glaciers [in “State of the Climate in 2014”]. *Bulletin*
10 *of the American Meteorological Society*, **96 (12)**, S19-S20.
11 <http://dx.doi.org/10.1175/2015BAMSSStateoftheClimate.1>
- 12 Perovich, D., S. Gerlnad, S. Hendricks, W. Meier, M. Nicolaus, and M. Tschudi, 2015: [The
13 Arctic] Sea ice cover [in “State of the Climate in 2014”]. *Bulletin of the American*
14 *Meteorological Society*, **96 (12)**, S145-S146.
15 <http://dx.doi.org/10.1175/2015BAMSSStateoftheClimate.1>
- 16 Peterson, T.C., R.R. Heim, R. Hirsch, D.P. Kaiser, H. Brooks, N.S. Diffenbaugh, R.M. Dole, J.P.
17 Giovannetone, K. Guirguis, T.R. Karl, R.W. Katz, K. Kunkel, D. Lettenmaier, G.J. McCabe,
18 C.J. Paciorek, K.R. Ryberg, S. Schubert, V.B.S. Silva, B.C. Stewart, A.V. Vecchia, G.
19 Villarini, R.S. Vose, J. Walsh, M. Wehner, D. Wolock, K. Wolter, C.A. Woodhouse, and D.
20 Wuebbles, 2013: Monitoring and understanding changes in heat waves, cold waves, floods
21 and droughts in the United States: State of knowledge. *Bulletin of the American*
22 *Meteorological Society*, **94**, 821-834. <http://dx.doi.org/10.1175/BAMS-D-12-00066.1>
- 23 Ramsayer, K., 2014: Antarctic sea ice reaches new record maximum.
24 <https://www.nasa.gov/content/goddard/antarctic-sea-ice-reaches-new-record-maximum>
- 25 Rahmstorf, S., J.E. Box, G. Feulner, M.E. Mann, A. Robinson, S. Rutherford, and E.J.
26 Schaffernicht, 2015: Exceptional twentieth-century slowdown in Atlantic Ocean overturning
27 circulation. *Nature Climate Change*, **5**, 475-480. <http://dx.doi.org/10.1038/nclimate2554>
- 28 Reyes-Fox, M., H. Steltzer, M.J. Trlica, G.S. McMaster, A.A. Andales, D.R. LeCain, and J.A.
29 Morgan, 2014: Elevated CO2 further lengthens growing season under warming conditions.
30 *Nature*, **510**, 259-262. <http://dx.doi.org/10.1038/nature13207>
- 31 Rhein, M., S.R. Rintoul, S. Aoki, E. Campos, D. Chambers, R.A. Feely, S. Gulev, G.C. Johnson,
32 S.A. Josey, A. Kostianoy, C. Mauritzen, D. Roemmich, L.D. Talley, and F. Wang, 2013:
33 Observations: Ocean. *Climate Change 2013: The Physical Science Basis. Contribution of*
34 *Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate*
35 *Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A.

- 1 Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge,
2 United Kingdom and New York, NY, USA, 255–316.
3 <http://www.climatechange2013.org/report/full-report/>
- 4 Richardson, M., K. Cowtan, E. Hawkins, and M.B. Stolpe, 2016: Reconciled climate response
5 estimates from climate models and the energy budget of Earth. *Nature Climate Change*, **6**,
6 931-935. <http://dx.doi.org/10.1038/nclimate3066>
- 7 Ridley, D.A., S. Solomon, J.E. Barnes, V.D. Burlakov, T. Deshler, S.I. Dolgii, A.B. Herber, T.
8 Nagai, R.R. Neely, A.V. Nevzorov, C. Ritter, T. Sakai, B.D. Santer, M. Sato, A. Schmidt, O.
9 Uchino, and J.P. Vernier, 2014: Total volcanic stratospheric aerosol optical depths and
10 implications for global climate change. *Geophysical Research Letters*, **41**, 7763-7769.
11 <http://dx.doi.org/10.1002/2014GL061541>
- 12 Rignot, E., I. Velicogna, M.R. van den Broeke, A. Monaghan, and J.T.M. Lenaerts, 2011:
13 Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise.
14 *Geophysical Research Letters*, **38**, L05503. <http://dx.doi.org/10.1029/2011GL046583>
- 15 Rignot, E., J. Mouginot, M. Morlighem, H. Seroussi, and B. Scheuchl, 2014: Widespread, rapid
16 grounding line retreat of Pine Island, Thwaites, Smith, and Kohler Glaciers, West Antarctica,
17 from 1992 to 2011. *Geophysical Research Letters*, **41**, 3502-3509.
18 <http://dx.doi.org/10.1002/2014GL060140>
- 19 Romanovsky, V.E., S.L. Smith, H.H. Christiansen, N.I. Shiklomanov, D.A. Streletskiy, D.S.
20 Drozdov, G.V. Malkova, N.G. Oberman, A.L. Kholodov, and S.S. Marchenko, 2015: [The
21 Arctic] Terrestrial permafrost [in “State of the Climate in 2014”]. *Bulletin of the American*
22 *Meteorological Society*, **96** (12), S139-S141.
23 <http://dx.doi.org/10.1175/2015BAMSSStateoftheClimate.1>
- 24 Rupp, D.E., P.W. Mote, N.L. Bindoff, P.A. Stott, and D.A. Robinson, 2013: Detection and
25 attribution of observed changes in Northern Hemisphere spring snow cover. *Journal of*
26 *Climate*, **26**, 6904-6914. <http://dx.doi.org/10.1175/JCLI-D-12-00563.1>
- 27 Sander, J., J.F. Eichner, E. Faust, and M. Steuer, 2013: Rising variability in thunderstorm-related
28 U.S. losses as a reflection of changes in large-scale thunderstorm forcing. *Weather, Climate,*
29 *and Society*, **5**, 317-331. <http://dx.doi.org/10.1175/WCAS-D-12-00023.1>
- 30 Santer, B.D., C. Mears, F.J. Wentz, K.E. Taylor, P.J. Gleckler, T.M.L. Wigley, T.P. Barnett, J.S.
31 Boyle, W. Brüggemann, N.P. Gillett, S.A. Klein, G.A. Meehl, T. Nozawa, D.W. Pierce, P.A.
32 Stott, W.M. Washington, and M.F. Wehner, 2007: Identification of human-induced changes
33 in atmospheric moisture content. *Proceedings of the National Academy of Sciences*, **104**,
34 15248-15253. <http://dx.doi.org/10.1073/pnas.0702872104>

- 1 Santer, B.D., C. Bonfils, J.F. Painter, M.D. Zelinka, C. Mears, S. Solomon, G.A. Schmidt, J.C.
2 Fyfe, J.N.S. Cole, L. Nazarenko, K.E. Taylor, and F.J. Wentz, 2014: Volcanic contribution to
3 decadal changes in tropospheric temperature. *Nature Geoscience*, **7**, 185-189.
4 <http://dx.doi.org/10.1038/ngeo2098>
- 5 Santer, B.D., S. Solomon, G. Pallotta, C. Mears, S. Po-Chedley, Q. Fu, F. Wentz, C.-Z. Zou, J.
6 Painter, I. Cvijanovic, and C. Bonfils, 2017a: Comparing tropospheric warming in climate
7 models and satellite data. *Journal of Climate*, **30**, 373-392. [http://dx.doi.org/10.1175/JCLI-D-](http://dx.doi.org/10.1175/JCLI-D-16-0333.1)
8 [16-0333.1](http://dx.doi.org/10.1175/JCLI-D-16-0333.1)
- 9 Santer, B.D., S. Solomon, F.J. Wentz, Q. Fu, S. Po-Chedley, C. Mears, J.F. Painter, and C.
10 Bonfils, 2017b: Tropospheric Warming Over The Past Two Decades. *Scientific Reports*, in
11 press.
- 12 Sardeshmukh, P.D., G.P. Compo, and C. Penland, 2015: Need for caution in interpreting extreme
13 weather statistics. *Journal of Climate*, **28**, 9166-9187. [http://dx.doi.org/10.1175/JCLI-D-15-](http://dx.doi.org/10.1175/JCLI-D-15-0020.1)
14 [0020.1](http://dx.doi.org/10.1175/JCLI-D-15-0020.1)
- 15 Schmidt, G.A., J.H. Jungclaus, C.M. Ammann, E. Bard, P. Braconnot, T.J. Crowley, G.
16 Delaygue, F. Joos, N.A. Krivova, R. Muscheler, B.L. Otto-Bliesner, J. Pongratz, D.T.
17 Shindell, S.K. Solanki, F. Steinhilber, and L.E.A. Vieira, 2011: Climate forcing
18 reconstructions for use in PMIP simulations of the last millennium (v1.0). *Geoscientific*
19 *Model Development*, **4**, 33-45. <http://dx.doi.org/10.5194/gmd-4-33-2011>
- 20 Schmidt, G.A., D.T. Shindell, and K. Tsigaridis, 2014: Reconciling warming trends. *Nature*
21 *Geoscience*, **7**, 158-160. <http://dx.doi.org/10.1038/ngeo2105>
- 22 Schwartz, M.D., R. Ahas, and A. Aasa, 2006: Onset of spring starting earlier across the Northern
23 Hemisphere. *Global Change Biology*, **12**, 343-351. [http://dx.doi.org/10.1111/j.1365-](http://dx.doi.org/10.1111/j.1365-2486.2005.01097.x)
24 [2486.2005.01097.x](http://dx.doi.org/10.1111/j.1365-2486.2005.01097.x)
- 25 Seneviratne, S.I., M.G. Donat, B. Mueller, and L.V. Alexander, 2014: No pause in the increase
26 of hot temperature extremes. *Nature Climate Change*, **4**, 161-163.
27 <http://dx.doi.org/10.1038/nclimate2145>
- 28 Seo, K.-W., C.R. Wilson, T. Scambos, B.-M. Kim, D.E. Waliser, B. Tian, B.-H. Kim, and J.
29 Eom, 2015: Surface mass balance contributions to acceleration of Antarctic ice mass loss
30 during 2003–2013. *Journal of Geophysical Research: Solid Earth*, **120**, 3617-3627.
31 <http://dx.doi.org/10.1002/2014JB011755>
- 32 Sheffield, J., E.F. Wood, and M.L. Roderick, 2012: Little change in global drought over the past
33 60 years. *Nature*, **491**, 435-438. <http://dx.doi.org/10.1038/nature11575>

- 1 Shiklomanov, N.E., D.A. Streletskiy, and F.E. Nelson, 2012: Northern Hemisphere component
2 of the global Circumpolar Active Layer Monitory (CALM) program. In *Proceedings of the*
3 *10th International Conference on Permafrost*, Salekhard, Russia. Kane, D.L. and K.M.
4 Hinkel, Eds., 377-382. http://research.iarc.uaf.edu/NICOP/proceedings/10th/TICOP_vol1.pdf
- 5 Sobel, A.H., S.J. Camargo, T.M. Hall, C.-Y. Lee, M.K. Tippett, and A.A. Wing, 2016: Human
6 influence on tropical cyclone intensity. *Science*, **353**, 242-246.
7 <http://dx.doi.org/10.1126/science.aaf6574>
- 8 Sokolov, A.P., D.W. Kicklighter, J.M. Melillo, B.S. Felzer, C.A. Schlosser, and T.W. Cronin,
9 2008: Consequences of considering carbon–nitrogen interactions on the feedbacks between
10 climate and the terrestrial carbon cycle. *Journal of Climate*, **21**, 3776-3796.
11 <http://dx.doi.org/10.1175/2008JCLI2038.1>
- 12 Solomon, S., K.H. Rosenlof, R.W. Portmann, J.S. Daniel, S.M. Davis, T.J. Sanford, and G.-K.
13 Plattner, 2010: Contributions of stratospheric water vapor to decadal changes in the rate of
14 global warming. *Science*, **327**, 1219-1223. <http://dx.doi.org/10.1126/science.1182488>
- 15 Sousa, P.M., R.M. Trigo, P. Aizpurua, R. Nieto, L. Gimeno, and R. Garcia-Herrera, 2011:
16 Trends and extremes of drought indices throughout the 20th century in the Mediterranean.
17 *Natural Hazards and Earth System Sciences*, **11**, 33-51. [http://dx.doi.org/10.5194/nhess-11-](http://dx.doi.org/10.5194/nhess-11-33-2011)
18 [33-2011](http://dx.doi.org/10.5194/nhess-11-33-2011)
- 19 Steinman, B.A., M.B. Abbott, M.E. Mann, N.D. Stansell, and B.P. Finney, 2012: 1,500 year
20 quantitative reconstruction of winter precipitation in the Pacific Northwest. *Proceedings of*
21 *the National Academy of Sciences*, **109**, 11619-11623.
22 <http://dx.doi.org/10.1073/pnas.1201083109>
- 23 Stott, P., 2016: How climate change affects extreme weather events. *Science*, **352**, 1517-1518.
24 <http://dx.doi.org/10.1126/science.aaf7271>
- 25 Stroeve, J.C., V. Kattsov, A. Barrett, M. Serreze, T. Pavlova, M. Holland, and W.N. Meier,
26 2012a: Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations. *Geophysical*
27 *Research Letters*, **39**, L16502. <http://dx.doi.org/10.1029/2012GL052676>
- 28 Stroeve, J.C., M.C. Serreze, M.M. Holland, J.E. Kay, J. Malanik, and A.P. Barrett, 2012b: The
29 Arctic's rapidly shrinking sea ice cover: A research synthesis. *Climatic Change*, **110**, 1005-
30 1027. <http://dx.doi.org/10.1007/s10584-011-0101-1>
- 31 Stroeve, J., A. Barrett, M. Serreze, and A. Schweiger, 2014a: Using records from submarine,
32 aircraft and satellites to evaluate climate model simulations of Arctic sea ice thickness. *The*
33 *Cryosphere*, **8**, 1839-1854. <http://dx.doi.org/10.5194/tc-8-1839-2014>

- 1 Stroeve, J.C., T. Markus, L. Boisvert, J. Miller, and A. Barrett, 2014b: Changes in Arctic melt
2 season and implications for sea ice loss. *Geophysical Research Letters*, **41**, 1216-1225.
3 <http://dx.doi.org/10.1002/2013GL058951>
- 4 Sweet, W.V., and J. Park, 2014: From the extreme to the mean: Acceleration and tipping points
5 of coastal inundation from sea level rise. *Earth's Future*, **2**, 579-600.
6 <http://dx.doi.org/10.1002/2014EF000272>
- 7 Sweet, W.V., R.E. Kopp, C.P. Weaver, J. Obeysekera, R.M. Horton, E.R. Thieler, and C. Zervas,
8 2017: Global and Regional Sea Level Rise Scenarios for the United States. NOAA Tech.
9 Rep. NOS CO-OPS 083. National Oceanic and Atmospheric Administration, National Ocean
10 Service, Silver Spring, MD. 75 pp.
11 [https://tidesandcurrents.noaa.gov/publications/techrpt83_Global_and_Regional_SLR_Scenar
12 ios_for_the_US_final.pdf](https://tidesandcurrents.noaa.gov/publications/techrpt83_Global_and_Regional_SLR_Scenarios_for_the_US_final.pdf)
- 13 Tedesco, M., X. Fettweis, M.R.v.d. Broeke, R.S.W.v.d. Wal, C.J.P.P. Smeets, W.J.v.d. Berg,
14 M.C. Serreze, and J.E. Box, 2011: The role of albedo and accumulation in the 2010 melting
15 record in Greenland. *Environmental Research Letters*, **6**, 014005.
16 <http://dx.doi.org/10.1088/1748-9326/6/1/014005>
- 17 Tedesco, M., X. Fettweis, T. Mote, J. Wahr, P. Alexander, J.E. Box, and B. Wouters, 2013:
18 Evidence and analysis of 2012 Greenland records from spaceborne observations, a regional
19 climate model and reanalysis data. *The Cryosphere*, **7**, 615-630. [http://dx.doi.org/10.5194/tc-
20 7-615-2013](http://dx.doi.org/10.5194/tc-7-615-2013)
- 21 Tedesco, M., E. Box, J. Cappelen, R.S. Fausto, X. Fettweis, K. Hansen, T. Mote, C.J.P.P.
22 Smeets, D.V. As, R.S.W.V.d. Wal, and J. Wahr, 2015: [The Arctic] Greenland ice sheet [in
23 "State of the Climate in 2014"]. *Bulletin of the American Meteorological Society*, **96** (12),
24 S137-S139. <http://dx.doi.org/10.1175/2015BAMSStateoftheClimate.1>
- 25 Thornton, P.E., S.C. Doney, K. Lindsay, J.K. Moore, N. Mahowald, J.T. Randerson, I. Fung, J.F.
26 Lamarque, J.J. Feddema, and Y.H. Lee, 2009: Carbon-nitrogen interactions regulate climate-
27 carbon cycle feedbacks: Results from an atmosphere-ocean general circulation model.
28 *Biogeosciences*, **6**, 2099-2120. <http://dx.doi.org/10.5194/bg-6-2099-2009>
- 29 Trenberth, K.E., 2015: Has there been a hiatus? *Science*, **349**, 691-692.
30 <http://dx.doi.org/10.1126/science.aac9225>
- 31 Trenberth, K.E., A. Dai, G. van der Schrier, P.D. Jones, J. Barichivich, K.R. Briffa, and J.
32 Sheffield, 2014: Global warming and changes in drought. *Nature Climate Change*, **4**, 17-22.
33 <http://dx.doi.org/10.1038/nclimate2067>

- 1 Turney, C.S.M. and R.T. Jones, 2010: Does the Agulhas Current amplify global temperatures
2 during super-interglacials? *Journal of Quaternary Science*, **25**, 839-843.
3 <http://dx.doi.org/10.1002/jqs.1423>
- 4 USGCRP, 2017: [National Climate Assessment] Indicators. U.S. Global Change Research
5 Program. <http://www.globalchange.gov/browse/indicators>
- 6 van der Werf, G.R., J.T. Randerson, L. Giglio, G.J. Collatz, M. Mu, P.S. Kasibhatla, D.C.
7 Morton, R.S. DeFries, Y. Jin, and T.T. van Leeuwen, 2010: Global fire emissions and the
8 contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009).
9 *Atmospheric Chemistry and Physics*, **10**, 11707-11735. [http://dx.doi.org/10.5194/acp-10-](http://dx.doi.org/10.5194/acp-10-11707-2010)
10 [11707-2010](http://dx.doi.org/10.5194/acp-10-11707-2010)
- 11 Velicogna, I. and J. Wahr, 2013: Time-variable gravity observations of ice sheet mass balance:
12 Precision and limitations of the GRACE satellite data. *Geophysical Research Letters*, **40**,
13 3055-3063. <http://dx.doi.org/10.1002/grl.50527>
- 14 Vihma, T., J. Screen, M. Tjernström, B. Newton, X. Zhang, V. Popova, C. Deser, M. Holland,
15 and T. Prowse, 2016: The atmospheric role in the Arctic water cycle: A review on processes,
16 past and future changes, and their impacts. *Journal of Geophysical Research:*
17 *Biogeosciences*, **121**, 586-620. <http://dx.doi.org/10.1002/2015JG003132>
- 18 Vose, R.S., D. Arndt, V.F. Banzon, D.R. Easterling, B. Gleason, B. Huang, E. Kearns, J.H.
19 Lawrimore, M.J. Menne, T.C. Peterson, R.W. Reynolds, T.M. Smith, C.N. Williams, and
20 D.L. Wuertz, 2012: NOAA's merged land-ocean surface temperature analysis. *Bulletin of the*
21 *American Meteorological Society*, **93**, 1677-1685. [http://dx.doi.org/10.1175/BAMS-D-11-](http://dx.doi.org/10.1175/BAMS-D-11-00241.1)
22 [00241.1](http://dx.doi.org/10.1175/BAMS-D-11-00241.1)
- 23 Walsh, J.E., J.E. Overland, P.Y. Groisman, and B. Rudolf, 2011: Ongoing climate change in the
24 Arctic. *Ambio*, **40**, 6-16. <http://dx.doi.org/10.1007/s13280-011-0211-z>
- 25 Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, P. Thorne, R. Vose, M.
26 Wehner, J. Willis, D. Anderson, S. Doney, R. Feely, P. Hennon, V. Kharin, T. Knutson, F.
27 Landerer, T. Lenton, J. Kennedy, and R. Somerville, 2014: Ch. 2: Our changing climate.
28 *Climate Change Impacts in the United States: The Third National Climate Assessment*.
29 Melillo, J.M., T.C. Richmond, and G.W. Yohe, Eds. U.S. Global Change Research Program,
30 Washington, D.C., 19-67. <http://dx.doi.org/10.7930/J0KW5CXT>
- 31 Wang, C., L. Zhang, S.-K. Lee, L. Wu, and C.R. Mechoso, 2014: A global perspective on
32 CMIP5 climate model biases. *Nature Climate Change*, **4**, 201-205.
33 <http://dx.doi.org/10.1038/nclimate2118>
- 34 Willett, K.M., D.J. Philip, W.T. Peter, and P.G. Nathan, 2010: A comparison of large scale
35 changes in surface humidity over land in observations and CMIP3 general circulation

- 1 models. *Environmental Research Letters*, **5**, 025210. <http://dx.doi.org/10.1088/1748-9326/5/2/025210>
- 2
- 3 Williams, S.D.P., P. Moore, M.A. King, and P.L. Whitehouse, 2014: Revisiting GRACE
4 Antarctic ice mass trends and accelerations considering autocorrelation. *Earth and Planetary
5 Science Letters*, **385**, 12-21. <http://dx.doi.org/10.1016/j.epsl.2013.10.016>
- 6 Wuebbles, D., G. Meehl, K. Hayhoe, T.R. Karl, K. Kunkel, B. Santer, M. Wehner, B. Colle,
7 E.M. Fischer, R. Fu, A. Goodman, E. Janssen, V. Kharin, H. Lee, W. Li, L.N. Long, S.C.
8 Olsen, Z. Pan, A. Seth, J. Sheffield, and L. Sun, 2014: CMIP5 climate model analyses:
9 Climate extremes in the United States. *Bulletin of the American Meteorological Society*, **95**,
10 571-583. <http://dx.doi.org/10.1175/BAMS-D-12-00172.1>
- 11 Zaehle, S., P. Friedlingstein, and A.D. Friend, 2010: Terrestrial nitrogen feedbacks may
12 accelerate future climate change. *Geophysical Research Letters*, **37**, L01401.
13 <http://dx.doi.org/10.1029/2009GL041345>
- 14 Zaehle, S. and A.D. Friend, 2010: Carbon and nitrogen cycle dynamics in the O-CN land surface
15 model: 1. Model description, site-scale evaluation, and sensitivity to parameter estimates.
16 *Global Biogeochemical Cycles*, **24**, n/a-n/a. <http://dx.doi.org/10.1029/2009GB003521>
- 17 Zemp, M., H. Frey, I. Gärtner-Roer, S.U. Nussbaumer, M. Hoelzle, F. Paul, W. Haerberli, F.
18 Denzinger, A.P. Ahlstrøm, B. Anderson, S. Bajracharya, C. Baroni, L.N. Braun, B.E.
19 Cáceres, G. Casassa, G. Cobos, L.R. Dávila, H. Delgado Granados, M.N. Demuth, L.
20 Espizua, A. Fischer, K. Fujita, B. Gadek, A. Ghazanfar, J.O. Hagen, P. Holmlund, N. Karimi,
21 Z. Li, M. Pelto, P. Pitte, V.V. Popovnin, C.A. Portocarrero, R. Prinz, C.V. Sangewar, I.
22 Severskiy, O. Sigurðsson, A. Soruco, R. Usubaliev, and C. Vincent, 2015: Historically
23 unprecedented global glacier decline in the early 21st century. *Journal of Glaciology*, **61**,
24 745-762. <http://dx.doi.org/10.3189/2015JoG15J017>
- 25 Zhang, R. and T.R. Knutson, 2013: The role of global climate change in the extreme low
26 summer Arctic sea ice extent in 2012 [in "Explaining Extreme Events of 2012 from a
27 Climate Perspective"]. *Bulletin of the American Meteorological Society*, **94** (9), S23-S26.
28 <http://dx.doi.org/10.1175/BAMS-D-13-00085.1>
- 29 Zhang, X., F.W. Zwiers, G.C. Hegerl, F.H. Lambert, N.P. Gillett, S. Solomon, P.A. Stott, and T.
30 Nozawa, 2007: Detection of human influence on twentieth-century precipitation trends.
31 *Nature*, **448**, 461-465. <http://dx.doi.org/10.1038/nature06025>
- 32 Zhang, X., H. Wan, F.W. Zwiers, G.C. Hegerl, and S.-K. Min, 2013: Attributing intensification
33 of precipitation extremes to human influence. *Geophysical Research Letters*, **40**, 5252-5257.
34 <http://dx.doi.org/10.1002/grl.51010>

- 1 Zhu, Z., S. Piao, R.B. Myneni, M. Huang, Z. Zeng, J.G. Canadell, P. Ciais, S. Sitch, P.
2 Friedlingstein, A. Arneth, C. Cao, L. Cheng, E. Kato, C. Koven, Y. Li, X. Lian, Y. Liu, R.
3 Liu, J. Mao, Y. Pan, S. Peng, J. Penuelas, B. Poulter, T.A.M. Pugh, B.D. Stocker, N. Viovy,
4 X. Wang, Y. Wang, Z. Xiao, H. Yang, S. Zaehle, and N. Zeng, 2016: Greening of the Earth
5 and its drivers. *Nature Climate Change*, **6**, 791-795. <http://dx.doi.org/10.1038/nclimate3004>
- 6 Zunz, V., H. Goosse, and F. Massonnet, 2013: How does internal variability influence the ability
7 of CMIP5 models to reproduce the recent trend in Southern Ocean sea ice extent? *The*
8 *Cryosphere*, **7**, 451-468. <http://dx.doi.org/10.5194/tc-7-451-2013>
- 9

FINAL DRAFT

2. Physical Drivers of Climate Change

Key Findings

1. Human activities continue to significantly affect Earth's climate by altering factors that change its radiative balance. These factors, known as radiative forcings, include changes in greenhouse gases, small airborne particles (aerosols), and the reflectivity of the Earth's surface. In the industrial era, human activities have been, and are increasingly, the dominant cause of climate warming. The increase in radiative forcing due to these activities has far exceeded the relatively small net increase due to natural factors, which include changes in energy from the sun and the cooling effect of volcanic eruptions. (*Very high confidence*)
2. Aerosols caused by human activity play a profound and complex role in the climate system through radiative effects in the atmosphere and on snow and ice surfaces and through effects on cloud formation and properties. The combined forcing of aerosol–radiation and aerosol–cloud interactions is negative (cooling) over the industrial era (*high confidence*), offsetting a substantial part of greenhouse gas forcing, which is currently the predominant human contribution. The magnitude of this offset, globally averaged, has declined in recent decades, despite increasing trends in aerosol emissions or abundances in some regions (*medium to high confidence*)
3. The interconnected Earth–atmosphere–ocean system includes a number of positive and negative feedback processes that can either strengthen (positive feedback) or weaken (negative feedback) the system's responses to human and natural influences. These feedbacks operate on a range of timescales from very short (essentially instantaneous) to very long (centuries). Global warming by net radiative forcing over the industrial era includes a substantial amplification from these feedbacks (approximately a factor of three) (*high confidence*). While there are large uncertainties associated with some of these feedbacks, the net feedback effect over the industrial era has been positive (amplifying warming) and will continue to be positive in coming decades (*Very high confidence*).

2.0 Introduction

Earth's climate is undergoing substantial change due to anthropogenic activities (Ch. 1: Our Globally Changing Climate). Understanding the causes of past and present climate change and confidence in future projected changes depend directly on our ability to understand and model the physical drivers of climate change (Clark et al. 2016). Our understanding is challenged by the complexity and interconnectedness of the components of the climate system (that is, the atmosphere, land, ocean, and cryosphere). This chapter lays out the foundation of climate change by describing its physical drivers, which are primarily associated with atmospheric composition (gases and aerosols) and cloud effects. We describe the principle radiative forcings and the variety of feedback responses which serve to amplify these forcings.

1 **2.1 Earth's Energy Balance and the Greenhouse Effect**

2 The temperature of the Earth system is determined by the amounts of incoming (short-
3 wavelength) and outgoing (both short- and long-wavelength) radiation. In the modern era,
4 radiative fluxes are well-constrained by satellite measurements (Figure 2.1). About a third
5 (29.4%) of incoming, short-wavelength energy from the sun is reflected back to space and the
6 remainder is absorbed by the Earth system. The fraction of sunlight scattered back to space is
7 determined by the reflectivity (albedo) of clouds, land surfaces (including snow and ice), oceans,
8 and particles in the atmosphere. The amount and albedo of clouds, snow cover, and ice cover are
9 particularly strong determinants of the amount of sunlight reflected back to space because their
10 albedos are much higher than that of land and oceans.

11 In addition to reflected sunlight, Earth loses energy through infrared (long-wavelength) radiation
12 from the surface and atmosphere. Greenhouse gases (GHGs) in the atmosphere absorb most of
13 this radiation, leading to a warming of the surface and atmosphere. Figure 2.1 illustrates the
14 importance of greenhouse gases in the energy balance of the Earth system. The naturally
15 occurring GHGs in Earth's atmosphere—principally water vapor and carbon dioxide—keep the
16 near-surface air temperature about 60°F (33°C) warmer than it would be in their absence,
17 assuming albedo is held constant (Lacis et al. 2010). Geothermal heat from Earth's interior,
18 direct heating from energy production, and frictional heating through tidal flows also contribute
19 to the amount of energy available for heating the Earth's surface and atmosphere, but their total
20 contribution is an extremely small fraction (< 0.1%) of that due to net solar (shortwave) and
21 infrared (longwave) radiation (e.g., see Davies and Davies 2010; Flanner 2009; Munk and
22 Wunsch 1998, where these forcings are quantified).

23 **[INSERT FIGURE 2.1 HERE]**

24 Thus, Earth's equilibrium temperature in the modern era is controlled by a short list of factors:
25 incoming sunlight, absorbed and reflected sunlight, emitted infrared radiation, and infrared
26 radiation absorbed and re-emitted in the atmosphere, primarily by GHGs. Changes in these
27 factors affect Earth's radiative balance and therefore its climate, including but not limited to the
28 average, near-surface air temperature. Anthropogenic activities have changed Earth's radiative
29 balance and its albedo by adding GHGs, particles (aerosols), and aircraft contrails to the
30 atmosphere, and through land-use changes. Changes in the radiative balance (or forcings)
31 produce changes in temperature, precipitation, and other climate variables through a complex set
32 of physical processes, many of which are coupled (Figure 2.2). These changes, in turn, trigger
33 feedback processes which can further amplify and/or dampen the changes in radiative balance
34 (Sections 2.5 and 2.6).

35 In the following sections, the principal components of the framework shown in Figure 2.2 are
36 described. Climate models are structured to represent these processes; climate models and their
37 components and associated uncertainties, are discussed in more detail in Chapter 4: Projections.

[INSERT FIGURE 2.2 HERE]

The processes and feedbacks connecting changes in Earth’s radiative balance to a climate response (Figure 2.2) operate on a large range of timescales. Reaching an equilibrium temperature distribution in response to anthropogenic activities takes decades or longer because some components of the Earth system—in particular the oceans and cryosphere—are slow to respond due to their large thermal masses and the long timescale of circulation between the ocean surface and the deep ocean. Of the substantial energy gained in the combined ocean–atmosphere system over the previous four decades, over 90% of it has gone into ocean warming (Rhein et al. 2013; see Box 3.1 Fig 1). Even at equilibrium, internal variability in Earth’s climate system causes limited annual- to decadal-scale variations in regional temperatures and other climate parameters that do not contribute to long-term trends. For example, it is *likely* that natural variability has contributed between -0.18°F (-0.1°C) and 0.18°F (0.1°C) to changes in surface temperatures from 1951 to 2010; by comparison, anthropogenic GHGs have *likely* contributed between 0.9°F (0.5°C) and 2.3°F (1.3°C) to observed surface warming over this same period (Bindoff et al. 2013). Due to these longer timescale responses and natural variability, changes in Earth’s radiative balance are not realized immediately as changes in climate, and even in equilibrium there will always be variability around mean conditions.

2.2 Radiative Forcing (RF) and Effective Radiative Forcing (ERF)

Radiative forcing (RF) is widely used to quantify a radiative imbalance in Earth’s atmosphere resulting from either natural changes or anthropogenic activities over the industrial era. It is expressed as a change in net radiative flux (W/m^2) either at the tropopause or top of the atmosphere (Myhre et al. 2013), with the latter nominally defined at 20 km altitude to optimize observation/model comparisons (Loeb et al. 2002). The instantaneous RF is defined as the immediate change in net radiative flux following a change in a climate driver. RF can also be calculated after allowing different types of system response: for example, after allowing stratospheric temperatures to adjust, after allowing both stratospheric and surface temperature to adjust, or after allowing temperatures to adjust everywhere (the equilibrium RF) (Figure 8.1 of Myhre et al. 2013).

In this report, we follow the Intergovernmental Panel on Climate Change (IPCC) recommendation that the RF caused by a forcing agent be evaluated as the net radiative flux change at the tropopause after stratospheric temperatures have adjusted to a new radiative equilibrium while assuming all other variables (for example, temperatures and cloud cover) are held fixed (Box 8.1 of Myhre et al. 2013). A change that results in a net increase in the downward flux (shortwave plus longwave) constitutes a positive RF, normally resulting in a warming of the surface and/or atmosphere and potential changes in other climate parameters. Conversely, a change that yields an increase in the net upward flux constitutes a negative RF, leading to a cooling of the surface and/or atmosphere and potential changes in other climate parameters.

1 RF serves as a metric to compare present, past, or future perturbations to the climate system
2 (e.g., Boer and Yu 2003; Gillett et al. 2004; Matthews et al. 2004; Meehl et al. 2004; Jones et al.
3 2007; Mahajan et al. 2013; Shiogama et al. 2013). For clarity and consistency, RF calculations
4 require that a time period be defined over which the forcing occurs. Here, this period is the
5 industrial era, defined as beginning in 1750 and extending to 2011, unless otherwise noted. The
6 2011 end date is that adopted by the CMIP5 calculations, which are the basis of RF evaluations
7 by the IPCC (Myhre et al. 2013).

8 A refinement of the RF concept introduced in the latest IPCC assessment (IPCC 2013) is the use
9 of effective radiative forcing (ERF). ERF for a climate driver is defined as its RF plus rapid
10 adjustment(s) to that RF (Myhre et al. 2013). These rapid adjustments occur on timescales much
11 shorter than, for example, the response of ocean temperatures. For an important subset of climate
12 drivers, ERF is more reliably correlated with the climate response to the forcing than is RF; as
13 such, it is an increasingly used metric when discussing forcing. For atmospheric components,
14 ERF includes rapid adjustments due to direct warming of the troposphere, which produces
15 horizontal temperature variations, variations in the vertical lapse rate, and changes in clouds and
16 vegetation, and it includes the microphysical effects of aerosols on cloud lifetime. Rapid changes
17 in land surface properties (temperature, snow and ice cover, and vegetation) are also included.
18 Not included in ERF are climate responses driven by changes in sea surface temperatures or sea
19 ice cover. For forcing by aerosols in snow (Section 2.3.2), ERF includes the effects of direct
20 warming of the snowpack by particulate absorption (for example, snow-grain size changes).
21 Changes in all of these parameters in response to RF are quantified in terms of their impact on
22 radiative fluxes (for example, albedo) and included in the ERF. The largest differences between
23 RF and ERF occur for forcing by light-absorbing aerosols because of their influence on clouds
24 and snow (Section 2.3.2). For most non-aerosol climate drivers, the differences between RF and
25 ERF are small.

26 **2.3 Drivers of Climate Change over the Industrial Era**

27 Climate drivers of significance over the industrial era include both those associated with
28 anthropogenic activity and, to a lesser extent, those of natural origin. The only significant natural
29 climate drivers in the industrial era are changes in solar irradiance, volcanic eruptions, and the El
30 Niño–Southern Oscillation. Natural emissions and sinks of GHGs and tropospheric aerosols have
31 varied over the industrial era but have not contributed significantly to RF. The effects of cosmic
32 rays on cloud formation have been studied, but global radiative effects are not considered
33 significant (Krissansen-Totton and Davies 2013). There are other known drivers of natural origin
34 that operate on longer timescales (for example, changes in Earth’s orbit [Milankovitch cycles]
35 and changes in atmospheric CO₂ via chemical weathering of rock). Anthropogenic drivers can be
36 divided into a number of categories, including well-mixed greenhouse gases (WMGHGs), short-
37 lived climate forcers (SLCFs, which include methane, some hydrofluorocarbons [HFCs], ozone,
38 and aerosols), contrails, and changes in albedo (for example, land-use changes). Some

1 WMGHGs are also considered SLCFs (for example, methane). Figures 2.3–2.7 summarize
2 features of the principal climate drivers in the industrial era. Each is described briefly in the
3 following.

4 **[INSERT FIGURE 2.3 HERE]**

5 **2.3.1 Natural Drivers**

6 **SOLAR IRRADIANCE**

7 Changes in solar irradiance directly impact the climate system because the irradiance is Earth's
8 primary energy source (Lean 1997). In the industrial era, the largest variations in total solar
9 irradiance follow an 11-year cycle (Frölich and Lean 2004; Gray et al. 2010). Direct solar
10 observations have been available since 1978 (Kopp 2014), though proxy indicators of solar
11 cycles are available back to the early 1600s (Kopp et al. 2016). Although these variations
12 amount to only 0.1% of the total solar output of about 1360 W/m² (Kopp and Lean 2011),
13 relative variations in irradiance at specific wavelengths can be much larger (tens of percent).
14 Spectral variations in solar irradiance are highest at near-ultraviolet (UV) and shorter
15 wavelengths (Floyd et al. 2003), which are also the most important wavelengths for driving
16 changes in ozone (Ermolli et al. 2013; Bolduc et al. 2015). By affecting ozone concentrations,
17 variations in total and spectral solar irradiance induce discernible changes in atmospheric heating
18 and changes in circulation (Gray et al. 2010; Lockwood 2012; Seppälä et al. 2014). The
19 relationships between changes in irradiance and changes in atmospheric composition, heating,
20 and dynamics are such that changes in total solar irradiance are not directly correlated with the
21 resulting radiative flux changes (Ermolli et al. 2013; Xu and Powell 2013; Gao et al. 2015).

22 The IPCC estimate of the RF due to changes in total solar irradiance over the industrial era is
23 0.05 W/m² (range: 0.0 to 0.10 W/m²) (Myhre et al. 2013). This forcing does not account for
24 radiative flux changes resulting from changes in ozone driven by changes in the spectral
25 irradiance. Understanding of the links between changes in spectral irradiance, ozone
26 concentrations, heating rates, and circulation changes has recently improved using, in particular,
27 satellite data starting in 2002 that provide solar spectral irradiance measurements through the UV
28 (Ermolli et al. 2013) along with a series of chemistry–climate modeling studies (Swartz et al.
29 2012; Chiodo et al. 2014; Dhomse et al. 2013; Ermolli et al. 2013; Bolduc et al. 2015). At the
30 regional scale, circulation changes driven by solar spectral irradiance variations may be
31 significant for some locations and seasons, but are poorly quantified (Lockwood 2012). Despite
32 remaining uncertainties, there is *very high confidence* that solar radiance-induced changes in RF
33 are small relative to RF from anthropogenic GHGs over the industrial era (Myhre et al. 2013)
34 (Figure 2.3).

35

1 VOLCANOES

2 Most volcanic eruptions are minor events with the effects of emissions confined to the
3 troposphere and only lasting for weeks to months. In contrast, explosive volcanic eruptions inject
4 substantial amounts of sulfur dioxide (SO₂) and ash into the stratosphere, which leads to
5 significant short-term climate effects (Myhre et al. 2013, and references therein). SO₂ oxidizes to
6 form sulfuric acid (H₂SO₄) which condenses, forming new particles or adding mass to
7 preexisting particles, thereby substantially enhancing the attenuation of sunlight transmitted
8 through the stratosphere (that is, increasing aerosol optical depth). These aerosols increase the
9 Earth's albedo by scattering sunlight back to space, creating a negative RF that cools the planet
10 (Andronova et al. 1999; Robock 2000). The RF persists for the lifetime of aerosol in the
11 stratosphere, which is a few years, far exceeding that in the troposphere (about a week). The
12 oceans respond to a negative volcanic RF through cooling and changes in ocean circulation
13 patterns that last for decades after major eruptions (for example, Mt. Tambora in 1815)
14 (Stenchikov et al. 2009; Otterå et al. 2010; Zanchettin et al. 2012; Zhang et al. 2013). In addition
15 to the direct RF, volcanic aerosol heats the stratosphere, altering circulation patterns, and
16 depletes ozone by enhancing surface reactions, which further changes heating and circulation.
17 The resulting impacts on advective heat transport can be larger than the temperature impacts of
18 the direct forcing (Robock 2000). Aerosol from both explosive and non-explosive eruptions also
19 affects the troposphere through changes in diffuse radiation and through aerosol–cloud
20 interactions. It has been proposed that major eruptions might “fertilize” the ocean with sufficient
21 iron to affect phytoplankton production and, therefore, enhance the ocean carbon sink
22 (Langmann 2014). Volcanoes also emit CO₂ and water vapor, although in small quantities
23 relative to other emissions. At present, conservative estimates of annual CO₂ emissions from
24 volcanoes are less than 1% of CO₂ emissions from all anthropogenic activities (Gerlach 2011).
25 The magnitude of volcanic effects on climate depend on the number and strengths of eruptions,
26 the latitude of injection and, for ocean temperature and circulation impacts, the timing of the
27 eruption relative to ocean temperature and circulation patterns (Zanchettin et al. 2012; Zhang et
28 al. 2013).

29 Volcanic eruptions represent the largest natural forcing within the industrial era. In the last
30 millennium, eruptions caused several multiyear, transient episodes of negative RF of up to
31 several W/m² (Figure 2.6). The RF of the last major volcanic eruption, Mt. Pinatubo in 1991,
32 decayed to negligible values later in the 1990s, with the temperature signal lasting about twice as
33 long due to the effects of changes in ocean heat uptake (Stenchikov et al. 2009). A net volcanic
34 RF has been omitted from the drivers of climate change in the industrial era in Figure 2.3
35 because the value from multiple, episodic eruptions is negligible compared with the other climate
36 drivers. While future explosive volcanic eruptions have the potential to again alter Earth's
37 climate for periods of several years, predictions of occurrence, intensity, and location remain
38 elusive. If a sufficient number of non-explosive eruptions occur over an extended time period in

1 the future, average changes in tropospheric composition or circulation could yield a significant
2 RF (Robock 2000).

3 **2.3.2 Anthropogenic Drivers**

4 **PRINCIPAL WELL-MIXED GREENHOUSE GASES (WMGHGs)**

5 The principal WMGHGs are carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O).
6 With atmospheric lifetimes of a decade or more, these gases have modest-to-small regional
7 variabilities and are circulated and mixed around the globe to yield small interhemispheric
8 gradients. The atmospheric abundances and associated radiative forcings of WMGHGs have
9 increased substantially over the industrial era (Figures 2.4–2.6). Contributions from natural
10 sources of these constituents are accounted for in the industrial-era RF calculations shown in
11 Figure 2.6.

12 **[INSERT FIGURES 2.4, 2.5, AND 2.6 HERE]**

13 CO₂ has substantial global sources and sinks (Figure 2.7). CO₂ emission sources have grown in
14 the industrial era primarily from fossil fuel combustion (that is, coal, gas, and oil), cement
15 manufacturing, and land-use change from activities such as deforestation (Ciais et al. 2013).
16 Carbonation of finished cement products is a sink of atmospheric CO₂, offsetting a substantial
17 fraction (0.43) of the industrial-era emissions from cement production (Xi et al. 2016). A number
18 of processes act to remove CO₂ from the atmosphere, including uptake in the oceans, residual
19 land uptake, and rock weathering. These combined processes yield an effective atmospheric
20 lifetime for emitted CO₂ of many decades to millennia, far greater than any other major GHG.
21 Seasonal variations in CO₂ atmospheric concentrations occur in response to seasonal changes in
22 photosynthesis in the biosphere, and to a lesser degree to seasonal variations in anthropogenic
23 emissions. In addition to fossil fuel reserves, there are large natural reservoirs of carbon in the
24 oceans, in vegetation and soils, and in permafrost.

25 In the industrial era, the CO₂ atmospheric growth rate has been exponential (Figure 2.4), with the
26 increase in atmospheric CO₂ approximately twice that absorbed by the oceans. Over at least the
27 last 50 years, CO₂ has shown the largest annual RF increases among all GHGs (Figures 2.4 and
28 2.5). The global average CO₂ concentration has increased by 40% over the industrial era,
29 increasing from 278 parts per million (ppm) in 1750 to 390 ppm in 2011 (Ciais et al. 2013); it
30 now exceeds 400 ppm (as of 2016) (<http://www.esrl.noaa.gov/gmd/ccgg/trends/>). CO₂ has been
31 chosen as the reference in defining the global warming potential (GWP) of other GHGs and
32 climate agents. The GWP of a GHG is the integrated RF over a specified time period (for
33 example, 100 years) from the emission of a given mass of the GHG divided by the integrated RF
34 from the same mass emission of CO₂.

35 **[INSERT FIGURE 2.7 HERE]**

1 The global mean methane concentration and RF have also grown substantially in the industrial
2 era (Figures 2.4 and 2.5). Methane is a stronger GHG than CO₂ for the same emission mass and
3 has a shorter atmospheric lifetime of about 12 years. Methane also has indirect climate effects
4 through induced changes in CO₂, stratospheric water vapor, and ozone (Lelieveld and Crutzen
5 1992). The 100-year GWP of methane is 28–36, depending on whether oxidation into CO₂ is
6 included and whether climate-carbon feedbacks are accounted for; its 20-year GWP is even
7 higher (84–86) (Myhre et al. 2013 Table 8.7). With a current global mean value near 1840 parts
8 per billion by volume (ppb), the methane concentration has increased by a factor of about 2.5
9 over the industrial era. The annual growth rate for methane has been more variable than that for
10 CO₂ and N₂O over the past several decades, and has occasionally been negative for short periods.

11 Methane emissions, which have a variety of natural and anthropogenic sources, totaled 556 ± 56
12 Tg CH₄ in 2011 based on top-down analyses, with about 60% from anthropogenic sources (Ciais
13 et al. 2013). The methane budget is complicated by the variety of natural and anthropogenic
14 sources and sinks that influence its atmospheric concentration. These include the global
15 abundance of the hydroxyl radical (OH), which controls the methane atmospheric lifetime;
16 changes in large-scale anthropogenic activities such as mining, natural gas extraction, animal
17 husbandry, and agricultural practices; and natural wetland emissions (Table 6.8, Ciais et al.
18 2013). The remaining uncertainty in the cause(s) of the approximately 20-year negative trend in
19 the methane annual growth rate starting in the mid-1980s and the rapid increases in the annual
20 rate in the last decade (Figure 2.4) reflect the complexity of the methane budget (Ciais et al.
21 2013; Saunio et al. 2016; Nisbet et al. 2016).

22 Growth rates in the global mean nitrous oxide (N₂O) concentration and RF over the industrial era
23 are smaller than for CO₂ and methane (Figures 2.4 and 2.5). N₂O is emitted in the nitrogen cycle
24 in natural ecosystems and has a variety of anthropogenic sources, including the use of synthetic
25 fertilizers in agriculture, motor vehicle exhaust, and some manufacturing processes. The current
26 global value near 330 ppb reflects steady growth over the industrial era with average increases in
27 recent decades of 0.75 ppb per year (Ciais et al. 2013) (Figure 2.4). Fertilization in global food
28 production is responsible for about 80% of the growth rate. Anthropogenic sources account for
29 approximately 40% of the annual N₂O emissions of 17.9 (8.1 to 30.7) TgN (Ciais et al., 2013).
30 N₂O has an atmospheric lifetime of about 120 years and a GWP in the range 265–298 (Myhre et
31 al. 2013 Table 8.7). The primary sink of N₂O is photochemical destruction in the stratosphere,
32 which produces nitrogen oxides (NO_x) that catalytically destroy ozone (e.g., Skiba and Rees
33 2014). Small indirect climate effects, such as the response of stratospheric ozone, are generally
34 not included in the N₂O RF.

35 N₂O is a component of the larger global budget of total nitrogen (N) comprising N₂O, ammonia
36 (NH₃), and reactive nitrogen (NO_x). Significant uncertainties are associated with balancing this
37 budget over oceans and land while accounting for deposition and emission processes (Ciais et al.
38 2013; Fowler et al. 2013). Furthermore, changes in climate parameters such as temperature,

1 moisture, and CO₂ concentrations are expected to affect the N₂O budget in the future, and
2 perhaps atmospheric concentrations.

3 **OTHER WELL-MIXED GREENHOUSE GASES**

4 Other WMGHGs include several categories of synthetic (i.e., manufactured) gases, including
5 chlorofluorocarbons (CFCs), halons, hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons
6 (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF₆), collectively known as
7 halocarbons. Natural sources of these gases in the industrial era are small compared to
8 anthropogenic sources. Important examples are the expanded use of CFCs as refrigerants and in
9 other applications beginning in the mid-20th century. The atmospheric abundances of principal
10 CFCs began declining in the 1990s after their regulation under the Montreal Protocol as
11 substances that deplete stratospheric ozone (Figure 2.4). All of these gases are GHGs covering a
12 wide range of GWPs, atmospheric concentrations, and trends. PFCs, SF₆, and HFCs are in the
13 basket of gases covered under the United Nations Framework Convention on Climate Change.
14 The United States joined other countries in proposing that HFCs be controlled as a WMGHGs
15 under the Montreal Protocol because of their large projected future abundances (Velders et al.
16 2015). In October 2016, the Montreal Protocol adopted an amendment to phase down global
17 HFC production and consumption, avoiding emissions equivalent to approximately 105 Gt CO₂
18 by 2100 based on earlier projections (Velders et al. 2015). The atmospheric growth rates of some
19 halocarbon concentrations are significant at present (for example, SF₆ and HFC-134a), although
20 their RF contributions remain small (Figure 2.5).

21 **WATER VAPOR**

22 Water vapor in the atmosphere acts as a powerful natural GHG, significantly increasing the
23 Earth's equilibrium temperature. In the stratosphere, water vapor abundances are controlled by
24 transport from the troposphere and from oxidation of methane. Increases in methane from
25 anthropogenic activities therefore increase stratospheric water vapor, producing a positive RF
26 (e.g., Solomon et al. 2010; Hegglin et al. 2014). Other less-important anthropogenic sources of
27 stratospheric water vapor are hydrogen oxidation (le Texier et al. 1988), aircraft exhaust
28 (Rosenlof et al. 2001; Morris et al. 2003), and explosive volcanic eruptions (Löffler et al. 2016).

29 In the troposphere, the amount of water vapor is controlled by temperature (Held and Soden
30 2000). Atmospheric circulation, especially convection, limits the buildup of water vapor in the
31 atmosphere such that the water vapor from direct emissions, for example by combustion of fossil
32 fuels or by large power plant cooling towers, does not accumulate in the atmosphere but actually
33 offsets water vapor that would otherwise evaporate from the surface. Direct changes in
34 atmospheric water vapor are negligible in comparison to the indirect changes caused by
35 temperature changes resulting from radiative forcing. As such, changes in tropospheric water
36 vapor are considered a feedback in the climate system (see Section 2.6.1 and Figure 2.2). As

1 increasing GHG concentrations warm the atmosphere, tropospheric water vapor concentrations
2 increase, thereby amplifying the warming effect (Held and Soden 2000).

3 **OZONE**

4 Ozone is a naturally occurring GHG in the troposphere and stratosphere and is produced and
5 destroyed in response to a variety of anthropogenic and natural emissions. Ozone abundances
6 have high spatial and temporal variability due to the nature and variety of the production, loss,
7 and transport processes controlling ozone abundances, which adds complexity to the ozone RF
8 calculations. In the global troposphere, emissions of methane, NO_x, carbon monoxide (CO), and
9 non-methane volatile organic compounds (VOCs) form ozone photochemically both near and far
10 downwind of these precursor source emissions, leading to regional and global positive RF
11 contributions (e.g., Dentener et al. 2005). Stratospheric ozone is destroyed photochemically in
12 reactions involving the halogen species chlorine and bromine. Halogens are released in the
13 stratosphere from the decomposition of some halocarbons emitted at the surface (WMO 2014).
14 Stratospheric ozone depletion, which is most notable in the polar regions, yields a net negative
15 RF (Myhre et al. 2013).

16 **AEROSOLS**

17 Atmospheric aerosols are perhaps the most complex and most uncertain component of forcing
18 due to anthropogenic activities (Myhre et al. 2013). Aerosols have diverse natural and
19 anthropogenic sources, and emissions from these sources interact in non-linear ways (Boucher et
20 al. 2013). Aerosol types are categorized by composition; namely, sulfate, black carbon, organic,
21 nitrate, dust, and sea salt. Individual particles generally include a mix of these components due to
22 chemical and physical transformations of aerosols and aerosol precursor gases following
23 emission. Aerosol tropospheric lifetimes are days to weeks due to the general hygroscopic nature
24 of primary and secondary particles and the ubiquity of cloud and precipitation systems in the
25 troposphere. Particles that act as cloud condensation nuclei (CCN) or are scavenged by cloud
26 droplets are removed from the troposphere in precipitation. The heterogeneity of aerosol sources
27 and locations combined with short aerosol lifetimes leads to the high spatial and temporal
28 variabilities observed in the global aerosol distribution and their associated forcings.

29 Aerosols from anthropogenic activities influence RF in three primary ways: through aerosol–
30 radiation interactions, through aerosol–cloud interactions, and through albedo changes from
31 absorbing-aerosol deposition on snow and ice (Boucher et al. 2013). RF from aerosol–radiation
32 interactions, also known as the aerosol “direct effect,” involves absorption and scattering of
33 longwave and shortwave radiation. RF from aerosol–cloud interactions, also known as the cloud
34 albedo “indirect effect,” results from changes in cloud droplet number and size due to changes in
35 aerosol (cloud condensation nuclei) number and composition. The RF for the global net aerosol–
36 radiation and aerosol–cloud interaction is negative (Myhre et al. 2013). However, the RF is not
37 negative for all aerosol types. Light-absorbing aerosols, such as black carbon, absorb sunlight,

1 producing a positive RF. This absorption warms the atmosphere; on net, this response is assessed
2 to increase cloud cover and therefore increase planetary albedo (the “semi-direct” effect). This
3 “rapid response” lowers the ERF of atmospheric black carbon by approximately 15% relative to
4 its RF from direct absorption alone (Bond et al. 2013). ERF for aerosol–cloud interactions
5 includes this rapid adjustment for absorbing aerosol (that is, the cloud response to atmospheric
6 heating) and it includes cloud lifetime effects (for example, glaciation and thermodynamic
7 effects) (Boucher et al. 2013). Light-absorbing aerosols also affect climate when present in
8 surface snow by lowering surface albedo, yielding a positive RF (e.g. Flanner et al. 2009). For
9 black carbon deposited on snow, the ERF is a factor of three higher than the RF because of
10 positive feedbacks that reduce snow albedo and accelerate snow melt (e.g., Flanner et al. 2009;
11 Bond et al. 2013). There is *very high confidence* that the RF from snow and ice albedo is positive
12 (Bond et al. 2013).

13 **LAND SURFACE**

14 Land-cover changes (LCC) due to anthropogenic activities in the industrial era have changed the
15 land surface brightness (albedo), principally through deforestation and afforestation. There is
16 strong evidence that these changes have increased Earth’s global surface albedo, creating a
17 negative (cooling) RF of $-0.15 \pm 0.10 \text{ W/m}^2$ (Myhre et al. 2013). In specific regions, however,
18 LCC has lowered surface albedo producing a positive RF (for example, through afforestation and
19 pasture abandonment). In addition to the direct radiative forcing through albedo changes, LCC
20 also have indirect forcing effects on climate, such as altering carbon cycles and altering dust
21 emissions through effects on the hydrologic cycle. These effects are generally not included in the
22 direct LCC RF calculations and are instead included in the net GHG and aerosol RFs over the
23 industrial era. These indirect forcings may be of opposite sign to that of the direct LCC albedo
24 forcing and may constitute a significant fraction of industrial-era RF driven by human activities
25 (Ward et al. 2014). Some of these effects, such as alteration of the carbon cycle, constitute
26 climate feedbacks (Figure 2.2) and are discussed more extensively in Chapter 10: Land Cover.
27 The increased use of satellite observations to quantify LCC has resulted in smaller negative LCC
28 RF values (e.g., Ju and Masek 2016). In areas with significant irrigation, surface temperatures
29 and precipitation are affected by a change in energy partitioning from sensible to latent heating.
30 Direct RF due to irrigation is generally small and can be positive or negative, depending on the
31 balance of longwave (surface cooling or increases in water vapor) and shortwave (increased
32 cloudiness) effects (Cook et al. 2015).

33 **CONTRAILS**

34 Line-shaped (linear) contrails are a special type of cirrus cloud that forms in the wake of jet-
35 engine aircraft operating in the mid- to upper troposphere under conditions of high ambient
36 humidity. Persistent contrails, which can last for many hours, form when ambient humidity
37 conditions are supersaturated with respect to ice. As persistent contrails spread and drift with the
38 local winds after formation, they lose their linear features, creating additional cirrus cloudiness

1 that is indistinguishable from background cloudiness. Contrails and contrail cirrus are additional
2 forms of cirrus cloudiness that interact with solar and thermal radiation to provide a global net
3 positive RF and thus are visible evidence of an anthropogenic contribution to climate change
4 (Burkhardt and Kärcher 2011).

5 **2.4 Industrial-era Changes in Radiative Forcing Agents**

6 The IPCC best-estimate values of present day RFs and ERFs from principal anthropogenic and
7 natural climate drivers are shown in Figure 2.3 and in Table 2.1. The past changes in the
8 industrial era leading up to present day RF are shown for anthropogenic gases in Figure 2.5 and
9 for all climate drivers in Figure 2.6.

10 The combined figures have several striking features. First, there is a large range in the
11 magnitudes of RF terms, with contrails, stratospheric ozone, black carbon on snow, and
12 stratospheric water vapor being small fractions of the largest term (CO_2). The sum of ERFs from
13 CO_2 and non- CO_2 GHGs, tropospheric ozone, stratospheric water, contrails, and black carbon on
14 snow shows a gradual increase from 1750 to the mid-1960s and accelerated annual growth in the
15 subsequent 50 years (Figure 2.6). The sum of aerosol effects, stratospheric ozone depletion, and
16 land use show a monotonically increasing cooling trend for the first two centuries of the depicted
17 time series. During the past several decades, however, this combined cooling trend has leveled
18 off due to reductions in the emissions of aerosols and aerosol precursors, largely as a result of
19 legislation designed to improve air quality (Smith and Bond 2014; Fiore et al. 2015). In contrast,
20 the volcanic RF reveals its episodic, short-lived characteristics along with large values that at
21 times dominate the total RF. Changes in total solar irradiance over the industrial era are
22 dominated by the 11-year solar cycle and other short-term variations. The solar irradiance RF
23 between 1745 and 2005 is 0.05 (range of 0.0–0.1) W/m^2 (Myhre et al. 2013), a very small
24 fraction of total anthropogenic forcing in 2011. The large relative uncertainty derives from
25 inconsistencies among solar models, which all rely on proxies of solar irradiance to fit the
26 industrial era. In total, ERF has increased substantially in the industrial era, driven almost
27 completely by anthropogenic activities, with annual growth in ERF notably higher after the mid-
28 1960s.

29 The principal anthropogenic activities that have increased ERF are those that increase net GHG
30 emissions. The atmospheric concentrations of CO_2 , CH_4 , and N_2O are higher now than they have
31 been in at least the past 800,000 years (Masson-Delmotte et al. 2013). All have increased
32 monotonically over the industrial era (Figure 2.4), and are now 40%, 250%, and 20%,
33 respectively, above their preindustrial concentrations as reflected in the RF time series in Figure
34 2.5. Tropospheric ozone has increased in response to growth in precursor emissions in the
35 industrial era. Emissions of synthetic GHGs have grown rapidly beginning in the mid-20th
36 century, with many bringing halogens to the stratosphere and causing ozone depletion in
37 subsequent decades. Aerosol RF effects are a sum over aerosol–radiation and aerosol–cloud
38 interactions; this RF has increased in the industrial era due to increased emissions of aerosol and

1 aerosol precursors (Figure 2.6). These global aerosol RF trends average across disparate trends at
2 the regional scale. The recent leveling off of global aerosol concentrations is the result of
3 declines in many regions that were driven by enhanced air quality regulations, particularly
4 starting in the 1980s (e.g., Philipona et al. 2009; Liebensperger et al. 2012; Wild 2016). These
5 declines are partially offset by increasing trends in other regions, such as much of Asia and
6 possibly the Arabian Peninsula (Hsu et al. 2012; Chin et al. 2014; Lynch et al. 2016). In highly
7 polluted regions, negative aerosol RF may fully offset positive GHG RF, in contrast to global
8 annual averages in which positive GHG forcing fully offsets negative aerosol forcing (Figures
9 2.3 and 2.6).

10 **2.5 The Complex Relationship between Concentrations, Forcing, and** 11 **Climate Response**

12 Climate changes occur in response to ERFs, which generally include certain rapid responses to
13 the underlying RF terms. (Figure 2.2). Responses within the Earth system to forcing can act to
14 either amplify (positive feedback) or reduce (negative feedback) the original forcing. These
15 feedbacks operate on a range of timescales, from days to centuries. Thus, in general, the full
16 climate impact of a given forcing is not immediately realized. Of interest are the climate
17 response at a given point in time under continuously evolving forcings and the total climate
18 response realized for a given forcing. A metric for the former, which approximates near-term
19 climate change from a GHG forcing, is the transient climate response (TCR), defined as the
20 change in global mean surface temperature when the atmospheric CO₂ concentration has doubled
21 in a scenario of concentration increasing at 1% per year. The latter is given by the equilibrium
22 climate sensitivity (ECS), defined as the change at equilibrium in annual and global mean
23 surface temperature following a doubling of the atmospheric CO₂ concentration (Flato et al.
24 2013). TCR is more representative of near-term climate change from a GHG forcing. To estimate
25 ECS, climate model runs have to simulate thousands of years in order to allow sufficient time for
26 ocean temperatures to reach equilibrium.

27 In the IPCC's Fifth Assessment Report, ECS is assessed to be a factor of 1.5 or more greater than
28 the TCR (ECS is 2.7°F to 8.1°F [1.5°C to 4.5°C] and TCR is 1.8°F to 4.5°F [1.0°C to 2.5°C];
29 Flato et al. 2013), exemplifying that longer time-scale feedbacks are both significant and
30 positive. Confidence in the model-based TCR and ECS values is increased by their agreement,
31 within respective uncertainties, with other methods of calculating these metrics (Collins et al.
32 2013; Box 12.2). The alternative methods include using reconstructed temperatures from
33 paleoclimate archives, the forcing/response relationship from past volcanic eruptions, and
34 observed surface and ocean temperature changes over the industrial era (Collins et al. 2013).

35 While TCR and ECS are defined specifically for the case of doubled CO₂, the climate sensitivity
36 factor, λ , more generally relates the equilibrium surface temperature response (ΔT) to a constant
37 forcing (ERF) as given by $\Delta T = \lambda \text{ERF}$ (Knutti and Hegerl 2008; Flato et al. 2013). The λ factor

1 is highly dependent on feedbacks within the Earth system; all feedbacks are quantified
2 themselves as radiative forcings, since each one acts by affecting Earth's albedo or its
3 greenhouse effect. Models in which feedback processes are more positive (that is, more strongly
4 amplify warming) tend to have a higher climate sensitivity (see Figure 9.43 of Flato et al. 2013).
5 In the absence of feedbacks, λ would be equal to $0.54^{\circ}\text{F}/(\text{W}/\text{m}^2)$ ($0.30^{\circ}\text{C}/[\text{W}/\text{m}^2]$). The
6 magnitude of λ for ERF over the industrial era varies across models, but in all cases λ is greater
7 than $0.54^{\circ}\text{F}/(\text{W}/\text{m}^2)$, indicating the sum of all climate feedbacks tends to be positive. Overall, the
8 global warming response to ERF includes a substantial amplification from feedbacks, with a
9 model mean λ of $0.86^{\circ}\text{F}/(\text{W}/\text{m}^2)$ ($0.48^{\circ}\text{C}/[\text{W}/\text{m}^2]$) with a 90% uncertainty range of
10 $\pm 0.23^{\circ}\text{F}/(\text{W}/\text{m}^2)$ ($\pm 0.13^{\circ}\text{C}/[\text{W}/\text{m}^2]$) (as derived from climate sensitivity parameter in Table 9.5 of
11 Flato et al. [2013] combined with methodology of Bony et al. [2006]). Thus, there is *high*
12 *confidence* that the response of the Earth system to the industrial-era net positive forcing is to
13 amplify that forcing (Figure 9.42 of Flato et al. 2013).

14 The models used to quantify λ account for the near-term feedbacks described below (Section
15 2.6.1), though with mixed levels of detail regarding feedbacks to atmospheric composition.
16 Feedbacks to the land and ocean carbon sink, land albedo and ocean heat uptake, most of which
17 operate on longer timescales (Section 2.6.2), are currently included on only a limited basis, or in
18 some cases not at all, in climate models. Climate feedbacks are the largest source of uncertainty
19 in quantifying climate sensitivity (Flato et al. 2013); namely, the responses of clouds, the carbon
20 cycle, ocean circulation and, to a lesser extent, land and sea ice to surface temperature and
21 precipitation changes.

22 The complexity of mapping forcings to climate responses on a global scale is enhanced by
23 geographic and seasonal variations in these forcings and responses, driven in part by similar
24 variations in anthropogenic emissions and concentrations. Studies show that the spatial pattern
25 and timing of climate responses are not always well correlated with the spatial pattern and timing
26 of a radiative forcing, since adjustments within the climate system can determine much of the
27 response (e.g., Shindell and Faluvegi 2009; Crook and Forster 2011; Knutti and Rugenstein
28 2015). The RF patterns of short-lived climate drivers with inhomogeneous source distributions,
29 such as aerosols, tropospheric ozone, contrails, and land cover change, are leading examples of
30 highly inhomogeneous forcings. Spatial and temporal variability in aerosol and aerosol precursor
31 emissions is enhanced by in-atmosphere aerosol formation and chemical transformations, and by
32 aerosol removal in precipitation and surface deposition. Even for relatively uniformly distributed
33 species (for example, WMGHGs), RF patterns are less homogenous than their concentrations.
34 The RF of a uniform CO_2 distribution, for example, depends on latitude and cloud cover
35 (Ramanathan et al. 1979). With the added complexity and variability of regional forcings, the
36 global mean RFs are known with more confidence than the regional RF patterns. Forcing
37 feedbacks in response to spatially variable forcings also have variable geographic and temporal
38 patterns.

1 Quantifying the relationship between spatial RF patterns and regional and global climate
2 responses in the industrial era is difficult because it requires distinguishing forcing responses
3 from the inherent internal variability of the climate system, which acts on a range of time scales.
4 The ability to test the accuracy of modeled responses to forcing patterns is limited by the sparsity
5 of long-term observational records of regional climate variables. As a result, there is generally
6 *very low confidence* in our understanding of the qualitative and quantitative forcing–response
7 relationships at the regional scale. However, there is *medium to high confidence* in other features,
8 such as aerosol effects altering the location of the Inter Tropical Convergence Zone (ITCZ) and
9 the positive feedback to reductions of snow and ice and albedo changes at high latitudes
10 (Boucher et al. 2013; Myhre et al. 2013).

11 **2.6 Radiative-forcing Feedbacks**

12 **2.6.1 Near-term Feedbacks**

13 **PLANCK FEEDBACK**

14 When the temperatures of Earth’s surface and atmosphere increase in response to RF, more
15 infrared radiation is emitted into the lower atmosphere; this serves to restore radiative balance at
16 the tropopause. This radiative feedback, defined as the Planck feedback, only partially offsets the
17 positive RF while triggering other feedbacks that affect radiative balance. The Planck feedback
18 magnitude is $-3.20 \pm 0.04 \text{ W/m}^2$ per 1.8°F (1°C) of warming and is the strongest and primary
19 stabilizing feedback in the climate system (Vial et al. 2013).

20 **WATER VAPOR AND LAPSE RATE FEEDBACKS**

21 Warmer air holds more moisture (water vapor) than cooler air—about 7% more per degree
22 Celsius—as dictated by the Clausius–Clapeyron relationship (Allen and Igram 2002). Thus, as
23 global temperatures increase, the total amount of water vapor in the atmosphere increases,
24 adding further to greenhouse warming—a positive feedback—with a mean value derived from a
25 suite of atmosphere/ocean global climate models (AOGCM) of $1.6 \pm 0.3 \text{ W/m}^2$ per 1.8°F (1°C)
26 of warming (Flato et al. 2013, Table 9.5). The water vapor feedback is responsible for more than
27 doubling the direct climate warming from CO_2 emissions alone (Bony et al. 2006; Soden and
28 Held 2006; Vial et al. 2013). Observations confirm that global tropospheric water vapor has
29 increased commensurate with measured warming (IPCC 2013, FAQ 3.2 and Figure 1a).
30 Interannual variations and trends in stratospheric water vapor, while influenced by tropospheric
31 abundances, are controlled largely by tropopause temperatures and dynamical processes (Dessler
32 et al. 2014). Increases in tropospheric water vapor have a larger warming effect in the upper
33 troposphere (where it is cooler) than in the lower troposphere, thereby decreasing the rate at
34 which temperatures decrease with altitude (the lapse rate). Warmer temperatures aloft increase
35 outgoing infrared radiation—a negative feedback—with a mean value derived from the same
36 AOGCM suite of $-0.6 \pm 0.4 \text{ W/m}^2$ per 1.8°F (1°C) warming. These feedback values remain

1 largely unchanged between recent IPCC assessments (IPCC 2007; 2013). Recent advances in
2 both observations and models have increased confidence that the net effect of the water vapor
3 and lapse rate feedbacks is a significant positive RF (Flato et al. 2013).

4 **CLOUD FEEDBACKS**

5 An increase in cloudiness has two direct impacts on radiative fluxes: first, it increases scattering
6 of sunlight, which increases Earth's albedo and cools the surface (the shortwave cloud radiative
7 effect); second, it increases trapping of infrared radiation, which warms the surface (the
8 longwave cloud radiative effect). A decrease in cloudiness has the opposite effects. Clouds have
9 a relatively larger shortwave effect when they form over dark surfaces (for example, oceans)
10 than over higher albedo surfaces, such as sea ice and deserts. For clouds globally, the shortwave
11 cloud radiative effect is about -50 W/m^2 and the longwave effect is about $+30 \text{ W/m}^2$, yielding a
12 net cooling influence (Loeb et al. 2009; Sohn et al. 2010). The relative magnitudes of both
13 effects vary with cloud type as well as with location. For low-altitude, thick clouds (for example,
14 stratus and stratocumulus) the shortwave radiative effect dominates, so they cause a net cooling.
15 For high-altitude, thin clouds (for example, cirrus) the longwave effect dominates, so they cause
16 a net warming (e.g., Hartmann et al. 1992; Chen et al. 2000). Therefore, an increase in low
17 clouds is a negative feedback to RF, while an increase in high clouds is a positive feedback. The
18 potential magnitude of cloud feedbacks is large compared with global RF (see Section 2.4).
19 Cloud feedbacks also influence natural variability within the climate system and may amplify
20 atmospheric circulation patterns and the El Niño–Southern Oscillation (Rädel et al. 2016).

21 The net radiative effect of cloud feedbacks is positive over the industrial era, with an assessed
22 value of $+0.27 \pm 0.42 \text{ W/m}^2$ per 1.8°F (1°C) warming (Vial et al. 2013). The net cloud feedback
23 can be broken into components, where the longwave cloud feedback is positive ($+0.24 \pm 0.26$
24 W/m^2 per 1.8°F [1°C] warming) and the shortwave feedback is near-zero ($+0.14 \pm 0.40 \text{ W/m}^2$ per
25 1.8°F [1°C] warming; Vial et al. 2013), though the two do not add linearly. The value of the
26 shortwave cloud feedback shows a significant sensitivity to computation methodology (Taylor et
27 al. 2011; Vial et al. 2013; Klocke et al. 2013). Uncertainty in cloud feedback remains the largest
28 source of inter-model differences in calculated climate sensitivity (Vial et al. 2013; Boucher et
29 al. 2013).

30 **SNOW, ICE, AND SURFACE ALBEDO**

31 Snow and ice are highly reflective to solar radiation relative to land surfaces and the ocean. Loss
32 of snow cover, glaciers, ice sheets, or sea ice resulting from climate warming lowers Earth's
33 surface albedo. The losses create the snow-albedo feedback because subsequent increases in
34 absorbed solar radiation lead to further warming as well as changes in turbulent heat fluxes at the
35 surface (Sejas et al. 2014). For seasonal snow, glaciers, and sea ice, a positive albedo feedback
36 occurs where light-absorbing aerosols are deposited to the surface, darkening the snow and ice

1 and accelerating the loss of snow and ice mass (e.g., Hansen and Nazarenko 2004; Jacobson
2 2004; Flanner et al. 2009; Skeie et al. 2011; Bond et al. 2013; Yang et al. 2015).

3 For ice sheets (for example, on Antarctica and Greenland—see Ch. 11: Arctic Changes), the
4 positive radiative feedback is further amplified by dynamical feedbacks on ice-sheet mass loss.
5 Specifically, since continental ice shelves limit the discharge rates of ice sheets into the ocean;
6 any melting of the ice shelves accelerates the discharge rate, creating a positive feedback on the
7 ice-stream flow rate and total mass loss (e.g., Holland et al. 2008; Schoof 2010; Rignot et al.
8 2010; Joughin et al. 2012). Warming oceans also lead to accelerated melting of basal ice (ice at
9 the base of a glacier or ice sheet) and subsequent ice-sheet loss (e.g., Straneo et al. 2013; Thoma
10 et al. 2015; Alley et al. 2016; Silvano et al. 2016). Feedbacks related to ice sheet dynamics occur
11 on longer timescales than other feedbacks—many centuries or longer. Significant ice-sheet melt
12 can also lead to changes in freshwater input to the oceans, which in turn can affect ocean
13 temperatures and circulation, ocean–atmosphere heat exchange and moisture fluxes, and
14 atmospheric circulation (Masson-Delmotte et al. 2013).

15 The complete contribution of ice-sheet feedbacks on timescales of millennia are not generally
16 included in CMIP5 climate simulations. These slow feedbacks are also not thought to change in
17 proportion to global mean surface temperature change, implying that the apparent climate
18 sensitivity changes with time, making it difficult to fully understand climate sensitivity
19 considering only the industrial age. This slow response increases the likelihood for tipping
20 points, as discussed further in Chapter 15: Potential Surprises.

21 The surface-albedo feedback is an important influence on interannual variations in sea ice as well
22 as on long-term climate change. While there is a significant range in estimates of the snow-
23 albedo feedback, it is assessed as positive (Hall and Qu 2006; Fernandes et al. 2009; Vial et al.
24 2013), with a best estimate of 0.27 ± 0.06 W/m² per 1.8°F (1°C) of warming globally. Within the
25 cryosphere, the surface-albedo feedback is most effective in polar regions (Winton 2006; Taylor
26 et al. 2011); there is also evidence that polar surface-albedo feedbacks might influence the
27 tropical climate as well (Hall 2004).

28 Changes in sea ice can also influence Arctic cloudiness. Recent work indicates that Arctic clouds
29 have responded to sea ice loss in fall but not summer (Kay and Gettelman 2009; Kay et al. 2011;
30 Kay and L'Ecuyer 2013; Pistone et al. 2014; Taylor et al. 2015). This has important implications
31 for future climate change, as an increase in summer clouds could offset a portion of the
32 amplifying surface-albedo feedback, slowing down the rate of arctic warming.

33 **ATMOSPHERIC COMPOSITION**

34 Climate change alters the atmospheric abundance and distribution of some radiatively active
35 species by changing natural emissions, atmospheric photochemical reaction rates, atmospheric
36 lifetimes, transport patterns, or deposition rates. These changes in turn alter the associated ERFs,
37 forming a feedback (Liao et al. 2009; Unger et al. 2009; Raes et al. 2010). Atmospheric

1 composition feedbacks occur through a variety of processes. Important examples include
2 climate-driven changes in temperature and precipitation that affect 1) natural sources of NO_x
3 from soils and lightning and VOC sources from vegetation, all of which affect ozone abundances
4 (Raes et al. 2010; Tai et al. 2013; Yue et al. 2015); 2) regional aridity, which influences surface
5 dust sources as well as susceptibility to wildfires; and 3) surface winds, which control the
6 emission of dust from the land surface and the emissions of sea salt and dimethyl sulfide—a
7 natural precursor to sulfate aerosol—from the ocean surface.

8 Climate-driven ecosystem changes that alter the carbon cycle potentially impact atmospheric
9 CO₂ and CH₄ abundances (Section 2.6.2). Atmospheric aerosols affect clouds and precipitation
10 rates, which in turn alter aerosol removal rates, lifetimes, and atmospheric abundances.
11 Longwave radiative feedbacks and climate-driven circulation changes also alter stratospheric
12 ozone abundance (Nowack et al. 2015). Investigation of these and other composition–climate
13 interactions is an active area of research (e.g., John et al. 2012; Pacifico et al. 2012; Morgenstern
14 et al. 2013; Holmes et al. 2013; Naik et al. 2013; Voulgarakis et al. 2013; Isaksen et al. 2014;
15 Dietmuller et al. 2014; Banerjee et al. 2014). While understanding of key processes is improving,
16 atmospheric composition feedbacks are absent or limited in many global climate modeling
17 studies used to project future climate, though this is rapidly changing (ACC-MIP 2017). For
18 some composition–climate feedbacks involving shorter-lived constituents, the net effects may be
19 near-zero at the global scale while significant at local to regional scales (e.g. Raes et al. 2010;
20 Han et al. 2013).

21 **2.6.2 Long-term Feedbacks**

22 **TERRESTRIAL ECOSYSTEMS AND CLIMATE CHANGE FEEDBACKS**

23 The cycling of carbon through the climate system is an important long-term climate feedback
24 that affects atmospheric CO₂ concentrations. The global mean atmospheric CO₂ concentration is
25 determined by emissions from burning fossil fuels, wildfires, and permafrost thaw balanced
26 against CO₂ uptake by the oceans and terrestrial biosphere (Ciais et al. 2013; Le Quéré et al.
27 2016) (Figures 2.2 and 2.7). During the past decade, just less than a third of anthropogenic CO₂
28 has been taken up by the terrestrial environment, and another quarter by the oceans (Le Quéré et
29 al. 2016 Table 8) through photosynthesis and through direct absorption by ocean surface waters.
30 The capacity of the land to continue uptake of CO₂ is uncertain and depends on land-use
31 management and on responses of the biosphere to climate change (see Ch. 10: Land Cover).
32 Altered uptake rates affect atmospheric CO₂ abundance, forcing, and rates of climate change.
33 Such changes are expected to evolve on the decadal and longer timescale, though abrupt changes
34 are possible.

35 Significant uncertainty exists in quantification of carbon-cycle feedbacks. Differences in the
36 assumed characteristics of the land carbon-cycle processes are the primary cause of the inter-
37 model spread in modeling the present-day carbon cycle and a leading source of uncertainty.

1 Significant uncertainties also exist in ocean carbon-cycle changes in future climate scenarios.
2 Basic principles of carbon cycle dynamics in terrestrial ecosystems suggest that increased
3 atmospheric CO₂ concentrations can directly enhance plant growth rates and, therefore, increase
4 carbon uptake (the “CO₂ fertilization” effect), nominally sequestering much of the added carbon
5 from fossil-fuel combustion (e.g., Wenzel et al. 2016). However, this effect is variable;
6 sometimes plants acclimate so that higher CO₂ concentrations no longer enhance growth (e.g.,
7 Franks et al. 2013). In addition, CO₂ fertilization is often offset by other factors limiting plant
8 growth, such as water and or nutrient availability and temperature and incoming solar radiation
9 that can be modified by changes in vegetation structure. Large-scale plant mortality through fire,
10 soil moisture drought, and/or temperature changes also impact successional processes that
11 contribute to reestablishment and revegetation (or not) of disturbed ecosystems, altering the
12 amount and distribution of plants available to uptake CO₂. With sufficient disturbance, it has
13 been argued that forests could, on net, turn into a source rather than a sink of CO₂ (Seppälä
14 2009).

15 Climate-induced changes in the horizontal (for example, landscape to biome) and vertical (soils
16 to canopy) structure of terrestrial ecosystems also alter the physical surface roughness and
17 albedo, as well as biogeochemical (carbon and nitrogen) cycles and biophysical
18 evapotranspiration and water demand. Combined, these responses constitute climate feedbacks
19 by altering surface albedo and atmospheric GHG abundances. Drivers of these changes in
20 terrestrial ecosystems include changes in the biophysical growing season, altered seasonality,
21 wildfire patterns, and multiple additional interacting factors (Ch.10: Land Cover).

22 Accurate determination of future CO₂ stabilization scenarios depends on accounting for the
23 significant role that the land biosphere plays in the global carbon cycle and feedbacks between
24 climate change and the terrestrial carbon cycle (Hibbard et al. 2007). Earth System Models
25 (ESMs) are increasing the representation of terrestrial carbon cycle processes, including plant
26 photosynthesis, plant and soil respiration and decomposition, and CO₂ fertilization, with the
27 latter based on the assumption that an increased atmospheric CO₂ concentration provides more
28 substrate for photosynthesis and productivity. Recent advances in ESMs are beginning to
29 account for other important factors such as nutrient limitations (Thornton et al. 2007; Brzostek et
30 al. 2014; Wieder et al. 2015). ESMs that do include carbon-cycle feedbacks appear, on average,
31 to overestimate terrestrial CO₂ uptake under the present-day climate (Anav et al. 2013; Smith et
32 al. 2016) and underestimate nutrient limitations to CO₂ fertilization (Wieder et al. 2015). The
33 sign of the land carbon-cycle feedback through 2100 remains unclear in the newest generation of
34 ESMs (Friedlingstein et al. 2006, 2014; Wieder et al. 2015). Eleven CMIP5 ESMs forced with
35 the same CO₂ emissions scenario—one consistent with RCP8.5 concentrations—produce a range
36 of 795 to 1145 ppm for atmospheric CO₂ concentration in 2100. The majority of the ESMs (7 out
37 of 11) simulated a CO₂ concentration larger (by 44 ppm on average) than their equivalent non-
38 interactive carbon cycle counterpart (Friedlingstein et al. 2014). This difference in CO₂ equates
39 to about 0.4°F (0.2°C) more warming by 2100. The inclusion of carbon-cycle feedbacks does not

1 alter the lower-end bound on climate sensitivity, but, in most climate models, inclusion pushes
2 the upper bound higher (Friedlingstein et al. 2014).

3 **OCEAN CHEMISTRY, ECOSYSTEM, AND CIRCULATION CHANGES**

4 The ocean plays a significant role in climate change by playing a critical role in controlling the
5 amount of GHGs (including CO₂, water vapor, and N₂O) and heat in the atmosphere (Figure 2.7).
6 To date most of the net energy increase in the climate system from anthropogenic RF is in the
7 form of ocean heat (Rhein et al. 2013; see Box 3.1 Figure 1). This additional heat is stored
8 predominantly (about 60%) in the upper 700 meters of the ocean (Johnson et al. 2016 and see
9 Ch. 12: Sea Level Rise and Ch. 13: Ocean Changes). Ocean warming and climate-driven
10 changes in ocean stratification and circulation alter oceanic biological productivity and therefore
11 CO₂ uptake; combined, these feedbacks affect the rate of warming from radiative forcing.

12 Marine ecosystems take up CO₂ from the atmosphere in the same way that plants do on land.
13 About half of the global net primary production (NPP) is by marine plants (approximately 50 ±
14 28 GtC/year; Falkowski et al. 2004; Carr et al. 2006; Chavez et al. 2011). Phytoplankton NPP
15 supports the biological pump, which transports 2–12 GtC/year of organic carbon to the deep sea
16 (Doney 2010; Passow and Carlson 2012), where it is sequestered away from the atmospheric
17 pool of carbon for 200–1,500 years. Since the ocean is an important carbon sink, climate-driven
18 changes in NPP represent an important feedback because they potentially change atmospheric
19 CO₂ abundance and forcing.

20 There are multiple links between RF-driven changes in climate, physical changes to the ocean
21 and feedbacks to ocean carbon and heat uptake. Changes in ocean temperature, circulation and
22 stratification driven by climate change alter phytoplankton NPP. Absorption of CO₂ by the ocean
23 also increases its acidity, which can also affect NPP and therefore the carbon sink (see Ch. 13:
24 Ocean Changes for a more detailed discussion of ocean acidification).

25 In addition to being an important carbon sink, the ocean dominates the hydrological cycle, since
26 most surface evaporation and rainfall occur over the ocean (Trenberth et al. 2007; Schanze et al.
27 2010). The ocean component of the water vapor feedback derives from the rate of evaporation,
28 which depends on surface wind stress and ocean temperature. Climate warming from radiative
29 forcing also is associated with intensification of the water cycle (Ch. 7: Precipitation Change).
30 Over decadal timescales the surface ocean salinity has increased in areas of high salinity, such as
31 the subtropical gyres, and decreased in areas of low salinity, such as the Warm Pool region (see
32 Ch. 13: Ocean Changes; Durack and Wijfels 2010; Good et al. 2013). This increase in
33 stratification in select regions and mixing in other regions are feedback processes because they
34 lead to altered patterns of ocean circulation, which impacts uptake of anthropogenic heat and
35 CO₂.

36 Increased stratification inhibits surface mixing, high-latitude convection, and deep-water
37 formation, thereby potentially weakening ocean circulations, in particular the Atlantic

1 Meridional Overturning Circulation (AMOC) (Andrews et al. 2012; Kostov et al. 2014; see also
2 Ch. 13: Ocean Changes). Reduced deep-water formation and slower overturning are associated
3 with decreased heat and carbon sequestration at greater depths. Observational evidence is mixed
4 regarding whether the AMOC has slowed over the past decades to century (see Sect. 13.2.1 of
5 Ch. 13: Ocean Changes). Future projections show that the strength of AMOC may significantly
6 decrease as the ocean warms and freshens and as upwelling in the Southern Ocean weakens due
7 to the storm track moving poleward (Rahmstorf et al. 2015; see also Ch. 13: Ocean Changes).
8 Such a slowdown of the ocean currents will impact the rate at which the ocean absorbs CO₂ and
9 heat from the atmosphere.

10 Increased ocean temperatures also accelerate ice sheet melt, particularly for the Antarctic Ice
11 Sheet where basal sea ice melting is important relative to surface melting due to colder surface
12 temperatures (Rignot and Thomas 2002). For the Greenland Ice Sheet, submarine melting at
13 tidewater margins is also contributing to volume loss (van den Broeke et al. 2009). In turn,
14 changes in ice sheet melt rates change cold- and freshwater inputs, also altering ocean
15 stratification. This affects ocean circulation and the ability of the ocean to absorb more GHGs
16 and heat (Enderlin and Hamilton 2014). Enhanced sea ice export to lower latitudes gives rise to
17 local salinity anomalies (such as the Great Salinity Anomaly; Gelderloos et al. 2012) and
18 therefore to changes in ocean circulation and air–sea exchanges of momentum, heat, and
19 freshwater, which in turn affect the atmospheric distribution of heat and GHGs.

20 Remote sensing of sea surface temperature and chlorophyll as well as model simulations and
21 sediment records suggest that global phytoplankton NPP may have increased recently as a
22 consequence of decadal-scale natural climate variability, such as the El Niño–Southern
23 Oscillation, which promotes vertical mixing and upwelling of nutrients (Bidigare et al. 2009;
24 Chavez et al. 2011; Zhai et al. 2013). Analyses of longer trends, however, suggest that
25 phytoplankton NPP has decreased by about 1% per year over the last 100 years (Behrenfeld et al.
26 2006; Boyce et al. 2010; Capotondi et al. 2012). The latter results, although controversial
27 (Rykaczewski and Dunne 2011), are the only studies of the global rate of change over this
28 period. In contrast, model simulations show decreases of only 6.6% in NPP and 8% in the
29 biological pump over the last five decades (Laufkötter et al. 2015). Total NPP is complex to
30 model, as there are still areas of uncertainty on how multiple physical factors affect
31 phytoplankton growth, grazing, and community composition, and as certain phytoplankton
32 species are more efficient at carbon export (Jin et al. 2006; Fu et al. 2016). As a result, model
33 uncertainty is still significant in NPP projections (Frölicher et al. 2016). While there are
34 variations across climate model projections, there is good agreement that in the future there will
35 be increasing stratification, decreasing NPP, and a decreasing sink of CO₂ to the ocean via
36 biological activity (Fu et al. 2016). Overall, compared to the 1990s, in 2090 total NPP is
37 expected to decrease by 2%–16% and export production (that is, particulate flux to the deep
38 ocean) could decline by 7%–18% (RCP 8.5; Fu et al. 2016). Consistent with this result, carbon
39 cycle feedbacks in the ocean were positive (that is, higher CO₂ concentrations leading to a lower

1 rate of CO₂ sequestration to the ocean, thereby accelerating the growth of atmospheric CO₂
2 concentrations) across the suite of CMIP5 models.

3 **PERMAFROST AND HYDRATES**

4 Permafrost and methane hydrates contain large stores of methane and (for permafrost) carbon in
5 the form of organic materials, mostly at northern high latitudes. With warming, this organic
6 material can thaw, making previously frozen organic matter available for microbial
7 decomposition, releasing CO₂ and methane to the atmosphere, providing additional radiative
8 forcing and accelerating warming. This process defines the permafrost–carbon feedback.
9 Combined data and modeling studies suggest that this feedback is *very likely* positive (Schaefer
10 et al. 2014; Koven et al. 2015a; Schuur et al. 2015). This feedback was not included in recent
11 IPCC projections but is an active area of research. Accounting for permafrost-carbon release
12 reduces the amount of emissions allowable from anthropogenic sources in future GHG
13 stabilization or mitigation scenarios (González-Eguino and Neumann 2016).

14 The permafrost–carbon feedback in the RCP8.5 emissions scenario (Section 1.2.2 and Figure
15 1.4) contributes 120 ± 85 Gt of additional carbon by 2100; this represents 6% of the total
16 anthropogenic forcing for 2100 and corresponds to a global temperature increase of $+0.52^\circ \pm$
17 0.38°F ($+0.29^\circ \pm 0.21^\circ\text{C}$) (Schaefer et al. 2014). Considering the broader range of forcing
18 scenarios (Figure 1.4), it is *likely* that the permafrost–carbon feedback increases carbon
19 emissions between 2% and 11% by 2100. A key feature of the permafrost feedback is that, once
20 initiated, it will continue for an extended period because emissions from decomposition occur
21 slowly over decades and longer. In the coming few decades, enhanced plant growth at high
22 latitudes and its associated CO₂ sink (Friedlingstein et al. 2006) are expected to partially offset
23 the increased emissions from permafrost thaw (Schaefer et al. 2014; Schuur et al. 2015);
24 thereafter, decomposition will dominate uptake. Recent evidence indicates that permafrost thaw
25 is occurring faster than expected; poorly understood deep-soil carbon decomposition and ice
26 wedge processes *likely* contribute (Koven et al. 2015b; Liljedahl et al. 2016). Chapter 11: Arctic
27 Changes includes a more detailed discussion of permafrost and methane hydrates in the Arctic.
28 Future changes in permafrost emissions and the potential for even greater emissions from
29 methane hydrates in the continental shelf are discussed further in Chapter 15: Potential Surprises.

30

1 TRACEABLE ACCOUNTS

2 Key Finding 1

3 Human activities continue to significantly affect Earth's climate by altering factors that change
4 its radiative balance. These factors, known as radiative forcings, include changes in greenhouse
5 gases, small airborne particles (aerosols), and the reflectivity of the Earth's surface. In the
6 industrial era, human activities have been, and are increasingly, the dominant cause of climate
7 warming. The increase in radiative forcing due to these activities has far exceeded the relatively
8 small net increase due to natural factors, which include changes in energy from the sun and the
9 cooling effect of volcanic eruptions. (*Very high confidence*)

10 Description of evidence base

11 The Key Finding and supporting text summarizes extensive evidence documented in the climate
12 science literature, including in previous national (NCA3; Melillo et al. 2014) and international
13 (IPCC 2013) assessments. The assertion that Earth's climate is controlled by its radiative balance
14 is a well-established physical property of the planet. Quantification of the changes in Earth's
15 radiative balance come from a combination of observations and calculations. Satellite data are
16 used directly to observe changes in Earth's outgoing visible and infrared radiation. Since 2002,
17 observations of incoming sunlight include both total solar irradiance and solar spectral irradiance
18 (Ermolli et al. 2013). Extensive in situ and remote sensing data are used to quantify atmospheric
19 concentrations of radiative forcing agents (greenhouse gases [e.g. Ciais et al. 2013; Le Quéré et
20 al. 2016] and aerosols [e.g. Bond et al. 2013; Boucher et al. 2013; Myhre et al. 2013; Jiao et al.
21 2014; Tsigaridis et al. 2014; Koffi et al. 2016]) and changes in land cover (Zhu et al. 2016; Mao
22 et al. 2016; Ju and Masek 2016), as well as the relevant properties of these agents (for example,
23 aerosol microphysical and optical properties). Climate models are constrained by these observed
24 concentrations and properties. Concentrations of long-lived greenhouse gases in particular are
25 well-quantified with observations because of their relatively high spatial homogeneity. Climate
26 model calculations of radiative forcing by greenhouse gases and aerosols are supported by
27 observations of radiative fluxes from the surface, from airborne research platforms, and from
28 satellites. Both direct observations and modeling studies show large, explosive eruptions affect
29 climate parameters for years to decades (Robock 2000; Raible et al. 2016). Over the industrial
30 era radiative forcing by volcanoes has been episodic and currently does not contribute
31 significantly to forcing trends. Observations indicate a positive but small increase in solar input
32 over the industrial era (Kopp 2014; Kopp et al. 2016; Myhre et al. 2013). Relatively higher
33 variations in solar input at shorter (UV) wavelengths (Floyd et al. 2003) may be leading to
34 indirect changes in Earth's radiative balance through their impact on ozone concentrations that
35 are larger than the radiative impact of changes in total solar irradiance (Ermolli et al. 2013;
36 Bolduc et al. 2015; Gray et al. 2010; Lockwood 2012; Seppälä et al. 2014), but these changes are
37 also small in comparison to anthropogenic greenhouse gas and aerosol forcing (Myhre et al.
38 2013). The finding of an increasingly strong positive forcing over the industrial era is supported

1 by observed increases in atmospheric temperatures (see Ch. 1: Our Globally Changing Climate)
2 and by observed increases in ocean temperatures (Ch. 1: Our Globally Changing Climate; Ch.
3 13: Ocean Changes). The attribution of climate change to human activities is supported by
4 climate models, which are able to reproduce observed temperature trends when RF from human
5 activities is included, and considerably deviate from observed trends when only natural forcings
6 are included (Ch. 3: Detection and Attribution, Figure 3.1).

7 **Major uncertainties**

8 The largest source of uncertainty in radiative forcing (both natural and anthropogenic) over the
9 industrial era is quantifying forcing by aerosols. This finding is consistent across previous
10 assessments (e.g., IPCC 2007; IPCC 2013). The major uncertainties associated with aerosol
11 forcing is discussed below in the Traceable Accounts for Key Finding 2.

12 Recent work has highlighted the potentially larger role of variations in UV solar irradiance,
13 versus total solar irradiance, in solar forcing. However, this increase in solar forcing uncertainty
14 is not sufficiently large to reduce confidence that anthropogenic activities dominate industrial-era
15 forcing.

16 **Assessment of confidence based on evidence and agreement, including short description of** 17 **nature of evidence and level of agreement**

18 There is *very high confidence* that anthropogenic radiative forcing exceeds natural forcing over
19 the industrial era based on quantitative assessments of known radiative forcing components.
20 Assessments of the natural forcings of solar irradiance changes and volcanic activity show with
21 *very high confidence* that both forcings are small over the industrial era relative to total
22 anthropogenic forcing. Total anthropogenic forcing is assessed to have become larger and more
23 positive during the industrial era, while natural forcings show no similar trend.

24 **Summary sentence or paragraph that integrates the above information**

25 This key finding is consistent with that in the IPCC Fourth Assessment Report (AR4) (IPCC
26 2007) and Fifth Assessment Report (AR5) (IPCC 2013); namely, anthropogenic radiative forcing
27 is positive (climate warming) and substantially larger than natural forcing from variations in
28 solar input and volcanic emissions. Confidence in this finding has increased from AR4 to AR5,
29 as anthropogenic GHG forcings have continued to increase, whereas solar forcing remains small
30 and volcanic forcing near-zero over decadal timescales.

31

32

1 **Key Finding 2**

2 Aerosols caused by human activity play a profound and complex role in the climate system
3 through radiative effects in the atmosphere and on snow and ice surfaces and through effects on
4 cloud formation and properties. The combined forcing of aerosol–radiation and aerosol–cloud
5 interactions is negative (cooling) over the industrial era (*high confidence*), offsetting a substantial
6 part of greenhouse gas forcing, which is currently the predominant human contribution. The
7 magnitude of this offset, globally averaged, has declined in recent decades, despite increasing
8 trends in aerosol emissions or abundances in some regions. (*Medium to high confidence*)

9 **Description of evidence base**

10 The Key Finding and supporting text summarize extensive evidence documented in the climate
11 science literature, including in previous national (NCA3; Melillo et al. 2014) and international
12 (IPCC 2013) assessments. Aerosols affect the Earth’s albedo by directly interacting with solar
13 radiation (scattering and absorbing sunlight) and by affecting cloud properties (albedo and
14 lifetime).

15 Fundamental physical principles show how atmospheric aerosols scatter and absorb sunlight
16 (aerosol–radiation interaction), and thereby directly reduce incoming solar radiation reaching the
17 surface. Extensive in situ and remote sensing data are used to measure emission of aerosols and
18 aerosol precursors from specific source types, the concentrations of aerosols in the atmosphere,
19 aerosol microphysical and optical properties, and, via remote sensing, their direct impacts on
20 radiative fluxes. Atmospheric models used to calculate aerosol forcings are constrained by these
21 observations (see Key Finding #1).

22 In addition to their direct impact on radiative fluxes, aerosols also act as cloud condensation
23 nuclei. Aerosol–cloud interactions are more complex, with a strong theoretical basis supported
24 by observational evidence. Multiple observational and modeling studies have concluded that
25 increasing the number of aerosols in the atmosphere increases cloud albedo and lifetime, adding
26 to the negative forcing (aerosol–cloud microphysical interactions) (e.g., Twohy 2005; Lohmann
27 and Feichter 2005; Quaas et al. 2009; Rosenfeld et al. 2014). Particles that absorb sunlight
28 increase atmospheric heating; if they are sufficiently absorbing, the net effect of scattering plus
29 absorption is a positive radiative forcing. Only a few source types (for example, from diesel
30 engines) produce aerosols that are sufficiently absorbing that they have a positive radiative
31 forcing (Bond et al. 2013). Modeling studies, combined with observational inputs, have
32 investigated the thermodynamic response to aerosol absorption in the atmosphere. Averaging
33 over aerosol locations relative to the clouds and other factors, the resulting changes in cloud
34 properties represent a negative forcing, offsetting approximately 15% of the positive radiative
35 forcing from heating by absorbing aerosols (specifically, black carbon) (Bond et al. 2013).

36 Modeling and observational evidence both show that annually averaged global aerosol ERF
37 increased until the 1980’s and since then has flattened or slightly declined (Wild 2009; Szopa et

1 al. 2013; Stjern and Krisjansson 2015; Wang et al. 2015), driven by the introduction of stronger
2 air quality regulations (Smith and Bond 2014; Fiore et al. 2015). In one recent study (Myhre et
3 al. 2017), global-mean aerosol RF has become more less negative since IPCC AR5 (Myhre et al.
4 2013), due to a combination of declining sulfur dioxide emissions (which produce negative RF)
5 and increasing black carbon emissions (which produce positive RF). Within these global trends
6 there are significant regional variations (e.g., Mao et al. 2014), driven by both changes in aerosol
7 abundance and changes in the relative contributions of primarily light-scattering and light-
8 absorbing aerosols (Fiore et al. 2015; Myhre et al. 2017). In Europe and North America, aerosol
9 ERF has significantly declined (become less negative) since the 1980s (Marmer et al. 2007;
10 Philipona et al. 2009; Murphy et al. 2011; Leibensperger et al. 2012; Kühn et al. 2014; Turnock
11 et al. 2015). In contrast, observations show significant increases in aerosol abundances over India
12 (Babu et al. 2013; Krishna Moorthy et al. 2013), and these increases are expected to continue
13 into the near future (Pietikainen et al. 2015). Several modeling and observational studies point to
14 aerosol ERF for China peaking around 1990 (Streets et al. 2008; Li et al. 2013; Wang et al.
15 2013), though in some regions of China aerosol abundances and ERF have continued to increase
16 (Wang et al. 2013). The suite of emissions scenarios used for future climate projection (i.e., the
17 scenarios shown in Ch. 1: Our Globally Changing Climate, Figure 1.4) includes emissions for
18 aerosols and aerosol precursors. Across this range of scenarios, globally averaged ERF of
19 aerosols is expected to decline (become less negative) in the coming decades (Szopa et al. 2013;
20 Smith and Bond 2014), reducing the current aerosol offset to the increasing RF from GHGs.

21 **Major uncertainties**

22 Aerosol–cloud interactions are the largest source of uncertainty in both aerosol and total
23 anthropogenic radiative forcing. These include the microphysical effects of aerosols on clouds
24 and changes in clouds that result from the rapid response to absorption of sunlight by aerosols.
25 This finding, consistent across previous assessments (e.g., Forster et al. 2007; Myhre et al. 2013),
26 is due to poor understanding of how both natural and anthropogenic aerosol emissions have
27 changed and how changing aerosol concentrations and composition affect cloud properties
28 (albedo and lifetime) (Boucher et al. 2013; Carslaw et al. 2013). From a theoretical standpoint,
29 aerosol–cloud interactions are complex, and using observations to isolate the effects of aerosols
30 on clouds is complicated by the fact that other factors (for example, the thermodynamic state of
31 the atmosphere) also strongly influence cloud properties. Further, changes in aerosol properties
32 and the atmospheric thermodynamic state are often correlated and interact in non-linear ways
33 (Stevens and Feingold 2009).

34 **Assessment of confidence based on evidence and agreement, including short description of** 35 **nature of evidence and level of agreement**

36 There is *very high confidence* that aerosol radiative forcing is negative on a global, annually
37 averaged basis, *medium confidence* in the magnitude of the aerosol RF, *high confidence* that
38 aerosol ERF is also, on average, negative, and *low to medium confidence* in the magnitude of

1 aerosol ERF. Lower confidence in the magnitude of aerosol ERF is due to large uncertainties in
2 the effects of aerosols on clouds. Combined, we assess a *high level of confidence* that aerosol
3 ERF is negative and sufficiently large to be substantially offsetting positive GHG forcing.
4 Improvements in the quantification of emissions, in observations (from both surface-based
5 networks and satellites), and in modeling capability give *medium to high confidence* in the
6 finding that aerosol forcing trends are decreasing in recent decades.

7 **Summary sentence or paragraph that integrates the above information**

8 This key finding is consistent with the findings of IPCC AR5 (Myhre et al. 2013) that aerosols
9 constitute a negative radiative forcing. While significant uncertainty remains in the quantification
10 of aerosol ERF, we assess with *high confidence* that aerosols offset about half of the positive
11 forcing by anthropogenic CO₂ and about a third of the forcing by all well-mixed anthropogenic
12 GHGs. The fraction of GHG forcing that is offset by aerosols has been decreasing over recent
13 decades, as aerosol forcing has leveled off while GHG forcing continues to increase.

14

15 **Key Finding 3**

16 The interconnected Earth–atmosphere–ocean climate system includes a number of positive and
17 negative feedback processes that can either strengthen (positive feedback) or weaken (negative
18 feedback) the system’s responses to human and natural influences. These feedbacks operate on a
19 range of timescales from very short (essentially instantaneous) to very long (centuries). Global
20 warming by net radiative forcing over the industrial era includes a substantial amplification from
21 these feedbacks (approximately a factor of three) (*high confidence*). While there are large
22 uncertainties associated with some of these feedbacks, the net feedback effect over the industrial
23 era has been positive (amplifying warming) and will continue to be positive in coming decades.
24 (*Very high confidence*)

25 **Description of evidence base**

26 The variety of climate system feedbacks all depend on fundamental physical principles and are
27 known with a range of uncertainties. The Planck feedback is based on well-known radiative
28 transfer models. The largest positive feedback is the water vapor feedback, which derives from
29 the dependence of vapor pressure on temperature. There is *very high confidence* that this
30 feedback is positive, approximately doubling the direct forcing due to CO₂ emissions alone. The
31 lapse rate feedback derives from thermodynamic principles. There is *very high confidence* that
32 this feedback is negative and partially offsets the water vapor feedback. The water vapor and
33 lapse-rate feedbacks are linked by the fact that both are driven by increases in atmospheric water
34 vapor with increasing temperature. Estimates of the magnitude of these two feedbacks have
35 changed little across recent assessments (Randall et al. 2007; Boucher et al. 2013). The snow–
36 and ice–albedo feedback is positive in sign, with the magnitude of the feedback dependent in part

1 on the timescale of interest (Hall and Qu 2006; Fernandes et al. 2009). The assessed strength of
2 this feedback has also not changed significantly since IPCC (2007). Cloud feedbacks modeled
3 using microphysical principles are either positive or negative, depending on the sign of the
4 change in clouds with warming (increase or decrease) and the type of cloud that changes (low or
5 high clouds). Recent international assessments (Randall et al. 2007; Boucher et al. 2013) and a
6 separate feedback assessment (Vial et al. 2013) all give best estimates of the cloud feedback as
7 net positive. Feedback via changes in atmospheric composition is not well-quantified, but is
8 expected to be small relative to water-vapor-plus-lapse-rate, snow, and cloud feedbacks at the
9 global scale (Raes et al. 2010). Carbon cycle feedbacks through changes in the land biosphere
10 are currently of uncertain sign, and have asymmetric uncertainties: they might be small and
11 negative but could also be large and positive (Seppälä 2009). Recent best estimates of the ocean
12 carbon-cycle feedback are that it is positive with significant uncertainty that includes the
13 possibility of a negative feedback for present-day CO₂ levels (Laufkötter et al. 2015; Steinacher
14 et al. 2010). The permafrost–carbon feedback is *very likely* positive, and as discussed in Chapter
15 15: Potential Surprises, could be a larger positive feedback in the longer term. Thus, in the
16 balance of multiple negative and positive feedback processes, the preponderance of evidence is
17 that positive feedback processes dominate the overall radiative forcing feedback from
18 anthropogenic activities.

19 **Major uncertainties**

20 Uncertainties in cloud feedbacks are the largest source of uncertainty in the net climate feedback
21 (and therefore climate sensitivity) on the decadal to century time-scale (Boucher et al. 2013; Vial
22 et al. 2013). This results from the fact cloud feedbacks can be either positive or negative,
23 depending not only on the direction of change (more or less cloud) but also on the type of cloud
24 affected and, to a lesser degree, the location of the cloud (Vial et al. 2013). On decadal and
25 longer timescales, the biological and physical responses of the ocean and land to climate change,
26 and the subsequent changes in land and oceanic sinks of CO₂, contribute significant uncertainty
27 to the net climate feedback (Ch. 13: Ocean Changes). Changes in the Brewer-Dobson
28 atmospheric circulation driven by climate change and subsequent effects on stratosphere–
29 troposphere coupling also contribute to climate feedback uncertainty (Hauglustaine et al. 2005;
30 Jiang et al. 2007; Li et al. 2008; Shepherd and McLandress 2011; Collins et al. 2013;
31 McLandress et al. 2014).

32 **Assessment of confidence based on evidence and agreement, including short description of** 33 **nature of evidence and level of agreement**

34 There is *high confidence* that the net effect of all feedback processes in the climate system is
35 positive, thereby amplifying warming. This confidence is based on consistency across multiple
36 assessments, including IPCC AR5 (IPCC 2013 and references therein), of the magnitude of, in
37 particular, the largest feedbacks in the climate system, two of which (water vapor feedback and
38 snow/ice albedo feedback) are definitively positive in sign. While significant increases in low

1 cloud cover with climate warming would be a large negative feedback to warming, modeling and
2 observational studies do not support the idea of increases, on average, in low clouds with climate
3 warming.

4 **Summary sentence or paragraph that integrates the above information**

5 The net effect of all identified feedbacks to forcing is positive based on the best current
6 assessments and therefore amplifies climate warming. Feedback uncertainties, which are large
7 for some processes, are included in these assessments. The various feedback processes operate
8 on different timescales with carbon cycle and snow– and ice–albedo feedbacks operating on
9 longer timelines than water vapor, lapse rate, cloud, and atmospheric composition feedbacks.

10

11

FINAL DRAFT

1 **TABLES**2 Table 2.1. Global mean RF and ERF values in 2011 for the industrial era ^a

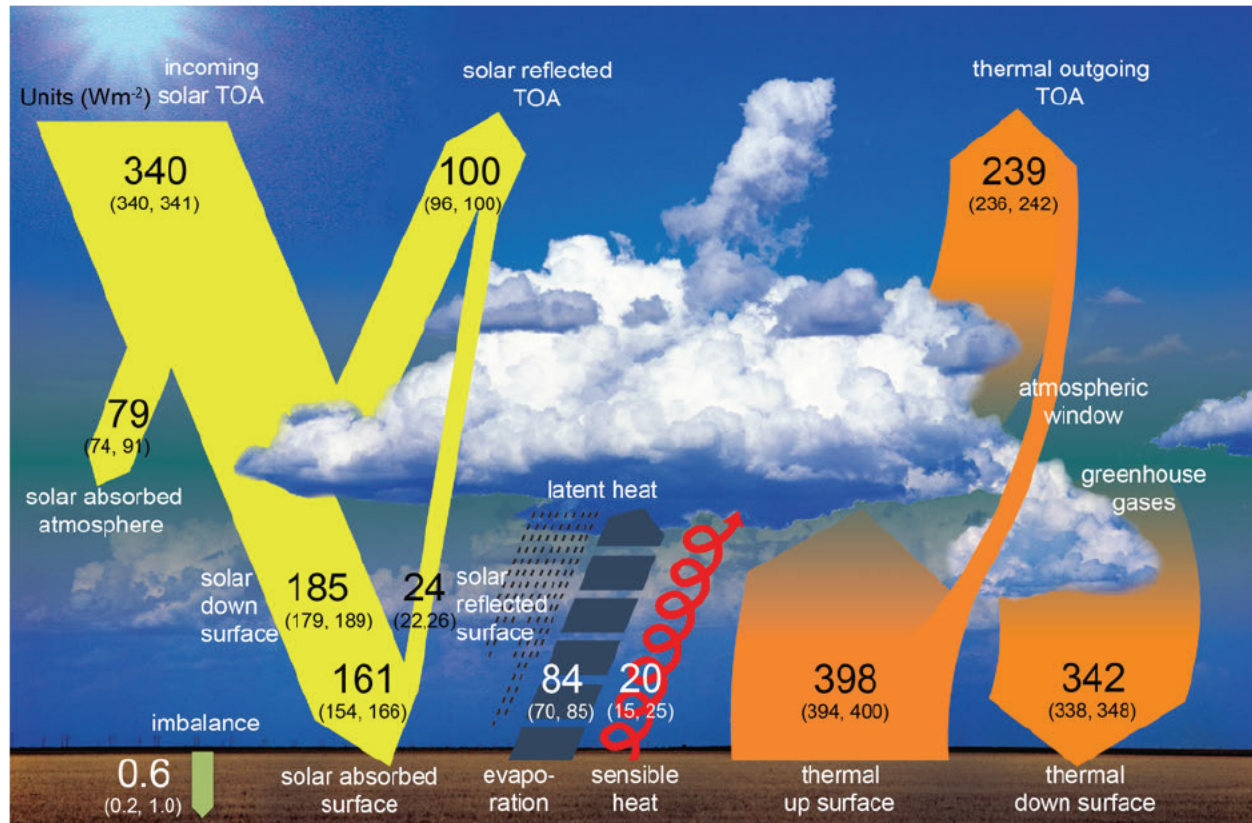
Radiative Forcing Term	Radiative forcing (W/m²)	Effective radiative forcing (W/m²) ^b
Well-mixed greenhouse gases (CO ₂ , CH ₄ , N ₂ O, and halocarbons)	+2.83 (2.54 to 3.12)	+2.83 (2.26 to 3.40)
Tropospheric ozone	+0.40 (0.20 to 0.60)	
Stratospheric ozone	-0.05 (-0.15 to +0.05)	
Stratospheric water vapor from CH ₄	+0.07 (+0.02 to +0.12)	
Aerosol-radiation interactions	-0.35 (-0.85 to +0.15)	-0.45 (-0.95 to +0.05)
Aerosol-cloud interactions	Not quantified	-0.45 (-1.2 to 0.0)
Surface albedo (land use)	-0.15 (-0.25 to -0.05)	
Surface albedo (black carbon aerosol on snow and ice)	+0.04 (+0.02 to +0.09)	
Contrails	+0.01 (+0.005 to +0.03)	
Combined contrails and contrail-induced cirrus	Not quantified	+0.05 (0.02 to 0.15)
Total anthropogenic	Not quantified	+2.3 (1.1 to 3.3)
Solar irradiance	+0.05 (0.0 to +0.10)	

3 ^a From IPCC (Myhre et al. 2013)4 ^b RF is a good estimate of ERF for most forcing agents except black carbon on snow and ice and aerosol-cloud
5 interactions.

6

7

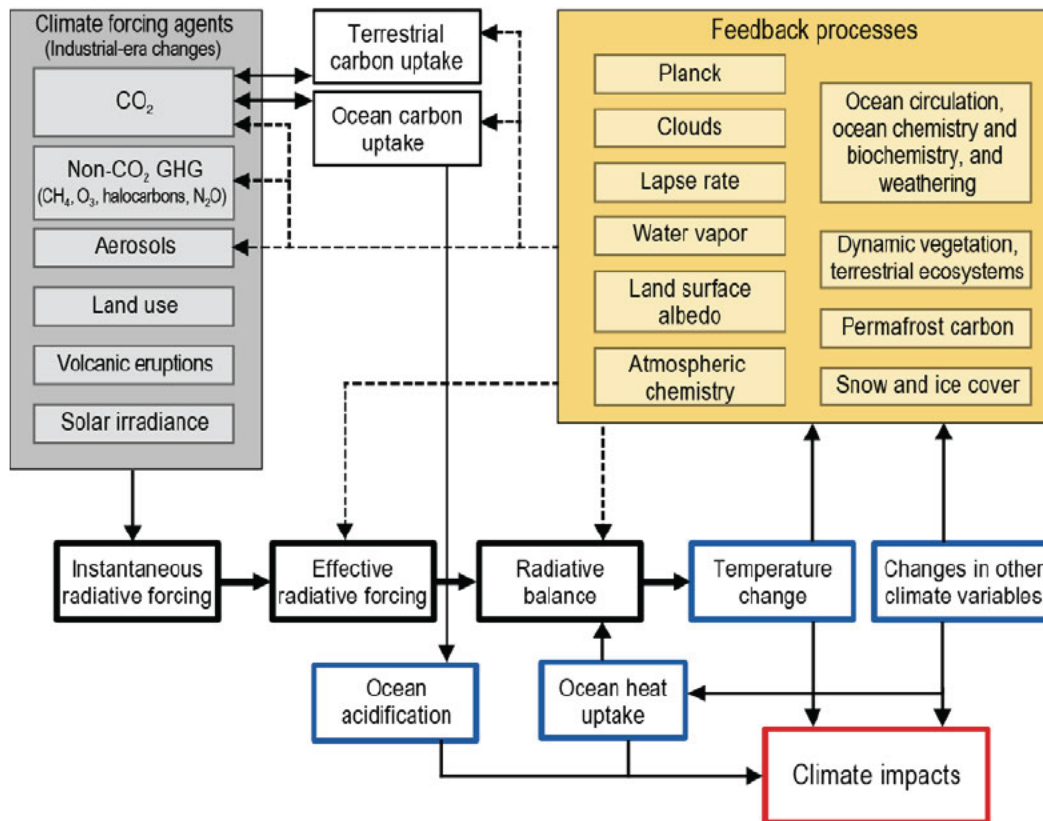
1 **FIGURES**



2
 3 **Figure 2.1:** Global mean energy budget of the Earth under present-day climate conditions.
 4 Numbers state magnitudes of the individual energy fluxes in watts per square meter (W/m^2)
 5 averaged over Earth’s surface, adjusted within their uncertainty ranges to balance the energy
 6 budgets of the atmosphere and the surface. Numbers in parentheses attached to the energy fluxes
 7 cover the range of values in line with observational constraints. Fluxes shown include those
 8 resulting from feedbacks. Note the net imbalance of $0.6 W/m^2$ in the global mean energy budget.
 9 The observational constraints are largely provided by satellite-based observations, which have
 10 directly measured solar and infrared fluxes at the top of the atmosphere over nearly the whole
 11 globe since 1984 (Barkstrom 1984; Smith et al. 1994). More advanced satellite-based
 12 measurements focusing on the role of clouds in Earth’s radiative fluxes have been available since
 13 1998 (Wielicki et al. 1995, 1996). Top of Atmosphere (TOA) reflected solar values given here
 14 are based on observations 2001–2010; TOA outgoing longwave is based on 2005–2010
 15 observations. (Figure source: Hartmann et al. 2013 Figure 2-11; © IPCC, used with permission).

16

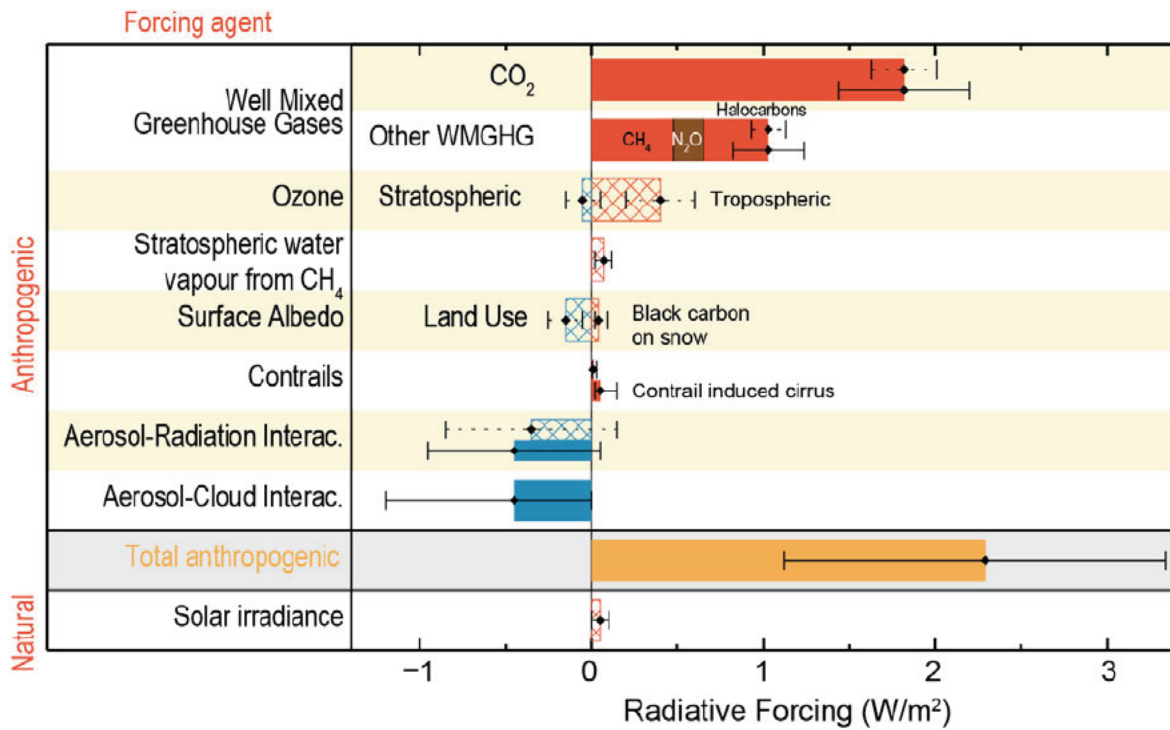
Simplified Conceptual Framework of the Climate System



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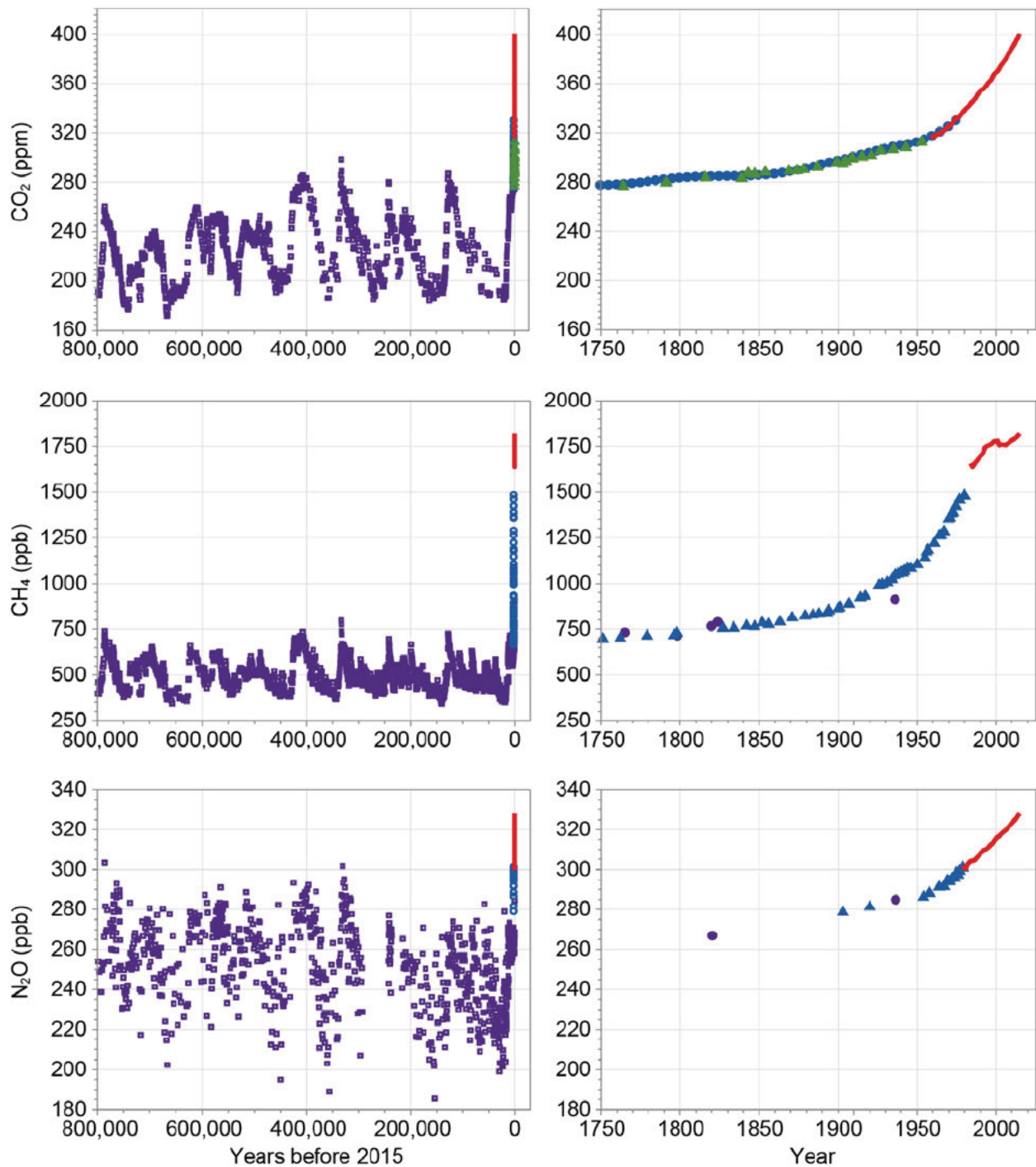
Figure 2.2: Simplified conceptual modeling framework for the climate system as implemented in many climate models (Ch. 4: Projections). Modeling components include forcing agents, feedback processes, carbon uptake processes, and radiative forcing and balance. The lines indicate physical interconnections (solid lines) and feedback pathways (dashed lines). Principal changes (blue boxes) lead to climate impacts (red box) and feedbacks. (Figure source: adapted from Knutti and Rugenstein 2015).

Radiative Forcing of Climate Between 1750 and 2011



1
 2 **Figure 2.3:** Bar chart for radiative forcing (RF; hatched) and effective radiative forcing (ERF;
 3 solid) for the period 1750–2011, where the total ERF is derived from the Intergovernmental
 4 Panel on Climate Change’s Fifth Assessment Report. Uncertainties (5% to 95% confidence
 5 range) are given for RF (dotted lines) and ERF (solid lines). Volcanic forcing is not shown
 6 because this forcing is intermittent, exerting forcing over only a few years for eruptions during
 7 the industrial era; the net forcing over the industrial era is negligible. (Figure source: Myhre et al.
 8 2013 Figure 8-15; © IPCC, used with permission).

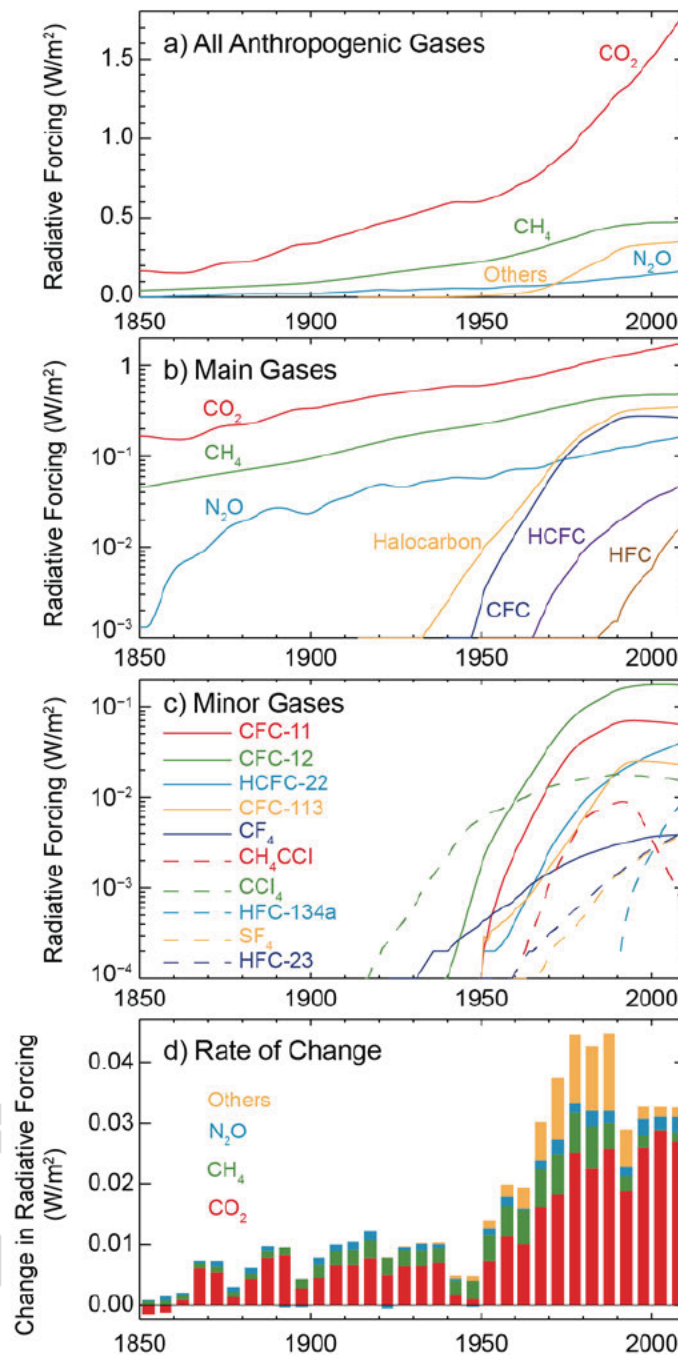
9



1

2 **Figure 2.4:** Atmospheric concentrations of CO₂ (top), CH₄ (middle), and N₂O (bottom) over the
 3 last 800,000 years (left panels) and for 1750–2015 (right panels). Measurements are shown from
 4 ice cores (symbols with different colors for different studies) and for direct atmospheric
 5 measurements (red lines). (Adapted from IPCC [2007], Figure SPM.1, © IPCC, used with
 6 permission; data are from [https://www.epa.gov/climate-indicators/climate-change-indicators-](https://www.epa.gov/climate-indicators/climate-change-indicators-atmospheric-concentrations-greenhouse-gases)
 7 [atmospheric-concentrations-greenhouse-gases](https://www.epa.gov/climate-indicators/climate-change-indicators-atmospheric-concentrations-greenhouse-gases)).

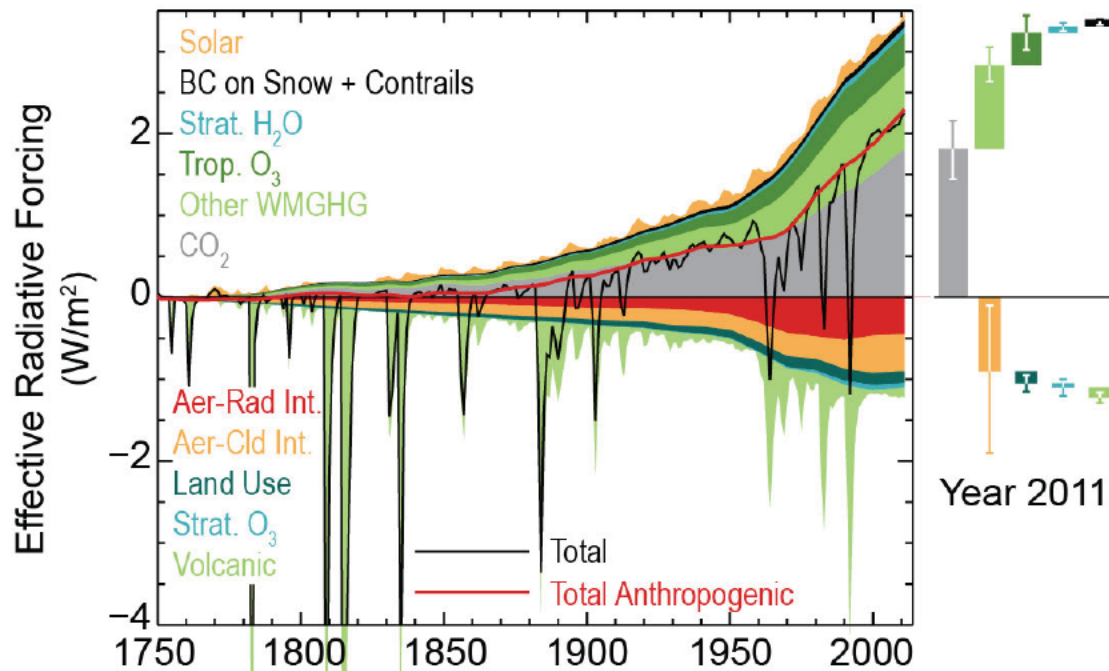
Radiative Forcing of Well-mixed Greenhouse Gases



1

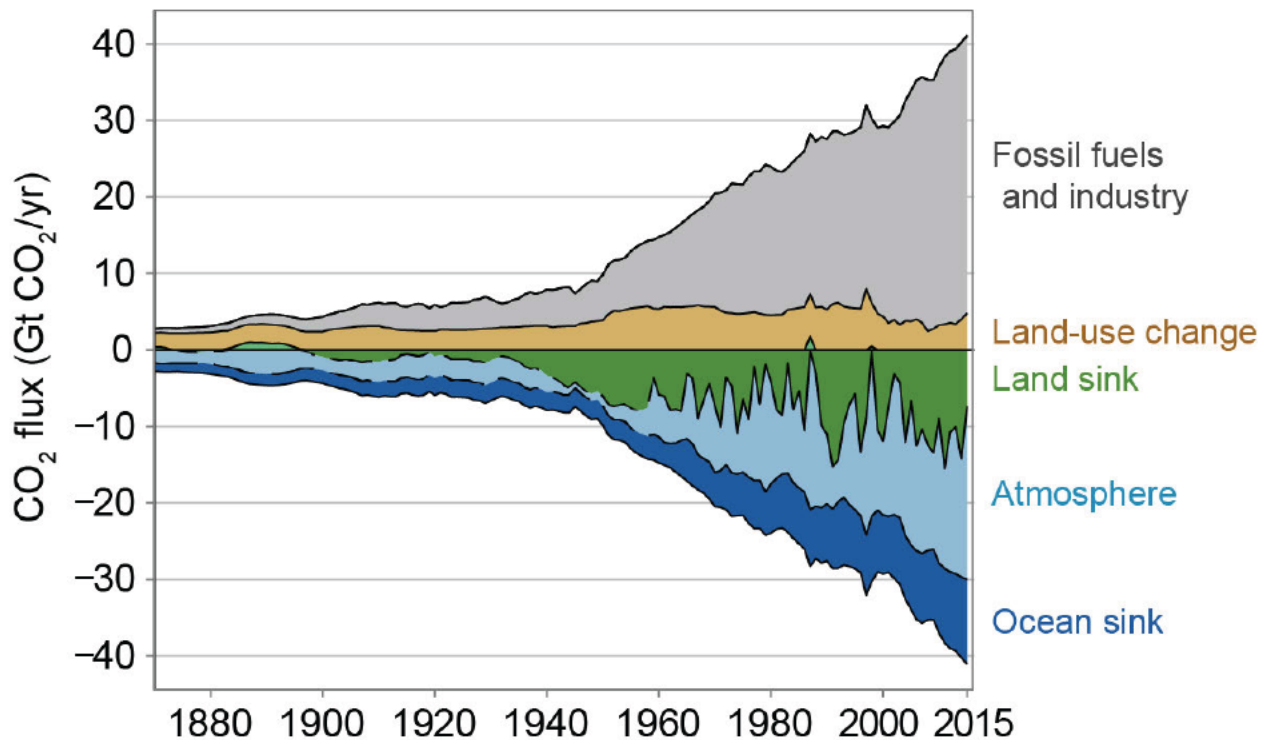
2 **Figure 2.5:** (a) Radiative forcing (RF) from the major WMGHGs and groups of halocarbons
 3 (Others) from 1850 to 2011; (b) the data in (a) with a logarithmic scale; (c) RFs from the minor
 4 WMGHGs from 1850 to 2011 (logarithmic scale); (d) the annual rate of change ($[W/m^2]/year$) in
 5 forcing from the major WMGHGs and halocarbons from 1850 to 2011. (Figure source: Myhre et
 6 al. 2013, Figure 8-06; © IPCC, used with permission).

Time Evolution of Forcings



1
 2 **Figure 2.6:** Changes in effective radiative forcing across the industrial era for anthropogenic and
 3 natural forcing mechanisms. Also shown are the sum of all forcings (Total; black line) and the
 4 sum of anthropogenic forcings (Total Anthropogenic; red line). Forcing due to changes in
 5 surface albedo through black carbon in snow (“BC on snow”) and forcing by contrails are
 6 grouped together in the plot. Bars with the forcing and uncertainty ranges (5% to 95%
 7 confidence range) at present (as of 2011) are given on the right side of the figure. For aerosols,
 8 the sum of ERF from aerosol–radiation interaction (“Aer–Rad Int.”) and aerosol–cloud (“Aer–
 9 Cld Int.”) are shown as a single orange bar to the right. The uncertainty ranges are for the change
 10 between 1750 and 2011 (Table 8.6). For aerosols, only the uncertainty in the total aerosol ERF is
 11 given, as noted above. For several of the forcing agents the relative uncertainty may be larger for
 12 certain time periods compared to present. See the Intergovernmental Panel on Climate Change
 13 Fifth Assessment Report (IPCC AR5) Supplementary Material Table 8.SM.8 (Myhre et al. 2013)
 14 for further information on the forcing time evolutions. Forcing numbers are provided in Annex II
 15 of IPCC AR5. The total anthropogenic forcing was 0.57 (0.29 to 0.85) W/m^2 in 1950, 1.25 (0.64
 16 to 1.86) W/m^2 in 1980, and 2.29 (1.13 to 3.33) W/m^2 in 2011. (Figure source: Myhre et al. 2013,
 17 Figure 8-18; © IPCC, used with permission).

18



1

2 **Figure 2.7:** CO₂ sources and sinks (GtCO₂/yr) over the period 1870–2015. The partitioning of
 3 atmospheric emissions among the atmosphere, land, and ocean is shown as equivalent negative
 4 emissions in the lower panel; of these, the land and ocean terms are sinks of atmospheric CO₂.
 5 CO₂ emissions from net land-use changes are mainly from deforestation. The atmospheric CO₂
 6 growth rate is derived from atmospheric observations and ice core data. The ocean CO₂ sink is
 7 derived from a combination of models and observations. The land sink is the residual of the other
 8 terms in a balanced CO₂ budget and represents the sink of anthropogenic CO₂ in natural land
 9 ecosystems. These terms only represent changes since 1750 and do not include natural CO₂
 10 fluxes (for example, from weathering and outgassing from lakes and rivers). (Figure source: Le
 11 Quéré et al. 2016, Figure 3).

12

1 **REFERENCES**

- 2 ACC-MIP, 2017: Atmospheric Chemistry and Climate MIP. WCRP Working Group on Coupled
3 Modeling. [https://www.wcrp-climate.org/modelling-wgcm-mip-catalogue/modelling-wgcm-](https://www.wcrp-climate.org/modelling-wgcm-mip-catalogue/modelling-wgcm-mips-2/226-modelling-wgcm-acc-mip)
4 [mips-2/226-modelling-wgcm-acc-mip](https://www.wcrp-climate.org/modelling-wgcm-mip-catalogue/modelling-wgcm-mips-2/226-modelling-wgcm-acc-mip).
- 5 Allen, M.R. and W.J. Ingram, 2002: Constraints on future changes in climate and the hydrologic
6 cycle. *Nature*, **419**, 224-232. <http://dx.doi.org/10.1038/nature01092>
- 7 Alley, K.E., T.A. Scambos, M.R. Siegfried, and H.A. Fricker, 2016: Impacts of warm water on
8 Antarctic ice shelf stability through basal channel formation. *Nature Geoscience*, **9**, 290-293.
9 <http://dx.doi.org/10.1038/ngeo2675>
- 10 Anav, A., P. Friedlingstein, M. Kidston, L. Bopp, P. Ciais, P. Cox, C. Jones, M. Jung, R.
11 Myneni, and Z. Zhu, 2013: Evaluating the land and ocean components of the global carbon
12 cycle in the CMIP5 earth system models. *Journal of Climate*, **26**, 6801-6843.
13 <http://dx.doi.org/10.1175/jcli-d-12-00417.1>
- 14 Andrews, T., J.M. Gregory, M.J. Webb, and K.E. Taylor, 2012: Forcing, feedbacks and climate
15 sensitivity in CMIP5 coupled atmosphere-ocean climate models. *Geophysical Research*
16 *Letters*, **39**, L09712. <http://dx.doi.org/10.1029/2012GL051607>
- 17 Andronova, N.G., E.V. Rozanov, F. Yang, M.E. Schlesinger, and G.L. Stenchikov, 1999:
18 Radiative forcing by volcanic aerosols from 1850 to 1994. *Journal of Geophysical Research:*
19 *Atmospheres*, **104**, 16807-16826.
- 20 Babu, S.S., M.R. Manoj, K.K. Moorthy, M.M. Gogoi, V.S. Nair, S.K. Kompalli, S.K. Satheesh,
21 K. Niranjana, K. Ramagopal, P.K. Bhuyan, and D. Singh, 2013: Trends in aerosol optical
22 depth over Indian region: Potential causes and impact indicators. *Journal of Geophysical*
23 *Research: Atmospheres*, **118**, 11,794-11,806. <http://dx.doi.org/10.1002/2013JD020507>
- 24 Banerjee, A., A.T. Archibald, A.C. Maycock, P. Telford, N.L. Abraham, X. Yang, P. Braesicke,
25 and J.A. Pyle, 2014: Lightning NO_x, a key chemistry–climate interaction: Impacts of future
26 climate change and consequences for tropospheric oxidising capacity. *Atmospheric*
27 *Chemistry and Physics*, **14**, 9871-9881. <http://dx.doi.org/10.5194/acp-14-9871-2014>
- 28 Barkstrom, B.R., 1984: The Earth Radiation Budget Experiment (ERBE). *Bulletin of the*
29 *American Meteorological Society*, **65**, 1170-1185. [http://dx.doi.org/10.1175/1520-](http://dx.doi.org/10.1175/1520-0477(1984)065<1170:terbe>2.0.co;2)
30 [0477\(1984\)065<1170:terbe>2.0.co;2](http://dx.doi.org/10.1175/1520-0477(1984)065<1170:terbe>2.0.co;2)
- 31 Behrenfeld, M.J., R.T. O'Malley, D.A. Siegel, C.R. McClain, J.L. Sarmiento, G.C. Feldman,
32 A.J. Milligan, P.G. Falkowski, R.M. Letelier, and E.S. Boss, 2006: Climate-driven trends in
33 contemporary ocean productivity. *Nature*, **444**, 752-755.
34 <http://dx.doi.org/10.1038/nature05317>

- 1 Bidigare, R.R., F. Chai, M.R. Landry, R. Lukas, C.C.S. Hannides, S.J. Christensen, D.M. Karl,
2 L. Shi, and Y. Chao, 2009: Subtropical ocean ecosystem structure changes forced by North
3 Pacific climate variations. *Journal of Plankton Research*, **31**, 1131-1139.
4 <http://dx.doi.org/10.1093/plankt/fbp064>
- 5 Bindoff, N.L., P.A. Stott, K.M. AchutaRao, M.R. Allen, N. Gillett, D. Gutzler, K. Hansingo, G.
6 Hegerl, Y. Hu, S. Jain, I.I. Mokhov, J. Overland, J. Perlwitz, R. Sebbari, and X. Zhang, 2013:
7 Detection and attribution of climate change: From global to regional. *Climate Change 2013:*
8 *The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report*
9 *of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M.
10 Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds.
11 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 867–
12 952. <http://www.climatechange2013.org/report/full-report/>
- 13 Boer, G. and B. Yu, 2003: Climate sensitivity and response. *Climate Dynamics*, **20**, 415-429.
14 <http://dx.doi.org/10.1007/s00382-002-0283-3>
- 15 Bolduc, C., M.S. Bourqui, and P. Charbonneau, 2015: A comparison of stratospheric
16 photochemical response to different reconstructions of solar ultraviolet radiative variability.
17 *Journal of Atmospheric and Solar-Terrestrial Physics*, **132**, 22-32.
18 <http://dx.doi.org/10.1016/j.jastp.2015.06.008>
- 19 Bond, T.C., S.J. Doherty, D.W. Fahey, P.M. Forster, T. Berntsen, B.J. DeAngelo, M.G. Flanner,
20 S. Ghan, B. Kärcher, D. Koch, S. Kinne, Y. Kondo, P.K. Quinn, M.C. Sarofim, M.G.
21 Schultz, M. Schulz, C. Venkataraman, H. Zhang, S. Zhang, N. Bellouin, S.K. Guttikunda,
22 P.K. Hopke, M.Z. Jacobson, J.W. Kaiser, Z. Klimont, U. Lohmann, J.P. Schwarz, D.
23 Shindell, T. Storelvmo, S.G. Warren, and C.S. Zender, 2013: Bounding the role of black
24 carbon in the climate system: A scientific assessment. *Journal of Geophysical Research:*
25 *Atmospheres*, **118**, 5380-5552. <http://dx.doi.org/10.1002/jgrd.50171>
- 26 Bony, S., R. Colman, V.M. Kattsov, R.P. Allan, C.S. Bretherton, J.-L. Dufresne, A. Hall, S.
27 Hallegatte, M.M. Holland, W. Ingram, D.A. Randall, B.J. Soden, G. Tselioudis, and M.J.
28 Webb, 2006: How well do we understand and evaluate climate change feedback processes?
29 *Journal of Climate*, **19**, 3445-3482. <http://dx.doi.org/10.1175/JCLI3819.1>
- 30 Boucher, O., D. Randall, P. Artaxo, C. Bretherton, G. Feingold, P. Forster, V.-M. Kerminen, Y.
31 Kondo, H. Liao, U. Lohmann, P. Rasch, S.K. Satheesh, S. Sherwood, B. Stevens, and X.Y.
32 Zhang, 2013: Clouds and aerosols. *Climate Change 2013: The Physical Science Basis.*
33 *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental*
34 *Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J.
35 Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press,
36 Cambridge, United Kingdom and New York, NY, USA, 571–658.
37 <http://www.climatechange2013.org/report/full-report/>

- 1 Boyce, D.G., M.R. Lewis, and B. Worm, 2010: Global phytoplankton decline over the past
2 century. *Nature*, **466**, 591-596. <http://dx.doi.org/10.1038/nature09268>
- 3 Brzostek, E.R., J.B. Fisher, and R.P. Phillips, 2014: Modeling the carbon cost of plant nitrogen
4 acquisition: Mycorrhizal trade-offs and multipath resistance uptake improve predictions of
5 retranslocation. *Journal of Geophysical Research: Biogeosciences*, **119**, 1684-1697.
6 <http://dx.doi.org/10.1002/2014JG002660>
- 7 Burkhardt, U. and B. Kärcher, 2011: Global radiative forcing from contrail cirrus. *Nature*
8 *Climate Change*, **1**, 54-58. <http://dx.doi.org/10.1038/nclimate1068>
- 9 Capotondi, A., M.A. Alexander, N.A. Bond, E.N. Curchitser, and J.D. Scott, 2012: Enhanced
10 upper ocean stratification with climate change in the CMIP3 models. *Journal of Geophysical*
11 *Research: Oceans*, **117**, C04031. <http://dx.doi.org/10.1029/2011JC007409>
- 12 Carr, M.-E., M.A.M. Friedrichs, M. Schmeltz, M. Noguchi Aita, D. Antoine, K.R. Arrigo, I.
13 Asanuma, O. Aumont, R. Barber, M. Behrenfeld, R. Bidigare, E.T. Buitenhuis, J. Campbell,
14 A. Ciotti, H. Dierssen, M. Dowell, J. Dunne, W. Esaias, B. Gentili, W. Gregg, S. Groom, N.
15 Hoepffner, J. Ishizaka, T. Kameda, C. Le Quéré, S. Lohrenz, J. Marra, F. Mélin, K. Moore,
16 A. Morel, T.E. Reddy, J. Ryan, M. Scardi, T. Smyth, K. Turpie, G. Tilstone, K. Waters, and
17 Y. Yamanaka, 2006: A comparison of global estimates of marine primary production from
18 ocean color. *Deep Sea Research Part II: Topical Studies in Oceanography*, **53**, 741-770.
19 <http://dx.doi.org/10.1016/j.dsr2.2006.01.028>
- 20 Carslaw, K.S., L.A. Lee, C.L. Reddington, K.J. Pringle, A. Rap, P.M. Forster, G.W. Mann, D.V.
21 Spracklen, M.T. Woodhouse, L.A. Regayre, and J.R. Pierce, 2013: Large contribution of
22 natural aerosols to uncertainty in indirect forcing. *Nature*, **503**, 67-71.
23 <http://dx.doi.org/10.1038/nature12674>
- 24 Chavez, F.P., M. Messié, and J.T. Pennington, 2011: Marine primary production in relation to
25 climate variability and change. *Annual Review of Marine Science*, **3**, 227-260.
26 <http://dx.doi.org/10.1146/annurev.marine.010908.163917>
- 27 Chen, T., W.B. Rossow, and Y. Zhang, 2000: Radiative effects of cloud-type variations. *Journal*
28 *of Climate*, **13**, 264-286. [http://dx.doi.org/10.1175/1520-0442\(2000\)013<0264:reoctv>2.0.co;2](http://dx.doi.org/10.1175/1520-0442(2000)013<0264:reoctv>2.0.co;2)
- 30 Chin, M., T. Diehl, Q. Tan, J.M. Prospero, R.A. Kahn, L.A. Remer, H. Yu, A.M. Sayer, H. Bian,
31 I.V. Geogdzhayev, B.N. Holben, S.G. Howell, B.J. Huebert, N.C. Hsu, D. Kim, T.L.
32 Kucsera, R.C. Levy, M.I. Mishchenko, X. Pan, P.K. Quinn, G.L. Schuster, D.G. Streets, S.A.
33 Strode, O. Torres, and X.P. Zhao, 2014: Multi-decadal aerosol variations from 1980 to 2009:
34 A perspective from observations and a global model. *Atmospheric Chemistry and Physics*,
35 **14**, 3657-3690. <http://dx.doi.org/10.5194/acp-14-3657-2014>

- 1 Chiodo, G., D.R. Marsh, R. Garcia-Herrera, N. Calvo, and J.A. García, 2014: On the detection of
2 the solar signal in the tropical stratosphere. *Atmospheric Chemistry and Physics*, **14**, 5251-
3 5269. <http://dx.doi.org/10.5194/acp-14-5251-2014>
- 4 Ciais, P., C. Sabine, G. Bala, L. Bopp, V. Brovkin, J. Canadell, A. Chhabra, R. DeFries, J.
5 Galloway, M. Heimann, C. Jones, C. Le Quéré, R.B. Myneni, S. Piao, and P. Thornton,
6 2013: Carbon and other biogeochemical cycles. *Climate Change 2013: The Physical Science*
7 *Basis. Contribution of Working Group I to the Fifth Assessment Report of the*
8 *Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M.
9 Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds.
10 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 465–
11 570. <http://www.climatechange2013.org/report/full-report/>
- 12 Clark, P.U., J.D. Shakun, S.A. Marcott, A.C. Mix, M. Eby, S. Kulp, A. Levermann, G.A. Milne,
13 P.L. Pfister, B.D. Santer, D.P. Schrag, S. Solomon, T.F. Stocker, B.H. Strauss, A.J. Weaver,
14 R. Winkelmann, D. Archer, E. Bard, A. Goldner, K. Lambeck, R.T. Pierrehumbert, and G.-
15 K. Plattner, 2016: Consequences of twenty-first-century policy for multi-millennial climate
16 and sea-level change. *Nature Climate Change*, **6**, 360-369.
17 <http://dx.doi.org/10.1038/nclimate2923>
- 18 Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J.
19 Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver, and M. Wehner,
20 2013: Long-term climate change: Projections, commitments and irreversibility. *Climate*
21 *Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth*
22 *Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D.
23 Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and
24 P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New
25 York, NY, USA, 1029–1136. <http://www.climatechange2013.org/report/full-report/>
- 26 Cook, B.I., S.P. Shukla, M.J. Puma, and L.S. Nazarenko, 2015: Irrigation as an historical climate
27 forcing. *Climate Dynamics*, **44**, 1715-1730. <http://dx.doi.org/10.1007/s00382-014-2204-7>
- 28 Crook, J.A. and P.M. Forster, 2011: A balance between radiative forcing and climate feedback in
29 the modeled 20th century temperature response. *Journal of Geophysical Research:*
30 *Atmospheres*, **116**, n/a-n/a. <http://dx.doi.org/10.1029/2011JD015924>
- 31 Davies, J.H. and D.R. Davies, 2010: Earth's surface heat flux. *Solid Earth*, **1**, 5-24.
32 <http://dx.doi.org/10.5194/se-1-5-2010>
- 33 Dentener, F., D. Stevenson, J. Cofala, R. Mechler, M. Amann, P. Bergamaschi, F. Raes, and R.
34 Derwent, 2005: The impact of air pollutant and methane emission controls on tropospheric
35 ozone and radiative forcing: CTM calculations for the period 1990-2030. *Atmospheric*
36 *Chemistry and Physics*, **5**, 1731-1755. <http://dx.doi.org/10.5194/acp-5-1731-2005>

- 1 Dessler, A.E., M.R. Schoeberl, T. Wang, S.M. Davis, K.H. Rosenlof, and J.P. Vernier, 2014:
2 Variations of stratospheric water vapor over the past three decades. *Journal of Geophysical*
3 *Research: Atmospheres*, **119**, 12,588-12,598. <http://dx.doi.org/10.1002/2014JD021712>
- 4 Dhomse, S.S., M.P. Chipperfield, W. Feng, W.T. Ball, Y.C. Unruh, J.D. Haigh, N.A. Krivova,
5 S.K. Solanki, and A.K. Smith, 2013: Stratospheric O₃ changes during 2001–2010: The small
6 role of solar flux variations in a chemical transport model. *Atmospheric Chemistry and*
7 *Physics*, **13**, 10113-10123. <http://dx.doi.org/10.5194/acp-13-10113-2013>
- 8 Dietmüller, S., M. Ponater, and R. Sausen, 2014: Interactive ozone induces a negative feedback
9 in CO₂-driven climate change simulations. *Journal of Geophysical Research: Atmospheres*,
10 **119**, 1796-1805. <http://dx.doi.org/10.1002/2013JD020575>
- 11 Doney, S.C., 2010: The growing human footprint on coastal and open-ocean biogeochemistry.
12 *Science*, **328**, 1512-6. <http://dx.doi.org/10.1126/science.1185198>
- 13 Durack, P.J. and S.E. Wijffels, 2010: Fifty-year trends in global ocean salinities and their
14 relationship to broad-scale warming. *Journal of Climate*, **23**, 4342-4362.
15 <http://dx.doi.org/10.1175/2010jcli3377.1>
- 16 Enderlin, E.M. and G.S. Hamilton, 2014: Estimates of iceberg submarine melting from high-
17 resolution digital elevation models: Application to Sermilik Fjord, East Greenland. *Journal*
18 *of Glaciology*, **60**, 1084-1092. <http://dx.doi.org/10.3189/2014JoG14J085>
- 19 Ermolli, I., K. Matthes, T. Dudok de Wit, N.A. Krivova, K. Tourpali, M. Weber, Y.C. Unruh, L.
20 Gray, U. Langematz, P. Pilewskie, E. Rozanov, W. Schmutz, A. Shapiro, S.K. Solanki, and
21 T.N. Woods, 2013: Recent variability of the solar spectral irradiance and its impact on
22 climate modelling. *Atmospheric Chemistry and Physics*, **13**, 3945-3977.
23 <http://dx.doi.org/10.5194/acp-13-3945-2013>
- 24 Falkowski, P.G., M.E. Katz, A.H. Knoll, A. Quigg, J.A. Raven, O. Schofield, and F.J.R. Taylor,
25 2004: The evolution of modern eukaryotic phytoplankton. *Science*, **305**, 354-360.
26 <http://dx.doi.org/10.1126/science.1095964>
- 27 Fernandes, R., H. Zhao, X. Wang, J. Key, X. Qu, and A. Hall, 2009: Controls on Northern
28 Hemisphere snow albedo feedback quantified using satellite Earth observations. *Geophysical*
29 *Research Letters*, **36**, L21702. <http://dx.doi.org/10.1029/2009GL040057>
- 30 Fiore, A.M., V. Naik, and E.M. Leibensperger, 2015: Air quality and climate connections.
31 *Journal of the Air & Waste Management Association*, **65**, 645-686.
32 <http://dx.doi.org/10.1080/10962247.2015.1040526>
- 33 Flanner, M.G., 2009: Integrating anthropogenic heat flux with global climate models.
34 *Geophysical Research Letters*, **36**, L02801. <http://dx.doi.org/10.1029/2008gl036465>

- 1 Flanner, M.G., C.S. Zender, P.G. Hess, N.M. Mahowald, T.H. Painter, V. Ramanathan, and P.J.
2 Rasch, 2009: Springtime warming and reduced snow cover from carbonaceous particles.
3 *Atmospheric Chemistry and Physics*, **9**, 2481-2497. [http://dx.doi.org/10.5194/acp-9-2481-](http://dx.doi.org/10.5194/acp-9-2481-2009)
4 2009
- 5 Flato, G., J. Marotzke, B. Abiodun, P. Braconnot, S.C. Chou, W. Collins, P. Cox, F. Driouech, S.
6 Emori, V. Eyring, C. Forest, P. Gleckler, E. Guilyardi, C. Jakob, V. Kattsov, C. Reason, and
7 M. Rummukainen, 2013: Evaluation of climate models. *Climate Change 2013: The Physical*
8 *Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the*
9 *Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M.
10 Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds.
11 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 741–
12 866. <http://www.climatechange2013.org/report/full-report/>
- 13 Floyd, L.E., J.W. Cook, L.C. Herring, and P.C. Crane, 2003: SUSIM'S 11-year observational
14 record of the solar UV irradiance. *Advances in Space Research*, **31**, 2111-2120.
15 [http://dx.doi.org/10.1016/S0273-1177\(03\)00148-0](http://dx.doi.org/10.1016/S0273-1177(03)00148-0)
- 16 Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, J. Haywood, J. Lean,
17 D.C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz, and R. Van Dorland, 2007:
18 Ch. 2: Changes in atmospheric constituents and in radiative forcing. *Climate Change 2007:*
19 *The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment*
20 *Report (AR4) of the Intergovernmental Panel on Climate Change*. Solomon, S., D. Qin, M.
21 Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, Eds. Cambridge
22 University Press, Cambridge, UK.
23 http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2.html
- 24 Fowler, D., M. Coyle, U. Skiba, M.A. Sutton, J.N. Cape, S. Reis, L.J. Sheppard, A. Jenkins, B.
25 Grizzetti, J.N. Galloway, P. Vitousek, A. Leach, A.F. Bouwman, K. Butterbach-Bahl, F.
26 Dentener, D. Stevenson, M. Amann, and M. Voss, 2013: The global nitrogen cycle in the
27 twenty-first century. *Philosophical Transactions of the Royal Society B: Biological Sciences*,
28 **368**, 20130164. <http://dx.doi.org/10.1098/rstb.2013.0164>
- 29 Franks, P.J., M.A. Adams, J.S. Amthor, M.M. Barbour, J.A. Berry, D.S. Ellsworth, G.D.
30 Farquhar, O. Ghannoum, J. Lloyd, N. McDowell, R.J. Norby, D.T. Tissue, and S. von
31 Caemmerer, 2013: Sensitivity of plants to changing atmospheric CO₂ concentration: From
32 the geological past to the next century. *New Phytologist*, **197**, 1077-1094.
33 <http://dx.doi.org/10.1111/nph.12104>
- 34 Friedlingstein, P., P. Cox, R. Betts, L. Bopp, W.v. Bloh, V. Brovkin, P. Cadule, S. Doney, M.
35 Eby, I. Fung, G. Bala, J. John, C. Jones, F. Joos, T. Kato, M. Kawamiya, W. Knorr, K.
36 Lindsay, H.D. Matthews, T. Raddatz, P. Rayner, C. Reick, E. Roeckner, K.-G. Schnitzler, R.
37 Schnur, K. Strassmann, A.J. Weaver, C. Yoshikawa, and N. Zeng, 2006: Climate-carbon

- 1 cycle feedback analysis: Results from the C⁴MIP model intercomparison. *Journal of Climate*,
2 **19**, 3337-3353. <http://dx.doi.org/10.1175/JCLI3800.1>
- 3 Friedlingstein, P., M. Meinshausen, V.K. Arora, C.D. Jones, A. Anav, S.K. Liddicoat, and R.
4 Knutti, 2014: Uncertainties in CMIP5 climate projections due to carbon cycle feedbacks.
5 *Journal of Climate*, **27**, 511-526. <http://dx.doi.org/10.1175/JCLI-D-12-00579.1>
- 6 Fröhlich, C. and J. Lean, 2004: Solar radiative output and its variability: Evidence and
7 mechanisms. *The Astronomy and Astrophysics Review*, **12**, 273-320.
8 <http://dx.doi.org/10.1007/s00159-004-0024-1>
- 9 Frölicher, T.L., K.B. Rodgers, C.A. Stock, and W.W.L. Cheung, 2016: Sources of uncertainties
10 in 21st century projections of potential ocean ecosystem stressors. *Global Biogeochemical*
11 *Cycles*, **30**, 1224-1243. <http://dx.doi.org/10.1002/2015GB005338>
- 12 Fu, W., J.T. Randerson, and J.K. Moore, 2016: Climate change impacts on net primary
13 production (NPP) and export production (EP) regulated by increasing stratification and
14 phytoplankton community structure in the CMIP5 models. *Biogeosciences*, **13**, 5151-5170.
15 <http://dx.doi.org/10.5194/bg-13-5151-2016>
- 16 Gao, F.-L., L.-R. Tao, G.-M. Cui, J.-L. Xu, and T.-C. Hua, 2015: The influence of solar spectral
17 variations on global radiative balance. *Advances in Space Research*, **55**, 682-687.
18 <http://dx.doi.org/10.1016/j.asr.2014.10.028>
- 19 Gelderloos, R., F. Straneo, and C.A. Katsman, 2012: Mechanisms behind the temporary
20 shutdown of deep convection in the Labrador Sea: Lessons from the great salinity anomaly
21 years 1968–71. *Journal of Climate*, **25**, 6743-6755. <http://dx.doi.org/10.1175/jcli-d-11-00549.1>
- 23 Gerlach, T., 2011: Volcanic versus anthropogenic carbon dioxide. *Eos, Transactions, American*
24 *Geophysical Union*, **92**, 201-202. <http://dx.doi.org/10.1029/2011EO240001>
- 25 Gillett, N.P., M.F. Wehner, S.F.B. Tett, and A.J. Weaver, 2004: Testing the linearity of the
26 response to combined greenhouse gas and sulfate aerosol forcing. *Geophysical Research*
27 *Letters*, **31**, L14201. <http://dx.doi.org/10.1029/2004GL020111>
- 28 González-Eguino, M. and M.B. Neumann, 2016: Significant implications of permafrost thawing
29 for climate change control. *Climatic Change*, **136**, 381-388.
30 <http://dx.doi.org/10.1007/s10584-016-1666-5>
- 31 Good, P., J.M. Gregory, J.A. Lowe, and T. Andrews, 2013: Abrupt CO₂ experiments as tools for
32 predicting and understanding CMIP5 representative concentration pathway projections.
33 *Climate Dynamics*, **40**, 1041-1053. <http://dx.doi.org/10.1007/s00382-012-1410-4>

- 1 Gray, L.J., J. Beer, M. Geller, J.D. Haigh, M. Lockwood, K. Matthes, U. Cubasch, D. Fleitmann,
2 G. Harrison, L. Hood, J. Luterbacher, G.A. Meehl, D. Shindell, B. van Geel, and W. White,
3 2010: Solar influences on climate. *Reviews of Geophysics*, **48**, RG4001.
4 <http://dx.doi.org/10.1029/2009RG000282>
- 5 Hall, A., 2004: The role of surface albedo feedback in climate. *Journal of Climate*, **17**, 1550-
6 1568. [http://dx.doi.org/10.1175/1520-0442\(2004\)017<1550:TROSAF>2.0.CO;2](http://dx.doi.org/10.1175/1520-0442(2004)017<1550:TROSAF>2.0.CO;2)
- 7 Hall, A. and X. Qu, 2006: Using the current seasonal cycle to constrain snow albedo feedback in
8 future climate change. *Geophysical Research Letters*, **33**, L03502.
9 <http://dx.doi.org/10.1029/2005GL025127>
- 10 Han, Z., J. Li, W. Guo, Z. Xiong, and W. Zhang, 2013: A study of dust radiative feedback on
11 dust cycle and meteorology over East Asia by a coupled regional climate-chemistry-aerosol
12 model. *Atmospheric Environment*, **68**, 54-63.
13 <http://dx.doi.org/10.1016/j.atmosenv.2012.11.032>
- 14 Hansen, J. and L. Nazarenko, 2004: Soot climate forcing via snow and ice albedos. *Proceedings*
15 *of the National Academy of Sciences of the United States of America*, **101**, 423-428.
16 <http://dx.doi.org/10.1073/pnas.2237157100>
- 17 Hartmann, D.L., M.E. Ockert-Bell, and M.L. Michelsen, 1992: The effect of cloud type on
18 Earth's energy balance: Global analysis. *Journal of Climate*, **5**, 1281-1304.
19 [http://dx.doi.org/10.1175/1520-0442\(1992\)005<1281:teocto>2.0.co;2](http://dx.doi.org/10.1175/1520-0442(1992)005<1281:teocto>2.0.co;2)
- 20 Hartmann, D.L., A.M.G. Klein Tank, M. Rusticucci, L.V. Alexander, S. Brönnimann, Y.
21 Charabi, F.J. Dentener, E.J. Dlugokencky, D.R. Easterling, A. Kaplan, B.J. Soden, P.W.
22 Thorne, M. Wild, and P.M. Zhai, 2013: Observations: Atmosphere and surface. *Climate*
23 *Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth*
24 *Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D.
25 Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and
26 P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New
27 York, NY, USA, 159–254. <http://www.climatechange2013.org/report/full-report/>
- 28 Hauglustaine, D.A., J. Lathière, S. Szopa, and G.A. Folberth, 2005: Future tropospheric ozone
29 simulated with a climate-chemistry-biosphere model. *Geophysical Research Letters*, **32**,
30 L24807. <http://dx.doi.org/10.1029/2005GL024031>
- 31 Hegglin, M.I., D.A. Plummer, T.G. Shepherd, J.F. Scinocca, J. Anderson, L. Froidevaux, B.
32 Funke, D. Hurst, A. Rozanov, J. Urban, T. von Clarmann, K.A. Walker, H.J. Wang, S.
33 Tegtmeier, and K. Weigel, 2014: Vertical structure of stratospheric water vapour trends
34 derived from merged satellite data. *Nature Geoscience*, **7**, 768-776.
35 <http://dx.doi.org/10.1038/ngeo2236>

- 1 Held, I.M. and B.J. Soden, 2000: Water vapor feedback and global warming. *Annual Review of*
2 *Energy and the Environment*, **25**, 441-475.
3 <http://dx.doi.org/10.1146/annurev.energy.25.1.441>
- 4 Hibbard, K.A., G.A. Meehl, P.M. Cox, and P. Friedlingstein, 2007: A strategy for climate change
5 stabilization experiments. *Eos, Transactions, American Geophysical Union*, **88**, 217-221.
6 <http://dx.doi.org/10.1029/2007EO200002>
- 7 Holland, D.M., R.H. Thomas, B. de Young, M.H. Ribergaard, and B. Lyberth, 2008:
8 Acceleration of Jakobshavn Isbrae triggered by warm subsurface ocean waters. *Nature*
9 *Geoscience*, **1**, 659-664. <http://dx.doi.org/10.1038/ngeo316>
- 10 Holmes, C.D., M.J. Prather, O.A. Søvde, and G. Myhre, 2013: Future methane, hydroxyl, and
11 their uncertainties: Key climate and emission parameters for future predictions. *Atmospheric*
12 *Chemistry and Physics*, **13**, 285-302. <http://dx.doi.org/10.5194/acp-13-285-2013>
- 13 Hsu, N.C., R. Gautam, A.M. Sayer, C. Bettenhausen, C. Li, M.J. Jeong, S.C. Tsay, and B.N.
14 Holben, 2012: Global and regional trends of aerosol optical depth over land and ocean using
15 SeaWiFS measurements from 1997 to 2010. *Atmospheric Chemistry and Physics*, **12**, 8037-
16 8053. <http://dx.doi.org/10.5194/acp-12-8037-2012>
- 17 IPCC, 2007: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group*
18 *I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*.
19 Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L.
20 Miller, Eds. Cambridge University Press, Cambridge. U.K, New York, NY, USA, 996 pp.
21 http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1
22 [_report_the_physical_science_basis.htm](http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1_report_the_physical_science_basis.htm)
- 23 IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group*
24 *I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.
25 Cambridge University Press, Cambridge, UK and New York, NY, 1535 pp.
26 <http://www.climatechange2013.org/report/>
- 27 Isaksen, I., T. Berntsen, S. Dalsøren, K. Eleftheratos, Y. Orsolini, B. Rognerud, F. Stordal, O.
28 Søvde, C. Zerefos, and C. Holmes, 2014: Atmospheric ozone and methane in a changing
29 climate. *Atmosphere*, **5**, 518. <http://dx.doi.org/10.3390/atmos5030518>
- 30 Jacobson, M.Z., 2004: Climate response of fossil fuel and biofuel soot, accounting for soot's
31 feedback to snow and sea ice albedo and emissivity. *Journal of Geophysical Research*, **109**,
32 D21201. <http://dx.doi.org/10.1029/2004JD004945>
- 33 Jiang, X., S.J. Eichelberger, D.L. Hartmann, R. Shia, and Y.L. Yung, 2007: Influence of doubled
34 CO₂ on ozone via changes in the Brewer–Dobson circulation. *Journal of the Atmospheric*
35 *Sciences*, **64**, 2751-2755. <http://dx.doi.org/10.1175/jas3969.1>

- 1 Jiao, C., M.G. Flanner, Y. Balkanski, S.E. Bauer, N. Bellouin, T.K. Berntsen, H. Bian, K.S.
2 Carslaw, M. Chin, N. De Luca, T. Diehl, S.J. Ghan, T. Iversen, A. Kirkevåg, D. Koch, X.
3 Liu, G.W. Mann, J.E. Penner, G. Pitari, M. Schulz, Ø. Seland, R.B. Skeie, S.D. Steenrod, P.
4 Stier, T. Takemura, K. Tsigaridis, T. van Noije, Y. Yun, and K. Zhang, 2014: An AeroCom
5 assessment of black carbon in Arctic snow and sea ice. *Atmospheric Chemistry and Physics*,
6 **14**, 2399-2417. <http://dx.doi.org/10.5194/acp-14-2399-2014>
- 7 Jin, X., N. Gruber, J.P. Dunne, J.L. Sarmiento, and R.A. Armstrong, 2006: Diagnosing the
8 contribution of phytoplankton functional groups to the production and export of particulate
9 organic carbon, CaCO₃, and opal from global nutrient and alkalinity distributions. *Global*
10 *Biogeochemical Cycles*, **20**, GB2015. <http://dx.doi.org/10.1029/2005GB002532>
- 11 John, J.G., A.M. Fiore, V. Naik, L.W. Horowitz, and J.P. Dunne, 2012: Climate versus emission
12 drivers of methane lifetime against loss by tropospheric OH from 1860–2100. *Atmospheric*
13 *Chemistry and Physics*, **12**, 12021-12036. <http://dx.doi.org/10.5194/acp-12-12021-2012>
- 14 Johnson, G.C., J.M. Lyman, T. Boyer, C.M. Domingues, M. Ishii, R. Killick, D. Monselesan,
15 and S.E. Wijffels, 2016: [Global Oceans] Ocean heat content [in “State of the Climate in
16 2015”]. *Bulletin of the American Meteorological Society*, **97**, S66-S70.
17 <http://dx.doi.org/10.1175/2016BAMSStateoftheClimate.1>
- 18 Jones, A., J.M. Haywood, and O. Boucher, 2007: Aerosol forcing, climate response and climate
19 sensitivity in the Hadley Centre climate model. *Journal of Geophysical Research*, **112**,
20 D20211. <http://dx.doi.org/10.1029/2007JD008688>
- 21 Joughin, I., R.B. Alley, and D.M. Holland, 2012: Ice-sheet response to oceanic forcing. *Science*,
22 **338**, 1172-1176. <http://dx.doi.org/10.1126/science.1226481>
- 23 Ju, J. and J.G. Masek, 2016: The vegetation greenness trend in Canada and US Alaska from
24 1984–2012 Landsat data. *Remote Sensing of Environment*, **176**, 1-16.
25 <http://dx.doi.org/10.1016/j.rse.2016.01.001>
- 26 Kay, J.E. and A. Gettelman, 2009: Cloud influence on and response to seasonal Arctic sea ice
27 loss. *Journal of Geophysical Research*, **114**, D18204.
28 <http://dx.doi.org/10.1029/2009JD011773>
- 29 Kay, J.E. and T. L'Ecuyer, 2013: Observational constraints on Arctic Ocean clouds and radiative
30 fluxes during the early 21st century. *Journal of Geophysical Research: Atmospheres*, **118**,
31 7219-7236. <http://dx.doi.org/10.1002/jgrd.50489>
- 32 Kay, J.E., K. Raeder, A. Gettelman, and J. Anderson, 2011: The boundary layer response to
33 recent Arctic sea ice loss and implications for high-latitude climate feedbacks. *Journal of*
34 *Climate*, **24**, 428-447. <http://dx.doi.org/10.1175/2010JCLI3651.1>

- 1 Klocke, D., J. Quaas, and B. Stevens, 2013: Assessment of different metrics for physical climate
2 feedbacks. *Climate Dynamics*, **41**, 1173-1185. <http://dx.doi.org/10.1007/s00382-013-1757-1>
- 3 Knutti, R. and G.C. Hegerl, 2008: The equilibrium sensitivity of the Earth's temperature to
4 radiation changes. *Nature Geoscience*, **1**, 735-743. <http://dx.doi.org/10.1038/ngeo337>
- 5 Knutti, R. and M.A.A. Rugenstein, 2015: Feedbacks, climate sensitivity and the limits of linear
6 models. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and*
7 *Engineering Sciences*, **373**. <http://dx.doi.org/10.1098/rsta.2015.0146>
- 8 Koffi, B., M. Schulz, F.-M. Bréon, F. Dentener, B.M. Steensen, J. Griesfeller, D. Winker, Y.
9 Balkanski, S.E. Bauer, N. Bellouin, T. Berntsen, H. Bian, M. Chin, T. Diehl, R. Easter, S.
10 Ghan, D.A. Hauglustaine, T. Iversen, A. Kirkevåg, X. Liu, U. Lohmann, G. Myhre, P. Rasch,
11 Ø. Seland, R.B. Skeie, S.D. Steenrod, P. Stier, J. Tackett, T. Takemura, K. Tsigaridis, M.R.
12 Vuolo, J. Yoon, and K. Zhang, 2016: Evaluation of the aerosol vertical distribution in global
13 aerosol models through comparison against CALIOP measurements: AeroCom phase II
14 results. *Journal of Geophysical Research: Atmospheres*, **121**, 7254-7283.
15 <http://dx.doi.org/10.1002/2015JD024639>
- 16 Kopp, G., 2014: An assessment of the solar irradiance record for climate studies. *Journal of*
17 *Space Weather and Space Climate*, **4**, A14. <http://dx.doi.org/10.1051/swsc/2014012>
- 18 Kopp, G. and J.L. Lean, 2011: A new, lower value of total solar irradiance: Evidence and climate
19 significance. *Geophysical Research Letters*, **38**, L01706.
20 <http://dx.doi.org/10.1029/2010GL045777>
- 21 Kopp, G., N. Krivova, C.J. Wu, and J. Lean, 2016: The impact of the revised sunspot record on
22 solar irradiance reconstructions. *Solar Physics*, **291**, 1965-1965.
23 <http://dx.doi.org/10.1007/s11207-016-0853-x>
- 24 Kostov, Y., K.C. Armour, and J. Marshall, 2014: Impact of the Atlantic meridional overturning
25 circulation on ocean heat storage and transient climate change. *Geophysical Research*
26 *Letters*, **41**, 2108-2116. <http://dx.doi.org/10.1002/2013GL058998>
- 27 Koven, C.D., E.A.G. Schuur, C. Schädel, T.J. Bohn, E.J. Burke, G. Chen, X. Chen, P. Ciais, G.
28 Grosse, J.W. Harden, D.J. Hayes, G. Hugelius, E.E. Jafarov, G. Krinner, P. Kuhry, D.M.
29 Lawrence, A.H. MacDougall, S.S. Marchenko, A.D. McGuire, S.M. Natali, D.J. Nicolsky, D.
30 Olefeldt, S. Peng, V.E. Romanovsky, K.M. Schaefer, J. Strauss, C.C. Treat, and M. Turetsky,
31 2015a: A simplified, data-constrained approach to estimate the permafrost carbon-climate
32 feedback. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and*
33 *Engineering Sciences*, **373**. <http://dx.doi.org/10.1098/rsta.2014.0423>
- 34 Koven, C.D., D.M. Lawrence, and W.J. Riley, 2015b: Permafrost carbon-climate feedback is
35 sensitive to deep soil carbon decomposability but not deep soil nitrogen dynamics.

- 1 *Proceedings of the National Academy of Sciences*, **112**, 3752-3757.
2 <http://dx.doi.org/10.1073/pnas.1415123112>
- 3 Krishna Moorthy, K., S. Suresh Babu, M.R. Manoj, and S.K. Satheesh, 2013: Buildup of
4 aerosols over the Indian Region. *Geophysical Research Letters*, **40**, 1011-1014.
5 <http://dx.doi.org/10.1002/grl.50165>
- 6 Krissansen-Totton, J. and R. Davies, 2013: Investigation of cosmic ray–cloud connections using
7 MISR. *Geophysical Research Letters*, **40**, 5240-5245. <http://dx.doi.org/10.1002/grl.50996>
- 8 Kühn, T., A.I. Partanen, A. Laakso, Z. Lu, T. Bergman, S. Mikkonen, H. Kokkola, H. Korhonen,
9 P. Räisänen, D.G. Streets, S. Romakkaniemi, and A. Laaksonen, 2014: Climate impacts of
10 changing aerosol emissions since 1996. *Geophysical Research Letters*, **41**, 4711-4718.
11 <http://dx.doi.org/10.1002/2014GL060349>
- 12 Lacis, A.A., G.A. Schmidt, D. Rind, and R.A. Ruedy, 2010: Atmospheric CO₂: Principal control
13 knob governing Earth's temperature. *Science*, **330**, 356-359.
14 <http://dx.doi.org/10.1126/science.1190653>
- 15 Langmann, B., 2014: On the role of climate forcing by volcanic sulphate and volcanic ash.
16 *Advances in Meteorology*, **2014**, 17. <http://dx.doi.org/10.1155/2014/340123>
- 17 Laufkötter, C., M. Vogt, N. Gruber, M. Aita-Noguchi, O. Aumont, L. Bopp, E. Buitenhuis, S.C.
18 Doney, J. Dunne, T. Hashioka, J. Hauck, T. Hirata, J. John, C. Le Quéré, I.D. Lima, H.
19 Nakano, R. Seferian, I. Totterdell, M. Vichi, and C. Völker, 2015: Drivers and uncertainties
20 of future global marine primary production in marine ecosystem models. *Biogeosciences*, **12**,
21 6955-6984. <http://dx.doi.org/10.5194/bg-12-6955-2015>
- 22 Le Quéré, C., R.M. Andrew, J.G. Canadell, S. Sitch, J.I. Korsbakken, G.P. Peters, A.C. Manning,
23 T.A. Boden, P.P. Tans, R.A. Houghton, R.F. Keeling, S. Alin, O.D. Andrews, P. Anthoni, L.
24 Barbero, L. Bopp, F. Chevallier, L.P. Chini, P. Ciais, K. Currie, C. Delire, S.C. Doney, P.
25 Friedlingstein, T. Gkritzalis, I. Harris, J. Hauck, V. Haverd, M. Hoppema, K. Klein
26 Goldewijk, A.K. Jain, E. Kato, A. Körtzinger, P. Landschützer, N. Lefèvre, A. Lenton, S.
27 Lienert, D. Lombardozzi, J.R. Melton, N. Metzl, F. Millero, P.M.S. Monteiro, D.R. Munro,
28 J.E.M.S. Nabel, S.I. Nakaoka, K. O'Brien, A. Olsen, A.M. Omar, T. Ono, D. Pierrot, B.
29 Poulter, C. Rödenbeck, J. Salisbury, U. Schuster, J. Schwinger, R. Séférian, I. Skjelvan, B.D.
30 Stocker, A.J. Sutton, T. Takahashi, H. Tian, B. Tilbrook, I.T. van der Laan-Luijkx, G.R. van
31 der Werf, N. Viovy, A.P. Walker, A.J. Wiltshire, and S. Zaehle, 2016: Global carbon budget
32 2016. *Earth System Science Data*, **8**, 605-649. <http://dx.doi.org/10.5194/essd-8-605-2016>
- 33 le Texier, H., S. Solomon, and R.R. Garcia, 1988: The role of molecular hydrogen and methane
34 oxidation in the water vapour budget of the stratosphere. *Quarterly Journal of the Royal
35 Meteorological Society*, **114**, 281-295. <http://dx.doi.org/10.1002/qj.49711448002>

- 1 Lean, J., 1997: The sun's variable radiation and its relevance for earth. *Annual Review of*
2 *Astronomy and Astrophysics*, **35**, 33-67. <http://dx.doi.org/10.1146/annurev.astro.35.1.33>
- 3 Leibensperger, E.M., L.J. Mickley, D.J. Jacob, W.T. Chen, J.H. Seinfeld, A. Nenes, P.J. Adams,
4 D.G. Streets, N. Kumar, and D. Rind, 2012: Climatic effects of 1950-2050 changes in US
5 anthropogenic aerosols – Part 1: Aerosol trends and radiative forcing. *Atmospheric Chemistry*
6 *and Physics* **12**, 3333-3348. <http://dx.doi.org/10.5194/acp-12-3333-2012>
- 7 Lelieveld, J. and P.J. Crutzen, 1992: Indirect chemical effects of methane on climate warming.
8 *Nature*, **355**, 339-342. <http://dx.doi.org/10.1038/355339a0>
- 9 Li, F., J. Austin, and J. Wilson, 2008: The strength of the Brewer–Dobson circulation in a
10 changing climate: Coupled chemistry–climate model simulations. *Journal of Climate*, **21**, 40-
11 57. <http://dx.doi.org/10.1175/2007jcli1663.1>
- 12 Li, J., Z. Han, and Z. Xie, 2013: Model analysis of long-term trends of aerosol concentrations
13 and direct radiative forcings over East Asia. *Tellus B: Chemical and Physical Meteorology*,
14 **65**, 20410. <http://dx.doi.org/10.3402/tellusb.v65i0.20410>
- 15 Liao, H., Y. Zhang, W.-T. Chen, F. Raes, and J.H. Seinfeld, 2009: Effect of chemistry-aerosol-
16 climate coupling on predictions of future climate and future levels of tropospheric ozone and
17 aerosols. *Journal of Geophysical Research: Atmospheres*, **114**, D10306.
18 <http://dx.doi.org/10.1029/2008JD010984>
- 19 Liljedahl, A.K., J. Boike, R.P. Daanen, A.N. Fedorov, G.V. Frost, G. Grosse, L.D. Hinzman, Y.
20 Iijma, J.C. Jorgenson, N. Matveyeva, M. Necsoiu, M.K. Reynolds, V.E. Romanovsky, J.
21 Schulla, K.D. Tape, D.A. Walker, C.J. Wilson, H. Yabuki, and D. Zona, 2016: Pan-Arctic
22 ice-wedge degradation in warming permafrost and its influence on tundra hydrology. *Nature*
23 *Geoscience*, **9**, 312-318. <http://dx.doi.org/10.1038/ngeo2674>
- 24 Lockwood, M., 2012: Solar influence on global and regional climates. *Surveys in Geophysics*,
25 **33**, 503-534. <http://dx.doi.org/10.1007/s10712-012-9181-3>
- 26 Loeb, N. G., S. Kato and B. A. Wielicki, 2002: Defining Top-of-the-Atmosphere Flux Reference
27 Level for Earth Radiation Budget Studies, *Journal of Climate*, **15**, 3301-
28 3309, [http://dx.doi.org/10.1175/1520-0442\(2002\)015<3301:DTOTAF>2.0.CO;2](http://dx.doi.org/10.1175/1520-0442(2002)015<3301:DTOTAF>2.0.CO;2)
- 29 Loeb, N.G., B.A. Wielicki, D.R. Doelling, G.L. Smith, D.F. Keyes, S. Kato, N. Manalo-Smith,
30 and T. Wong, 2009: Toward optimal closure of the Earth's top-of-atmosphere radiation
31 budget. *Journal of Climate*, **22**, 748-766. <http://dx.doi.org/10.1175/2008JCLI2637.1>
- 32 Löffler, M., S. Brinkop, and P. Jöckel, 2016: Impact of major volcanic eruptions on stratospheric
33 water vapour. *Atmospheric Chemistry and Physics*, **16**, 6547-6562.
34 <http://dx.doi.org/10.5194/acp-16-6547-2016>

- 1 Lohmann, U. and J. Feichter, 2005: Global indirect aerosol effects: A review. *Atmospheric*
2 *Chemistry and Physics*, **5**, 715-737. <http://dx.doi.org/10.5194/acp-5-715-2005>
- 3 Lynch, P., J.S. Reid, D.L. Westphal, J. Zhang, T.F. Hogan, E.J. Hyer, C.A. Curtis, D.A. Hegg, Y.
4 Shi, J.R. Campbell, J.I. Rubin, W.R. Sessions, F.J. Turk, and A.L. Walker, 2016: An 11-year
5 global gridded aerosol optical thickness reanalysis (v1.0) for atmospheric and climate
6 sciences. *Geoscientific Model Development*, **9**, 1489-1522. [http://dx.doi.org/10.5194/gmd-9-](http://dx.doi.org/10.5194/gmd-9-1489-2016)
7 [1489-2016](http://dx.doi.org/10.5194/gmd-9-1489-2016)
- 8 Mahajan, S., K.J. Evans, J.J. Hack, and J.E. Truesdale, 2013: Linearity of climate response to
9 increases in black carbon aerosols. *Journal of Climate*, **26**, 8223-8237.
10 <http://dx.doi.org/10.1175/JCLI-D-12-00715.1>
- 11 Mao, J., A. Ribes, B. Yan, X. Shi, P.E. Thornton, R. Seferian, P. Ciais, R.B. Myneni, H.
12 Douville, S. Piao, Z. Zhu, R.E. Dickinson, Y. Dai, D.M. Ricciuto, M. Jin, F.M. Hoffman, B.
13 Wang, M. Huang, and X. Lian, 2016: Human-induced greening of the northern extratropical
14 land surface. *Nature Climate Change*, **6**, 959-963. <http://dx.doi.org/10.1038/nclimate3056>
- 15 Mao, K.B., Y. Ma, L. Xia, W.Y. Chen, X.Y. Shen, T.J. He, and T.R. Xu, 2014: Global aerosol
16 change in the last decade: An analysis based on MODIS data. *Atmospheric Environment*, **94**,
17 680-686. <http://dx.doi.org/10.1016/j.atmosenv.2014.04.053>
- 18 Marmer, E., B. Langmann, H. Fagerli, and V. Vestreng, 2007: Direct shortwave radiative forcing
19 of sulfate aerosol over Europe from 1900 to 2000. *Journal of Geophysical Research*, **112**,
20 D23S17. <http://dx.doi.org/10.1029/2006JD008037>
- 21 Masson-Delmotte, V., M. Schulz, A. Abe-Ouchi, J. Beer, A. Ganopolski, J.F. González Rouco,
22 E. Jansen, K. Lambeck, J. Luterbacher, T. Naish, T. Osborn, B. Otto-Bliesner, T. Quinn, R.
23 Ramesh, M. Rojas, X. Shao, and A. Timmermann, 2013: Information from paleoclimate
24 archives. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group*
25 *I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker,
26 T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex,
27 and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New
28 York, NY, USA, 383–464. <http://www.climatechange2013.org/report/full-report/>
- 29 Matthews, H.D., A.J. Weaver, K.J. Meissner, N.P. Gillett, and M. Eby, 2004: Natural and
30 anthropogenic climate change: Incorporating historical land cover change, vegetation
31 dynamics and the global carbon cycle. *Climate Dynamics*, **22**, 461-479.
32 <http://dx.doi.org/10.1007/s00382-004-0392-2>
- 33 McLandress, C., T.G. Shepherd, M.C. Reader, D.A. Plummer, and K.P. Shine, 2014: The climate
34 impact of past changes in halocarbons and CO₂ in the tropical UTLS region. *Journal of*
35 *Climate*, **27**, 8646-8660. <http://dx.doi.org/10.1175/jcli-d-14-00232.1>

- 1 Meehl, G.A., W.M. Washington, C.M. Ammann, J.M. Arblaster, T.M.L. Wigley, and C. Tebaldi,
2 2004: Combinations of natural and anthropogenic forcings in twentieth-century climate.
3 *Journal of Climate*, **17**, 3721-3727. <http://dx.doi.org/10.1175/1520->
4 0442(2004)017<3721:CONAAF>2.0.CO;2
- 5 Melillo, J.M., T.C. Richmond, and G.W. Yohe, eds., 2014: *Climate Change Impacts in the*
6 *United States: The Third National Climate Assessment*. U.S. Global Change Research
7 Program: Washington, D.C., 842 pp. <http://dx.doi.org/10.7930/J0Z31WJ2>
- 8 Morgenstern, O., G. Zeng, N. Luke Abraham, P.J. Telford, P. Braesicke, J.A. Pyle, S.C.
9 Hardiman, F.M. O'Connor, and C.E. Johnson, 2013: Impacts of climate change, ozone
10 recovery, and increasing methane on surface ozone and the tropospheric oxidizing capacity.
11 *Journal of Geophysical Research: Atmospheres*, **118**, 1028-1041.
12 <http://dx.doi.org/10.1029/2012JD018382>
- 13 Morris, G.A., J.E. Rosenfield, M.R. Schoeberl, and C.H. Jackman, 2003: Potential impact of
14 subsonic and supersonic aircraft exhaust on water vapor in the lower stratosphere assessed
15 via a trajectory model. *Journal of Geophysical Research: Atmospheres*, **108**, 4103.
16 <http://dx.doi.org/10.1029/2002JD002614>
- 17 Munk, W. and C. Wunsch, 1998: Abyssal recipes II: Energetics of tidal and wind mixing. *Deep*
18 *Sea Research Part I: Oceanographic Research Papers*, **45**, 1977-2010.
19 [http://dx.doi.org/10.1016/S0967-0637\(98\)00070-3](http://dx.doi.org/10.1016/S0967-0637(98)00070-3)
- 20 Murphy, D.M., J.C. Chow, E.M. Leibensperger, W.C. Malm, M. Pitchford, B.A. Schichtel, J.G.
21 Watson, and W.H. White, 2011: Decreases in elemental carbon and fine particle mass in the
22 United States. *Atmospheric Chemistry and Physics*, **11**, 4679-4686.
23 <http://dx.doi.org/10.5194/acp-11-4679-2011>
- 24 Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestedt, J. Huang, D. Koch, J.-F.
25 Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura, and H.
26 Zhang, 2013: Anthropogenic and natural radiative forcing. *Climate Change 2013: The*
27 *Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of*
28 *the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M.
29 Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds.
30 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 659–
31 740. <http://www.climatechange2013.org/report/full-report/>
- 32 Myhre, G., W. Aas, R. Cherian, W. Collins, G. Faluvegi, M. Flanner, P. Forster, Ø. Hodnebrog,
33 Z. Klimont, M.T. Lund, J. Mülmenstädt, C. Lund Myhre, D. Olivié, M. Prather, J. Quaas,
34 B.H. Samset, J.L. Schnell, M. Schulz, D. Shindell, R.B. Skeie, T. Takemura, and S. Tsyro,
35 2017: Multi-model simulations of aerosol and ozone radiative forcing due to anthropogenic

- 1 emission changes during the period 1990–2015. *Atmospheric Chemistry and Physics*, **17**,
2 2709-2720. <http://dx.doi.org/10.5194/acp-17-2709-2017>
- 3 Naik, V., A. Voulgarakis, A.M. Fiore, L.W. Horowitz, J.F. Lamarque, M. Lin, M.J. Prather, P.J.
4 Young, D. Bergmann, P.J. Cameron-Smith, I. Cionni, W.J. Collins, S.B. Dalsøren, R.
5 Doherty, V. Eyring, G. Faluvegi, G.A. Folberth, B. Josse, Y.H. Lee, I.A. MacKenzie, T.
6 Nagashima, T.P.C. van Noije, D.A. Plummer, M. Righi, S.T. Rumbold, R. Skeie, D.T.
7 Shindell, D.S. Stevenson, S. Strode, K. Sudo, S. Szopa, and G. Zeng, 2013: Preindustrial to
8 present-day changes in tropospheric hydroxyl radical and methane lifetime from the
9 Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP).
10 *Atmospheric Chemistry and Physics*, **13**, 5277-5298. [http://dx.doi.org/10.5194/acp-13-5277-](http://dx.doi.org/10.5194/acp-13-5277-2013)
11 2013
- 12 Nisbet, E.G., E.J. Dlugokencky, M.R. Manning, D. Lowry, R.E. Fisher, J.L. France, S.E. Michel,
13 J.B. Miller, J.W.C. White, B. Vaughn, P. Bousquet, J.A. Pyle, N.J. Warwick, M. Cain, R.
14 Brownlow, G. Zazzeri, M. Lanoisellé, A.C. Manning, E. Gloor, D.E.J. Worthy, E.G. Brunke,
15 C. Labuschagne, E.W. Wolff, and A.L. Ganesan, 2016: Rising atmospheric methane: 2007–
16 2014 growth and isotopic shift. *Global Biogeochemical Cycles*, **30**, 1356-1370.
17 <http://dx.doi.org/10.1002/2016GB005406>
- 18 Nowack, P.J., N. Luke Abraham, A.C. Maycock, P. Braesicke, J.M. Gregory, M.M. Joshi, A.
19 Osprey, and J.A. Pyle, 2015: A large ozone-circulation feedback and its implications for
20 global warming assessments. *Nature Climate Change*, **5**, 41-45.
21 <http://dx.doi.org/10.1038/nclimate2451>
- 22 Otterå, O.H., M. Bentsen, H. Drange, and L. Suo, 2010: External forcing as a metronome for
23 Atlantic multidecadal variability. *Nature Geoscience*, **3**, 688-694.
24 <http://dx.doi.org/10.1038/ngeo955>
- 25 Pacifico, F., G.A. Folberth, C.D. Jones, S.P. Harrison, and W.J. Collins, 2012: Sensitivity of
26 biogenic isoprene emissions to past, present, and future environmental conditions and
27 implications for atmospheric chemistry. *Journal of Geophysical Research*, **117**, D22302.
28 <http://dx.doi.org/10.1029/2012JD018276>
- 29 Passow, U. and C.A. Carlson, 2012: The biological pump in a high CO₂ world. *Marine Ecology*
30 *Progress Series*, **470**, 249-271. <http://dx.doi.org/10.3354/meps09985>
- 31 Philipona, R., K. Behrens, and C. Ruckstuhl, 2009: How declining aerosols and rising
32 greenhouse gases forced rapid warming in Europe since the 1980s. *Geophysical Research*
33 *Letters*, **36**, L02806. <http://dx.doi.org/10.1029/2008GL036350>
- 34 Pietikäinen, J.P., K. Kupiainen, Z. Klimont, R. Makkonen, H. Korhonen, R. Karinkanta, A.P.
35 Hyvärinen, N. Karvosenoja, A. Laaksonen, H. Lihavainen, and V.M. Kerminen, 2015:

- 1 Impacts of emission reductions on aerosol radiative effects. *Atmospheric Chemistry and*
2 *Physics*, **15**, 5501-5519. <http://dx.doi.org/10.5194/acp-15-5501-2015>
- 3 Pistone, K., I. Eisenman, and V. Ramanathan, 2014: Observational determination of albedo
4 decrease caused by vanishing Arctic sea ice. *Proceedings of the National Academy of*
5 *Sciences*, **111**, 3322-3326. <http://dx.doi.org/10.1073/pnas.1318201111>
- 6 Quaas, J., Y. Ming, S. Menon, T. Takemura, M. Wang, J.E. Penner, A. Gettelman, U. Lohmann,
7 N. Bellouin, O. Boucher, A.M. Sayer, G.E. Thomas, A. McComiskey, G. Feingold, C.
8 Hoose, J.E. Kristjánsson, X. Liu, Y. Balkanski, L.J. Donner, P.A. Ginoux, P. Stier, B.
9 Grandey, J. Feichter, I. Sednev, S.E. Bauer, D. Koch, R.G. Grainger, Kirkev, aring, A. g, T.
10 Iversen, Ø. Seland, R. Easter, S.J. Ghan, P.J. Rasch, H. Morrison, J.F. Lamarque, M.J.
11 Iacono, S. Kinne, and M. Schulz, 2009: Aerosol indirect effects – general circulation model
12 intercomparison and evaluation with satellite data. *Atmospheric Chemistry and Physics*, **9**,
13 8697-8717. <http://dx.doi.org/10.5194/acp-9-8697-2009>
- 14 Rädcl, G., T. Mauritsen, B. Stevens, D. Dommengct, D. Matei, K. Bellomo, and A. Clement,
15 2016: Amplification of El Niño by cloud longwave coupling to atmospheric circulation.
16 *Nature Geoscience*, **9**, 106-110. <http://dx.doi.org/10.1038/ngeo2630>
- 17 Raes, F., H. Liao, W.-T. Chen, and J.H. Seinfeld, 2010: Atmospheric chemistry-climate
18 feedbacks. *Journal of Geophysical Research*, **115**, D12121.
19 <http://dx.doi.org/10.1029/2009JD013300>
- 20 Rahmstorf, S., J.E. Box, G. Feulner, M.E. Mann, A. Robinson, S. Rutherford, and E.J.
21 Schaffernicht, 2015: Exceptional twentieth-century slowdown in Atlantic Ocean overturning
22 circulation. *Nature Climate Change*, **5**, 475-480. <http://dx.doi.org/10.1038/nclimate2554>
- 23 Raible, C.C., S. Brönnimann, R. Auchmann, P. Brohan, T.L. Frölicher, H.-F. Graf, P. Jones, J.
24 Luterbacher, S. Muthers, R. Neukom, A. Robock, S. Self, A. Sudrajat, C. Timmreck, and M.
25 Wegmann, 2016: Tambora 1815 as a test case for high impact volcanic eruptions: Earth
26 system effects. *Wiley Interdisciplinary Reviews: Climate Change*, **7**, 569-589.
27 <http://dx.doi.org/10.1002/wcc.407>
- 28 Ramanathan, V., M.S. Lian, and R.D. Cess, 1979: Increased atmospheric CO₂: Zonal and
29 seasonal estimates of the effect on the radiation energy balance and surface temperature.
30 *Journal of Geophysical Research: Oceans*, **84**, 4949-4958.
31 <http://dx.doi.org/10.1029/JC084iC08p04949>
- 32 Randall, D.A., R.A. Wood, S. Bony, R. Colman, T. Fichefet, J. Fyfe, V. Kattsov, A. Pitman, J.
33 Shukla, J. Srinivasan, R.J. Stouffer, A. Sumi, and K.E. Taylor, 2007: Ch. 8: Climate models
34 and their evaluation. *Climate Change 2007: The Physical Science Basis. Contribution of*
35 *Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on*

- 1 *Climate Change*. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.
2 Tignor, and H.L. Miller, Eds. Cambridge University Press, Cambridge, United Kingdom and
3 New York, NY, USA, 589-662. [www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-
chapter8.pdf](http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-
4 chapter8.pdf)
- 5 Rhein, M., S.R. Rintoul, S. Aoki, E. Campos, D. Chambers, R.A. Feely, S. Gulev, G.C. Johnson,
6 S.A. Josey, A. Kostianoy, C. Mauritzen, D. Roemmich, L.D. Talley, and F. Wang, 2013:
7 Observations: Ocean. *Climate Change 2013: The Physical Science Basis. Contribution of*
8 *Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate*
9 *Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A.
10 Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge,
11 United Kingdom and New York, NY, USA, 255–316.
12 <http://www.climatechange2013.org/report/full-report/>
- 13 Rignot, E. and R.H. Thomas, 2002: Mass balance of polar ice sheets. *Science*, **297**, 1502-1506.
14 <http://dx.doi.org/10.1126/science.1073888>
- 15 Rignot, E., M. Koppes, and I. Velicogna, 2010: Rapid submarine melting of the calving faces of
16 West Greenland glaciers. *Nature Geoscience*, **3**, 187-191. <http://dx.doi.org/10.1038/ngeo765>
- 17 Robock, A., 2000: Volcanic eruptions and climate. *Reviews of Geophysics*, **38**, 191-219.
18 <http://dx.doi.org/10.1029/1998RG000054>
- 19 Rosenfeld, D., M.O. Andreae, A. Asmi, M. Chin, G. de Leeuw, D.P. Donovan, R. Kahn, S.
20 Kinne, N. Kivekäs, M. Kulmala, W. Lau, K.S. Schmidt, T. Suni, T. Wagner, M. Wild, and J.
21 Quaas, 2014: Global observations of aerosol–cloud–precipitation–climate interactions.
22 *Reviews of Geophysics*, **52**, 750-808. <http://dx.doi.org/10.1002/2013RG000441>
- 23 Rosenlof, K.H., S.J. Oltmans, D. Kley, J.M. Russell, E.W. Chiou, W.P. Chu, D.G. Johnson, K.K.
24 Kelly, H.A. Michelsen, G.E. Nedoluha, E.E. Remsberg, G.C. Toon, and M.P. McCormick,
25 2001: Stratospheric water vapor increases over the past half-century. *Geophysical Research*
26 *Letters*, **28**, 1195-1198. <http://dx.doi.org/10.1029/2000GL012502>
- 27 Rykaczewski, RR and JP Dunne. 2011. A measured look at ocean chlorophyll
28 trends. *Nature*, 472:E5-E6, <http://dx.doi.org/10.1038/nature09952>
- 29 Saunio, M., R.B. Jackson, P. Bousquet, B. Poulter, and J.G. Canadell, 2016: The growing role
30 of methane in anthropogenic climate change. *Environmental Research Letters*, **11**, 120207.
31 <http://dx.doi.org/10.1088/1748-9326/11/12/120207>
- 32 Schaefer, K., H. Lantuit, E.R. Vladimirov, E.A.G. Schuur, and R. Witt, 2014: The impact of the
33 permafrost carbon feedback on global climate. *Environmental Research Letters*, **9**, 085003.
34 <http://dx.doi.org/10.1088/1748-9326/9/8/085003>

- 1 Schanze, J.J., R.W. Schmitt, and L.L. Yu, 2010: The global oceanic freshwater cycle: A state-of-
2 the-art quantification. *Journal of Marine Research*, **68**, 569-595.
3 <http://dx.doi.org/10.1357/002224010794657164>
- 4 Schoof, C., 2010: Ice-sheet acceleration driven by melt supply variability. *Nature*, **468**, 803-806.
5 <http://dx.doi.org/10.1038/nature09618>
- 6 Schuur, E.A.G., A.D. McGuire, C. Schadel, G. Grosse, J.W. Harden, D.J. Hayes, G. Hugelius,
7 C.D. Koven, P. Kuhry, D.M. Lawrence, S.M. Natali, D. Olefeldt, V.E. Romanovsky, K.
8 Schaefer, M.R. Turetsky, C.C. Treat, and J.E. Vonk, 2015: Climate change and the
9 permafrost carbon feedback. *Nature*, **520**, 171-179. <http://dx.doi.org/10.1038/nature14338>
- 10 Sejas, S.A., M. Cai, A. Hu, G.A. Meehl, W. Washington, and P.C. Taylor, 2014: Individual
11 feedback contributions to the seasonality of surface warming. *Journal of Climate*, **27**, 5653-
12 5669. <http://dx.doi.org/10.1175/JCLI-D-13-00658.1>
- 13 Seppälä, R., 2009: A global assessment on adaptation of forests to climate change. *Scandinavian*
14 *Journal of Forest Research*, **24**, 469-472. <http://dx.doi.org/10.1080/02827580903378626>
- 15 Seppälä, A., K. Matthes, C.E. Randall, and I.A. Mironova, 2014: What is the solar influence on
16 climate? Overview of activities during CAUSES-II. *Progress in Earth and Planetary*
17 *Science*, **1**, 1-12. <http://dx.doi.org/10.1186/s40645-014-0024-3>
- 18 Shepherd, T.G. and C. McLandress, 2011: A robust mechanism for strengthening of the Brewer-
19 Dobson circulation in response to climate change: Critical-layer control of subtropical wave
20 breaking. *Journal of the Atmospheric Sciences*, **68**, 784-797.
21 <http://dx.doi.org/10.1175/2010jas3608.1>
- 22 Shindell, D. and G. Faluvegi, 2009: Climate response to regional radiative forcing during the
23 twentieth century. *Nature Geoscience*, **2**, 294-300. <http://dx.doi.org/10.1038/ngeo473>
- 24 Shiogama, H., D.A. Stone, T. Nagashima, T. Nozawa, and S. Emori, 2013: On the linear
25 additivity of climate forcing-response relationships at global and continental scales.
26 *International Journal of Climatology*, **33**, 2542-2550. <http://dx.doi.org/10.1002/joc.3607>
- 27 Silvano, A., S.R. Rintoul, and L. Herraiz-Borreguero, 2016: Ocean-ice shelf interaction in East
28 Antarctica. *Oceanography*, **29**, 130-143. <http://dx.doi.org/10.5670/oceanog.2016.105>
- 29 Skeie, R.B., T. Berntsen, G. Myhre, C.A. Pedersen, J. Ström, S. Gerland, and J.A. Ogren, 2011:
30 Black carbon in the atmosphere and snow, from pre-industrial times until present.
31 *Atmospheric Chemistry and Physics*, **11**, 6809-6836. [http://dx.doi.org/10.5194/acp-11-6809-](http://dx.doi.org/10.5194/acp-11-6809-2011)
32 2011

- 1 Skiba, U.M. and R.M. Rees, 2014: Nitrous oxide, climate change and agriculture. *CAB Reviews*,
2 **9**, 7. <http://dx.doi.org/10.1079/PAVSNNR20149010>
- 3 Smith, G.L., B.R. Barkstrom, E.F. Harrison, R.B. Lee, and B.A. Wielicki, 1994: Radiation
4 budget measurements for the eighties and nineties. *Advances in Space Research*, **14**, 81-84.
5 [http://dx.doi.org/10.1016/0273-1177\(94\)90351-4](http://dx.doi.org/10.1016/0273-1177(94)90351-4)
- 6 Smith, S.J. and T.C. Bond, 2014: Two hundred fifty years of aerosols and climate: The end of
7 the age of aerosols. *Atmospheric Chemistry and Physics*, **14**, 537-549.
8 <http://dx.doi.org/10.5194/acp-14-537-2014>
- 9 Smith, W.K., S.C. Reed, C.C. Cleveland, A.P. Ballantyne, W.R.L. Anderegg, W.R. Wieder, Y.Y.
10 Liu, and S.W. Running, 2016: Large divergence of satellite and Earth system model
11 estimates of global terrestrial CO₂ fertilization. *Nature Climate Change*, **6**, 306-310.
12 <http://dx.doi.org/10.1038/nclimate2879>
- 13 Soden, B.J. and I.M. Held, 2006: An assessment of climate feedbacks in coupled ocean–
14 atmosphere models. *Journal of Climate*, **19**, 3354-3360.
15 <http://dx.doi.org/10.1175/JCLI3799.1>
- 16 Sohn, B.J., T. Nakajima, M. Satoh, and H.S. Jang, 2010: Impact of different definitions of clear-
17 sky flux on the determination of longwave cloud radiative forcing: NICAM simulation
18 results. *Atmospheric Chemistry and Physics*, **10**, 11641-11646. [http://dx.doi.org/10.5194/acp-](http://dx.doi.org/10.5194/acp-10-11641-2010)
19 [10-11641-2010](http://dx.doi.org/10.5194/acp-10-11641-2010)
- 20 Solomon, S., K.H. Rosenlof, R.W. Portmann, J.S. Daniel, S.M. Davis, T.J. Sanford, and G.-K.
21 Plattner, 2010: Contributions of stratospheric water vapor to decadal changes in the rate of
22 global warming. *Science*, **327**, 1219-1223. <http://dx.doi.org/10.1126/science.1182488>
- 23 Steinacher, M., F. Joos, T.L. Frölicher, L. Bopp, P. Cadule, V. Cocco, S.C. Doney, M. Gehlen,
24 K. Lindsay, and J.K. Moore, 2010: Projected 21st century decrease in marine productivity: A
25 multi-model analysis. *Biogeosciences*, **7**, 979-1005. <http://dx.doi.org/10.5194/bg-7-979-2010>
- 26 Stenchikov, G., T.L. Delworth, V. Ramaswamy, R.J. Stouffer, A. Wittenberg, and F. Zeng, 2009:
27 Volcanic signals in oceans. *Journal of Geophysical Research*, **114**, D16104.
28 <http://dx.doi.org/10.1029/2008JD011673>
- 29 Stevens, B. and G. Feingold, 2009: Untangling aerosol effects on clouds and precipitation in a
30 buffered system. *Nature*, **461**, 607-613. <http://dx.doi.org/10.1038/nature08281>
- 31 Stjern, C.W. and J.E. Kristjánsson, 2015: Contrasting influences of recent aerosol changes on
32 clouds and precipitation in Europe and East Asia. *Journal of Climate*, **28**, 8770-8790.
33 <http://dx.doi.org/10.1175/jcli-d-14-00837.1>

- 1 Straneo, F. and P. Heimbach, 2013: North Atlantic warming and the retreat of Greenland's outlet
2 glaciers. *Nature*, **504**, 36-43. <http://dx.doi.org/10.1038/nature12854>
- 3 Streets, D.G., C. Yu, Y. Wu, M. Chin, Z. Zhao, T. Hayasaka, and G. Shi, 2008: Aerosol trends
4 over China, 1980–2000. *Atmospheric Research*, **88**, 174-182.
5 <http://dx.doi.org/10.1016/j.atmosres.2007.10.016>
- 6 Swartz, W.H., R.S. Stolarski, L.D. Oman, E.L. Fleming, and C.H. Jackman, 2012: Middle
7 atmosphere response to different descriptions of the 11-yr solar cycle in spectral irradiance in
8 a chemistry-climate model. *Atmospheric Chemistry and Physics*, **12**, 5937-5948.
9 <http://dx.doi.org/10.5194/acp-12-5937-2012>
- 10 Szopa, S., Y. Balkanski, M. Schulz, S. Bekki, D. Cugnet, A. Fortems-Cheiney, S. Turquety, A.
11 Cozic, C. Déandreis, D. Hauglustaine, A. Idelkadi, J. Lathière, F. Lefevre, M. Marchand, R.
12 Vuolo, N. Yan, and J.-L. Dufresne, 2013: Aerosol and ozone changes as forcing for climate
13 evolution between 1850 and 2100. *Climate Dynamics*, **40**, 2223-2250.
14 <http://dx.doi.org/10.1007/s00382-012-1408-y>
- 15 Tai, A.P.K., L.J. Mickley, C.L. Heald, and S. Wu, 2013: Effect of CO₂ inhibition on biogenic
16 isoprene emission: Implications for air quality under 2000 to 2050 changes in climate,
17 vegetation, and land use. *Geophysical Research Letters*, **40**, 3479-3483.
18 <http://dx.doi.org/10.1002/grl.50650>
- 19 Taylor, P.C., R.G. Ellingson, and M. Cai, 2011: Geographical distribution of climate feedbacks
20 in the NCAR CCSM3.0. *Journal of Climate*, **24**, 2737-2753.
21 <http://dx.doi.org/10.1175/2010JCLI3788.1>
- 22 Taylor, P.C., S. Kato, K.-M. Xu, and M. Cai, 2015: Covariance between Arctic sea ice and
23 clouds within atmospheric state regimes at the satellite footprint level. *Journal of*
24 *Geophysical Research: Atmospheres*, **120**, 12656-12678.
25 <http://dx.doi.org/10.1002/2015JD023520>
- 26 Thoma, M., J. Determann, K. Grosfeld, S. Goeller, and H.H. Hellmer, 2015: Future sea-level rise
27 due to projected ocean warming beneath the Filchner Ronne Ice Shelf: A coupled model
28 study. *Earth and Planetary Science Letters*, **431**, 217-224.
29 <http://dx.doi.org/10.1016/j.epsl.2015.09.013>
- 30 Thornton, P.E., J.-F. Lamarque, N.A. Rosenbloom, and N.M. Mahowald, 2007: Influence of
31 carbon-nitrogen cycle coupling on land model response to CO₂ fertilization and climate
32 variability. *Global Biogeochemical Cycles*, **21**, GB4018.
33 <http://dx.doi.org/10.1029/2006GB002868>
- 34 Trenberth, K.E., P.D. Jones, P. Ambenje, R. Bojariu, D. Easterling, A.K. Tank, D. Parker, F.
35 Rahimzadeh, J.A. Renwick, M. Rusticucci, B. Soden, and P. Zhai, 2007: Observations:

- 1 Surface and atmospheric climate change. *Climate Change 2007: The Physical Science Basis.*
2 *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental*
3 *Panel on Climate Change.* Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B.
4 Averyt, M. Tignor, and H.L. Miller, Eds. Cambridge University Press, Cambridge, United
5 Kingdom and New York, NY, USA.
6 http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch3.html
- 7 Tsigaridis, K., N. Daskalakis, M. Kanakidou, P.J. Adams, P. Artaxo, R. Bahadur, Y. Balkanski,
8 S.E. Bauer, N. Bellouin, A. Benedetti, T. Bergman, T.K. Berntsen, J.P. Beukes, H. Bian, K.S.
9 Carslaw, M. Chin, G. Curci, T. Diehl, R.C. Easter, S.J. Ghan, S.L. Gong, A. Hodzic, C.R.
10 Hoyle, T. Iversen, S. Jathar, J.L. Jimenez, J.W. Kaiser, A. Kirkevåg, D. Koch, H. Kokkola,
11 Y.H. Lee, G. Lin, X. Liu, G. Luo, X. Ma, G.W. Mann, N. Mihalopoulos, J.J. Morcrette, J.F.
12 Müller, G. Myhre, S. Myriokefalitakis, N.L. Ng, D. O'Donnell, J.E. Penner, L. Pozzoli, K.J.
13 Pringle, L.M. Russell, M. Schulz, J. Sciare, Ø. Seland, D.T. Shindell, S. Sillman, R.B. Skeie,
14 D. Spracklen, T. Stavrakou, S.D. Steenrod, T. Takemura, P. Tiitta, S. Tilmes, H. Tost, T. van
15 Noije, P.G. van Zyl, K. von Salzen, F. Yu, Z. Wang, Z. Wang, R.A. Zaveri, H. Zhang, K.
16 Zhang, Q. Zhang, and X. Zhang, 2014: The AeroCom evaluation and intercomparison of
17 organic aerosol in global models. *Atmospheric Chemistry and Physics*, **14**, 10845-10895.
18 <http://dx.doi.org/10.5194/acp-14-10845-2014>
- 19 Turnock, S.T., D.V. Spracklen, K.S. Carslaw, G.W. Mann, M.T. Woodhouse, P.M. Forster, J.
20 Haywood, C.E. Johnson, M. Dalvi, N. Bellouin, and A. Sanchez-Lorenzo, 2015: Modelled
21 and observed changes in aerosols and surface solar radiation over Europe between 1960 and
22 2009. *Atmospheric Chemistry and Physics*, **15**, 9477-9500. [http://dx.doi.org/10.5194/acp-15-](http://dx.doi.org/10.5194/acp-15-9477-2015)
23 [9477-2015](http://dx.doi.org/10.5194/acp-15-9477-2015)
- 24 Twohy, C.H., M.D. Petters, J.R. Snider, B. Stevens, W. Tahnk, M. Wetzel, L. Russell, and F.
25 Burnet, 2005: Evaluation of the aerosol indirect effect in marine stratocumulus clouds:
26 Droplet number, size, liquid water path, and radiative impact. *Journal of Geophysical*
27 *Research: Atmospheres*, **110**, D08203. <http://dx.doi.org/10.1029/2004JD005116>
- 28 Unger, N., S. Menon, D.M. Koch, and D.T. Shindell, 2009: Impacts of aerosol-cloud interactions
29 on past and future changes in tropospheric composition. *Atmospheric Chemistry and Physics*,
30 **9**, 4115-4129. <http://dx.doi.org/10.5194/acp-9-4115-2009>
- 31 van den Broeke, M., J. Bamber, J. Ettema, E. Rignot, E. Schrama, W.J. van de Berg, E. van
32 Meijgaard, I. Velicogna, and B. Wouters, 2009: Partitioning recent Greenland mass loss.
33 *Science*, **326**, 984-986. <http://dx.doi.org/10.1126/science.1178176>
- 34 Velders, G.J.M., D.W. Fahey, J.S. Daniel, S.O. Andersen, and M. McFarland, 2015: Future
35 atmospheric abundances and climate forcings from scenarios of global and regional
36 hydrofluorocarbon (HFC) emissions. *Atmospheric Environment*, **123, Part A**, 200-209.
37 <http://dx.doi.org/10.1016/j.atmosenv.2015.10.071>

- 1 Vial, J., J.-L. Dufresne, and S. Bony, 2013: On the interpretation of inter-model spread in CMIP5
2 climate sensitivity estimates. *Climate Dynamics*, **41**, 3339-3362.
3 <http://dx.doi.org/10.1007/s00382-013-1725-9>
- 4 Voulgarakis, A., V. Naik, J.F. Lamarque, D.T. Shindell, P.J. Young, M.J. Prather, O. Wild, R.D.
5 Field, D. Bergmann, P. Cameron-Smith, I. Cionni, W.J. Collins, S.B. Dalsøren, R.M.
6 Doherty, V. Eyring, G. Faluvegi, G.A. Folberth, L.W. Horowitz, B. Josse, I.A. MacKenzie,
7 T. Nagashima, D.A. Plummer, M. Righi, S.T. Rumbold, D.S. Stevenson, S.A. Strode, K.
8 Sudo, S. Szopa, and G. Zeng, 2013: Analysis of present day and future OH and methane
9 lifetime in the ACCMIP simulations. *Atmospheric Chemistry and Physics*, **13**, 2563-2587.
10 <http://dx.doi.org/10.5194/acp-13-2563-2013>
- 11 Wang, Y., Y. Yang, S. Han, Q. Wang, and J. Zhang, 2013: Sunshine dimming and brightening in
12 Chinese cities (1955-2011) was driven by air pollution rather than clouds. *Climate Research*,
13 **56**, 11-20. <http://dx.doi.org/10.3354/cr01139>
- 14 Wang, Y., J.H. Jiang, and H. Su, 2015: Atmospheric responses to the redistribution of
15 anthropogenic aerosols. *Journal of Geophysical Research: Atmospheres*, **120**, 9625-9641.
16 <http://dx.doi.org/10.1002/2015JD023665>
- 17 Ward, D.S., N.M. Mahowald, and S. Kloster, 2014: Potential climate forcing of land use and
18 land cover change. *Atmospheric Chemistry and Physics*, **14**, 12701-12724.
19 <http://dx.doi.org/10.5194/acp-14-12701-2014>
- 20 Wenzel, S., P.M. Cox, V. Eyring, and P. Friedlingstein, 2016: Projected land photosynthesis
21 constrained by changes in the seasonal cycle of atmospheric CO₂. *Nature*, **538**, 499-501.
22 <http://dx.doi.org/10.1038/nature19772>
- 23 Wieder, W.R., C.C. Cleveland, W.K. Smith, and K. Todd-Brown, 2015: Future productivity and
24 carbon storage limited by terrestrial nutrient availability. *Nature Geoscience*, **8**, 441-444.
25 <http://dx.doi.org/10.1038/ngeo2413>
- 26 Wielicki, B.A., E.F. Harrison, R.D. Cess, M.D. King, and D.A. Randall, 1995: Mission to planet
27 Earth: Role of clouds and radiation in climate. *Bulletin of the American Meteorological*
28 *Society*, **76**, 2125-2153. [http://dx.doi.org/10.1175/1520-0477\(1995\)076<2125:mtpero>2.0.co;2](http://dx.doi.org/10.1175/1520-0477(1995)076<2125:mtpero>2.0.co;2)
- 30 Wielicki, B.A., B.R. Barkstrom, E.F. Harrison, R.B. Lee, III, G.L. Smith, and J.E. Cooper, 1996:
31 Clouds and the Earth's Radiant Energy System (CERES): An Earth observing system
32 experiment. *Bulletin of the American Meteorological Society*, **77**, 853-868.
33 [http://dx.doi.org/10.1175/1520-0477\(1996\)077<0853:catere>2.0.co;2](http://dx.doi.org/10.1175/1520-0477(1996)077<0853:catere>2.0.co;2)
- 34 Wild, M., 2009: Global dimming and brightening: A review. *Journal of Geophysical Research:*
35 *Atmospheres*, **114**, D00D16. <http://dx.doi.org/10.1029/2008JD011470>

- 1 Wild, M., 2016: Decadal changes in radiative fluxes at land and ocean surfaces and their
2 relevance for global warming. *Wiley Interdisciplinary Reviews: Climate Change*, **7**, 91-107.
3 <http://dx.doi.org/10.1002/wcc.372>
- 4 Winton, M., 2006: Surface albedo feedback estimates for the AR4 climate models. *Journal of*
5 *Climate*, **19**, 359-365. <http://dx.doi.org/10.1175/JCLI3624.1>
- 6 WMO, 2014: Scientific Assessment of Ozone Depletion: 2014. Report No. 55. World
7 Meteorological Organization Geneva, Switzerland. 416 pp.
8 <http://www.esrl.noaa.gov/csd/assessments/ozone/2014/>
- 9 Xi, F., S.J. Davis, P. Ciais, D. Crawford-Brown, D. Guan, C. Pade, T. Shi, M. Syddall, J. Lv, L.
10 Ji, L. Bing, J. Wang, W. Wei, K.-H. Yang, B. Lagerblad, I. Galan, C. Andrade, Y. Zhang,
11 and Z. Liu, 2016: Substantial global carbon uptake by cement carbonation. *Nature*
12 *Geoscience*, **9**, 880-883. <http://dx.doi.org/10.1038/ngeo2840>
- 13 Xu, J. and A.M. Powell, 2013: What happened to surface temperature with sunspot activity in the
14 past 130 years? *Theoretical and Applied Climatology*, **111**, 609-622.
15 <http://dx.doi.org/10.1007/s00704-012-0694-y>
- 16 Yang, S., B. Xu, J. Cao, C.S. Zender, and M. Wang, 2015: Climate effect of black carbon aerosol
17 in a Tibetan Plateau glacier. *Atmospheric Environment*, **111**, 71-78.
18 <http://dx.doi.org/10.1016/j.atmosenv.2015.03.016>
- 19 Yue, X., L.J. Mickley, J.A. Logan, R.C. Hudman, M.V. Martin, and R.M. Yantosca, 2015:
20 Impact of 2050 climate change on North American wildfire: consequences for ozone air
21 quality. *Atmospheric Chemistry and Physics*, **15**, 10033-10055.
22 <http://dx.doi.org/10.5194/acp-15-10033-2015>
- 23 Zanchettin, D., C. Timmreck, H.-F. Graf, A. Rubino, S. Lorenz, K. Lohmann, K. Krüger, and
24 J.H. Jungclaus, 2012: Bi-decadal variability excited in the coupled ocean-atmosphere system
25 by strong tropical volcanic eruptions. *Climate Dynamics*, **39**, 419-444.
26 <http://dx.doi.org/10.1007/s00382-011-1167-1>
- 27 Zhai, P.-W., Y. Hu, C.A. Hostetler, B. Cairns, R.A. Ferrare, K.D. Knobelspiesse, D.B. Josset,
28 C.R. Trepte, P.L. Luckner, and J. Chowdhary, 2013: Uncertainty and interpretation of aerosol
29 remote sensing due to vertical inhomogeneity. *Journal of Quantitative Spectroscopy and*
30 *Radiative Transfer*, **114**, 91-100. <http://dx.doi.org/10.1016/j.jqsrt.2012.08.006>
- 31 Zhang, D., R. Blender, and K. Fraedrich, 2013: Volcanoes and ENSO in millennium simulations:
32 Global impacts and regional reconstructions in East Asia. *Theoretical and Applied*
33 *Climatology*, **111**, 437-454. <http://dx.doi.org/10.1007/s00704-012-0670-6>

1 Zhu, Z., S. Piao, R.B. Myneni, M. Huang, Z. Zeng, J.G. Canadell, P. Ciais, S. Sitch, P.
2 Friedlingstein, A. Arneth, C. Cao, L. Cheng, E. Kato, C. Koven, Y. Li, X. Lian, Y. Liu, R.
3 Liu, J. Mao, Y. Pan, S. Peng, J. Penuelas, B. Poulter, T.A.M. Pugh, B.D. Stocker, N. Viovy,
4 X. Wang, Y. Wang, Z. Xiao, H. Yang, S. Zaehle, and N. Zeng, 2016: Greening of the Earth
5 and its drivers. *Nature Climate Change*, **6**, 791-795. <http://dx.doi.org/10.1038/nclimate3004>

6

FINAL DRAFT

1 **3. Detection and Attribution of Climate Change**

2 **Key Findings**

- 3 1. The *likely* range of the human contribution to the global mean temperature increase over the
4 period 1951–2010 is 1.1° to 1.4°F (0.6° to 0.8°C), and the central estimate of the observed
5 warming of 1.2°F (0.65°C) lies within this range (*high confidence*). This translates to
6 a *likely* human contribution of 93%–123% of the observed 1951–2010 change. It is *extremely*
7 *likely* that more than half of the global mean temperature increase since 1951 was caused by
8 human influence on climate (*high confidence*). The *likely* contributions of natural forcing and
9 internal variability to global temperature change over that period are minor (*high*
10 *confidence*).
- 11 2. The science of event attribution is rapidly advancing through improved understanding of the
12 mechanisms that produce extreme events and the marked progress in development of
13 methods that are used for event attribution (*high confidence*).

14 **3.1 Introduction**

15 Detection and attribution of climate change involves assessing the causes of observed changes in
16 the climate system through systematic comparison of climate models and observations using
17 various statistical methods. Detection and attribution studies are important for a number of
18 reasons. For example, such studies can help determine whether a human influence on climate
19 variables (for example, temperature) can be distinguished from natural variability. Detection and
20 attribution studies can help evaluate whether model simulations are consistent with observed
21 trends or other changes in the climate system. Results from detection and attribution studies can
22 inform decision making on climate policy and adaptation.

23 There are several general types of detection and attribution studies, including: attribution of
24 trends or long-term changes in climate variables; attribution of changes in extremes; attribution
25 of weather or climate events; attribution of climate-related impacts; and the estimation of climate
26 sensitivity using observational constraints. Paleoclimate proxies can also be useful for detection
27 and attribution studies, particularly to provide a longer-term perspective on climate variability as
28 a baseline on which to compare recent climate changes of the past century or so (for example,
29 see Figure 12.2 from Ch. 12: Sea Level Rise). Detection and attribution studies can be done at
30 various scales, from global to regional.

31 Since the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5)
32 chapter on detection and attribution (Bindoff et al. 2013) and the Third National Climate
33 Assessment (NCA3, Melillo et al. 2014), the science of detection and attribution has advanced,
34 with a major scientific question being the issue of attribution of extreme events (Hulme 2014;
35 Stott 2016; Easterling et al. 2016; NAS 2016). Therefore, the methods used in this developing

1 area of the science are briefly reviewed in Appendix C: Detection and Attribution Methods,
2 along with a brief overview of the various general detection and attribution methodologies,
3 including some recent developments in these areas. Detection and attribution of changes in
4 extremes in general presents a number of challenges (Zwiers et al. 2013), including limitations of
5 observations, models, statistical methods, process understanding for extremes, and uncertainties
6 about the natural variability of extremes. Although the present report does not focus on climate
7 impacts on ecosystems or human systems, a relatively new and developing area of detection and
8 attribution science (reviewed in Stone et al. 2013), concerns detecting and attributing the impacts
9 of climate change on natural or human systems. Many new developments in detection and
10 attribution science have been fostered by the International Detection and Attribution Group
11 (IDAG; <http://www.image.ucar.edu/idag/> and [http://www.clivar.org/clivar-](http://www.clivar.org/clivar-panels/etccdi/idag/international-detection-attribution-group-idag)
12 [panels/etccdi/idag/international-detection-attribution-group-idag](http://www.clivar.org/clivar-panels/etccdi/idag/international-detection-attribution-group-idag)) which is an international group
13 of scientists who have collaborated since 1995 on “assessing and reducing uncertainties in the
14 estimates of climate change.”

15 In the remainder of this chapter, we review highlights of detection and attribution science,
16 particularly key attribution findings for the rise in global mean temperature. However, as this is a
17 U.S.-focused assessment, the report as a whole will focus more on the detection and attribution
18 findings for particular regional phenomena (for example, regional temperature, precipitation) or
19 at least global-scale phenomena that are directly affecting the United States (for example, sea
20 level rise). Most of these findings are contained in the individual phenomena chapters, rather
21 than in this general overview chapter on detection and attribution. We provide summary links to
22 the chapters where particular detection and attribution findings are presented in more detail.

23 **3.2 Detection and Attribution of Global Temperature Changes**

24 The concept of detection and attribution is illustrated in Figure 3.1, which shows a very simple
25 example of detection and attribution of global mean temperature. While more powerful pattern-
26 based detection and attribution methods (discussed later), and even greater use of time averaging,
27 can result in much stronger statements about detection and attribution, the example in Figure 3.1
28 serves to illustrate the general concept. In the figure, observed global mean temperature
29 anomalies (relative to a 1901–1960 baseline) are compared with anomalies from historical
30 simulations of CMIP5 models. The spread of different individual model simulations (the blue
31 and red shading) arises both from differences between the models in their responses to the
32 different specified climate forcing agents (natural and anthropogenic) and from internal
33 (unforced) climate variability. Observed annual temperatures after about 1980 are shown to be
34 inconsistent with models that include only natural forcings (blue shading) and are consistent with
35 the model simulations that include both anthropogenic and natural forcing (red shading). This
36 implies that the observed global warming is attributable in large part to anthropogenic forcing. A
37 key aspect of a detection and attribution finding will be the assessment of the adequacy of the

1 models and observations used for these conclusions, as discussed and assessed in Flato et al.
2 (2013), Bindoff et al. (2013), and IPCC (2013a).

3 **[INSERT FIGURE 3.1 HERE]**

4 The detection and attribution of global temperature change to human causes has been one of the
5 most important and visible findings over the course of the past global climate change scientific
6 assessments by the IPCC. The first IPCC report (IPCC 1990) concluded that a human influence
7 on climate had not yet been detected, but judged that “the unequivocal detection of the enhanced
8 greenhouse effect from observations is not likely for a decade or more.” The second IPCC report
9 (IPCC 1996) concluded that “the balance of evidence suggests a discernible human influence on
10 climate.” The third IPCC report (IPCC 2001) strengthened this conclusion to: “most of the
11 observed warming over the last 50 years is likely to have been due to the increase of greenhouse
12 gas concentrations.” The fourth IPCC report (IPCC 2007) further strengthened the conclusion to:
13 “Most of the observed increase in global average temperatures since the mid-20th century is very
14 likely due to the observed increase in anthropogenic greenhouse gas concentrations.” The fifth
15 IPCC report (IPCC 2013a) further strengthened this to: “It is extremely likely that more than half
16 of the observed increase in global average surface temperature from 1951 to 2010 was caused by
17 the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings
18 together.” These increasingly confident statements have resulted from scientific advances,
19 including better observational datasets, improved models and detection/attribution methods, and
20 improved estimates of climate forcings. Importantly, the continued long-term warming of the
21 global climate system since the time of the first IPCC report and the broad-scale agreement of
22 the spatial pattern of observed temperature changes with climate model projections of
23 greenhouse gas-induced changes as published in the late 1980s (e.g., Stouffer and Manabe 2017)
24 give more confidence in the attribution of observed warming since 1951 as being due primarily
25 to human activity.

26 The IPCC AR5 presented an updated assessment of detection and attribution research at the
27 global to regional scale (Bindoff et al. 2013) which is briefly summarized here. Key attribution
28 assessment results from IPCC AR5 for global mean temperature are summarized in Figure 3.2,
29 which shows assessed *likely* ranges and midpoint estimates for several factors contributing to
30 increases in global mean temperature. According to Bindoff et al., the *likely* range of the
31 anthropogenic contribution to global mean temperature increases over 1951–2010 was 0.6°C to
32 0.8°C (1.1°F to 1.4°F), compared with the observed warming 5th to 95th percentile range of
33 0.59°C to 0.71°C (1.1°F to 1.3°F). The estimated *likely* contribution ranges for natural forcing
34 and internal variability were both much smaller (–0.1°C to 0.1°C, or –0.2°F to 0.2°F) than the
35 observed warming. The confidence intervals that encompass the *extremely likely* range for the
36 anthropogenic contribution are wider than the *likely* range. Using these wider confidence limits,
37 the lower limit of attributable warming contribution range still lies above 50% of the observed
38 warming rate, and thus Bindoff et al. concluded that it is *extremely likely* that more than half of

1 the global mean temperature increase since 1951 was caused by human influence on climate.
2 This assessment concurs with the Bindoff et al. assessment of attributable warming and cooling
3 influences.

4 **[INSERT FIGURE 3.2 HERE]**

5 Apart from formal detection attribution studies such as those underlying the results above, which
6 use global climate model output and pattern-based regression methods, anthropogenic influences
7 on global mean temperature can also be estimated using simpler empirical models, such as
8 multiple linear regression/energy balance models (e.g., Canty et al. 2013; Zhou and Tung, 2013).
9 For example, Figure 3.3 illustrates how the global mean surface temperature changes since the
10 late 1800s can be decomposed into components linearly related to several forcing variables
11 (anthropogenic forcing, solar variability, volcanic forcing, plus an internal variability component,
12 here related to El Niño–Southern Oscillation). Using this approach, Canty et al. also infer a
13 substantial contribution of anthropogenic forcing to the rise in global mean temperature since the
14 late 1800s. Stern and Kaufmann (2014) use another method—Granger causality tests—and again
15 infer that “human activity is partially responsible for the observed rise in global temperature and
16 that this rise in temperature also has an effect on the global carbon cycle.” They also conclude
17 that anthropogenic sulfate aerosol effects may only be about half as large as inferred in a number
18 of previous studies.

19 Multi-century to multi-millennial-scale climate model integrations with unchanging external
20 forcing provide a means of estimating potential contributions of internal climate variability to
21 observed trends. Bindoff et al. (2013) conclude, based on multimodel assessments, that the likely
22 range contribution of internal variability to observed trends over 1951–2010 is about $\pm 0.2^{\circ}\text{F}$,
23 compared to the observed warming of about 1.2°F over that period. A recent 5,200 year
24 integration of the CMIP5 model having apparently the largest global mean temperature
25 variability among CMIP5 models shows rare instances of multidecadal global warming
26 approaching the observed 1951–2010 warming trend (Knutson et al. 2016). However, even that
27 most extreme model cannot simulate century-scale warming trends from internal variability that
28 approach the observed global mean warming over the past century. According to a multimodel
29 analysis of observed versus CMIP5 modeled global temperature trends (Knutson et al. 2013a,
30 Fig. 7a), the modeled natural fluctuations (forced plus internal) would need to be larger by about
31 a factor of three for even an unusual natural variability episode (95th percentile) to approach the
32 observed trend since 1900. Thus, using present models there is no known source of internal
33 climate variability that can reproduce the observed warming over the past century without
34 including strong positive forcing from anthropogenic greenhouse gas emissions (Figure 3.1). The
35 modeled century-scale trend due to natural forcings (solar and volcanic) is also minor (Figure
36 3.1), so that, using present models, there is no known source of natural variability that can
37 reproduce the observed global warming over the past century. One study (Laepfle and Huybers
38 2014) comparing paleoclimate data with models concluded that current climate models may

1 substantially underestimate regional sea surface temperature variability on multidecadal to multi-
2 centennial timescales, especially at low latitudes. The causes of this apparent discrepancy--
3 whether due to data issues, external forcings/response, or simulated internal variability issues--
4 and its implications for simulations of global temperature variability in climate models remain
5 unresolved. In summary, we are not aware of any convincing evidence that natural variability
6 alone could have accounted for the amount and timing of global warming that was observed over
7 the industrial era.

8 **[INSERT FIGURE 3.3 HERE]**

9 While most detection and attribution studies focus on changes in temperature and other variables
10 in the historical record since about 1860 or later, some studies relevant to detection and
11 attribution focus on changes over much longer periods. For example, geological and tide-based
12 reconstructions of global mean sea level (Ch. 12: Sea Level Rise, Figure 12.2b) suggest that the
13 rate of sea level rise in the last century was faster than during any century over the past ~2,800
14 years. As an example for northern hemisphere annual mean temperatures, Schurer et al. (2013)
15 use detection and attribution fingerprinting methods along with paleoclimate reconstructions and
16 millennial-scale climate model simulations from eight models to explore causes for temperature
17 variations from 850 AD to the present, including the Medieval Climate Anomaly (MCA, around
18 900 to 1200 AD) and the Little Ice Age (LIA, around 1450 to 1800 AD). They conclude that
19 solar variability and volcanic eruptions were the main causal factors for changes in northern
20 hemisphere temperatures from 1400 to 1900, but that greenhouse gas changes of uncertain origin
21 apparently contributed to the cool conditions during 1600–1800. Their study provides further
22 support for previous IPCC report conclusions (e.g., IPCC 2007) that internal variability alone
23 was extremely unlikely to have been the cause of the recent observed 50- and 100-year warming
24 trends. Andres and Peltier (2016) also inferred from millennial-scale climate model simulations
25 that volcanoes, solar variability, greenhouse gases, and orbital variations all contributed
26 significantly to the transition from the MCA to the LIA.

27 An active and important area of climate research that involves detection and attribution science is
28 the estimation of global climate sensitivity, based on past observational constraints. An important
29 measure of climate sensitivity, with particular relevance for climate projections over the coming
30 decades, is the transient climate response (TCR), defined as the rise in global mean surface
31 temperature at the time of CO₂ doubling for a 1% per year transient increase of atmospheric CO₂.
32 (Equilibrium climate sensitivity is discussed in Ch. 2: Physical Drivers of Climate Change). The
33 TCR of the climate system has an estimated range of 0.9° to 2.0°C (1.6° to 3.6°F) and 0.9° to
34 2.5°C (1.6° to 4.5°F), according to two recent assessments (Otto et al. 2013 and Lewis and Curry
35 2015, respectively). Marvel et al. (2016) suggest, based on experiments with a single climate
36 model, that after accounting for the different efficacies of various historical climate forcing
37 agents, the TCR could be adjusted upward from the Otto et al. and Lewis and Curry estimates.
38 Richardson et al. (2016) report a best estimate for TCR of 1.66°C (2.99 °F), with a 5% to 95%

1 confidence range of 1.0°C to 3.3°C (1.8°F to 5.9°F). Furthermore, Richardson et al. conclude
2 that the earlier studies noted above may underestimate TCR, because the surface temperature
3 data set they used undersamples rapidly warming regions due to limited coverage and because
4 surface water warms less than surface air. Gregory et al. (2015) note, within CMIP5 models, that
5 the TCR to the second doubling of CO₂ (that is, from doubling to quadrupling) is 40% higher
6 than that for the first doubling. They explore the various physical reasons for this finding, and
7 conclude this may also lead to an underestimate of TCR in the empirical observation-based
8 studies. In summary, estimation of TCR from observations continues to be an active area of
9 research with considerable remaining uncertainties, as discussed above.

10 **3.3 Detection and Attribution with a United States Regional Focus**

11 Detection and attribution at regional scales is generally more challenging than at the global scale
12 for a number of reasons. At the regional scale, the magnitude of natural variability swings are
13 typically larger than for global means. If the climate change signal is similar in magnitude at the
14 regional and global scales, this makes it more difficult to detect anthropogenic climate changes at
15 the regional scale. Further, there is less spatial pattern information at the regional scale that can
16 be used to distinguish contributions from various forcings. Other forcings that have typically
17 received less attention than greenhouse gases, such as land-use change, could be more important
18 at regional scales than globally (Pielke et al. 2016). Also, simulated internal variability at
19 regional scales may be less reliable than at global scales (Bindoff et al. 2013). While detection
20 and attribution of changes in extremes (including at the regional scale) presents a number of key
21 challenges (Zwiers et al. 2013), previous studies (e.g., Zwiers et al. 2011) have demonstrated
22 how detection and attribution methods, combined with generalized extreme value distributions,
23 can be used to detect a human influence on extreme temperatures at the regional scale, including
24 over North America.

25 In IPCC AR5 (Bindoff et al. 2013), which had a broader global focus than this report,
26 attributable human contributions were reported for warming over all continents except
27 Antarctica. Changes in daily temperature extremes throughout the world; ocean surface and
28 subsurface temperature and salinity sea level pressure patterns; Arctic sea ice loss; northern
29 hemispheric snow cover decrease; global mean sea level rise; and ocean acidification were all
30 associated with human activity in AR5 (Bindoff et al. 2013). IPCC AR5 also reported medium
31 confidence in anthropogenic contributions to increased atmospheric specific humidity, zonal
32 mean precipitation over northern hemisphere mid to high latitudes, and intensification of heavy
33 precipitation over land regions. IPCC AR5 had weaker attribution conclusions than IPCC AR4
34 on some phenomena, including tropical cyclone and drought changes.

35 Although the present assessment follows most of the IPCC AR5 conclusions on detection and
36 attribution of relevance to the United States, we make some additional attribution assessment
37 statements in the relevant chapters of this report. Among the notable detection and attribution-
38 relevant findings in this report are the following (refer to the listed chapters for further details):

- 1 • Ch. 5: Circulation and Variability: Human activities have played a role in the observed
2 expansion of the tropics (by 70 to 200 miles since 1979), although confidence is presently
3 *low* regarding the magnitude of the human contribution relative to natural variability.
- 4 • Ch. 6: Temperature Change: Detectable anthropogenic warming since 1901 has occurred
5 over the western and northern regions of the contiguous United States according to
6 observations and CMIP5 models, although over the southeastern United States there has
7 been no detectable warming trend since 1901. The combined influence of natural and
8 anthropogenic forcings on temperature *extremes* have been detected over large
9 subregions of North America.
- 10 • Ch. 7: Precipitation Change: For the continental United States, there is *high confidence* in
11 the detection of extreme precipitation increases, while there is *low confidence* in
12 attributing the extreme precipitation changes purely to anthropogenic forcing. There is
13 stronger evidence for a human contribution (*medium confidence*) when taking into
14 account process-based understanding (for example, increased water vapor in a warmer
15 atmosphere).
- 16 • Ch. 8: Drought, Floods, and Wildfire: No detectable change in long-term U.S. drought
17 statistics has emerged. Detectable changes—a mix of increases and decreases—in some
18 classes of flood frequency have occurred in parts of the United States, although
19 attribution studies have not established a robust connection between increased riverine
20 flooding and human-induced climate change. There is *medium confidence* for a human-
21 caused climate change contribution to increased forest fire activity in Alaska in recent
22 decades and *low to medium confidence* in the western United States.
- 23 • Ch. 9: Extreme Storms: There is broad agreement in the literature that human factors
24 (greenhouse gases and aerosols) have had a measurable impact on the observed oceanic
25 and atmospheric variability in the North Atlantic, and there is *medium confidence* that
26 this has contributed to the observed increase in hurricane activity since the 1970s. There
27 is no consensus on the relative magnitude of human and natural influences on past
28 changes in hurricane activity.
- 29 • Ch. 10: Land Cover: Modifications to land use and land cover due to human activities
30 produce changes in surface albedo and in atmospheric aerosol and greenhouse gas
31 concentrations, accounting for an estimated $40\% \pm 16\%$ of the human-caused global
32 radiative forcing from 1850 to 2010.
- 33 • Ch. 11: Arctic Changes: It is *virtually certain* that human activities have contributed to
34 arctic surface temperature warming, sea ice loss since 1979, glacier mass loss, and
35 northern hemisphere snow extent decline observed across the Arctic. Human activities

1 have *likely* contributed to more than half of the observed arctic surface temperature rise
2 and September sea ice decline since 1979.

3 • Ch. 12: Sea Level Rise: Human-caused climate change has made a substantial
4 contribution to global mean sea level rise since 1900, contributing to a rate of rise faster
5 than during any comparable period over the past ~2,800 years.

6 • Ch. 13: Ocean Changes: The world's oceans have absorbed more than 90% of the excess
7 heat caused by greenhouse warming since the mid-20th Century. The world's oceans are
8 currently absorbing more than a quarter of the carbon dioxide emitted to the atmosphere
9 annually from human activities (*very high confidence*), making them more acidic.

10 **3.4 Extreme Event Attribution**

11 Since the IPCC AR5 and NCA3 (Melillo et al. 2014), the attribution of extreme weather and
12 climate events has been an emerging area in the science of detection and attribution. Attribution
13 of extreme weather events under a changing climate is now an important and highly visible
14 aspect of climate science. As discussed in the recent National Academy of Sciences report (NAS
15 2016), the science of event attribution is rapidly advancing, including the understanding of the
16 mechanisms that produce extreme events and the rapid progress in development of methods used
17 for event attribution.

18 When an extreme weather event occurs, the question is often asked: was this event caused by
19 climate change? A generally more appropriate framing for the question is whether climate
20 change has altered the odds of occurrence of an extreme event like the one just experienced.
21 Extreme event attribution studies to date have generally been concerned with answering the latter
22 question. In recent developments, Hannart et al. (2016b) discuss the application of causal theory
23 to event attribution, including discussion of conditions under which stronger causal statements
24 can be made, in principle, based on theory of causality and distinctions between necessary and
25 sufficient causality.

26 Several recent studies, including NAS (2016), have reviewed aspects of extreme event attribution
27 (Hulme 2014; Stott 2016; Easterling et al. 2016). Hulme (2014) and NAS (2016) discuss the
28 motivations for scientists to be pursuing extreme event attribution, including the need to inform
29 risk management and adaptation planning. Hulme (2014) categorizes event attribution
30 studies/statements into general types, including those based on: physical reasoning, statistical
31 analysis of time series, fraction of attributable risk (FAR) estimation (discussed in the
32 Appendix), or those that rely on the philosophical argument that there are no longer any purely
33 natural weather events. The NAS (2016) report outlines two general approaches to event
34 attribution: 1) using observations to estimate a change in probability of magnitude of events, or
35 2) using model simulations to compare an event in the current climate versus that in a
36 hypothetical "counterfactual" climate not influenced by human activities. As discussed by

1 Trenberth et al. (2015), Shepherd (2016), and Horton et al. 2016, an ingredients-based or
2 conditional attribution approach can also be used, when one examines the impact of certain
3 environmental changes (for example, greater atmospheric moisture) on the character of an
4 extreme event using model experiments, all else being equal. Further discussion of
5 methodologies is given in Appendix C.

6 Examples of extreme event attribution studies are numerous. Many are cited by Hulme (2014),
7 NAS (2016), Easterling et al. (2016), and there are many further examples in an annual
8 collection of studies of extreme events of the previous year, published in the *Bulletin of the*
9 *American Meteorological Society* (Peterson et al. 2012, 2013; Herring et al. 2014, 2015, 2016).

10 While an extensive review of extreme event attribution is beyond the scope of this report,
11 particularly given the recent publication of several assessments or review papers on the topic,
12 some general findings from the more comprehensive NAS (2016) report are summarized here:

- 13 • Confidence in attribution findings of anthropogenic influence is greatest for extreme events
14 that are related to an aspect of temperature, followed by hydrological drought and heavy
15 precipitation, with little or no confidence for severe convective storms or extratropical
16 storms.
- 17 • Event attribution is more reliable when based on sound physical principles, consistent
18 evidence from observations, and numerical models that can replicate the event.
- 19 • Statements about attribution are sensitive to the way the questions are posed (that is,
20 framing).
- 21 • Assumptions used in studies must be clearly stated and uncertainties estimated in order for a
22 clear, unambiguous interpretation of an event attribution to be possible.

23 The NAS report noted that uncertainties about the roles of low-frequency natural variability and
24 confounding factors (for example, the effects of dams on flooding) could be sources of
25 difficulties in event attribution studies. In addition, the report noted that attribution conclusions
26 would be more robust in cases where observed changes in the event being examined are
27 consistent with expectations from model-based attribution studies. The report endorsed the need
28 for more research to improve understanding of a number of important aspects of event attribution
29 studies, including physical processes, models and their capabilities, natural variability, reliable
30 long-term observational records, statistical methods, confounding factors, and future projections
31 of the phenomena of interest.

32 As discussed in Appendix C: Detection and Attribution Methodologies, confidence is typically
33 lower for an attribution-without-detection statement than for an attribution statement
34 accompanied by an established, detectable anthropogenic influence (for example, a detectable
35 and attributable long-term trend or increase in variability) for the phenomenon itself. An example

1 of the former would be stating that a change in the probability or magnitude of a heat wave in the
2 southeastern United States was attributable to rising greenhouse gases, because there has not
3 been a detectable century-scale trend in either temperature or temperature variability in this
4 region (e.g., Ch. 6: Temperature Change; Knutson et al. 2013a).

5 To our knowledge, no extreme weather event observed to date has been found to have zero
6 probability of occurrence in a preindustrial climate, according to climate model simulations.
7 Therefore, the causes of attributed extreme events are a combination of natural variations in the
8 climate system compounded (or alleviated) by the anthropogenic change to the climate system.
9 Event attribution statements quantify the relative contribution of these human and natural causal
10 factors. In the future, as the climate change signal gets stronger compared to natural variability,
11 humans may experience weather events which are essentially impossible to simulate in a
12 preindustrial climate. This is already becoming the case at large time and spatial scales, where
13 for example the record global mean surface temperature anomaly observed in 2016 (relative to a
14 1901–1960 baseline) is essentially impossible for global climate models to reproduce under
15 preindustrial climate forcing conditions (for example, see Figure 3.1).

16 The European heat wave of 2003 (Stott et al. 2004) and Australia’s extreme temperatures and
17 heat indices of 2013 (e.g., Arblaster et al. 2014; King et al. 2014; Knutson et al. 2014; Lewis and
18 Karoly 2014; Perkins et al. 2014) are examples of extreme weather or climate events where
19 relatively strong evidence for a human contribution to the event has been found. Similarly, in the
20 United States, the science of event attribution for weather and climate extreme events has been
21 actively pursued since the NCA3. For example, for the case of the recent California drought,
22 investigators have attempted to determine, using various methods discussed in this chapter,
23 whether human-caused climate change contributed to the event (see discussion in Ch. 8:
24 Droughts, Floods, and Wildfires).

25 As an example, illustrating different methods of attribution for an event in the United States,
26 Hoerling et al. (2013) concluded that the 2011 Texas heat wave/meteorological drought was
27 primarily caused by antecedent and concurrent negative rainfall anomalies due mainly to natural
28 variability and the La Niña conditions at the time of the event, but with a relatively small (not
29 detected) warming contribution from anthropogenic forcing. The anthropogenic contribution
30 nonetheless doubled the chances of reaching a new temperature record in 2011 compared to the
31 1981–2010 reference period, according to their study. Rupp et al. (2012), meanwhile, concluded
32 that extreme heat events in Texas were about 20 times more likely for 2008 La Niña conditions
33 than similar conditions during the 1960s. This pair of studies illustrates how the framing of the
34 attribution question can matter. For example, the studies used different baseline reference periods
35 to determine the magnitude of anomalies, which can also affect quantitative conclusions, since
36 using an earlier baseline period typically results in larger magnitude anomalies (in a generally
37 warming climate). The Hoerling et al. analysis focused on both what caused most of the
38 magnitude of the anomalies as well as changes in probability of the event, whereas Rupp et al.

1 focused on the changes in the probability of the event. Otto et al. (2012) showed for the case of
2 the Russian heat wave of 2010 how a different focus of attribution (fraction of anomaly
3 explained vs. change in probability of occurrence over a threshold) can give seemingly
4 conflicting results, yet have no real fundamental contradiction. In the illustrative case for the
5 2011 Texas heat/drought, we conclude that there is *medium* confidence that anthropogenic
6 forcing contributed to the heat wave, both in terms of a small contribution to the anomaly
7 magnitude and a significant increase in the probability of occurrence of the event.

8 In this report, we do not assess or compile all individual weather or climate extreme events for
9 which an attributable anthropogenic climate change has been claimed in a published study, as
10 there are now many such studies that provide this information. Some event attribution-related
11 studies that focus on the United States are discussed in more detail in Chapters 6–9, which
12 primarily examine phenomena such as precipitation extremes, droughts, floods, severe storms,
13 and temperature extremes. For example, as discussed in Chapter 6: Temperature Change (Table
14 6.3), a number of extreme temperature events (warm anomalies) in the United States have been
15 partly attributed to anthropogenic influence on climate.

1 TRACEABLE ACCOUNTS

2 Key Finding 1

3 The *likely* range of the human contribution to the global mean temperature increase over the
4 period 1951–2010 is 1.1°F to 1.4°F (0.6°C to 0.8°C), and the central estimate of the observed
5 warming of 1.2°F (0.65°C) lies within this range (*high confidence*). This translates to
6 a *likely* human contribution of 93%–123% of the observed 1951–2010 change. It is *extremely*
7 *likely* that more than half of the global mean temperature increase since 1951 was caused by
8 human influence on climate (*high confidence*). The *likely* contributions of natural forcing and
9 internal variability to global temperature change over that period are minor (*high confidence*).

10 Description of evidence base

11 This Key Finding summarizes key detection and attribution evidence documented in the climate
12 science literature and in the IPCC AR5 (Bindoff et al. 2013), and references therein. The Key
13 Finding is essentially the same as the summary assessment of IPCC AR5.

14 According to Bindoff et al. (2013), the *likely* range of the anthropogenic contribution to global
15 mean temperature increases over 1951–2010 was 1.1°F to 1.4°F (0.6°C to 0.8°C, compared with
16 the observed warming 5th to 95th percentile range of 1.1°F to 1.3°F (0.59°C to 0.71°C). The
17 estimated *likely* contribution ranges for natural forcing and internal variability were both much
18 smaller (–0.2°F to 0.2°F, or –0.1°F to 0.1°F) than the observed warming. The confidence
19 intervals that encompass the *extremely likely* range for the anthropogenic contribution are wider
20 than the *likely* range, but nonetheless allow for the conclusion that it is *extremely likely* that more
21 than half of the global mean temperature increase since 1951 was caused by human influence on
22 climate (*high confidence*).

23 The attribution of temperature increases since 1951 is based largely on the detection and
24 attribution analyses of Gillett et al. (2013), Jones et al. (2013), and consideration of Ribes and
25 Terray (2013), Huber and Knutti (2011), Wigley and Santer (2013), and IPCC AR4 (Hegerl et al.
26 2007). The IPCC finding receives further support from alternative approaches, such as multiple
27 linear regression/energy balance modeling (Canty et al. 2013) and a new methodological
28 approach to detection and attribution that uses additive decomposition and hypothesis testing
29 (Ribes et al. 2017), which infer similar attributable warming results. Individual study results used
30 to derive the IPCC finding are summarized in Figure 10.4 of Bindoff et al. (2013), which also
31 assesses model dependence by comparing results obtained from several individual CMIP5
32 models. The estimated potential influence of internal variability is based on Knutson et al.
33 (2013a) and Huber and Knutti (2011), with consideration of the above references. Moreover,
34 simulated global temperature multidecadal variability is assessed to be adequate (Bindoff et al.
35 2013), with *high confidence* that models reproduce global and northern hemisphere temperature
36 variability across a range of timescales (Flato et al. 2013). Further support for these assessments
37 comes from assessments of paleoclimate data (Masson-Delmotte et al. 2013) and increased

1 confidence in physical understanding and models of the climate system (IPCC 2013a; Stouffer
2 and Manabe 2017). A more detailed traceable account is contained in Bindoff et al. (2013). Post-
3 IPCC AR5 supporting evidence includes additional analyses showing the unusual nature of
4 observed global warming since the late 1800s compared to simulated internal climate variability
5 (Knutson et al. 2016), and the recent occurrence of new record high global mean temperatures
6 are consistent with model projections of continued warming on multidecadal scales (for example,
7 Figure 3.1).

8 **Major uncertainties**

9 As discussed in the main text, estimation of the transient climate response (TCR), defined as the
10 global mean surface temperature change at the time of CO₂ doubling in a 1% per year CO₂
11 transient increase experiment, continues to be an active area of research with considerable
12 remaining uncertainties. Some detection attribution methods use model-based methods together
13 with observations to attempt to infer scaling magnitudes of the forced responses based on
14 regression methods (that is, they do not use the models' climate sensitivities directly). However,
15 if climate models are significantly more sensitive to CO₂ increases than the real world, as
16 suggested by the studies of Otto et al. 2013 and Lewis and Curry (2014) (though see differing
17 conclusions from other studies in the main text), this could lead to an overestimate of attributable
18 warming estimates, at least as obtained using some detection and attribution methods. In any
19 case it is important to better constrain the TCR to have higher confidence in general in
20 attributable warming estimates obtained using various methods.

21 The global temperature change since 1951 attributable to anthropogenic forcings other than
22 greenhouse gases has a wide estimated *likely* range (−1.1 to +0.2°F in Fig. 3.1). This wide range
23 is largely due to the considerable uncertainty of estimated total radiative forcing due to aerosols
24 (i.e., the direct effect combined with the effects of aerosols on clouds [Myhre et al. 2013]).
25 Although more of the relevant physical processes are being included in models, confidence in
26 these model representations remains low (Boucher et al. 2013). In detection/attribution studies
27 there are substantial technical challenges in quantifying the separate attributable contributions to
28 temperature change from greenhouse gases and aerosols (Bindoff et al. 2013). Finally, there is a
29 range of estimates of the potential contributions of internal climate variability, and some sources
30 of uncertainty around modeled estimates (e.g., Laepple and Huybers 2014). However, current
31 CMIP5 multimodel estimates (*likely* range of ±0.2°F, or 0.1°C, over 60 years) would have to
32 increase by a factor of about three for even half of the observed 60-year trend to lie within a
33 revised *likely* range of potential internal variability (e.g., Knutson et al. 2013a; Huber and Knutti
34 2012). Recently, Knutson et al. (2016) examined a 5000-year integration of the CMIP5 model
35 having the strongest internal multidecadal variability among 25 CMIP5 models they examined.
36 While the internal variability within this strongly varying model can on rare occasions produce
37 60-year warmings approaching that observed from 1951–2010, even this most extreme model

1 did not produce any examples of centennial-scale internal variability warming that could match
2 the observed global warming since the late 1800s, even in a 5000-year integration.

3 **Assessment of confidence based on evidence and agreement, including short description of**
4 **nature of evidence and level of agreement**

5 There is *very high confidence* that global temperature has been increasing and that anthropogenic
6 forcings have played a major role in the increase observed over the past 60 years, with strong
7 evidence from several studies using well-established detection and attribution techniques. There
8 is *high confidence* that the role of internal variability is minor, as the CMIP5 climate models as a
9 group simulate only a minor role for internal variability over the past 60 years, and the models
10 have been assessed by IPCC AR5 as adequate for the purpose of estimating the potential role of
11 internal variability.

12 **If appropriate, estimate likelihood of impact or consequence, including short description of**
13 **basis of estimate**

14 The amount of historical warming attributable to anthropogenic forcing has a very high
15 likelihood of consequence, as it is related to the amount of future warming to be expected under
16 various emission scenarios, and the impacts of global warming are generally larger for higher
17 warming rates and higher warming amounts.

18 **Summary sentence or paragraph that integrates the above information**

19 Detection and attribution studies, climate models, observations, paleoclimate data, and physical
20 understanding lead to *high confidence (extremely likely)* that more than half of the observed
21 global mean warming since 1951 was caused by humans, and *high confidence* that internal
22 climate variability played only a minor role (and possibly even a negative contribution) in the
23 observed warming since 1951. The key message and supporting text summarizes extensive
24 evidence documented in the peer-reviewed detection and attribution literature, including in the
25 IPCC AR5.

26

27 **Key Finding 2**

28 The science of event attribution is rapidly advancing through improved understanding of the
29 mechanisms that produce extreme events and the marked progress in development of methods
30 that are used for event attribution (*high confidence*).

31 **Description of evidence base**

32 This Key Finding paraphrases a conclusion of the National Academy of Sciences report (NAS
33 2016) on attribution of extreme weather events in the context of climate change. That report

1 discusses advancements in event attribution in more detail than possible here due to space
2 limitations. Weather and climate science in general continue to seek improved physical
3 understanding of extreme weather events. One aspect of improved understanding is the ability to
4 more realistically simulate extreme weather events in models, as the models embody current
5 physical understanding in a simulation framework that can be tested on sample cases. NAS
6 (2016) provides references to studies that evaluate weather and climate models used to simulated
7 extreme events in a climate context. Such models can include coupled climate models (e.g.,
8 Taylor et al. 2012; Flato et al. 2013), atmospheric models with specified sea surface
9 temperatures, regional models for dynamical downscaling, weather forecasting models, or
10 statistical downscaling models. Appendix C includes a brief description of the evolving set of
11 methods used for event attribution, discussed in more detail in references such as NAS (2016),
12 Hulme (2014), Trenberth et al. (2015), Shepherd (2016), Horton et al. (2016), Hannart (2016),
13 and Hannart et al. (2016a,b). Most of this methodology as applied to extreme weather and
14 climate event attribution, has evolved since the European heat wave study of Stott et al. (2004).

15 **Major uncertainties**

16 While the science of event attribution is rapidly advancing, studies of individual events will
17 typically contain caveats. In some cases, attribution statements are made without a clear
18 detection of an anthropogenic influence on observed occurrences of events similar to the one in
19 question, so that there is reliance on models to assess probabilities of occurrence. In such cases
20 there will typically be uncertainties in the model-based estimations of the anthropogenic
21 influence, in the estimation of the influence of natural variability on the event's occurrence, and
22 even in the observational records related to the event (e.g., long-term records of hurricane
23 occurrence). Despite these uncertainties in individual attribution studies, the science of event
24 attribution is advancing through increased physical understanding and development of new
25 methods of attribution and evaluation of models.

26 **Assessment of confidence based on evidence and agreement, including short description of 27 nature of evidence and level of agreement**

28 There is *very high confidence* that weather and climate science are advancing in their
29 understanding of the physical mechanisms that produce extreme events. For example, hurricane
30 track forecasts have improved in part due to improved models. There is *high confidence* that new
31 methods being developed will help lead to further advances in the science of event attribution.

32 **If appropriate, estimate likelihood of impact or consequence, including short description of 33 basis of estimate**

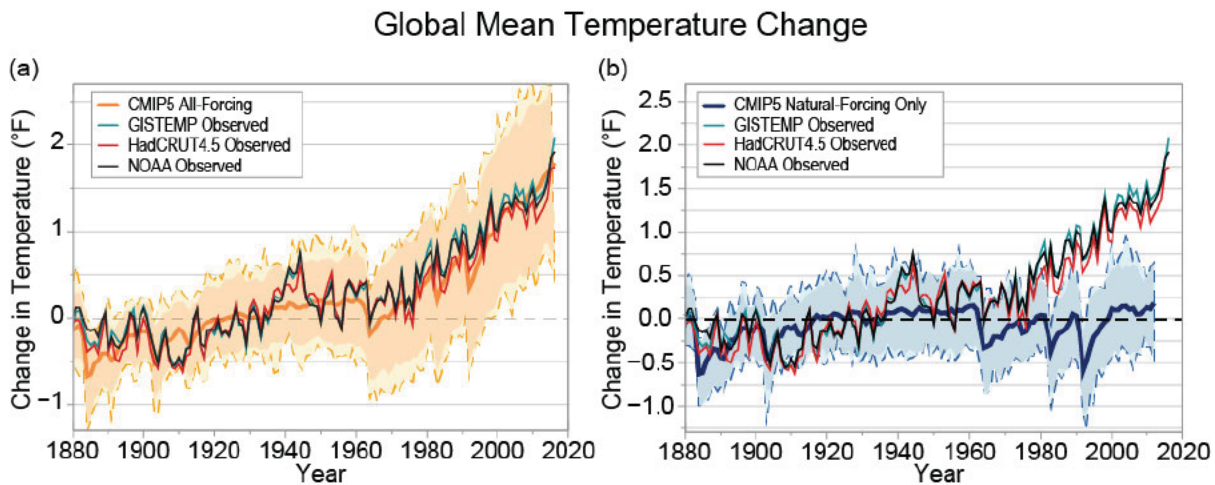
34 Improving science of event attribution has a high likelihood of impact, as it is one means by
35 which scientists can better understand the relationship between occurrence of extreme events and
36 long-term climate change. A further impact will be the improved ability to communicate this

1 information to the public and to policymakers for various uses, including improved adaptation
2 planning (Hulme 2014; NAS 2016).

3 **Summary sentence or paragraph that integrates the above information**

4 Owing to the improved physical understanding of extreme weather and climate events as the
5 science in these fields progress, and owing to the high promise of newly developed methods for
6 exploring the roles of different influences on occurrence of extreme events, there is *high*
7 *confidence* that the science of event attribution is rapidly advancing.

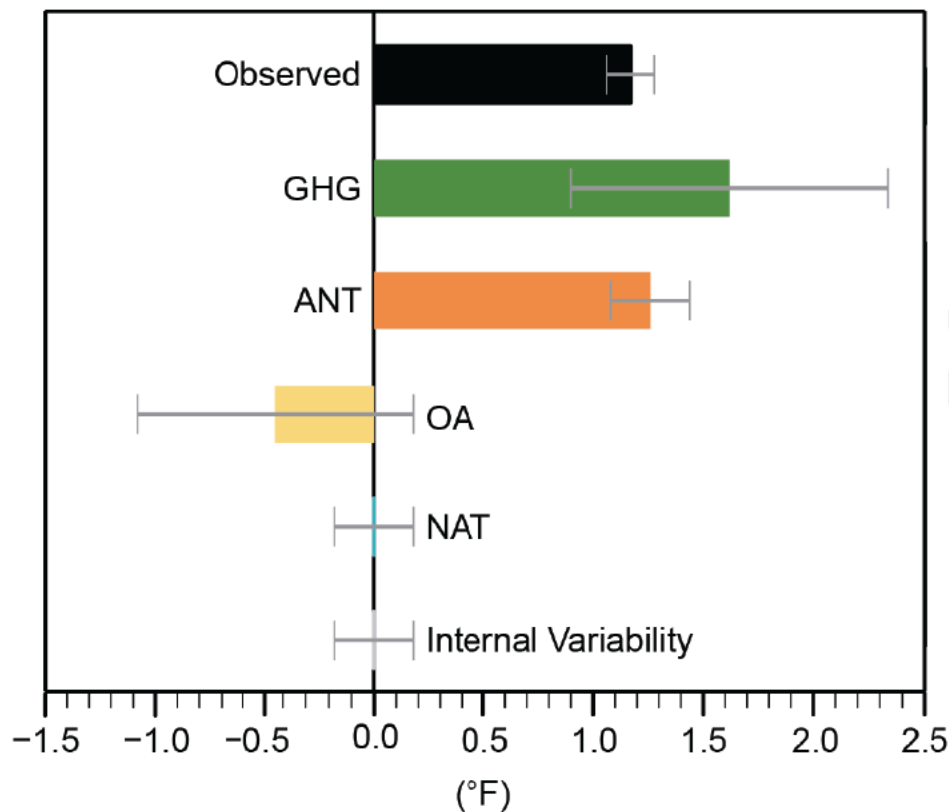
FINAL DRAFT

1 **FIGURES**

2

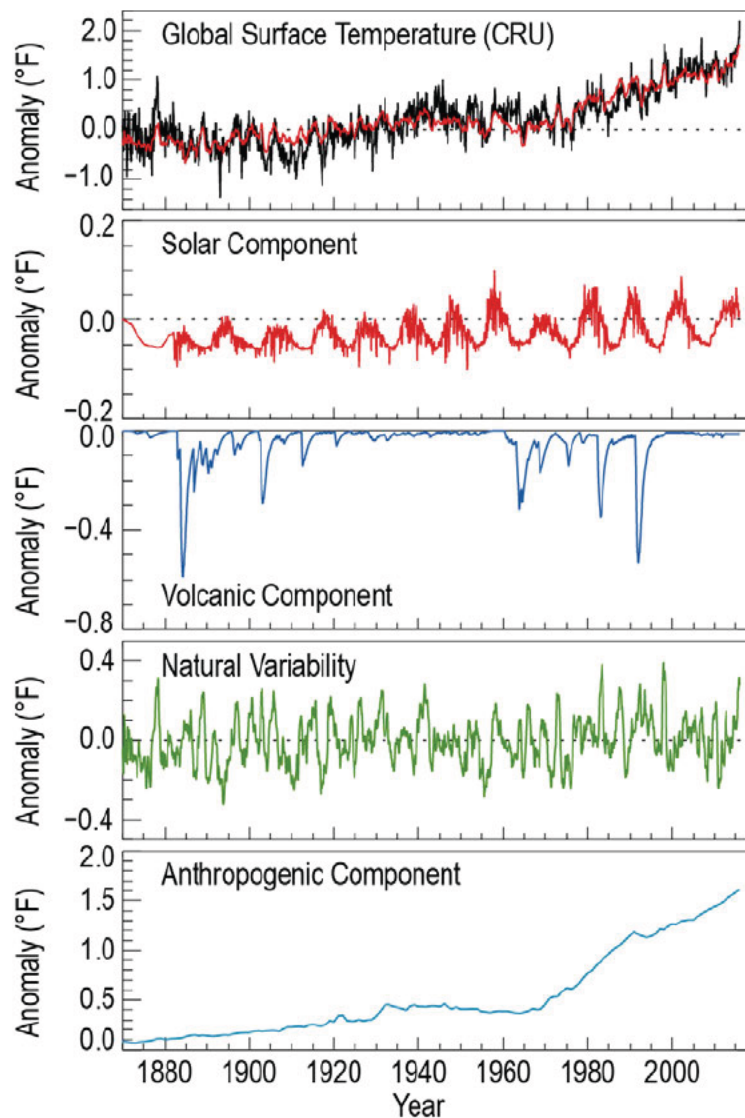
3 **Figure 3.1:** Comparison of observed global mean temperature anomalies from three
 4 observational datasets to CMIP5 climate model historical experiments using: (a) anthropogenic
 5 and natural forcings combined, or (b) natural forcings only. In (a) the thick orange curve is the
 6 CMIP5 grand ensemble mean across 36 models while the orange shading and outer dashed lines
 7 depict the ± 2 standard deviation and absolute ranges of annual anomalies across all individual
 8 simulations of the 36 models. Model data are a masked blend of surface air temperature over
 9 land regions and sea surface temperature over ice-free ocean regions to be more consistent with
 10 observations than using surface air temperature alone. All time series ($^{\circ}\text{F}$) are referenced to a
 11 1901–1960 baseline value. The simulations in (a) have been extended from 2006 through 2016
 12 using the RCP8.5 scenario projections. (b) As in (a) but the blue curves and shading are based on
 13 18 CMIP5 models using natural forcings only. See legends to identify observational datasets.
 14 Observations after about 1980 are shown to be inconsistent with the natural forcing-only models
 15 (indicating detectable warming) and also consistent with the models that include both
 16 anthropogenic and natural forcing, implying that the warming is attributable in part to
 17 anthropogenic forcing according to the models.

18



GHG - well-mixed greenhouse gases OA - other anthropogenic forcings
 ANT - all anthropogenic forcings combined NAT - natural forcings

1
 2 **Figure 3.2:** Observed global mean temperature trend (black bar) and attributable warming or
 3 cooling influences of anthropogenic and natural forcings over 1951–2010. Observations are from
 4 HadCRUT4, along with observational uncertainty (5% to 95%) error bars (Morice et al. 2012).
 5 Likely ranges (bar-whisker plots) and midpoint values (colored bars) for attributable forcings are
 6 from IPCC AR5 (Bindoff et al. 2013). GHG refers to well-mixed greenhouse gases, OA to other
 7 anthropogenic forcings, NAT to natural forcings, and ANT to all anthropogenic forcings
 8 combined. Likely ranges are broader for contributions from well-mixed greenhouse gases and for
 9 other anthropogenic forcings, assessed separately, than for the contributions from all
 10 anthropogenic forcings combined, as it is more difficult to quantitatively constrain the separate
 11 contributions of the various anthropogenic forcing agents. (Figure source: redrawn from Bindoff
 12 et al. 2013; © IPCC. Used with permission.)



1

2 **Figure 3.3:** Estimates of the contributions of several forcing factors and internal variability to
 3 global mean temperature change since 1870, based on an empirical approach using multiple
 4 linear regression and energy balance models. The top panel shows global temperature anomalies
 5 (°F) from the observations (Morice et al. 2012) in black with the multiple linear regression result
 6 in red (1901–1960 base period). The lower four panels show the estimated contribution to global
 7 mean temperature anomalies from four factors: solar variability; volcanic eruptions; internal
 8 variability related to El Niño/Southern Oscillation; and anthropogenic forcing. The
 9 anthropogenic contribution includes a warming component from greenhouse gases
 10 concentrations and a cooling component from anthropogenic aerosols. (Figure source: adapted
 11 from Canty et al. 2013.)

1 **REFERENCES**

- 2 Andres, H.J. and W.R. Peltier, 2016: Regional influences of natural external forcings on the
3 transition from the Medieval Climate Anomaly to the Little Ice Age. *Journal of Climate*, **29**,
4 5779-5800. <http://dx.doi.org/10.1175/jcli-d-15-0599.1>
- 5 Arblaster, J.M., E.-P. Lim, H.H. Hendon, B.C. Trewin, M.C. Wheeler, G. Liu, and K. Braganza,
6 2014: Understanding Australia's hottest September on record [in "Explaining Extreme
7 Events of 2013 from a Climate Perspective"]. *Bulletin of the American Meteorological*
8 *Society*, **95 (9)**, S37-S41. <http://dx.doi.org/10.1175/1520-0477-95.9.S1.1>
- 9 Bindoff, N.L., P.A. Stott, K.M. AchutaRao, M.R. Allen, N. Gillett, D. Gutzler, K. Hansingo, G.
10 Hegerl, Y. Hu, S. Jain, I.I. Mokhov, J. Overland, J. Perlwitz, R. Sebbari, and X. Zhang, 2013:
11 Detection and attribution of climate change: From global to regional. *Climate Change 2013:*
12 *The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report*
13 *of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M.
14 Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds.
15 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 867–
16 952. <http://www.climatechange2013.org/report/full-report/>
- 17 Boucher, O., D. Randall, P. Artaxo, C. Bretherton, G. Feingold, P. Forster, V.-M. Kerminen, Y.
18 Kondo, H. Liao, U. Lohmann, P. Rasch, S.K. Satheesh, S. Sherwood, B. Stevens, and X.Y.
19 Zhang, 2013: Clouds and aerosols. *Climate Change 2013: The Physical Science Basis.*
20 *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental*
21 *Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J.
22 Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press,
23 Cambridge, United Kingdom and New York, NY, USA, 571–658.
24 <http://www.climatechange2013.org/report/full-report/>
- 25 Canty, T., N.R. Mascioli, M.D. Smarte, and R.J. Salawitch, 2013: An empirical model of global
26 climate – Part 1: A critical evaluation of volcanic cooling. *Atmospheric Chemistry and*
27 *Physics*, **13**, 3997-4031. <http://dx.doi.org/10.5194/acp-13-3997-2013>
- 28 Easterling, D.R., K.E. Kunkel, M.F. Wehner, and L. Sun, 2016: Detection and attribution of
29 climate extremes in the observed record. *Weather and Climate Extremes*, **11**, 17-27.
30 <http://dx.doi.org/10.1016/j.wace.2016.01.001>
- 31 Flato, G., J. Marotzke, B. Abiodun, P. Braconnot, S.C. Chou, W. Collins, P. Cox, F. Driouech, S.
32 Emori, V. Eyring, C. Forest, P. Gleckler, E. Guilyardi, C. Jakob, V. Kattsov, C. Reason, and
33 M. Rummukainen, 2013: Evaluation of climate models. *Climate Change 2013: The Physical*
34 *Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the*
35 *Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M.
36 Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds.

- 1 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 741–
2 866. <http://www.climatechange2013.org/report/full-report/>
- 3 Gillett, N.P., J.C. Fyfe, and D.E. Parker, 2013: Attribution of observed sea level pressure trends
4 to greenhouse gas, aerosol, and ozone changes. *Geophysical Research Letters*, **40**, 2302–
5 2306. <http://dx.doi.org/10.1002/grl.50500>
- 6 Gregory, J.M., T. Andrews, and P. Good, 2015: The inconstancy of the transient climate
7 response parameter under increasing CO₂. *Philosophical Transactions of the Royal Society*
8 *A: Mathematical, Physical and Engineering Sciences*, **373**, 20140417.
9 <http://dx.doi.org/10.1098/rsta.2014.0417>
- 10 Hannart, A., 2016: Integrated optimal fingerprinting: Method description and illustration.
11 *Journal of Climate*, **29**, 1977–1998. <http://dx.doi.org/10.1175/jcli-d-14-00124.1>
- 12 Hannart, A., A. Carrassi, M. Bocquet, M. Ghil, P. Naveau, M. Pulido, J. Ruiz, and P. Tandeo,
13 2016a: DADA: data assimilation for the detection and attribution of weather and climate-
14 related events. *Climatic Change*, **136**, 155–174. <http://dx.doi.org/10.1007/s10584-016-1595-3>
- 15 Hannart, A., J. Pearl, F.E.L. Otto, P. Naveau, and M. Ghil, 2016b: Causal counterfactual theory
16 for the attribution of weather and climate-related events. *Bulletin of the American*
17 *Meteorological Society*, **97**, 99–110. <http://dx.doi.org/10.1175/bams-d-14-00034.1>
- 18 Hegerl, G.C., F.W. Zwiers, P. Braconnot, N.P. Gillett, Y. Luo, J.A.M. Orsini, N. Nicholls, J.E.
19 Penner, and P.A. Stott, 2007: Understanding and attributing climate change. *Climate Change*
20 *2007: The Physical Science Basis. Contribution of Working Group I to the Fourth*
21 *Assessment Report of the Intergovernmental Panel on Climate Change*. Solomon, S., D. Qin,
22 M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, Eds.
23 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 663–
24 745. http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch9.html
- 25 Herring, S.C., M.P. Hoerling, T.C. Peterson, and P.A. Stott, 2014: Explaining Extreme Events of
26 2013 from a Climate Perspective. *Bulletin of the American Meteorological Society*, **95**, S1–
27 S104. <http://dx.doi.org/10.1175/1520-0477-95.9.s1.1>
- 28 Herring, S.C., M.P. Hoerling, J.P. Kossin, T.C. Peterson, and P.A. Stott, 2015: Explaining
29 Extreme Events of 2014 from a Climate Perspective. *Bulletin of the American*
30 *Meteorological Society*, **96**, S1–S172. [http://dx.doi.org/10.1175/BAMS-
31 ExplainingExtremeEvents2014.1](http://dx.doi.org/10.1175/BAMS-ExplainingExtremeEvents2014.1)
- 32 Herring, S.C., A. Hoell, M.P. Hoerling, J.P. Kossin, C.J. Schreck III, and P.A. Stott, 2016:
33 Explaining Extreme Events of 2015 from a Climate Perspective. *Bulletin of the American*
34 *Meteorological Society*, **97**, S1–S145. [http://dx.doi.org/10.1175/BAMS-
35 ExplainingExtremeEvents2015.1](http://dx.doi.org/10.1175/BAMS-ExplainingExtremeEvents2015.1)

- 1 Hoerling, M., M. Chen, R. Dole, J. Eischeid, A. Kumar, J.W. Nielsen-Gammon, P. Pegion, J.
2 Perlwitz, X.-W. Quan, and T. Zhang, 2013: Anatomy of an extreme event. *Journal of*
3 *Climate*, **26**, 2811–2832. <http://dx.doi.org/10.1175/JCLI-D-12-00270.1>
- 4 Horton, R.M., J.S. Mankin, C. Lesk, E. Coffel, and C. Raymond, 2016: A review of recent
5 advances in research on extreme heat events. *Current Climate Change Reports*, **2**, 242-259.
6 <http://dx.doi.org/10.1007/s40641-016-0042-x>
- 7 Huber, M. and R. Knutti, 2012: Anthropogenic and natural warming inferred from changes in
8 Earth's energy balance. *Nature Geoscience*, **5**, 31-36. <http://dx.doi.org/10.1038/ngeo1327>
- 9 Hulme, M., 2014: Attributing weather extremes to ‘climate change’. *Progress in Physical*
10 *Geography*, **38**, 499-511. <http://dx.doi.org/10.1177/0309133314538644>
- 11 IPCC, 1990: *Climate Change: The IPCC Scientific Assessment*. Houghton, J.T., G.J. Jenkins, and
12 J.J. Ephraums, Eds. Cambridge University Press, Cambridge, United Kingdom and New
13 York, NY, USA, 212 pp.
- 14 IPCC, 1996: *Climate Change 1995: The Science of Climate Change. Contribution of Working*
15 *Group I to the Second Assessment Report of the Intergovernmental Panel on Climate*
16 *Change*. Houghton, J.T., L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K.
17 Maskell, Eds. Cambridge University Press, Cambridge, United Kingdom and New York,
18 NY, USA, 584 pp.
- 19 IPCC, 2001: *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the*
20 *Third Assessment Report of the Intergovernmental Panel on Climate Change*. Houghton,
21 J.T., Y. Ding, D.J. Griggs, M. Noquer, P.J. van der Linden, X. Dai, K. Maskell, and C.A.
22 Johnson, Eds. Cambridge University Press, Cambridge, United Kingdom and New York,
23 NY, USA, 881 pp.
- 24 IPCC, 2007: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group*
25 *I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*.
26 Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L.
27 Miller, Eds. Cambridge University Press, Cambridge. U.K, New York, NY, USA, 996 pp.
28 [http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1](http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1_report_the_physical_science_basis.htm)
29 [_report_the_physical_science_basis.htm](http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1_report_the_physical_science_basis.htm)
- 30 IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group*
31 *I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.
32 Cambridge University Press, Cambridge, UK and New York, NY, 1535 pp.
33 <http://www.climatechange2013.org/report/>

- 1 Jones, G.S., P.A. Stott, and N. Christidis, 2013: Attribution of observed historical near surface
2 temperature variations to anthropogenic and natural causes using CMIP5 simulations.
3 *Journal of Geophysical Research*, **118**, 4001-4024. <http://dx.doi.org/10.1002/jgrd.50239>
- 4 King, A.D., D.J. Karoly, M.G. Donat, and L.V. Alexander, 2014: Climate change turns
5 Australia's 2013 Big Dry into a year of record-breaking heat [in "Explaining Extreme Events
6 of 2013 from a Climate Perspective"]. *Bulletin of the American Meteorological Society*, **95**
7 (**9**), S41-S45. <http://dx.doi.org/10.1175/1520-0477-95.9.S1.1>
- 8 Knutson, T.R., F. Zeng, and A.T. Wittenberg, 2013: Multimodel assessment of regional surface
9 temperature trends: CMIP3 and CMIP5 twentieth-century simulations. *Journal of Climate*,
10 **26**, 8709-8743. <http://dx.doi.org/10.1175/JCLI-D-12-00567.1>
- 11 Knutson, T.R., F. Zeng, and A.T. Wittenberg, 2014: Multimodel assessment of extreme annual-
12 mean warm anomalies during 2013 over regions of Australia and the western tropical Pacific
13 [in "Explaining Extreme Events of 2013 from a Climate Perspective"]. *Bulletin of the*
14 *American Meteorological Society*, **95** (**9**), S26-S30. [http://dx.doi.org/10.1175/1520-0477-](http://dx.doi.org/10.1175/1520-0477-95.9.S1.1)
15 [95.9.S1.1](http://dx.doi.org/10.1175/1520-0477-95.9.S1.1)
- 16 Knutson, T.R., R. Zhang, and L.W. Horowitz, 2016: Prospects for a prolonged slowdown in
17 global warming in the early 21st century. *Nature Communications*, **7**, 13676.
18 <http://dx.doi.org/10.1038/ncomms13676>
- 19 Laepple, T. and P. Huybers 2014: Ocean surface temperature variability: large model-data
20 differences at decadal and longer periods. *Proceedings of the National Academy of Sciences*,
21 **111**, 16682-16687. <http://dx.doi.org/10.1073/pnas.1412077111>
- 22 Lewis, N. and J.A. Curry, 2015: The implications for climate sensitivity of AR5 forcing and heat
23 uptake estimates. *Climate Dynamics*, **45**, 1009-1023. [http://dx.doi.org/10.1007/s00382-014-](http://dx.doi.org/10.1007/s00382-014-2342-y)
24 [2342-y](http://dx.doi.org/10.1007/s00382-014-2342-y)
- 25 Lewis, S. and D.J. Karoly, 2014: The role of anthropogenic forcing in the record 2013 Australia-
26 wide annual and spring temperatures [in "Explaining Extreme Events of 2013 from a Climate
27 Perspective"]. *Bulletin of the American Meteorological Society*, **95** (**9**), S31-S33.
28 <http://dx.doi.org/10.1175/1520-0477-95.9.S1.1>
- 29 Marvel, K., G.A. Schmidt, R.L. Miller, and L.S. Nazarenko, 2016: Implications for climate
30 sensitivity from the response to individual forcings. *Nature Climate Change*, **6**, 386-389.
31 <http://dx.doi.org/10.1038/nclimate2888>
- 32 Masson-Delmotte, V., M. Schulz, A. Abe-Ouchi, J. Beer, A. Ganopolski, J.F. González Rouco,
33 E. Jansen, K. Lambeck, J. Luterbacher, T. Naish, T. Osborn, B. Otto-Bliesner, T. Quinn, R.
34 Ramesh, M. Rojas, X. Shao, and A. Timmermann, 2013: Information from paleoclimate
35 archives. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group*

- 1 *I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker,
2 T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex,
3 and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New
4 York, NY, USA, 383–464. <http://www.climatechange2013.org/report/full-report/>
- 5 Melillo, J.M., T.C. Richmond, and G.W. Yohe, eds., 2014: *Climate Change Impacts in the*
6 *United States: The Third National Climate Assessment*. U.S. Global Change Research
7 Program: Washington, D.C., 842 pp. <http://dx.doi.org/10.7930/JOZ31WJ2>
- 8 Morice, C.P., J.J. Kennedy, N.A. Rayner, and P.D. Jones, 2012: Quantifying uncertainties in
9 global and regional temperature change using an ensemble of observational estimates: The
10 HadCRUT4 dataset. *Journal of Geophysical Research*, **117**, D08101.
11 <http://dx.doi.org/10.1029/2011JD017187>
- 12 Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestedt, J. Huang, D. Koch, J.-F.
13 Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura, and H.
14 Zhang, 2013: Anthropogenic and natural radiative forcing. *Climate Change 2013: The*
15 *Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of*
16 *the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M.
17 Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds.
18 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 659–
19 740. <http://www.climatechange2013.org/report/full-report/>
- 20 NAS, 2016: *Attribution of Extreme Weather Events in the Context of Climate Change*. The
21 National Academies Press, Washington, DC, 186 pp. <http://dx.doi.org/10.17226/21852>
- 22 Otto, A., F.E.L. Otto, O. Boucher, J. Church, G. Hegerl, P.M. Forster, N.P. Gillett, J. Gregory,
23 G.C. Johnson, R. Knutti, N. Lewis, U. Lohmann, J. Marotzke, G. Myhre, D. Shindell, B.
24 Stevens, and M.R. Allen, 2013: Energy budget constraints on climate response. *Nature*
25 *Geoscience*, **6**, 415–416. <http://dx.doi.org/10.1038/ngeo1836>
- 26 Otto, F.E.L., N. Massey, G.J. van Oldenborgh, R.G. Jones, and M.R. Allen, 2012: Reconciling
27 two approaches to attribution of the 2010 Russian heat wave. *Geophysical Research Letters*,
28 **39**, L04702. <http://dx.doi.org/10.1029/2011GL050422>
- 29 Perkins, S.E., S.C. Lewis, A.D. King, and L.V. Alexander, 2014: Increased simulated risk of the
30 hot Australian summer of 2012/13 due to anthropogenic activity as measured by heat wave
31 frequency and intensity [in "Explaining Extreme Events of 2013 from a Climate
32 Perspective"]. *Bulletin of the American Meteorological Society*, **95** (9), S34–S37.
33 <http://dx.doi.org/10.1175/1520-0477-95.9.S1.1>

- 1 Peterson, T.C., P.A. Stott, and S. Herring, 2012: Explaining extreme events of 2011 from a
2 climate perspective. *Bulletin of the American Meteorological Society*, **93**, 1041-1067.
3 <http://dx.doi.org/10.1175/BAMS-D-12-00021.1>
- 4 Peterson, T.C., M.P. Hoerling, P.A. Stott, and S.C. Herring, 2013: Explaining Extreme Events of
5 2012 from a Climate Perspective. *Bulletin of the American Meteorological Society*, **94**, S1-
6 S74. <http://dx.doi.org/10.1175/bams-d-13-00085.1>
- 7 Pielke Sr., R.A., R. Mahmood, and C. McAlpine, 2016: Land's complex role in climate change.
8 *Physics Today*, **69**, 40-46. <http://dx.doi.org/10.1063/PT.3.3364>
- 9 Ribes, A. and L. Terray, 2013: Application of regularised optimal fingerprinting to attribution.
10 Part II: Application to global near-surface temperature. *Climate Dynamics*, **41**, 2837-2853.
11 <http://dx.doi.org/10.1007/s00382-013-1736-6>
- 12 Ribes, A., F.W. Zwiers, J.-M. Azaïs, and P. Naveau, 2017: A new statistical approach to climate
13 change detection and attribution. *Climate Dynamics*, **48**, 367-386.
14 <http://dx.doi.org/10.1007/s00382-016-3079-6>
- 15 Richardson, M., K. Cowtan, E. Hawkins, and M.B. Stolpe, 2016: Reconciled climate response
16 estimates from climate models and the energy budget of Earth. *Nature Climate Change*, **6**,
17 931-935. <http://dx.doi.org/10.1038/nclimate3066>
- 18 Rupp, D.E., P.W. Mote, N. Massey, C.J. Rye, R. Jones, and M.R. Allen, 2012: Did human
19 influence on climate make the 2011 Texas drought more probable? [in Explaining Extreme
20 Events of 2011 from a Climate Perspective]. *Bulletin of the American Meteorological
21 Society*, **93**, 1052-1054. <http://dx.doi.org/10.1175/BAMS-D-12-00021.1>
- 22 Schurer, A.P., G.C. Hegerl, M.E. Mann, S.F.B. Tett, and S.J. Phipps, 2013: Separating forced
23 from chaotic climate variability over the past millennium. *Journal of Climate*, **26**, 6954-6973.
24 <http://dx.doi.org/10.1175/jcli-d-12-00826.1>
- 25 Shepherd, T.G., 2016: A common framework for approaches to extreme event attribution.
26 *Current Climate Change Reports*, **2**, 28-38. <http://dx.doi.org/10.1007/s40641-016-0033-y>
- 27 Stern, D.I. and R.K. Kaufmann, 2014: Anthropogenic and natural causes of climate change.
28 *Climatic Change*, **122**, 257-269. <http://dx.doi.org/10.1007/s10584-013-1007-x>
- 29 Stone, D., M. Auffhammer, M. Carey, G. Hansen, C. Huggel, W. Cramer, D. Lobell, U. Molau,
30 A. Solow, L. Tibig, and G. Yohe, 2013: The challenge to detect and attribute effects of
31 climate change on human and natural systems. *Climatic Change*, **121**, 381-395.
32 <http://dx.doi.org/10.1007/s10584-013-0873-6>

- 1 Stott, P., 2016: How climate change affects extreme weather events. *Science*, **352**, 1517-1518.
2 <http://dx.doi.org/10.1126/science.aaf7271>
- 3 Stott, P.A., D.A. Stone, and M.R. Allen, 2004: Human contribution to the European heatwave of
4 2003. *Nature*, **432**, 610-614. <http://dx.doi.org/10.1038/nature03089>
- 5 Stouffer, R.J. and S. Manabe, 2017: Assessing temperature pattern projections made in 1989.
6 *Nature Climate Change*, **7**, 163-165. <http://dx.doi.org/10.1038/nclimate3224>
- 7 Taylor, K.E., R.J. Stouffer, and G.A. Meehl, 2012: An overview of CMIP5 and the experiment
8 design. *Bulletin of the American Meteorological Society*, **93**, 485-498.
9 <http://dx.doi.org/10.1175/BAMS-D-11-00094.1>
- 10 Trenberth, K.E., J.T. Fasullo, and T.G. Shepherd, 2015: Attribution of climate extreme events.
11 *Nature Climate Change*, **5**, 725-730. <http://dx.doi.org/10.1038/nclimate2657>
- 12 Wigley, T.M.L. and B.D. Santer, 2013: A probabilistic quantification of the anthropogenic
13 component of twentieth century global warming. *Climate Dynamics*, **40**, 1087-1102.
14 <http://dx.doi.org/10.1007/s00382-012-1585-8>
- 15 Zhou, J. and K.-K. Tung, 2013: Deducing multidecadal anthropogenic global warming trends
16 using multiple regression analysis. *Journal of the Atmospheric Sciences*, **70**, 3-8.
17 <http://dx.doi.org/10.1175/jas-d-12-0208.1>
- 18 Zwiers, F.W., L.V. Alexander, G.C. Hegerl, T.R. Knutson, J.P. Kossin, P. Naveau, N. Nicholls,
19 C. Schär, S.I. Seneviratne, and X. Zhang, 2013: Climate extremes: Challenges in estimating
20 and understanding recent changes in the frequency and intensity of extreme climate and
21 weather events. *Climate Science for Serving Society: Research, Modeling and Prediction*
22 *Priorities*. Asrar, G.R. and J.W. Hurrell, Eds. Springer Netherlands, Dordrecht, 339-389.
23 http://dx.doi.org/10.1007/978-94-007-6692-1_13
- 24 Zwiers, F.W., X.B. Zhang, and Y. Feng, 2011: Anthropogenic influence on long return period
25 daily temperature extremes at regional scales. *Journal of Climate*, **24**, 881-892.
26 <http://dx.doi.org/10.1175/2010jcli3908.1>

27

4. Climate Models, Scenarios, and Projections

KEY FINDINGS

1. If greenhouse gas concentrations were stabilized at their current level, existing concentrations would commit the world to at least an additional 1.1°F (0.6°C) of warming over this century relative to the last few decades (*high confidence* in continued warming, *medium confidence* in amount of warming).
2. Over the next two decades, global temperature increase is projected to be between 0.5°F and 1.3°F (0.3°–0.7°C) (*medium confidence*). This range is primarily due to uncertainties in natural sources of variability that affect short-term trends. In some regions, this means that the trend may not be distinguishable from natural variability (*high confidence*).
3. Beyond the next few decades, the magnitude of climate change depends primarily on cumulative emissions of greenhouse gases and aerosols and the sensitivity of the climate system to those emissions (*high confidence*). Projected changes range from 4.7°–8.6°F (2.6°–4.8°C) under the higher RCP8.5 scenario to 0.5°–1.3°F (0.3°–1.7°C) under the lower RCP2.6 scenario, for 2081–2100 relative to 1986–2005 (*medium confidence*).
4. Global mean atmospheric carbon dioxide (CO₂) concentration has now passed 400 ppm, a level that last occurred about 3 million years ago, when global average temperature and sea level were significantly higher than today (*high confidence*). Continued growth in CO₂ emissions over this century and beyond would lead to an atmospheric concentration not experienced in tens of millions of years (*medium confidence*). The present-day emissions rate of nearly 10 GtC per year suggests that there is no climate analog for this century any time in at least the last 50 million years (*medium confidence*).
5. The observed increase in global carbon emissions over the past 15–20 years has been consistent with higher scenarios (*very high confidence*). In 2014 and 2015, emission growth rates slowed as economic growth has become less carbon-intensive (*medium confidence*). Even if this trend continues, however, it is not yet at a rate that would meet the long-term temperature goal of the Paris Agreement of holding the increase in the global average temperature to well below 3.6°F (2°C) above preindustrial levels (*high confidence*).
6. Combining output from global climate models and dynamical and statistical downscaling models using advanced averaging, weighting, and pattern scaling approaches can result in more relevant and robust future projections. For some regions, sectors, and impacts, these techniques are increasing the ability of the scientific community to provide guidance on the use of climate projections for quantifying regional-scale changes and impacts (*medium to high confidence*).

1 **4.1. The Human Role in Future Climate**

2 The Earth's climate, past and future, is not static; it changes in response to both natural and
3 anthropogenic drivers (see Ch. 2: Physical Drivers of Climate Change). Human emissions of
4 carbon dioxide (CO₂), methane (CH₄), and other greenhouse gases now overwhelm the influence
5 of natural drivers on the external forcing of the Earth's climate (see Ch. 3: Detection and
6 Attribution). Climate change (see Ch. 1: Our Globally Changing Climate) and ocean
7 acidification (see Ch. 13: Ocean Changes) are already occurring due to the buildup of
8 atmospheric CO₂ from human emissions in the industrial era (Hartmann et al. 2013; Rhein et al.
9 2013).

10 Even if existing concentrations could be immediately stabilized, temperature would continue to
11 increase by an estimated 1.1°F (0.6°C) over this century, relative to 1980–1999 (Collins et al.
12 2013). This is because of the long timescale over which some climate feedbacks act (Ch. 2:
13 Physical Drivers of Climate Change). Over the next few decades, concentrations are projected to
14 increase and the resulting global temperature increase is projected to range from 0.5°F to 1.3°F
15 (0.3°C to 0.7°C). This range depends on natural variability, on emissions of short-lived species
16 such as CH₄ and black carbon that contribute to warming, and on emissions of sulfur dioxide
17 (SO₂) and other aerosols that have a net cooling effect (Ch. 2: Physical Drivers of Climate
18 Change). The role of emission reductions of non-CO₂ gases and aerosols in achieving various
19 global temperature targets is discussed in Chapter 14: Mitigation.

20 Over the past 15–20 years, the growth rate in carbon emissions from human activities has
21 increased from 1.5 to 2 parts per million (ppm) per year due to increasing carbon emissions from
22 human activities that track the rate projected under higher scenarios, in large part to growing
23 contributions from developing economies (Tans and Keeling 2017; Raupach et al. 2007; Le
24 Quéré et al. 2009). One possible analog for the rapid pace of change occurring today is the
25 relatively abrupt warming of 9°–14°F (5°–8°C) that occurred during the Paleocene-Eocene
26 Thermal Maximum (PETM), approximately 55–56 million years ago (Bowen et al. 2015;
27 Kirtland Turner et al. 2014; Penman et al. 2014; Crowley et al. 1990). However, emissions today
28 are nearly 10 GtC per year. During the PETM, the rate of maximum sustained carbon release was
29 less than 1.1 GtC per year, with significant differences in both background conditions and
30 forcing relative to today. This suggests that there is no precise past analog any time in the last 66
31 million years for the conditions occurring today (Zeebe et al. 2016; Crowley et al. 1990).

32 Since 2014, growth rates of global carbon emissions have declined, a trend cautiously attributed
33 to declining coal use in China, despite large uncertainties in emissions reporting (Jackson et al.
34 2016; Korsbakken et al. 2016). Economic growth is becoming less carbon-intensive, as both
35 developed and emerging economies begin to phase out coal and transition to natural gas and
36 renewable, non-carbon energy (IEA 2016; Green and Stern 2016).

1 Beyond the next few decades, the magnitude of future climate change will be primarily a
2 function of future carbon emissions and the response of the climate system to those emissions.
3 This chapter describes the scenarios that provide the basis for the range of future projections
4 presented in this report: from those consistent with continued increases in greenhouse gas
5 emissions, to others that can only be achieved by various levels of emission reductions (see Ch.
6 14: Mitigation). This chapter also describes the models used to quantify projected changes at the
7 global to regional scale and how it is possible to estimate the range in potential climate change—
8 as determined by climate sensitivity, which is the response of global temperature to a natural or
9 anthropogenic forcing (see Ch. 2: Physical Drivers of Climate Change)—that would result from
10 a given scenario (Collins et al. 2013).

11 **4.2. Future Scenarios**

12 Climate projections are typically presented for a range of plausible pathways, scenarios, or
13 targets that capture the relationships between human choices, emissions, concentrations, and
14 temperature change. Some scenarios are consistent with continued dependence on fossil fuels,
15 while others can only be achieved by deliberate actions to reduce emissions. The resulting range
16 reflects the uncertainty inherent in quantifying human activities (including technological change)
17 and their influence on climate.

18 The first Intergovernmental Panel on Climate Change Assessment Report (IPCC FAR) in 1990
19 discussed three types of scenarios: equilibrium scenarios, in which CO₂ concentration is fixed;
20 transient scenarios, in which CO₂ concentration increased by a fixed percentage each year over
21 the duration of the scenario; and four brand-new Scientific Assessment (SA90) emission
22 scenarios based on World Bank population projections (Bretherton et al. 1990). Today, that
23 original portfolio has expanded to encompass a wide variety of time-dependent or transient
24 scenarios that project how population, energy sources, technology, emissions, atmospheric
25 concentrations, radiative forcing, and/or global temperature change over time.

26 Other scenarios are simply expressed in terms of an end-goal or target, such as capping
27 cumulative carbon emissions at a specific level or stabilizing global temperature at or below a
28 certain threshold. The 2015 Paris Agreement, for example, includes an aim of “holding the
29 increase in the global average temperature to well below 2°C above pre-industrial levels and
30 pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels”
31 (UNFCCC 2015). To stabilize climate, however, it is not enough to halt the growth in annual
32 carbon emissions. It is projected that global net carbon emissions will eventually need to reach
33 zero (Collins et al. 2013) and negative emissions may be needed for a greater than 50% chance
34 of limiting warming below 3.6°F (2°C) (Smith et al. 2016; see also Ch. 14: Mitigation for a
35 discussion of negative emissions scenarios).

36 And finally some scenarios, like the “commitment” scenario in Key Finding 1 and the fixed-CO₂
37 equilibrium scenarios described above, continue to explore hypothetical questions such as, “what

1 would the world look like, long-term, if humans were able to stabilize atmospheric CO₂
2 concentration at a given level?" This section describes the different types of scenarios used
3 today, and their relevance to assessing impacts and informing policy targets.

4 **4.2.1. Emission Scenarios, Representative Concentration Pathways, and** 5 **Shared Socioeconomic Pathways**

6 The standard sets of time-dependent scenarios used by the climate modeling community as input
7 to global climate model simulations provide the basis for the majority of the future projections
8 presented in IPCC assessment reports and U.S. National Climate Assessments (NCA).

9 Developed by the integrated assessment modeling community, these sets of standard scenarios
10 have become more comprehensive with each new generation, as the original SA90 scenarios
11 (IPCC 1990) were replaced by the IS92 emission scenarios of the 1990s (Leggett et al. 1992),
12 which were in turn succeeded by the Special Report on Emissions Scenarios in 2000 (SRES,
13 Nakicenovic et al. 2000) and by the Representative Concentration Pathways in 2010 (RCPs,
14 Moss et al. 2010).

15 SA90, IS92, and SRES are all emission-based scenarios. They begin with a set of storylines that
16 were based on population projections initially. By SRES, they had become much more complex,
17 laying out a consistent picture of demographics, international trade, flow of information and
18 technology, and other social, technological, and economic characteristics of future worlds. These
19 assumptions are then fed through socioeconomic and Integrated Assessment Models (IAMs) to
20 derive emissions. For SRES, the use of various IAMs resulted in multiple emissions scenarios
21 corresponding to each storyline; however, one scenario for each storyline was selected as the
22 representative "marker" scenario to be used as input to global models to calculate the resulting
23 atmospheric concentrations, radiative forcing, and climate change for the higher A1fi (fossil-
24 intensive), mid-high A2, mid-low B2, and lower B1 storylines. IS92-based projections were used
25 in the IPCC Second and Third Assessment Reports (SAR and TAR; Kattenberg et al. 1996;
26 Cubasch et al. 2001) and the first NCA (NAO 2001). Projections based on SRES scenarios were
27 used in the second and third NCAs (Karl et al. 2009; Melillo et al. 2014) as well as the IPCC
28 TAR and Fourth Assessment Reports (AR4; Cubasch et al. 2001; Meehl et al. 2007).

29 The most recent set of time-dependent scenarios, RCPs, builds on these two decades of scenario
30 development. However, RCPs differ from previous sets of standard scenarios in at least four
31 important ways. First, RCPs are not emissions scenarios; they are radiative forcing scenarios.
32 Each scenario is tied to one value: the change in radiative forcing at the tropopause by 2100
33 relative to preindustrial levels. The four RCPs are numbered according to the change in radiative
34 forcing by 2100: +2.6, +4.5, +6.0 and +8.5 watts per square meter (W/m²) (van Vuuren et al.
35 2011; Thomson et al. 2011; Masui et al. 2011; Riahi et al. 2011).

36 The second difference is that, starting from these radiative forcing values, IAMs are used to work
37 backwards to derive a range of emissions trajectories and corresponding policies and

1 technological strategies for each RCP that would achieve the same ultimate impact on radiative
2 forcing. From the multiple emissions pathways that could lead to the same 2100 radiative forcing
3 value, an associated pathway of annual carbon dioxide and other anthropogenic emissions of
4 greenhouse gases, aerosols, air pollutants, and other short-lived species has been selected for
5 each RCP to use as input to future climate model simulations (e.g., Meinshausen et al. 2011;
6 Cubasch et al. 2013). In addition, RCPs provide climate modelers with gridded trajectories of
7 land use and land cover.

8 A third difference between the RCPs and previous scenarios is that while none of the SRES
9 scenarios included a scenario with explicit policies and measures to limit climate forcing, all of
10 the three lower RCP scenarios (2.6, 4.5, and 6.0) are climate-policy scenarios. At the higher end
11 of the range, the RCP8.5 scenario corresponds to a future where carbon and methane emissions
12 continue to rise as a result of fossil fuel use, albeit with significant declines in emission growth
13 rates over the second half of the century (Figure 4.1), significant reduction in aerosols, and
14 modest improvements in energy intensity and technology (Riahi et al. 2011). Atmospheric
15 carbon dioxide levels for RCP8.5 are similar to those of the SRES A1fi scenario: they rise from
16 current-day levels of 400 up to 936 parts per million (ppm). CO₂-equivalent levels (including
17 emissions of other non-CO₂ greenhouse gases, aerosols, and other substances that affect climate)
18 reach more than 1200 ppm by 2100, and global temperature is projected to increase by 5.4°–
19 9.9°F (3°–5.5°C) by 2100 relative to the 1986–2005 average. RCP8.5 reflects the upper range of
20 the open literature on emissions, but is not intended to serve as an upper limit on possible
21 emissions nor as a business-as-usual or reference scenario for the other three scenarios.

22 Under the lower RCP4.5 and RCP2.6 scenarios (van Vuuren et al. 2011; Thomson et al. 2011),
23 atmospheric CO₂ levels remain below 550 and 450 ppm by 2100, respectively. Emissions of
24 other substances are also lower; by 2100, CO₂-equivalent concentrations that include all
25 emissions from human activities reach 580 ppm under RCP4.5 and 425 ppm under RCP2.6.
26 RCP4.5 is similar to SRES B1, but the RCP2.6 scenario is much lower than any SRES scenario
27 because it includes the option of using policies to achieve net negative carbon dioxide emissions
28 before the end of the century, while SRES scenarios do not. RCP-based projections were used in
29 the most recent IPCC Fifth Assessment Report (AR5; Collins et al. 2013) and the third NCA
30 (Melillo et al. 2014) and will be used in the upcoming fourth NCA as well.

31 Within the RCP family, individual scenarios have not been assigned a formal likelihood. Higher-
32 numbered scenarios correspond to higher emissions and a larger and more rapid global
33 temperature change (Figure 4.1); the range of values covered by the scenarios was chosen to
34 reflect the then-current range in the open literature. Since the choice of scenario constrains the
35 magnitudes of future changes, most assessments (including this one; see Ch. 6: Temperature
36 Change) quantify future change and corresponding impacts under a range of future scenarios that
37 reflect the uncertainty in the consequences of human choices over the coming century.

1 Fourth, a broad range of socioeconomic scenarios were developed independently from the RCPs
2 and a subset of these constrained, using emissions limitations policies consistent with their
3 underlying storylines, to create five Shared Socioeconomic Pathways (SSPs) with climate
4 forcing that matches the RCP values. This pairing of SSPs and RCPs is designed to meet the
5 needs of the impacts, adaptation, and vulnerability (IAV) communities, enabling them to couple
6 alternative socioeconomic scenarios with the climate scenarios developed using RCPs to explore
7 the socioeconomic challenges to climate mitigation and adaptation (O'Neill et al. 2014). The five
8 SSPs consist of SSP1 ("Sustainability"; low challenges to mitigation and adaptation), SSP2
9 ("Middle of the Road"; middle challenges to mitigation and adaptation), SSP3 ("Regional
10 Rivalry"; high challenges to mitigation and adaptation), SSP4 ("Inequality"; low challenges to
11 mitigation, high challenges to adaptation), and SSP5 ("Fossil-fueled Development"; high
12 challenges to mitigation, low challenges to adaptation). Each scenario has an underlying SSP
13 narrative, as well as consistent assumptions regarding demographics, urbanization, economic
14 growth, and technology development. Only SSP5 produces a reference scenario that is consistent
15 with RCP8.5; climate forcing in the other SSPs' reference scenarios that don't include climate
16 policy remains below 8.5 W/m^2 . In addition, the nature of SSP3 makes it impossible for that
17 scenario to produce a climate forcing as low as 2.6 W/m^2 . While new research is under way to
18 explore scenarios that limit climate forcing to 2.0 W/m^2 , neither the RCPs nor the SSPs have
19 produced scenarios in that range.

20 **[INSERT FIGURE 4.1 HERE]**

21 **4.2.2. Alternative Scenarios**

22 The emissions and radiative forcing scenarios described above include a component of time: how
23 much will climate change, and by when? Ultimately, however, the magnitude of human-induced
24 climate change depends less on the year-to-year emissions than it does on the net amount of
25 carbon, or cumulative carbon, emitted into the atmosphere. The lower the atmospheric
26 concentrations of CO_2 , the greater the chance that eventual global temperature change will not
27 reach the high-end temperature projections, or possibly remain below 3.6°F (2°C) relative to
28 preindustrial levels, consistent with the long-term temperature goal included in the Paris
29 Agreement.

30 Cumulative carbon targets offer an alternative approach to expressing a goal designed to limit
31 global temperature to a certain level. As discussed in Chapter 14: Mitigation, it is possible to
32 quantify the expected amount of carbon that can be emitted globally in order to meet a specific
33 global warming target such as 3.6°F (2°C) or even 2.7°F (1.5°C)—although if current carbon
34 emission rates of just under 10 GtC per year were to continue, the lower target would be reached
35 in a matter of years. The higher target would be reached in a matter of decades (see Ch. 14:
36 Mitigation).

1 Under RCP4.5, global temperature change is more likely than not to exceed 3.6°F (2°C) (IIASA
2 2016; Collins et al. 2013), whereas under RCP2.6 it is likely to remain below 3.6°F (2°C)
3 (Sanderson et al. 2016a; Collins et al. 2013). While new research is under way to explore
4 scenarios consistent with limiting climate forcing to 2.0 W/m², a level consistent with limiting
5 global mean surface temperature change to 2.7°F (1.5°C), neither the RCPs nor the SSPs have
6 produced scenarios that allow for such a small amount of temperature change (Sanderson et al.
7 2016a; see also Ch. 14: Mitigation).

8 **[INSERT FIGURE 4.2 HERE]**

9 Future projections are most commonly summarized for a given future scenario (for example,
10 RCP8.5 or 4.5) over a range of future climatological time periods (for example, temperature
11 change in 2040–2079 or 2070–2099 relative to 1980–2009). While this approach has the
12 advantage of developing projections for a specific time horizon, uncertainty in future projections
13 is relatively high, incorporating both the uncertainty due to multiple scenarios as well as
14 uncertainty regarding the response of the climate system to human emissions. These
15 uncertainties increase the further out in time the projections go. Using these same transient,
16 scenario-based simulations, however, it is possible to analyze the projected changes for a given
17 global mean temperature (GMT) threshold by extracting a time slice (typically 20 years)
18 centered around the point in time at which that change is reached (Fig. 4.2).

19 Derived GMT scenarios offer a way for the public and policymakers to understand the impacts
20 for any given temperature threshold, as many physical changes and impacts have been shown to
21 scale with global mean surface temperature (GMT), including shifts in average precipitation,
22 extreme heat, runoff, drought risk, wildfire, temperature-related crop yield changes, and even
23 risk of coral bleaching (e.g., NRC 2011; Collins et al. 2013; Frieler et al. 2013; Swain and
24 Hayhoe 2015). They also allow scientists to highlight the effect of global mean temperature on
25 projected regional change by de-emphasizing the uncertainty due to both climate sensitivity and
26 future scenarios (Herger et al. 2015; Swain and Hayhoe 2015). This approach is less useful for
27 those impacts that vary based on rate of change, such as species migrations, or where equilibrium
28 changes are very different from transient effects, such as sea level rise.

29 Pattern scaling techniques (Mitchell 2003) are based on a similar assumption to GMT scenarios,
30 namely that large-scale patterns of regional change will scale with global temperature change.
31 These techniques can be used to quantify regional projections for scenarios that are not readily
32 available in preexisting databases of global climate model simulations, including changes in both
33 mean and extremes (e.g., Fix et al. 2016). A comprehensive assessment both confirms and
34 constrains the validity of applying pattern scaling to quantify climate response to a range of
35 projected future changes (Tebaldi and Arblaster 2014). For temperature-based climate targets,
36 these pattern scaling frames or GMT scenarios offer the basis for more consistent comparisons
37 across studies examining regional change or potential risks and impacts.

1 **4.2.3. Analogs from the Paleoclimate Record**

2 Most CMIP5 simulations project transient changes in climate through 2100; a few simulations
3 extend to 2200, 2300, or beyond. However, as discussed in Chapter 2: Physical Drivers of
4 Climate Change, the long-term impact of human activities on the carbon cycle and Earth's
5 climate over the next few decades and for the remainder of this century can only be assessed by
6 considering changes that occur over multiple centuries and even millennia (NRC 2011).

7 In the past, there have been several examples of “hothouse” climates where carbon dioxide
8 concentrations and/or global mean temperatures were similar to preindustrial, current, or
9 plausible future levels. These periods are sometimes referenced as analogs, albeit imperfect and
10 incomplete, of future climate (e.g., Crowley 1990).

11 The last interglacial period, approximately 125,000 years ago, is known as the Eemian. During
12 that time, CO₂ concentration was similar to preindustrial, around 280 ppm (Schneider et al.
13 2013). Global mean temperature was approximately 1.8°–3.6°F (1°–2°C) higher than
14 preindustrial levels (Lunt et al. 2012; Otto-Bleisner et al. 2013), although the poles were
15 significantly warmer (NEEM 2013; Jouzel et al. 2007) and sea level was 6 to 9 meters (20 to 30
16 feet) higher than today (Fig. 4.3; Kopp et al. 2009). During the Pliocene, approximately 3 million
17 years ago, long-term CO₂ concentration was similar to today's, around 400 ppm (Seki et al.
18 2010)—although this level was sustained over long periods of time, whereas today CO₂
19 concentration is increasing rapidly. At that time, global mean temperature was approximately
20 3.6°–6.3°F (2°–3.5°C) above preindustrial, and sea level was somewhere between 66 ± 33 feet
21 (20 ± 10 meters) higher than today (Haywood et al. 2013; Dutton et al. 2015; Miller et al. 2012).

22 Under the RCP8.5 scenario, CO₂ concentrations are projected to reach 936 ppm by 2100. During
23 the Eocene, 35 to 55 million years ago, CO₂ levels were between 680 and 1260 ppm, or
24 somewhere between two and a half to four and a half times above preindustrial levels (Jagniecki
25 et al. 2015). If Eocene conditions are used as an analog, this suggests that if the CO₂
26 concentrations projected to occur under the RCP8.5 scenario by 2100 were sustained over long
27 periods of time, global temperatures would be approximately 9°–14°F (5°–8°C) above
28 preindustrial levels (Royer 2014). During the Eocene, there were no permanent land-based ice
29 sheets; Antarctic glaciation did not begin until approximately 34 million years ago (Pagani et al.
30 2011). Calibrating sea level rise models against past climate suggests that, under the RCP8.5
31 scenario, Antarctica could contribute 3 feet (1 meter) of sea level rise by 2100 and 50 feet (15
32 meters) by 2500 (DeConto and Pollard 2016). If atmospheric CO₂ were sustained at levels
33 approximately two to three times above preindustrial for tens of thousands of years, it is
34 estimated that Greenland and Antarctic ice sheets could melt entirely (Gasson et al. 2014),
35 resulting in approximately 215 feet (65 meters) of sea level rise (Vaughn et al. 2013).

36

1 **4.3. Modeling Tools**

2 Using transient scenarios such as SRES and RCP as input, global climate models (GCMs)
3 produce trajectories of future climate change, including global and regional changes in
4 temperature, precipitation, and other physical characteristics of the climate system (Collins et al.
5 2013; Kirtman et al. 2013; see also Ch. 6: Temperature Change and Ch. 7: Precipitation Change).
6 The resolution of global models has increased significantly since IPCC FAR (IPCC 1990).
7 However, even the latest experimental high-resolution simulations at 25–50 km (15–30 miles)
8 per gridbox, are unable to simulate all of the important fine-scale processes occurring at regional
9 to local scales. Instead, downscaling methods are often used to correct systematic biases, or
10 offsets relative to observations, in global projections and translate them into the higher-resolution
11 information typically required for impact assessments.

12 Dynamical downscaling with regional climate models (RCMs) directly simulates the response of
13 regional climate processes to global change, while empirical statistical downscaling models
14 (ESDMs) tend to be more flexible and computationally efficient. Comparing the ability of
15 dynamical and statistical methods to reproduce observed climate shows that the relative
16 performance of the two approaches depends on the assessment criteria (Vattinada Ayar et al.
17 2016). Although dynamical and statistical methods can be combined into a hybrid framework,
18 many assessments still tend to rely on one or the other type of downscaling, where the choice is
19 based on the needs of the assessment. The projections shown in this report, for example, are
20 either based on the original GCM simulations or on simulations that have been statistically
21 downscaled using the LOcalized Constructed Analogs method (LOCA; Pierce et al. 2014). This
22 section describes the global climate models used today, briefly summarizes their development
23 over the past few decades, and explains the general characteristics and relative strengths and
24 weaknesses of the dynamical and statistical downscaling.

25 **4.3.1. Global Climate Models**

26 Global climate models (GCMs) are mathematical frameworks that were originally built on
27 fundamental equations of physics. They account for the conservation of energy, mass, and
28 momentum and how these are exchanged among different components of the climate system.
29 Using these fundamental relationships, GCMs are able to simulate many important aspects of
30 Earth's climate: large-scale patterns of temperature and precipitation, general characteristics of
31 storm tracks and extratropical cyclones, and observed changes in global mean temperature and
32 ocean heat content as a result of human emissions (Flato et al. 2013).

33 The complexity of climate models has grown over time, as they incorporate additional
34 components of the Earth's climate system (Figure 4.3). For example, GCMs were previously
35 referred to as “general circulation models” when they included only the physics needed to
36 simulate the general circulation of the atmosphere. Today, global climate models simulate many
37 more aspects of the climate system: atmospheric chemistry and aerosols, land surface

1 interactions including soil and vegetation, land and sea ice, and increasingly even an interactive
2 carbon cycle and/or biogeochemistry. Models that include this last component are also referred
3 to as Earth system models (ESMs).

4 **[INSERT FIGURE 4.3 HERE]**

5 In addition to expanding the number of processes in the models and improving the treatment of
6 existing processes, the total number of GCMs and the average horizontal spatial resolution of the
7 models has increased over time, as computers become more powerful, and with each successive
8 version of the World Climate Research Programme's (WCRP's) Coupled Model
9 Intercomparison Project (CMIP). CMIP5 provides output from over 50 GCMs with spatial
10 resolutions ranging from about 50 to 300 km (30 to 200 miles) per horizontal size and variable
11 vertical resolution on the order of hundreds of meters in the troposphere or lower atmosphere.

12 It is often assumed that higher-resolution, more complex, and more up-to-date models will
13 perform better and/or produce more robust projections than previous-generation models.
14 However, a large body of research comparing CMIP3 and CMIP5 simulations concludes that,
15 although the spatial resolution of CMIP5 has improved relative to CMIP3, the overall
16 improvement in performance is relatively minor. For certain variables, regions, and seasons,
17 there is some improvement; for others, there is little difference or even sometimes degradation in
18 performance, as greater complexity does not necessarily imply improved performance (Knutti
19 and Sedlacek 2012; Kumar et al. 2014; Sheffield et al. 2013, 2014). CMIP5 simulations do show
20 modest improvement in model ability to simulate ENSO (Bellenger et al. 2014), some aspects of
21 cloud characteristics (Lauer and Hamilton 2012), and the rate of Arctic sea ice loss (Wang and
22 Overland 2012), as well as greater consensus regarding projected drying in the southwestern
23 United States and Mexico (Sheffield et al. 2014),

24 Projected changes in hurricane rainfall rates and the reduction in tropical storm frequency are
25 similar, but CMIP5-based projections of increases in the frequency of the strongest hurricanes
26 are generally smaller than CMIP3-based projections (Knutson et al. 2013). On the other hand,
27 many studies find little to no significant difference in large-scale patterns of changes in both
28 mean and extreme temperature and precipitation from CMIP3 to CMIP5 (Kharin et al. 2013;
29 Knutti and Sedlacek 2013; Sheffield et al. 2014; Sun et al. 2015). Also, CMIP3 simulations are
30 driven by SRES scenarios, while CMIP5 simulations are driven by RCP scenarios. Although
31 some scenarios have comparable CO₂ concentration pathways (Figure 4.1), differences in non-
32 CO₂ species and aerosols could be responsible for some of the differences between the
33 simulations (Sheffield et al. 2014). In NCA3, projections were based on simulations from both
34 CMIP3 and CMIP5. In this report, future projections are based on CMIP5 alone.

35 GCMs are constantly being expanded to include more physics, chemistry, and, increasingly, even
36 the biology and biogeochemistry at work in the climate system (Figure 4.3). Interactions within
37 and between the various components of the climate system result in positive and negative

1 feedbacks that can act to enhance or dampen the effect of human emissions on the climate
2 system. The extent to which models explicitly resolve or incorporate these processes determines
3 their climate sensitivity, or response to external forcing (see Ch. 2: Physical Drivers of Climate
4 Change, Section 2.5 on climate sensitivity, and Ch. 15: Potential Surprises on the importance of
5 processes not included in present-day GCMs). These models build on previous generations and
6 therefore many models are not independent from each other. Many share both ideas and model
7 components or code, complicating the interpretation of multimodel ensembles that often are
8 assumed to be independent (Knutti et al. 2013; Sanderson et al. 2015). Consideration of the
9 independence of different models is one of the key pieces of information going into the
10 weighting approach used in this report (see Appendix B: Weighting Strategy).

11 **4.3.2. Regional Climate Models**

12 Dynamical downscaling models are often referred to as regional climate models (RCMs), since
13 they include many of the same physical processes that make up a global climate model, but
14 simulate these processes at higher spatial resolution over smaller regions, such as the western or
15 eastern United States (Figure 4.4; Kotamarthi et al. 2016). Most RCM simulations use GCM
16 fields from pre-computed global simulations as boundary conditions. This approach allows
17 RCMs to draw from a broad set of GCM simulations, such as CMIP5, but does not allow for
18 possible two-way feedbacks and interactions between the regional to global scales. Dynamical
19 downscaling can also be conducted interactively through nesting a higher-resolution regional
20 grid or model into a global model during a simulation. Both approaches directly simulate the
21 dynamics of the regional climate system, but only the second allows for two-way interactions
22 between regional and global change.

23 RCMs are computationally intensive, providing a broad range of output variables that resolve
24 regional climate features important for assessing climate impacts. The size of individual grid
25 cells can be as fine as 1 to 2 km (0.6 to 1.2 miles) per gridbox in some studies, but more
26 commonly range from about 10 to 50 km (6 to 30 miles). At smaller spatial scales, and for
27 specific variables and areas with complex terrain, such as coastlines or mountains, regional
28 climate models have been shown to add value (Feser et al. 2011). As model resolution increases,
29 RCMs are also able to explicitly resolve some processes that are parameterized in global models.
30 For example, some models with spatial scales below 4 km (2.5 miles) are able to dispense with
31 the parameterization of convective precipitation, a significant source of error and uncertainty in
32 coarser models (Prein et al. 2015). RCMs can also incorporate changes in land use, land cover, or
33 hydrology into local climate at spatial scales relevant to planning and decision-making at the
34 regional level.

35 Despite the differences in resolution, RCMs are still subject to many of the same types of
36 uncertainty as GCMs. Even the highest-resolution RCM cannot explicitly model physical
37 processes that occur at even smaller scales than the model is able to resolve; instead,
38 parameterizations are required. Similarly, RCMs might not include a process or an interaction

1 that is not yet well understood, even if it is able to be resolved at the spatial scale of the model.
2 One additional source of uncertainty unique to RCMs arises from the fact that at their boundaries
3 RCMs require output from GCMs to provide large-scale circulation such as winds, temperature,
4 and moisture; the degree to which the driving GCM correctly captures large-scale circulation and
5 climate will affect the performance of the RCM (Wang et al. 2004). RCMs can be evaluated by
6 directly comparing their output to observations; although this process can be challenging and
7 time-consuming, it is often necessary to quantify the appropriate level of confidence that can be
8 placed in their output (Kotamarthi et al. 2016).

9 Studies have also highlighted the importance of large ensemble simulations when quantifying
10 regional change (Xie et al. 2015). However, due to their computational demand, extensive
11 ensembles of RCM-based projections are rare. The largest ensemble of RCM simulations for
12 North America is hosted by the North American Regional Climate Change Assessment Program
13 (NARCCAP). NARCCAP simulations are useful for examining patterns of change over North
14 America and providing a broad suite of surface and upper-air variables to characterize future
15 impacts. Since this ensemble is based on four simulations from four CMIP3 GCMs for a single
16 mid-high SRES scenario, these runs do not encompass the full range of uncertainty in future
17 projections due to human activities, natural variability, and climate sensitivity.

18 **[INSERT FIGURE 4.4 HERE]**

19 **4.3.3. Empirical Statistical Downscaling Models**

20 Empirical statistical downscaling models (ESDMs) combine GCM output with historical
21 observations to translate large-scale predictors or patterns into high-resolution projections at the
22 scale of observations. The observations used in an ESDM can range from individual weather
23 stations to gridded datasets. As output, they can generate a range of products, from large grids to
24 analyses optimized for a specific location, variable, or decision-context.

25 Statistical techniques are varied, from the simple difference or delta approaches used in the first
26 NCA (subtracting historical simulated values from future values, and adding the resulting delta
27 to historical observations; NAST 2001) to the parametric quantile mapping approach used in
28 NCA2 and 3 (Stoner et al. 2012; Karl et al. 2009; Melillo et al. 2014). Even more complex
29 clustering and advanced mathematical modeling techniques can rival dynamical downscaling in
30 their demand for computational resources (e.g. Vrac et al. 2007).

31 Statistical models are generally flexible and less computationally demanding than RCMs. A
32 number of databases using a variety of methods, including LOCA, provide statistically
33 downscaled projections for a continuous period from 1960 to 2100 using a large ensemble of
34 global models and a range of higher and lower future scenarios to capture uncertainty due to
35 human activities. ESDMs are also effective at removing biases in historical simulated values,
36 leading to a good match between the average (multidecadal) statistics of observed and

1 statistically downscaled climate at the spatial scale and over the historical period of the
2 observational data used to train the statistical model. Unless methods can simultaneously
3 downscale multiple variables, however, statistical downscaling carries the risk of altering some
4 of the physical interdependences between variables. ESDMs are also limited in that they require
5 observational data as input; the longer and more complete the record, the greater the confidence
6 that the ESDM is being trained on a representative sample of climatic conditions for that
7 location. Application of ESDMs to remote locations with sparse temporal and/or spatial records
8 is challenging, though in many cases reanalysis (Brands et al. 2012) or even monthly satellite
9 data (Thrasher et al. 2013) can be used in lieu of in situ observations. Lack of data availability
10 can also limit the use of ESDMs in applications that require more variables than temperature and
11 precipitation. Finally, statistical models are based on the key assumption that the relationship
12 between large-scale weather systems and local climate or the spatial pattern of surface climate
13 will remain stationary over the time horizon of the projections. This assumption may not hold if
14 climate change alters local feedback processes that affect these relationships.

15 ESDMs can be evaluated in three different ways, each of which provides useful insight into
16 model performance (Kotamarthi et al. 2016). First, the model's goodness-of-fit can be quantified
17 by comparing downscaled simulations for the historical period with the identical observations
18 used to train the model. Second, the generalizability of the model can be determined by
19 comparing downscaled historical simulations with observations from a different time period than
20 was used to train the model; this is often accomplished via cross-validation. Third and most
21 importantly, the stationarity of the model can be evaluated through a "perfect model" experiment
22 using coarse-resolution GCM simulations to generate future projections, then comparing these
23 with high-resolution GCM simulations for the same future time period. Initial analyses using the
24 perfect model approach have demonstrated that the assumption of stationarity can vary
25 significantly by ESDM method, by quantile, and by the time scale (daily or monthly) of the
26 GCM input (Dixon et al. 2016).

27 ESDMs are best suited for analyses that require a broad range of future projections of standard,
28 near-surface variables such as temperature and precipitation, at the scale of observations that
29 may already be used for planning purposes. If the study needs to evaluate the full range of
30 projected changes provided by multiple models and scenarios, then statistical downscaling may
31 be more appropriate than dynamical downscaling. However, even within statistical downscaling,
32 selecting an appropriate method for any given study depends on the questions being asked (see
33 Kotamarthi et al. 2016 for further discussion on selection of appropriate downscaling methods).
34 This report uses projections generated by the LOcalized Constructed Analogs approach (LOCA;
35 Pierce et al. 2014) that spatially matches model-simulated days, past and future, to analogs from
36 observations.

37

1 **4.3.4. Averaging, Weighting, and Selection of Global Models**

2 The results of individual climate model simulations using the same inputs can differ from each
3 other over shorter time scales ranging from several years to several decades (Deser et al.
4 2012a,b). These differences are the result of normal, natural variability, as well as the various
5 ways models characterize various small-scale processes. Although decadal predictability is an
6 active research area (Deser et al. 2014), the timing of specific natural variations is largely
7 unpredictable beyond several seasons. For this reason, multimodel simulations are generally
8 averaged to remove the effects of randomly occurring natural variations from long-term trends
9 and make it easier to discern the impact of external drivers, both human and natural, on the
10 Earth's climate. Multimodel averaging is typically the last stage in any analysis, used to prepare
11 figures showing projected changes in quantities such as annual or seasonal temperature or
12 precipitation (see Ch. 6: Temperature Change and Ch. 7: Precipitation Change). While the effect
13 of averaging on the systematic errors depends on the extent to which models have similar errors
14 or offsetting errors, there is growing recognition of the value of large ensembles of climate
15 model simulations in addressing uncertainty in both natural variability and scientific modeling
16 (e.g., Deser et al. 2012a).

17 Previous assessments have used a simple average to calculate the multimodel ensemble. This
18 approach implicitly assumes each climate model is independent from the others and of equal
19 ability. Neither of these assumptions, however, are completely valid. Some models share many
20 components with other models in the CMIP5 archive, whereas others have been developed
21 largely in isolation (Knutti et al. 2013; Sanderson et al. 2015). Also, some models are more
22 successful than others at replicating observed climate and trends over the past century, at
23 simulating the large-scale dynamical features responsible for creating or affecting the average
24 climate conditions over a certain region, such as the Arctic or the Caribbean (e.g., M. Wang et al.
25 2007; C. Wang et al. 2014; Ryu and Hayhoe 2014), or at simulating past climates with very
26 different states than present day (Braconnot et al. 2012). Evaluation of the success of a specific
27 model often depends on the variable or metric being considered in the analysis, with some
28 models performing better than others for certain regions or variables. However, all future
29 simulations agree that both global and regional temperatures will increase over this century in
30 response to increasing emissions of greenhouse gases from human activities.

31 Can more sophisticated weighting or model selection schemes improve the quality of future
32 projections? In the past, model weights were often based on historical performance; yet
33 performance varies by region and variable, and may not equate to improved future projections
34 (Knutti and Sedlacek 2013). For example, ranking GCMs based on their average biases in
35 temperature gives a very different result than when the same models are ranked based on their
36 ability to simulate observed temperature trends (Jun et al. 2008; Giorgi and Coppola 2010). If
37 GCMs are weighted in a way that does not accurately capture the true uncertainty in regional
38 change, the result can be less robust than an equally-weighted mean (Weigel et al. 2010).

1 Although the intent of weighting models is to increase the robustness of the projections, by
2 giving lesser weight to outliers a weighting scheme may increase the risk of underestimating the
3 range of uncertainty, a tendency that has already been noted in multi-model ensembles (see Ch.
4 15: Potential Surprises).

5 Despite these challenges, for the first time in an official U.S. Global Change Research Program
6 report, this assessment uses model weighting to refine future climate change projections (Knutti
7 et al. 2017; see also Appendix B: Weighting Strategy). The weighting approach is unique: it
8 takes into account the interdependence of individual climate models as well as their relative
9 abilities in simulating North American climate. Understanding of model history, together with
10 the fingerprints of particular model biases, has been used to identify model pairs that are not
11 independent. In this report, model independence and selected global and North American model
12 quality metrics are considered in order to determine the weighting parameters (Knutti et al.
13 2017). Evaluation of this approach shows improved performance of the weighted ensemble over
14 the Arctic, a region where model-based trends often differ from observations, but little change in
15 global-scale temperature response and in other regions where modeled and observed trends are
16 similar, although there are small regional differences in the statistical significance of projected
17 changes. The choice of metric used to evaluate models has very little effect on the independence
18 weighting, and some moderate influence on the skill weighting if only a small number of
19 variables are used to assess model quality. Because a large number of variables are combined to
20 produce a comprehensive “skill metric,” the metric is not highly sensitive to any single variable.
21 All multimodel figures in this report use the approach described in Appendix B: Weighting
22 Strategy.

23 **4.4. Uncertainty in Future Projections**

24 The timing and magnitude of projected future climate change is uncertain due to the ambiguity
25 introduced by human choices (as discussed in Section 4.2), natural variability, and scientific
26 uncertainty (Hawkins and Sutton 2009, 2011; Deser et al. 2012a), which includes uncertainty in
27 both scientific modeling and climate sensitivity (see Ch. 2: Physical Drivers of Climate Change).
28 Confidence in projections of specific aspects of future climate change increases if formal
29 detection and attribution analyses (Ch. 3: Detection and Attribution) indicate that an observed
30 change has been influenced by human activities, and the projection is consistent with attribution.
31 However, in many cases, especially at the regional scales considered in this assessment, a
32 human-forced response may not yet have emerged from the noise of natural climate variability
33 but may be expected to in the future (e.g., Hawkins and Sutton 2009, 2010). In such cases,
34 confidence in such “projections without attribution” may still be significant under higher
35 scenarios, if the relevant physical mechanisms of change are well understood.

36 Scientific uncertainty encompasses multiple factors. The first is parametric uncertainty—the
37 ability of GCMs to simulate processes that occur on spatial or temporal scales smaller than they
38 can resolve. The second is structural uncertainty—whether GCMs include and accurately

1 represent all the important physical processes occurring on scales they can resolve. Structural
2 uncertainty can arise because a process is not yet recognized—such as “tipping points” or
3 mechanisms of abrupt change—or because it is known but is not yet understood well enough to
4 be modeled accurately—such as dynamical mechanisms that are important to melting ice sheets
5 (see Ch. 15: Potential Surprises). The third is climate sensitivity—a measure of the response of
6 the planet to increasing levels of CO₂, which is formally defined in Chapter 2: Physical Drivers
7 of Climate Change as the equilibrium temperature change resulting from a doubling of CO₂
8 levels in the atmosphere relative to preindustrial levels. Various lines of evidence constrain the
9 likely value of climate sensitivity to between 2.7°F and 8.1°F (1.5°C and 4.5°C; IPCC 2013b;
10 see Ch. 2: Physical Drivers of Climate Change for further discussion).

11 Which of these sources of uncertainty—human, natural, and scientific—is most important
12 depends on the time frame and the variable considered. As future scenarios diverge (Figure 4.1),
13 so too do projected changes in global and regional temperature (Hawkins and Sutton 2009).
14 Uncertainty in the magnitude and sign of projected changes in precipitation and other aspects of
15 climate is even greater. The processes that lead to precipitation happen at scales smaller than
16 what can be resolved by even high-resolution models, requiring significant parameterization.
17 Precipitation also depends on many large-scale aspects of climate, including atmospheric
18 circulation, storm tracks, and moisture convergence. Due to the greater level of complexity
19 associated with modeling precipitation, scientific uncertainty tends to dominate in precipitation
20 projections throughout the entire century, affecting both the magnitude and sometimes
21 (depending on location) the sign of the projected change in precipitation (Hawkins and Sutton
22 2011).

23 Over the next few decades, the greater part of the range or uncertainty in projected global and
24 regional change will be the result of a combination of natural variability (mostly related to
25 uncertainty in specifying the initial conditions of the state of the ocean; Deser et al. 2012b) and
26 scientific limitations in our ability to model and understand the Earth’s climate system (Figure
27 4.5). Differences in future scenarios, shown in orange in Figure 4.5, represent the difference
28 between scenarios, or human activity. Over the short term, this uncertainty is relatively small. As
29 time progresses, however, differences in various possible future pathways become larger and the
30 delayed ocean response to these differences begins to be realized. By about 2030, the human
31 source of uncertainty becomes increasingly important in determining the magnitude and patterns
32 of future global warming. Even though natural variability will continue to occur, most of the
33 difference between present and future climates will be determined by choices that society makes
34 today and over the next few decades. The further out in time we look, the greater the influence of
35 these human choices are on the magnitude of future warming.

36 **[INSERT FIGURE 4.5 HERE]**

37

1 TRACEABLE ACCOUNTS

2 Key Finding 1

3 If greenhouse gas concentrations were stabilized at their current level, existing concentrations
4 would commit the world to at least an additional 1.1°F (0.6°C) of warming over this century
5 relative to the last few decades (*high confidence* in continued warming, *medium confidence* in
6 amount of warming).

7 Description of evidence base

8 The basic physics underlying the impact of human emissions on global climate, and the role of
9 climate sensitivity in moderating the impact of those emissions on global temperature, has been
10 documented since the 1800s in a series of peer-reviewed journal articles that is summarized in a
11 collection titled, “The Warming Papers: The Scientific Foundation for the Climate Change
12 Forecast” (Archer and Pierrehumbert 2011).

13 The estimate of committed warming at constant atmospheric concentrations is based on IPCC
14 AR5 WG1, Chapter 12, section 12.5.2, page 1103 (Collins et al. 2013) which is in turn derived
15 from AR4 WG1, Chapter 10, section 10.7.1, page 822 (Meehl et al. 2007).

16 Major uncertainties

17 The uncertainty in projected change under a commitment scenario is low and primarily the result
18 of uncertainty in climate sensitivity. This key finding describes a hypothetical scenario that
19 assumes all human-caused emissions cease and the Earth system responds only to what is already
20 in the atmosphere.

21 Assessment of confidence based on evidence and agreement, including short description of 22 nature of evidence and level of agreement

23 The statement has *high confidence* in the sign of future change and *medium confidence* in the
24 amount of warming, based on the estimate of committed warming at constant atmospheric
25 concentrations from Collins et al. (2013) based on Meehl et al. (2007) for a hypothetical scenario
26 where concentrations in the atmosphere were fixed at a known level.

27 Summary sentence or paragraph that integrates the above information

28 The key finding is based on the basic physical principles of radiative transfer that have been well
29 established for decades to centuries; the amount of estimated warming for this hypothetical
30 scenario is derived from Collins et al. (2013) which is in turn based on Meehl et al. (2007) using
31 CMIP3 models.

32

1 **Key Finding 2**

2 Over the next two decades, global temperature increase is projected to be between 0.5°F and
3 1.3°F (0.3°–0.7°C) (*medium confidence*). This range is primarily due to uncertainties in natural
4 sources of variability that affect short-term trends. In some regions, this means that the trend may
5 not be distinguishable from natural variability (*high confidence*).

6 **Description of evidence base**

7 The estimate of projected near-term warming under continued emissions of carbon dioxide and
8 other greenhouse gases and aerosols was obtained directly from IPCC AR5 WG1 (Kirtman et al.
9 2013).

10 The statement regarding the sources of uncertainty in near-term projections and regional
11 uncertainty is based on Hawkins and Sutton (2009, 2011) and Deser et al. (2012a,b).

12 **Major uncertainties**

13 As stated in the key finding, natural variability is the primary uncertainty in quantifying the
14 amount of global temperature change over the next two decades.

15 **Assessment of confidence based on evidence and agreement, including short description of 16 nature of evidence and level of agreement**

17 The first statement regarding projected warming over the next two decades has *medium*
18 *confidence* in the amount of warming due to the uncertainties described in the key finding. The
19 second statement has *high confidence*, as the literature strongly supports the statement that
20 natural variability is the primary source of uncertainty over time scales of years to decades
21 (Deser et al. 2012a,b, 2014).

22 **Summary sentence or paragraph that integrates the above information**

23 The estimated warming presented in this KF is based on calculations reported by Kirtman et al.
24 (2013). The key finding that natural variability is the most important uncertainty over the near-
25 term is based on multiple peer reviewed publications.

26

27 **Key Finding 3**

28 Beyond the next few decades, the magnitude of climate change depends primarily on cumulative
29 emissions of greenhouse gases and aerosols and the sensitivity of the climate system to those
30 emissions (*high confidence*). Projected changes range from 4.7°–8.6°F (2.6°–4.8°C) under the
31 higher RCP8.5 scenario to 0.5°–1.3°F (0.3°–1.7°C) under the lower RCP2.6 scenario, for 2081–
32 2100 relative to 1986–2005 (*medium confidence*).

1 **Description of evidence base**

2 The estimate of projected long-term warming under continued emissions of carbon dioxide and
3 other greenhouse gases and aerosols under the RCP scenarios was obtained directly from IPCC
4 AR5 WG1 (Collins et al. 2013).

5 All credible climate models assessed in Chapter 9 of the IPCC WG1 AR5 (IPCC 2013a) from the
6 simplest to the most complex respond with elevated global mean temperature, the simplest
7 indicator of climate change, when atmospheric concentrations of greenhouse gases increase. It
8 follows then that an emissions pathway that tracks or exceeds RCP8.5 would lead to larger
9 amounts of climate change.

10 The statement regarding the sources of uncertainty in long-term projections is based on Hawkins
11 and Sutton (2009, 2011).

12 **Major uncertainties**

13 As stated in the key finding, the magnitude of climate change over the long term is uncertain due
14 to human emissions of greenhouse gases and climate sensitivity.

15 **Assessment of confidence based on evidence and agreement, including short description of 16 nature of evidence and level of agreement**

17 The first statement regarding additional warming and its dependence on human emissions and
18 climate sensitivity has *high confidence*, as understanding of the radiative properties of
19 greenhouse gases and the existence of both positive and negative feedbacks in the climate system
20 is basic physics, dating to the 19th century. The second has *medium confidence* in the specific
21 magnitude of warming, due to the uncertainties described in the key finding.

22 **Summary sentence or paragraph that integrates the above information**

23 The estimated warming presented in this key finding is based on calculations reported by Collins
24 et al. (2013). The key finding that human emissions and climate sensitivity are the most
25 important sources of uncertainty over the long-term is based on both basic physics regarding the
26 radiative properties of greenhouse gases, as well as a large body of peer reviewed publications.

27

28 **Key Finding 4**

29 Global mean atmospheric carbon dioxide (CO₂) concentration has now passed 400 ppm, a level
30 that last occurred about 3 million years ago, when global average temperature and sea level were
31 significantly higher than today (*high confidence*). Continued growth in CO₂ emissions over this
32 century and beyond would lead to an atmospheric concentration not experienced in tens of
33 millions of years (*medium confidence*). The present-day emissions rate of nearly 10 GtC per year

1 suggests that there is no climate analog for this century any time in at least the last 50 million
2 years (*medium confidence*).

3 **Description of evidence base**

4 The key finding is based on a large body of research including Crowley (1990), Schneider et al.
5 (2013), Lunt et al. (2012), Otto-Bleisner et al. (2013), NEEM (2013), Jouzel et al. (2007), Dutton
6 et al. (2015), Seki et al. (2010), Haywood et al. (2013), Miller et al. (2012), Royer (2014),
7 Bowen et al. (2015), Kirtland Turner et al. (2014), Penman et al. (2014), Zeebe et al. (2016), and
8 summarized in NRC (2011) and Masson-Delmotte et al. (2013).

9 **Major uncertainties**

10 The largest uncertainty is the measurement of past sea level, given the contributions of not only
11 changes in land ice mass, but also in solid earth, mantle, isostatic adjustments, etc. that occur on
12 timescales of millions of years. This uncertainty increases the further back in time we go;
13 however, the signal (and forcing) size is also much greater. There are also associated
14 uncertainties in precise quantification of past global mean temperature and carbon dioxide levels.
15 There is uncertainty in the age models used to determine rates of change and coincidence of
16 response at shorter, sub-millennial timescales.

17 **Assessment of confidence based on evidence and agreement, including short description of** 18 **nature of evidence and level of agreement**

19 *High confidence* in the likelihood statement that past global mean temperature and sea level rise
20 were higher with similar or higher CO₂ concentrations is based on Masson-Delmotte et al. (2013)
21 in IPCC AR5. *Medium confidence* that no precise analog exists in 66 million years is based on
22 Zeebe et al. (2016) as well as the larger body of literature summarized in Masson-Delmotte et al.
23 (2013).

24 **Summary sentence or paragraph that integrates the above information**

25 The key finding is based on a vast body of literature that summarizes the results of observations,
26 paleoclimate analyses, and paleoclimate modeling over the past 50 years and more.

27

28 **Key Finding 5**

29 The observed increase in global carbon emissions over the past 15–20 years has been consistent
30 with higher scenarios (*very high confidence*). In 2014 and 2015, emission growth rates slowed as
31 economic growth has become less carbon-intensive (*medium confidence*). Even if this trend
32 continues, however, it is not yet at a rate that would meet the long-term temperature goal of the

1 Paris Agreement of holding the increase in the global average temperature to well below 3.6°F
2 (2°C) above preindustrial levels (*high confidence*).

3 **Description of Evidence Base**

4 Observed emissions for 2014 and 2015 and estimated emissions for 2016 suggest a decrease in
5 the growth rate and possibly even emissions of carbon; this shift is attributed primarily to
6 decreased coal use in China although with significant uncertainty as noted in the references in
7 the text. This statement is based on Tans and Keeling 2017; Raupach et al. 2007; Le Quéré et al.
8 2009; Jackson et al. 2016; Korsbakken et al. 2016 and personal communication with Le Quéré
9 (2017).

10 The statement that the growth rate of carbon dioxide increased over the past 15–20 years is based
11 on the data available here: <https://www.esrl.noaa.gov/gmd/ccgg/trends/gr.html>

12 The evidence that actual emission rates track or exceed the RCP8.5 scenario are as follows. The
13 actual emission of CO₂ from fossil fuel consumption and concrete manufacture over the period
14 2005–2014 is 90.11 Pg (Le Quéré et al. 2015). The RCP8.5 emissions over the same period
15 assuming linear trends between years 2000, 2005, 2010, and 2020 in the specification is 99.24
16 Pg.

17 Actual emissions:

18 <http://www.globalcarbonproject.org/> and Le Quéré et al. (2015)

19 RCP8.5 emissions

20 <http://tntcat.iiasa.ac.at:8787/RcpDb/dsd?Action=htmlpage&page=compare>

21 The numbers for fossil fuel and industrial emissions (RCP) compared to fossil fuel and cement
22 emissions (observed) in units of GtC are

	RCP8.5	Actual	difference
2005	7.97	8.23	0.26
2006	8.16	8.53	0.36
2007	8.35	8.78	0.42
2008	8.54	8.96	0.42
2009	8.74	8.87	0.14
2010	8.93	9.21	0.28
2011	9.19	9.54	0.36
2012	9.45	9.69	0.24

2013	9.71	9.82	0.11
2014	9.97	9.89	-0.08
2015	10.23	9.90	-0.34
total	99.24	101.41	2.18

1

2 **Major Uncertainties**

3 None

4 **Assessment of confidence based on evidence and agreement, including short description of** 5 **nature of evidence and level of agreement**

6 *Very high confidence* in increasing emissions over the last 20 years and *high confidence* in the
7 fact that recent emission trends will not be sufficient to avoid 2°C. *Medium confidence* in recent
8 findings that the growth rate is slowing. Climate change scales with the amount of anthropogenic
9 greenhouse gas in the atmosphere. If emissions exceed RCP8.5, the likely range of changes
10 temperatures and climate variables will be larger than projected.

11 **Summary sentence or paragraph that integrates the above information**

12 The key finding is based on basic physics relating emissions to concentrations, radiative forcing,
13 and resulting change in global mean temperature, as well as on IEA data on national emissions as
14 reported in the peer-reviewed literature.

15

16 **Key Finding 6**

17 Combining output from global climate models and dynamical and statistical downscaling models
18 using advanced averaging, weighting, and pattern scaling approaches can result in more relevant
19 and robust future projections. For some regions, sectors, and impacts, these techniques are
20 increasing the ability of the scientific community to provide guidance on the use of climate
21 projections for quantifying regional-scale changes and impacts (*medium to high confidence*).

22 **Description of evidence base**

23 The contribution of weighting and pattern scaling to improving the robustness of multimodel
24 ensemble projections is described and quantified by a large body of literature as summarized in
25 the text, including Sanderson et al. (2015) and Knutti et al. (2017). The state of the art of
26 dynamical and statistical downscaling and the scientific community's ability to provide guidance

1 regarding the application of climate projections to regional impact assessments is summarized in
2 Kotamarthi et al. (2016) and supported by Feser et al. (2011) and Prein et al. (2015).

3 **Major uncertainties**

4 Regional climate models are subject to the same structural and parametric uncertainties as global
5 models, as well as the uncertainty due to incorporating boundary conditions. The primary source
6 of error in application of empirical statistical downscaling methods is inappropriate application,
7 followed by stationarity.

8 **Assessment of confidence based on evidence and agreement, including short description of** 9 **nature of evidence and level of agreement**

10 Advanced weighting techniques have significantly improved over previous Bayesian approaches;
11 confidence in their ability to improve the robustness of multimodel ensembles, while currently
12 rated as *medium*, is likely to grow in coming years. Downscaling has evolved significantly over
13 the last decade and is now broadly viewed as a robust source for high-resolution climate
14 projections that can be used as input to regional impact assessments.

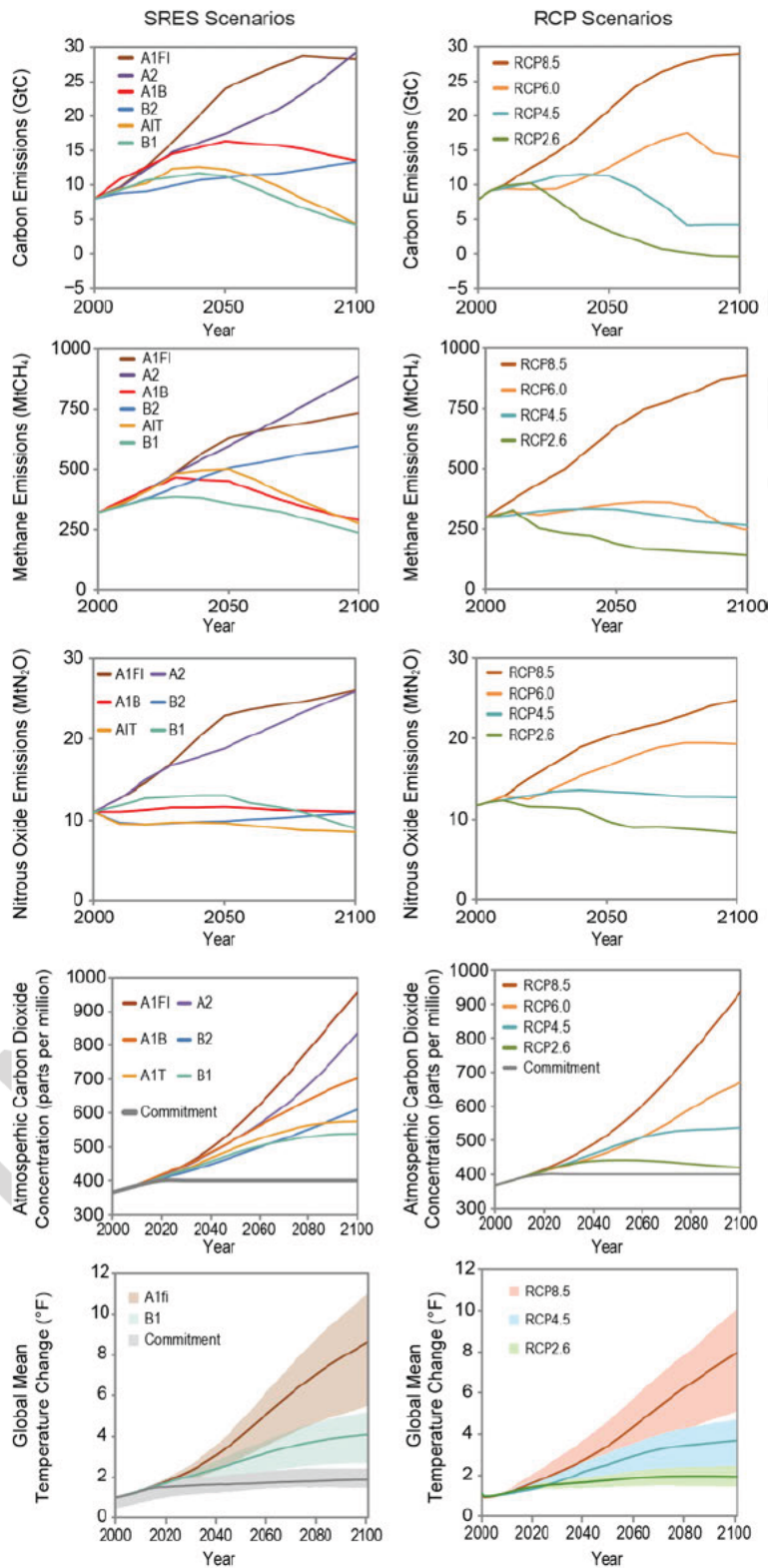
15 **Summary sentence or paragraph that integrates the above information**

16 Scientific understanding of climate projections, downscaling, multimodel ensembles, and
17 weighting has evolved significantly over the last decades to the extent that appropriate methods
18 are now broadly viewed as robust sources for climate projections that can be used as input to
19 regional impact assessments.

20

1 FIGURES

Emissions, Concentrations, and Temperature Projections

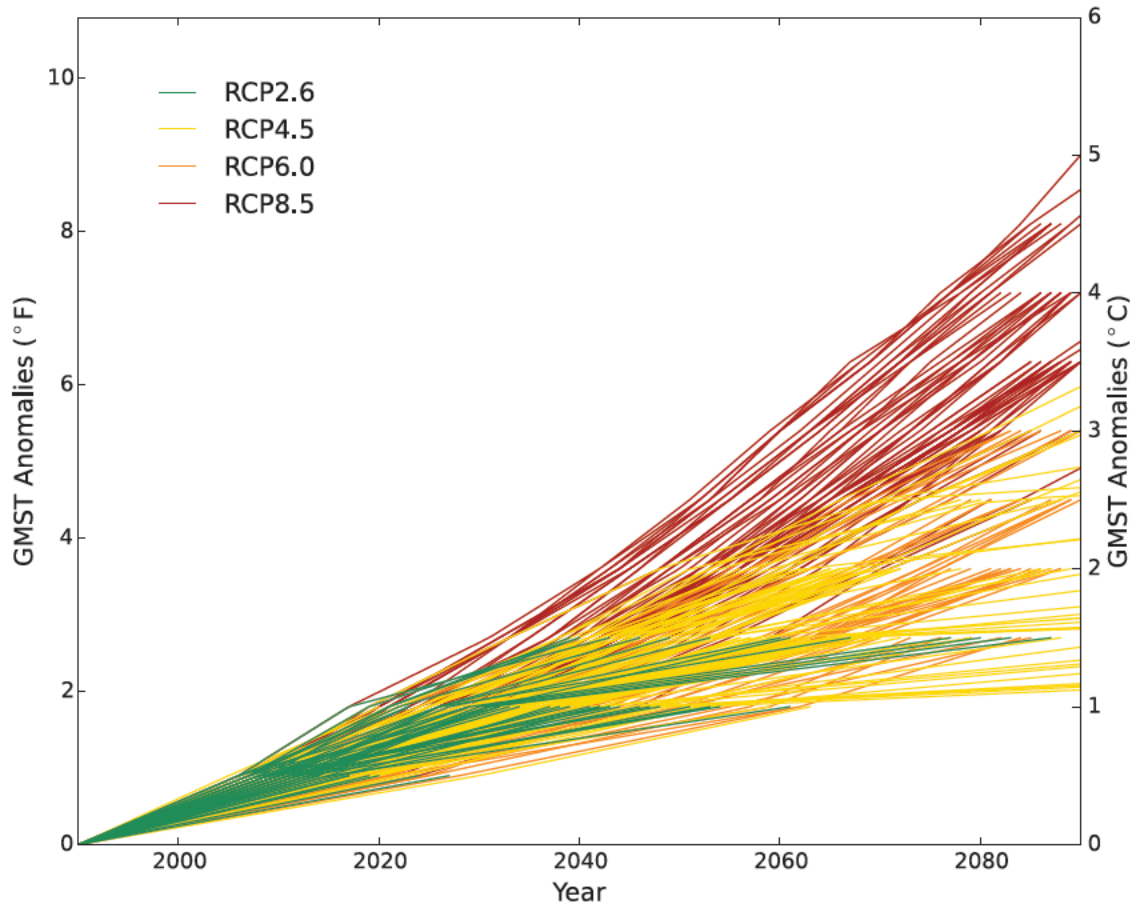


2

1 **Figure 4.1:** The climate projections used in this report are based on the 2010 Representative
2 Concentration Pathways (RCP, right). They are largely consistent with scenarios used in
3 previous assessments, the 2000 Special Report on Emission Scenarios (SRES, left). This figure
4 compares SRES and RCP annual carbon emissions (GtC, first row), annual methane emissions
5 (MtCH₄, second row), nitrous oxide emissions (MtN₂O, third row), carbon dioxide concentration
6 in the atmosphere (ppm, fourth row), global mean temperature change relative to 1900–1960 that
7 would result from the central estimate (lines) and the likely range (shaded areas) of climate
8 sensitivity as calculated by an energy balance model (°F, fifth row), and global mean temperature
9 change relative to 1900–1960 as simulated by CMIP3 models for the SRES scenarios and
10 CMIP5 models for the RCP scenarios (°F, sixth row). Note that global mean temperature from
11 SRES A1fi simulations are only available from four global climate models, hence the much
12 smaller range. (Data from IIASA, CMIP3, and CMIP5).

13

14



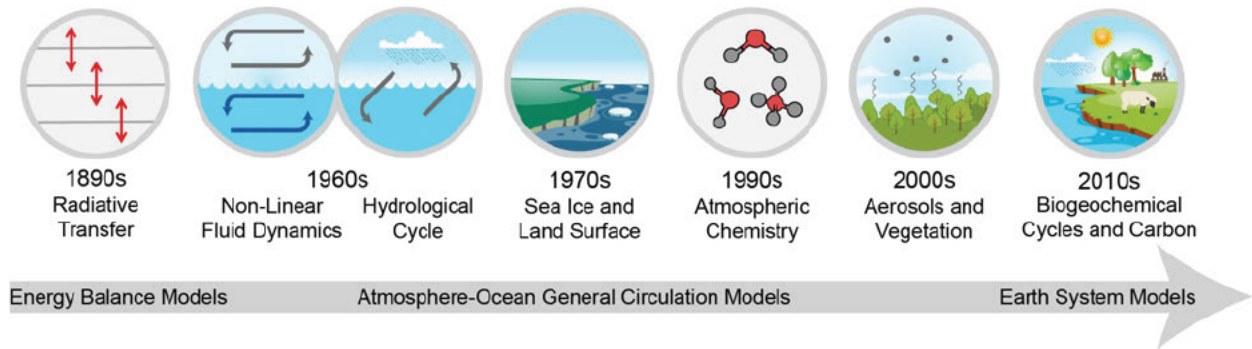
1

2 **Figure 4.2:** Global mean surface temperature anomalies (°F) relative to 1976–2005 for four RCP
3 scenarios, 2.6 (green), 4.5 (yellow), 6.0 (orange), and 8.5 (red). Each line represents an
4 individual simulation from the CMIP5 archive. Every RCP-based simulation with annual or
5 monthly temperature outputs available was used here. The values shown here were calculated in
6 0.5°C increments; since not every simulation reaches the next 0.5°C increment before end of
7 century, many lines terminate before 2100. (Figure source: adapted from Swain and Hayhoe
8 2015).

9

1

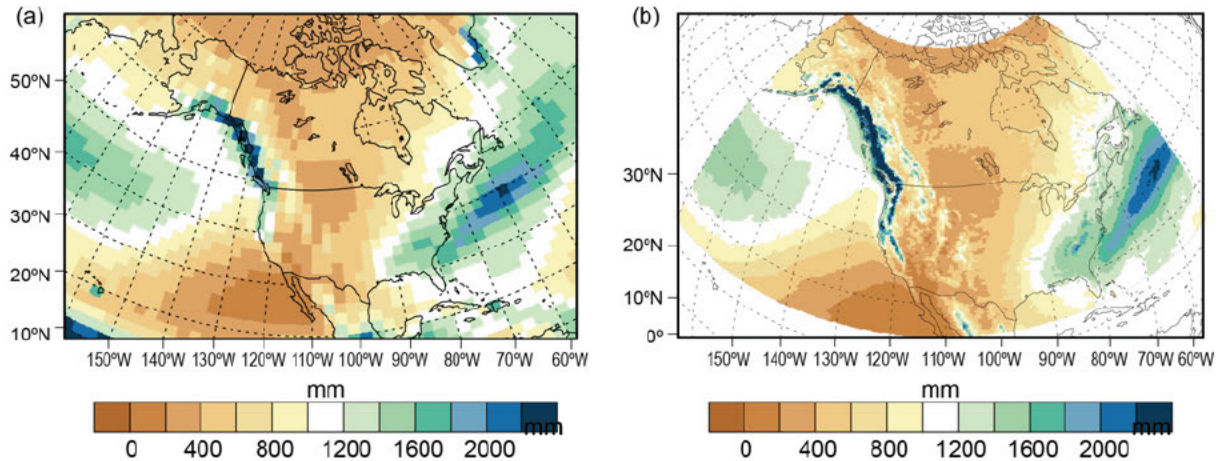
A Climate Modeling Timeline
(When Various Components Became Commonly Used)



2

3 **Figure 4.3:** As climate modeling has evolved over the last 120 years, increasing amounts of
 4 physical science have been incorporated into the models. This figure shows when various
 5 components of the climate system became regularly included in global climate model
 6 simulations.

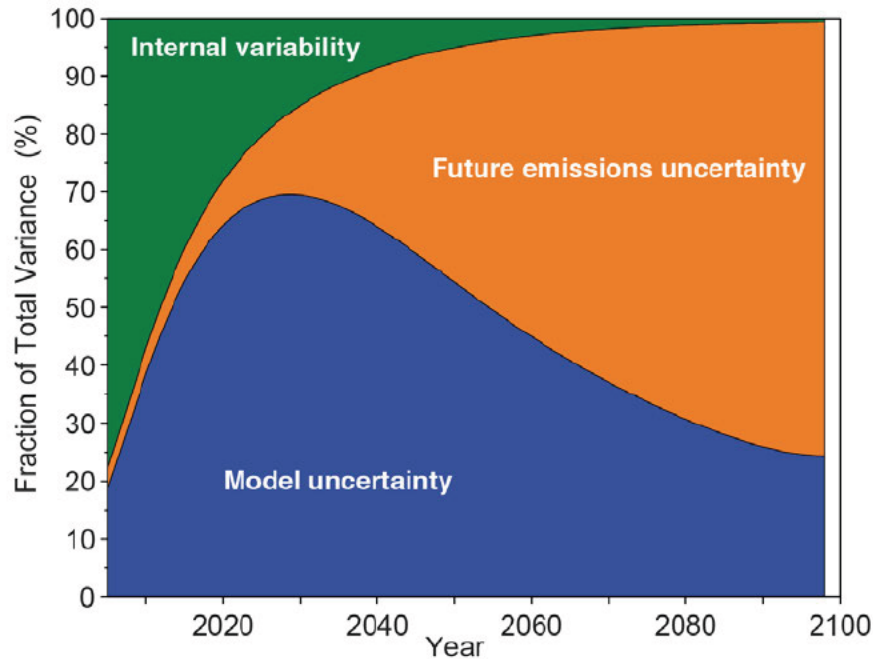
7



1

2 **Figure 4.4:** CMIP5 global climate models typically operate at coarser horizontal spatial scales
 3 on the order of 50 to 300 km (30 to 200 miles), while regional climate models have much finer
 4 resolutions, on the order of 10 to 50 km (6 to 30 miles). This figure compares annual average
 5 precipitation (in millimeters) for the historical period 1979–2008 using (a) a resolution of 250
 6 km or 150 miles with (b) a resolution of 25 km or 15 miles to illustrate the importance of spatial
 7 scale in resolving key topographical features, particularly along the coasts and in mountainous
 8 areas. In this case, both simulations are by the GFDL HIRAM model, an experimental high-
 9 resolution model. (Figure source: adapted from Dixon et al. 2016).

10



1

2 **Figure 4.5:** The fraction of total variance in decadal mean surface air temperature predictions
 3 explained by the three components of total uncertainty is shown for the lower 48 states (similar
 4 results are seen for Hawai'i and Alaska, not shown). Orange regions represent human or scenario
 5 uncertainty, blue regions represent model uncertainty, and green regions represent the internal
 6 variability component. As the size of the region is reduced, the relative importance of internal
 7 variability increases. In interpreting this figure, it is important to remember that it shows the
 8 fractional sources of uncertainty. Total uncertainty increases as time progresses. (Figure source:
 9 adapted from Hawkins and Sutton 2009).

10

1 **REFERENCES**

- 2 Archer, D. and R. Pierrehumbert, eds., 2011: *The Warming Papers: The Scientific Foundation*
3 *for the Climate Change Forecast*. Wiley-Blackwell: Oxford, UK, 432 pp.
- 4 Bellenger, H., E. Guilyardi, J. Leloup, M. Lengaigne, and J. Vialard, 2014: ENSO representation
5 in climate models: From CMIP3 to CMIP5. *Climate Dynamics*, **42**, 1999-2018.
6 <http://dx.doi.org/10.1007/s00382-013-1783-z>
- 7 Bowen, G.J., B.J. Maibauer, M.J. Kraus, U. Rohl, T. Westerhold, A. Steimke, P.D. Gingerich,
8 S.L. Wing, and W.C. Clyde, 2015: Two massive, rapid releases of carbon during the onset of
9 the Palaeocene-Eocene thermal maximum. *Nature Geoscience*, **8**, 44-47.
10 <http://dx.doi.org/10.1038/ngeo2316>
- 11 Braconnot, P., S.P. Harrison, M. Kageyama, P.J. Bartlein, V. Masson-Delmotte, A. Abe-Ouchi,
12 B. Otto-Bliesner, and Y. Zhao, 2012: Evaluation of climate models using palaeoclimatic data.
13 *Nature Climate Change*, **2**, 417-424. <http://dx.doi.org/10.1038/nclimate1456>
- 14 Brands, S., J.M. Gutiérrez, S. Herrera, and A.S. Cofiño, 2012: On the use of reanalysis data for
15 downscaling. *Journal of Climate*, **25**, 2517-2526. <http://dx.doi.org/10.1175/jcli-d-11-00251.1>
- 16 Bretherton, F., K. Bryan, J. Woods, J. Hansen, M. Hoffert, X. Jiang, S. Manabe, G. Meehl, S.
17 Raper, D. Rind, M. Schlesinger, R. Stouffer, T. Volk, and T. Wigley, 1990: Time-dependent
18 greenhouse-gas-induced climate change. *Climate Change: The IPCC Scientific Assessment*
19 *Report prepared for Intergovernmental Panel on Climate Change by Working Group I*
20 Houghton, J.T., G.J. Jenkins, and J.J. Ephraums, Eds. Cambridge University Press,
21 Cambridge, United Kingdom and New York, NY, USA, 173-193.
- 22 Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J.
23 Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver, and M. Wehner,
24 2013: Long-term climate change: Projections, commitments and irreversibility. *Climate*
25 *Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth*
26 *Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin,
27 G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M.
28 Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY,
29 USA, 1029–1136. <http://www.climatechange2013.org/report/full-report/>
- 30 Crowley, T.J., 1990: Are there any satisfactory geologic analogs for a future greenhouse
31 warming? *Journal of Climate*, **3**, 1282-1292. [http://dx.doi.org/10.1175/1520-](http://dx.doi.org/10.1175/1520-0442(1990)003<1282:atasga>2.0.co;2)
32 [0442\(1990\)003<1282:atasga>2.0.co;2](http://dx.doi.org/10.1175/1520-0442(1990)003<1282:atasga>2.0.co;2)
- 33 Cubasch, U., G. Meehl, G. Boer, R. Stouffer, M. Dix, A. Noda, C. Senior, S. Raper, and K. Yap,
34 2001: Projections of future climate change. *Climate Change 2001: The Scientific Basis.*
35 *Contribution of Working Group I to the Third Assessment Report of the Intergovernmental*

- 1 *Panel on Climate Change*. Houghton, J.T., Y. Ding, D.J. Griggs, M. Noquer, P.J. van der
2 Linden, X. Dai, K. Maskell, and C.A. Johnson, Eds. Cambridge University Press, Cambridge,
3 United Kingdom and New York, NY, USA, 525-582.
4 <https://www.ipcc.ch/ipccreports/tar/wg1/pdf/TAR-09.PDF>
- 5 Cubasch, U., D. Wuebbles, D. Chen, M.C. Facchini, D. Frame, N. Mahowald, and J.-G. Winther,
6 2013: Introduction. *Climate Change 2013: The Physical Science Basis. Contribution of*
7 *Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate*
8 *Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels,
9 Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United
10 Kingdom and New York, NY, USA, 119–158. [http://www.climatechange2013.org/report/full-](http://www.climatechange2013.org/report/full-report/)
11 [report/](http://www.climatechange2013.org/report/full-report/)
- 12 DeConto, R.M. and D. Pollard, 2016: Contribution of Antarctica to past and future sea-level rise.
13 *Nature*, **531**, 591-597. <http://dx.doi.org/10.1038/nature17145>
- 14 Deser, C., R. Knutti, S. Solomon, and A.S. Phillips, 2012b: Communication of the role of natural
15 variability in future North American climate. *Nature Climate Change*, **2**, 775-779.
16 <http://dx.doi.org/10.1038/nclimate1562>
- 17 Deser, C., A. Phillips, V. Bourdette, and H. Teng, 2012a: Uncertainty in climate change
18 projections: The role of internal variability. *Climate Dynamics*, **38**, 527-546.
19 <http://dx.doi.org/10.1007/s00382-010-0977-x>
- 20 Deser, C., A.S. Phillips, M.A. Alexander, and B.V. Smoliak, 2014: Projecting North American
21 climate over the next 50 years: Uncertainty due to internal variability. *Journal of Climate*, **27**,
22 2271-2296. <http://dx.doi.org/10.1175/JCLI-D-13-00451.1>
- 23 Dixon, K.W., J.R. Lanzante, M.J. Nath, K. Hayhoe, A. Stoner, A. Radhakrishnan, V. Balaji, and
24 C.F. Gaitán, 2016: Evaluating the stationarity assumption in statistically downscaled climate
25 projections: Is past performance an indicator of future results? *Climatic Change*, **135**, 395-
26 408. <http://dx.doi.org/10.1007/s10584-016-1598-0>
- 27 Dutton, A., A.E. Carlson, A.J. Long, G.A. Milne, P.U. Clark, R. DeConto, B.P. Horton, S.
28 Rahmstorf, and M.E. Raymo, 2015: Sea-level rise due to polar ice-sheet mass loss during past
29 warm periods. *Science*, **349**. <http://dx.doi.org/10.1126/science.aaa4019>
- 30 Feser, F., B. Rockel, H.v. Storch, J. Winterfeldt, and M. Zahn, 2011: Regional climate models
31 add value to global model data: A review and selected examples. *Bulletin of the American*
32 *Meteorological Society*, **92**, 1181-1192. <http://dx.doi.org/10.1175/2011BAMS3061.1>
- 33 Fix, M.J., D. Cooley, S.R. Sain, and C. Tebaldi, 2016: A comparison of U.S. precipitation
34 extremes under RCP8.5 and RCP4.5 with an application of pattern scaling. *Climatic Change*,
35 **First online**, 1-13. <http://dx.doi.org/10.1007/s10584-016-1656-7>

- 1 Frieler, K., M. Meinshausen, A. Golly, M. Mengel, K. Lebek, S.D. Donner, and O. Hoegh-
2 Guldberg, 2013: Limiting global warming to 2°C is unlikely to save most coral reefs. *Nature*
3 *Climate Change*, **3**, 165-170. <http://dx.doi.org/10.1038/nclimate1674>
- 4 Gasson, E., D.J. Lunt, R. DeConto, A. Goldner, M. Heinemann, M. Huber, A.N. LeGrande, D.
5 Pollard, N. Sahoo, M. Siddall, A. Winguth, and P.J. Valdes, 2014: Uncertainties in the
6 modelled CO₂ threshold for Antarctic glaciation. *Climate of the Past*, **10**, 451-466.
7 <http://dx.doi.org/10.5194/cp-10-451-2014>
- 8 Giorgi, F. and E. Coppola, 2010: Does the model regional bias affect the projected regional
9 climate change? An analysis of global model projections. *Climatic Change*, **100**, 787-795.
10 <http://dx.doi.org/10.1007/s10584-010-9864-z>
- 11 Green, F. and N. Stern, 2016: China's changing economy: Implications for its carbon dioxide
12 emissions. *Climate Policy*, **17**, 423-442. <http://dx.doi.org/10.1080/14693062.2016.1156515>
- 13 Hartmann, D.L., A.M.G. Klein Tank, M. Rusticucci, L.V. Alexander, S. Brönnimann, Y.
14 Charabi, F.J. Dentener, E.J. Dlugokencky, D.R. Easterling, A. Kaplan, B.J. Soden, P.W.
15 Thorne, M. Wild, and P.M. Zhai, 2013: Observations: Atmosphere and surface. *Climate*
16 *Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth*
17 *Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin,
18 G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M.
19 Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY,
20 USA, 159–254. <http://www.climatechange2013.org/report/full-report/>
- 21 Hawkins, E. and R. Sutton, 2009: The potential to narrow uncertainty in regional climate
22 predictions. *Bulletin of the American Meteorological Society*, **90**, 1095-1107.
23 <http://dx.doi.org/10.1175/2009BAMS2607.1>
- 24 Hawkins, E. and R. Sutton, 2011: The potential to narrow uncertainty in projections of regional
25 precipitation change. *Climate Dynamics*, **37**, 407-418. [http://dx.doi.org/10.1007/s00382-010-](http://dx.doi.org/10.1007/s00382-010-0810-6)
26 [0810-6](http://dx.doi.org/10.1007/s00382-010-0810-6)
- 27 Haywood, A.M., D.J. Hill, A.M. Dolan, B.L. Otto-Bliesner, F. Bragg, W.L. Chan, M.A.
28 Chandler, C. Contoux, H.J. Dowsett, A. Jost, Y. Kamae, G. Lohmann, D.J. Lunt, A. Abe-
29 Ouchi, S.J. Pickering, G. Ramstein, N.A. Rosenbloom, U. Salzmann, L. Sohl, C. Stepanek, H.
30 Ueda, Q. Yan, and Z. Zhang, 2013: Large-scale features of Pliocene climate: Results from the
31 Pliocene Model Intercomparison Project. *Climate of the Past*, **9**, 191-209.
32 <http://dx.doi.org/10.5194/cp-9-191-2013>
- 33 Herger, N., B.M. Sanderson, and R. Knutti, 2015: Improved pattern scaling approaches for the
34 use in climate impact studies. *Geophysical Research Letters*, **42**, 3486-3494.
35 <http://dx.doi.org/10.1002/2015GL063569>

- 1 IEA, 2016: Decoupling of global emissions and economic growth confirmed. International
2 Energy Agency, March 16.
3 [https://www.iea.org/newsroomandevents/pressreleases/2016/march/decoupling-of-global-](https://www.iea.org/newsroomandevents/pressreleases/2016/march/decoupling-of-global-emissions-and-economic-growth-confirmed.html)
4 [emissions-and-economic-growth-confirmed.html](https://www.iea.org/newsroomandevents/pressreleases/2016/march/decoupling-of-global-emissions-and-economic-growth-confirmed.html)
- 5 IIASA, 2016: RCP Database. Version 2.0.5. International Institute for Applied Systems
6 Analysis. <https://tntcat.iiasa.ac.at/RcpDb/dsd?Action=htmlpage&page=compare>
- 7 IPCC, 1990: *Climate Change: The IPCC Scientific Assessment*. Houghton, J.T., G.J. Jenkins, and
8 J.J. Ephraums, Eds. Cambridge University Press, Cambridge, United Kingdom and New
9 York, NY, USA, 212 pp.
- 10 IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group*
11 *I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.
12 Cambridge University Press, Cambridge, UK and New York, NY, 1535 pp.
13 <http://www.climatechange2013.org/report/>
- 14 IPCC, 2013: Summary for policymakers. *Climate Change 2013: The Physical Science Basis.*
15 *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental*
16 *Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J.
17 Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press,
18 Cambridge, United Kingdom and New York, NY, USA, 1–30.
19 <http://www.climatechange2013.org/report/>
- 20 Jackson, R.B., J.G. Canadell, C. Le Quere, R.M. Andrew, J.I. Korsbakken, G.P. Peters, and N.
21 Nakicenovic, 2016: Reaching peak emissions. *Nature Climate Change*, **6**, 7-10.
22 <http://dx.doi.org/10.1038/nclimate2892>
- 23 Jagniecki, E.A., T.K. Lowenstein, D.M. Jenkins, and R.V. Demicco, 2015: Eocene atmospheric
24 CO₂ from the nahcolite proxy. *Geology*, **43**, 1075-1078. <http://dx.doi.org/10.1130/g36886.1>
- 25 Jouzel, J., V. Masson-Delmotte, O. Cattani, G. Dreyfus, S. Falourd, G. Hoffmann, B. Minster, J.
26 Nouet, J.M. Barnola, J. Chappellaz, H. Fischer, J.C. Gallet, S. Johnsen, M. Leuenberger, L.
27 Loulergue, D. Luethi, H. Oerter, F. Parrenin, G. Raisbeck, D. Raynaud, A. Schilt, J.
28 Schwander, E. Selmo, R. Souchez, R. Spahni, B. Stauffer, J.P. Steffensen, B. Stenni, T.F.
29 Stocker, J.L. Tison, M. Werner, and E.W. Wolff, 2007: Orbital and millennial Antarctic
30 climate variability over the past 800,000 years. *Science*, **317**, 793-796.
31 <http://dx.doi.org/10.1126/science.1141038>
- 32 Jun, M., R. Knutti, and D.W. Nychka, 2008: Local eigenvalue analysis of CMIP3 climate model
33 errors. *Tellus A*, **60**, 992-1000. <http://dx.doi.org/10.1111/j.1600-0870.2008.00356.x>

- 1 Karl, T.R., J.T. Melillo, and T.C. Peterson, eds., 2009: *Global Climate Change Impacts in the*
2 *United States*. Cambridge University Press: New York, NY, 189 pp.
3 <http://downloads.globalchange.gov/usimpacts/pdfs/climate-impacts-report.pdf>
- 4 Kattenberg, A., F. Giorgi, H. Grassl, G. Meehl, J. Mitchell, R. Stouffer, T. Tokioka, A. Weaver,
5 and T. Wigley, 1996: Climate models - projections of future climate. *Climate Change 1995:*
6 *The Science of Climate Change. Contribution of Working Group I to the Second Assessment*
7 *Report of the Intergovernmental Panel on Climate Change*. Houghton, J.T., L.G. Meira Filho,
8 B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell, Eds. Cambridge University Press,
9 Cambridge, United Kingdom and New York, NY, USA, 285-358.
10 https://www.ipcc.ch/ipccreports/sar/wg_I/ipcc_sar_wg_I_full_report.pdf
- 11 Kharin, V.V., F.W. Zwiers, X. Zhang, and M. Wehner, 2013: Changes in temperature and
12 precipitation extremes in the CMIP5 ensemble. *Climatic Change*, **119**, 345-357.
13 <http://dx.doi.org/10.1007/s10584-013-0705-8>
- 14 Kirtland Turner, S., P.F. Sexton, C.D. Charles, and R.D. Norris, 2014: Persistence of carbon
15 release events through the peak of early Eocene global warmth. *Nature Geoscience*, **7**, 748-
16 751. <http://dx.doi.org/10.1038/ngeo2240>
- 17 Kirtman, B., S.B. Power, J.A. Adedoyin, G.J. Boer, R. Bojariu, I. Camilloni, F.J. Doblas-Reyes,
18 A.M. Fiore, M. Kimoto, G.A. Meehl, M. Prather, A. Sarr, C. Schär, R. Sutton, G.J.
19 van Oldenborgh, G. Vecchi, and H.J. Wang, 2013: Near-term climate change: Projections and
20 predictability. *Climate Change 2013: The Physical Science Basis. Contribution of Working*
21 *Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.
22 Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia,
23 V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, UK and New York,
24 NY, USA, 953–1028. <http://www.climatechange2013.org/report/full-report/>
- 25 Knutson, T.R., J.J. Sirutis, G.A. Vecchi, S. Garner, M. Zhao, H.-S. Kim, M. Bender, R.E.
26 Tuleya, I.M. Held, and G. Villarini, 2013: Dynamical downscaling projections of twenty-first-
27 century Atlantic hurricane activity: CMIP3 and CMIP5 model-based scenarios. *Journal of*
28 *Climate*, **27**, 6591-6617. <http://dx.doi.org/10.1175/jcli-d-12-00539.1>
- 29 Knutti, R., D. Masson, and A. Gettelman, 2013: Climate model genealogy: Generation CMIP5
30 and how we got there. *Geophysical Research Letters*, **40**, 1194-1199.
31 <http://dx.doi.org/10.1002/grl.50256>
- 32 Knutti, R. and J. Sedlacek, 2013: Robustness and uncertainties in the new CMIP5 climate model
33 projections. *Nature Climate Change*, **3**, 369-373. <http://dx.doi.org/10.1038/nclimate1716>

- 1 Knutti, R., J. Sedláček, B.M. Sanderson, R. Lorenz, E.M. Fischer, and V. Eyring, 2017: A
2 climate model projection weighting scheme accounting for performance and interdependence.
3 *Geophysical Research Letters*, **44**, 1909-1918. <http://dx.doi.org/10.1002/2016GL072012>
- 4 Kopp, R.E., F.J. Simons, J.X. Mitrovica, A.C. Maloof, and M. Oppenheimer, 2009: Probabilistic
5 assessment of sea level during the last interglacial stage. *Nature*, **462**, 863-867.
6 <http://dx.doi.org/10.1038/nature08686>
- 7 Korsbakken, J.I., G.P. Peters, and R.M. Andrew, 2016: Uncertainties around reductions in
8 China's coal use and CO2 emissions. *Nature Climate Change*, **6**, 687-690.
9 <http://dx.doi.org/10.1038/nclimate2963>
- 10 Kotamarthi, R., L. Mearns, K. Hayhoe, C. Castro, and D. Wuebbles, 2016: Use of Climate
11 Information for Decision-Making and Impact Research. U.S. Department of Defense,
12 Strategic Environment Research and Development Program Report, 55 pp.
13 <http://dx.doi.org/10.13140/RG.2.1.1986.0085>
- 14 Kumar, D., E. Kodra, and A.R. Ganguly, 2014: Regional and seasonal intercomparison of
15 CMIP3 and CMIP5 climate model ensembles for temperature and precipitation. *Climate*
16 *Dynamics*, **43**, 2491-2518. <http://dx.doi.org/10.1007/s00382-014-2070-3>
- 17 Lauer, A. and K. Hamilton, 2013: Simulating clouds with global climate models: A comparison
18 of CMIP5 results with CMIP3 and satellite data. *Journal of Climate*, **26**, 3823-3845.
19 <http://dx.doi.org/10.1175/jcli-d-12-00451.1>
- 20 Le Quéré, C., R. Moriarty, R.M. Andrew, J.G. Canadell, S. Sitch, J.I. Korsbakken, P.
21 Friedlingstein, G.P. Peters, R.J. Andres, T.A. Boden, R.A. Houghton, J.I. House, R.F.
22 Keeling, P. Tans, A. Arneeth, D.C.E. Bakker, L. Barbero, L. Bopp, J. Chang, F. Chevallier,
23 L.P. Chini, P. Ciais, M. Fader, R.A. Feely, T. Gkritzalis, I. Harris, J. Hauck, T. Ilyina, A.K.
24 Jain, E. Kato, V. Kitidis, K. Klein Goldewijk, C. Koven, P. Landschützer, S.K. Lauvset, N.
25 Lefèvre, A. Lenton, I.D. Lima, N. Metzl, F. Millero, D.R. Munro, A. Murata, J.E.M.S. Nabel,
26 S. Nakaoka, Y. Nojiri, K. O'Brien, A. Olsen, T. Ono, F.F. Pérez, B. Pfeil, D. Pierrot, B.
27 Poulter, G. Rehder, C. Rödenbeck, S. Saito, U. Schuster, J. Schwinger, R. Séférian, T.
28 Steinhoff, B.D. Stocker, A.J. Sutton, T. Takahashi, B. Tilbrook, I.T. van der Laan-Luijkx,
29 G.R. van der Werf, S. van Heuven, D. Vandemark, N. Viovy, A. Wiltshire, S. Zaehle, and N.
30 Zeng, 2015: Global carbon budget 2015. *Earth System Science Data*, **7**, 349-396.
31 <http://dx.doi.org/10.5194/essd-7-349-2015>
- 32 Le Quéré, C., M.R. Raupach, J.G. Canadell, G. Marland, L. Bopp, P. Ciais, T.J. Conway, S.C.
33 Doney, R.A. Feely, P. Foster, P. Friedlingstein, K. Gurney, R.A. Houghton, J.I. House, C.
34 Huntingford, P.E. Levy, M.R. Lomas, J. Majkut, N. Metzl, J.P. Ometto, G.P. Peters, I.C.
35 Prentice, J.T. Randerson, S.W. Running, J.L. Sarmiento, U. Schuster, S. Sitch, T. Takahashi,

- 1 N. Viovy, G.R. van der Werf, and F.I. Woodward, 2009: Trends in the sources and sinks of
2 carbon dioxide. *Nature Geoscience*, **2**, 831-836. <http://dx.doi.org/10.1038/ngeo689>
- 3 Leggett, J., W.J. Pepper, R.J. Swart, J. Edmonds, L.G.M. Filho, I. Mintzer, M.X. Wang, and J.
4 Watson, 1992: Emissions scenarios for the IPCC: An update. *Climate Change 1992: The
5 Supplementary Report to the IPCC Scientific Assessment*. Houghton, J.T., B.A. Callander, and
6 S.K. Varney, Eds. Cambridge University Press, Cambridge, United Kingdom, New York, NY,
7 USA, and Victoria, Australia, 73-95.
8 [https://www.ipcc.ch/ipccreports/1992%20IPCC%20Supplement/IPCC_Suppl_Report_1992_
9 wg_I/ipcc_wg_I_1992_suppl_report_section_a3.pdf](https://www.ipcc.ch/ipccreports/1992%20IPCC%20Supplement/IPCC_Suppl_Report_1992_wg_I/ipcc_wg_I_1992_suppl_report_section_a3.pdf)
- 10 Lunt, D.J., T. Dunkley Jones, M. Heinemann, M. Huber, A. LeGrande, A. Winguth, C. Loptson,
11 J. Marotzke, C.D. Roberts, J. Tindall, P. Valdes, and C. Winguth, 2012: A model–data
12 comparison for a multi-model ensemble of early Eocene atmosphere–ocean simulations:
13 EoMIP. *Climate of the Past*, **8**, 1717-1736. <http://dx.doi.org/10.5194/cp-8-1717-2012>
- 14 Masson-Delmotte, V., M. Schulz, A. Abe-Ouchi, J. Beer, A. Ganopolski, J.F. González Rouco,
15 E. Jansen, K. Lambeck, J. Luterbacher, T. Naish, T. Osborn, B. Otto-Bliesner, T. Quinn, R.
16 Ramesh, M. Rojas, X. Shao, and A. Timmermann, 2013: Information from paleoclimate
17 archives. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group
18 I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker,
19 T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex,
20 and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New
21 York, NY, USA, 383–464. <http://www.climatechange2013.org/report/full-report/>
- 22 Masui, T., K. Matsumoto, Y. Hijioka, T. Kinoshita, T. Nozawa, S. Ishiwatari, E. Kato, P.R.
23 Shukla, Y. Yamagata, and M. Kainuma, 2011: An emission pathway for stabilization at
24 6 Wm^{-2} radiative forcing. *Climatic Change*, **109**, 59. [http://dx.doi.org/10.1007/s10584-011-
25 0150-5](http://dx.doi.org/10.1007/s10584-011-0150-5)
- 26 Meehl, G.A., T.F. Stocker, W.D. Collins, P. Friedlingstein, A.T. Gaye, J.M. Gregory, A. Kitoh,
27 R. Knutti, J.M. Murphy, A. Noda, S.C.B. Raper, I.G. Watterson, A.J. Weaver, and Z.-C.
28 Zhao, 2007: Ch. 10: Global climate projections. *Climate Change 2007: The Physical Science
29 basis: Contribution of Working Group I to the Fourth Assessment Report of the
30 Intergovernmental Panel on Climate Change*. Solomon, S., D. Qin, M. Manning, Z. Chen, M.
31 Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, Eds. Cambridge University Press,
32 Cambridge, UK and New York, NY, 747-845. [http://www.ipcc.ch/pdf/assessment-
33 report/ar4/wg1/ar4-wg1-chapter10.pdf](http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter10.pdf)
- 34 Meinshausen, M., S.J. Smith, K. Calvin, J.S. Daniel, M.L.T. Kainuma, J.-F. Lamarque, K.
35 Matsumoto, S.A. Montzka, S.C.B. Raper, K. Riahi, A. Thomson, G.J.M. Velders, and D.P.P.
36 van Vuuren, 2011: The RCP greenhouse gas concentrations and their extensions from 1765 to
37 2300. *Climatic Change*, **109**, 213-241. <http://dx.doi.org/10.1007/s10584-011-0156-z>

- 1 Melillo, J.M., T.C. Richmond, and G.W. Yohe, eds., 2014: *Climate Change Impacts in the*
2 *United States: The Third National Climate Assessment*. U.S. Global Change Research
3 Program: Washington, D.C., 841 pp. <http://dx.doi.org/10.7930/J0Z31WJ2>
- 4 Miller, K.G., J.D. Wright, J.V. Browning, A. Kulpecz, M. Kominz, T.R. Naish, B.S. Cramer, Y.
5 Rosenthal, W.R. Peltier, and S. Sosdian, 2012: High tide of the warm Pliocene: Implications
6 of global sea level for Antarctic deglaciation. *Geology*, **40**, 407-410.
7 <http://dx.doi.org/10.1130/g32869.1>
- 8 Mitchell, T.D., 2003: Pattern scaling: An examination of the accuracy of the technique for
9 describing future climates. *Climatic Change*, **60**, 217-242.
10 <http://dx.doi.org/10.1023/a:1026035305597>
- 11 Moss, R.H., J.A. Edmonds, K.A. Hibbard, M.R. Manning, S.K. Rose, D.P. van Vuuren, T.R.
12 Carter, S. Emori, M. Kainuma, T. Kram, G.A. Meehl, J.F.B. Mitchell, N. Nakicenovic, K.
13 Riahi, S.J. Smith, R.J. Stouffer, A.M. Thomson, J.P. Weyant, and T.J. Wilbanks, 2010: The
14 next generation of scenarios for climate change research and assessment. *Nature*, **463**, 747-
15 756. <http://dx.doi.org/10.1038/nature08823>
- 16 Nakicenovic, N., J. Alcamo, G. Davis, B.d. Vries, J. Fenhann, S. Gaffin, K. Gregory, A. Grüber,
17 T.Y. Jung, T. Kram, E.L.L. Rovere, L. Michaelis, S. Mori, T. Morita, W. Pepper, H. Pitcher,
18 L. Price, K. Riahi, A. Roehrl, H.-H. Rogner, A. Sankovski, M. Schlesinger, P. Shukla, S.
19 Smith, R. Swart, S.v. Rooijen, N. Victor, and Z. Dadi, 2000: IPCC Special Report on
20 Emissions Scenarios. Nakicenovic, N. and R. Swart (Eds.). Cambridge University Press.
21 <http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=0>
- 22 NAST, 2001: Climate Change Impacts on the United States: The Potential Consequences of
23 Climate Variability and Change, Report for the US Global Change Research Program. U.S.
24 Global Climate Research Program, National Assessment Synthesis Team, Cambridge, UK.
25 620 pp. [http://www.globalchange.gov/browse/reports/climate-change-impacts-united-states-](http://www.globalchange.gov/browse/reports/climate-change-impacts-united-states-potential-consequences-climate-variability-and-3)
26 [potential-consequences-climate-variability-and-3](http://www.globalchange.gov/browse/reports/climate-change-impacts-united-states-potential-consequences-climate-variability-and-3)
- 27 NEEM, 2013: Eemian interglacial reconstructed from a Greenland folded ice core. *Nature*, **493**,
28 489-494. <http://dx.doi.org/10.1038/nature11789>
- 29 NRC, 2011: *Climate Stabilization Targets: Emissions, Concentrations, and Impacts over*
30 *Decades to Millennia*. National Research Council. The National Academies Press,
31 Washington, D.C., 298 pp. <http://dx.doi.org/10.17226/12877>
- 32 O'Neill, B.C., E. Kriegler, K. Riahi, K.L. Ebi, S. Hallegatte, T.R. Carter, R. Mathur, and D.P.
33 van Vuuren, 2014: A new scenario framework for climate change research: The concept of
34 shared socioeconomic pathways. *Climatic Change*, **122**, 387-400.
35 <http://dx.doi.org/10.1007/s10584-013-0905-2>

- 1 Otto-Bliesner, B.L., N. Rosenbloom, E.J. Stone, N.P. McKay, D.J. Lunt, E.C. Brady, and J.T.
2 Overpeck, 2013: How warm was the last interglacial? New model–data comparisons.
3 *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering*
4 *Sciences*, **371**. <http://dx.doi.org/10.1098/rsta.2013.0097>
- 5 Pagani, M., M. Huber, Z. Liu, S.M. Bohaty, J. Henderiks, W. Sijp, S. Krishnan, and R.M.
6 DeConto, 2011: The role of carbon dioxide during the onset of Antarctic glaciation. *Science*,
7 **334**, 1261-1264. <http://dx.doi.org/10.1126/science.1203909>
- 8 Penman, D.E., B. Hönisch, R.E. Zeebe, E. Thomas, and J.C. Zachos, 2014: Rapid and sustained
9 surface ocean acidification during the Paleocene-Eocene Thermal Maximum.
10 *Paleoceanography*, **29**, 357-369. <http://dx.doi.org/10.1002/2014PA002621>
- 11 Pierce, D.W., D.R. Cayan, and B.L. Thrasher, 2014: Statistical downscaling using Localized
12 Constructed Analogs (LOCA). *Journal of Hydrometeorology*, **15**, 2558-2585.
13 <http://dx.doi.org/10.1175/jhm-d-14-0082.1>
- 14 Prein, A.F., W. Langhans, G. Fosser, A. Ferrone, N. Ban, K. Goergen, M. Keller, M. Tölle, O.
15 Gutjahr, F. Feser, E. Brisson, S. Kollet, J. Schmidli, N.P.M. van Lipzig, and R. Leung, 2015:
16 A review on regional convection-permitting climate modeling: Demonstrations, prospects,
17 and challenges. *Reviews of Geophysics*, **53**, 323-361.
18 <http://dx.doi.org/10.1002/2014RG000475>
- 19 Raupach, M.R., G. Marland, P. Ciais, C. Le Quéré, J.G. Canadell, G. Klepper, and C.B. Field,
20 2007: Global and regional drivers of accelerating CO₂ emissions. *Proceedings of the National*
21 *Academy of Sciences*, **104**, 10288-10293. <http://dx.doi.org/10.1073/pnas.0700609104>
- 22 Rhein, M., S.R. Rintoul, S. Aoki, E. Campos, D. Chambers, R.A. Feely, S. Gulev, G.C. Johnson,
23 S.A. Josey, A. Kostianoy, C. Mauritzen, D. Roemmich, L.D. Talley, and F. Wang, 2013:
24 Observations: Ocean. *Climate Change 2013: The Physical Science Basis. Contribution of*
25 *Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate*
26 *Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels,
27 Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United
28 Kingdom and New York, NY, USA, 255–316. [http://www.climatechange2013.org/report/full-](http://www.climatechange2013.org/report/full-report/)
29 [report/](http://www.climatechange2013.org/report/full-report/)
- 30 Riahi, K., S. Rao, V. Krey, C. Cho, V. Chirkov, G. Fischer, G. Kindermann, N. Nakicenovic, and
31 P. Rafaj, 2011: RCP 8.5—A scenario of comparatively high greenhouse gas emissions.
32 *Climatic Change*, **109**, 33-57. <http://dx.doi.org/10.1007/s10584-011-0149-y>
- 33 Royer, D.L., 2014: 6.11 - Atmospheric CO₂ and O₂ during the Phanerozoic: Tools, patterns, and
34 impacts. *Treatise on Geochemistry (Second Edition)*. Holland, H.D. and K.K. Turekian, Eds.

- 1 Elsevier, Amsterdam, Netherlands, 251-267. [http://dx.doi.org/10.1016/B978-0-08-095975-](http://dx.doi.org/10.1016/B978-0-08-095975-7.01311-5)
2 [7.01311-5](http://dx.doi.org/10.1016/B978-0-08-095975-7.01311-5)
- 3 Ryu, J.-H. and K. Hayhoe, 2013: Understanding the sources of Caribbean precipitation biases in
4 CMIP3 and CMIP5 simulations. *Climate Dynamics*, **42**, 3233-3252.
5 <http://dx.doi.org/10.1007/s00382-013-1801-1>
- 6 Sanderson, B.M., R. Knutti, and P. Caldwell, 2015: A representative democracy to reduce
7 interdependency in a multimodel ensemble. *Journal of Climate*, **28**, 5171-5194.
8 <http://dx.doi.org/10.1175/JCLI-D-14-00362.1>
- 9 Sanderson, B.M., B.C. O'Neill, and C. Tebaldi, 2016a: What would it take to achieve the Paris
10 temperature targets? *Geophysical Research Letters*, **43**, 7133-7142.
11 <http://dx.doi.org/10.1002/2016GL069563>
- 12 Sanderson, B.M., M. Wehner, and R. Knutti, 2016b: Skill and independence weighting for multi-
13 model assessment. *Geoscientific Model Development Discussions*, **In Review**.
14 <http://dx.doi.org/10.5194/gmd-2016-285>
- 15 Schneider, R., J. Schmitt, P. Köhler, F. Joos, and H. Fischer, 2013: A reconstruction of
16 atmospheric carbon dioxide and its stable carbon isotopic composition from the penultimate
17 glacial maximum to the last glacial inception. *Clim. Past*, **9**, 2507-2523.
18 <http://dx.doi.org/10.5194/cp-9-2507-2013>
- 19 Seki, O., G.L. Foster, D.N. Schmidt, A. Mackensen, K. Kawamura, and R.D. Pancost, 2010:
20 Alkenone and boron-based Pliocene pCO₂ records. *Earth and Planetary Science Letters*, **292**,
21 201-211. <http://dx.doi.org/10.1016/j.epsl.2010.01.037>
- 22 Sheffield, J., A. Barrett, D. Barrie, S.J. Camargo, E.K.M. Chang, B. Colle, D.N. Fernando, R. Fu,
23 K.L. Geil, Q. Hu, X. Jiang, N. Johnson, K.B. Karnauskas, S.T. Kim, J. Kinter, S. Kumar, B.
24 Langenbrunner, K. Lombardo, L.N. Long, E. Maloney, A. Mariotti, J.E. Meyerson, K.C. Mo,
25 J.D. Neelin, S. Nigam, Z. Pan, T. Ren, A. Ruiz-Barradas, R. Seager, Y.L. Serra, A. Seth, D.-
26 Z. Sun, J.M. Thibeault, J.C. Stroeve, C. Wang, S.-P. Xie, Z. Yang, L. Yin, J.-Y. Yu, T. Zhang,
27 and M. Zhao, 2014: Regional Climate Processes and Projections for North America:
28 CMIP3/CMIP5 Differences, Attribution and Outstanding Issues. NOAA Climate Program
29 Office, Silver Spring, MD. 47 pp. <http://dx.doi.org/10.7289/V5DB7ZRC>
- 30 Sheffield, J., A.P. Barrett, B. Colle, D.N. Fernando, R. Fu, K.L. Geil, Q. Hu, J. Kinter, S. Kumar,
31 B. Langenbrunner, K. Lombardo, L.N. Long, E. Maloney, A. Mariotti, J.E. Meyerson, K.C.
32 Mo, J.D. Neelin, S. Nigam, Z. Pan, T. Ren, A. Ruiz-Barradas, Y.L. Serra, A. Seth, J.M.
33 Thibeault, J.C. Stroeve, Z. Yang, and L. Yin, 2013: North American climate in CMIP5
34 experiments. Part I: Evaluation of historical simulations of continental and regional
35 climatology. *Journal of Climate*, **26**, 9209-9245. <http://dx.doi.org/10.1175/jcli-d-12-00592.1>

- 1 Smith, P., S.J. Davis, F. Creutzig, S. Fuss, J. Minx, B. Gabrielle, E. Kato, R.B. Jackson, A.
2 Cowie, E. Kriegler, D.P. van Vuuren, J. Rogelj, P. Ciais, J. Milne, J.G. Canadell, D.
3 McCollum, G. Peters, R. Andrew, V. Krey, G. Shrestha, P. Friedlingstein, T. Gasser, A.
4 Grubler, W.K. Heidug, M. Jonas, C.D. Jones, F. Kraxner, E. Littleton, J. Lowe, J.R. Moreira,
5 N. Nakicenovic, M. Obersteiner, A. Patwardhan, M. Rogner, E. Rubin, A. Sharifi, A.
6 Torvanger, Y. Yamagata, J. Edmonds, and C. Yongsung, 2015: Biophysical and economic
7 limits to negative CO₂ emissions. *Nature Climate Change*, **6**, 42-50.
8 <http://dx.doi.org/10.1038/nclimate2870>
- 9 Stoner, A.M.K., K. Hayhoe, X. Yang, and D.J. Wuebbles, 2012: An asynchronous regional
10 regression model for statistical downscaling of daily climate variables. *International Journal*
11 *of Climatology*, **33**, 2473-2494. <http://dx.doi.org/10.1002/joc.3603>
- 12 Sun, L., K.E. Kunkel, L.E. Stevens, A. Buddenberg, J.G. Dobson, and D.R. Easterling, 2015:
13 Regional Surface Climate Conditions in CMIP3 and CMIP5 for the United States:
14 Differences, Similarities, and Implications for the U.S. National Climate Assessment.
15 National Oceanic and Atmospheric Administration, National Environmental Satellite, Data,
16 and Information Service, 111 pp. <http://dx.doi.org/10.7289/V5RB72KG>
- 17 Swain, S. and K. Hayhoe, 2015: CMIP5 projected changes in spring and summer drought and
18 wet conditions over North America. *Climate Dynamics*, **44**, 2737-2750.
19 <http://dx.doi.org/10.1007/s00382-014-2255-9>
- 20 Tans, P. and R. Keeling, 2017: Trends in Atmospheric Carbon Dioxide. Annual Mean Growth
21 Rate of CO₂ at Mauna Loa. NOAA Earth System Research Laboratory.
22 <https://www.esrl.noaa.gov/gmd/ccgg/trends/gr.html>
- 23 Tebaldi, C. and J.M. Arblaster, 2014: Pattern scaling: Its strengths and limitations, and an update
24 on the latest model simulations. *Climatic Change*, **122**, 459-471.
25 <http://dx.doi.org/10.1007/s10584-013-1032-9>
- 26 Thomson, A.M., K.V. Calvin, S.J. Smith, G.P. Kyle, A. Volke, P. Patel, S. Delgado-Arias, B.
27 Bond-Lamberty, M.A. Wise, and L.E. Clarke, 2011: RCP4.5: A pathway for stabilization of
28 radiative forcing by 2100. *Climatic Change*, **109**, 77-94. [http://dx.doi.org/10.1007/s10584-](http://dx.doi.org/10.1007/s10584-011-0151-4)
29 [011-0151-4](http://dx.doi.org/10.1007/s10584-011-0151-4)
- 30 Thrasher, B., J. Xiong, W. Wang, F. Melton, A. Michaelis, and R. Nemani, 2013: Downscaled
31 climate projections suitable for resource management. *Eos, Transactions, American*
32 *Geophysical Union*, **94**, 321-323. <http://dx.doi.org/10.1002/2013EO370002>
- 33 UNFCCC, 2015: Paris Agreement. United Nations Framework Convention on Climate Change,
34 [Bonn, Germany]. 25 pp.

- 1 http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf
2
- 3 Vaithinada Ayar, P., M. Vrac, S. Bastin, J. Carreau, M. Déqué, and C. Gallardo, 2016:
4 Intercomparison of statistical and dynamical downscaling models under the EURO- and
5 MED-CORDEX initiative framework: Present climate evaluations. *Climate Dynamics*, **46**,
6 1301-1329. <http://dx.doi.org/10.1007/s00382-015-2647-5>
- 7 van Vuuren, D.P., S. Deetman, M.G.J. den Elzen, A. Hof, M. Isaac, K. Klein Goldewijk, T.
8 Kram, A. Mendoza Beltran, E. Stehfest, and J. van Vliet, 2011: RCP2.6: Exploring the
9 possibility to keep global mean temperature increase below 2°C. *Climatic Change*, **109**, 95-
10 116. <http://dx.doi.org/10.1007/s10584-011-0152-3>
- 11 Vaughan, D.G., J.C. Comiso, I. Allison, J. Carrasco, G. Kaser, R. Kwok, P. Mote, T. Murray, F.
12 Paul, J. Ren, E. Rignot, O. Solomina, K. Steffen, and T. Zhang, 2013: Observations:
13 Cryosphere. *Climate Change 2013: The Physical Science Basis. Contribution of Working*
14 *Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.
15 Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia,
16 V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom
17 and New York, NY, USA, 317–382. <http://www.climatechange2013.org/report/full-report/>
- 18 Vrac, M., M. Stein, and K. Hayhoe, 2007: Statistical downscaling of precipitation through
19 nonhomogeneous stochastic weather typing. *Climate Research*, **34**, 169-184.
20 <http://dx.doi.org/10.3354/cr00696>
- 21 Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, P. Thorne, R. Vose, M.
22 Wehner, J. Willis, D. Anderson, S. Doney, R. Feely, P. Hennon, V. Kharin, T. Knutson, F.
23 Landerer, T. Lenton, J. Kennedy, and R. Somerville, 2014: Ch. 2: Our changing climate.
24 *Climate Change Impacts in the United States: The Third National Climate Assessment*.
25 Melillo, J.M., T.C. Richmond, and G.W. Yohe, Eds. U.S. Global Change Research Program,
26 Washington, D.C., 19-67. <http://dx.doi.org/10.7930/J0KW5CXT>
- 27 Wang, C., L. Zhang, S.-K. Lee, L. Wu, and C.R. Mechoso, 2014: A global perspective on
28 CMIP5 climate model biases. *Nature Climate Change*, **4**, 201-205.
29 <http://dx.doi.org/10.1038/nclimate2118>
- 30 Wang, M. and J.E. Overland, 2012: A sea ice free summer Arctic within 30 years: An update
31 from CMIP5 models. *Geophysical Research Letters*, **39**, L18501.
32 <http://dx.doi.org/10.1029/2012GL052868>
- 33 Wang, M., J.E. Overland, V. Kattsov, J.E. Walsh, X. Zhang, and T. Pavlova, 2007: Intrinsic
34 versus forced variation in coupled climate model simulations over the Arctic during the
35 twentieth century. *Journal of Climate*, **20**, 1093-1107. <http://dx.doi.org/10.1175/JCLI4043.1>

- 1 Wang, Y., L.R. Leung, J.L. McGregor, D.-K. Lee, W.-C. Wang, Y. Ding, and F. Kimura, 2004:
2 Regional climate modeling: Progress, challenges, and prospects. *Journal of the*
3 *Meteorological Society of Japan. Ser. II*, **82**, 1599-1628.
4 <http://dx.doi.org/10.2151/jmsj.82.1599>
- 5 Weigel, A.P., R. Knutti, M.A. Liniger, and C. Appenzeller, 2010: Risks of model weighting in
6 multimodel climate projections. *Journal of Climate*, **23**, 4175-4191.
7 <http://dx.doi.org/10.1175/2010jcli3594.1>
- 8 Xie, S.-P., C. Deser, G.A. Vecchi, M. Collins, T.L. Delworth, A. Hall, E. Hawkins, N.C.
9 Johnson, C. Cassou, A. Giannini, and M. Watanabe, 2015: Towards predictive understanding
10 of regional climate change. *Nature Climate Change*, **5**, 921-930.
11 <http://dx.doi.org/10.1038/nclimate2689>
- 12 Zeebe, R.E., A. Ridgwell, and J.C. Zachos, 2016: Anthropogenic carbon release rate
13 unprecedented during the past 66 million years. *Nature Geoscience*, **9**, 325-329.
14 <http://dx.doi.org/10.1038/ngeo2681>

1 **5. Large-Scale Circulation and Climate Variability**

2 **KEY FINDINGS**

- 3 1. The tropics have expanded poleward by about 70 to 200 miles in each hemisphere over
4 the period 1979–2009, with an accompanying shift of the subtropical dry zones,
5 midlatitude jets, and storm tracks (*medium to high confidence*). Human activities have
6 played a role in this change (*medium confidence*), although confidence is presently *low*
7 regarding the magnitude of the human contribution relative to natural variability.
- 8 2. Recurring patterns of variability in large-scale atmospheric circulation (such as the North
9 Atlantic Oscillation and Northern Annular Mode) and the atmosphere–ocean system
10 (such as El Niño–Southern Oscillation) cause year-to-year variations in U.S. temperatures
11 and precipitation (*high confidence*). Changes in the occurrence of these patterns or their
12 properties have contributed to recent U.S. temperature and precipitation trends (*medium*
13 *confidence*), although confidence is *low* regarding the size of the role of human activities
14 in these changes.

15 **5.1.Introduction**

16 The causes of regional climate trends cannot be understood without considering the impact of
17 variations in large-scale atmospheric circulation and an assessment of the role of internally
18 generated climate variability. There are contributions to regional climate trends from changes in
19 large-scale latitudinal circulation, which is generally organized into three cells in each
20 hemisphere—Hadley cell, Ferrell cell and Polar cell—and which determines the location of
21 subtropical dry zones and midlatitude jet streams (Figure 5.1). These circulation cells are
22 expected to shift poleward during warmer periods (Frierson et al. 2007; Sun et al. 2013; Vallis et
23 al. 2015; Mbengue and Schneider 2017), which could result in poleward shifts in precipitation
24 patterns, affecting natural ecosystems, agriculture, and water resources (Seidel et al. 2008; Feng
25 and Fu 2013).

26 **[INSERT FIGURE 5.1 HERE]**

27 In addition, regional climate can be strongly affected by non-local response to recurring patterns
28 (or modes) of variability of the atmospheric circulation or the coupled atmosphere–ocean system.
29 These modes of variability represent preferred spatial patterns and their temporal variation. They
30 account for gross features in variance and for teleconnections which describe climate links
31 between geographically separated regions. Modes of variability are often described as a product
32 of a spatial climate pattern and an associated climate index time series that are identified based
33 on statistical methods like Principal Component Analysis (PC analysis), which is also called
34 Empirical Orthogonal Function Analysis (EOF analysis), and cluster analysis.

1 On intraseasonal to interannual time scales, the climate of the United States is strongly affected
2 by modes of atmospheric circulation variability like the North Atlantic Oscillation
3 (NAO)/Northern Annular Mode (NAM), North Pacific Oscillation (NPO), and Pacific/North
4 American Pattern (PNA) (Hurrell and Deser 2009; Linkin and Nigam 2008; Ning and Bradley
5 2016). These modes are closely linked to other atmospheric circulation phenomena like blocking
6 and quasi-stationary wave patterns and jet streams that can lead to weather and climate extremes
7 (Grotjahn et al. 2016). On an interannual time scale, coupled atmosphere–ocean phenomena like
8 El Niño–Southern Oscillation (ENSO) have a prominent effect (Halpert and Ropelewski 1992).
9 On longer time scales, U.S. climate anomalies are linked to slow variations of sea surface
10 temperature related to the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal
11 Oscillation (AMO) (Newman et al. 2016; Enfield et al. 2001; Goldenberg et al. 2001).

12 These modes of variability can affect the local-to-regional climate response to external forcing in
13 various ways. The climate response may be altered by the forced response of these existing,
14 recurring modes of variability (Perlwitz et al. 2008). Further, the structure and strength of
15 regional temperature and precipitation impacts of these recurring modes of variability may be
16 modified due to a change in the background climate (Palmer et al. 2008). Modes of internal
17 variability of the climate system also contribute to observed decadal and multidecadal
18 temperature and precipitation trends on local to regional scales, masking possible systematic
19 changes due to an anthropogenic influence (Deser et al. 2016). However, there are still large
20 uncertainties in our understanding of the impact of human-induced climate change on
21 atmospheric circulation (Shepherd 2014; Vallis et al. 2015). Furthermore, the confidence in
22 any specific projected change in ENSO variability in the 21st century remains *low*
23 (Christensen et al. 2013).

24 **5.2 Modes of Variability: Past and Projected Changes**

25 **5.2.1 Width of the Tropics and Global Circulation**

26 Evidence continues to mount for an expansion of the tropics over the past several decades, with a
27 poleward expansion of the Hadley cell and an associated poleward shift of the subtropical dry
28 zones and storm tracks in each hemisphere (Hartmann et al. 2013; Davis and Birner 2013; Feng
29 and Fu 2013; Birner et al. 2014; Karauskas and Ummenhofer 2014; Lucas et al. 2014; Quan et
30 al. 2014; Brönnimann et al. 2015; Garfinkel et al. 2015; Norris et al. 2016; Reichler 2016). The
31 rate of expansion is uncertain and depends on the metrics and data sources that are used. Recent
32 estimates of the widening of the global tropics for the period 1979–2009 range between 1° and
33 3° latitude (between about 70 and 200 miles) in each hemisphere, an average trend of between
34 approximately 0.5° and 1.0° per decade (Lucas et al. 2014). While the roles of increasing
35 greenhouse gases in both hemispheres (Bindoff et al. 2013; Vallis et al. 2015), stratospheric
36 ozone depletion in the Southern Hemisphere (Waugh et al. 2015), and anthropogenic aerosols in
37 the Northern Hemisphere (Allen et al. 2012; Kovilakam and Mahajan 2015) have been

1 implicated as contributors to the observed expansion, there is uncertainty in the relative
2 contributions of natural and anthropogenic factors, and natural variability may be dominating
3 (Adam et al. 2014; Allen et al. 2014; Garfinkel et al. 2015).

4 Most of the previous work on tropical expansion to date has focused on zonally averaged
5 changes. There are only a few recent studies that diagnose regional characteristics of tropical
6 expansion. The findings depend on analysis methods and datasets. For example, a northward
7 expansion of the tropics in most regions of the Northern Hemisphere, including the Eastern
8 Pacific with impact on drying in the American Southwest, is found based on diagnosing outgoing
9 longwave radiation (Chen et al. 2014). However, other studies do not find a significant poleward
10 expansion of the tropics over the Eastern Pacific and North America (Lucas and Nguyen 2015;
11 Schwendike et al. 2015). Thus, while some studies associate the observed drying of the U.S.
12 Southwest with the poleward expansion of the tropics (Feng and Fu 2013; Prein et al. 2016),
13 regional impacts of the observed zonally averaged changes in the width of the tropics are not
14 understood.

15 Due to human-induced greenhouse gas increases, the Hadley cell is likely to widen in the future,
16 with an accompanying poleward shift in the subtropical dry zones, midlatitude jets, and storm
17 tracks (Scheff and Frierson 2012a,b; Barnes and Polvani 2013; Collins et al. 2013; Feng and Fu
18 2013; Vallis et al. 2015; Mbengue and Schneider 2017). Large uncertainties remain in projected
19 changes in non-zonal to regional circulation components and related changes in precipitation
20 patterns (Barnes and Polvani 2013; Shepherd 2014; Simpson et al. 2014, 2016). Uncertainties in
21 projected changes in midlatitude jets are also related to the projected rate of arctic amplification
22 and variations in the stratospheric polar vortex. Both factors could shift the midlatitude jet
23 equatorward, especially in the North Atlantic region (Karpechko and Manzini 2012; Scaife et al.
24 2012; Cattiaux and Cassou 2013; Barnes and Polvani 2015).

25 **5.2.2 El Niño–Southern Oscillation**

26 El Niño–Southern Oscillation (ENSO) is a main source of climate variability, with a two- to
27 seven-year timescale, originating from coupled ocean–atmosphere interactions in the tropical
28 Pacific. Major ENSO events affect weather patterns over many parts of the globe through
29 atmospheric teleconnections. ENSO strongly affects precipitation and temperature in the United
30 States with impacts being most pronounced during the cold season (Figure 5.2) (Ropelewski and
31 Halpert 1987; Kiladis and Diaz 1989; Halpert and Ropelewski 1992; Hoerling et al. 2001; T.
32 Zhang et al. 2016). A cooling trend of the tropical Pacific Ocean that resembles La Niña
33 conditions contributed to drying in southwestern North America from 1979 to 2006 (Hoerling et
34 al. 2010) and is found to explain most of the decrease in heavy daily precipitation events in the
35 southern United States from 1979 to 2013 (Hoerling et al. 2016).

36 **[INSERT FIGURE 5.2 HERE]**

1 El Niño teleconnections are modulated by the location of maximum anomalous tropical Pacific
2 sea surface temperatures (SST). Eastern Pacific (EP) El Niño events affect winter temperatures
3 primarily over the Great Lakes, Northeast, and Southwest, while Central Pacific (CP) events
4 influence temperatures primarily over the northwestern and southeastern United States (Yu et al.
5 2012). The CP El Niño also enhances the drying effect, but weakens the wetting effect, typically
6 produced by traditional EP El Niño events on the United States winter precipitation (Yu and Zou
7 2013). It is not clear whether observed decadal-scale modulations of ENSO properties, including
8 an increase in ENSO amplitude (Li et al. 2011) and an increase in frequency of CP El Niño
9 events (Yeh et al. 2009; Lee and McPhaden 2010), are due to internal variability or
10 anthropogenic forcing. Uncertainties in both the diagnosed distinct U.S. climate effects of EP
11 and CP events and causes for the decadal scale changes result from the limited sample size of
12 observed ENSO events in each category (Garfinkel et al. 2013; Deser et al. 2017) and the
13 relatively short record of the comprehensive observations (since late 1970s) that would allow the
14 investigation of ENSO-related coupled atmosphere–ocean feedbacks (Christensen et al. 2013).
15 Furthermore, unforced global climate model simulations show that decadal to centennial
16 modulations of ENSO can be generated without any change in external forcing (Capotondi et al.
17 2015). A model study based on large, single-model ensembles of atmospheric and coupled
18 atmosphere–ocean models finds that external radiative forcing resulted in an atmospheric
19 teleconnection pattern that is independent of ENSO-like variations during the 1979–2014 period
20 and is characterized by a hemisphere-scale increasing trend in heights (T. Zhang et al. 2016).

21 The representation of ENSO in climate models has improved from CMIP3 to CMIP5 models,
22 especially in relation to ENSO amplitude (Flato et al. 2013; Bellenger et al. 2014). However,
23 CMIP5 models still cannot capture the seasonal timing of ENSO events (Sheffield et al. 2013).
24 Furthermore, they still exhibit errors in simulating key atmospheric feedbacks, and the
25 improvement in ENSO amplitudes might therefore result from error compensations (Bellenger
26 et al. 2014). Limited observational records and the nonstationarity of tropical Pacific
27 teleconnections to North America on multidecadal time scales pose challenges for evaluating
28 teleconnections between ENSO and U.S. climate in coupled atmosphere–ocean models (Coats
29 et al. 2013; Deser et al. 2017). For a given SST forcing, however, the atmospheric component of
30 CMIP5 models simulate the sign of the precipitation change over the southern section of North
31 America (Langenbrunner and Neelin, 2013).

32 Climate projections suggest that ENSO will remain a primary mode of natural climate variability
33 in the 21st century (Christensen et al. 2013). Climate models do not agree, however, on projected
34 changes in the intensity or spatial pattern of ENSO (Christensen et al. 2013). This uncertainty is
35 related to a model dependence of simulated changes in the zonal gradient of tropical Pacific sea
36 surface temperature in a warming climate (Christensen et al. 2013). Model studies suggest an
37 eastward shift of ENSO-induced teleconnection patterns due to greenhouse gas-induced climate
38 change (Meehl and Teng 2007; Kug et al. 2010; Stevenson 2012; Zhou et al. 2014). However,

1 the impact of such a shift on ENSO-induced climate anomalies in the United States is not well
2 understood (Seager et al. 2012; Zhou et al. 2014).

3 In summary, there is *high confidence* that, in the 21st century, ENSO will remain a main source
4 of climate variability over the United States on seasonal to interannual timescales. There is *low*
5 *confidence* for a specific projected change in ENSO variability.

6 **5.2.3 Extra-tropical Modes of Variability and Phenomena**

7 **NORTH ATLANTIC OSCILLATION AND NORTHERN ANNULAR MODE**

8 The North Atlantic Oscillation (NAO), the leading recurring mode of variability in the
9 extratropical North Atlantic region, describes an opposing pattern of sea level pressure between
10 the Atlantic subtropical high and the Iceland/Arctic low. Variations in the NAO are accompanied
11 by changes in the location and intensity of the Atlantic midlatitude storm track and blocking
12 activity that affect climate over the North Atlantic and surrounding continents. A negative NAO
13 phase is related to anomalously cold conditions and an enhanced number of cold outbreaks in the
14 eastern United States, while a strong positive phase of the NAO tends to be associated with
15 above-normal temperatures in this region (Hurrell and Deser 2009; Thompson and Wallace
16 2001). The positive phase of the NAO is associated with increased precipitation frequency and
17 positive daily rainfall anomalies, including extreme daily precipitation anomalies in the
18 northeastern United States (Archambault et al. 2008; Durkee et al. 2008).

19 The Northern Annular Mode/Arctic Oscillation (NAM/AO) is closely related to the NAO. It
20 describes a pressure seesaw between mid- and high latitudes on a hemispheric scale, and thus
21 includes a third anomaly center over the North Pacific Ocean (Thompson and Wallace 1998;
22 Thompson and Wallace 2000). The time series of the NAO and NAM/AO are highly correlated,
23 with persistent NAO and NAM/AO events being indistinguishable (Deser 2000; Feldstein and
24 Franzke 2006).

25 The wintertime NAO/NAM index exhibits pronounced variability on multidecadal time scales,
26 with an increase from the 1960s to the 1990s, a shift to a more negative phase since the 1990s
27 due to a series of winters like 2009–2010 and 2010–2011 (which had exceptionally low index
28 values), and a return to more positive values after 2011 (Bindoff et al. 2013). Decadal scale
29 temperature trends in the eastern United States, including occurrences of cold outbreaks during
30 recent years, are linked to these changes in the NAO/NAM (Hurrell 1995; Cohen and Barlow
31 2005; Overland et al. 2015; Overland and Wang 2015).

32 The NAO's influence on the ocean occurs through changes in heat content, gyre circulations,
33 mixed layer depth, salinity, high-latitude deep water formation, and sea ice cover (Hurrell and
34 Deser 2009; Delworth et al. 2016). Climate model simulations show that multidecadal variations
35 in the NAO induce multidecadal variations in the strength of the Atlantic Meridional
36 Overturning Circulation (AMOC) and poleward ocean heat transport in the Atlantic, extending to

1 the Arctic, with potential impacts on recent Arctic sea ice loss and Northern Hemisphere
2 warming (Delworth et al. 2016). However, other model simulations suggest that the NAO and
3 recent changes in Northern Hemisphere climate were affected by recent variations in the AMOC
4 (Peings and Magnusdottir 2014) for which enhanced freshwater discharge from the Greenland
5 Ice Sheet (GrIS) may have been a contributing cause (Yang et al. 2016).

6 Climate models are widely analyzed for their ability to simulate the spatial patterns of the
7 NAO/NAM and their relationship to temperature and precipitation anomalies over the United
8 States (Flato et al. 2013; Ning and Bradley 2016; Gong et al. 2017). Climate models reproduce
9 the broad spatial and temporal features of the NAO, although there are large differences among
10 the individual models in the location of the NAO centers of action and their average magnitude.
11 These differences affect the agreement between observed and simulated climate anomalies
12 related to the NAO (Flato et al. 2013; Ning and Bradley 2016). Climate models tend to have a
13 NAM pattern that is more annular than observed (Flato et al. 2013; Gong et al. 2017), resulting
14 in a strong bias in the Pacific center of the NAM. As a result, temperature anomalies over the
15 northwestern United States associated with the NAM in most models are of opposite sign
16 compared to observation (Gong et al. 2017). Biases in the model representation of NAO/NAM
17 features are linked to limited abilities of general circulation models to reproduce dynamical
18 processes, including atmospheric blocking (Davini and Cagnazzo, 2014), troposphere–
19 stratosphere coupling (Shaw et al. 2014), and climatological stationary waves (Lee and Black
20 2013; Shaw et al. 2014).

21 The CMIP5 models on average simulate a progressive shift of the NAO/NAM towards the
22 positive phase due to human-induced climate change (Gillett and Fyfe 2013). However, the
23 spread between model simulations is larger than the projected multimodel increase (Christensen
24 et al. 2013), and there are uncertainties related to emissions scenarios (Ning and Bradley
25 2016). Furthermore, it is found that shifts between preferred periods of positive and negative
26 NAO phase will continue to occur similar to those observed in the past (Deser et al. 2012;
27 Christensen et al. 2013). There is no consensus on the location of changes of NAO centers
28 among the global climate models under future warming scenarios (Ning and Bradley 2016).
29 Uncertainties in future projections of the NAO/NAM in some seasons are linked to model spread
30 in projected future Arctic warming (Cattiaux and Cassou 2013; Barnes and Polvani 2015; Ch.
31 11: Arctic Changes) and to how models resolve stratospheric processes (Christensen et al. 2013;
32 Manzini et al. 2014).

33 In summary, while it is *likely* that the NAO/NAM index will become slightly more positive (on
34 average) due to increases in GHGs, there is *low confidence* in temperature and precipitation
35 changes over the United States related to such variations in the NAO/NAM.

36

1 NORTH PACIFIC OSCILLATION/WEST PACIFIC OSCILLATION

2 The North Pacific Oscillation (NPO) is a recurring mode of variability in the extratropical North
3 Pacific region and is characterized by a north-south seesaw in sea level pressure. Effects of NPO
4 on U.S. hydroclimate and marginal ice zone extent in the Arctic seas have been reported (Linkin
5 and Nigam 2008).

6 The NPO is linked to tropical sea surface temperature variability. Specifically, NPO contributes
7 to the excitation of ENSO events via the “Seasonal Footprinting Mechanism” (Vimont et al.
8 2003; Alexander et al. 2010). In turn, warm events in the central tropical Pacific Ocean are
9 suggested to force an NPO-like circulation pattern (Di Lorenzo et al. 2010). There is *low*
10 *confidence* in future projections of the NPO due to the small number of modeling studies as well
11 as the finding that many climate models do not properly simulate the observed linkages between
12 NPO and tropical sea surface temperature variability (Furtado et al. 2011; Christensen et al.
13 2013).

14 PACIFIC/NORTH AMERICAN PATTERN

15 The Pacific/North American (PNA) pattern is the leading recurring mode of internal atmospheric
16 variability over the North Pacific and the North American continent, especially during the cold
17 season. It describes a quadrupole pattern of mid-tropospheric height anomalies, with anomalies of
18 similar sign located over the subtropical northeastern Pacific and northwestern North America
19 and of the opposite sign centered over the Gulf of Alaska and the southeastern United States. The
20 PNA pattern is associated with strong fluctuations in the strength and location of the East Asian
21 jet stream. The positive phase of the PNA pattern is associated with above average temperatures
22 over the western and northwestern United States, and below average temperatures across the
23 south-central and southeastern United States, including enhanced occurrence of extreme cold
24 temperatures (Leathers et al. 1991; Loikith and Broccoli 2012; Ning and Bradley 2016).

25 Significant negative correlation between the PNA and winter precipitation over the Ohio River
26 Valley has been documented (Leathers et al. 1991; Coleman and Rogers 2003; Ning and Bradley
27 2016). The PNA is related to ENSO events (Nigam 2003) and also serves as a bridge linking
28 ENSO and NAO variability (Li and Lau 2012).

29 Climate models are able to reasonably represent the atmospheric circulation and climate
30 anomalies associated with the PNA pattern. However, individual models exhibit differences
31 compared to the observed relationship, due to displacements of the simulated PNA centers of
32 action and offsets in their magnitudes (Ning and Bradley 2016). Climate models do not show
33 consistent location changes of the PNA centers due to increases in GHGs (Zhou et al. 2014;
34 Ning and Bradley 2016). Therefore, there is *low confidence* for projected changes in the PNA
35 and the association with temperature and precipitation variations over the United States.

36

1 **BLOCKING AND QUASI-STATIONARY WAVES**

2 Anomalous atmospheric flow patterns in the extratropics that remain in place for an extended
3 period of time (for example, blocking and quasi-stationary Rossby waves)—and thus affect a
4 region with similar weather conditions like rain or clear sky for several days to weeks—can lead
5 to flooding, drought, heat waves, and cold waves (Petoukhov et al. 2013; Grotjahn et al. 2016;
6 Whan et al. 2016). Specifically, blocking describes large-scale, persistent high pressure systems
7 that interrupt the typical westerly flow, while planetary waves (Rossby waves) describe large-
8 scale meandering of the atmospheric jet stream.

9 A persistent pattern of high pressure in the circulation off the West Coast of the United States
10 has been associated with the recent multiyear California drought (Ch. 8: Droughts, Floods, and
11 Wildfire; Swain et al. 2014; Seager et al. 2015; Teng and Branstator 2017). Blocking in the
12 Alaskan region, which is enhanced during La Niña winters (Figure 5.2) (Renwick and Wallace
13 1996), is associated with higher temperatures in western Alaska but shift to lower mean and
14 extreme surface temperatures from the Yukon southward to the southern Plains (Carrera et al.
15 2004). The anomalously cold winters of 2009–2010 and 2010–2011 in the United States are
16 linked to the blocked (or negative) phase of the NAO (Guirguis et al. 2011). Stationary Rossby
17 wave patterns may have contributed to the North American temperature extremes during
18 summers like 2011 (Wang et al. 2014). It has been suggested that arctic amplification has already
19 led to weakened westerly winds and hence more slowly moving and amplified wave patterns and
20 enhanced occurrence of blocking (Francis and Vavrus 2012; Francis et al. 2017; Ch. 11: Arctic
21 Changes). While some studies suggest an observed increase in the metrics of these persistent
22 circulation patterns (Francis and Vavrus 2012; Hanna et al. 2016), other studies suggest that
23 observed changes are small compared to atmospheric internal variability (Barnes 2013; Screen
24 and Simmonds 2013; Barnes et al. 2014).

25 A decrease of blocking frequency with climate change is found in CMIP3, CMIP5, and higher-
26 resolution models (Christensen et al. 2013; Hoskins and Woollings 2015; Kennedy et al. 2016).
27 Climate models robustly project a change in Northern Hemisphere winter quasi-stationary wave
28 fields that are linked to a wetting of the North American West Coast (Brandefelt and Körnich
29 2008; Haarsma and Selten 2012; Simpson et al. 2014), due to a strengthening of the zonal mean
30 westerlies in the subtropical upper troposphere. However, CMIP5 models still underestimate
31 observed blocking activity in the North Atlantic sector while they tend to overestimate activity in
32 the North Pacific, although with a large intermodel spread (Christensen et al. 2013). Most
33 climate models also exhibit biases in the representation of relevant stationary waves (Simpson et
34 al. 2016).

35 In summary, there is *low confidence* in projected changes in atmospheric blocking and
36 wintertime quasi-stationary waves. Therefore, our confidence is *low* on the association between
37 observed and projected changes in weather and climate extremes over the United States and
38 variations in these persistent atmospheric circulation patterns.

1 **5.2.4 Modes of Variability on Decadal to Multidecadal Time Scales**

2 **PACIFIC DECADAL OSCILLATION (PDO) / INTERDECADAL PACIFIC** 3 **OSCILLATION (IPO)**

4 The Pacific Decadal Oscillation (PDO) was first introduced by Mantua et al. (1997) as the
5 leading empirical orthogonal function of North Pacific (20°–70°N) monthly averaged sea surface
6 temperature anomalies (Newman et al. 2016). Interdecadal Pacific Oscillation (IPO) refers to the
7 same phenomenon and is based on Pacific-wide sea surface temperatures. PDO/IPO lacks a
8 characteristic timescale and represents a combination of physical processes that span the tropics
9 and extratropics, including both remote tropical forcing and local North Pacific atmosphere–
10 ocean interactions (Newman et al. 2016). Consequently, PDO-related variations in temperature
11 and precipitation in the United States are very similar to (and indeed may be caused by)
12 variations associated with ENSO and the strength of the Aleutian low (North Pacific Index, NPI),
13 as shown in Figure 5.3. A PDO-related temperature variation in Alaska is also apparent
14 (Hartmann and Wendler 2005; McAfee 2014).

15 **[INSERT FIGURE 5.3 HERE]**

16 The PDO does not show a long-term trend either in SST reconstructions or in the ensemble mean
17 of historical CMIP3 and CMIP5 simulations (Newman et al. 2016). Emerging science suggests
18 that externally forced natural and anthropogenic factors have contributed to the observed PDO-
19 like variability. For example, a model study finds that the observed PDO phase is affected by
20 large volcanic events and the variability in incoming solar radiation (Wang et al. 2012). Aerosols
21 from anthropogenic sources could change the temporal variability of the North Pacific SST
22 through modifications of the atmospheric circulation (Yeh et al. 2013; Boo et al. 2015).
23 Furthermore, some studies show that periods with near zero warming trends of global mean
24 temperature and periods of accelerated temperatures could result from the interplay between
25 internally generated PDO/IPO-like temperature variations in tropical Pacific Ocean and
26 greenhouse gas-induced ocean warming (Meehl et al. 2013, 2016).

27 Future changes in the spatial and temporal characteristics of PDO/IPO are uncertain. Based on
28 CMIP3 models, one study finds that most of these models do not exhibit significant changes
29 (Furtado et al. 2011), while another study points out that the PDO/IPO becomes weaker and
30 more frequent by the end of the 21st century in some models (Lapp et al. 2012). Furthermore,
31 future changes in ENSO variability, which strongly contributes to the PDO/IPO (Newman 2007),
32 are also uncertain (Section 5.2.2). Therefore, there is *low confidence* in projected future changes
33 in the PDO/IPO.

34

1 **ATLANTIC MULTIDECADAL VARIABILITY (AMV) / ATLANTIC MULTIDECADAL** 2 **OSCILLATION (AMO)**

3 The North Atlantic Ocean region exhibits coherent multidecadal variability that exerts
4 measurable impacts on regional climate for variables such as U.S. precipitation (Enfield et al.
5 2001; Seager et al. 2008; Feng et al. 2011; Kavvda et al. 2013) and Atlantic hurricane activity
6 (Gray et al. 1997; Landsea et al. 1999; Goldenberg et al. 2001; Chylek and Lesins 2008; Zhang
7 and Delworth 2009; Kossin 2017). This observed Atlantic multidecadal variability, or AMV, is
8 generally understood to be driven by a combination of internal and external factors (Delworth
9 and Mann 2000; Enfield et al. 2001; Knight et al. 2006; Frankcombe et al. 2010; Mann et al.
10 2014; Terray 2012; Caron et al. 2015; Delworth et al. 2017; Moore et al. 2017). The AMV
11 manifests in sea surface temperature (SST) variability and patterns as well as synoptic-scale
12 variability of atmospheric conditions. The internal part of the observed AMV is often referred to
13 as the Atlantic Multidecadal Oscillation (AMO) and is putatively driven by changes in the
14 strength of the Atlantic Meridional Overturning Circulation (AMOC) (Delworth and Mann 2000;
15 Miles et al. 2014; Trenary and DelSole 2016; Delworth et al. 2017). It is important to understand
16 the distinction between the AMO, which is often assumed to be natural (because of its putative
17 relationship with natural AMOC variability), and AMV, which simply represents the observed
18 multidecadal variability as a whole.

19 The relationship between observed AMV and the AMOC has recently been called into question
20 and arguments have been made that AMV can occur in the absence of the AMOC via stochastic
21 forcing of the ocean by coherent atmospheric circulation variability, but this is presently a topic
22 of debate (Clement et al. 2015, 2016; R. Zhang et al. 2016; Srivastava and DelSole 2017).
23 Despite the ongoing debates, it is generally acknowledged that observed AMV, as a whole,
24 represents a complex conflation of natural internal variability of the AMOC, natural red-noise
25 stochastic forcing of the ocean by the atmosphere (Mann et al. 2014), natural external variability
26 from volcanic events (Evan 2012; Canty et al. 2013) and mineral aerosols (Evan et al. 2009), and
27 anthropogenic forcing from greenhouse gases and pollution aerosols (Mann and Emanuel 2006;
28 Booth et al. 2012; Dunstone et al. 2013; Sobel et al. 2016).

29 As also discussed in Chapter 9: Extreme Storms (in the context of Atlantic hurricanes),
30 determining the relative contributions of each mechanism to the observed multidecadal
31 variability in the Atlantic is presently an active area of research and debate, and no consensus has
32 yet been reached (Ting et al. 2009; Carlaw et al. 2013; Zhang et al. 2013; Tung and Zhao 2013;
33 Mann et al. 2014; Stevens 2015; Sobel et al. 2016). Still, despite the level of disagreement about
34 the relative magnitude of human influences (particularly whether natural or anthropogenic
35 factors are dominating), there is broad agreement in the literature of the past decade or so that
36 human factors have had a measurable impact on the observed AMV. Furthermore, the AMO, as
37 measured by indices constructed from environmental data (e.g., Enfield et al. 2001), is generally
38 based on detrended SST data and is then, by construction, segregated from the century-scale

1 linear SST trends that are likely forced by increasing greenhouse gas concentrations. In
2 particular, removal of a linear trend is not expected to account for all of the variability forced by
3 changes in sulfate aerosol concentrations that have occurred over the past century. In this case,
4 increasing sulfate aerosols are argued to cause cooling of Atlantic SST, thus offsetting the
5 warming caused by increasing greenhouse gas concentration. After the Clean Air Act and
6 Amendments of the 1970s, however, a steady reduction of sulfate aerosols is argued to have
7 caused SST warming that compounds the warming from the ongoing increases in greenhouse gas
8 concentrations (Mann and Emanuel 2006; Sobel et al. 2016). This combination of greenhouse
9 gas and sulfate aerosol forcing, by itself, can lead to Atlantic multidecadal SST variability that
10 would not be removed by removing a linear trend (Canty et al. 2013).

11 In summary, it is unclear what the statistically derived AMO indices represent, and it is not
12 readily supportable to treat AMO index variability as tacitly representing natural variability, nor
13 is it clear that the observed AMV is truly oscillatory in nature (Vincze and Jánosí 2011). There is
14 a physical basis for treating the AMOC as oscillatory (via thermohaline circulation arguments)
15 (Dima and Lohmann et al. 2007), but there is no expectation of true oscillatory behavior in the
16 hypothesized external forcing agents for the remaining variability. Detrending the SST data used
17 to construct the AMO indices may partially remove the century-scale trends forced by increasing
18 greenhouse gas concentrations, but it is not adequate for removing multidecadal variability
19 forced by aerosol concentration variability. There is evidence that natural AMOC variability has
20 been occurring for hundreds of years (Gray et al. 2004; Mann et al. 2009; Chylek et al. 2011;
21 Knudsen et al. 2014; Miles et al. 2014), and this has apparently played some role in the observed
22 AMV as a whole, but a growing body of evidence shows that external factors, both natural and
23 anthropogenic, have played a substantial additional role in the past century.

24 **5.3. Quantifying the Role of Internal Variability on Past and Future U.S.** 25 **Climate Trends**

26 The role of internal variability in masking trends is substantially increased on regional and local
27 scales relative to the global scale, and in the extratropics relative to the tropics (Ch. 4:
28 Projections). Approaches have been developed to better quantify the externally forced and
29 internally driven contributions to observed and future climate trends and variability and further
30 separate these contributions into thermodynamically and dynamically driven factors (Deser et al.
31 2016). Specifically, large “initial condition” climate model ensembles with 30 ensemble
32 members and more (Deser et al. 2012; Deser et al. 2014; Wettstein and Deser 2014) and long
33 control runs (Thompson et al. 2015) have been shown to be useful tools to characterize
34 uncertainties in climate change projections at local/regional scales.

35 North American temperature and precipitation trends on timescales of up to a few decades are
36 strongly affected by intrinsic atmospheric circulation variability (Deser et al. 2014; Deser et al.
37 2016). For example, it is estimated that internal circulation trends account for approximately

1 one-third of the observed wintertime warming over North America during the past 50 years. In a
2 few areas, such as the central Rocky Mountains and far western Alaska, internal dynamics have
3 offset the warming trend by 10%–30% (Deser et al. 2016). Natural climate variability
4 superimposed upon forced climate change will result in a large range of possible trends for
5 surface air temperature and precipitation in the United States over the next 50 years (Figure 5.4)
6 (Deser et al. 2014).

7 **[INSERT FIGURE 5.4 HERE]**

8 Climate models are evaluated with respect to their proper simulation of internal decadal
9 variability. Comparing observed and simulated variability estimates at timescales longer than 10
10 years suggest that models tend to overestimate the internal variability in the northern
11 extratropics, including over the continental United States, but underestimate it over much of the
12 tropics and subtropical ocean regions (Deser et al. 2012; Knutson et al. 2013). Such biases affect
13 signal-to-noise estimates of regional scale climate change response and thus assessment of
14 internally driven contributions to regional/local trends.

15

1 TRACEABLE ACCOUNTS

2 Key Finding 1

3 The tropics have expanded poleward by about 70 to 200 miles in each hemisphere over the
4 period 1979–2009, with an accompanying shift of the subtropical dry zones, midlatitude jets, and
5 storm tracks (*medium to high confidence*). Human activities have played a role in this change
6 (*medium confidence*), although confidence is presently *low* regarding the magnitude of the
7 human contribution relative to natural variability

8 Description of evidence base

9 The Key Finding is supported by statements of the previous international IPCC AR5 assessment
10 (Hartmann et al. 2013) and a large number of more recent studies that examined the magnitude
11 of the observed tropical widening and various causes (Davis and Birner 2013; Feng and Fu 2013;
12 Birner et al. 2014; Karnauskas and Ummenhofer 2014; Lucas et al. 2014; Quan et al. 2014;
13 Garfinkel et al. 2015; Waugh et al. 2015; Norris et al. 2016; Reichler 2016). Additional evidence
14 for an impact of greenhouse gas increases on the widening of the tropical belt and poleward
15 shifts of the midlatitude jets is provided by the diagnosis of CMIP5 simulations (Barnes and
16 Polvani 2013; Vallis et al. 2015). There is emerging evidence for an impact of anthropogenic
17 aerosols on the tropical expansion in the Northern Hemisphere (Allen et al. 2012; Kovilakam and
18 Mahajan 2015). Recent studies provide new evidence on the significance of internal variability
19 on recent changes in the tropical width (Adam et al. 2014; Allen et al. 2014; Garfinkel et al.
20 2015).

21 Major uncertainties

22 The rate of observed expansion of tropics depends on which metric is used. The linkages
23 between different metrics are not fully explored. Uncertainties also result from the utilization of
24 reanalysis to determine trends and from limited observational records of free atmosphere
25 circulation, precipitation, and evaporation. The dynamical mechanisms behind changes in the
26 width of the tropical belt (e.g., tropical–extratropical interactions and baroclinic eddies) are not
27 fully understood. There is also a limited understanding of how various climate forcings, such as
28 anthropogenic aerosols, affect the width of tropics. The coarse horizontal and vertical resolution
29 of global climate models may limit the ability of these models to properly resolve latitudinal
30 changes in the atmospheric circulation. Limited observational records affect the ability to
31 accurately estimate the contribution of natural decadal to multi-decadal variability on observed
32 expansion of the tropics.

33

1 **Assessment of confidence based on evidence and agreement, including short description of**
2 **nature of evidence and level of agreement**

3 *Medium to high confidence* that the tropics and related features of the global circulation have
4 expanded poleward is based upon the results of a large number of observational studies, using a
5 wide variety of metrics and data sets, which reach similar conclusions. A large number of studies
6 utilizing modeling of different complexity and theoretical considerations provide compounding
7 evidence that human activities, including increases in greenhouse gases, ozone depletion, and
8 anthropogenic aerosols, contributed to the observed poleward expansion of the tropics. Climate
9 models forced with these anthropogenic drivers cannot explain the observed magnitude of
10 tropical expansion and some studies suggest a possibly large contribution of internal variability.
11 These multiple lines of evidence lead to the conclusion of *medium confidence* that human
12 activities contributed to observed expansion of the tropics.

13 **Summary sentence or paragraph that integrates the above information**

14 The tropics have expanded poleward in each hemisphere over the period 1979–2009 (*medium to*
15 *high confidence*) as shown by a large number of studies using a variety of metrics, observations
16 and reanalysis. Modeling studies and theoretical considerations illustrate that human activities,
17 including increases in greenhouse gases, ozone depletion, and anthropogenic aerosols, cause a
18 widening of the tropics. There is *medium confidence* that human activities have contributed to
19 the observed poleward expansion, taking into account uncertainties in the magnitude of observed
20 trends and a possible large contribution of natural climate variability.

21

22 **Key Finding 2**

23 Recurring patterns of variability in large-scale atmospheric circulation (such as the North
24 Atlantic Oscillation and Northern Annular Mode) and the atmosphere–ocean system (such as El
25 Niño–Southern Oscillation) cause year-to-year variations in U.S. temperatures and precipitation
26 (*high confidence*). Changes in the occurrence of these patterns or their properties have
27 contributed to recent U.S. temperature and precipitation trends (*medium confidence*), although
28 confidence is *low* regarding the size of the role of human activities in these changes.

29 **Description of evidence base**

30 The Key Finding is supported by a large number of studies that diagnose recurring patterns of
31 variability and their changes, as well as their impact on climate over the United States.
32 Regarding year-to-year variations, a large number of studies based on models and observations
33 show statistically significant associations between North Atlantic Oscillation/Northern Annular
34 Mode and United States temperature and precipitation (Thompson and Wallace 2001;
35 Archambault et al. 2008; Durkee et al. 2008; Hurrell and Deser 2009; Ning and Bradley 2016;

1 Gong et al. 2017), as well as El Niño–Southern Oscillation and related U.S. climate
2 teleconnections (Ropelewski and Halpert 1987; Kiladis and Diaz 1989; Halpert and Ropelewski
3 1992; Hoerling et al. 2001; Yu et al. 2012; Yu and Zou 2013; T. Zhang et al. 2016). Regarding
4 recent decadal trends, several studies provide evidence for concurrent changes in the North
5 Atlantic Oscillation/Northern Annular Mode and climate anomalies over the United States
6 (Hurrell 1995; Cohen and Barlow 2005; Overland and Wang 2015; Overland et al. 2015).
7 Modeling studies provide evidence for a linkage between cooling trends of the tropical Pacific
8 Ocean that resemble La Niña and precipitation changes in the southern United States (Hoerling
9 et al. 2010; Hoerling et al. 2016). Several studies describe a decadal modification of ENSO (Yeh
10 et al. 2009; Lee and McPhaden 2010; Li et al. 2011; Capotondi et al. 2013). Modeling evidence
11 is provided that such decadal modifications can be due to internal variability (Capotondi et al.
12 2015). Climate models are widely analyzed for their ability to simulate recurring patterns of
13 variability and teleconnections over the United States (Furtado et al. 2011; Flato et al. 2013;
14 Langenbrunner and Neelin 2013; Bellenger et al. 2014; Ning and Bradley 2016; Gong et al.
15 2017). Climate model projections are also widely analyzed to diagnose the impact of human
16 activities on NAM/NAO, ENSO teleconnections, and other recurring modes of variability
17 associated with climate anomalies (Christensen et al. 2013; Gillett and Fyfe 2013; Zhou et al.
18 2014; Ning and Bradley 2016).

19 **Major uncertainties**

20 A key uncertainty is related to limited observational records and our capability to properly
21 simulate climate variability on decadal to multidecadal time scales, as well as properly simulate
22 recurring patterns of climate variability, underlying physical mechanisms, and associated
23 variations in temperature and precipitation over the United States.

24 **Assessment of confidence based on evidence and agreement, including short description of** 25 **nature of evidence and level of agreement**

26 There is *high confidence* that preferred patterns of variability affect U.S. temperature on a year-
27 to-year timescale, based on a large number of studies that diagnose observational data records
28 and long simulations. There is *medium confidence* that changes in the occurrence of these
29 patterns or their properties have contributed to recent U.S. temperature and precipitation trends.
30 Several studies agree on a linkage between decadal changes in the NAO/NAM and climate
31 trends over the United States, and there is some modeling evidence for a linkage between a La
32 Niña-like cooling trend over the tropical Pacific and precipitation changes in the southwestern
33 United States. There is no robust evidence for observed decadal changes in the properties of
34 ENSO and related United States climate impacts. Confidence is *low* regarding the size of the role
35 of human influences in these changes because models do not agree on the impact of human
36 activity on preferred patterns of variability or because projected changes are small compared to
37 internal variability.

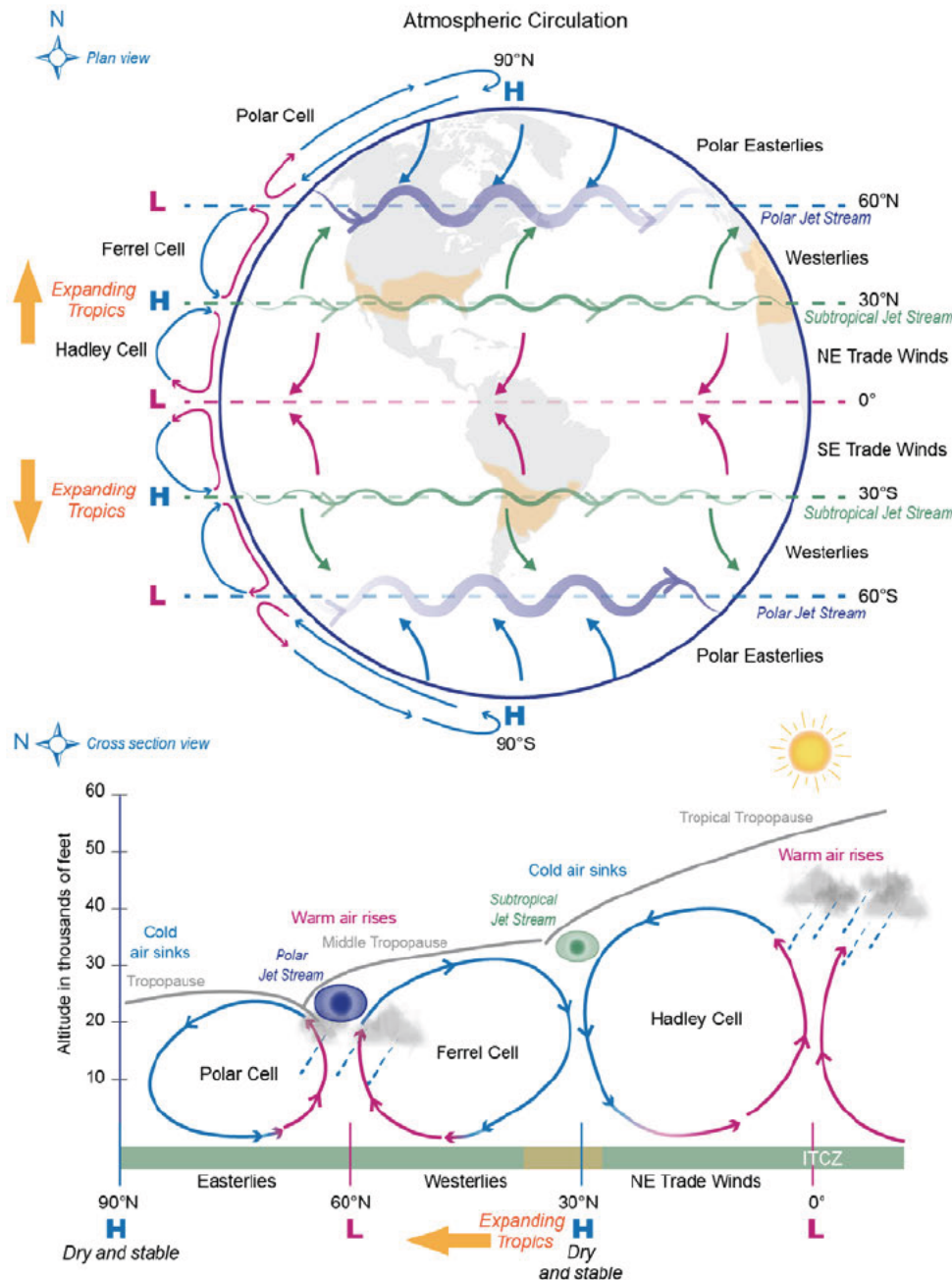
1 **Summary sentence or paragraph that integrates the above information**

2 Recurring modes of variability strongly affect temperature and precipitation over the United
3 States on interannual timescales (*high confidence*) as supported by a very large number of
4 observational and modeling studies. Changes in some recurring patterns of variability have
5 contributed to recent trends in U.S. temperature and precipitation (*medium confidence*). The
6 causes of these changes are uncertain due to the limited observational record and because models
7 exhibit some difficulties simulating these recurring patterns of variability and their underlying
8 physical mechanisms.

9

FINAL DRAFT

1 FIGURES



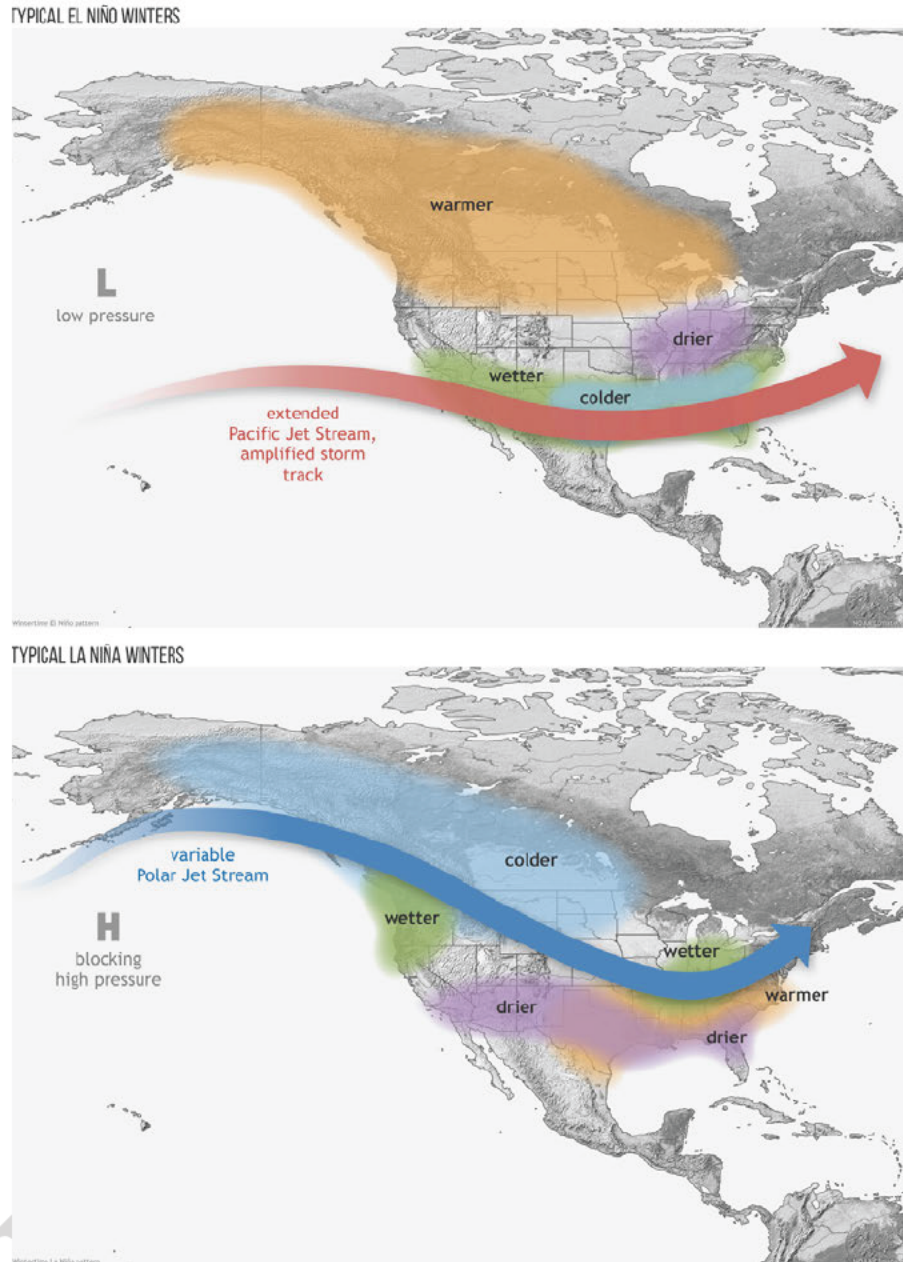
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3 **Figure 5.1:** (Top) Plan and (bottom) cross-section schematic view representations of the general
 4 circulation of the atmosphere. Three main circulations exist between the equator and poles due to
 5 solar heating and Earth’s rotation: 1) **Hadley cell** – Low-latitude air moves toward the equator.
 6 Due to solar heating, air near the equator rises vertically and moves poleward in the upper
 7 atmosphere. 2) **Ferrel cell** – A midlatitude mean atmospheric circulation cell. In this cell, the air
 8 flows poleward and eastward near the surface and equatorward and westward at higher levels. 3)
 9 **Polar cell** – Air rises, diverges, and travels toward the poles. Once over the poles, the air sinks,

1 forming the polar highs. At the surface, air diverges outward from the polar highs. Surface winds
2 in the polar cell are easterly (polar easterlies). A high pressure band is located at about 30° N/S
3 latitude, leading to dry/hot weather due to descending air motion (subtropical dry zones are
4 indicated in orange in the schematic views). Expanding tropics (indicted by orange arrows) are
5 associated with a poleward shift of the subtropical dry zones. A low pressure band is found at
6 50°–60° N/S, with rainy and stormy weather in relation to the polar jet stream bands of strong
7 westerly wind in the upper levels of the atmosphere. (Figure source: adapted from NWS 2016).

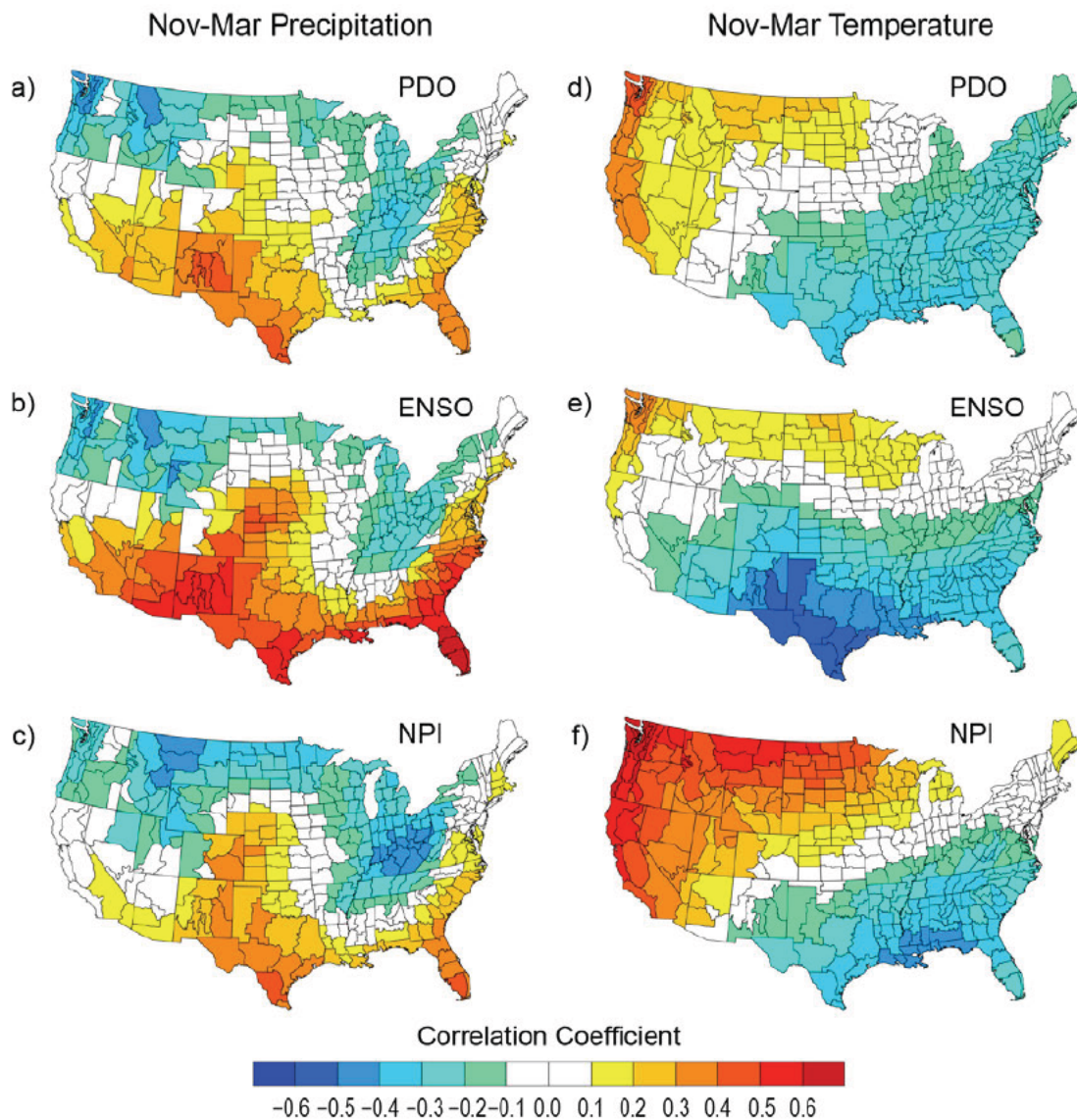
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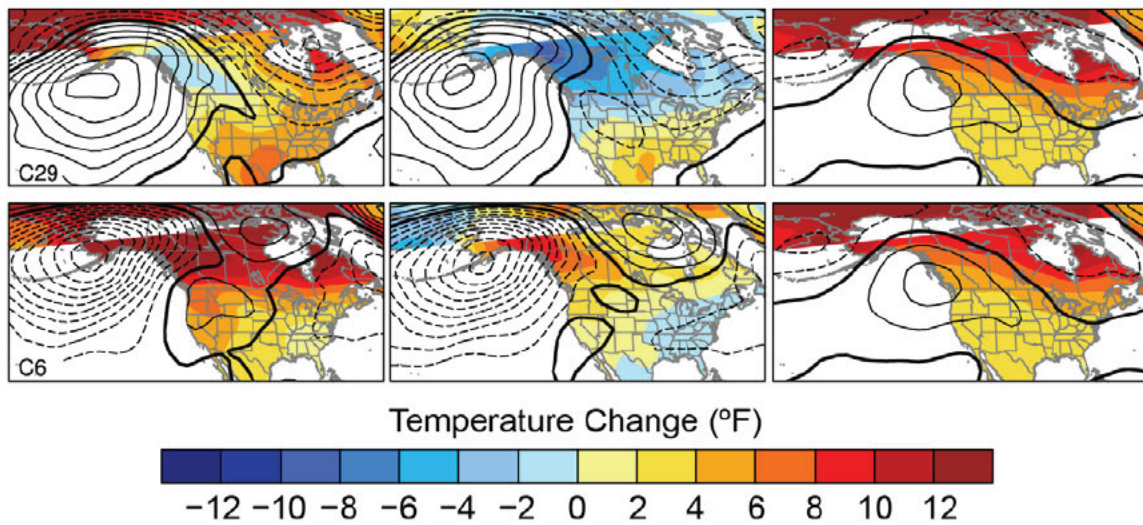
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 2 **Figure 5.2:** El Niño- and La Niña-related winter features over North America. Shown are typical
 3 January to March weather anomalies and atmospheric circulation during moderate to strong El
 4 Niño and La Niña conditions: (top) During El Niño, there is a tendency for a strong jet stream
 5 and storm track across the southern part of the United States. The southern tier of Alaska and the
 6 U.S. Pacific Northwest tend to be warmer than average, whereas the southern tier of United
 7 States tends to be cooler and wetter than average. (bottom) During La Niña, there is a tendency
 8 of a very wave-like jet stream flow over the United States and Canada, with colder and stormier
 9 than average conditions across the North, and warmer and less stormy conditions across the
 10 South. (Figure source: adapted from Lindsey 2016).

Cold Season Relationship between Climate Indices and Precipitation/Temperature Anomalies

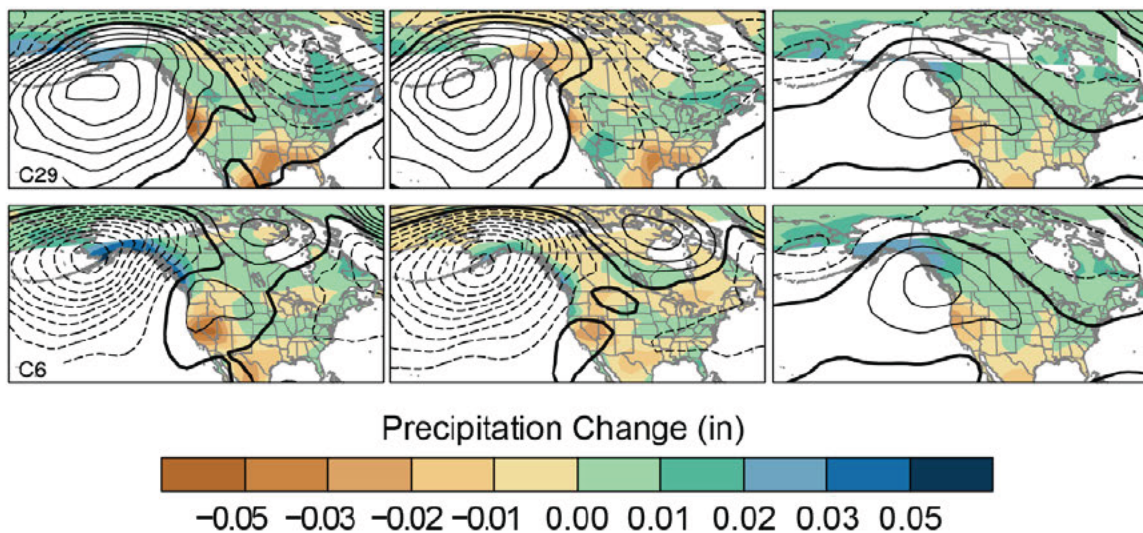


1
2 **Figure 5.3:** Cold season relationship between climate indices and U.S. precipitation and
3 temperature anomalies determined from U.S. climate division data (Vose et al. 2014), for the
4 years 1901–2014. November–March mean U.S. precipitation anomalies correlated with (a) the
5 Pacific Decadal oscillation (PDO) index, (b) the El Niño–Southern Oscillation (ENSO) index,
6 and (c) the North Pacific Index (NPI). November–March U.S. temperature anomalies correlated
7 with (d) the PDO index, (e) the ENSO index, and (f) the NPI. United States temperature and
8 precipitation related to the Pacific Decadal oscillation are very similar to (and indeed may be
9 caused by) variations associated with ENSO and the Aleutian low strength (North Pacific Index).
10 (Figure source: Newman et al. 2016; © American Meteorological Society, used with
11 permission).

a) Winter surface air temperature and sea level pressure



b) Winter precipitation and sea level pressure



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Figure 5.4: (left) Total 2010–2060 winter trends decomposed into (center) internal and (right) forced components for two contrasting CCSM3 ensemble members (runs 29 and 6) for (a) surface air temperature [color shading; °F/(51 years)] and sea level pressure (SLP; contours) and (b) precipitation [color shading; inches per day/(51 years)] and SLP (contours). SLP contour interval is 1 hPa/(51 years), with solid (dashed) contours for positive (negative) values; the zero contour is thickened. The same climate model (CCSM3) simulates a large range of possible trends in North American climate over the 2010–2060 period because of the influence of internal climate variability superposed upon forced climate trends. (Figure source: adapted from Deser et al. 2014; © American Meteorological Society, used with permission).

1 **REFERENCES**

- 2 Adam, O., T. Schneider, and N. Harnik, 2014: Role of changes in mean temperatures versus
3 temperature gradients in the recent widening of the Hadley circulation. *Journal of Climate*,
4 **27**, 7450-7461. <http://dx.doi.org/10.1175/JCLI-D-14-00140.1>
- 5 Alexander, M.A., D.J. Vimont, P. Chang, and J.D. Scott, 2010: The impact of extratropical
6 atmospheric variability on ENSO: Testing the seasonal footprinting mechanism using
7 coupled model experiments. *Journal of Climate*, **23**, 2885-2901.
8 <http://dx.doi.org/10.1175/2010jcli3205.1>
- 9 Allen, R.J., S.C. Sherwood, J.R. Norris, and C.S. Zender, 2012: Recent Northern Hemisphere
10 tropical expansion primarily driven by black carbon and tropospheric ozone. *Nature*, **485**,
11 350-354. <http://dx.doi.org/10.1038/nature11097>
- 12 Allen, R.J., J.R. Norris, and M. Kovilakam, 2014: Influence of anthropogenic aerosols and the
13 Pacific decadal oscillation on tropical belt width. *Nature Geoscience*, **7**, 270-274.
14 <http://dx.doi.org/10.1038/ngeo2091>
- 15 Archambault, H.M., L.F. Bosart, D. Keyser, and A.R. Aiyyer, 2008: Influence of large-scale
16 flow regimes on cool-season precipitation in the northeastern United States. *Monthly*
17 *Weather Review*, **136**, 2945-2963. <http://dx.doi.org/10.1175/2007MWR2308.1>
- 18 Barnes, E.A., 2013: Revisiting the evidence linking Arctic amplification to extreme weather in
19 midlatitudes. *Geophysical Research Letters*, **40**, 4734-4739.
20 <http://dx.doi.org/10.1002/grl.50880>
- 21 Barnes, E.A., E. Dunn-Sigouin, G. Masato, and T. Woollings, 2014: Exploring recent trends in
22 Northern Hemisphere blocking. *Geophysical Research Letters*, **41**, 638-644.
23 <http://dx.doi.org/10.1002/2013GL058745>
- 24 Barnes, E.A. and L. Polvani, 2013: Response of the midlatitude jets, and of their variability, to
25 increased greenhouse gases in the CMIP5 models. *Journal of Climate*, **26**, 7117-7135.
26 <http://dx.doi.org/10.1175/JCLI-D-12-00536.1>
- 27 Barnes, E.A. and L.M. Polvani, 2015: CMIP5 projections of Arctic amplification, of the North
28 American/North Atlantic circulation, and of their relationship. *Journal of Climate*, **28**, 5254-
29 5271. <http://dx.doi.org/10.1175/JCLI-D-14-00589.1>
- 30 Bellenger, H., E. Guilyardi, J. Leloup, M. Lengaigne, and J. Vialard, 2014: ENSO representation
31 in climate models: from CMIP3 to CMIP5. *Climate Dynamics*, **42**, 1999-2018.
32 <http://dx.doi.org/10.1007/s00382-013-1783-z>

- 1 Bindoff, N.L., P.A. Stott, K.M. AchutaRao, M.R. Allen, N. Gillett, D. Gutzler, K. Hansingo, G.
2 Hegerl, Y. Hu, S. Jain, I.I. Mokhov, J. Overland, J. Perlwitz, R. Sebbari, and X. Zhang, 2013:
3 Detection and attribution of climate change: From global to regional. *Climate Change 2013:*
4 *The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report*
5 *of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M.
6 Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds.
7 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 867–
8 952. <http://www.climatechange2013.org/report/full-report/>
- 9 Birner, T., S.M. Davis, and D.J. Seidel, 2014: The changing width of Earth's tropical belt.
10 *Physcis Today*, **67**, 38-44. <http://dx.doi.org/10.1063/PT.3.2620>
- 11 Boo, K.-O., B.B.B. Booth, Y.-H. Byun, J. Lee, C. Cho, S. Shim, and K.-T. Kim, 2015: Influence
12 of aerosols in multidecadal SST variability simulations over the North Pacific. *Journal of*
13 *Geophysical Research: Atmospheres*, **120**, 517-531. <http://dx.doi.org/10.1002/2014JD021933>
- 14 Booth, B.B.B., N.J. Dunstone, P.R. Halloran, T. Andrews, and N. Bellouin, 2012: Aerosols
15 implicated as a prime driver of twentieth-century North Atlantic climate variability. *Nature*,
16 **484**, 228-232. <http://dx.doi.org/10.1038/nature10946>
- 17 Brandefelt, J. and H. Körnich, 2008: Northern Hemisphere stationary waves in future climate
18 projections. *Journal of Climate*, **21**, 6341-6353. <http://dx.doi.org/10.1175/2008JCLI2373.1>
- 19 Brönnimann, S., A.M. Fischer, E. Rozanov, P. Poli, G.P. Compo, and P.D. Sardeshmukh, 2015:
20 Southward shift of the northern tropical belt from 1945 to 1980. *Nature Geoscience*, **8**, 969-
21 974. <http://dx.doi.org/10.1038/ngeo2568>
- 22 Canty, T., N.R. Mascioli, M.D. Smarte, and R.J. Salawitch, 2013: An empirical model of global
23 climate – Part 1: A critical evaluation of volcanic cooling. *Atmospheric Chemistry and*
24 *Physics*, **13**, 3997-4031. <http://dx.doi.org/10.5194/acp-13-3997-2013>
- 25 Capotondi, A., A.T. Wittenberg, M. Newman, E.D. Lorenzo, J.-Y. Yu, P. Braconnot, J. Cole, B.
26 Dewitte, B. Giese, E. Guilyardi, F.-F. Jin, K. Karnauskas, B. Kirtman, T. Lee, N. Schneider,
27 Y. Xue, and S.-W. Yeh, 2015: Understanding ENSO diversity. *Bulletin of the American*
28 *Meteorological Society*, **96 (12)**, 921-938. <http://dx.doi.org/10.1175/BAMS-D-13-00117.1>
- 29 Caron, L.-P., M. Boudreault, and C.L. Bruyère, 2015: Changes in large-scale controls of Atlantic
30 tropical cyclone activity with the phases of the Atlantic multidecadal oscillation. *Climate*
31 *Dynamics*, **44**, 1801-1821. <http://dx.doi.org/10.1007/s00382-014-2186-5>
- 32 Carrera, M.L., R.W. Higgins, and V.E. Kousky, 2004: Downstream weather impacts associated
33 with atmospheric blocking over the northeast Pacific. *Journal of Climate*, **17**, 4823-4839.
34 <http://dx.doi.org/10.1175/JCLI-3237.1>

- 1 Carslaw, K.S., L.A. Lee, C.L. Reddington, K.J. Pringle, A. Rap, P.M. Forster, G.W. Mann, D.V.
2 Spracklen, M.T. Woodhouse, L.A. Regayre, and J.R. Pierce, 2013: Large contribution of
3 natural aerosols to uncertainty in indirect forcing. *Nature*, **503**, 67-71.
4 <http://dx.doi.org/10.1038/nature12674>
- 5 Cattiaux, J. and C. Cassou, 2013: Opposite CMIP3/CMIP5 trends in the wintertime Northern
6 Annular Mode explained by combined local sea ice and remote tropical influences.
7 *Geophysical Research Letters*, **40**, 3682-3687. <http://dx.doi.org/10.1002/grl.50643>
- 8 Chen, S., K. Wei, W. Chen, and L. Song, 2014: Regional changes in the annual mean Hadley
9 circulation in recent decades. *Journal of Geophysical Research: Atmospheres*, **119**, 7815-
10 7832. <http://dx.doi.org/10.1002/2014JD021540>
- 11 Christensen, J.H., K. Krishna Kumar, E. Aldrian, S.-I. An, I.F.A. Cavalcanti, M. de Castro, W.
12 Dong, P. Goswami, A. Hall, J.K. Kanyanga, A. Kitoh, J. Kossin, N.-C. Lau, J. Renwick, D.B.
13 Stephenson, S.-P. Xie, and T. Zhou, 2013: Climate phenomena and their relevance for future
14 regional climate change. *Climate Change 2013: The Physical Science Basis. Contribution of*
15 *Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate*
16 *Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A.
17 Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge,
18 United Kingdom and New York, NY, USA, 1217–1308.
19 <http://www.climatechange2013.org/report/full-report/>
- 20 Chylek, P. and G. Lesins, 2008: Multidecadal variability of Atlantic hurricane activity: 1851–
21 2007. *Journal of Geophysical Research*, **113**, D22106.
22 <http://dx.doi.org/10.1029/2008JD010036>
- 23 Chylek, P., C.K. Folland, H.A. Dijkstra, G. Lesins, and M.K. Dubey, 2011: Ice-core data
24 evidence for a prominent near 20 year time-scale of the Atlantic Multidecadal Oscillation.
25 *Geophysical Research Letters*, **38**, L13704. <http://dx.doi.org/10.1029/2011GL047501>
- 26 Clement, A., K. Bellomo, L.N. Murphy, M.A. Cane, T. Mauritsen, G. Rädcl, and B. Stevens,
27 2015: The Atlantic Multidecadal Oscillation without a role for ocean circulation. *Science*,
28 **350**, 320-324. <http://dx.doi.org/10.1126/science.aab3980>
- 29 Clement, A., M.A. Cane, L.N. Murphy, K. Bellomo, T. Mauritsen, and B. Stevens, 2016:
30 Response to Comment on “The Atlantic Multidecadal Oscillation without a role for ocean
31 circulation”. *Science*, **352**, 1527-1527. <http://dx.doi.org/10.1126/science.aaf2575>
- 32 Coats, S., J.E. Smerdon, B.I. Cook, and R. Seager, 2013: Stationarity of the tropical pacific
33 teleconnection to North America in CMIP5/PMIP3 model simulations. *Geophysical*
34 *Research Letters*, **40**, 4927-4932. <http://dx.doi.org/10.1002/grl.50938>

- 1 Cohen, J. and M. Barlow, 2005: The NAO, the AO, and global warming: How closely related?
2 *Journal of Climate*, **18**, 4498-4513. <http://dx.doi.org/10.1175/jcli3530.1>
- 3 Coleman, J.S.M. and J.C. Rogers, 2003: Ohio River valley winter moisture conditions associated
4 with the Pacific–North American teleconnection pattern. *Journal of Climate*, **16**, 969-981.
5 [http://dx.doi.org/10.1175/1520-0442\(2003\)016<0969:ORVWMC>2.0.CO;2](http://dx.doi.org/10.1175/1520-0442(2003)016<0969:ORVWMC>2.0.CO;2)
- 6 Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J.
7 Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver, and M. Wehner,
8 2013: Long-term climate change: Projections, commitments and irreversibility. *Climate*
9 *Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth*
10 *Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D.
11 Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and
12 P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New
13 York, NY, USA, 1029–1136. <http://www.climatechange2013.org/report/full-report/>
- 14 Davini, P. and C. Cagnazzo, 2014: On the misinterpretation of the North Atlantic Oscillation in
15 CMIP5 models. *Climate Dynamics*, **43**, 1497-1511. [http://dx.doi.org/10.1007/s00382-013-](http://dx.doi.org/10.1007/s00382-013-1970-y)
16 [1970-y](http://dx.doi.org/10.1007/s00382-013-1970-y)
- 17 Davis, N.A. and T. Birner, 2013: Seasonal to multidecadal variability of the width of the tropical
18 belt. *Journal of Geophysical Research: Atmospheres*, **118**, 7773-7787.
19 <http://dx.doi.org/10.1002/jgrd.50610>
- 20 Delworth, L.T. and E.M. Mann, 2000: Observed and simulated multidecadal variability in the
21 Northern Hemisphere. *Climate Dynamics*, **16**, 661-676.
22 <http://dx.doi.org/10.1007/s003820000075>
- 23 Delworth, T.L., F. Zeng, G.A. Vecchi, X. Yang, L. Zhang, and R. Zhang, 2016: The North
24 Atlantic Oscillation as a driver of rapid climate change in the Northern Hemisphere. *Nature*
25 *Geoscience*, **9**, 509-512. <http://dx.doi.org/10.1038/ngeo2738>
- 26 Delworth, T.L., F. Zeng, L. Zhang, R. Zhang, G.A. Vecchi, and X. Yang, 2017: The central role
27 of ocean dynamics in connecting the North Atlantic Oscillation to the extratropical
28 component of the Atlantic Multidecadal Oscillation. *Journal of Climate*, **30**, 3789-3805.
29 <http://dx.doi.org/10.1175/jcli-d-16-0358.1>
- 30 Deser, C., 2000: On the teleconnectivity of the “Arctic Oscillation”. *Geophysical Research*
31 *Letters*, **27**, 779-782. <http://dx.doi.org/10.1029/1999GL010945>
- 32 Deser, C., A. Phillips, V. Bourdette, and H. Teng, 2012: Uncertainty in climate change
33 projections: The role of internal variability. *Climate Dynamics*, **38**, 527-546.
34 <http://dx.doi.org/10.1007/s00382-010-0977-x>

- 1 Deser, C., A.S. Phillips, M.A. Alexander, and B.V. Smoliak, 2014: Projecting North American
2 climate over the next 50 years: Uncertainty due to internal variability. *Journal of Climate*, **27**,
3 2271-2296. <http://dx.doi.org/10.1175/JCLI-D-13-00451.1>
- 4 Deser, C., L. Terray, and A.S. Phillips, 2016: Forced and internal components of winter air
5 temperature trends over North America during the past 50 years: Mechanisms and
6 implications. *Journal of Climate*, **29**, 2237-2258. <http://dx.doi.org/10.1175/JCLI-D-15-0304.1>
- 7
8 Deser, C., I.R. Simpson, K.A. McKinnon, and A.S. Phillips, 2017: The Northern Hemisphere
9 extra-tropical atmospheric circulation response to ENSO: How well do we know it and how
10 do we evaluate models accordingly? *Journal of Climate*. <http://dx.doi.org/10.1175/jcli-d-16-0844.1>
- 11
12 Di Lorenzo, E., K.M. Cobb, J.C. Furtado, N. Schneider, B.T. Anderson, A. Bracco, M.A.
13 Alexander, and D.J. Vimont, 2010: Central Pacific El Niño and decadal climate change in the
14 North Pacific Ocean. *Nature Geoscience*, **3**, 762-765. <http://dx.doi.org/10.1038/ngeo984>
- 15 Dima, M. and G. Lohmann, 2007: A hemispheric mechanism for the Atlantic Multidecadal
16 Oscillation. *Journal of Climate*, **20**, 2706-2719. <http://dx.doi.org/10.1175/jcli4174.1>
- 17 Dunstone, N.J., D.M. Smith, B.B.B. Booth, L. Hermanson, and R. Eade, 2013: Anthropogenic
18 aerosol forcing of Atlantic tropical storms. *Nature Geoscience*, **6**, 534-539.
19 <http://dx.doi.org/10.1038/ngeo1854>
- 20 Durkee, J.D., J.D. Frye, C.M. Fuhrmann, M.C. Lacke, H.G. Jeong, and T.L. Mote, 2008: Effects
21 of the North Atlantic Oscillation on precipitation-type frequency and distribution in the
22 eastern United States. *Theoretical and Applied Climatology*, **94**, 51-65.
23 <http://dx.doi.org/10.1007/s00704-007-0345-x>
- 24 Enfield, D.B., A.M. Mestas-Nuñez, and P.J. Trimble, 2001: The Atlantic Multidecadal
25 Oscillation and its relation to rainfall and river flows in the continental U.S. *Geophysical
26 Research Letters*, **28**, 2077-2080. <http://dx.doi.org/10.1029/2000GL012745>
- 27 Evan, A.T., 2012: Atlantic hurricane activity following two major volcanic eruptions. *Journal of
28 Geophysical Research*, **117**, D06101. <http://dx.doi.org/10.1029/2011JD016716>
- 29 Evan, A.T., D.J. Vimont, A.K. Heidinger, J.P. Kossin, and R. Bennartz, 2009: The role of
30 aerosols in the evolution of tropical North Atlantic Ocean temperature anomalies. *Science*,
31 **324**, 778-781. <http://dx.doi.org/10.1126/science.1167404>
- 32 Feldstein, S.B. and C. Franzke, 2006: Are the North Atlantic Oscillation and the Northern
33 Annular Mode distinguishable? *Journal of the Atmospheric Sciences*, **63**, 2915-2930.
34 <http://dx.doi.org/10.1175/JAS3798.1>

- 1 Feng, S. and Q. Fu, 2013: Expansion of global drylands under a warming climate. *Atmospheric*
2 *Chemistry and Physics*, **13**, 10081-10094. <http://dx.doi.org/10.5194/acp-13-10081-2013>
- 3 Feng, S., Q. Hu, and R.J. Oglesby, 2011: Influence of Atlantic sea surface temperatures on
4 persistent drought in North America. *Climate Dynamics*, **37**, 569-586.
5 <http://dx.doi.org/10.1007/s00382-010-0835-x>
- 6 Flato, G., J. Marotzke, B. Abiodun, P. Braconnot, S.C. Chou, W. Collins, P. Cox, F. Driouech, S.
7 Emori, V. Eyring, C. Forest, P. Gleckler, E. Guilyardi, C. Jakob, V. Kattsov, C. Reason, and
8 M. Rummukainen, 2013: Evaluation of climate models. *Climate Change 2013: The Physical*
9 *Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the*
10 *Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M.
11 Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds.
12 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 741–
13 866. <http://www.climatechange2013.org/report/full-report/>
- 14 Francis, J.A. and S.J. Vavrus, 2012: Evidence linking Arctic amplification to extreme weather in
15 mid-latitudes. *Geophysical Research Letters*, **39**, L06801.
16 <http://dx.doi.org/10.1029/2012GL051000>
- 17 Francis, J.A., S.J. Vavrus, and J. Cohen, 2017: Amplified Arctic warming and mid-latitude
18 weather: New perspectives on emerging connections. WIREs Climate Change.
19 <http://dx.doi.org/10.1002/wcc.474>
- 20 Frankcombe, L.M., A.v.d. Heydt, and H.A. Dijkstra, 2010: North Atlantic multidecadal climate
21 variability: An investigation of dominant time scales and processes. *Journal of Climate*, **23**,
22 3626-3638. <http://dx.doi.org/10.1175/2010jcli3471.1>
- 23 Frierson, D.M.W., J. Lu, and G. Chen, 2007: Width of the Hadley cell in simple and
24 comprehensive general circulation models. *Geophysical Research Letters*, **34**, L18804.
25 <http://dx.doi.org/10.1029/2007GL031115>
- 26 Furtado, J.C., E.D. Lorenzo, N. Schneider, and N.A. Bond, 2011: North Pacific decadal
27 variability and climate change in the IPCC AR4 models. *Journal of Climate*, **24**, 3049-3067.
28 <http://dx.doi.org/10.1175/2010JCLI3584.1>
- 29 Garfinkel, C.I., M.M. Hurwitz, D.W. Waugh, and A.H. Butler, 2013: Are the teleconnections of
30 Central Pacific and Eastern Pacific El Niño distinct in boreal wintertime? *Climate Dynamics*,
31 **41**, 1835-1852. <http://dx.doi.org/10.1007/s00382-012-1570-2>
- 32 Garfinkel, C.I., D.W. Waugh, and L.M. Polvani, 2015: Recent Hadley cell expansion: The role
33 of internal atmospheric variability in reconciling modeled and observed trends. *Geophysical*
34 *Research Letters*, **42**, 10,824-10,831. <http://dx.doi.org/10.1002/2015GL066942>

- 1 Gillett, N.P. and J.C. Fyfe, 2013: Annular mode changes in the CMIP5 simulations. *Geophysical*
2 *Research Letters*, **40**, 1189-1193. <http://dx.doi.org/10.1002/grl.50249>
- 3 Goldenberg, S.B., C.W. Landsea, A.M. Mestas-Nuñez, and W.M. Gray, 2001: The recent
4 increase in Atlantic hurricane activity: Causes and implications. *Science*, **293**, 474-479.
5 <http://dx.doi.org/10.1126/science.1060040>
- 6 Gong, H., L. Wang, W. Chen, X. Chen, and D. Nath, 2017: Biases of the wintertime Arctic
7 Oscillation in CMIP5 models. *Environmental Research Letters*, **12**, 014001.
8 <http://dx.doi.org/10.1088/1748-9326/12/1/014001>
- 9 Gray, S.T., L.J. Graumlich, J.L. Betancourt, and G.T. Pederson, 2004: A tree-ring based
10 reconstruction of the Atlantic Multidecadal Oscillation since 1567 A.D. *Geophysical*
11 *Research Letters*, **31**, L12205. <http://dx.doi.org/10.1029/2004GL019932>
- 12 Gray, W.M., J.D. Sheaffer, and C.W. Landsea, 1997: Climate trends associated with
13 multidecadal variability of Atlantic hurricane activity. *Hurricanes: Climate and*
14 *Socioeconomic Impacts*. Diaz, H.F. and R.S. Pulwarty, Eds. Springer, Berlin, Heidelberg, 15-
15 53. http://dx.doi.org/10.1007/978-3-642-60672-4_2
- 16 Grotjahn, R., R. Black, R. Leung, M.F. Wehner, M. Barlow, M. Bosilovich, A. Gershunov, W.J.
17 Gutowski, J.R. Gyakum, R.W. Katz, Y.-Y. Lee, Y.-K. Lim, and Prabhat, 2016: North
18 American extreme temperature events and related large scale meteorological patterns: A
19 review of statistical methods, dynamics, modeling, and trends. *Climate Dynamics*, **46**, 1151-
20 1184. <http://dx.doi.org/10.1007/s00382-015-2638-6>
- 21 Guirguis, K., A. Gershunov, R. Schwartz, and S. Bennett, 2011: Recent warm and cold daily
22 winter temperature extremes in the Northern Hemisphere. *Geophysical Research Letters*, **38**,
23 L17701. <http://dx.doi.org/10.1029/2011GL048762>
- 24 Haarsma, R.J. and F. Selten, 2012: Anthropogenic changes in the Walker circulation and their
25 impact on the extra-tropical planetary wave structure in the Northern Hemisphere. *Climate*
26 *Dynamics*, **39**, 1781-1799. <http://dx.doi.org/10.1007/s00382-012-1308-1>
- 27 Halpert, M.S. and C.F. Ropelewski, 1992: Surface temperature patterns associated with the
28 Southern Oscillation. *Journal of Climate*, **5**, 577-593. [http://dx.doi.org/10.1175/1520-0442\(1992\)005<0577:STPAWT>2.0.CO;2](http://dx.doi.org/10.1175/1520-0442(1992)005<0577:STPAWT>2.0.CO;2)
- 30 Hanna, E., T.E. Cropper, R.J. Hall, and J. Cappelen, 2016: Greenland blocking index 1851–
31 2015: A regional climate change signal. *International Journal of Climatology*, **36**, 4847-
32 4861. <http://dx.doi.org/10.1002/joc.4673>

- 1 Hartmann, B. and G. Wendler, 2005: The significance of the 1976 Pacific climate shift in the
2 climatology of Alaska. *Journal of Climate*, **18**, 4824-4839.
3 <http://dx.doi.org/10.1175/JCLI3532.1>
- 4 Hartmann, D.L., A.M.G. Klein Tank, M. Rusticucci, L.V. Alexander, S. Brönnimann, Y.
5 Charabi, F.J. Dentener, E.J. Dlugokencky, D.R. Easterling, A. Kaplan, B.J. Soden, P.W.
6 Thorne, M. Wild, and P.M. Zhai, 2013: Observations: Atmosphere and surface. *Climate*
7 *Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth*
8 *Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D.
9 Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and
10 P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New
11 York, NY, USA, 159–254. <http://www.climatechange2013.org/report/full-report/>
- 12 Hoerling, M.P., A. Kumar, and T. Xu, 2001: Robustness of the nonlinear climate response to
13 ENSO's extreme phases. *Journal of Climate*, **14**, 1277-1293. [http://dx.doi.org/10.1175/1520-](http://dx.doi.org/10.1175/1520-0442(2001)014<1277:ROTNCR>2.0.CO;2)
14 [0442\(2001\)014<1277:ROTNCR>2.0.CO;2](http://dx.doi.org/10.1175/1520-0442(2001)014<1277:ROTNCR>2.0.CO;2)
- 15 Hoerling, M., J. Eischeid, and J. Perlwitz, 2010: Regional precipitation trends: Distinguishing
16 natural variability from anthropogenic forcing. *Journal of Climate*, **23**, 2131-2145.
17 <http://dx.doi.org/10.1175/2009jcli3420.1>
- 18 Hoerling, M., J. Eischeid, J. Perlwitz, X.-W. Quan, K. Wolter, and L. Cheng, 2016:
19 Characterizing recent trends in U.S. heavy precipitation. *Journal of Climate*, **29**, 2313-2332.
20 <http://dx.doi.org/10.1175/jcli-d-15-0441.1>
- 21 Hoskins, B. and T. Woollings, 2015: Persistent extratropical regimes and climate extremes.
22 *Current Climate Change Reports*, **1**, 115-124. <http://dx.doi.org/10.1007/s40641-015-0020-8>
- 23 Hurrell, J.W., 1995: Decadal trends in the North Atlantic oscillation: Regional temperatures and
24 precipitation. *Science*, **269**, 676-679. <http://dx.doi.org/10.1126/science.269.5224.676>
- 25 Hurrell, J.W. and C. Deser, 2009: North Atlantic climate variability: The role of the North
26 Atlantic oscillation. *Journal of Marine Systems*, **78**, 28-41.
27 <http://dx.doi.org/10.1016/j.jmarsys.2008.11.026>
- 28 Karnauskas, K.B. and C.C. Ummenhofer, 2014: On the dynamics of the Hadley circulation and
29 subtropical drying. *Climate Dynamics*, **42**, 2259-2269. [http://dx.doi.org/10.1007/s00382-014-](http://dx.doi.org/10.1007/s00382-014-2129-1)
30 [2129-1](http://dx.doi.org/10.1007/s00382-014-2129-1)
- 31 Karpechko, A.Y. and E. Manzini, 2012: Stratospheric influence on tropospheric climate change
32 in the Northern Hemisphere. *Journal of Geophysical Research: Atmospheres*, **117**, D05133.
33 <http://dx.doi.org/10.1029/2011JD017036>

- 1 Kavvada, A., A. Ruiz-Barradas, and S. Nigam, 2013: AMO's structure and climate footprint in
2 observations and IPCC AR5 climate simulations. *Climate Dynamics*, **41**, 1345-1364.
3 <http://dx.doi.org/10.1007/s00382-013-1712-1>
- 4 Kennedy, D., T. Parker, T. Woollings, B. Harvey, and L. Shaffrey, 2016: The response of high-
5 impact blocking weather systems to climate change. *Geophysical Research Letters*, **43**, 7250-
6 7258. <http://dx.doi.org/10.1002/2016GL069725>
- 7 Kiladis, G.N. and H.F. Diaz, 1989: Global climatic anomalies associated with extremes in the
8 Southern Oscillation. *Journal of Climate*, **2**, 1069-1090. [http://dx.doi.org/10.1175/1520-
9 0442\(1989\)002<1069:GCAAWE>2.0.CO;2](http://dx.doi.org/10.1175/1520-0442(1989)002<1069:GCAAWE>2.0.CO;2)
- 10 Knight, J.R., C.K. Folland, and A.A. Scaife, 2006: Climate impacts of the Atlantic Multidecadal
11 Oscillation. *Geophysical Research Letters*, **33**, L17706.
12 <http://dx.doi.org/10.1029/2006GL026242>
- 13 Knudsen, M.F., B.H. Jacobsen, M.-S. Seidenkrantz, and J. Olsen, 2014: Evidence for external
14 forcing of the Atlantic Multidecadal Oscillation since termination of the Little Ice Age.
15 *Nature Communications*, **5**, 3323. <http://dx.doi.org/10.1038/ncomms4323>
- 16 Knutson, T.R., F. Zeng, and A.T. Wittenberg, 2013: Multimodel assessment of regional surface
17 temperature trends: CMIP3 and CMIP5 twentieth-century simulations. *Journal of Climate*,
18 **26**, 8709-8743. <http://dx.doi.org/10.1175/JCLI-D-12-00567.1>
- 19 Kossin, J.P., 2017: Hurricane intensification along U. S. coast suppressed during active hurricane
20 periods. *Nature*, **541**, 390-393. <http://dx.doi.org/10.1038/nature20783>
- 21 Kovilakam, M. and S. Mahajan, 2015: Black carbon aerosol-induced Northern Hemisphere
22 tropical expansion. *Geophysical Research Letters*, **42**, 4964-4972.
23 <http://dx.doi.org/10.1002/2015GL064559>
- 24 Kug, J.-S., S.-I. An, Y.-G. Ham, and I.-S. Kang, 2010: Changes in El Niño and La Niña
25 teleconnections over North Pacific–America in the global warming simulations. *Theoretical
26 and Applied Climatology*, **100**, 275-282. <http://dx.doi.org/10.1007/s00704-009-0183-0>
- 27 Landsea, C.W., R.A. Pielke Jr., A.M. Mestas-Nuñez, and J.A. Knaff, 1999: Atlantic basin
28 hurricanes: Indices of climatic changes. *Climatic Change*, **42**, 89-129.
29 <http://dx.doi.org/10.1023/a:1005416332322>
- 30 Langenbrunner, B. and J.D. Neelin, 2013: Analyzing ENSO teleconnections in CMIP models as
31 a measure of model fidelity in simulating precipitation. *Journal of Climate*, **26**, 4431-4446.
32 <http://dx.doi.org/10.1175/jcli-d-12-00542.1>

- 1 Lapp, S.L., J.-M. St. Jacques, E.M. Barrow, and D.J. Sauchyn, 2012: GCM projections for the
2 Pacific Decadal Oscillation under greenhouse forcing for the early 21st century. *International*
3 *Journal of Climatology*, **32**, 1423-1442. <http://dx.doi.org/10.1002/joc.2364>
- 4 Leathers, D.J., B. Yarnal, and M.A. Palecki, 1991: The Pacific/North American teleconnection
5 pattern and United States climate. Part I: Regional temperature and precipitation associations.
6 *Journal of Climate*, **4**, 517-528. [http://dx.doi.org/10.1175/1520-
7 0442\(1991\)004<0517:TPATPA>2.0.CO;2](http://dx.doi.org/10.1175/1520-0442(1991)004<0517:TPATPA>2.0.CO;2)
- 8 Lee, T. and M.J. McPhaden, 2010: Increasing intensity of El Niño in the central-equatorial
9 Pacific. *Geophysical Research Letters*, **37**, L14603.
10 <http://dx.doi.org/10.1029/2010GL044007>
- 11 Lee, Y.-Y. and R.X. Black, 2013: Boreal winter low-frequency variability in CMIP5 models.
12 *Journal of Geophysical Research: Atmospheres*, **118**, 6891-6904.
13 <http://dx.doi.org/10.1002/jgrd.50493>
- 14 Li, J., S.-P. Xie, E.R. Cook, G. Huang, R. D'Arrigo, F. Liu, J. Ma, and X.-T. Zheng, 2011:
15 Interdecadal modulation of El Niño amplitude during the past millennium. *Nature Climate*
16 *Change*, **1**, 114-118. <http://dx.doi.org/10.1038/nclimate1086>
- 17 Li, Y. and N.-C. Lau, 2012: Impact of ENSO on the atmospheric variability over the North
18 Atlantic in late winter—Role of transient eddies. *Journal of Climate*, **25**, 320-342.
19 <http://dx.doi.org/10.1175/JCLI-D-11-00037.1>
- 20 Lindsey, R., 2016: How El Niño and La Niña affect the winter jet stream and U.S. climate.
21 Climate.gov. [https://www.climate.gov/news-features/featured-images/how-el-ni%C3%B1o-
22 and-la-ni%C3%B1a-affect-winter-jet-stream-and-us-climate](https://www.climate.gov/news-features/featured-images/how-el-ni%C3%B1o-and-la-ni%C3%B1a-affect-winter-jet-stream-and-us-climate)
- 23 Linkin, M.E. and S. Nigam, 2008: The North Pacific Oscillation–West Pacific teleconnection
24 pattern: Mature-phase structure and winter impacts. *Journal of Climate*, **21**, 1979-1997.
25 <http://dx.doi.org/10.1175/2007JCLI2048.1>
- 26 Loikith, P.C. and A.J. Broccoli, 2012: Characteristics of observed atmospheric circulation
27 patterns associated with temperature extremes over North America. *Journal of Climate*, **25**,
28 7266-7281. <http://dx.doi.org/10.1175/JCLI-D-11-00709.1>
- 29 Lucas, C. and H. Nguyen, 2015: Regional characteristics of tropical expansion and the role of
30 climate variability. *Journal of Geophysical Research: Atmospheres*, **120**, 6809-6824.
31 <http://dx.doi.org/10.1002/2015JD023130>
- 32 Lucas, C., B. Timbal, and H. Nguyen, 2014: The expanding tropics: A critical assessment of the
33 observational and modeling studies. *Wiley Interdisciplinary Reviews: Climate Change*, **5**, 89-
34 112. <http://dx.doi.org/10.1002/wcc.251>

- 1 Mann, M.E. and K.A. Emanuel, 2006: Atlantic hurricane trends linked to climate change. *Eos*,
2 *Transactions, American Geophysical Union*, **87**, 233-244.
3 <http://dx.doi.org/10.1029/2006EO240001>
- 4 Mann, M.E., J.D. Woodruff, J.P. Donnelly, and Z. Zhang, 2009: Atlantic hurricanes and climate
5 over the past 1,500 years. *Nature*, **460**, 880-883. <http://dx.doi.org/10.1038/nature08219>
- 6 Mann, M.E., B.A. Steinman, and S.K. Miller, 2014: On forced temperature changes, internal
7 variability, and the AMO. *Geophysical Research Letters*, **41**, 3211-3219.
8 <http://dx.doi.org/10.1002/2014GL059233>
- 9 Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis, 1997: A Pacific interdecadal
10 climate oscillation with impacts on salmon production. *Bulletin of the American*
11 *Meteorological Society*, **78**, 1069-1080. [http://dx.doi.org/10.1175/1520-](http://dx.doi.org/10.1175/1520-0477(1997)078<1069:APICOW>2.0.CO;2)
12 [0477\(1997\)078<1069:APICOW>2.0.CO;2](http://dx.doi.org/10.1175/1520-0477(1997)078<1069:APICOW>2.0.CO;2)
- 13 Manzini, E., A.Y. Karpechko, J. Anstey, M.P. Baldwin, R.X. Black, C. Cagnazzo, N. Calvo, A.
14 Charlton-Perez, B. Christiansen, P. Davini, E. Gerber, M. Giorgetta, L. Gray, S.C. Hardiman,
15 Y.Y. Lee, D.R. Marsh, B.A. McDaniel, A. Purich, A.A. Scaife, D. Shindell, S.W. Son, S.
16 Watanabe, and G. Zappa, 2014: Northern winter climate change: Assessment of uncertainty
17 in CMIP5 projections related to stratosphere-troposphere coupling. *Journal of Geophysical*
18 *Research: Atmospheres*, **119**, 7979-7998. <http://dx.doi.org/10.1002/2013JD021403>
- 19 Mbengue, C. and T. Schneider, 2017: Storm-track shifts under climate change: Toward a
20 mechanistic understanding using baroclinic mean available potential energy. *Journal of the*
21 *Atmospheric Sciences*, **74**, 93-110. <http://dx.doi.org/10.1175/jas-d-15-0267.1>
- 22 McAfee, S.A., 2014: Consistency and the lack thereof in Pacific decadal oscillation impacts on
23 North American winter climate. *Journal of Climate*, **27**, 7410-7431.
24 <http://dx.doi.org/10.1175/JCLI-D-14-00143.1>
- 25 Meehl, G.A. and H. Teng, 2007: Multi-model changes in El Niño teleconnections over North
26 America in a future warmer climate. *Climate Dynamics*, **29**, 779-790.
27 <http://dx.doi.org/10.1007/s00382-007-0268-3>
- 28 Meehl, G.A., A. Hu, J.M. Arblaster, J. Fasullo, and K.E. Trenberth, 2013: Externally forced and
29 internally generated decadal climate variability associated with the Interdecadal Pacific
30 Oscillation. *Journal of Climate*, **26**, 7298-7310. [http://dx.doi.org/10.1175/JCLI-D-12-](http://dx.doi.org/10.1175/JCLI-D-12-00548.1)
31 [00548.1](http://dx.doi.org/10.1175/JCLI-D-12-00548.1)
- 32 Meehl, G.A., A. Hu, B.D. Santer, and S.-P. Xie, 2016: Contribution of the Interdecadal Pacific
33 Oscillation to twentieth-century global surface temperature trends. *Nature Climate Change*,
34 **6**, 1005-1008. <http://dx.doi.org/10.1038/nclimate3107>

- 1 Miles, M.W., D.V. Divine, T. Furevik, E. Jansen, M. Moros, and A.E.J. Ogilvie, 2014: A signal
2 of persistent Atlantic multidecadal variability in Arctic sea ice. *Geophysical Research*
3 *Letters*, **41**, 463-469. <http://dx.doi.org/10.1002/2013GL058084>
- 4 Moore, G.W.K., J. Halfar, H. Majeed, W. Adey, and A. Kronz, 2017: Amplification of the
5 Atlantic Multidecadal Oscillation associated with the onset of the industrial-era warming.
6 *Scientific Reports*, **7**, 40861. <http://dx.doi.org/10.1038/srep40861>
- 7 Newman, M., 2007: Interannual to decadal predictability of tropical and North Pacific sea
8 surface temperatures. *Journal of Climate*, **20**, 2333-2356.
9 <http://dx.doi.org/10.1175/jcli4165.1>
- 10 Newman, M., M.A. Alexander, T.R. Ault, K.M. Cobb, C. Deser, E.D. Lorenzo, N.J. Mantua,
11 A.J. Miller, S. Minobe, H. Nakamura, N. Schneider, D.J. Vimont, A.S. Phillips, J.D. Scott,
12 and C.A. Smith, 2016: The Pacific decadal oscillation, revisited. *Journal of Climate*, **29**,
13 4399-4427. <http://dx.doi.org/10.1175/JCLI-D-15-0508.1>
- 14 Nigam, S., 2003: Teleconnections. *Encyclopedia of Atmospheric Sciences*. Holton, J.R., Ed.
15 Academic Press, 2243-2269.
- 16 Ning, L. and R.S. Bradley, 2016: NAO and PNA influences on winter temperature and
17 precipitation over the eastern United States in CMIP5 GCMs. *Climate Dynamics*, **46**, 1257-
18 1276. <http://dx.doi.org/10.1007/s00382-015-2643-9>
- 19 Norris, J.R., R.J. Allen, A.T. Evan, M.D. Zelinka, C.W. O'Dell, and S.A. Klein, 2016: Evidence
20 for climate change in the satellite cloud record. *Nature*, **536**, 72-75.
21 <http://dx.doi.org/10.1038/nature18273>
- 22 NWS, 2016: Global Circulations in NWS Jet Stream: An Online School for Weather. National
23 Weather Service. <http://www.srh.noaa.gov/jetstream/global/circ.html>
- 24 Overland, J.E. and M. Wang, 2015: Increased variability in the early winter subarctic North
25 American atmospheric circulation. *Journal of Climate*, **28**, 7297-7305.
26 <http://dx.doi.org/10.1175/jcli-d-15-0395.1>
- 27 Overland, J., J.A. Francis, R. Hall, E. Hanna, S.-J. Kim, and T. Vihma, 2015: The melting Arctic
28 and midlatitude weather patterns: Are they connected? *Journal of Climate*, **28**, 7917-7932.
29 <http://dx.doi.org/10.1175/JCLI-D-14-00822.1>
- 30 Palmer, T.N., F.J. Doblas-Reyes, A. Weisheimer, and M.J. Rodwell, 2008: Toward seamless
31 prediction: Calibration of climate change projections using seasonal forecasts. *Bulletin of the*
32 *American Meteorological Society*, **89**, 459-470. <http://dx.doi.org/10.1175/bams-89-4-459>

- 1 Peings, Y. and G. Magnusdottir, 2014: Forcing of the wintertime atmospheric circulation by the
2 multidecadal fluctuations of the North Atlantic ocean. *Environmental Research Letters*, **9**,
3 034018. <http://dx.doi.org/10.1088/1748-9326/9/3/034018>
- 4 Perlwitz, J., S. Pawson, R.L. Fogt, J.E. Nielsen, and W.D. Neff, 2008: Impact of stratospheric
5 ozone hole recovery on Antarctic climate. *Geophysical Research Letters*, **35**, L08714.
6 <http://dx.doi.org/10.1029/2008GL033317>
- 7 Petoukhov, V., S. Rahmstorf, S. Petri, and H.J. Schellnhuber, 2013: Quasiresonant amplification
8 of planetary waves and recent Northern Hemisphere weather extremes. *Proceedings of the*
9 *National Academy of Sciences*, **110**, 5336-5341. <http://dx.doi.org/10.1073/pnas.1222000110>
- 10 Prein, A.F., G.J. Holland, R.M. Rasmussen, M.P. Clark, and M.R. Tye, 2016: Running dry: The
11 U.S. Southwest's drift into a drier climate state. *Geophysical Research Letters*, **43**, 1272-
12 1279. <http://dx.doi.org/10.1002/2015GL066727>
- 13 Quan, X.-W., M.P. Hoerling, J. Perlwitz, H.F. Diaz, and T. Xu, 2014: How fast are the tropics
14 expanding? *Journal of Climate*, **27**, 1999-2013. <http://dx.doi.org/10.1175/JCLI-D-13-00287.1>
- 16 Reichler, T., 2016: Chapter 6 - Poleward expansion of the atmospheric circulation *Climate*
17 *Change (Second Edition)*. Letcher, T.M., Ed. Elsevier, Boston, 79-104.
18 <http://dx.doi.org/10.1016/B978-0-444-63524-2.00006-3>
- 19 Renwick, J.A. and J.M. Wallace, 1996: Relationships between North Pacific wintertime
20 blocking, El Niño, and the PNA pattern. *Monthly Weather Review*, **124**, 2071-2076.
21 [http://dx.doi.org/10.1175/1520-0493\(1996\)124<2071:RBNPWB>2.0.CO;2](http://dx.doi.org/10.1175/1520-0493(1996)124<2071:RBNPWB>2.0.CO;2)
- 22 Ropelewski, C.F. and M.S. Halpert, 1987: Global and regional scale precipitation patterns
23 associated with the El Niño/Southern Oscillation. *Monthly Weather Review*, **115**, 1606-1626.
24 [http://dx.doi.org/10.1175/1520-0493\(1987\)115<1606:GARSPP>2.0.CO;2](http://dx.doi.org/10.1175/1520-0493(1987)115<1606:GARSPP>2.0.CO;2)
- 25 Scaife, A.A., T. Spanghel, D.R. Fereday, U. Cubasch, U. Langematz, H. Akiyoshi, S. Bekki, P.
26 Braesicke, N. Butchart, M.P. Chipperfield, A. Gettelman, S.C. Hardiman, M. Michou, E.
27 Rozanov, and T.G. Shepherd, 2012: Climate change projections and stratosphere–
28 troposphere interaction. *Climate Dynamics*, **38**, 2089-2097.
29 <http://dx.doi.org/10.1007/s00382-011-1080-7>
- 30 Scheff, J. and D. Frierson, 2012: Twenty-first-century multimodel subtropical precipitation
31 declines are mostly midlatitude shifts. *Journal of Climate*, **25**, 4330-4347.
32 <http://dx.doi.org/10.1175/JCLI-D-11-00393.1>

- 1 Scheff, J. and D.M.W. Frierson, 2012: Robust future precipitation declines in CMIP5 largely
2 reflect the poleward expansion of model subtropical dry zones. *Geophysical Research*
3 *Letters*, **39**, L18704. <http://dx.doi.org/10.1029/2012GL052910>
- 4 Schwendike, J., G.J. Berry, M.J. Reeder, C. Jakob, P. Govekar, and R. Wardle, 2015: Trends in
5 the local Hadley and local Walker circulations. *Journal of Geophysical Research:*
6 *Atmospheres*, **120**, 7599-7618. <http://dx.doi.org/10.1002/2014JD022652>
- 7 Screen, J.A. and I. Simmonds, 2013: Exploring links between Arctic amplification and mid-
8 latitude weather. *Geophysical Research Letters*, **40**, 959-964.
9 <http://dx.doi.org/10.1002/grl.50174>
- 10 Seager, R., Y. Kushnir, M. Ting, M. Cane, N. Naik, and J. Miller, 2008: Would advance
11 knowledge of 1930s SSTs have allowed prediction of the Dust Bowl drought? *Journal of*
12 *Climate*, **21**, 3261-3281. <http://dx.doi.org/10.1175/2007JCLI2134.1>
- 13 Seager, R., N. Naik, and L. Vogel, 2012: Does global warming cause intensified interannual
14 hydroclimate variability? *Journal of Climate*, **25**, 3355-3372. <http://dx.doi.org/10.1175/JCLI->
15 [D-11-00363.1](http://dx.doi.org/10.1175/JCLI-D-11-00363.1)
- 16 Seager, R., M. Hoerling, S. Schubert, H. Wang, B. Lyon, A. Kumar, J. Nakamura, and N.
17 Henderson, 2015: Causes of the 2011–14 California drought. *Journal of Climate*, **28**, 6997-
18 7024. <http://dx.doi.org/10.1175/JCLI-D-14-00860.1>
- 19 Seidel, D.J., Q. Fu, W.J. Randel, and T.J. Reichler, 2008: Widening of the tropical belt in a
20 changing climate. *Nature Geoscience*, **1**, 21-24. <http://dx.doi.org/10.1038/ngeo.2007.38>
- 21 Shaw, T.A., J. Perlwitz, and O. Weiner, 2014: Troposphere-stratosphere coupling: Links to
22 North Atlantic weather and climate, including their representation in CMIP5 models. *Journal*
23 *of Geophysical Research: Atmospheres*, **119**, 5864-5880.
24 <http://dx.doi.org/10.1002/2013JD021191>
- 25 Sheffield, J., S.J. Camargo, R. Fu, Q. Hu, X. Jiang, N. Johnson, K.B. Karnauskas, S.T. Kim, J.
26 Kinter, S. Kumar, B. Langenbrunner, E. Maloney, A. Mariotti, J.E. Meyerson, J.D. Neelin, S.
27 Nigam, Z. Pan, A. Ruiz-Barradas, R. Seager, Y.L. Serra, D.-Z. Sun, C. Wang, S.-P. Xie, J.-
28 Y. Yu, T. Zhang, and M. Zhao, 2013: North American climate in CMIP5 experiments. Part
29 II: Evaluation of historical simulations of intraseasonal to decadal variability. *Journal of*
30 *Climate*, **26**, 9247-9290. <http://dx.doi.org/10.1175/jcli-d-12-00593.1>
- 31 Shepherd, T.G., 2014: Atmospheric circulation as a source of uncertainty in climate change
32 projections. *Nature Geoscience*, **7**, 703-708. <http://dx.doi.org/10.1038/ngeo2253>

- 1 Simpson, I.R., T.A. Shaw, and R. Seager, 2014: A diagnosis of the seasonally and longitudinally
2 varying midlatitude circulation response to global warming. *Journal of the Atmospheric*
3 *Sciences*, **71**, 2489-2515. <http://dx.doi.org/10.1175/JAS-D-13-0325.1>
- 4 Simpson, I.R., R. Seager, M. Ting, and T.A. Shaw, 2016: Causes of change in Northern
5 Hemisphere winter meridional winds and regional hydroclimate. *Nature Climate Change*, **6**,
6 65-70. <http://dx.doi.org/10.1038/nclimate2783>
- 7 Sobel, A.H., S.J. Camargo, T.M. Hall, C.-Y. Lee, M.K. Tippett, and A.A. Wing, 2016: Human
8 influence on tropical cyclone intensity. *Science*, **353**, 242-246.
9 <http://dx.doi.org/10.1126/science.aaf6574>
- 10 Srivastava, A. and T. DelSole, 2017: Decadal predictability without ocean dynamics.
11 *Proceedings of the National Academy of Sciences*, **114**, 2177-2182.
12 <http://dx.doi.org/10.1073/pnas.1614085114>
- 13 Stevens, B., 2015: Rethinking the lower bound on aerosol radiative forcing. *Journal of Climate*,
14 **28**, 4794-4819. <http://dx.doi.org/10.1175/jcli-d-14-00656.1>
- 15 Stevenson, S.L., 2012: Significant changes to ENSO strength and impacts in the twenty-first
16 century: Results from CMIP5. *Geophysical Research Letters*, **39**, L17703.
17 <http://dx.doi.org/10.1029/2012GL052759>
- 18 Sun, Y., G. Ramstein, C. Contoux, and T. Zhou, 2013: A comparative study of large-scale
19 atmospheric circulation in the context of a future scenario (RCP4.5) and past warmth (mid-
20 Pliocene). *Climate of the Past*, **9**, 1613-1627. <http://dx.doi.org/10.5194/cp-9-1613-2013>
- 21 Swain, D., M. Tsiang, M. Haughen, D. Singh, A. Charland, B. Rajarthan, and N.S. Diffenbaugh,
22 2014: The extraordinary California drought of 2013/14: Character, context and the role of
23 climate change [in "Explaining Extreme Events of 2013 from a Climate Perspective"].
24 *Bulletin of the American Meteorological Society*, **95** (9), S3-S6.
25 <http://dx.doi.org/10.1175/1520-0477-95.9.S1.1>
- 26 Teng, H. and G. Branstator, 2017: Causes of extreme ridges that induce California droughts.
27 *Journal of Climate*, **30**, 1477-1492. <http://dx.doi.org/10.1175/jcli-d-16-0524.1>
- 28 Terray, L., 2012: Evidence for multiple drivers of North Atlantic multi-decadal climate
29 variability. *Geophysical Research Letters*, **39**, L19712.
30 <http://dx.doi.org/10.1029/2012GL053046>
- 31 Thompson, D.W.J. and J.M. Wallace, 1998: The Arctic oscillation signature in the wintertime
32 geopotential height and temperature fields. *Geophysical Research Letters*, **25**, 1297-1300.
33 <http://dx.doi.org/10.1029/98GL00950>

- 1 Thompson, D.W.J. and J.M. Wallace, 2000: Annular modes in the extratropical circulation. Part
2 I: Month-to-month variability. *Journal of Climate*, **13**, 1000-1016.
3 [http://dx.doi.org/10.1175/1520-0442\(2000\)013<1000:AMITEC>2.0.CO;2](http://dx.doi.org/10.1175/1520-0442(2000)013<1000:AMITEC>2.0.CO;2)
- 4 Thompson, D.W.J. and J.M. Wallace, 2001: Regional climate impacts of the Northern
5 Hemisphere annular mode. *Science*, **293**, 85-89. <http://dx.doi.org/10.1126/science.1058958>
- 6 Thompson, D.W.J., E.A. Barnes, C. Deser, W.E. Foust, and A.S. Phillips, 2015: Quantifying the
7 role of internal climate variability in future climate trends. *Journal of Climate*, **28**, 6443-
8 6456. <http://dx.doi.org/10.1175/JCLI-D-14-00830.1>
- 9 Ting, M., Y. Kushnir, R. Seager, and C. Li, 2009: Forced and internal twentieth-century SST
10 trends in the North Atlantic. *Journal of Climate*, **22**, 1469-1481.
11 <http://dx.doi.org/10.1175/2008jcli2561.1>
- 12 Trenary, L. and T. DelSole, 2016: Does the Atlantic Multidecadal Oscillation get its
13 predictability from the Atlantic Meridional Overturning Circulation? *Journal of Climate*, **29**,
14 5267-5280. <http://dx.doi.org/10.1175/jcli-d-16-0030.1>
- 15 Tung, K.-K. and J. Zhou, 2013: Using data to attribute episodes of warming and cooling in
16 instrumental records. *Proceedings of the National Academy of Sciences*, **110**, 2058-2063.
17 <http://dx.doi.org/10.1073/pnas.1212471110>
- 18 Vallis, G.K., P. Zurita-Gotor, C. Cairns, and J. Kidston, 2015: Response of the large-scale
19 structure of the atmosphere to global warming. *Quarterly Journal of the Royal
20 Meteorological Society*, **141**, 1479-1501. <http://dx.doi.org/10.1002/qj.2456>
- 21 Vimont, D.J., J.M. Wallace, and D.S. Battisti, 2003: The seasonal footprinting mechanism in the
22 Pacific: Implications for ENSO. *Journal of Climate*, **16**, 2668-2675.
23 [http://dx.doi.org/10.1175/1520-0442\(2003\)016<2668:tsfmit>2.0.co;2](http://dx.doi.org/10.1175/1520-0442(2003)016<2668:tsfmit>2.0.co;2)
- 24 Vincze, M. and I.M. János, 2011: Is the Atlantic Multidecadal Oscillation (AMO) a statistical
25 phantom? *Nonlinear Processes in Geophysics*, **18**, 469-475. [http://dx.doi.org/10.5194/npg-
26 18-469-2011](http://dx.doi.org/10.5194/npg-18-469-2011)
- 27 Vose, R.S., S. Applequist, M. Squires, I. Durre, M.J. Menne, C.N. Williams, Jr., C. Fenimore, K.
28 Gleason, and D. Arndt, 2014: Improved historical temperature and precipitation time series
29 for U.S. climate divisions. *Journal of Applied Meteorology and Climatology*, **53**, 1232-1251.
30 <http://dx.doi.org/10.1175/JAMC-D-13-0248.1>
- 31 Wang, H., S. Schubert, R. Koster, Y.-G. Ham, and M. Suarez, 2014: On the role of SST forcing
32 in the 2011 and 2012 extreme U.S. heat and drought: A study in contrasts. *Journal of
33 Hydrometeorology*, **15**, 1255-1273. <http://dx.doi.org/10.1175/JHM-D-13-069.1>

- 1 Wang, T., O.H. Otterå, Y. Gao, and H. Wang, 2012: The response of the North Pacific Decadal
2 Variability to strong tropical volcanic eruptions. *Climate Dynamics*, **39**, 2917-2936.
3 <http://dx.doi.org/10.1007/s00382-012-1373-5>
- 4 Waugh, D.W., C.I. Garfinkel, and L.M. Polvani, 2015: Drivers of the recent tropical expansion
5 in the Southern Hemisphere: Changing SSTs or ozone depletion? *Journal of Climate*, **28**,
6 6581-6586. <http://dx.doi.org/10.1175/JCLI-D-15-0138.1>
- 7 Wettstein, J.J. and C. Deser, 2014: Internal variability in projections of twenty-first-century
8 Arctic sea ice loss: Role of the large-scale atmospheric circulation. *Journal of Climate*, **27**,
9 527-550. <http://dx.doi.org/10.1175/JCLI-D-12-00839.1>
- 10 Whan, K., F. Zwiers, and J. Sillmann, 2016: The influence of atmospheric blocking on extreme
11 winter minimum temperatures in North America. *Journal of Climate*, **29**, 4361-4381.
12 <http://dx.doi.org/10.1175/JCLI-D-15-0493.1>
- 13 Yang, Q., T.H. Dixon, P.G. Myers, J. Bonin, D. Chambers, and M.R. van den Broeke, 2016:
14 Recent increases in Arctic freshwater flux affects Labrador Sea convection and Atlantic
15 overturning circulation. *Nature Communications*, **7**, 10525.
16 <http://dx.doi.org/10.1038/ncomms10525>
- 17 Yeh, S.-W., J.-S. Kug, B. Dewitte, M.-H. Kwon, B.P. Kirtman, and F.-F. Jin, 2009: El Niño in a
18 changing climate. *Nature*, **461**, 511-514. <http://dx.doi.org/10.1038/nature08316>
- 19 Yeh, S.-W., W.-M. Kim, Y.H. Kim, B.-K. Moon, R.J. Park, and C.-K. Song, 2013: Changes in
20 the variability of the North Pacific sea surface temperature caused by direct sulfate aerosol
21 forcing in China in a coupled general circulation model. *Journal of Geophysical Research:*
22 *Atmospheres*, **118**, 1261-1270. <http://dx.doi.org/10.1029/2012JD017947>
- 23 Yu, J.-Y. and Y. Zou, 2013: The enhanced drying effect of Central-Pacific El Niño on US
24 winter. *Environmental Research Letters*, **8**, 014019. <http://dx.doi.org/10.1088/1748->
25 [9326/8/1/014019](http://dx.doi.org/10.1088/1748-9326/8/1/014019)
- 26 Yu, J.-Y., Y. Zou, S.T. Kim, and T. Lee, 2012: The changing impact of El Niño on US winter
27 temperatures. *Geophysical Research Letters*, **39**, L15702.
28 <http://dx.doi.org/10.1029/2012GL052483>
- 29 Zhang, R. and T.L. Delworth, 2009: A new method for attributing climate variations over the
30 Atlantic hurricane basin's main development region. *Geophysical Research Letters*, **36**,
31 L06701. <http://dx.doi.org/10.1029/2009GL037260>
- 32 Zhang, R., T.L. Delworth, R. Sutton, D.L.R. Hodson, K.W. Dixon, I.M. Held, Y. Kushnir, J.
33 Marshall, Y. Ming, R. Msadek, J. Robson, A.J. Rosati, M. Ting, and G.A. Vecchi, 2013:

- 1 Have aerosols caused the observed Atlantic multidecadal variability? *Journal of the*
2 *Atmospheric Sciences*, **70**, 1135-1144. <http://dx.doi.org/10.1175/jas-d-12-0331.1>
- 3 Zhang, R., R. Sutton, G. Danabasoglu, T.L. Delworth, W.M. Kim, J. Robson, and S.G. Yeager,
4 2016: Comment on “The Atlantic Multidecadal Oscillation without a role for ocean
5 circulation”. *Science*, **352**, 1527-1527. <http://dx.doi.org/10.1126/science.aaf1660>
- 6 Zhang, T., M.P. Hoerling, J. Perlwitz, and T. Xu, 2016: Forced atmospheric teleconnections
7 during 1979–2014. *Journal of Climate*, **29**, 2333-2357. [http://dx.doi.org/10.1175/jcli-d-15-](http://dx.doi.org/10.1175/jcli-d-15-0226.1)
8 0226.1
- 9 Zhou, Z.-Q., S.-P. Xie, X.-T. Zheng, Q. Liu, and H. Wang, 2014: Global warming–induced
10 changes in El Niño teleconnections over the North Pacific and North America. *Journal of*
11 *Climate*, **27**, 9050-9064. <http://dx.doi.org/10.1175/JCLI-D-14-00254.1>

FINAL DRAFT

6. Temperature Changes in the United States

KEY FINDINGS

1. Average annual temperature over the contiguous United States has increased by 1.2°F (0.7°C) for the period 1986–2016 relative to 1901–1960 and by 1.8°F (1.0°C) based on a linear regression for the period 1895–2016 (*very high confidence*). Surface and satellite data are consistent in their depiction of rapid warming since 1979 (*high confidence*). Paleo-temperature evidence shows that recent decades are the warmest of the past 1,500 years (*medium confidence*).
2. There have been marked changes in temperature extremes across the contiguous United States. The frequency of cold waves has decreased since the early 1900s, and the frequency of heat waves has increased since the mid-1960s (the Dust Bowl remains the peak period for extreme heat). The number of high temperature records set in the past two decades far exceeds the number of low temperature records. (*Very high confidence*)
3. Average annual temperature over the contiguous United States is projected to rise (*very high confidence*). Increases of about 2.5°F (1.4°C) are projected for the next few decades in all emission scenarios, implying recent record-setting years may be “common” in the near future (*high confidence*). Much larger rises are projected by late century: 2.8°–7.3°F (1.6°–4.1°C) in a lower emissions scenario (RCP4.5) and 5.8°–11.9°F (3.2°–6.6°C) in a higher emissions scenario (RCP8.5) (*high confidence*).
4. Extreme temperatures in the contiguous United States are projected to increase even more than average temperatures. The temperatures of extremely cold days and extremely warm days are both expected to increase. Cold waves are projected to become less intense while heat waves will become more intense. The number of days below freezing is projected to decline while the number above 90°F will rise. (*Very high confidence*)

Introduction

Temperature is among the most important climatic elements used in decision-making. For example, builders and insurers use temperature data for planning and risk management while energy companies and regulators use temperature data to predict demand and set utility rates. Temperature is also a key indicator of climate change: recent increases are apparent over the land, ocean, and troposphere, and substantial changes are expected for this century. This chapter summarizes the major observed and projected changes in near-surface air temperature over the United States, emphasizing new data sets and model projections since the Third National Climate Assessment (NCA3). Changes are depicted using a spectrum of observations, including surface weather stations, moored ocean buoys, polar-orbiting satellites, and temperature-sensitive proxies. Projections are based on global models and downscaled products from CMIP5 (Coupled

1 Model Intercomparison Project Phase 5) using a suite of Representative Concentration Pathways
2 (RCPs; see Ch. 4: Projections for more on RCPs and future scenarios).

3 **6.1 Historical Changes**

4 **6.1.1. Average Temperatures**

5 Changes in average temperature are described using a suite of observational datasets. As in
6 NCA3, changes in land temperature are assessed using the nClimGrid dataset (Vose et al. 2014,
7 2017). Along U.S. coastlines, changes in sea surface temperatures are quantified using a new
8 reconstruction (Huang et al. 2015) that forms the ocean component of the NOAA Global
9 Temperature dataset (Vose et al. 2012). Changes in middle tropospheric temperature are
10 examined using updated versions of multiple satellite datasets (Zou and Li 2014; Mears and
11 Wentz 2016; Spencer et al. 2017).

12 The average annual temperature of the contiguous United States has risen since the start of the
13 20th century. In general, temperature increased until about 1940, decreased until about 1970, and
14 increased rapidly through 2016. Because the increase was not constant over time, multiple
15 methods were evaluated in this report (as in NCA3) to quantify the trend. All methods yielded
16 rates of warming that were significant at the 95% level. The lowest estimate of 1.2°F (0.7°C) was
17 obtained by computing the difference between the average for 1986–2016 (i.e., present-day) and
18 the average for 1901–1960 (i.e., the first half of the last century). The highest estimate of 1.8°F
19 (1.0°C) was obtained by fitting a linear (least-squares) regression line through the period 1895–
20 2016. Thus, the temperature increase cited in this assessment is 1.2°–1.8°F (0.7°–1.0°C).

21 This increase is about 0.1°F (0.06°C) less than presented in NCA3, and it results from the use of
22 slightly different periods in each report. In particular, the decline in the lower bound stems from
23 the use of different time periods to represent present-day climate (NCA3 used 1991–2012, which
24 was slightly warmer than the 1986–2016 period used here). The decline in the upper bound stems
25 mainly from temperature differences late in the record (e.g., the last year of data available for
26 NCA3 was 2012, which was the warmest year on record for the contiguous United States).

27 Each NCA region experienced a net warming through 2016 (Table 6.1). The largest changes
28 were in the western United States, where average temperature increased by more than 1.5°F
29 (0.8°C) in Alaska, the Northwest, the Southwest, and also in the Northern Great Plains. As noted
30 in NCA3, the Southeast had the least warming, driven by a combination of natural variations and
31 human influences (Meehl et al. 2012). In most regions, average minimum temperature increased
32 at a slightly higher rate than average maximum temperature, with the Midwest having the largest
33 discrepancy, and the Southwest and Northwest having the smallest. This differential rate of
34 warming resulted in a continuing decrease in the diurnal temperature range that is consistent with
35 other parts of the globe (Thorne et al. 2016). Average annual sea surface temperature also
36 increased along all regional coastlines (see Figure 1.3), though changes were generally smaller

1 than over land owing to the higher heat capacity of water. Increases were largest in Alaska
2 (greater than 1.0°F [0.6°C]) while increases were smallest (less than 0.5°F [0.3°C]) in coastal
3 areas of the Southeast.

4 **[INSERT TABLE 6.1 HERE]**

5 More than 95% of the land surface of the contiguous United States had an increase in average
6 annual temperature (Figure 6.1). In contrast, only small (and somewhat dispersed) parts of the
7 Southeast and Southern Great Plains experienced cooling. From a seasonal perspective, warming
8 was greatest and most widespread in winter, with increases of over 1.5°F (0.8°C) in most areas.
9 In summer, warming was less extensive (mainly along the East Coast and in the western third of
10 the Nation), while cooling was evident in parts of the Southeast, Midwest, and Great Plains.

11 **[INSERT FIGURE 6.1 HERE]**

12 There has been a rapid increase in the average temperature of the contiguous United States over
13 the past several decades. There is general consistency on this point between the surface
14 thermometer record from NOAA (Vose et al. 2014) and the middle tropospheric satellite records
15 from Remote Sensing Systems (RSS; Mears and Wentz 2016), NOAA's Center for Satellite
16 Applications and Research (STAR; Zou and Li 2014), and the University of Alabama in
17 Huntsville (UAH; Spencer et al. 2017). In particular, for the period 1979–2016, the rate of
18 warming in the surface record was 0.512°F (0.284°C) per decade, versus trends of 0.455°F
19 (0.253°C), 0.421°F (0.234°C), and 0.289°F (0.160 °C) per decade for RSS version 4, STAR
20 version 3, and UAH version 6, respectively (after accounting for stratospheric influences). All
21 trends are statistically significant at the 95% level. For the contiguous United States, the year
22 2016 was the second-warmest on record at the surface and in the middle troposphere (2012 was
23 the warmest year at the surface, and 2015 was the warmest in the middle troposphere). Generally
24 speaking, surface and satellite records do not have identical trends because they do not represent
25 the same physical quantity; surface measurements are made using thermometers in shelters about
26 1.5 meters above the ground whereas satellite measurements are mass-weighted averages of
27 microwave emissions from deep atmospheric layers. The UAH record likely has a lower trend
28 because it differs from the other satellite products in the treatment of target temperatures from
29 the NOAA-9 satellite as well as in the correction for diurnal drift (Po-Chedley et al. 2015).

30 Recent paleo-temperature evidence confirms the unusual character of wide-scale warming during
31 the past few decades as determined from the instrumental record. The most important new
32 paleoclimate study since NCA3 showed that for each of the seven continental regions, the
33 reconstructed area-weighted average temperature for 1971–2000 was higher than for any other
34 time in nearly 1,400 years (PAGES 2k 2013), although with significant uncertainty around the
35 central estimate that leads to this conclusion. Recent (up to 2006) 30-year smoothed temperatures
36 across temperate North America (including most of the continental United States) are similarly
37 reconstructed as the warmest over the past 1,500 years (Trouet et al. 2013) (Figure 6.2). Unlike

1 the PAGES 2k seven-continent result mentioned above, this conclusion for North America is
2 robust in relation to the estimated uncertainty range. Reconstruction data since 1500 for western
3 temperate North America show the same conclusion at the annual time scale for 1986–2005.
4 This time period and the running 20-year periods thereafter are warmer than all possible
5 continuous 20-year sequences in a 1,000-member statistical reconstruction ensemble (Wahl and
6 Smerdon 2012).

7 **[INSERT FIGURE 6.2 HERE]**

8 **6.1.2. Temperature Extremes**

9 Shifts in temperature extremes are examined using a suite of societally relevant climate change
10 indices (Zhang et al. 2011; Russo et al. 2014) derived from long-term observations of daily
11 surface temperature (Menne et al. 2012). The coldest and warmest temperatures of the year are
12 of particular relevance given their widespread use in engineering, agricultural, and other sectoral
13 applications (for example, extreme annual design conditions by the American Society of
14 Heating, Refrigeration, and Air Conditioning; plant hardiness zones by the U.S. Department of
15 Agriculture). Cold waves and heat waves (that is, extended periods of below or above normal
16 temperature) are likewise of great importance because of their numerous societal and
17 environmental impacts, which span from human health to plant and animal phenology. Changes
18 are considered for a spectrum of event frequencies and intensities, ranging from the typical
19 annual extreme to the 1-in-10 year event (an extreme that only has a 10% chance of occurrence
20 in any given year). The discussion focuses on the contiguous United States; Alaska, Hawai'i, and
21 the Caribbean do not have a sufficient number of long-term stations for a century-scale analysis.

22 Cold extremes have become less severe over the past century. For example, the coldest daily
23 temperature of the year has increased at most locations in the contiguous United States (Figure
24 6.3). All regions experienced net increases (Table 6.2), with the largest rises in the Northern
25 Great Plains and the Northwest (roughly 4.5°F [2.5°C]), and the smallest in the Southeast (about
26 1.0°F [0.6°C]). In general, there were increases throughout the record, with a slight acceleration
27 in recent decades (Figure 6.3). The temperature of extremely cold days (1-in-10 year events)
28 generally exhibited the same pattern of increases as the coldest daily temperature of the year.
29 Consistent with these increases, the number of cool nights per year (those with a minimum
30 temperature below the 10th percentile for 1961–1990) declined in all regions, with much of the
31 West having decreases of roughly two weeks. The frequency of cold waves (6-day periods with a
32 minimum temperature below the 10th percentile for 1961–1990) has fallen over the past century
33 (Figure 6.4). The frequency of intense cold waves (4-day, 1-in-5 year events) peaked in the
34 1980s and then reached record-low levels in the 2000s (Peterson et al. 2013).

35 **[INSERT TABLE 6.2 AND FIGURES 6.3 AND 6.4 HERE]**

36 Changes in warm extremes are more nuanced than changes in cold extremes. For instance, the
37 warmest daily temperature of the year increased in some parts of the West over the past century

1 (Figure 6.3), but there were decreases in almost all locations east of the Rocky Mountains. In
2 fact, all eastern regions experienced a net decrease (Table 6.2), most notably the Midwest (about
3 2.2°F [1.2°C]) and the Southeast (roughly 1.5°F [0.8°C]). The decreases in the eastern half of
4 Nation, particularly in the Great Plains, are mainly tied to the unprecedented summer heat of the
5 1930s Dust Bowl era, which was exacerbated by land-surface feedbacks driven by springtime
6 precipitation deficits and land mismanagement (Donat et al. 2016). However, anthropogenic
7 aerosol forcing may also have reduced summer temperatures in the Northeast and Southeast from
8 the early 1950s to the mid-1970s (Mascioli et al. 2017), and agricultural intensification may have
9 suppressed the hottest extremes in the Midwest (Mueller et al. 2016). Since the mid-1960s, there
10 has been only a very slight increase in the warmest daily temperature of the year (amidst large
11 interannual variability). Heat waves (6-day periods with a maximum temperature above the 90th
12 percentile for 1961–1990) increased in frequency until the mid-1930s, became considerably less
13 common through the mid-1960s, and increased in frequency again thereafter (Figure 6.4). As
14 with warm daily temperatures, heat wave magnitude reached a maximum in the 1930s. The
15 frequency of intense heat waves (4-day, 1-in-5 year events) has generally increased since the
16 1960s in most regions except the Midwest and the Great Plains (Peterson et al. 2013; Smith et al.
17 2013). Since the early 1980s (Figure 6.4), there is suggestive evidence of a slight increase in the
18 intensity of heat waves nationwide (Russo et al. 2014) as well as an increase in the concurrence
19 of droughts and heat waves (Mazdiyasi and AghaKouchak 2015).

20 Changes in the occurrence of record-setting daily temperatures are also apparent. Very generally,
21 the number of record lows has been declining since the late-1970s while the number of record
22 highs has been rising (Meehl et al. 2016). By extension, there has been an increase in the ratio of
23 the number of record highs to record lows (Figure 6.5). Over the past two decades, the average of
24 this ratio exceeds two (meaning that twice as many high-temperature records have been set as
25 low-temperature records). The number of new highs has surpassed the number of new lows in 15
26 of the last 20 years, with 2012 and 2016 being particularly extreme (ratios of seven and five,
27 respectively).

28 **[INSERT FIGURE 6.5 HERE]**

29 **6.2 Detection and Attribution**

30 **6.2.1 Average Temperatures**

31 While a confident attribution of global temperature increases to anthropogenic forcing has been
32 made (Bindoff et al. 2013), detection and attribution assessment statements for smaller regions
33 are generally much weaker. Nevertheless, some detectable anthropogenic influences on average
34 temperature have been reported for North America and parts of the United States (e.g., Christidis
35 et al. 2010; Bonfils et al. 2008; Pierce et al. 2009). Figure 6.6 shows an example for linear trends
36 for 1901–2015, indicating a detectable anthropogenic warming since 1901 over the western and
37 northern regions of the contiguous United States for the CMIP5 multimodel ensemble—a

1 condition that was also met for most of the individual models (Knutson et al. 2013a). The
2 Southeast stands out as the only region with no “detectable” warming since 1901; observed
3 trends there were inconsistent with CMIP5 All Forcing historical runs (Knutson et al. 2013a).
4 The cause of this “warming hole,” or lack of a long-term warming trend, remains uncertain,
5 though it is likely a combination of natural and human causes. Some studies conclude that
6 changes in anthropogenic aerosols have played a crucial role (e.g., Leibensperger et al. 2012a,b;
7 Yu et al. 2014), whereas other studies infer a possible large role for atmospheric circulation
8 (Abatzoglou et al. 2007), internal climate variability (e.g., Meehl et al. 2012; Knutson et al.
9 2013a), and changes in land use (e.g., Goldstein et al. 2009; Xu et al. 2015). Notably, the
10 Southeast has been warming rapidly since the early 1960s (Walsh et al. 2014; Pan et al. 2013).

11 **[INSERT FIGURE 6.6 HERE]**

12 **6.2.2 Temperature Extremes**

13 IPCC AR5 (Bindoff et al. 2013) concluded that it is very likely that human influence has
14 contributed to the observed changes in frequency and intensity of temperature extremes on the
15 global scale since the mid-20th century. The combined influence of anthropogenic and natural
16 forcings was also detectable over large subregions of North America (e.g., Zwiers et al. 2011;
17 Min et al. 2013). In general, however, results for the contiguous United States are not as
18 compelling as for global land areas, in part because detection of changes in U.S. regional
19 temperature extremes is affected by extreme temperature in the 1930s (Peterson et al. 2013).
20 Table 6.3 summarizes available attribution statements for recent extreme U.S. temperature
21 events. As an example, the recent record or near-record high March–May average temperatures
22 occurring in 2012 over the eastern United States were attributed in part to external (natural plus
23 anthropogenic) forcing (Knutson et al. 2013b); the century-scale trend response of temperature to
24 external forcing is typically a close approximation to the anthropogenic forcing response alone.
25 Another study found that although the extreme March 2012 warm anomalies over the United
26 States were mostly due to natural variability, anthropogenic warming contributed to the severity
27 (Dole et al. 2014). Such statements reveal that both natural and anthropogenic factors influence
28 the severity of extreme temperature events. Nearly every modern analysis of current extreme hot
29 and cold events reveals some degree of attributable human influence.

30 **[INSERT TABLE 6.3 HERE]**

31 **6.3 Projected Changes**

32 **6.3.1 Average Temperatures**

33 Temperature projections are based on global model results and associated downscaled products
34 from CMIP5 using a suite of Representative Concentration Pathways (RCPs). In contrast to
35 NCA3, model weighting is employed to refine projections of temperature for each RCP (Ch. 4:
36 Projections; Appendix B: Model Weighting). Weighting parameters are based on model

1 independence and skill over North America for seasonal temperature and annual extremes.
2 Unless stated otherwise, all changes presented here represent the weighted multimodel mean.
3 The weighting scheme helps refine confidence and likelihood statements, but projections of U.S.
4 surface air temperature remain very similar to those in NCA3. Generally speaking, extreme
5 temperatures are projected to increase even more than average temperatures (Collins et al. 2013).

6 The average annual temperature of the contiguous United States is projected to rise throughout
7 the century. Near-term increases (that is, by roughly 2030) are projected to be about 2.5°F
8 (1.4°C) for RCP4.5 and 2.9°F (1.6°C) for RCP8.5; the similarity in warming reflects the
9 similarity in greenhouse gas concentrations during this period (Figure 4.1). Notably, a 2.5°F
10 (1.4°C) increase makes the near-term average comparable to the hottest year in the historical
11 record (2012). In other words, recent record-breaking years could be “normal” by about 2030.
12 By late-century, the RCPs diverge significantly, leading to different rates of warming:
13 approximately 5.0°F (2.8°C) for RCP4.5 and 8.7°F (4.8°C) for RCP8.5. Likewise, there are
14 different ranges of warming for each scenario: 2.8°–7.3°F (1.6°–4.1°C) for RCP4.5 and 5.8°–
15 11.9°F (3.2°–6.6°C) for RCP8.5. (The range is defined here as the difference between the
16 average increase in the three coolest models and the average increase in the three warmest
17 models.) For both RCPs, slightly greater increases are projected in summer than winter (except
18 for Alaska), and average maximums will rise slightly faster than average minimums (except in
19 the Southeast and Southern Great Plains).

20 Statistically significant warming is projected for all parts of the United States throughout the
21 century (Figure 6.7). Consistent with polar amplification, warming rates (and spatial gradients)
22 are greater at higher latitudes. For example, warming is largest in Alaska (more than 12.0°F
23 [6.7°C] in the northern half of the state by late-century under RCP8.5), driven in part by a
24 decrease in snow cover and thus surface albedo. Similarly, northern regions of the contiguous
25 United States have slightly more warming than other regions (roughly 9.0°F [5.5°C] in the
26 Northeast, Midwest, and Northern Great Plains by late-century under RCP8.5; Table 6.4). The
27 Southeast has slightly less warming because of latent heat release from increases in
28 evapotranspiration (as is already evident in the observed record). Warming is smallest in Hawai‘i
29 and the Caribbean (roughly 4.0°–6.0°F [2.2°–3.3°C] by late century under RCP8.5) due to the
30 moderating effects of surrounding oceans. From a sub-regional perspective, less warming is
31 projected along the coasts of the contiguous United States, again due to maritime influences,
32 although increases are still substantial. Warming at higher elevations may be underestimated
33 because the resolution of the CMIP5 models does not capture orography in detail.

34 **[INSERT FIGURE 6.7 AND TABLE 6.4 HERE]**

35 **6.3.2 Temperature Extremes**

36 Daily extreme temperatures are projected to increase substantially in the contiguous United
37 States, particularly under RCP8.5. For instance, the coldest and warmest daily temperatures of

1 the year are expected to increase at least 5°F (2.8°C) in most areas by mid-century (Fischer et al.
2 2013), rising to 10°F (5.5°C) or more by late-century (Sillmann et al. 2013). In general, there
3 will be larger increases in the coldest temperatures of the year, especially in the northern half of
4 the Nation, whereas the warmest temperatures will exhibit somewhat more uniform changes
5 geographically (Figure 6.8). By mid-century, the upper bound for projected changes (i.e., the
6 average of the three warmest models) is about 2°F (1.1°C) greater than the weighted multimodel
7 mean. On a regional basis, annual extremes (Table 6.5) are consistently projected to rise faster
8 than annual averages (Table 6.4). Future changes in “very rare” extremes are also striking; by
9 late century, current 1-in-20 year maximums are projected to occur every year, while current 1-
10 in-20 year minimums are not expected to occur at all (Wuebbles et al. 2014).

11 **[INSERT FIGURE 6.8 AND TABLE 6.5 HERE]**

12 The frequency and intensity of cold waves is projected to decrease while the frequency and
13 intensity of heat waves is projected to increase throughout the century. The frequency of cold
14 waves (6-day periods with a minimum temperature below the 10th percentile) will decrease the
15 most in Alaska and the least in the Northeast while the frequency of heat waves (6-day periods
16 with a maximum temperature above the 90th percentile) will increase in all regions, particularly
17 the Southeast, Southwest, and Alaska. By mid-century, decreases in the frequency of cold waves
18 are similar across RCPs whereas increases in the frequency of heat waves are about 50% greater
19 in RCP8.5 than RCP4.5 (Sun et al. 2015). The intensity of cold waves is projected to decrease
20 while the intensity of heat waves is projected to increase, dramatically so under RCP8.5. By mid-
21 century, both extreme cold waves and extreme heat waves (5-day, 1-in-10 year events) are
22 projected to have temperature increases of at least 11.0°F (6.1°C) nationwide, with larger
23 increases in northern regions (the Northeast, Midwest, Northern Great Plains, and Northwest;
24 Table 6.5).

25 There are large projected changes in the number of days exceeding key temperature thresholds
26 throughout the contiguous United States. For instance, there are about 20–30 more days per year
27 with a maximum over 90°F (32°C) in most areas by mid-century under RCP8.5, with increases
28 of 40–50 days in much of the Southeast (Figure 6.9). The upper bound for projected changes is
29 very roughly 10 days greater than the weighted multimodel mean. Consistent with widespread
30 warming, there are 20–30 fewer days per year with a minimum temperature below freezing in the
31 northern and eastern parts of the nation, with decreases of more than 40–50 days in much the
32 West. The upper bound for projected changes in freezing events is very roughly 10–20 days
33 fewer than the weighted multimodel mean in many areas.

34 **[INSERT FIGURE 6.9 HERE]**

1 TRACEABLE ACCOUNTS

2 Key Finding 1

3 Average annual temperature over the contiguous United States has increased by 1.2°F (0.7°C)
4 for the period 1986–2016 relative to 1901–1960 and by 1.8°F (1.0°C) based on a linear
5 regression for the period 1895–2016 (*very high confidence*). Surface and satellite data are
6 consistent in their depiction of rapid warming since 1979 (*high confidence*). Paleo-temperature
7 evidence shows that recent decades are the warmest of the past 1,500 years (*medium confidence*).

8 Description of Evidence Base

9 The key finding and supporting text summarize extensive evidence documented in the climate
10 science literature. Similar statements about changes exist in other reports (e.g., NCA3; Melillo et
11 al. 2014; Global Climate Change Impacts in the United States; Karl et al. 2009; SAP 1.1:
12 Temperature trends in the lower atmosphere; Climate Change Science Program [CCSP] 2006).

13 Evidence for changes in U.S. climate arises from multiple analyses of data from in situ, satellite,
14 and other records undertaken by many groups over several decades. The primary dataset for
15 surface temperatures in the United States is nClimGrid (Vose et al. 2014, 2017), though trends
16 are similar in the U.S. Historical Climatology Network, the Global Historical Climatology
17 Network, and other datasets. Several atmospheric reanalyses (e.g., 20th Century Reanalysis,
18 Climate Forecast System Reanalysis, ERA-Interim, Modern Era Reanalysis for Research and
19 Applications) confirm rapid warming at the surface since 1979, observed trends closely tracking
20 the ensemble mean of the reanalyses (Vose et al. 2012). Several recently improved satellite
21 datasets document changes in middle tropospheric temperatures (Mears and Wentz 2016; Zou
22 and Li 2016; Spencer et al. 2017). Longer-term changes are depicted using multiple paleo
23 analyses (e.g., Wahl and Smerdon 2012; Trouet et al. 2013).

24 Major Uncertainties

25 The primary uncertainties for surface data relate to historical changes in station location,
26 temperature instrumentation, observing practice, and spatial sampling (particularly in areas and
27 periods with low station density, such as the intermountain West in the early 20th century).
28 Satellite records are similarly impacted by non-climatic changes such as orbital decay, diurnal
29 sampling, and instrument calibration to target temperatures. Several uncertainties are inherent in
30 temperature-sensitive proxies, such as dating techniques and spatial sampling.

31 Assessment of confidence based on evidence and agreement, including short description of 32 nature of evidence and level of agreement

33 *Very high* (since 1895), *High* (for surface/satellite agreement since 1979), *Medium* (for paleo)

34

1 **Likelihood of Impact**

2 *Extremely Likely*

3 **Summary sentence or paragraph that integrates the above information**

4 There is *very high confidence* in observed changes in average temperature over the United States
5 based upon the convergence of evidence from multiple data sources, analyses, and assessments.

7 **Key Finding 2**

8 There have been marked changes in temperature extremes across the contiguous United States.
9 The frequency of cold waves has decreased since the early 1900s, and the frequency of heat
10 waves has increased since the mid-1960s (the Dust Bowl remains the peak period for extreme
11 heat). The number of high temperature records set in the past two decades far exceeds the
12 number of low temperature records. (*Very high confidence*)

13 **Description of Evidence Base**

14 The key finding and supporting text summarize extensive evidence documented in the climate
15 science literature. Similar statements about changes have also been made in other reports (e.g.,
16 NCA3, Melillo et al. 2014; SAP 3.3: Weather and Climate Extremes in a Changing Climate,
17 CCSP 2008; IPCC Special Report on Managing the Risks of Extreme Events and Disasters to
18 Advance Climate Change Adaptation, IPCC 2012).

19 Evidence for changes in U.S. climate arises from multiple analyses of in situ data using widely
20 published climate extremes indices. For the analyses presented here, the source of in situ data is
21 the Global Historical Climatology Network – Daily dataset (Menne et al. 2012), changes in
22 extremes being assessed using long-term stations with minimal missing data to avoid network-
23 induced variability on the long-term time series. Cold wave frequency was quantified using the
24 Cold Spell Duration Index (Zhang et al. 2011), heat wave frequency was quantified using the
25 Warm Spell Duration Index (Zhang et al. 2011), and heat wave intensity were quantified using
26 the Heat Wave Magnitude Index Daily (Russo et al. 2014). Station-based index values were
27 averaged into 4° grid boxes, which were then area-averaged into a time series for the contiguous
28 United States. Note that a variety of other threshold and percentile-based indices were also
29 evaluated, with consistent results (e.g., the Dust Bowl was consistently the peak period for
30 extreme heat). Changes in record-setting temperatures were quantified as in Meehl et al. (2016).

31 **Major Uncertainties**

32 The primary uncertainties for in situ data relate to historical changes in station location,
33 temperature instrumentation, observing practice, and spatial sampling (particularly the precision

1 of estimates of change in areas and periods with low station density, such as the intermountain
2 West in the early 20th century).

3 **Assessment of confidence based on evidence and agreement, including short description of**
4 **nature of evidence and level of agreement**

5 *Very high*

6 **Likelihood of Impact**

7 *Extremely likely*

8 **Summary sentence or paragraph that integrates the above information**

9 There is *very high confidence* in observed changes in temperature extremes over the United
10 States based upon the convergence of evidence from multiple data sources, analyses, and
11 assessments.

12

13 **Key Finding 3**

14 Average annual temperature over the contiguous United States is projected to rise (*very high*
15 *confidence*). Increases of about 2.5°F (1.4°C) are projected for the next few decades in all
16 emission scenarios, implying recent record-setting years may be “common” in the near future
17 (*high confidence*). Much larger rises are projected by late century: 2.8°–7.3°F (1.6°–4.1°C) in a
18 lower emissions scenario (RCP4.5) and 5.8°–11.9°F (3.2°–6.6°C) in a higher emissions scenario
19 (RCP8.5) (*high confidence*).

20 **Description of Evidence Base**

21 The key finding and supporting text summarize extensive evidence documented in the climate
22 science literature. Similar statements about changes have also been made in other reports (e.g.,
23 NCA3, Melillo et al. 2014; Global Climate Change Impacts in the United States, Karl et al.
24 2009). The basic physics underlying the impact of human emissions on climate has also been
25 documented in every IPCC assessment.

26 Projections are based on global model results and associated downscaled products from CMIP5
27 for RCP4.5 (lower emissions) and RCP8.5 (higher emissions). Model weighting is employed to
28 refine projections for each RCP. Weighting parameters are based on model independence and
29 skill over North America for seasonal temperature and annual extremes. The multimodel mean is
30 based on 32 model projections that were statistically downscaled using the Localized
31 Constructed Analogs technique (Pierce et al. 2014). The range is defined as the difference
32 between the average increase in the three coolest models and the average increase in the three
33 warmest models. All increases are significant (i.e., more than 50% of the models show a

1 statistically significant change, and more than 67% agree on the sign of the change; Sun et al.
2 2015).

3 **Major Uncertainties**

4 Global climate models are subject to structural and parametric uncertainty, resulting in a range of
5 estimates of future changes in average temperature. This is partially mitigated through the use of
6 model weighting and pattern scaling. Furthermore, virtually every ensemble member of every
7 model projection contains an increase in temperature by mid- and late-century. Empirical
8 downscaling introduces additional uncertainty (e.g., with respect to stationarity).

9 **Assessment of confidence based on evidence and agreement, including short description of** 10 **nature of evidence and level of agreement**

11 *Very high* for projected change in average annual temperature; *high confidence* for record-setting
12 years becoming the norm in the near future; *high confidence* for much larger temperature
13 increases by late century under a higher emissions scenario (RCP8.5).

14 **Likelihood of Impact**

15 *Extremely likely*

16 **Summary sentence or paragraph that integrates the above information**

17 There is *very high confidence* in projected changes in average temperature over the United States
18 based upon the convergence of evidence from multiple model simulations, analyses, and
19 assessments.

20

21 **Key Finding 4**

22 Extreme temperatures in the contiguous United States are projected to increase even more than
23 average temperatures. The temperatures of extremely cold days and extremely warm days are
24 both expected to increase. Cold waves are projected to become less intense while heat waves will
25 become more intense. The number of days below freezing is projected to decline while the
26 number above 90°F will rise. (*Very high confidence*)

27 **Description of Evidence Base**

28 The key finding and supporting text summarize extensive evidence documented in the climate
29 science literature (e.g., Fischer et al. 2013; Sillmann et al. 2013; Wuebbles et al. 2014; Sun et al.
30 2015). Similar statements about changes have also been made in other national assessments
31 (such as NCA3) and in reports by the Climate Change Science Program (such as SAP 3.3:
32 Weather and Climate Extremes in a Changing Climate, CCSP 2008).

1 Projections are based on global model results and associated downscaled products from CMIP5
2 for RCP4.5 (lower emissions) and RCP8.5 (higher emissions). Model weighting is employed to
3 refine projections for each RCP. Weighting parameters are based on model independence and
4 skill over North America for seasonal temperature and annual extremes. The multimodel mean is
5 based on 32 model projections that were statistically downscaled using the Localized
6 Constructed Analogs technique (Pierce et al. 2014). Downscaling improves on the coarse model
7 output, establishing a more geographically accurate baseline for changes in extremes and the
8 number of days per year over key thresholds. The upper bound for projected changes is the
9 average of the three warmest models. All increases are significant (i.e., more than 50% of the
10 models show a statistically significant change, and more than 67% agree on the sign of the
11 change; Sun et al. 2015).

12 **Major Uncertainties**

13 Global climate models are subject to structural and parametric uncertainty, resulting in a range of
14 estimates of future changes in temperature extremes. This is partially mitigated through the use
15 of model weighting and pattern scaling. Furthermore, virtually every ensemble member of every
16 model projection contains an increase in temperature by mid- and late-century. Empirical
17 downscaling introduces additional uncertainty (e.g., with respect to stationarity).

18 **Assessment of confidence based on evidence and agreement, including short description of** 19 **nature of evidence and level of agreement**

20 *Very high*

21 **Likelihood of Impact**

22 *Extremely likely*

23 **Summary Sentence**

24 There is *very high confidence* in projected changes in temperature extremes over the United
25 States based upon the convergence of evidence from multiple model simulations, analyses, and
26 assessments.

1 **TABLES**

2 **Table 6.1.** Observed changes in average annual temperature (°F) for each National Climate
 3 Assessment region. Changes are the difference between the average for present-day (1986–2016)
 4 and the average for the first half of the last century (1901–1960 for the contiguous United States,
 5 1925–1960 for Alaska, Hawai'i, and the Caribbean). Estimates are derived from the nClimDiv
 6 dataset (Vose et al. 2014, 2017).

NCA Region	Change in Average Annual Temperature	Change in Average Annual Maximum Temperature	Change in Average Annual Minimum Temperature
Contiguous U.S.	1.23°F	1.06°F	1.41°F
Northeast	1.43°F	1.16°F	1.70°F
Southeast	0.46°F	0.16°F	0.76°F
Midwest	1.26°F	0.77°F	1.75°F
Great Plains North	1.69°F	1.66°F	1.72°F
Great Plains South	0.76°F	0.56°F	0.96°F
Southwest	1.61°F	1.61°F	1.61°F
Northwest	1.54°F	1.52°F	1.56°F
Alaska	1.67°F	1.43°F	1.91°F
Hawaii	1.26°F	1.01°F	1.49°F
Caribbean	1.35°F	1.08°F	1.60°F

7

1 **Table 6.2.** Observed changes in the coldest and warmest daily temperatures (°F) of the year for
 2 each National Climate Assessment region in the contiguous United States. Changes are the
 3 difference between the average for present-day (1986–2016) and the average for the first half of
 4 the last century (1901–1960). Estimates are derived from long-term stations with minimal
 5 missing data in the Global Historical Climatology Network–Daily dataset (Menne et al. 2012).

6

NCA Region	Change in Coldest Day of the Year	Change in Warmest Day of the Year
Northeast	2.83°F	–0.92°F
Southeast	1.13°F	–1.49°F
Midwest	2.93°F	–2.22°F
Great Plains North	4.40°F	–1.08°F
Great Plains South	3.25°F	–1.07°F
Southwest	3.99°F	0.50°F
Northwest	4.78°F	–0.17°F

7

1 **Table 6.3.** Extreme temperature events in the United States for which attribution statements have
 2 been made. There are three possible attribution statements: “+” shows an attributable human-
 3 induced increase in frequency or intensity, “-” shows an attributable human-induced decrease in
 4 frequency or intensity, “0” shows no attributable human contribution.

Study	Period	Region	Type	Statement
Rupp et al. 2012 Angélil et al. 2017	Spring/Summer 2011	Texas	Hot	+ +
Hoerling et al. 2013	Summer 2011	Texas	Hot	+
Diffenbaugh and Scherer 2013 Angélil et al. 2017	July 2012	Northcentral and Northeast	Hot	+ +
Cattiaux and Yiou 2013 Angélil et al. 2017	Spring 2012	East	Hot	0 +
Knutson et al. 2013b Angelil et al. 2017	Spring 2012	East	Hot	+ +
Jeon et al 2016	Summer 2011	Texas/Oklahoma	Hot	+
Dole et al. 2014	March 2012	Upper Midwest	Hot	+
Seager et al. 2014	2011-2014	California	Hot	+
Wolter et al. 2015	Winter 2014	Midwest	Cold	-
Trenary et al. 2015	Winter 2014	East	Cold	0

5

1 **Table 6.4.** Projected changes in average annual temperature (°F) for each National Climate
 2 Assessment region in the contiguous United States. Changes are the difference between the
 3 average for mid-century (2036–2065) or late-century (2071–2100) and the average for near-
 4 present (1976–2005) under RCP8.5 and RCP4.5. Estimates are derived from 32 climate models
 5 that were statistically downscaled using the Localized Constructed Analogs technique (Pierce et
 6 al. 2014). Increases are statistically significant in all areas (that is, more than 50% of the models
 7 show a statistically significant change, and more than 67% agree on the sign of the change; Sun et
 8 al. 2015).

NCA Region	RCP4.5	RCP 8.5	RCP 4.5	RCP 8.5
	Mid-Century (2036–2065)	Mid-Century (2036–2065)	Late-Century (2071–2100)	Late-Century (2071–2100)
Northeast	3.98°F	5.09°F	5.27°F	9.11°F
Southeast	3.40°F	4.30°F	4.43°F	7.72°F
Midwest	4.21°F	5.29°F	5.57°F	9.49°F
Great Plains North	4.05°F	5.10°F	5.44°F	9.37°F
Great Plains South	3.62°F	4.61°F	4.78°F	8.44°F
Southwest	3.72°F	4.80°F	4.93°F	8.65°F
Northwest	3.66°F	4.67°F	4.99°F	8.51°F

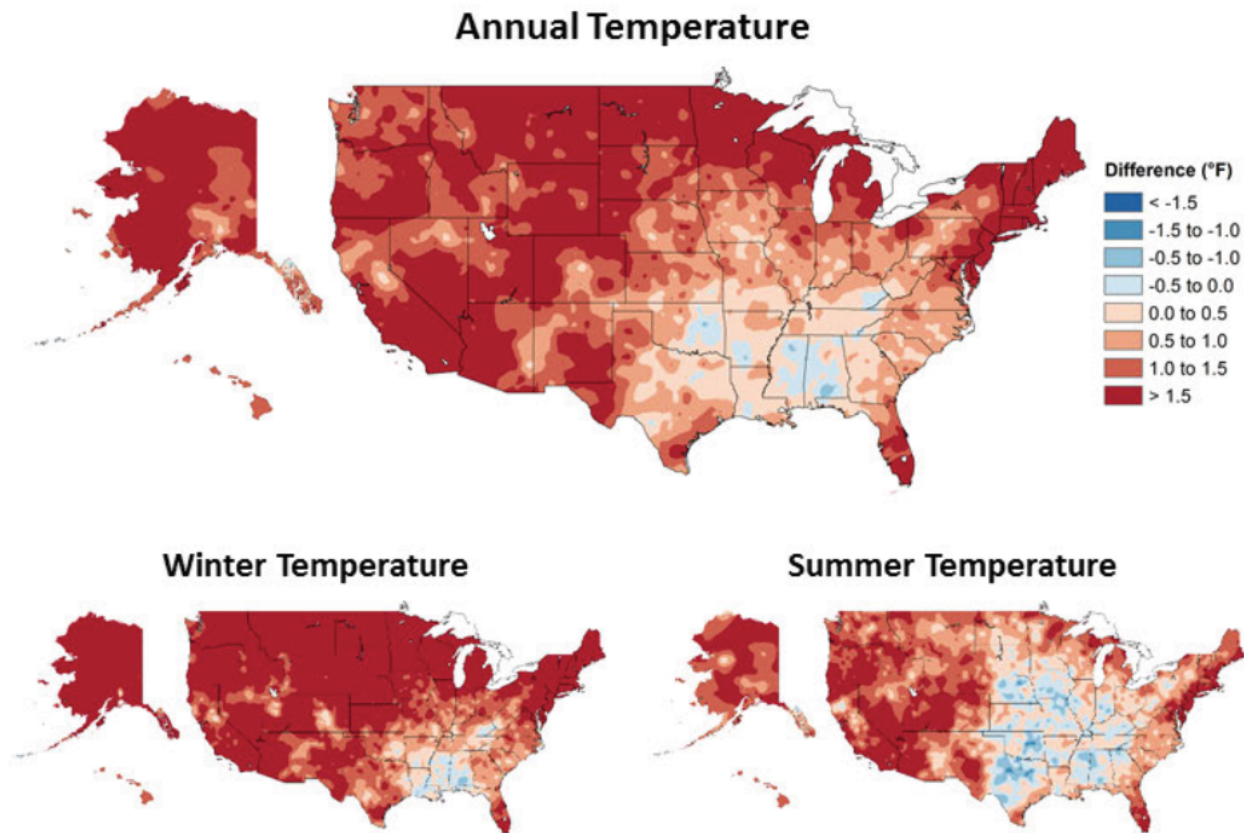
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1 **Table 6.5.** Projected changes in temperature extremes (°F) for each National Climate Assessment
 2 region in the contiguous United States. Changes are the difference between the average for mid-
 3 century (2036–2065) and the average for near-present (1976–2005) under RCP8.5. Estimates are
 4 derived from 32 climate models that were statistically downscaled using the Localized
 5 Constructed Analogs technique (Pierce et al. 2014). Increases are statistically significant in all
 6 areas (that is, more than 50% of the models show a statistically significant change, and more than
 7 67% agree on the sign of the change; Sun et al. 2015).

NCA Region	Change in Coldest Day of the Year	Change in Coldest 5-Day 1-in-10 Year Event	Change in Warmest Day of the Year	Change in Warmest 5-Day 1-in-10 Year Event
Northeast	9.51°F	15.93°F	6.51°F	12.88°F
Southeast	4.97°F	8.84°F	5.79°F	11.09°F
Midwest	9.44°F	15.52°F	6.71°F	13.02°F
Great Plains North	8.01°F	12.01°F	6.48°F	12.00°F
Great Plains South	5.49°F	9.41°F	5.70°F	10.73°F
Southwest	6.13°F	10.20°F	5.85°F	11.17°F
Northwest	7.33°F	10.95°F	6.25°F	12.31°F

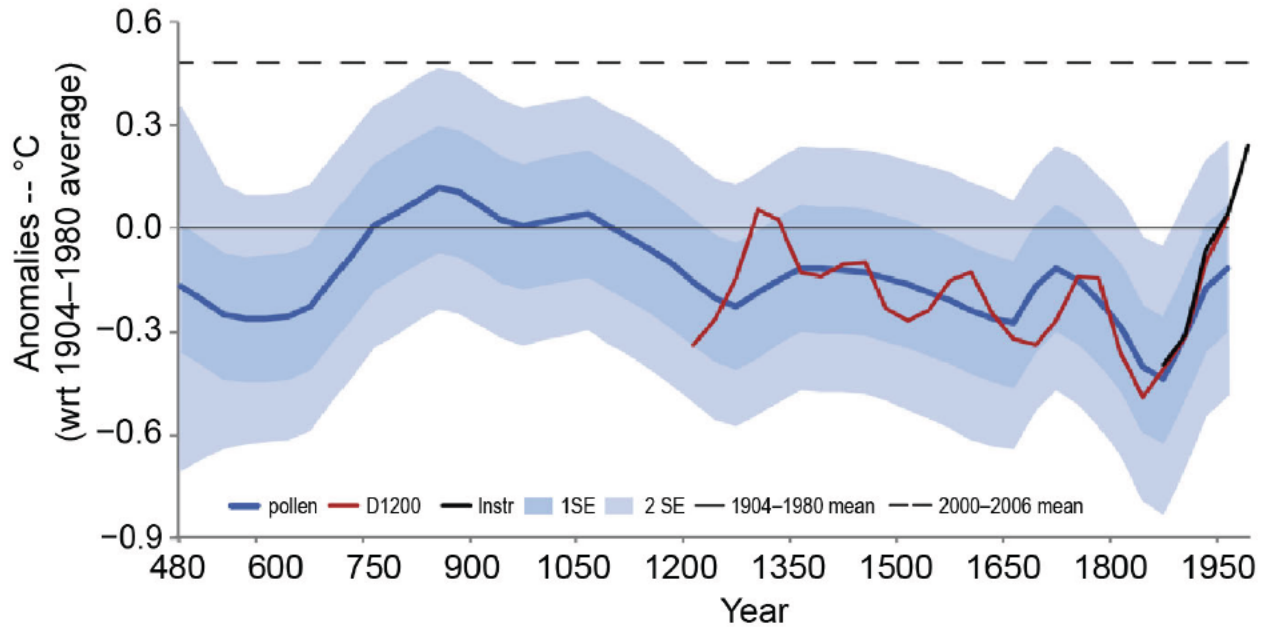
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1 **FIGURES**

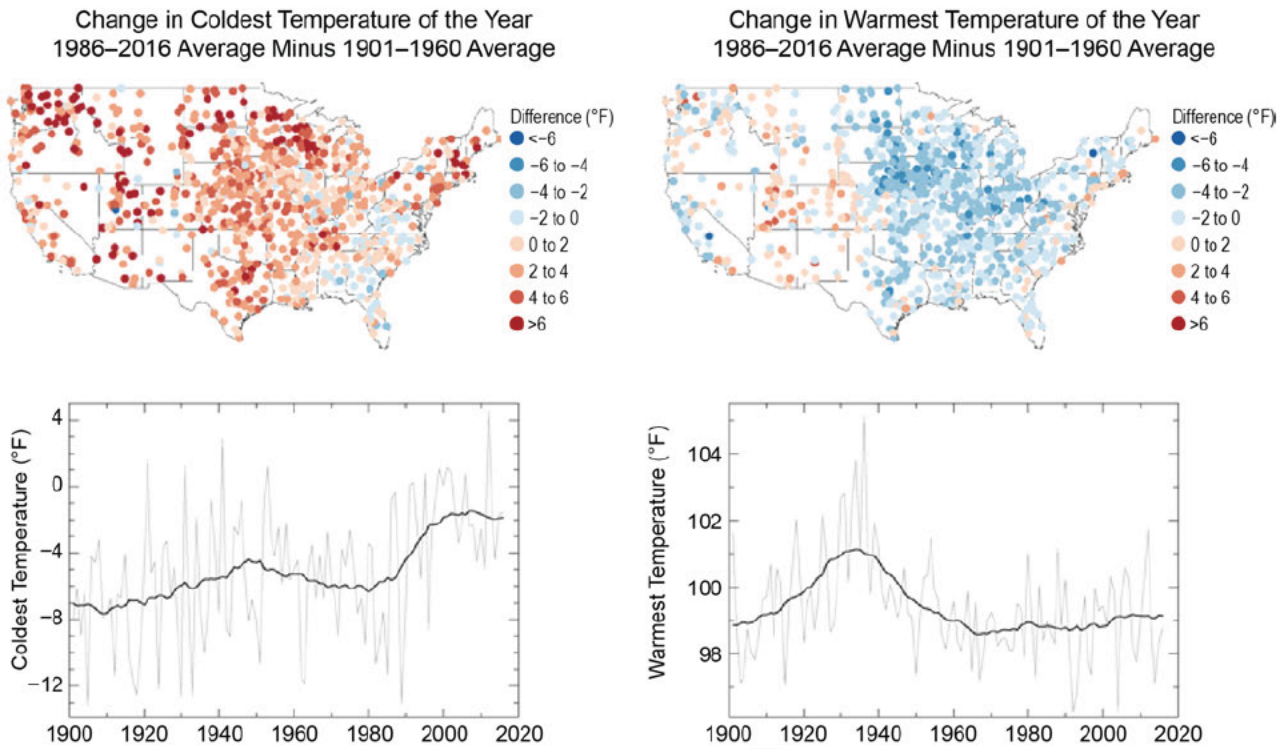


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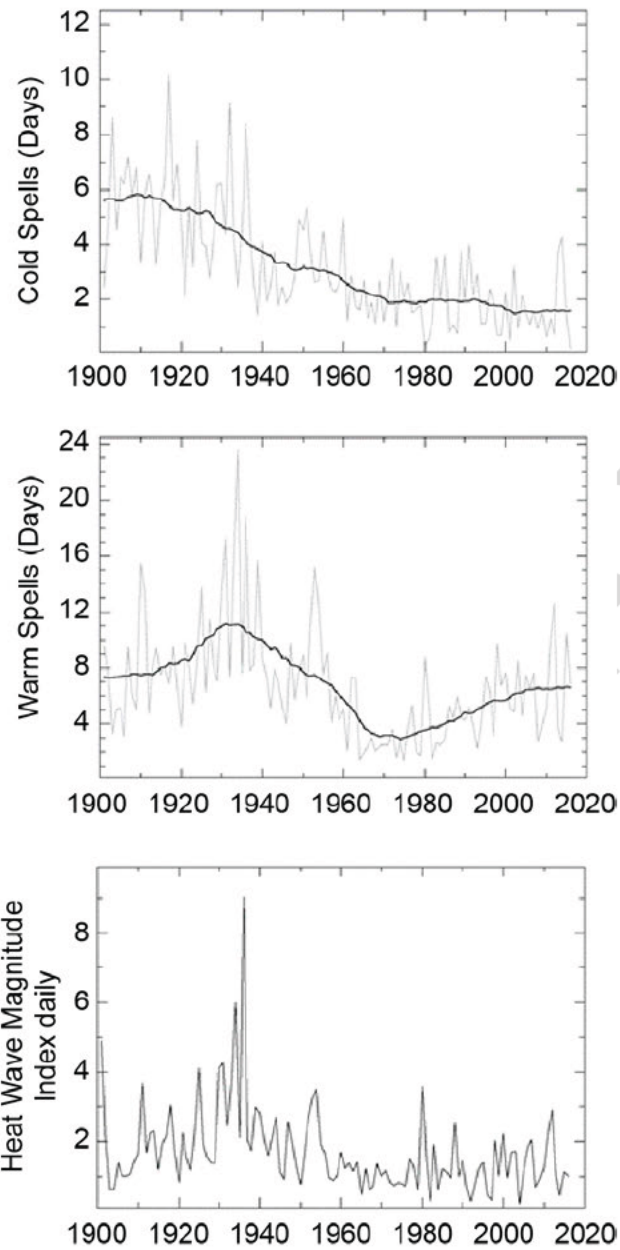
3 **Figure 6.1.** Observed changes in annual, winter, and summer temperature (°F). Changes are the
 4 difference between the average for present-day (1986–2016) and the average for the first half of
 5 the last century (1901–1960 for the contiguous United States, 1925–1960 for Alaska and
 6 Hawai‘i). Estimates are derived from the nClimDiv dataset (Vose et al. 2014, 2017). (Figure
 7 source: NOAA/NCEI).



1
 2 **Figure 6.2.** Pollen-based temperature reconstruction for temperate North America. The blue
 3 curve depicts the pollen-based reconstruction of 30-year averages (as anomalies from 1904 to
 4 1980) for the temperate region (30°–55°N, 75°–130°W). The red curve shows the corresponding
 5 tree ring-based decadal average reconstruction, which was smoothed and used to calibrate the
 6 lower-frequency pollen-based estimate. Light (medium) blue zones indicate 2 standard error (1
 7 standard error) uncertainty estimations associated with each 30-year value. The black curve
 8 shows comparably smoothed instrumental temperature values up to 1980. The dashed black line
 9 represents the average temperature anomaly of comparably smoothed instrumental data for the
 10 period 2000–2006. (Figure source: NOAA/NCEI).

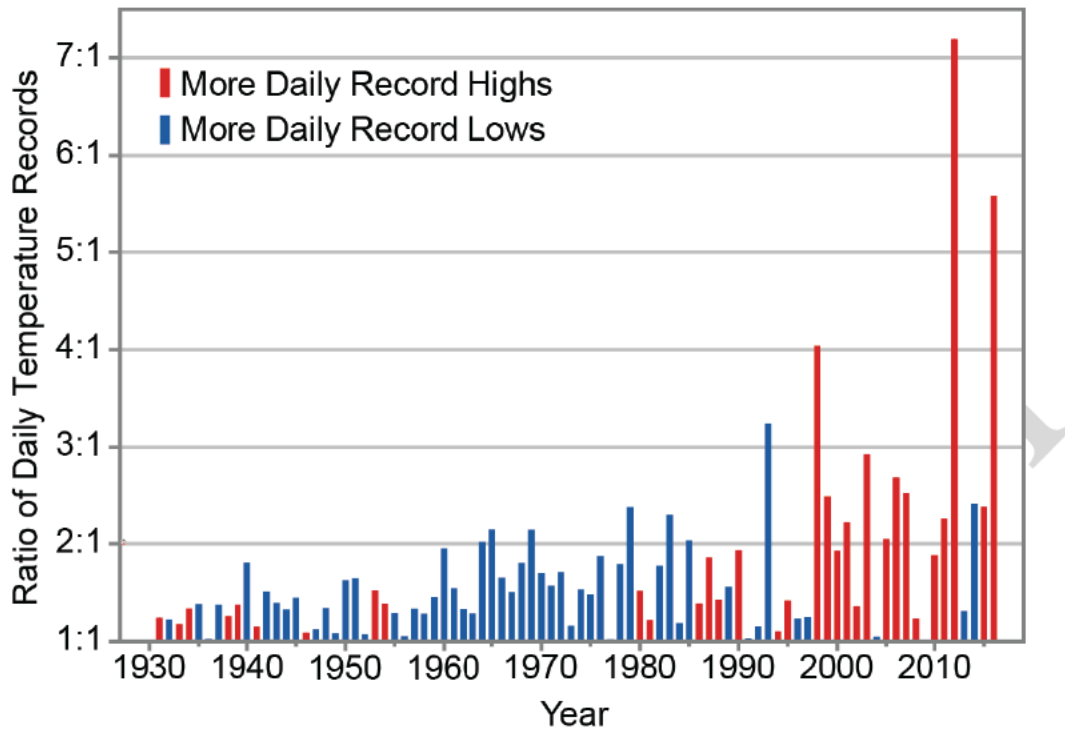


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 2 **Figure 6.3.** Observed changes in the coldest and warmest daily temperatures (°F) of the year in
 3 the contiguous United States. Maps (top) depict changes at stations; changes are the difference
 4 between the average for present-day (1986–2016) and the average for the first half of the last
 5 century (1901–1960). Time series (bottom) depict the area-weighted average for the contiguous
 6 United States. Estimates are derived from long-term stations with minimal missing data in the
 7 Global Historical Climatology Network–Daily dataset (Menne et al. 2012). (Figure source:
 8 NOAA/NCEI).



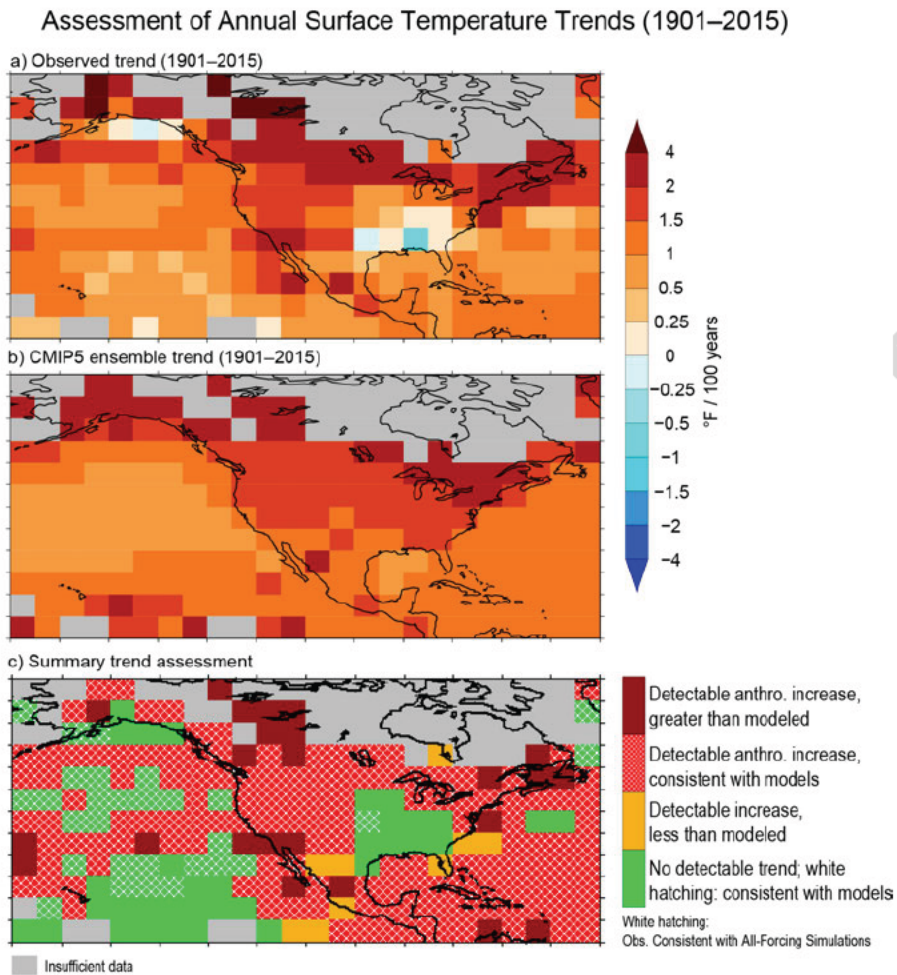
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2 **Figure 6.4.** Observed changes in cold and heat waves in the contiguous United States. The top
 3 panel depicts changes in the frequency of cold waves; the middle panel depicts changes in the
 4 frequency of heat waves; and the bottom panel depicts changes in the intensity of heat waves.
 5 Cold and heat wave frequency indices are defined in Zhang et al. (2011), and the heat wave
 6 intensity index is defined in Russo et al. (2014). Estimates are derived from long-term stations
 7 with minimal missing data in the Global Historical Climatology Network–Daily dataset (Menne
 8 et al. 2012). (Figure source: NOAA/NCEI).



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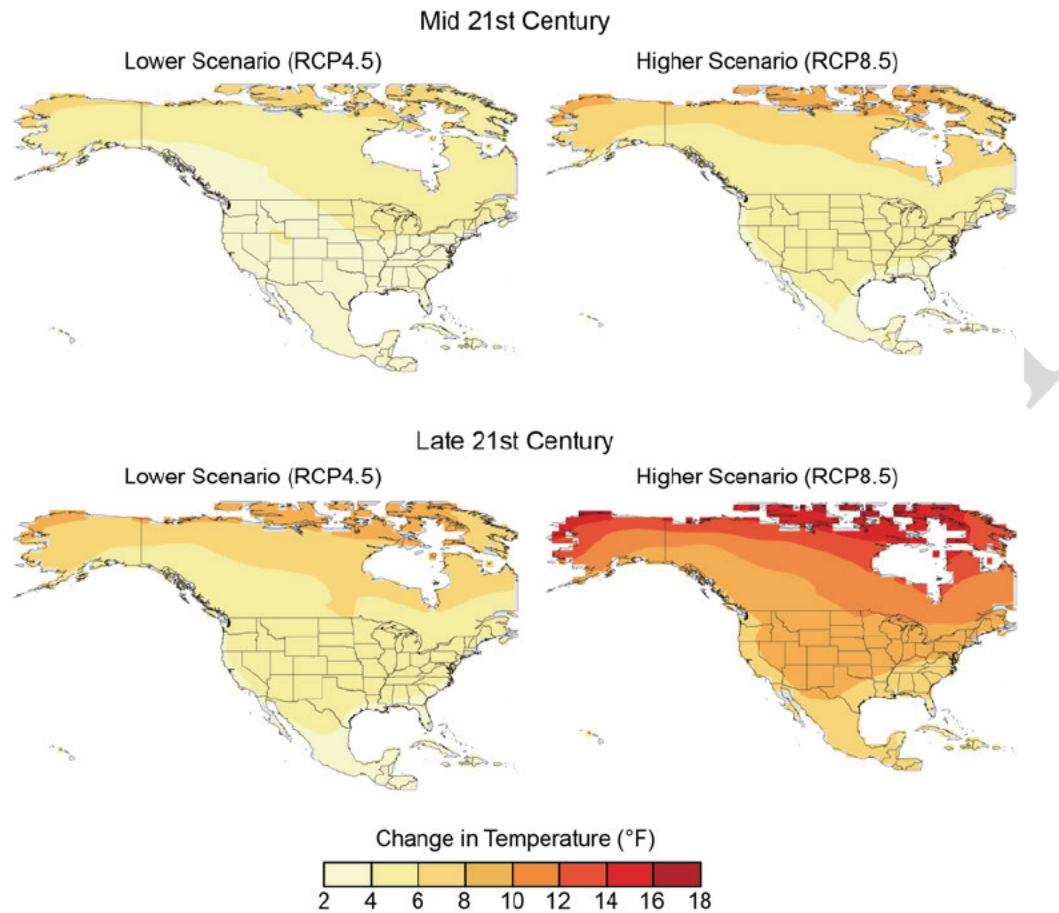
2 **Figure 6.5.** Observed changes in the occurrence of record-setting daily temperatures in the
3 contiguous United States. Red bars indicate a year with more daily record highs than daily record
4 lows, while blue bars indicate a year with more record lows than highs. The height of the bar
5 indicates the ratio of record highs to lows (red) or of record lows to highs (blue). For example, a
6 ratio of 2:1 for a blue bar means that there were twice as many record daily lows as daily record
7 highs that year. Estimates are derived from long-term stations with minimal missing data in the
8 Global Historical Climatology Network–Daily dataset (Menne et al. 2012). (Figure source:
9 NOAA/NCEI).



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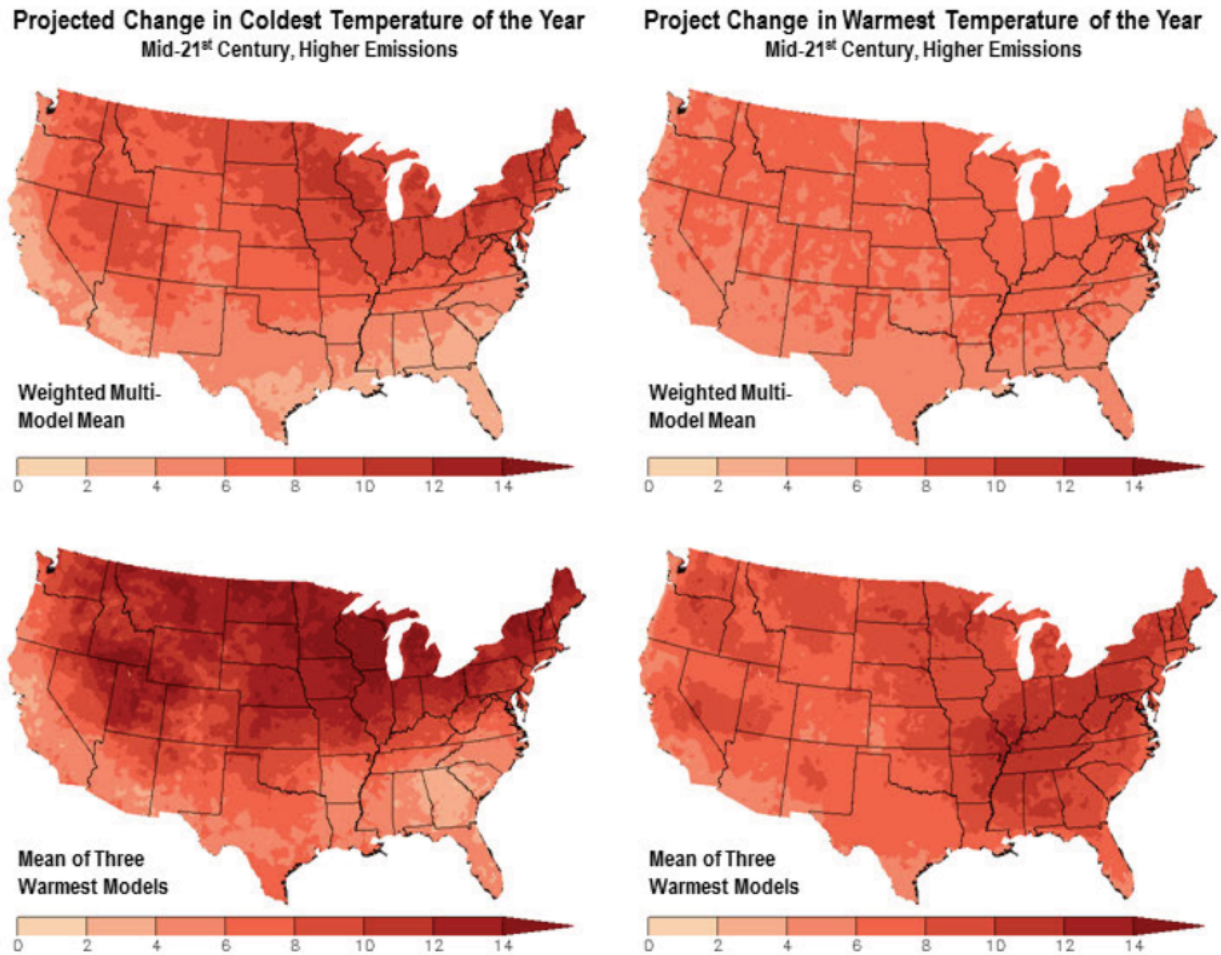
2 **Figure 6.6.** Detection and attribution assessment of trends in average annual temperature (°F).
 3 Grid-box values indicate whether linear trends for 1901–2015 are detectable (that is, distinct
 4 from natural variability) and/or consistent with CMIP5 historical All-Forcing runs. If the grid-
 5 box trend is found to be both detectable and either consistent with or greater than the warming in
 6 the All-Forcing runs, then the grid box is assessed as having a detectable anthropogenic
 7 contribution to warming over the period. Gray regions represent grid boxes with data that are too
 8 sparse for detection and attribution. (Figure source: updated from Knutson et al. 2013a; ©
 9 American Meteorological Society. Used with permission.)

Projected Changes in Average Annual Temperature



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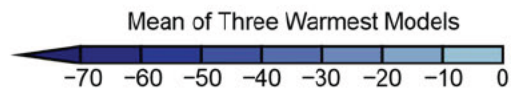
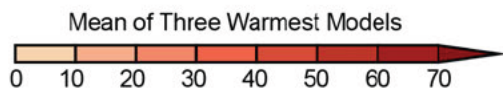
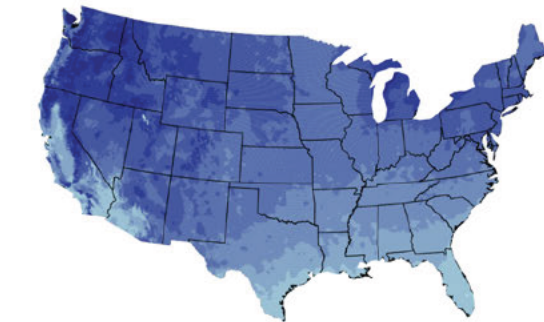
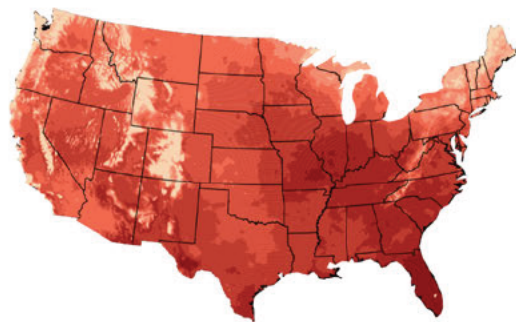
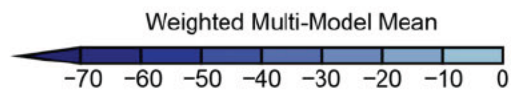
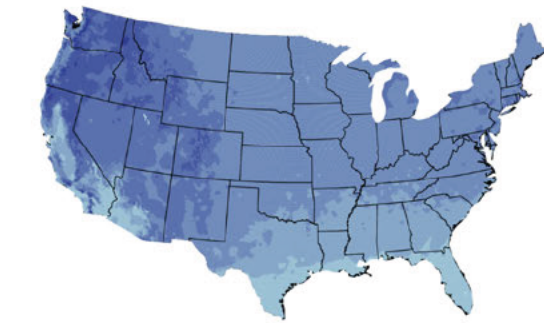
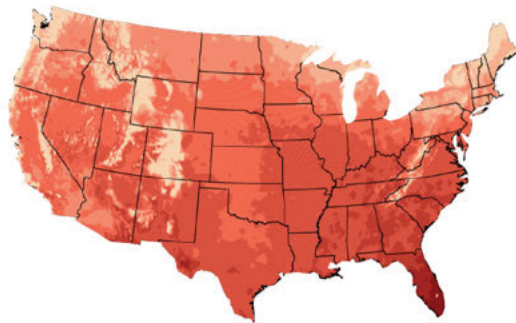
2 **Figure 6.7.** Projected changes in average annual temperatures (°F). Changes are the difference
 3 between the average for mid-century (2036–2065; top) or late-century (2071–2100, bottom) and
 4 the average for near-present (1976–2005). Each map depicts the weighted multimodel mean.
 5 Increases are statistically significant in all areas (that is, more than 50% of the models show a
 6 statistically significant change, and more than 67% agree on the sign of the change; Sun et al.
 7 2015). (Figure source: CICS-NC / NOAA/NCEI).



1
 2 **Figure 6.8.** Projected changes in the coldest and warmest daily temperatures (°F) of the year in
 3 the contiguous United States. Changes are the difference between the average for mid-century
 4 (2036–2065) and the average for near-present (1976–2005) under RCP8.5. Maps in the top row
 5 depict the weighted multimodel mean whereas maps on the bottom row depict the mean of the
 6 three warmest models (that is, the models with the largest temperature increase). Maps are
 7 derived from 32 climate model projections that were statistically downscaled using the Localized
 8 Constructed Analogs technique (Pierce et al. 2014). Increases are statistically significant in all
 9 areas (that is, more than 50% of the models show a statistically significant change, and more than
 10 67% agree on the sign of the change; Sun et al. 2015). (Figure source: CICS-NC /
 11 NOAA/NCEI).

Projected Change in Number of Days Above 90°F
Mid 21st Century, Higher Scenario (RCP8.5)

Projected Change in Number of Days Below 32°F
Mid 21st Century, Higher Scenario (RCP8.5)



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Figure 6.9. Projected changes in the number of days per year with a maximum temperature above 90°F and a minimum temperature below 32°F in the contiguous United States. Changes are the difference between the average for mid-century (2036–2065) and the average for near-present (1976–2005) under RCP8.5. Maps in the top row depict the weighted multimodel mean whereas maps on the bottom row depict the mean of the three warmest models (that is, the models with the largest temperature increase). Maps are derived from 32 climate model projections that were statistically downscaled using the Localized Constructed Analogs technique (Pierce et al. 2014). Changes are statistically significant in all areas (that is, more than 50% of the models show a statistically significant change, and more than 67% agree on the sign of the change; Sun et al. 2015). (Figure source: CICS-NC / NOAA/NCEI).

1 **REFERENCES**

- 2 Abatzoglou, J.T. and K.T. Redmond, 2007: Asymmetry between trends in spring and autumn
3 temperature and circulation regimes over western North America. *Geophysical Research*
4 *Letters*, **34**, L18808. <http://dx.doi.org/10.1029/2007GL030891>
- 5 Angéllil, O., D. Stone, M. Wehner, C.J. Paciorek, H. Krishnan, and W. Collins, 2017: An
6 independent assessment of anthropogenic attribution statements for recent extreme
7 temperature and rainfall events. *Journal of Climate*, **30**, 5-16. [http://dx.doi.org/10.1175/JCLI-](http://dx.doi.org/10.1175/JCLI-D-16-0077.1)
8 [D-16-0077.1](http://dx.doi.org/10.1175/JCLI-D-16-0077.1)
- 9 Bindoff, N.L., P.A. Stott, K.M. AchutaRao, M.R. Allen, N. Gillett, D. Gutzler, K. Hansingo, G.
10 Hegerl, Y. Hu, S. Jain, I.I. Mokhov, J. Overland, J. Perlwitz, R. Sebbari, and X. Zhang, 2013:
11 Detection and attribution of climate change: From global to regional. *Climate Change 2013:*
12 *The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report*
13 *of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M.
14 Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds.
15 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 867–
16 952. <http://www.climatechange2013.org/report/full-report/>
- 17 Bonfils, C., P.B. Duffy, B.D. Santer, T.M.L. Wigley, D.B. Lobell, T.J. Phillips, and C.
18 Doutriaux, 2008: Identification of external influences on temperatures in California. *Climatic*
19 *Change*, **87**, 43-55. <http://dx.doi.org/10.1007/s10584-007-9374-9>
- 20 Cattiaux, J. and P. Yiou, 2013: U.S. heat waves of spring and summer 2012 from the flow
21 analogue perspective [in "Explaining Extreme Events of 2012 from a Climate Perspective"].
22 *Bulletin of the American Meteorological Society*, **94** (9), S10-S13.
23 <http://dx.doi.org/10.1175/BAMS-D-13-00085.1>
- 24 CCSP, 2006: *Temperature Trends in the Lower Atmosphere: Steps for Understanding and*
25 *Reconciling Differences. A Report by the U.S. Climate Change Science Program and the*
26 *Subcommittee on Global Change Research*. Karl, T.R., S.J. Hassol, C.D. Miller, and W.L.
27 Murray (Eds.). National Oceanic and Atmospheric Administration, Washington, D.C., 164
28 pp. [http://www.globalchange.gov/browse/reports/sap-11-temperature-trends-lower-](http://www.globalchange.gov/browse/reports/sap-11-temperature-trends-lower-atmosphere-steps-understanding-reconciling)
29 [atmosphere-steps-understanding-reconciling](http://www.globalchange.gov/browse/reports/sap-11-temperature-trends-lower-atmosphere-steps-understanding-reconciling)
- 30 CCSP, 2008: *Weather and Climate Extremes in a Changing Climate - Regions of Focus - North*
31 *America, Hawaii, Caribbean, and U.S. Pacific Islands. A Report by the U.S. Climate Change*
32 *Science Program and the Subcommittee on Global Change Research*. Karl, T.R., G.A.
33 Meehl, C.D. Miller, S.J. Hassol, A.M. Waple, and W.L. Murray, Eds. Department of
34 Commerce, NOAA's National Climatic Data Center, Washington, D.C., 164 pp.
35 <http://downloads.globalchange.gov/sap/sap3-3/sap3-3-final-all.pdf>

- 1 Christidis, N., P.A. Stott, F.W. Zwiers, H. Shiogama, and T. Nozawa, 2010: Probabilistic
2 estimates of recent changes in temperature: A multi-scale attribution analysis. *Climate*
3 *Dynamics*, **34**, 1139-1156. <http://dx.doi.org/10.1007/s00382-009-0615-7>
- 4 Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J.
5 Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver, and M. Wehner,
6 2013: Long-term climate change: Projections, commitments and irreversibility. *Climate*
7 *Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth*
8 *Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D.
9 Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and
10 P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New
11 York, NY, USA, 1029–1136. <http://www.climatechange2013.org/report/full-report/>
- 12 Diffenbaugh, N.S. and M. Scherer, 2013: Likelihood of July 2012 U.S. temperatures in pre-
13 industrial and current forcing regimes [in "Explaining Extreme Events of 2013 from a
14 Climate Perspective"]. *Bulletin of the American Meteorological Society*, **94** (9), S6-S9.
15 <http://dx.doi.org/10.1175/BAMS-D-13-00085.1>
- 16 Dole, R., M. Hoerling, A. Kumar, J. Eischeid, J. Perlwitz, X.-W. Quan, G. Kiladis, R. Webb, D.
17 Murray, M. Chen, K. Wolter, and T. Zhang, 2014: The making of an extreme event: Putting
18 the pieces together. *Bulletin of the American Meteorological Society*, **95**, 427-440.
19 <http://dx.doi.org/10.1175/BAMS-D-12-00069.1>
- 20 Donat, M.G., A.D. King, J.T. Overpeck, L.V. Alexander, I. Durre, and D.J. Karoly, 2016:
21 Extraordinary heat during the 1930s US Dust Bowl and associated large-scale conditions.
22 *Climate Dynamics*, **46**, 413-426. <http://dx.doi.org/10.1007/s00382-015-2590-5>
- 23 Fischer, E.M., U. Beyerle, and R. Knutti, 2013: Robust spatially aggregated projections of
24 climate extremes. *Nature Climate Change*, **3**, 1033-1038.
25 <http://dx.doi.org/10.1038/nclimate2051>
- 26 Goldstein, A.H., C.D. Koven, C.L. Heald, and I.Y. Fung, 2009: Biogenic carbon and
27 anthropogenic pollutants combine to form a cooling haze over the southeastern United States.
28 *Proceedings of the National Academy of Sciences*, **106**, 8835-8840.
29 <http://dx.doi.org/10.1073/pnas.0904128106>
- 30 Hoerling, M., M. Chen, R. Dole, J. Eischeid, A. Kumar, J.W. Nielsen-Gammon, P. Pegion, J.
31 Perlwitz, X.-W. Quan, and T. Zhang, 2013: Anatomy of an extreme event. *Journal of*
32 *Climate*, **26**, 2811–2832. <http://dx.doi.org/10.1175/JCLI-D-12-00270.1>
- 33 Huang, B., V.F. Banzon, E. Freeman, J. Lawrimore, W. Liu, T.C. Peterson, T.M. Smith, P.W.
34 Thorne, S.D. Woodruff, and H.-M. Zhang, 2015: Extended Reconstructed Sea Surface

- 1 Temperature Version 4 (ERSST.v4). Part I: Upgrades and intercomparisons. *Journal of*
2 *Climate*, **28**, 911-930. <http://dx.doi.org/10.1175/JCLI-D-14-00006.1>
- 3 IPCC, 2012: Managing the Risks of Extreme Events and Disasters to Advance Climate Change
4 Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on
5 Climate Change. Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D.
6 Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (Eds.).
7 Cambridge University Press, Cambridge, UK and New York, NY. 582 pp. [http://ipcc-](http://ipcc-wg2.gov/SREX/images/uploads/SREX-All_FINAL.pdf)
8 [wg2.gov/SREX/images/uploads/SREX-All_FINAL.pdf](http://ipcc-wg2.gov/SREX/images/uploads/SREX-All_FINAL.pdf)
- 9 Jeon, S., C.J. Paciorek, and M.F. Wehner, 2016: Quantile-based bias correction and uncertainty
10 quantification of extreme event attribution statements. *Weather and Climate Extremes*, **12**,
11 24-32. <http://dx.doi.org/10.1016/j.wace.2016.02.001>
- 12 Karl, T.R., J.T. Melillo, and T.C. Peterson, eds., 2009: *Global Climate Change Impacts in the*
13 *United States*. ed. Karl, T.R., J.T. Melillo, and T.C. Peterson. Cambridge University Press:
14 New York, NY, 189 pp. [http://downloads.globalchange.gov/usimpacts/pdfs/climate-impacts-](http://downloads.globalchange.gov/usimpacts/pdfs/climate-impacts-report.pdf)
15 [report.pdf](http://downloads.globalchange.gov/usimpacts/pdfs/climate-impacts-report.pdf)
- 16 Knutson, T.R., F. Zeng, and A.T. Wittenberg, 2013: Multimodel assessment of regional surface
17 temperature trends: CMIP3 and CMIP5 twentieth-century simulations. *Journal of Climate*,
18 **26**, 8709-8743. <http://dx.doi.org/10.1175/JCLI-D-12-00567.1>
- 19 Knutson, T.R., F. Zeng, and A.T. Wittenberg, 2013: The extreme March-May 2012 warm
20 anomaly over the eastern United States: Global context and multimodel trend analysis [in
21 "Explaining Extreme Events of 2012 from a Climate Perspective"]. *Bulletin of the American*
22 *Meteorological Society*, **94** (9), S13-S17. <http://dx.doi.org/10.1175/BAMS-D-13-00085.1>
- 23 Leibensperger, E.M., L.J. Mickley, D.J. Jacob, W.T. Chen, J.H. Seinfeld, A. Nenes, P.J. Adams,
24 D.G. Streets, N. Kumar, and D. Rind, 2012: Climatic effects of 1950-2050 changes in US
25 anthropogenic aerosols – Part 1: Aerosol trends and radiative forcing. *Atmospheric Chemistry*
26 *and Physics* **12**, 3333-3348. <http://dx.doi.org/10.5194/acp-12-3333-2012>
- 27 Leibensperger, E.M., L.J. Mickley, D.J. Jacob, W.T. Chen, J.H. Seinfeld, A. Nenes, P.J. Adams,
28 D.G. Streets, N. Kumar, and D. Rind, 2012: Climatic effects of 1950–2050 changes in US
29 anthropogenic aerosols – Part 2: Climate response. *Atmospheric Chemistry and Physics*, **12**,
30 3349-3362. <http://dx.doi.org/10.5194/acp-12-3349-2012>
- 31 Mascioli, N.R., M. Previdi, A.M. Fiore, and M. Ting, 2017: Timing and seasonality of the United
32 States ‘warming hole’. *Environmental Research Letters*, **12**, 034008.
33 <http://dx.doi.org/10.1088/1748-9326/aa5ef4>

- 1 Mazdiyasni, O. and A. AghaKouchak, 2015: Substantial increase in concurrent droughts and
2 heatwaves in the United States. *Proceedings of the National Academy of Sciences*, **112**,
3 11484-11489. <http://dx.doi.org/10.1073/pnas.1422945112>
- 4 Mears, C.A. and F.J. Wentz, 2016: Sensitivity of satellite-derived tropospheric temperature
5 trends to the diurnal cycle adjustment. *Journal of Climate*, **29**, 3629-3646.
6 <http://dx.doi.org/10.1175/JCLI-D-15-0744.1>
- 7 Meehl, G.A., J.M. Arblaster, and G. Branstator, 2012: Mechanisms contributing to the warming
8 hole and the consequent US east–west differential of heat extremes. *Journal of Climate*, **25**,
9 6394-6408. <http://dx.doi.org/10.1175/JCLI-D-11-00655.1>
- 10 Meehl, G.A., C. Tebaldi, and D. Adams-Smith, 2016: US daily temperature records past, present,
11 and future. *Proceedings of the National Academy of Sciences*, **113**, 13977-13982.
12 <http://dx.doi.org/10.1073/pnas.1606117113>
- 13 Melillo, J.M., T.C. Richmond, and G.W. Yohe, eds., 2014: *Climate Change Impacts in the*
14 *United States: The Third National Climate Assessment*. U.S. Global Change Research
15 Program: Washington, DC, 842 pp. <http://dx.doi.org/10.7930/J0Z31WJ2>
- 16 Menne, M.J., I. Durre, R.S. Vose, B.E. Gleason, and T.G. Houston, 2012: An overview of the
17 global historical climatology network-daily database. *Journal of Atmospheric and Oceanic*
18 *Technology*, **29**, 897-910. <http://dx.doi.org/10.1175/JTECH-D-11-00103.1>
- 19 Min, S.-K., X. Zhang, F. Zwiers, H. Shiogama, Y.-S. Tung, and M. Wehner, 2013: Multimodel
20 detection and attribution of extreme temperature changes. *Journal of Climate*, **26**, 7430-7451.
21 <http://dx.doi.org/10.1175/JCLI-D-12-00551.1>
- 22 Mueller, N.D., E.E. Butler, K.A. McKinnon, A. Rhines, M. Tingley, N.M. Holbrook, and P.
23 Huybers, 2016: Cooling of U.S. Midwest summer temperature extremes from cropland
24 intensification. *Nature Climate Change*, **6**, 317-322, doi:10.1038/nclimate2825.
- 25 PAGES 2K Consortium, 2013: Continental-scale temperature variability during the past two
26 millennia. *Nature Geoscience*, **6**, 339-346. <http://dx.doi.org/10.1038/ngeo1797>
- 27 Pan, Z., X. Liu, S. Kumar, Z. Gao, and J. Kinter, 2013: Intermodel variability and mechanism
28 attribution of central and southeastern U.S. anomalous cooling in the twentieth century as
29 simulated by CMIP5 models. *Journal of Climate*, **26**, 6215-6237.
30 <http://dx.doi.org/10.1175/JCLI-D-12-00559.1>
- 31 Peterson, T.C., R.R. Heim, R. Hirsch, D.P. Kaiser, H. Brooks, N.S. Diffenbaugh, R.M. Dole, J.P.
32 Giovannetone, K. Guirguis, T.R. Karl, R.W. Katz, K. Kunkel, D. Lettenmaier, G.J. McCabe,
33 C.J. Paciorek, K.R. Ryberg, S. Schubert, V.B.S. Silva, B.C. Stewart, A.V. Vecchia, G.
34 Villarini, R.S. Vose, J. Walsh, M. Wehner, D. Wolock, K. Wolter, C.A. Woodhouse, and D.

- 1 Wuebbles, 2013: Monitoring and understanding changes in heat waves, cold waves, floods
2 and droughts in the United States: State of knowledge. *Bulletin of the American*
3 *Meteorological Society*, **94**, 821-834. <http://dx.doi.org/10.1175/BAMS-D-12-00066.1>
- 4 Pierce, D.W., T.P. Barnett, B.D. Santer, and P.J. Gleckler, 2009: Selecting global climate models
5 for regional climate change studies. *Proceedings of the National Academy of Sciences*, **106**,
6 8441-8446. <http://dx.doi.org/10.1073/pnas.0900094106>
- 7 Pierce, D.W., D.R. Cayan, and B.L. Thrasher, 2014: Statistical downscaling using Localized
8 Constructed Analogs (LOCA). *Journal of Hydrometeorology*, **15**, 2558-2585.
9 <http://dx.doi.org/10.1175/jhm-d-14-0082.1>
- 10 Po-Chedley, S., T.J. Thorsen, and Q. Fu, 2015: Removing diurnal cycle contamination in
11 satellite-derived tropospheric temperatures: Understanding tropical tropospheric trend
12 discrepancies. *Journal of Climate*, **28**, 2274-2290. [http://dx.doi.org/10.1175/JCLI-D-13-](http://dx.doi.org/10.1175/JCLI-D-13-00767.1)
13 [00767.1](http://dx.doi.org/10.1175/JCLI-D-13-00767.1)
- 14 Rupp, D.E., P.W. Mote, N. Massey, C.J. Rye, R. Jones, and M.R. Allen, 2012: Did human
15 influence on climate make the 2011 Texas drought more probable? [in Explaining Extreme
16 Events of 2011 from a Climate Perspective]. *Bulletin of the American Meteorological*
17 *Society*, **93**, 1052-1054. <http://dx.doi.org/10.1175/BAMS-D-12-00021.1>
- 18 Russo, S., A. Dosio, R.G. Graversen, J. Sillmann, H. Carrao, M.B. Dunbar, A. Singleton, P.
19 Montagna, P. Barbola, and J.V. Vogt, 2014: Magnitude of extreme heat waves in present
20 climate and their projection in a warming world. *Journal of Geophysical Research:*
21 *Atmospheres*, **119**, 12,500-12,512. <http://dx.doi.org/10.1002/2014JD022098>
- 22 Seager, R., M. Hoerling, D.S. Siegfried, h. Wang, B. Lyon, A. Kumar, J. Nakamura, and N.
23 Henderson, 2014: Causes and Predictability of the 2011-14 California Drought. National
24 Oceanic and Atmospheric Administration, Drought Task Force Narrative Team, 40 pp.
25 <http://dx.doi.org/10.7289/V58K771F>
- 26 Sillmann, J., V.V. Kharin, F.W. Zwiers, X. Zhang, and D. Bronaugh, 2013: Climate extremes
27 indices in the CMIP5 multimodel ensemble: Part 2. Future climate projections. *Journal of*
28 *Geophysical Research: Atmospheres*, **118**, 2473-2493. <http://dx.doi.org/10.1002/jgrd.50188>
- 29 Smith, T.T., B.F. Zaitchik, and J.M. Gohlke, 2013: Heat waves in the United States: Definitions,
30 patterns and trends. *Climatic Change*, **118**, 811-825. [http://dx.doi.org/10.1007/s10584-012-](http://dx.doi.org/10.1007/s10584-012-0659-2)
31 [0659-2](http://dx.doi.org/10.1007/s10584-012-0659-2)
- 32 Spencer, R.W., J.R. Christy, and W.D. Braswell, 2017: UAH Version 6 global satellite
33 temperature products: Methodology and results. *Asia-Pacific Journal of Atmospheric*
34 *Sciences*, **53**, 121-130. <http://dx.doi.org/10.1007/s13143-017-0010-y>

- 1 Sun, L., K.E. Kunkel, L.E. Stevens, A. Buddenberg, J.G. Dobson, and D.R. Easterling, 2015:
2 Regional Surface Climate Conditions in CMIP3 and CMIP5 for the United States:
3 Differences, Similarities, and Implications for the U.S. National Climate Assessment.
4 National Oceanic and Atmospheric Administration, National Environmental Satellite, Data,
5 and Information Service, 111 pp. <http://dx.doi.org/10.7289/V5RB72KG>
- 6 Thorne, P.W., M.G. Donat, R.J.H. Dunn, C.N. Williams, L.V. Alexander, J. Caesar, I. Durre, I.
7 Harris, Z. Hausfather, P.D. Jones, M.J. Menne, R. Rohde, R.S. Vose, R. Davy, A.M.G.
8 Klein-Tank, J.H. Lawrimore, T.C. Peterson, and J.J. Rennie, 2016: Reassessing changes in
9 diurnal temperature range: Intercomparison and evaluation of existing global data set
10 estimates. *Journal of Geophysical Research: Atmospheres*, **121**, 5138-5158.
11 <http://dx.doi.org/10.1002/2015JD024584>
- 12 Trenary, L., T. DelSole, B. Doty, and M.K. Tippett, 2015: Was the cold eastern US Winter of
13 2014 due to increased variability? *Bulletin of the American Meteorological Society*, **96 (12)**,
14 S15-S19. <http://dx.doi.org/10.1175/bams-d-15-00138.1>
- 15 Trouet, V., H.F. Diaz, E.R. Wahl, A.E. Viau, R. Graham, N. Graham, and E.R. Cook, 2013: A
16 1500-year reconstruction of annual mean temperature for temperate North America on
17 decadal-to-multidecadal time scales. *Environmental Research Letters*, **8**, 024008.
18 <http://dx.doi.org/10.1088/1748-9326/8/2/024008>
- 19 Vose, R.S., D. Arndt, V.F. Banzon, D.R. Easterling, B. Gleason, B. Huang, E. Kearns, J.H.
20 Lawrimore, M.J. Menne, T.C. Peterson, R.W. Reynolds, T.M. Smith, C.N. Williams, and
21 D.L. Wuertz, 2012: NOAA's merged land-ocean surface temperature analysis. *Bulletin of the*
22 *American Meteorological Society*, **93**, 1677-1685. [http://dx.doi.org/10.1175/BAMS-D-11-](http://dx.doi.org/10.1175/BAMS-D-11-00241.1)
23 [00241.1](http://dx.doi.org/10.1175/BAMS-D-11-00241.1)
- 24 Vose, R.S., S. Applequist, M. Squires, I. Durre, M.J. Menne, C.N. Williams, Jr., C. Fenimore, K.
25 Gleason, and D. Arndt, 2014: Improved historical temperature and precipitation time series
26 for U.S. climate divisions. *Journal of Applied Meteorology and Climatology*, **53**, 1232-1251.
27 <http://dx.doi.org/10.1175/JAMC-D-13-0248.1>
- 28 Vose, R.S., S. Applequist, M. Squires, I. Durre, M.J. Menne, C.N. Williams, C. Fenimore, K.
29 Gleason, and D. Arndt, 2017: Improved historical temperature and precipitation time series
30 for Alaska climate divisions. *Journal of Service Climatology (in press)*
- 31 Wahl, E.R. and J.E. Smerdon, 2012: Comparative performance of paleoclimate field and index
32 reconstructions derived from climate proxies and noise-only predictors. *Geophysical*
33 *Research Letters*, **39**, L06703. <http://dx.doi.org/10.1029/2012GL051086>
- 34 Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, P. Thorne, R. Vose, M.
35 Wehner, J. Willis, D. Anderson, S. Doney, R. Feely, P. Hennon, V. Kharin, T. Knutson, F.

- 1 Landerer, T. Lenton, J. Kennedy, and R. Somerville, 2014: Ch. 2: Our changing climate.
2 *Climate Change Impacts in the United States: The Third National Climate Assessment*.
3 Melillo, J.M., T.C. Richmond, and G.W. Yohe, Eds. U.S. Global Change Research Program,
4 Washington, D.C., 19-67. <http://dx.doi.org/10.7930/J0KW5CXT>
- 5 Wolter, K., J.K. Eischeid, X.-W. Quan, T.N. Chase, M. Hoerling, R.M. Dole, G.J.V.
6 Oldenborgh, and J.E. Walsh, 2015: How unusual was the cold winter of 2013/14 in the
7 Upper Midwest? [in "Explaining Extreme Events of 2014 from a Climate Perspective"].
8 *Bulletin of the American Meteorological Society*, **96 (12)**, S10-S14.
9 <http://dx.doi.org/10.1175/bams-d-15-00126.1>
- 10 Wuebbles, D., G. Meehl, K. Hayhoe, T.R. Karl, K. Kunkel, B. Santer, M. Wehner, B. Colle,
11 E.M. Fischer, R. Fu, A. Goodman, E. Janssen, V. Kharin, H. Lee, W. Li, L.N. Long, S.C.
12 Olsen, Z. Pan, A. Seth, J. Sheffield, and L. Sun, 2014: CMIP5 climate model analyses:
13 Climate extremes in the United States. *Bulletin of the American Meteorological Society*, **95**,
14 571-583. <http://dx.doi.org/10.1175/BAMS-D-12-00172.1>
- 15 Xu, L., H. Guo, C.M. Boyd, M. Klein, A. Bougiatioti, K.M. Cerully, J.R. Hite, G. Isaacman-
16 VanWertz, N.M. Kreisberg, C. Knote, K. Olson, A. Koss, A.H. Goldstein, S.V. Hering, J. de
17 Gouw, K. Baumann, S.-H. Lee, A. Nenes, R.J. Weber, and N.L. Ng, 2015: Effects of
18 anthropogenic emissions on aerosol formation from isoprene and monoterpenes in the
19 southeastern United States. *Proceedings of the National Academy of Sciences*, **112**, 37-42.
20 <http://dx.doi.org/10.1073/pnas.1417609112>
- 21 Yu, S., K. Alapaty, R. Mathur, J. Pleim, Y. Zhang, C. Nolte, B. Eder, K. Foley, and T.
22 Nagashima, 2014: Attribution of the United States "warming hole": Aerosol indirect effect
23 and precipitable water vapor. *Scientific Reports*, **4**, 6929. <http://dx.doi.org/10.1038/srep06929>
- 24 Zhang, X., L. Alexander, G.C. Hegerl, P. Jones, A.K. Tank, T.C. Peterson, B. Trewin, and F.W.
25 Zwiers, 2011: Indices for monitoring changes in extremes based on daily temperature and
26 precipitation data. *Wiley Interdisciplinary Reviews: Climate Change*, **2**, 851-870.
27 <http://dx.doi.org/10.1002/wcc.147>
- 28 Zou, C.-Z. and J. Li, 2014: NOAA MSU Mean Layer Temperature. National Oceanic and
29 Atmospheric Administration, Center for Satellite Applications and Research, 35 pp.
30 [http://www.star.nesdis.noaa.gov/smcd/emb/mscat/documents/MSU_TCDR_CATBD_Zou_Li](http://www.star.nesdis.noaa.gov/smcd/emb/mscat/documents/MSU_TCDR_CATBD_Zou_Li.pdf)
31 .pdf
- 32 Zwiers, F.W., X.B. Zhang, and Y. Feng, 2011: Anthropogenic influence on long return period
33 daily temperature extremes at regional scales. *Journal of Climate*, **24**, 881-892.
34 <http://dx.doi.org/10.1175/2010jcli3908.1>

1 **7. Precipitation Change in the United States**

2 **KEY FINDINGS**

- 3 1. Annual precipitation has decreased in much of the West, Southwest, and Southeast and
4 increased in most of the Northern and Southern Plains, Midwest, and Northeast. A
5 national average increase of 4% in annual precipitation since 1901 is mostly a result of
6 large increases in the fall season. (*Medium confidence*)
- 7 2. Heavy precipitation events in most parts of the United States have increased in both
8 intensity and frequency since 1901 (*high confidence*). There are important regional
9 differences in trends, with the largest increases occurring in the northeastern United
10 States (*high confidence*). In particular, mesoscale convective systems (organized clusters
11 of thunderstorms)—the main mechanism for warm season precipitation in the central part
12 of the United States—have increased in occurrence and precipitation amounts since 1979
13 (*medium confidence*).
- 14 3. The frequency and intensity of heavy precipitation events are projected to continue to
15 increase over the 21st century (*high confidence*). Mesoscale convective systems in the
16 central United States, are expected to continue to increase in number and intensity in the
17 future (*medium confidence*). There are, however, important regional and seasonal
18 differences in projected changes in total precipitation: the northern United States,
19 including Alaska, is projected to receive more precipitation in the winter and spring, and
20 parts of the southwestern United States are projected to receive less precipitation in the
21 winter and spring (*medium confidence*).
- 22 4. Northern Hemisphere spring snow cover extent, North America maximum snow depth,
23 snow water equivalent in the western United States, and extreme snowfall years in the
24 southern and western United States have all declined, while extreme snowfall years in
25 parts of the northern United States have increased (*medium confidence*). Projections
26 indicate large declines in snowpack in the western United States and shifts to more
27 precipitation falling as rain than snow in the cold season in many parts of the central and
28 eastern United States (*high confidence*).

29 **Introduction**

30 Changes in precipitation are one of the most important potential outcomes of a warming world
31 because precipitation is integral to the very nature of society and ecosystems. These systems
32 have developed and adapted to the past envelope of precipitation variations. Any large changes
33 beyond the historical envelope may have profound societal and ecological impacts.

34 Historical variations in precipitation, as observed from both instrumental and proxy records,
35 establish the context around which future projected changes can be interpreted, because it is

1 within that context that systems have evolved. Long-term station observations from core climate
2 networks serve as a primary source to establish observed changes in both means and extremes.
3 Proxy records, which are used to reconstruct past climate conditions, are varied and include
4 sources such as tree ring and ice core data. Projected changes are examined using the Coupled
5 Model Intercomparison Project Phase 5 (CMIP5) suite of model simulations. They establish the
6 likelihood of distinct regional and seasonal patterns of change.

7 **7.1 Historical Changes**

8 **7.1.1 Mean Changes**

9 Annual precipitation averaged across the United States has increased approximately 4% over the
10 1901–2015 period, slightly less than the 5% increase reported in the Third National Climate
11 Assessment (NCA3) over the 1901–2012 period (Walsh et al. 2014). There continue to be
12 important regional and seasonal differences in precipitation changes (Figure 7.1). Seasonally,
13 national increases are largest in the fall, while little change is observed for winter. Regional
14 differences are apparent, as the Northeast, Midwest, and Great Plains have had increases while
15 parts of the Southwest and Southeast have had decreases. The slight decrease in the change in
16 annual precipitation across the United States since NCA3 appears to be the result of the recent
17 lingering droughts in the western and southwestern United States (NOAA 2016a; Barnston and
18 Lyon 2016). However, the recent meteorological drought in California that began in late 2011
19 (Seager et al. 2015; NOAA 2016b) now appears to be largely over, due to the substantial
20 precipitation and snowpack the state received in the winter of 2016–2017. The year 2015 was the
21 third wettest on record, just behind 1973 and 1983 (all of which were years marked by El Niño
22 events). Interannual variability is substantial, as evidenced by large multiyear meteorological and
23 agricultural droughts in the 1930s and 1950s.

24 **[INSERT FIGURE 7.1 HERE]**

25 Changes in precipitation differ markedly across the seasons, as do regional patterns of increases
26 and decreases. For the contiguous United States, fall exhibits the largest (10%) and most
27 widespread increase, exceeding 15% in much of the Northern Great Plains, Southeast, and
28 Northeast. Winter average for the United States has the smallest increase (2%), with drying over
29 most of the western United States as well as parts of the Southeast. In particular, a reduction in
30 streamflow in the northwestern United States has been linked to a decrease in orographic
31 enhancement of precipitation since 1950 (Luce et al. 2013). Spring and summer have comparable
32 increases (about 3.5%) but substantially different patterns. In spring, the northern half of the
33 contiguous United States has become wetter, and the southern half has become drier. In summer,
34 there is a mixture of increases and decreases across the Nation. Alaska shows little change in
35 annual precipitation (+1.5%); however, in all seasons, central Alaska shows declines and the
36 panhandle shows increases. Hawai'i shows a decline of more than 15% in annual precipitation.

1 7.1.2 Snow

2 Changes in snow cover extent (SCE) in the Northern Hemisphere exhibit a strong seasonal
3 dependence (Vaughan et al. 2013). There has been little change in winter SCE since the 1960s
4 (when the first satellite records became available), while fall SCE has increased. However, the
5 decline in spring SCE is larger than the increase in fall and is due in part to higher temperatures
6 that shorten the time snow spends on the ground in the spring. This tendency is highlighted by
7 the recent occurrences of both unusually high and unusually low monthly (October–June) SCE
8 values, including the top 5 highest and top 5 lowest values in the 48 years of data. From 2010
9 onward, 7 of the 45 highest monthly SCE values occurred, all in the fall or winter (mostly in
10 November and December), while 9 of the 10 lowest May and June values occurred. This reflects
11 the trend toward earlier spring snowmelt, particularly at high latitudes (Kunkel et al. 2016). An
12 analysis of seasonal maximum snow depth for 1961–2015 over North America indicates a
13 statistically significant downward trend of 0.11 standardized anomalies per decade and a trend
14 toward the seasonal maximum snow depth occurring earlier—approximately one week earlier on
15 average since the 1960s (Kunkel et al. 2016). There has been a statistically significant decrease
16 over the period of 1930–2007 in the frequency of years with a large number of snowfall days
17 (years exceeding the 90th percentile) in the southern United States and the U.S. Pacific
18 Northwest and an increase in the northern United States (Kliver and Leathers 2015). In the snow
19 belts of the Great Lakes, lake effect snowfall has increased overall since the early 20th century
20 for Lakes Superior, Michigan-Huron, and Erie (Kunkel et al. 2010). However, individual studies
21 for Lakes Michigan (Bard and Kristovich 2012) and Ontario (Harnett et al. 2014) indicate that
22 this increase has not been continuous. In both cases, upward trends were observed till the
23 1970s/early 1980s. Since then, however, lake effect snowfall has decreased in these regions.
24 Lake effect snows along the Great Lakes are affected greatly by ice cover extent and lake water
25 temperatures. As ice cover diminishes in winter, the expectation is for more lake effect snow
26 until temperatures increase enough such that much of what now falls as snow instead falls as rain
27 (Wright et al. 2013; Vavrus et al. 2013).

28 End of season snow water equivalent (SWE)—especially important where water supply is
29 dominated by spring snow melt (for example, in much of the American West)—has declined
30 since 1980 in the western United States, based on analysis of in situ observations, and is
31 associated with springtime warming (Pederson et al. 2013). Satellite measurements of SWE
32 based on brightness temperature also show a decrease over this period (Gan et al. 2013). The
33 variability of western United States SWE is largely driven by the most extreme events, with the
34 top decile of events explaining 69% of the variability (Lute and Abatzoglou 2014). The recent
35 drought in the western United States was highlighted by the extremely dry 2014–2015 winter
36 that followed three previous dry winters. At Donner Summit, CA, (approximate elevation of
37 2,100 meters) in the Sierra Nevada Mountains, end-of-season SWE on April 1, 2015, was the
38 lowest on record, based on survey measurements back to 1910, at only 0.51 inches (1.3 cm), or
39 less than 2% of the long-term average. This followed the previous record low in 2014. The

1 estimated return period of this drought is at least 500 years based on paleoclimatic
2 reconstructions (Belmecheri et al. 2016).

3 **7.1.3 Observed changes in U.S. seasonal extreme precipitation.**

4 Extreme precipitation events occur when the air is nearly completely saturated. Hence, extreme
5 precipitation events are generally observed to increase in intensity by about 6% to 7% for each
6 degree Celsius of temperature increase, as dictated by the Clausius–Clapeyron relation. Figure
7 7.2 shows the observed change in the 20-year return value of the seasonal maximum 1-day
8 precipitation totals over the period 1948–2015. A mix of increases and decreases is shown, with
9 the Northwest showing very small changes in all seasons, the southern Great Plains showing a
10 large increase in winter, and the Southeast showing a large increase in the fall.

11 **[INSERT FIGURE 7.2 HERE]**

12 A U.S. index of extreme precipitation from NCA3 was updated (Figure 7.3) through 2016. This
13 is the number of 2-day precipitation events exceeding the threshold for a 5-year recurrence. The
14 values were calculated by first arithmetically averaging the station data for all stations within
15 each 1° by 1° latitude/longitude grid for each year and then averaging over the grid values across
16 CONUS for each year during the period of 1896–2015. The number of events has been well
17 above average for the last three decades. The slight drop from 2006–2010 to 2011–2016 reflects
18 a below average number during the widespread severe meteorological drought year of 2012,
19 while the other years in this pentad were well above average. The index value for 2015 was 80%
20 above the 1901–1960 reference period average and the third highest value in the 120 years of
21 record (after 1998 and 2008).

22 **[INSERT FIGURE 7.3 HERE]**

23 Maximum daily precipitation totals were calculated for consecutive 5-year blocks from 1901
24 (1901–1905, 1906–1910, 1911–1915, ..., 2011–2016) for individual long-term stations. For each
25 5-year block, these values were aggregated to the regional scale by first arithmetically averaging
26 the station 5-year maximum for all stations within each 2° by 2° latitude/longitude grid and then
27 averaging across all grids within each region to create a regional time series. Finally, a trend was
28 computed for the resulting regional time series. The difference between these two periods
29 (Figure 7.4, upper left panel) indicates substantial increases over the eastern United States,
30 particularly the northeastern United States with an increase of 27% since 1901. The increases are
31 much smaller over the western United States, with the southwestern and northwestern United
32 States showing little increase.

33 Another index of extreme precipitation from NCA3 (the total precipitation falling in the top 1%
34 of all days with precipitation) was updated through 2016 (Figure 7.4, upper right panel). This
35 analysis is for 1958–2016. There are increases in all regions, with the largest increases again in
36 the northeastern United States. There are some changes in the values compared to NCA3, with

1 small increases in some regions such as the Midwest and Southwest and small decreases in
2 others such as the Northeast, but the overall picture of changes is the same.

3 The national results shown in Figure 7.3 were disaggregated into regional values for two periods:
4 1901–2016 (Figure 7.4, lower left panel) and 1958–2016 (Figure 7.4, lower right panel) for
5 comparison with Figure 7.4, upper right panel. As with the other metrics, there are large
6 increases over the eastern half of the United States while the increases in the western United
7 States are smaller and there are actually small decreases in the Southwest.

8 There are differences in the magnitude of changes among the four different regional metrics in
9 Figure 7.4, but the overall picture is the same: large increases in the eastern half of the United
10 States and smaller increases, or slight decreases, in the western United States.

11 **[INSERT FIGURE 7.4 HERE]**

12 **7.1.4 Extratropical Cyclones and Mesoscale Convective Systems**

13 As described in Chapter 9: Extreme Storms, there is uncertainty about future changes in winter
14 extratropical cyclones (ETCs) (Colle et al. 2013). Thus, the potential effects on winter extreme
15 precipitation events is also uncertain. Summertime ETC activity across North America has
16 decreased since 1979, with a reduction of more than 35% in the number of strong summertime
17 ETCs (Chang et al. 2016). Most climate models simulate little change over this same historical
18 period, but they project a decrease in summer ETC activity during the remainder of the 21st
19 century (Chang et al. 2016). This is potentially relevant to extreme precipitation in the
20 northeastern quadrant of the United States because a large percentage of the extreme
21 precipitation events in this region are caused by ETCs and their associated fronts (Kunkel et al.
22 2012). This suggests that in the future there may be fewer opportunities in the summer for
23 extreme precipitation, although increases in water vapor are likely to overcompensate for any
24 decreases in ETCs by increasing the likelihood that an ETC will produce excessive rainfall
25 amounts. A very idealized set of climate simulations (Pfahl et al. 2015) suggests that substantial
26 projected warming will lead to a decrease in the number of ETCs but an increase in the intensity
27 of the strongest ETCs. One factor potentially causing this model ETC intensification is an
28 increase in latent heat release in these storms related to a moister atmosphere. Because of the
29 idealized nature of these simulations, the implications of these results for the real earth–
30 atmosphere system is uncertain. However, the increased latent heat mechanism is likely to occur
31 given the high confidence in a future moister atmosphere. For eastern North America, CMIP5
32 simulations of the future indicate an increase in strong ETCs (Colle et al. 2013). Thus, it is
33 possible that the most extreme precipitation events associated with ETCs may increase in the
34 future.

35 Mesoscale convective systems (MCSs), which contribute substantially to warm season
36 precipitation in the tropics and subtropics (Nesbitt et al. 2006), account for about half of rainfall
37 in the central United States (Frisch et al. 1986). Schumacher and Johnson (2006) reported that

1 74% of all warm season extreme rain events over the eastern two-thirds of the United States
2 during the period 1999–2003 were associated with an MCS. Feng et al. (2016) found that large
3 regions of the central United States experienced statistically significant upward trends in April–
4 June MCS rainfall of 0.4–0.8 mm per day (approximately 20%–40%) per decade from 1979 to
5 2014. They further found upward trends in MCS frequency of occurrence, lifetime, and
6 precipitation amount, which they attribute to an enhanced west-to-east pressure gradient
7 (enhanced Great Plains Low-Level Jet) and enhanced specific humidity throughout the eastern
8 Great Plains.

9 **7.1.5 Detection and Attribution**

10 **TRENDS**

11 Detectability of trends (compared to internal variability) for a number of precipitation metrics
12 over the continental United States has been examined; however, trends identified for the U.S.
13 regions have not been clearly attributed to anthropogenic forcing (Anderson et al. 2015;
14 Easterling et al. 2016). One study concluded that increasing precipitation trends in some north-
15 central U.S. regions and the extreme annual anomalies there in 2013 were at least partly
16 attributable to the combination of anthropogenic and natural forcing (Knutson et al. 2014).

17 There is *medium confidence* that anthropogenic forcing has contributed to global-scale
18 intensification of heavy precipitation over land regions with sufficient data coverage (Bindoff et
19 al. 2013). Global changes in extreme precipitation have been attributed to anthropogenically
20 forced climate change (Min et al. 2011, 2013), including annual maximum 1-day and 5-day
21 accumulated precipitation over northern hemisphere land regions and (relevant to this report)
22 over the North American continent (Zhang et al. 2013). Although the United States was not
23 separately assessed, the parts of North America with sufficient data for analysis included the
24 continental United States and parts of southern Canada, Mexico, and Central America. Since the
25 covered region was predominantly over the United States, these detection/attribution findings are
26 applicable to the continental United States.

27 Analyses of precipitation extreme changes over the United States by region (20-year return
28 values of seasonal daily precipitation over 1948–2015, Figure 7.2) show statistically significant
29 increases consistent with theoretical expectations and previous analyses (Westra et al. 2013).
30 Further, a significant increase in the area affected by precipitation extremes over North America
31 has also been detected (Dittus et al. 2015). There is likely an anthropogenic influence on the
32 upward trend in heavy precipitation (Dittus et al. 2016), although models underestimate the
33 magnitude of the trend. Extreme rainfall from U.S. landfalling tropical cyclones has been higher
34 in recent years (1994–2008) than the long-term historical average, even accounting for temporal
35 changes in storm frequency (Kunkel et al. 2010).

36 Based on current evidence, it is concluded that detectable but not attributable increases in mean
37 precipitation have occurred over parts of the central United States. Formal detection-attribution

1 studies indicate a human contribution to extreme precipitation increases over the continental
2 United States, but confidence is *low* based on those studies alone due to the short observational
3 period, high natural variability, and model uncertainty.

4 In summary, based on available studies, it is concluded that for the continental United States
5 there is *high confidence* in the detection of extreme precipitation increases, while there is *low*
6 *confidence* in attributing the extreme precipitation changes purely to anthropogenic forcing.
7 There is stronger evidence for a human contribution (*medium confidence*) when taking into
8 account process-based understanding (increased water vapor in a warmer atmosphere), evidence
9 from weather and climate models, and trends in other parts of the world.

10 **EVENT ATTRIBUTION**

11 A number of recent heavy precipitation events have been examined to determine the degree to
12 which their occurrence and severity can be attributed to human-induced climate change. Table
13 7.1 summarizes available attribution statements for recent extreme U.S. precipitation events.
14 Seasonal and annual precipitation extremes occurring in the north-central and eastern U.S.
15 regions in 2013 were examined for evidence of an anthropogenic influence on their occurrence
16 (Knutson et al. 2014). Increasing trends in annual precipitation were detected in the northern tier
17 of states, March–May precipitation in the upper Midwest, and June–August precipitation in the
18 eastern United States since 1900. These trends are attributed to external forcing (anthropogenic
19 and natural) but could not be directly attributed to anthropogenic forcing alone. However, based
20 on this analysis, it is concluded that the probability of these kinds of extremes has increased due
21 to anthropogenic forcing.

22 The human influence on individual storms has been investigated with conflicting results. For
23 example, in examining the attribution of the 2013 Colorado floods, one study finds that despite
24 the expected human-induced increase in available moisture, the GEOS-5 model produces fewer
25 extreme storms in the 1983–2012 period compared to the 1871–1900 period in Colorado during
26 the fall season; the study attributes that behavior to changes in the large-scale circulation
27 (Hoerling et al. 2014). However, another study finds that such coarse models cannot produce the
28 observed magnitude of precipitation due to resolution constraints (Pall et al. 2017). Based on a
29 highly conditional set of hindcast simulations imposing the large-scale meteorology and a
30 substantial increase in both the probability and magnitude of the observed precipitation
31 accumulation magnitudes in that particular meteorological situation, the study could not address
32 the question of whether such situations have become more or less probable. Extreme
33 precipitation event attribution is inherently limited by the rarity of the necessary meteorological
34 conditions and the limited number of model simulations that can be performed to examine rare
35 events. This remains an open and active area of research. However, based on these two studies,
36 the anthropogenic contribution to the 2013 Colorado heavy rainfall-flood event is unclear.

37 **[INSERT TABLE 7.1 HERE]**

1 7.2 Projections

2 Changes in precipitation in a warmer climate are governed by many factors. Although energy
3 constraints can be used to understand global changes in precipitation, projecting regional
4 changes is much more difficult because of uncertainty in projecting changes in the large-scale
5 circulation that plays important roles in the formation of clouds and precipitation (Shepherd
6 2014). For the contiguous United States (CONUS), future changes in seasonal average
7 precipitation will include a mix of increases, decreases, or little change, depending on location
8 and season (Figure 7.5). High-latitude regions are generally projected to become wetter while the
9 subtropical zone is projected to become drier. As the CONUS lies between these two regions,
10 there is significant uncertainty about the sign and magnitude of future anthropogenic changes to
11 seasonal precipitation in much of the region, particularly in the middle latitudes of the Nation.
12 However, because the physical mechanisms controlling extreme precipitation differ from those
13 controlling seasonal average precipitation (Section 7.1.4), in particular atmospheric water vapor
14 will increase with increasing temperatures, confidence is *high* that precipitation extremes will
15 increase in frequency and intensity in the future throughout the CONUS.

16 Global climate models used to project precipitation changes exhibit varying degrees of fidelity in
17 capturing the observed climatology and seasonal variations of precipitation across the United
18 States. Global or regional climate models with higher horizontal resolution generally achieve
19 better skill than the CMIP5 models in capturing the spatial patterns and magnitude of winter
20 precipitation in the western and southeastern United States (e.g., Mearns et al. 2012; Wehner
21 2013; Bacmeister et al. 2014; Wehner et al. 2014), leading to improved simulations of snowpack
22 and runoff (e.g., Rauscher et al. 2008; Rasmussen et al. 2011). Simulation of present and future
23 summer precipitation remains a significant challenge, as current convective parameterizations
24 fail to properly represent the statistics of mesoscale convective systems (Boyle and Klein 2010).
25 As a result, high-resolution models that still require the parameterization of deep convection
26 exhibit mixed results (Wehner et al. 2014; Sakaguchi et al. 2015). Advances in computing
27 technology are beginning to enable regional climate modeling at the higher resolutions (1–4 km),
28 permitting the direct simulation of convective clouds systems (e.g., Ban et al. 2014) and
29 eliminating the need for this class of parameterization. However, projections from such models
30 are not yet ready for inclusion in this report.

31 Important progress has been made by the climate modeling community in providing multimodel
32 ensembles such as CMIP5 (Taylor et al. 2012) and NARCCAP (Mearns et al. 2012) to
33 characterize projection uncertainty arising from model differences and large ensemble
34 simulations such as CESM-LE (Kay et al. 2015) to characterize uncertainty inherent in the
35 climate system due to internal variability. These provide an important resource for examining the
36 uncertainties in future precipitation projections.

37

1 7.2.1 Future Changes in U.S. Seasonal Mean Precipitation

2 In the United States, projected changes in seasonal mean precipitation span the range from
3 profound decreases to profound increases. And in many regions and seasons, projected changes
4 in precipitation are not large compared to natural variations. The general pattern of change is
5 clear and consistent with theoretical expectations. Figure 7.5 shows the weighted CMIP5
6 multimodel average seasonal change at the end of the century compared to the present under the
7 RCP8.5 scenario (see Ch. 4: Projections for discussion of RCPs). In this figure, changes
8 projected with high confidence to be larger than natural variations are stippled. Regions where
9 future changes are projected with high confidence to be smaller than natural variations are
10 hatched. In winter and spring, the northern part of the country is projected to become wetter as
11 the global climate warms. In the early to middle parts of this century, this will likely be
12 manifested as increases in snowfall (O’Gorman 2014). By the latter half of the century, as
13 temperature continues to increase, it will be too warm to snow in many current snow-producing
14 situations, and precipitation will mostly be rainfall. In the southwestern United States,
15 precipitation will decrease in the spring but the changes are only a little larger than natural
16 variations. Many other regions of the country will not experience significant changes in average
17 precipitation. This is also the case over most of the country in the summer and fall.

18 **[INSERT FIGURE 7.5 HERE]**

19 This pattern of projected precipitation change arises because of changes in locally available
20 water vapor and weather system shifts. In the northern part of the continent, increases in water
21 vapor, together with changes in circulation that are the result of expansion of the Hadley cell,
22 bring more moisture to these latitudes while maintaining or increasing the frequency of
23 precipitation-producing weather systems. This change in the Hadley circulation (see Ch. 5:
24 Circulation and Variability for discussion of circulation changes) also causes the subtropics, the
25 region between the northern and southern edges of the tropics and the midlatitudes (about 35° of
26 latitude), to be drier in warmer climates as well as moving the mean storm track northward and
27 away from the subtropics, decreasing the frequency of precipitation-producing systems. The
28 combination of these two factors results in precipitation decreases in the southwestern United
29 States, Mexico, and the Caribbean (Collins et al. 2013).

30 PROJECTED CHANGES IN SNOW

31 The Third National Climate Assessment (Georgakakos et al. 2014) projected reductions in
32 annual snowpack of up to 40% in the western United States based on the SRES A2 emissions
33 scenario in the CMIP3 suite of climate model projections. Recent research using the CMIP5 suite
34 of climate model projections forced with the RCP8.5 scenario and statistically downscaled for
35 the western United States continues to show the expected declines in various snow metrics,
36 including snow water equivalent, the number of extreme snowfall events, and number of
37 snowfall days (Lute et al. 2015). A northward shift in the rain–snow transition zone in the central

1 and eastern United States was found using statistically downscaled CMIP5 simulations forced
2 with RCP8.5. By the end of the 21st century, large areas that are currently snow-dominated in
3 the cold season are expected to be rainfall dominated (Ning and Bradley 2015).

4 The Variable Infiltration Capacity (VIC) model has been used to investigate the potential effects
5 of climate change on SWE. Declines in SWE are projected in all western U.S. mountain ranges
6 during the 21st century with the virtual disappearance of snowpack in the southernmost
7 mountains by the end of the 21st century under both the RCP4.5 and RCP8.5 scenarios (Gergel
8 et al. 2017). The projected decreases are most robust at the lower elevations of areas where
9 snowpack accumulation is now reliable (for example, the Cascades and northern Sierra Nevada
10 ranges). In these areas, future decreases in SWE are largely driven by increases in temperature.
11 At higher (colder) elevations, projections are driven more by precipitation changes and are thus
12 more uncertain.

13 **7.2.2 Extremes**

14 **HEAVY PRECIPITATION EVENTS**

15 Studies project that the observed increase in heavy precipitation events will continue in the future
16 (e.g. Janssen et al. 2014, 2016). Similar to observed changes, increases are expected in all
17 regions, even those regions where total precipitation is projected to decline, such as the
18 southwestern United States. Under the RCP8.5 scenario the number of extreme events
19 (exceeding a 5-year return period) increases by two to three times the historical average in every
20 region (Figure 7.6) by the end of the 21st century, with the largest increases in the Northeast.
21 Under the RCP4.5 scenario, increases are 50%–100%. Research shows that there is strong
22 evidence, both from the observed record and modeling studies, that increased water vapor
23 resulting from higher temperatures is the primary cause of the increases (Kunkel et al. 2013a,b;
24 Wehner 2013). Additional effects on extreme precipitation due to changes in dynamical
25 processes are poorly understood. However atmospheric rivers (ARs), especially along the West
26 Coast of the United States, are projected to increase in number and water vapor transport
27 (Dettinger 2011) and experience landfall at lower latitudes (Shields and Kiehl 2016) by the end
28 of the 21st century.

29 **[INSERT FIGURE 7.6 HERE]**

30 Projections of changes in the 20-year return period amount for daily precipitation (Figure 7.7)
31 using Locally Constructed Analogs (LOCA) downscaled data also show large percentage
32 increases for both the middle and late 21st century. The lower emissions projections (RCP4.5)
33 show increases of around 10% for mid-century and up to 14% for the late century projections.
34 The higher emissions projections show even larger increases for both mid-century and late
35 century projections, with increases of around 20% by late 20th century. No region in either
36 emissions scenario shows a decline in heavy precipitation. The increases in extreme precipitation

1 tend to increase with return level, such that increases for the 100-year return level are about 30%
2 by the end of the century under a high emissions scenario.

3 **[INSERT FIGURE 7.7 HERE]**

4 Projections of changes in the distribution of daily precipitation amounts (Figure 7.8) indicate an
5 overall more extreme precipitation climate. Specifically, the projections indicate a slight increase
6 in the numbers of dry days and the very lightest precipitation days and a large increase in the
7 heaviest days. The number of days with precipitation amounts greater than the 95th percentile of
8 all non-zero precipitation days increases by more than 25%. At the same time, the number of
9 days with precipitation amounts in the 10th–80th percentile range decreases.

10 **[INSERT FIGURE 7.8 HERE]**

11 Most global climate models lack sufficient resolution to project changes in MCSs in a changing
12 climate (Kooperman et al. 2013). However, research by Cook et al. (2008) attempted to identify
13 clues to changes in dynamical forcing that create MCSs. To do this, they examined the ability of
14 18 coupled ocean–atmosphere global climate models (GCMs) to simulate potential 21st century
15 changes in warm-season flow and the associated U.S. Midwest hydrology resulting from
16 increases in greenhouse gases. They selected a subset of six models that best captured the low-
17 level flow and associated dynamics of the present-day climate of the central United States and
18 then analyzed these models for changes due to enhanced greenhouse gas forcing. In each of these
19 models, springtime precipitation increases significantly (by 20%–40%) in the upper Mississippi
20 Valley and decreases to the south. The enhanced moisture convergence leading to modeled
21 future climate rainfall increases in the U.S. Midwest is caused by meridional convergence at 850
22 hPa, connecting the rainfall changes with the Great Plains Low-Level Jet intensification (Higgins
23 et al. 1997). This is consistent with findings from Feng et al. (2016) in the observational record
24 for the period 1979–2014 and by Pan et al. (2004) by use of a regional climate model.

25 Changes in intense hourly precipitation events were simulated by Prein et al. 2017 where they
26 found the most intense hourly events (99.9 percentile) in the central United States increase at the
27 expense of moderate intense (97.5 percentile) hourly events in the warm season. They also found
28 the frequency of seasonal hourly precipitation extremes is expected to increase in all regions by
29 up to five times in the same areas that show the highest increases in extreme precipitation rates.

30 **HURRICANE PRECIPITATION**

31 Regional model projections of precipitation from landfalling tropical cyclones over the United
32 States, based on downscaling of CMIP5 model climate changes, suggest that the occurrence
33 frequency of post-landfall tropical cyclones over the United States will change little compared to
34 present day during the 21st century, as the reduced frequency of tropical cyclones over the
35 Atlantic domain is mostly offset by a greater landfalling fraction. However, when downscaling
36 from CMIP3 model climate changes, projections showed a reduced occurrence frequency over

1 U.S. land, indicating uncertainty about future outcomes. The average tropical cyclone rainfall
2 rates within 500 km (about 311 miles) of the storm center increased by 8% to 17% in the
3 simulations, which was at least as much as expected from the water vapor content increase factor
4 alone.

5 Several studies have projected increases of precipitation rates within hurricanes over ocean
6 regions (Knutson et al. 2010), particularly for the Atlantic basin (Knutson et al. 2013). The
7 primary physical mechanism for this increase is the enhanced water vapor content in the warmer
8 atmosphere, which enhances moisture convergence into the storm for a given circulation
9 strength, although a more intense circulation can also contribute (Wang et al. 2015). Since
10 hurricanes are responsible for many of the most extreme precipitation events in the southeastern
11 United States (Kunkel et al. 2010, 2012), such events are likely to be even heavier in the future.
12 In a set of idealized forcing experiments, this effect was partly offset by differences in warming
13 rates at the surface and at altitude (Villarini et al. 2014).

14

FINAL DRAFT

1 TRACEABLE ACCOUNTS

2 Key Finding 1

3 Annual precipitation has decreased in much of the West, Southwest, and Southeast and increased
4 in most of the Northern and Southern Plains, Midwest, and Northeast. A national average
5 increase of 4% in annual precipitation since 1901 is mostly a result of large increases in the fall
6 season. (*Medium confidence*)

7 Description of evidence base

8 The key finding and supporting text summarizes extensive evidence documented in the climate
9 science peer-reviewed literature. Evidence of long-term changes in precipitation is based on
10 analysis of daily precipitation observations from the U.S. Cooperative Observer Network
11 (<http://www.nws.noaa.gov/om/coop/>) and shown in Figure 7.1. Published work, such as the
12 Third National Climate Assessment (Melillo et al. 2014), and Figure 7.1 show important regional
13 and seasonal differences in U.S. precipitation change since 1901.

14 Major uncertainties

15 The main source of uncertainty is the sensitivity of observed precipitation trends to the spatial
16 distribution of observing stations and to historical changes in station location, rain gauges, the
17 local landscape, and observing practices. These issues are mitigated somewhat by new methods
18 to produce spatial grids through time (Vose et al. 2014).

19 Assessment of confidence based on evidence and agreement, including short description of 20 nature of evidence and level of agreement

21 Based on the evidence and understanding of the issues leading to uncertainties, confidence is
22 *medium* that average annual precipitation has increased in the United States. Furthermore,
23 confidence is also *medium* that the important regional and seasonal differences in changes
24 documented in the text and in Figure 7.1 are robust.

25 Summary sentence or paragraph that integrates the above information

26 Based on the patterns shown in Figure 7.1 and numerous additional studies of precipitation
27 changes in the United States, there is *medium confidence* in the observed changes in annual and
28 seasonal precipitation over the various regions and the United States as a whole.

29

30 Key Finding 2

31 Heavy precipitation events in most parts of the United States have increased in both intensity and
32 frequency since 1901 (*high confidence*). There are important regional differences in trends, with

1 the largest increases occurring in the northeastern United States (*high confidence*). In particular,
2 mesoscale convective systems (organized clusters of thunderstorms)—the main mechanism for
3 warm season precipitation in the central part of the United States—have increased in occurrence
4 and precipitation amounts since 1979 (*medium confidence*).

5 **Description of evidence base**

6 The key finding and supporting text summarizes extensive evidence documented in the climate
7 science peer-reviewed literature. Numerous papers have been written documenting observed
8 changes in heavy precipitation events in the United States, including those cited in the Third
9 National Climate Assessment and in this assessment. Although station based analyses (e.g.,
10 Westra et al. 2013) do not show large numbers of statistically significant station-based trends,
11 area averaging reduces the noise inherent in station-based data and produces robust increasing
12 signals (see Figures 7.2 and 7.3). Evidence of long-term changes in precipitation is based on
13 analysis of daily precipitation observations from the U.S. Cooperative Observer Network
14 (<http://www.nws.noaa.gov/om/coop/>) and shown in Figures 7.2, 7.3, and 7.4.

15 **Major uncertainties**

16 The main source of uncertainty is the sensitivity of observed precipitation trends to the spatial
17 distribution of observing stations and to historical changes in station location, rain gauges, and
18 observing practices. These issues are mitigated somewhat by methods used to produce spatial
19 grids through gridbox averaging.

20 **Assessment of confidence based on evidence and agreement, including short description of** 21 **nature of evidence and level of agreement**

22 Based on the evidence and understanding of the issues leading to uncertainties, confidence is
23 *high* that heavy precipitation events have increased in the United States. Furthermore, confidence
24 is also *high* that the important regional and seasonal differences in changes documented in the
25 text and in Figures 7.2, 7.3, and 7.4 are robust.

26 **Summary sentence or paragraph that integrates the above information**

27 Based on numerous analyses of the observed record in the United States there is *high confidence*
28 in the observed changes in heavy precipitation events, and *medium confidence* in observed
29 changes in mesoscale convective systems.

30

31 **Key Finding 3**

32 The frequency and intensity of heavy precipitation events are projected to continue to increase
33 over the 21st century (*high confidence*). Mesoscale convective systems in the central United

1 States, are expected to continue to increase in number and intensity in the future (*medium*
2 *confidence*). There are, however, important regional and seasonal differences in projected
3 changes in total precipitation: the northern United States, including Alaska, is projected to
4 receive more precipitation in the winter and spring, and parts of the southwestern United States
5 are projected to receive less precipitation in the winter and spring (*medium confidence*).

6 **Description of evidence base**

7 Evidence for future changes in precipitation is based on climate model projections and our
8 understanding of the climate system's response to increasing greenhouse gases and of regional
9 mechanisms behind the projected changes. In particular, Figure 7.7 documents projected changes
10 in the 20-year return period amount using the LOCA data, and Figure 7.6 shows changes in 2
11 day totals for the 5-year return period using the CMIP5 suite of models. Each figure shows
12 robust changes in extreme precipitation events as they are defined in the figure. However, Figure
13 7.5, which shows changes in seasonal and annual precipitation, indicate where confidence in the
14 changes is higher based on consistency between the models and that there are large areas where
15 the projected change is uncertain.

16 **Major uncertainties**

17 A key issue is how well climate models simulate precipitation, which is one of the more
18 challenging aspects of weather and climate simulation. In particular, comparisons of model
19 projections for total precipitation (from both CMIP3 and CMIP5, see Sun et al. 2015) by NCA3
20 region show a spread of responses in some regions (for example, the Southwest) such that they
21 are opposite from the ensemble average response. The continental United States is positioned in
22 the transition zone between expected drying in the sub-tropics and wetting in the mid- and
23 higher-latitudes. There are some differences in the location of this transition between CMIP3 and
24 CMIP5 models and thus there remains uncertainty in the exact location of the transition zone.

25 **Assessment of confidence based on evidence and agreement, including short description of** 26 **nature of evidence and level of agreement**

27 Based on evidence from climate model simulations and our fundamental understanding of the
28 relationship of water vapor to temperature, confidence is *high* that extreme precipitation will
29 increase in all regions of the United States. However, based on the evidence and understanding
30 of the issues leading to uncertainties, confidence is *medium* that that more total precipitation is
31 projected for the northern U.S. and less for the Southwest.

32 **Summary sentence or paragraph that integrates the above information**

33 Based on numerous analyses of model simulations and our understanding of the climate system
34 there is *high confidence* in the projected changes in precipitation extremes and *medium*
35 *confidence* in projected changes in total precipitation over the United States.

1 Key Finding 4

2 Northern Hemisphere spring snow cover extent, North America maximum snow depth, snow
3 water equivalent in the western United States, and extreme snowfall years in the southern and
4 western United States have all declined, while extreme snowfall years in parts of the northern
5 United States have increased (*medium confidence*). Projections indicate large declines in
6 snowpack in the western United States and shifts to more precipitation falling as rain than snow
7 in the cold season in many parts of the central and eastern United States (*high confidence*).

8 Description of evidence base

9 Evidence of historical changes in snow cover extent and a reduction in extreme snowfall years is
10 consistent with our understanding of the climate system's response to increasing greenhouse
11 gases. Furthermore, climate models continue to consistently show future declines in snowpack in
12 the western United States. Recent model projections for the eastern United States also confirm a
13 future shift from snowfall to rainfall during the cold season in colder portions of the central and
14 eastern United States. Each of these changes is documented in the peer-reviewed literature and
15 are cited in the main text of this chapter.

16 Major uncertainties

17 The main source of uncertainty is the sensitivity of observed snow changes to the spatial
18 distribution of observing stations and to historical changes in station location, rain gauges, and
19 observing practices, particularly for snow. Another key issue is the ability of climate models to
20 simulate precipitation, particularly snow. Future changes in the frequency and intensity of
21 meteorological systems causing heavy snow are less certain than temperature changes.

**22 Assessment of confidence based on evidence and agreement, including short description of
23 nature of evidence and level of agreement**

24 Given the evidence base and uncertainties, confidence is *medium* that snow cover extent has
25 declined in the United States and *medium* that extreme snowfall years have declined in recent
26 years. Confidence is *high* that western United States snowpack will decline in the future, and
27 confidence is *medium* that a shift from snow domination to rain domination will occur in the
28 parts of the central and eastern United States cited in the text.

29 Summary sentence or paragraph that integrates the above information

30 Based on observational analyses of snow cover, depth and water equivalent there is *medium*
31 *confidence* in the observed changes, and based on model simulations for the future there is *high*
32 *confidence* in snowpack declines in the Western United States and *medium confidence* in the
33 shift to rain from snow in the eastern United States.

34

1 **TABLE**

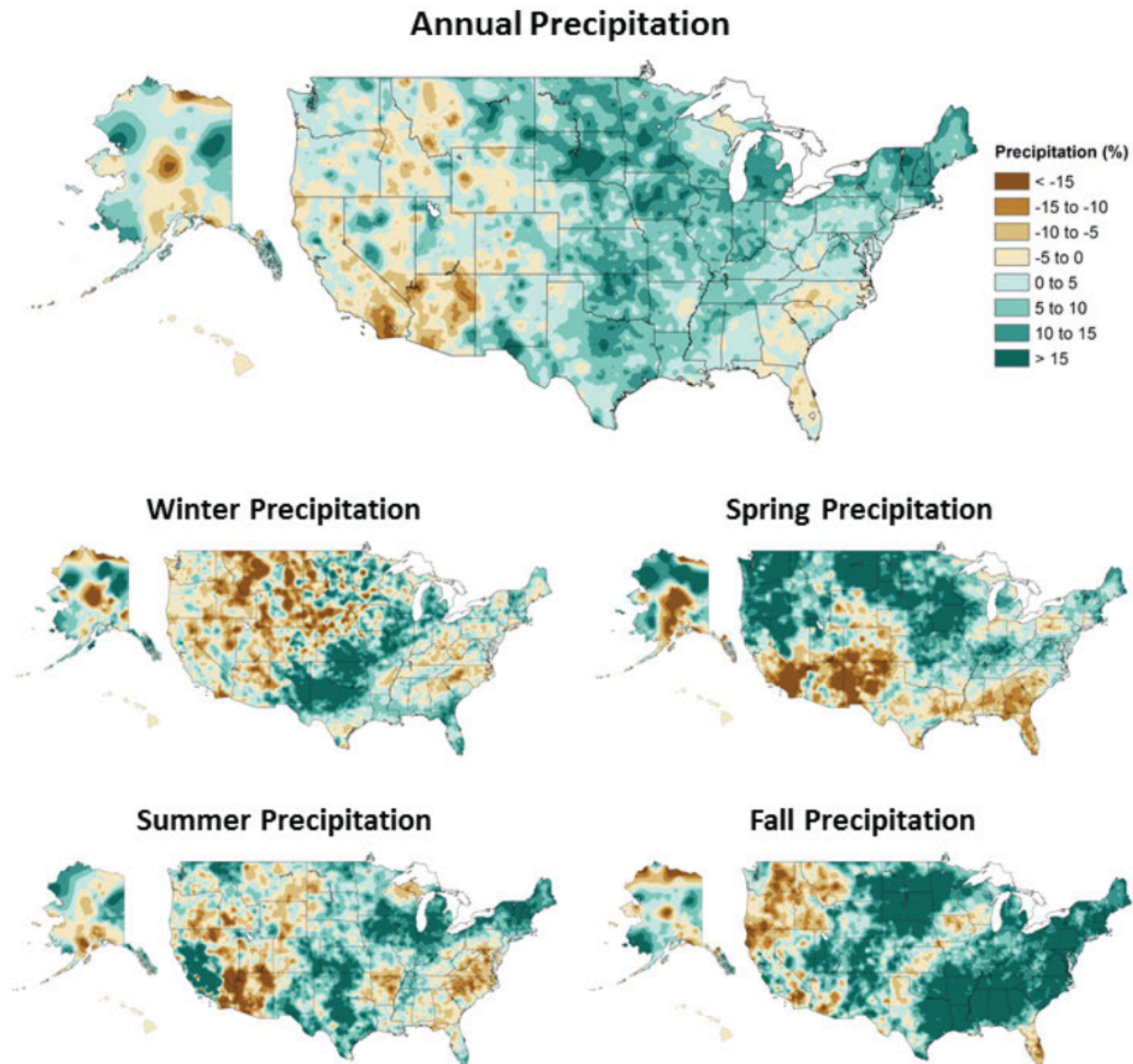
2 **Table 7.1:** A list of U.S. extreme precipitation events for which attribution statements have been
 3 made. In the last column, “+” indicates that an attributable human-induced increase in frequency
 4 and/or magnitude was found, “-“ indicates that an attributable human-induced decrease in
 5 frequency and/or magnitude was found, “0” indicates no attributable human contribution was
 6 identified. As in tables 6.1 and 8.2, several of the events were originally examined in the *Bulletin*
 7 *of the American Meteorological Society’s* (BAMS) State of the Climate Reports and reexamined
 8 by Angélil et al. (2017). In these cases, both attribution statements are listed with the original
 9 authors first. Source: M. Wehner.

Authors	Event year and duration	Region	Type	Attribution statement
Knutson et al. 2014 / Angélil et al. 2017	ANN 2013	U.S. Northern Tier	Wet	+/0
Knutson et al. 2014 / Angélil et al. 2017	MAM 2013	U.S. Upper Midwest	Wet	+/+
Knutson et al. 2014 / Angélil et al. 2017	JJA 2013	Eastern U.S. Region	Wet	+/-
Edwards et al. 2014	October 4-5, 2013	South Dakota	Blizzard	0
Hoerling et al. 2014	September 10-14, 2013	Colorado	Wet	0
Pall et al. 2017	September 10-14, 2013	Colorado	Wet	+

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11

1 **FIGURES**

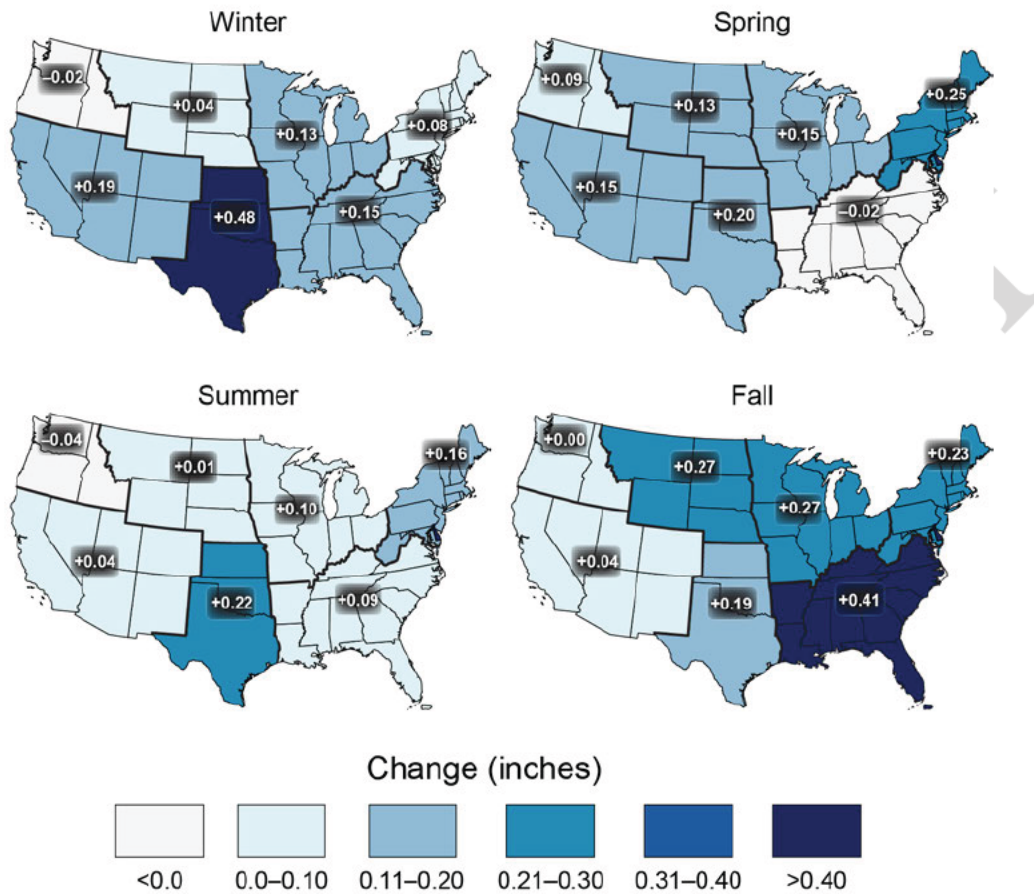


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3 **Figure 7.1:** Annual and seasonal changes in precipitation over the contiguous United States.
 4 Changes are the average for present-day (1986–2015) minus the average for the first half of the
 5 last century (1901–1960 for the contiguous United States, 1925–1960 for Alaska and Hawaii)
 6 divided by the average for the first half of the century. (Figure source: [top panel] adapted from
 7 Peterson et al. 2013, © American Meteorological Society. Used with permission; [bottom four
 8 panels] NOAA NCEI, data source: nCLIMDiv].

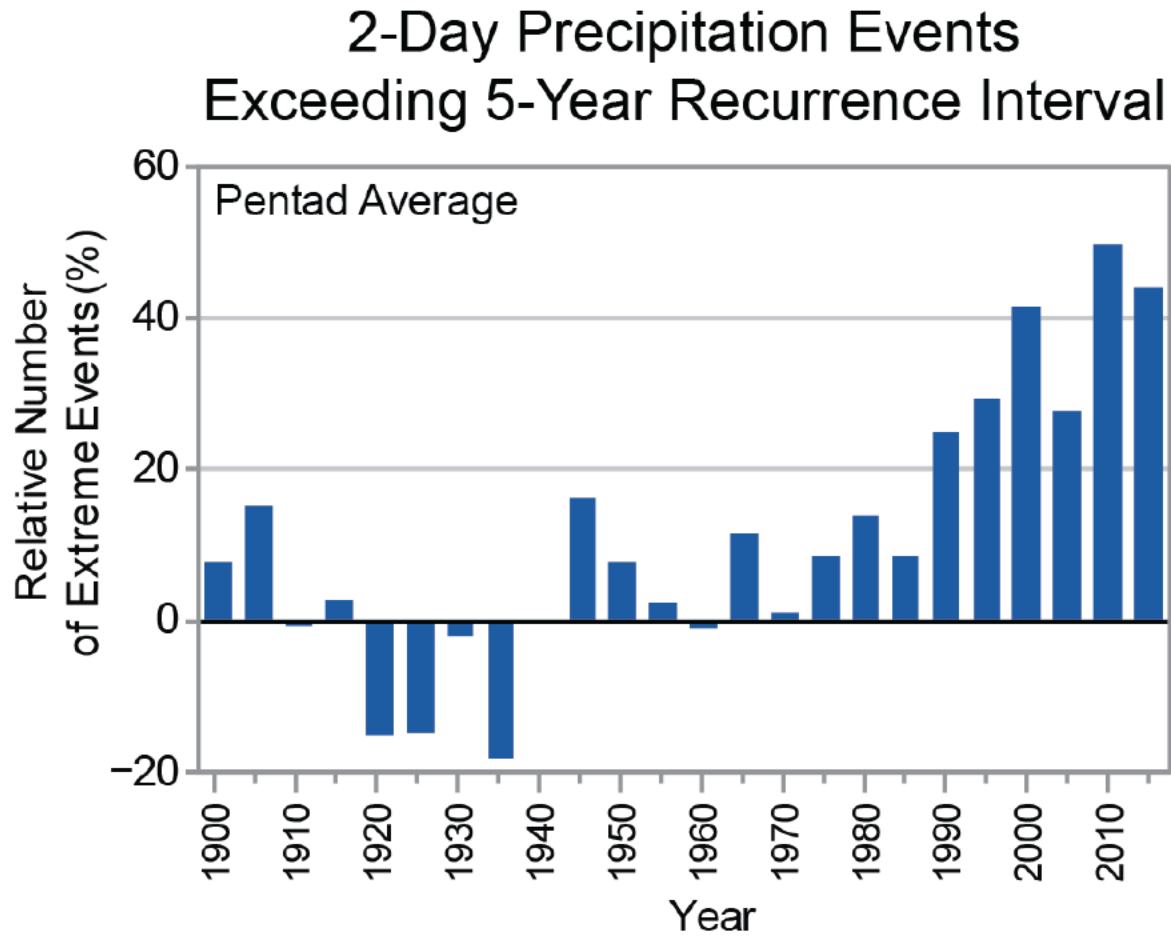
9

Observed Change in Daily, 20-year Return Level Precipitation



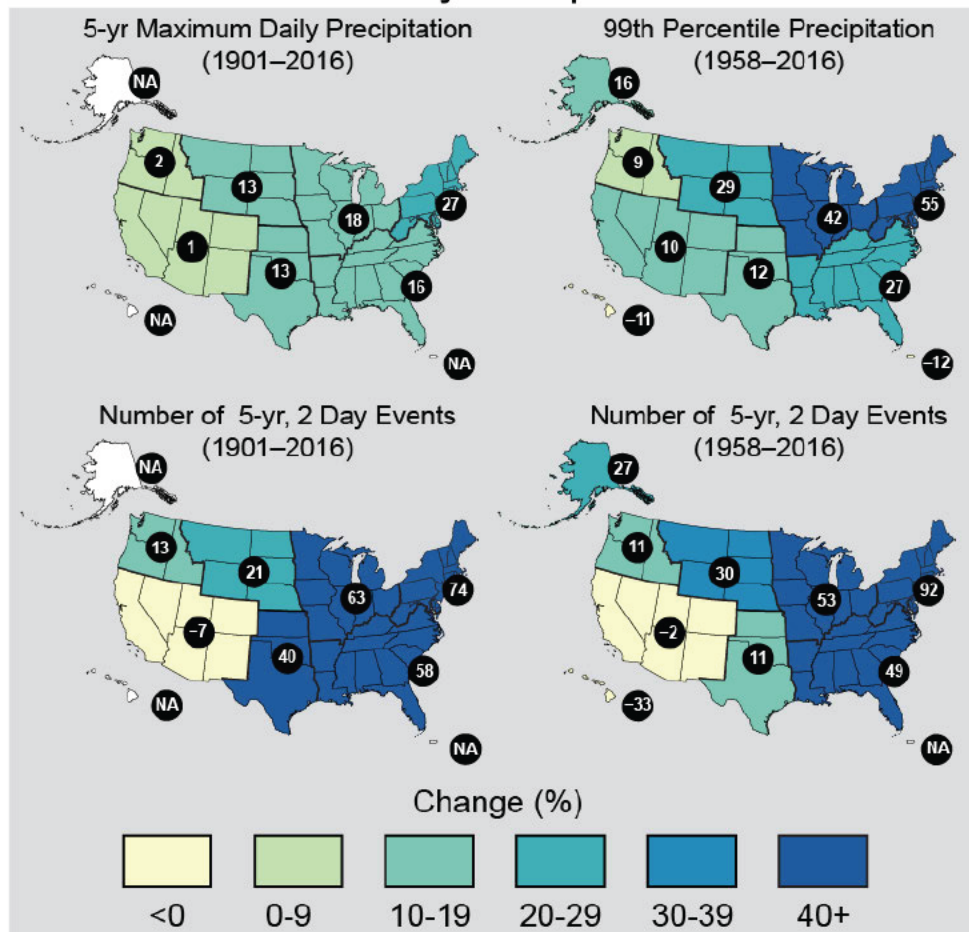
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Figure 7.2: Observed changes in the 20-year return value of the seasonal daily precipitation totals over the period 1948 to 2015 using data from the Global Historical Climatology Network (GHCN) dataset. (Figure source: adapted from Kunkel et al. 2013; © American Meteorological Society. Used with permission.)



1
 2 **Figure 7.3:** Index of the number of 2-day precipitation events exceeding the station-specific
 3 threshold for a 5-year recurrence interval, expressed as a percentage difference from the 1901–
 4 1960 mean. The annual values are averaged over 5-year periods, with the pentad label indicating
 5 the ending year of the period. Annual time series of the number of events are first calculated at
 6 individual stations. Next, the grid box time series are calculated as the average of all stations in
 7 the grid box. Finally, a national time series is calculated as the average of the grid box time
 8 series. Data source: GHCN-Daily. (Figure source: CICS-NC / NOAA NCEI).

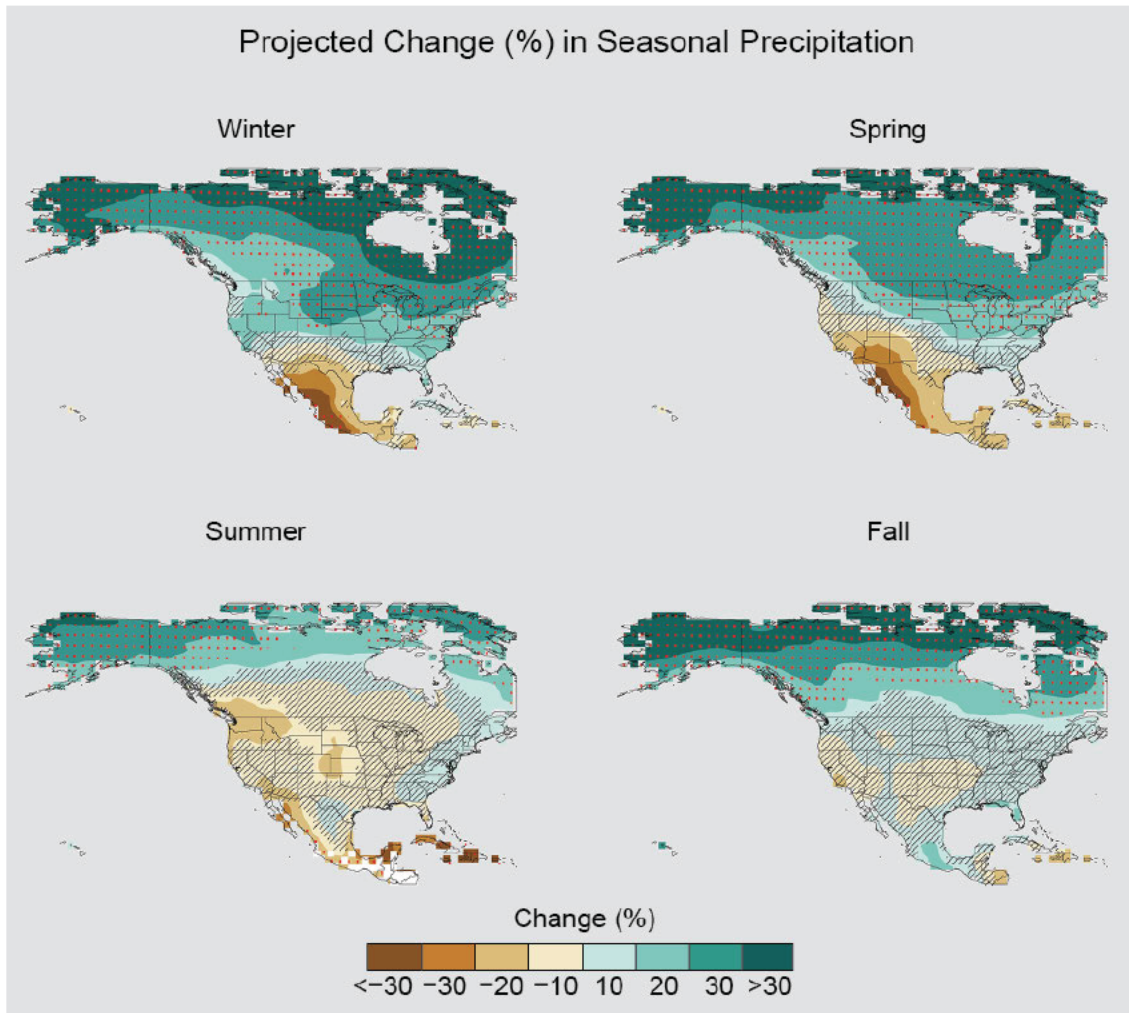
Observed Change in Heavy Precipitation



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Figure 7.4: These maps show the change in several metrics of extreme precipitation by NCA4 region, including (upper left) the maximum daily precipitation in consecutive 5-year blocks, (upper right) the amount of precipitation falling in daily events that exceed the 99th percentile of all non-zero precipitation days, (lower left) the number of 2-day events with a precipitation total exceeding the largest 2-day amount that is expected to occur, on average, only once every 5 years, as calculated over 1901–2016, and (lower right) the number of 2-day events with a precipitation total exceeding the largest 2-day amount that is expected to occur, on average, only once every 5 years, as calculated over 1958–2016. The numerical value is the percent change over the entire period, either 1901–2016 or 1958–2016. The percentages are first calculated for individual stations, then averaged over 2° latitude by 2° longitude grid boxes, and finally averaged over each NCA4 region. Note that Alaska and Hawai‘i are not included in the 1901–2016 maps owing to a lack of observations in the earlier part of the 20th century. (Figure source: CICS-NC / NOAA NCEI).

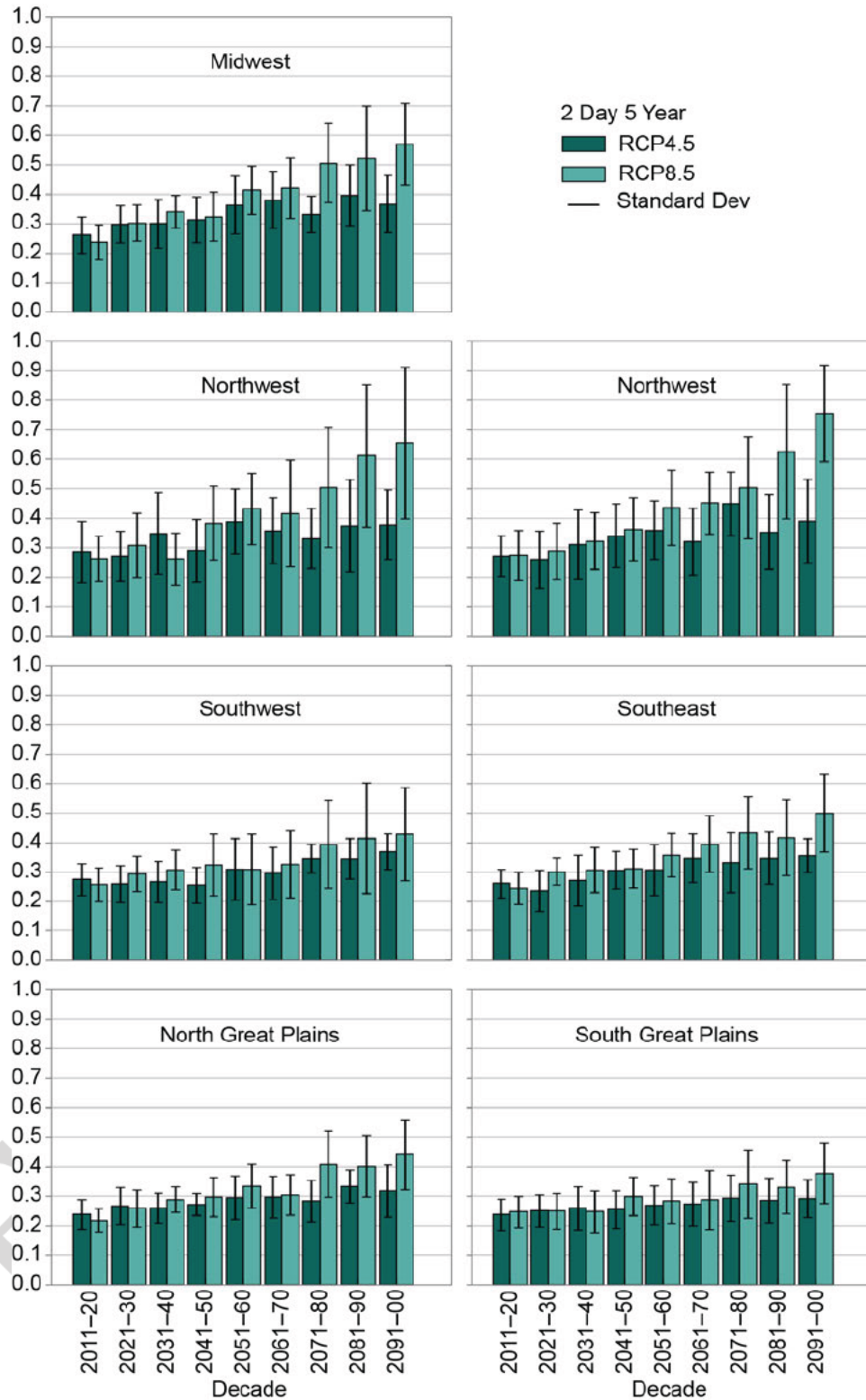
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3 **Figure 7.5:** Projected change (%) in total seasonal precipitation from CMIP5 simulations for
 4 2070-2099. The values are weighted multimodel means and expressed as the percent change
 5 relative to the 1976–2005 average. These are results for the RCP8.5 pathway. Stippling indicates
 6 that changes are assessed to be large compared to natural variations. Hatching indicates that
 7 changes are assessed to be small compared to natural variations. Blank regions (if any) are where
 8 projections are assessed to be inconclusive. Data source: World Climate Research Program's
 9 (WCRP's) Coupled Model Intercomparison Project. (Figure source: NOAA NCEI).

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2 **Figure 7.6:** Regional extreme precipitation event frequency for RCP4.5 (green; 16 CMIP5
 3 models) and RCP8.5 (blue; 14 CMIP5 models) for a 2-day duration and 5-year return. Calculated
 4 for 2006–2100 but decadal anomalies begin in 2011. Error bars are ± 1 standard deviation;

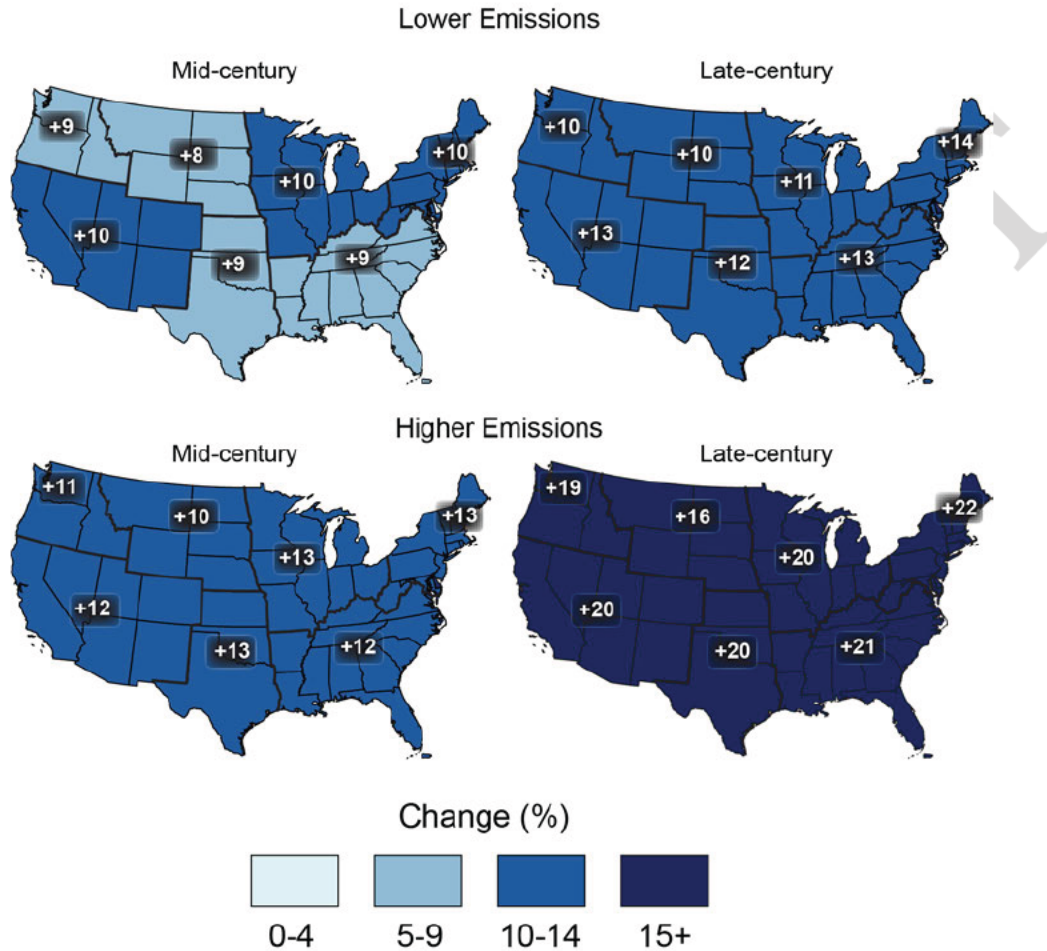
1 standard deviation is calculated from the 14 or 16 model values that represent the aggregated
2 average over the regions, over the decades, and over the ensemble members of each model. The
3 average frequency for the historical reference period is 0.2 by definition and the values in this
4 graph should be interpreted with respect to a comparison with this historical average value.
5 (Figure source: Janssen et al. 2014).

6

FINAL DRAFT

1

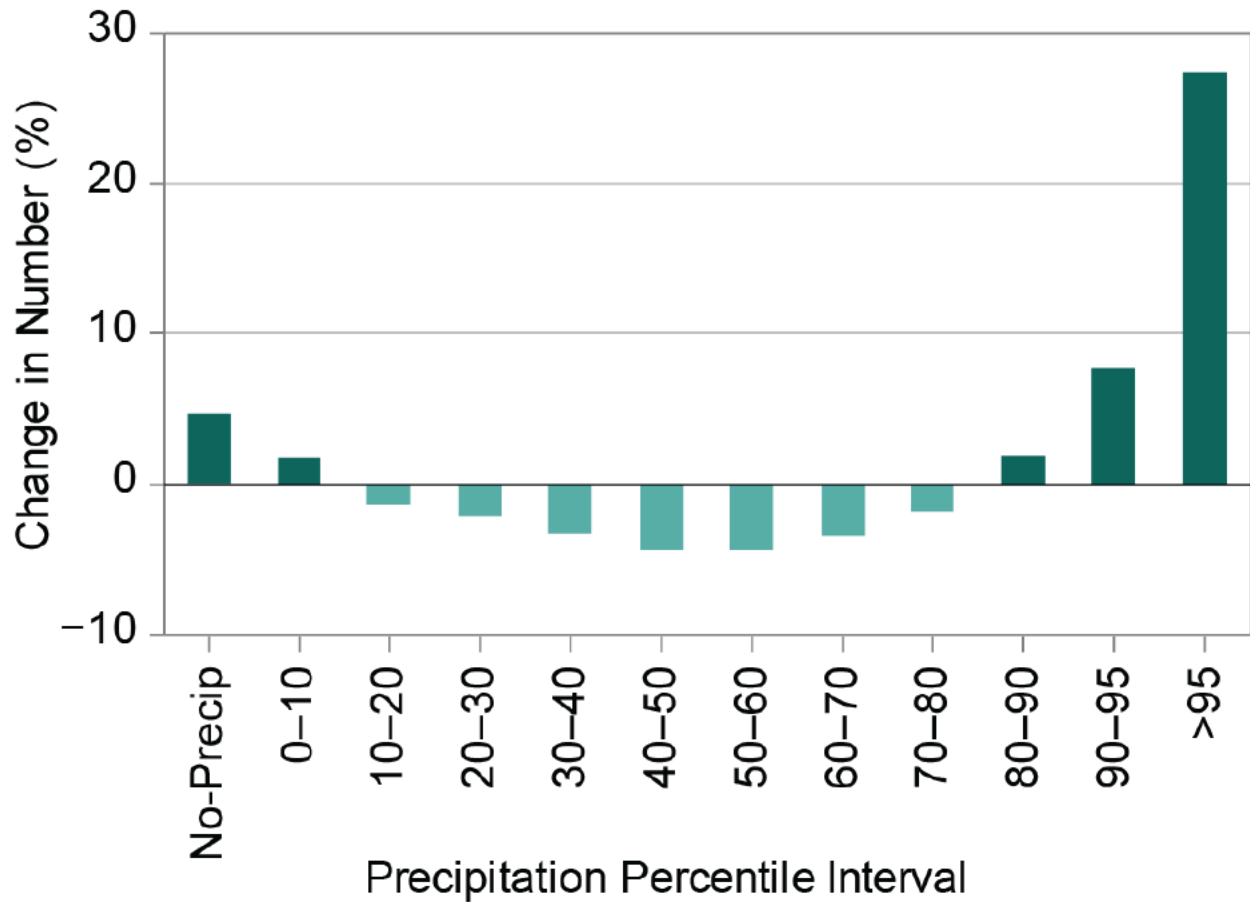
Projected Change in Daily, 20-year Extreme Precipitation



2

3 **Figure 7.7:** Projected change in the 20-year return period amount for daily precipitation for mid-
 4 (left maps) and late-21st century (right maps). Results are shown for a lower emissions scenario
 5 (top maps; RCP4.5) and for a higher emissions scenario (bottom maps, RCP8.5). These results
 6 are calculated from the LOCA downscaled data. (Figure source: CICS-NC / NOAA NCEI).

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Figure 7.8: Projected change (percentage change relative to the 1976–2005 reference period average) in the number of daily zero (“No-Precip”) and non-zero precipitation days (by percentile bins) for late-21st century under a high emissions scenario (RCP8.5). The precipitation percentile bin thresholds are based on daily non-zero precipitation amounts from the 1976–2005 reference period that have been ranked from low to high. These results are calculated from the LOCA downscaled data. (Figure source: CICS-NC / NOAA NCEI).

1 **REFERENCES**

- 2 Anderson, B.T., D.J. Gianotti, and G.D. Salvucci, 2015: Detectability of historical trends in
3 station-based precipitation characteristics over the continental United States. *Journal of*
4 *Geophysical Research: Atmospheres*, **120**, 4842-4859.
5 <http://dx.doi.org/10.1002/2014JD022960>
- 6 Angéllil, O., D. Stone, M. Wehner, C.J. Paciorek, H. Krishnan, and W. Collins, 2017: An
7 independent assessment of anthropogenic attribution statements for recent extreme
8 temperature and rainfall events. *Journal of Climate*, **30**, 5-16. [http://dx.doi.org/10.1175/JCLI-](http://dx.doi.org/10.1175/JCLI-D-16-0077.1)
9 [D-16-0077.1](http://dx.doi.org/10.1175/JCLI-D-16-0077.1)
- 10 Bacmeister, J.T., M.F. Wehner, R.B. Neale, A. Gettelman, C. Hannay, P.H. Lauritzen, J.M.
11 Caron, and J.E. Truesdale, 2014: Exploratory high-resolution climate simulations using the
12 Community Atmosphere Model (CAM). *Journal of Climate*, **27**, 3073-3099.
13 <http://dx.doi.org/10.1175/JCLI-D-13-00387.1>
- 14 Ban, N., J. Schmidli, and C. Schär, 2014: Evaluation of the convection-resolving regional
15 climate modeling approach in decade-long simulations. *Journal of Geophysical Research:*
16 *Atmospheres*, **119**, 7889-7907. <http://dx.doi.org/10.1002/2014JD021478>
- 17 Bard, L. and D.A.R. Kristovich, 2012: Trend reversal in Lake Michigan contribution to snowfall.
18 *Journal of Applied Meteorology and Climatology*, **51**, 2038-2046.
19 <http://dx.doi.org/10.1175/jamc-d-12-064.1>
- 20 Barnston, A.G. and B. Lyon, 2016: Does the NMME capture a recent decadal shift toward
21 increasing drought occurrence in the southwestern United States? *Journal of Climate*, **29**,
22 561-581. <http://dx.doi.org/10.1175/JCLI-D-15-0311.1>
- 23 Belmecheri, S., F. Babst, E.R. Wahl, D.W. Stahle, and V. Trouet, 2016: Multi-century evaluation
24 of Sierra Nevada snowpack. *Nature Climate Change*, **6**, 2-3.
25 <http://dx.doi.org/10.1038/nclimate2809>
- 26 Boyle, J., and Stephen A. Klein, 2010: Impact of horizontal resolution on climate model
27 forecasts of tropical convection and diabatic heating for the TWP-ICE period *Journal of*
28 *Geophysical Research*, **115**, D23113, doi: 10.1029/2010JD014262 .
- 29 Bindoff, N.L., P.A. Stott, K.M. AchutaRao, M.R. Allen, N. Gillett, D. Gutzler, K. Hansingo, G.
30 Hegerl, Y. Hu, S. Jain, I.I. Mokhov, J. Overland, J. Perlwitz, R. Sebbari, and X. Zhang, 2013:
31 Detection and attribution of climate change: From global to regional. *Climate Change 2013:*
32 *The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report*
33 *of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M.
34 Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds.

- 1 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 867–
2 952. <http://www.climatechange2013.org/report/full-report/>
- 3 Chang, E.K.M., C.-G. Ma, C. Zheng, and A.M.W. Yau, 2016: Observed and projected decrease
4 in Northern Hemisphere extratropical cyclone activity in summer and its impacts on
5 maximum temperature. *Geophysical Research Letters*, **43**, 2200-2208.
6 <http://dx.doi.org/10.1002/2016GL068172>
- 7 Colle, B.A., Z. Zhang, K.A. Lombardo, E. Chang, P. Liu, and M. Zhang, 2013: Historical
8 evaluation and future prediction of eastern North American and western Atlantic
9 extratropical cyclones in the CMIP5 models during the cool season. *Journal of Climate*, **26**,
10 6882-6903. <http://dx.doi.org/10.1175/JCLI-D-12-00498.1>
- 11 Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J.
12 Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver, and M. Wehner,
13 2013: Long-term climate change: Projections, commitments and irreversibility. *Climate*
14 *Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth*
15 *Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D.
16 Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and
17 P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New
18 York, NY, USA, 1029–1136. <http://www.climatechange2013.org/report/full-report/>
- 19 Cook, K.H., E.K. Vizi, Z.S. Launer, and C.M. Patricola, 2008: Springtime intensification of the
20 Great Plains low-level jet and midwest precipitation in GCM simulations of the twenty-first
21 century. *Journal of Climate*, **21**, 6321-6340. <http://dx.doi.org/10.1175/2008jcli2355.1>
- 22 Dettinger, M., 2011: Climate change, atmospheric rivers, and floods in California—a multimodel
23 analysis of storm frequency and magnitude changes. *Journal of the American Water*
24 *Resources Association*, **47**, 514-523. <http://dx.doi.org/10.1111/j.1752-1688.2011.00546.x>
- 25 Dittus, A.J., D.J. Karoly, S.C. Lewis, and L.V. Alexander, 2015: A multiregion assessment of
26 observed changes in the areal extent of temperature and precipitation extremes. *Journal of*
27 *Climate*, **28**, 9206-9220. <http://dx.doi.org/10.1175/JCLI-D-14-00753.1>
- 28 Dittus, A.J., D.J. Karoly, S.C. Lewis, L.V. Alexander, and M.G. Donat, 2016: A multiregion
29 model evaluation and attribution study of historical changes in the area affected by
30 temperature and precipitation extremes. *Journal of Climate*, **29**, 8285-8299.
31 <http://dx.doi.org/10.1175/jcli-d-16-0164.1>
- 32 Easterling, D.R., K.E. Kunkel, M.F. Wehner, and L. Sun, 2016: Detection and attribution of
33 climate extremes in the observed record. *Weather and Climate Extremes*, **11**, 17-27.
34 <http://dx.doi.org/10.1016/j.wace.2016.01.001>

- 1 Edwards, L.M., M. Bunkers, J.T. Abatzoglou, D.P. Todey, and L.E. Parker, 2014: October 2013
2 blizzard in western South Dakota [in "Explaining Extreme Events of 2013 from a Climate
3 Perspective"]. *Bulletin of the American Meteorological Society*, **95** (9), S23-S26.
4 <http://dx.doi.org/10.1175/1520-0477-95.9.S1.1>
- 5 Feng, Z., L.R. Leung, S. Hagos, R.A. Houze, C.D. Burleyson, and K. Balaguru, 2016: More
6 frequent intense and long-lived storms dominate the springtime trend in central US rainfall.
7 *Nature Communications*, **7**, 13429. <http://dx.doi.org/10.1038/ncomms13429>
- 8 Fritsch, J.M., R.J. Kane, and C.R. Chelius, 1986: The contribution of mesoscale convective
9 weather systems to the warm-season precipitation in the United States. *Journal of Climate
10 and Applied Meteorology*, **25**, 1333-1345. [http://dx.doi.org/10.1175/1520-
11 0450\(1986\)025<1333:tcomcw>2.0.co;2](http://dx.doi.org/10.1175/1520-0450(1986)025<1333:tcomcw>2.0.co;2)
- 12 Gan, T.Y., R.G. Barry, M. Gizaw, A. Gobena, and R. Balaji, 2013: Changes in North American
13 snowpacks for 1979–2007 detected from the snow water equivalent data of SMMR and
14 SSM/I passive microwave and related climatic factors. *Journal of Geophysical Research:
15 Atmospheres*, **118**, 7682–7697. <http://dx.doi.org/10.1002/jgrd.50507>
- 16 Georgakakos, A., P. Fleming, M. Dettinger, C. Peters-Lidard, T.C. Richmond, K. Reckhow, K.
17 White, and D. Yates, 2014: Ch. 3: Water resources. *Climate Change Impacts in the United
18 States: The Third National Climate Assessment*. Melillo, J.M., T.C. Richmond, and G.W.
19 Yohe, Eds. U.S. Global Change Research Program, Washington, D.C., 69-112.
20 <http://dx.doi.org/10.7930/J0G44N6T>
- 21 Gergel, D.R., B. Nijssen, J.T. Abatzoglou, D.P. Lettenmaier, and M.R. Stumbaugh, 2017: Effects
22 of climate change on snowpack and fire potential in the western USA. *Climatic Change*, **141**,
23 287-299. <http://dx.doi.org/10.1007/s10584-017-1899-y>
- 24 Hartnett, J.J., J.M. Collins, M.A. Baxter, and D.P. Chambers, 2014: Spatiotemporal snowfall
25 trends in central New York. *Journal of Applied Meteorology and Climatology*, **53**, 2685-
26 2697. <http://dx.doi.org/10.1175/jamc-d-14-0084.1>
- 27 Higgins, R.W., Y. Yao, E.S. Yarosh, J.E. Janowiak, and K.C. Mo, 1997: Influence of the Great
28 Plains low-level jet on summertime precipitation and moisture transport over the central
29 United States. *Journal of Climate*, **10**, 481-507. [http://dx.doi.org/10.1175/1520-
30 0442\(1997\)010<0481:iotgpl>2.0.co;2](http://dx.doi.org/10.1175/1520-0442(1997)010<0481:iotgpl>2.0.co;2)
- 31 Hoerling, M., K. Wolter, J. Perlwitz, X. Quan, J. Eischeid, H. Want, S. Schubert, H. Diaz, and R.
32 Dole, 2014: Northeast Colorado extreme rains interpreted in a climate change context [in
33 "Explaining Extreme Events of 2013 from a Climate Perspective"]. *Bulletin of the American
34 Meteorological Society*, **95** (9), S15-S18. <http://dx.doi.org/10.1175/1520-0477-95.9.S1.1>

- 1 Janssen, E., D.J. Wuebbles, K.E. Kunkel, S.C. Olsen, and A. Goodman, 2014: Observational-
2 and model-based trends and projections of extreme precipitation over the contiguous United
3 States. *Earth's Future*, **2**, 99-113. <http://dx.doi.org/10.1002/2013EF000185>
- 4 Janssen, E., R.L. Sriver, D.J. Wuebbles, and K.E. Kunkel, 2016: Seasonal and regional variations
5 in extreme precipitation event frequency using CMIP5. *Geophysical Research Letters*, **43**,
6 5385-5393. <http://dx.doi.org/10.1002/2016GL069151>
- 7 Kay, J.E., C. Deser, A. Phillips, A. Mai, C. Hannay, G. Strand, J.M. Arblaster, S.C. Bates, G.
8 Danabasoglu, J. Edwards, M. Holland, P. Kushner, J.-F. Lamarque, D. Lawrence, K.
9 Lindsay, A. Middleton, E. Munoz, R. Neale, K. Oleson, L. Polvani, and M. Vertenstein,
10 2015: The Community Earth System Model (CESM) large ensemble project: A community
11 resource for studying climate change in the presence of internal climate variability. *Bulletin*
12 *of the American Meteorological Society*, **96 (12)**, 1333-1349.
13 <http://dx.doi.org/10.1175/BAMS-D-13-00255.1>
- 14 Kluver, D. and D. Leathers, 2015: Regionalization of snowfall frequency and trends
15 over the contiguous United States. *International Journal of Climatology*, **35**, 4348-4358.
16 <http://dx.doi.org/10.1002/joc.4292>
- 17 Knutson, T.R., J.L. McBride, J. Chan, K. Emanuel, G. Holland, C. Landsea, I. Held, J.P. Kossin,
18 A.K. Srivastava, and M. Sugi, 2010: Tropical cyclones and climate change. *Nature*
19 *Geoscience*, **3**, 157-163. <http://dx.doi.org/10.1038/ngeo779>
- 20 Knutson, T.R., J.J. Sirutis, G.A. Vecchi, S. Garner, M. Zhao, H.-S. Kim, M. Bender, R.E.
21 Tuleya, I.M. Held, and G. Villarini, 2013: Dynamical downscaling projections of twenty-
22 first-century Atlantic hurricane activity: CMIP3 and CMIP5 model-based scenarios. *Journal*
23 *of Climate*, **27**, 6591-6617. <http://dx.doi.org/10.1175/jcli-d-12-00539.1>
- 24 Knutson, T.R., F. Zeng, and A.T. Wittenberg, 2014: Seasonal and annual mean precipitation
25 extremes occurring during 2013: A U.S. focused analysis [in "Explaining Extreme Events of
26 2013 from a Climate Perspective"]. *Bulletin of the American Meteorological Society*, **95 (9)**,
27 S19-S23. <http://dx.doi.org/10.1175/1520-0477-95.9.S1.1>
- 28 Kooperman, G.J., M.S. Pritchard, and R.C.J. Somerville, 2013: Robustness and sensitivities of
29 central U.S. summer convection in the super-parameterized CAM: Multi-model
30 intercomparison with a new regional EOF index. *Geophysical Research Letters*, **40**, 3287-
31 3291. <http://dx.doi.org/10.1002/grl.50597>
- 32 Kunkel, K.E., D.R. Easterling, D.A.R. Kristovich, B. Gleason, L. Stoecker, and R. Smith, 2010:
33 Recent increases in U.S. heavy precipitation associated with tropical cyclones. *Geophysical*
34 *Research Letters*, **37**, L24706. <http://dx.doi.org/10.1029/2010GL045164>

- 1 Kunkel, K.E., D.R. Easterling, D.A. Kristovich, B. Gleason, L. Stoecker, and R. Smith, 2012:
2 Meteorological causes of the secular variations in observed extreme precipitation events for
3 the conterminous United States. *Journal of Hydrometeorology*, **13**, 1131-1141.
4 <http://dx.doi.org/10.1175/JHM-D-11-0108.1>
- 5 Kunkel, K.E., T.R. Karl, H. Brooks, J. Kossin, J. Lawrimore, D. Arndt, L. Bosart, D. Changnon,
6 S.L. Cutter, N. Doesken, K. Emanuel, P.Y. Groisman, R.W. Katz, T. Knutson, J. O'Brien,
7 C.J. Paciorek, T.C. Peterson, K. Redmond, D. Robinson, J. Trapp, R. Vose, S. Weaver, M.
8 Wehner, K. Wolter, and D. Wuebbles, 2013: Monitoring and understanding trends in extreme
9 storms: State of knowledge. *Bulletin of the American Meteorological Society*, **94**.
10 <http://dx.doi.org/10.1175/BAMS-D-11-00262.1>
- 11 Kunkel, K.E., T.R. Karl, D.R. Easterling, K. Redmond, J. Young, X. Yin, and P. Hennon, 2013:
12 Probable maximum precipitation and climate change. *Geophysical Research Letters*, **40**,
13 1402-1408. <http://dx.doi.org/10.1002/grl.50334>
- 14 Kunkel, K.E., D.A. Robinson, S. Champion, X. Yin, T. Estilow, and R.M. Frankson, 2016:
15 Trends and extremes in Northern Hemisphere snow characteristics. *Current Climate Change*
16 *Reports*, **2**, 65-73. <http://dx.doi.org/10.1007/s40641-016-0036-8>
- 17 Luce, C.H., J.T. Abatzoglou and Z.A. Holden, Z.A., 2013: The missing mountain water: Slower
18 westerlies decrease orographic enhancement in the Pacific Northwest USA. *Science*, **342**,
19 1360-1364
- 20 Lute, A.C. and J.T. Abatzoglou, 2014: Role of extreme snowfall events in interannual variability
21 of snowfall accumulation in the western United States. *Water Resources Research*, **50**, 2874-
22 2888. <http://dx.doi.org/10.1002/2013WR014465>
- 23 Lute, A.C., J.T. Abatzoglou, and K.C. Hegewisch, 2015: Projected changes in snowfall extremes
24 and interannual variability of snowfall in the western United States. *Water Resources*
25 *Research*, **51**, 960-972. <http://dx.doi.org/10.1002/2014WR016267>
- 26 Mearns, L.O., R. Arritt, S. Biner, M.S. Bukovsky, S. Stain, S. Sain, D. Caya, J. Correia, Jr., D.
27 Flory, W. Gutowski, E.S. Takle, R. Jones, R. Leung, W. Moufouma-Okia, L. McDaniel,
28 A.M.B. Nunes, Y. Qian, J. Roads, L. Sloan, and M. Snyder, 2012: The North American
29 regional climate change assessment program: Overview of phase I results. *Bulletin of the*
30 *American Meteorological Society*, **93**, 1337-1362. <http://dx.doi.org/10.1175/BAMS-D-11-00223.1>
31
- 32 Melillo, J. M., T. C. Richmond, and G. W. Yohe, Eds., 2014: *Climate Change Impacts in the*
33 *United States: The Third National Climate Assessment*. U.S. Global Change Research
34 Program, 841 pp.

- 1 Min, S.K., X. Zhang, F.W. Zwiers, and G.C. Hegerl, 2011: Human contribution to more-intense
2 precipitation extremes. *Nature*, **470**, 378-381. <http://dx.doi.org/10.1038/nature09763>
- 3 Min, S.-K., X. Zhang, F. Zwiers, H. Shiogama, Y.-S. Tung, and M. Wehner, 2013: Multimodel
4 detection and attribution of extreme temperature changes. *Journal of Climate*, **26**, 7430-7451.
5 <http://dx.doi.org/10.1175/JCLI-D-12-00551.1>
- 6 Nesbitt, S.W., R. Cifelli, and S.A. Rutledge, 2006: Storm morphology and rainfall characteristics
7 of TRMM precipitation features. *Monthly Weather Review*, **134**, 2702-2721.
8 <http://dx.doi.org/10.1175/mwr3200.1>
- 9 Ning, L. and R.S. Bradley, 2015: Snow occurrence changes over the central and eastern United
10 States under future warming scenarios. *Scientific Reports*, **5**, 17073.
11 <http://dx.doi.org/10.1038/srep17073>
- 12 NOAA, 2016: Climate at a Glance. [http://www.ncdc.noaa.gov/cag/time-](http://www.ncdc.noaa.gov/cag/time-series/us/107/0/pdsi/12/12/1895-2016?base_prd=true&firstbaseyear=1901&lastbaseyear=2000)
13 [series/us/107/0/pdsi/12/12/1895-](http://www.ncdc.noaa.gov/cag/time-series/us/107/0/pdsi/12/12/1895-2016?base_prd=true&firstbaseyear=1901&lastbaseyear=2000)
14 [2016?base_prd=true&firstbaseyear=1901&lastbaseyear=2000](http://www.ncdc.noaa.gov/cag/time-series/us/107/0/pdsi/12/12/1895-2016?base_prd=true&firstbaseyear=1901&lastbaseyear=2000)
- 15 NOAA, 2016: Climate at a Glance. [http://www.ncdc.noaa.gov/cag/time-](http://www.ncdc.noaa.gov/cag/time-series/us/4/0/pdsi/12/9/1895-2016?base_prd=true&firstbaseyear=1901&lastbaseyear=2000)
16 [series/us/4/0/pdsi/12/9/1895-2016?base_prd=true&firstbaseyear=1901&lastbaseyear=2000](http://www.ncdc.noaa.gov/cag/time-series/us/4/0/pdsi/12/9/1895-2016?base_prd=true&firstbaseyear=1901&lastbaseyear=2000)
- 17 O'Gorman, P.A., 2014: Contrasting responses of mean and extreme snowfall to climate change.
18 *Nature*, **512**, 416-418. <http://dx.doi.org/10.1038/nature13625>
- 19 Pall, P.C.M.P., M.F. Wehner, D.A. Stone, C.J. Paciorek, and W.D. Collins, 2017: Diagnosing
20 anthropogenic contributions to heavy Colorado rainfall in September 2013. *Weather and*
21 *Climate Extremes*, **In Press**. <http://dx.doi.org/10.1016/j.wace.2017.03.004>
- 22 Pan, Z., R.W. Arritt, E.S. Takle, W.J. Gutowski, Jr., C.J. Anderson, and M. Segal, 2004: Altered
23 hydrologic feedback in a warming climate introduces a “warming hole”. *Geophysical*
24 *Research Letters*, **31**, L17109. <http://dx.doi.org/10.1029/2004GL020528>
- 25 Pederson, G.T., J.L. Betancourt, and G.J. McCabe, 2013: Regional patterns and proximal causes
26 of the recent snowpack decline in the Rocky Mountains, U.S. *Geophysical Research Letters*,
27 **40**, 1811-1816. <http://dx.doi.org/10.1002/grl.50424>
- 28 Peterson, T.C., R.R. Heim, R. Hirsch, D.P. Kaiser, H. Brooks, N.S. Diffenbaugh, R.M. Dole, J.P.
29 Giovannetone, K. Guirguis, T.R. Karl, R.W. Katz, K. Kunkel, D. Lettenmaier, G.J. McCabe,
30 C.J. Paciorek, K.R. Ryberg, S. Schubert, V.B.S. Silva, B.C. Stewart, A.V. Vecchia, G.
31 Villarini, R.S. Vose, J. Walsh, M. Wehner, D. Wolock, K. Wolter, C.A. Woodhouse, and D.
32 Wuebbles, 2013: Monitoring and understanding changes in heat waves, cold waves, floods
33 and droughts in the United States: State of knowledge. *Bulletin of the American*
34 *Meteorological Society*, **94**, 821-834. <http://dx.doi.org/10.1175/BAMS-D-12-00066.1>

- 1 Pfahl, S., P.A. O’Gorman, and M.S. Singh, 2015: Extratropical cyclones in idealized simulations
2 of changed climates. *Journal of Climate*, **28**, 9373-9392. [http://dx.doi.org/10.1175/JCLI-D-](http://dx.doi.org/10.1175/JCLI-D-14-00816.1)
3 [14-00816.1](http://dx.doi.org/10.1175/JCLI-D-14-00816.1)
- 4 Prein, A.F., R.M. Rasmussen, K. Ikeda, C. Liu, M.P. Clark, and G.J. Holland, 2017: The future
5 intensification of hourly precipitation extremes. *Nature Climate Change*, **7**, 48-52.
6 <http://dx.doi.org/10.1038/nclimate3168>
- 7 Rasmussen, R., C. Liu, K. Ikeda, D. Gochis, D. Yates, F. Chen, M. Tewari, M. Barlage, J.
8 Dudhia, W. Yu, K. Miller, K. Arsenault, V. Grubišić, G. Thompson, and E. Gutmann, 2011:
9 High-resolution coupled climate runoff simulations of seasonal snowfall over Colorado: A
10 process study of current and warmer climate. *Journal of Climate*, **24**, 3015-3048.
11 <http://dx.doi.org/10.1175/2010JCLI3985.1>
- 12 Rauscher, S.A., J.S. Pal, N.S. Diffenbaugh, and M.M. Benedetti, 2008: Future changes in
13 snowmelt-driven runoff timing over the western US. *Geophysical Research Letters*, **35**,
14 L16703. <http://dx.doi.org/10.1029/2008GL034424>
- 15 Sakaguchi, K., L.R. Leung, C. Zhao, Q. Yang, J. Lu, S. Hagos, S.A. Rauscher, L. Dong, T.D.
16 Ringler, and P.H. Lauritzen, 2015: Exploring a multiresolution approach using AMIP
17 simulations. *Journal of Climate*, **28**, 5549-5574. [http://dx.doi.org/10.1175/JCLI-D-14-](http://dx.doi.org/10.1175/JCLI-D-14-00729.1)
18 [00729.1](http://dx.doi.org/10.1175/JCLI-D-14-00729.1)
- 19 Schumacher, R.S. and R.H. Johnson, 2006: Characteristics of U.S. extreme rain events during
20 1999–2003. *Weather and Forecasting*, **21**, 69-85. <http://dx.doi.org/10.1175/waf900.1>
- 21 Seager, R., M. Hoerling, S. Schubert, H. Wang, B. Lyon, A. Kumar, J. Nakamura, and N.
22 Henderson, 2015: Causes of the 2011–14 California drought. *Journal of Climate*, **28**, 6997-
23 7024. <http://dx.doi.org/10.1175/JCLI-D-14-00860.1>
- 24 Shepherd, T.G., 2014: Atmospheric circulation as a source of uncertainty in climate change
25 projections. *Nature Geoscience*, **7**, 703-708. <http://dx.doi.org/10.1038/ngeo2253>
- 26 Shields, C.A. and J.T. Kiehl, 2016: Atmospheric river landfall-latitude changes in future climate
27 simulations. *Geophysical Research Letters*, **43**, 8775-8782.
28 <http://dx.doi.org/10.1002/2016GL070470>
- 29 Sun, L., K.E. Kunkel, L.E. Stevens, A. Buddenberg, J.G. Dobson, and D.R. Easterling, 2015:
30 Regional Surface Climate Conditions in CMIP3 and CMIP5 for the United States:
31 Differences, Similarities, and Implications for the U.S. National Climate Assessment.
32 National Oceanic and Atmospheric Administration, National Environmental Satellite, Data,
33 and Information Service, 111 pp. <http://dx.doi.org/10.7289/V5RB72KG>

- 1 Taylor, K.E., R.J. Stouffer, and G.A. Meehl, 2012: An overview of CMIP5 and the experiment
2 design. *Bulletin of the American Meteorological Society*, **93**, 485-498.
3 <http://dx.doi.org/10.1175/BAMS-D-11-00094.1>
- 4 Vaughan, D.G., J.C. Comiso, I. Allison, J. Carrasco, G. Kaser, R. Kwok, P. Mote, T. Murray, F.
5 Paul, J. Ren, E. Rignot, O. Solomina, K. Steffen, and T. Zhang, 2013: Observations:
6 Cryosphere. *Climate Change 2013: The Physical Science Basis. Contribution of Working*
7 *Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.*
8 Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia,
9 V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom
10 and New York, NY, USA, 317–382. <http://www.climatechange2013.org/report/full-report/>
- 11 Vavrus, S., M. Notaro, and A. Zarrin, 2013: The role of ice cover in heavy lake-effect
12 snowstorms over the Great Lakes Basin as simulated by RegCM4. *Monthly Weather Review*,
13 **141**, 148-165. <http://dx.doi.org/10.1175/mwr-d-12-00107.1>
- 14 Villarini, G., D.A. Lavers, E. Scoccimarro, M. Zhao, M.F. Wehner, G.A. Vecchi, T.R. Knutson,
15 and K.A. Reed, 2014: Sensitivity of tropical cyclone rainfall to idealized global-scale
16 forcings. *Journal of Climate*, **27**, 4622-4641. <http://dx.doi.org/10.1175/JCLI-D-13-00780.1>
- 17 Vose, R.S., S. Applequist, M. Squires, I. Durre, M.J. Menne, C.N. Williams, Jr., C. Fenimore, K.
18 Gleason, and D. Arndt, 2014: Improved historical temperature and precipitation time series
19 for U.S. climate divisions. *Journal of Applied Meteorology and Climatology*, **53**, 1232-1251.
20 <http://dx.doi.org/10.1175/JAMC-D-13-0248.1>
- 21 Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, P. Thorne, R. Vose, M.
22 Wehner, J. Willis, D. Anderson, S. Doney, R. Feely, P. Hennon, V. Kharin, T. Knutson, F.
23 Landerer, T. Lenton, J. Kennedy, and R. Somerville, 2014: Ch. 2: Our changing climate.
24 *Climate Change Impacts in the United States: The Third National Climate Assessment.*
25 Melillo, J.M., T.C. Richmond, and G.W. Yohe, Eds. U.S. Global Change Research Program,
26 Washington, D.C., 19-67. <http://dx.doi.org/10.7930/J0KW5CXT>
- 27 Wang, C.-C., B.-X. Lin, C.-T. Chen, and S.-H. Lo, 2015: Quantifying the effects of long-term
28 climate change on tropical cyclone rainfall using a cloud-resolving model: Examples of two
29 landfall typhoons in Taiwan. *Journal of Climate*, **28**, 66-85. [http://dx.doi.org/10.1175/JCLI-](http://dx.doi.org/10.1175/JCLI-D-14-00044.1)
30 [D-14-00044.1](http://dx.doi.org/10.1175/JCLI-D-14-00044.1)
- 31 Wehner, M.F., 2013: Very extreme seasonal precipitation in the NARCCAP ensemble: Model
32 performance and projections. *Climate Dynamics*, **40**, 59-80.
33 <http://dx.doi.org/10.1007/s00382-012-1393-1>
- 34 Wehner, M.F., K.A. Reed, F. Li, Prabhat, J. Bacmeister, C.-T. Chen, C. Paciorek, P.J. Gleckler,
35 K.R. Sperber, W.D. Collins, A. Gettelman, and C. Jablonowski, 2014: The effect of

- 1 horizontal resolution on simulation quality in the Community Atmospheric Model, CAM5.1.
2 *Journal of Advances in Modeling Earth Systems*, **6**, 980-997.
3 <http://dx.doi.org/10.1002/2013MS000276>
- 4 Westra, S., L.V. Alexander, and F.W. Zwiers, 2013: Global increasing trends in annual
5 maximum daily precipitation. *Journal of Climate*, **26**, 3904-3918.
6 <http://dx.doi.org/10.1175/JCLI-D-12-00502.1>
- 7 Wright, D.M., D.J. Posselt, and A.L. Steiner, 2013: Sensitivity of lake-effect snowfall to lake ice
8 cover and temperature in the Great Lakes region. *Monthly Weather Review*, **141**, 670-689.
9 <http://dx.doi.org/10.1175/mwr-d-12-00038.1>
- 10 Zhang, X., H. Wan, F.W. Zwiers, G.C. Hegerl, and S.-K. Min, 2013: Attributing intensification
11 of precipitation extremes to human influence. *Geophysical Research Letters*, **40**, 5252-5257.
12 <http://dx.doi.org/10.1002/grl.51010>

13

8. Droughts, Floods, and Wildfires

KEY FINDINGS

1. Recent droughts and associated heat waves have reached record intensity in some regions of the United States; however, by geographical scale and duration, the Dust Bowl era of the 1930s remains the benchmark drought and extreme heat event in the historical record (*very high confidence*). While by some measures, drought has decreased over much of the continental United States in association with long-term increases in precipitation, neither the precipitation increases nor inferred drought decreases have been confidently attributed to anthropogenic forcing.
2. The human effect on recent major U.S. droughts is complicated. Little evidence is found for a human influence on observed precipitation deficits, but much evidence is found for a human influence on surface soil moisture deficits due to increased evapotranspiration caused by higher temperatures. (*High confidence*)
3. Future decreases in surface (top 10 cm) soil moisture from anthropogenic forcing over most of the United States are *likely* as the climate warms under the higher emissions scenarios. (*Medium confidence*)
4. Substantial reductions in western U.S. winter and spring snowpack are projected as the climate warms. Earlier spring melt and reduced snow water equivalent have been formally attributed to human induced warming (*high confidence*) and will *very likely* be exacerbated as the climate continues to warm (*very high confidence*). Under higher emissions scenarios, and assuming no change to current water resources management, chronic, long-duration hydrological drought is increasingly possible by the end of this century (*very high confidence*).
5. Detectable changes in some classes of flood frequency have occurred in parts of the United States and are a mix of increases and decreases. Extreme precipitation, one of the controlling factors in flood statistics, is observed to have generally increased and is projected to continue to do so across the United States in a warming atmosphere. However, formal attribution approaches have not established a significant connection of increased riverine flooding to human-induced climate change, and the timing of any emergence of a future detectable anthropogenic change in flooding is unclear. (*Medium confidence*)
6. The incidence of large forest fires in the western United States and Alaska has increased since the early 1980s (*high confidence*) and is projected to further increase in those regions as the climate warms, with profound changes to certain ecosystems (*medium confidence*).

1 **8.1. Drought**

2 The word “drought” brings to mind abnormally dry conditions. However, the meaning of “dry”
3 can be ambiguous and lead to confusion in how drought is actually defined. Three different
4 classes of droughts are defined by NOAA and describe a useful hierarchal set of water deficit
5 characterization, each with different impacts. “Meteorological drought” describes conditions of
6 precipitation deficit. “Agricultural drought” describes conditions of soil moisture deficit.
7 “Hydrological drought” describes conditions of deficit in runoff (NOAA 2008). Clearly these
8 three characterizations of drought are related but are also different descriptions of water
9 shortages with different target audiences and different timescales. In particular, agricultural
10 drought is of concern to producers of food while hydrological drought is of concern to water
11 system managers. Soil moisture is a function of both precipitation and evapotranspiration.
12 Because potential evapotranspiration increases with temperature, anthropogenic climate change
13 generally results in drier soils and often less runoff in the long term. In fact, under the RCP8.5
14 scenario (see Ch. 4: Projections for a description of the RCP scenarios) at the end of the 21st
15 century, no region of the planet is projected to experience significantly higher levels of annual
16 average surface soil moisture due to the sensitivity of evapotranspiration to temperature, even
17 though much higher precipitation is projected in some regions (Collins et al. 2013). Seasonal and
18 annual total runoff, on the other hand, are projected to either increase or decrease, depending on
19 location and season under the same conditions (Collins et al. 2013), illustrating the complex
20 relationships between the various components of the hydrological system. Meteorological
21 drought can occur on a range of timescales, in addition to seasonal or annual timescales. “Flash
22 droughts” can result from just a few weeks of dry weather (Mo and Lettenmaier 2015), and the
23 paleoclimate record contains droughts of several decades. Hence, it is vital to describe precisely
24 the definition of drought in any public discussion to avoid confusion due to this complexity. As
25 the climate changes, conditions currently considered “abnormally” dry may become relatively
26 “normal” in those regions undergoing aridification, or extremely unlikely in those regions
27 becoming wetter. Hence, the reference conditions defining drought may need to be modified
28 from those currently used in practice.

29 **8.1.1. Historical Context**

30 The United States has experienced all three types of droughts in the past, always driven, at least
31 in some part, by natural variations in seasonal and/or annual precipitation amounts. As the
32 climate changes, we can expect that human activities will alter the effect of these natural
33 variations. The “Dust Bowl” drought of the 1930s is still the most significant meteorological and
34 agricultural drought experienced in the United States in terms of its geographic and temporal
35 extent. However, even though it happened prior to most of the current global warming, human
36 activities exacerbated the dryness of the soil by the farming practices of the time (Bennet et al.
37 1936). Tree ring archives reveal that such droughts (in the agricultural sense) have occurred
38 occasionally over the last 1,000 years (Cook et al. 2004). Climate model simulations suggest that

1 droughts lasting several years to decades occur naturally in the southwestern United States
2 (Coats et al. 2015). The Intergovernmental Panel on Climate Change Fifth Assessment Report
3 (IPCC AR5; Bindoff et al. 2013) concluded “there is low confidence in detection and attribution
4 of changes in (meteorological) drought over global land areas since the mid-20th century, owing
5 to observational uncertainties and difficulties in distinguishing decadal-scale variability in
6 drought from long-term trends.” As they noted, this was a weaker attribution statement than in
7 the Fourth Assessment Report (Hegerl et al. 2007), which had concluded “that an increased risk
8 of drought was *more likely than not* due to anthropogenic forcing during the second half of the
9 20th century.” The weaker statement in AR5 reflected additional studies with conflicting
10 conclusions on global drought trends (e.g., Sheffield et al. 2012; Dai 2013). Western North
11 America was noted as a region where determining if observed recent droughts were unusual
12 compared to natural variability was particularly difficult. This was due to evidence from
13 paleoclimate proxies of cases of central U.S. droughts during the past 1,000 years that were
14 longer and more intense than historical U.S. droughts (Masson-Delmotte et al. 2013). Drought is,
15 of course, directly connected to seasonal precipitation totals. Figure 7.1 shows detectable
16 observed recent changes in seasonal precipitation. In fact, the increases in observed summer and
17 fall precipitation are at odds with the projections in Figure 7.5. As a consequence of this
18 increased precipitation, drought statistics over the entire CONUS have declined (Andreadis and
19 Lettenmaier 2006; Mo and Lettenmaier 2015). Furthermore, there is no detectable change in
20 meteorological drought at the global scale (Sheffield et al. 2012). However, a number of
21 individual event attribution studies suggest that if a drought occurs, anthropogenic temperature
22 increases can exacerbate soil moisture deficits (e.g., Seager et al. 2015; Trenberth et al. 2014).
23 Future projections of the anthropogenic contribution to changes in drought risk and severity must
24 be considered in the context of the significant role of natural variability.

25 **8.1.2. Recent Major U.S. Droughts**

26 **METEOROLOGICAL AND AGRICULTURAL DROUGHT**

27 The United States has suffered a number of very significant droughts of all types since 2011.
28 Each of these droughts was a result of different persistent, large-scale meteorological patterns of
29 mostly natural origins, with varying degrees of attributable human influence. Table 8.1
30 summarizes available attribution statements for recent extreme U.S. droughts. Statements about
31 meteorological drought are decidedly mixed, revealing the complexities in interpreting the low
32 tail of the distribution of precipitation. Statements about agricultural drought consistently
33 maintain a human influence if only surface soil moisture measures are considered. The single
34 agricultural drought attribution study at root depth comes to the opposite conclusion (Cheng et
35 al. 2016). In all cases, these attribution statements are examples of attribution without detection
36 (see Appendix C). The absence of moisture during the 2011 Texas/Oklahoma drought and heat
37 wave was found to be an event whose likelihood was enhanced by the La Niña state of the ocean,
38 but the human interference in the climate system still doubled the chances of reaching such high

1 temperatures (Hoerling et al. 2013). This study illustrates that the effect of human-induced
2 climate change is combined with natural variations and can compound or inhibit the realized
3 severity of any given extreme weather event.

4 **[INSERT TABLE 8.1 HERE]**

5 The Great Plains/Midwest drought of 2012 was the most severe summer meteorological drought
6 in the observational record for that region (Hoerling et al. 2014). An unfortunate string of three
7 different patterns of large-scale meteorology from May through August 2012 precluded the
8 normal frequency of summer thunderstorms, and was not predicted by the NOAA seasonal
9 forecasts (Hoerling et al. 2014). Little influence of the global sea surface temperature (SST)
10 pattern on meteorological drought frequency has been found in model simulations (Hoerling et
11 al. 2014). No evidence of a human contribution to the 2012 precipitation deficit in the Great
12 Plains and Midwest is found in numerous studies (Rupp et al. 2013; Hoerling et al. 2014; Angéilil
13 et al. 2017). However, an alternative view is that the 2012 central U.S. drought can be classified
14 as a “heat wave flash drought” (Mo and Lettenmaier 2016), a type of rapidly evolving drought
15 that has decreased in frequency over the past century (Mo and Lettenmaier 2015). Also, an
16 increase in the chances of the unusually high temperatures seen in the United States in 2012,
17 partly associated with resultant dry summer soil moisture anomalies, was attributed to the human
18 interference with the climate system (Diffenbaugh and Scherer 2013), indicating the strong
19 feedback between lower soil moisture and higher surface air temperatures during periods of low
20 precipitation. One study found that most, but not all, of the 2012 surface moisture deficit in the
21 Great Plains was attributable to the precipitation deficit (Livneh and Hoerling 2016). That study
22 also noted that Great Plains root depth and deeper soil moisture was higher than normal in 2012
23 despite the surface drying, due to wet conditions in prior years, indicating the long timescales
24 relevant below the surface (Livneh and Hoerling 2016).

25 The recent California drought, which began in 2011, is unusual in different respects. In this case,
26 the precipitation deficit from 2011 to 2014 was a result of the “ridiculously resilient ridge” of
27 high pressure. This very stable high pressure system steered storms towards the north, away from
28 the highly engineered California water resource system (Swain et al. 2014; Seager et al. 2014,
29 2015). The ridge itself was due to a slow-moving high sea surface temperature (SST) anomaly,
30 referred to as “The Blob”—which was caused by a persistent ridge that weakened the normal
31 cooling mechanisms for that region of the upper ocean (Bond et al. 2015). Atmospheric
32 modeling studies showed that the ridge that caused the Blob was favored by a pattern of
33 persistent tropical SST anomalies that were warm in the western equatorial Pacific and
34 simultaneously cool in the far eastern equatorial Pacific (Hartman 2015; Seager et al. 2014). It
35 was also favored by reduced arctic sea ice and from feedbacks with “The Blob” SST anomalies
36 (Lee et al. 2015). These studies also suggest that internal variability likely played a prominent
37 role in the persistence of the 2013–2014 ridge off the west coast of North America. A principal
38 attribution question regarding the precipitation deficit concerns the causes of this SST anomaly.

1 Observational records are not long enough and the anomaly was unusual enough that similarly
2 long-lived patterns have not been often seen before. Hence, attribution statements, such as that
3 about an increasing anthropogenic influence on the frequency of geopotential height anomalies
4 similar to 2012–2014 (e.g., Swain et al. 2014), are without associated detection (Ch. 3: Detection
5 and Attribution). A secondary attribution question concerns the anthropogenic precipitation
6 response in the presence of this SST anomaly. In attribution studies with a prescribed 2013 SST
7 anomaly, a consistent increase in the human influence on the chances of very dry California
8 conditions was found (Angélil et al. 2017).

9 Anthropogenic climate change did increase the risk of the high temperatures in California in the
10 winters of 2013–2014 and 2014–2015, especially the latter (Seager et al. 2015; Diffenbaugh et
11 al. 2015; Wang and Schubert 2014), further exacerbating the soil moisture deficit and the
12 associated stress on irrigation systems. This raises the question, as yet unanswered, of whether
13 droughts in the western United States are shifting from precipitation control (Mao et al. 2015) to
14 temperature control. There is some evidence to support a relationship between mild winter and/or
15 warm spring temperatures and drought occurrence (Mote et al. 2016), but long-term warming
16 trends in the tropical and North Pacific do not appear to have led to trends toward less
17 precipitation over California (Funk et al. 2014). An anthropogenic contribution to commonly
18 used measures of agricultural drought, including the Palmer Drought Severity Index (PDSI), was
19 found in California (Diffenbaugh et al. 2015; Williams et al. 2015) and is consistent with
20 previous projections of changes in PDSI (Dai 2013; Wehner et al. 2011; Walsh et al. 2014) and
21 with an attribution study (Brown et al. 2008). Due to its simplicity, the PDSI has been criticized
22 as being overly sensitive to higher temperatures and thus may exaggerate the human contribution
23 to soil dryness (Milly and Dunne 2016). In fact, this study also finds that formulations of
24 potential evaporation used in more complicated hydrologic models are similarly biased,
25 undermining confidence in the magnitude but not the sign of projected surface soil moisture
26 changes in a warmer climate. Seager et al. (2015) analyzed climate model output directly,
27 finding that precipitation minus evaporation in the southwestern United States is projected to
28 experience significant decreases in surface water availability, leading to surface runoff decreases
29 in California, Nevada, Texas, and the Colorado River headwaters even in the near term.
30 However, the criticisms of PDSI also apply to most of the CMIP5 land surface model
31 evapotranspiration formulations. Analysis of soil moisture in the CMIP5 models at deeper levels
32 is complicated by the wide variety in sophistication of their component land models. A pair of
33 studies reveals less sensitivity at depth to surface air temperature increases than at near surface
34 levels (Cook et al. 2015; Cheng et al. 2016). Berg et al. (2017) adjust for the differences in land
35 component model vertical treatments, finding projected change in vertically integrated soil
36 moisture down to 3 meters depth is mixed, with projected decreases in the Southwest and in the
37 south central United States, but increases over the northern plains. Nonetheless, the warming
38 trend has led to declines in a number of indicators, including Sierra snow water equivalent, that
39 are relevant to hydrological drought (Mao et al. 2015). Attribution of the California drought and
40 heat wave remains an interesting and controversial research topic.

1 In summary, there has not yet been a formal identification of a human influence on past changes
2 in United States meteorological drought through the analysis of precipitation trends. Some, but
3 not all, U.S. meteorological drought event attribution studies, largely in the “without detection”
4 class, exhibit a human influence. Attribution of a human influence on past changes in U.S.
5 agricultural drought are limited both by availability of soil moisture observations and a lack of
6 sub-surface modeling studies. While a human influence on surface soil moisture trends has been
7 identified with *medium confidence*, its relevance to agriculture may be exaggerated.

8 **RUNOFF AND HYDROLOGICAL DROUGHT**

9 Several studies focused on the Colorado River basin in the United States that used more
10 sophisticated runoff models driven by the CMIP3 models (Christensen and Lettenmaier 2007;
11 McCabe and Wolock 2007; Barnett and Pierce 2009; Barnett et al. 2008; Hoerling et al. 2009)
12 showed that annual runoff reductions in a warmer western United States climate occur through a
13 combination of evapotranspiration increases and precipitation decreases, with the overall
14 reduction in river flow exacerbated by human water demands on the basin’s supply. Reduced
15 U.S. snowfall accumulations in much warmer future climates are virtually certain as frozen
16 precipitation is replaced by rain regardless of the projected changes in total precipitation amounts
17 discussed in Chapter 7: Precipitation Change (Figure 7.6). The profound change in the hydrology
18 of snowmelt-driven flows in the western United States is well documented. Earlier spring runoff
19 (Stewart et al. 2005) reduced the fraction of precipitation falling as snow (Knowles et al. 2006)
20 and the snowpack water content at the end of winter (Mote 2003; Mote et al. 2005), consistent
21 with warmer temperatures. Formal detection and attribution (Ch. 3: Detection and Attribution) of
22 the observed shift towards earlier snowmelt driven flows in the western United States reveals
23 that the shift is detectably different from natural variability and attributable to anthropogenic
24 climate change (Hidalgo et al 2009). Similarly, observed declines in the snow water equivalent in
25 the region have been formally attributed to anthropogenic climate change (Pierce et al. 2008) as
26 have temperature, river flow, and snow pack (Barnett et al. 2008; Bonfils et al. 2008). As a
27 harbinger of things to come, the unusually low western U.S. snowpack of 2015 may become the
28 norm (Mote et al. 2016).

29 In the northwestern United States, long-term trends in streamflow have seen declines, with the
30 strongest trends in drought years (Luce and Holden 2009) that are attributed to a decline in
31 winter precipitation (Luce et al. 2013). These reductions in precipitation are linked to decreased
32 westerly wind speeds in winter over the region. Furthermore, the trends in westerlies are
33 consistent with CMIP5-projected wind speed changes due to a decreasing meridional
34 temperature and pressure gradients rather than low-frequency climate variability modes. Such
35 precipitation changes have been a primary source of change in hydrological drought in the
36 Northwest over the last 60 years (Kormos et al. 2016) and are in addition to changes in snowpack
37 properties.

1 We conclude with *high confidence* that these observed in changes temperature controlled aspects
2 of western U.S. hydrology are *likely* a consequence of human changes to the climate system.

3 **8.1.3. Projections of Future Droughts**

4 The future changes in seasonal precipitation shown in Chapter 7: Precipitation Change (Figure
5 7.6) indicate that the southwestern United States may experience chronic future precipitation
6 deficits, particularly in the spring. In much warmer climates, expansion of the tropics and
7 subtropics, traceable to changes in the Hadley circulation, cause shifts in seasonal precipitation
8 that are particularly evident in such arid and semi-arid regions and increase the risk of
9 meteorological drought. However, uncertainty in the magnitude and timing of future
10 southwestern drying is high. We note that the weighted and downscaled projections of Figure 7.6
11 exhibit significantly less drying and are assessed to be less significant in comparison to natural
12 variations than the original unweighted CMIP5 projections (Walsh et al. 2014).

13 Western U.S. hydrological drought is currently controlled by the frequency and intensity of
14 extreme precipitation events, particularly atmospheric rivers, as these events represent the source
15 of nearly half of the annual water supply and snowpack for the western coastal states (Dettinger
16 2011; Guan et al. 2013). Climate projections indicate greater frequency of atmospheric rivers in
17 the future (e.g., Dettinger 2011; Warner et al. 2015; Gao et al. 2015; see further discussion in Ch.
18 9: Extreme Storms). Sequences of these extreme storms have played a critical role in ending
19 recent hydrological droughts along the U.S. West Coast (Dettinger 2013). However, as winter
20 temperatures increase, the fraction of precipitation falling as snow will decrease, potentially
21 disrupting western U.S. water management practices.

22 Significant U.S. seasonal precipitation deficits are not confidently projected outside of the
23 Southwest. However, future higher temperatures will *likely* lead to greater frequencies and
24 magnitudes of agricultural droughts throughout the continental United States as the resulting
25 increases in evapotranspiration outpace projected precipitation increases (Collins et al. 2013).
26 Figure 8.1 shows the weighted multimodel projection of the percent change in near-surface soil
27 moisture at the end of the 21st century under the RCP8.5 scenario, indicating widespread drying
28 over the entire continental United States. Previous National Climate Assessments (Karl et al.
29 2009; Walsh et al. 2014) have discussed the implication of these future drier conditions in the
30 context of the Palmer Drought Severity Index (PDSI), finding that the future normal condition
31 would be considered drought at the present time, and that the incidence of “extreme drought”
32 (PDSI < -4) would be significantly increased. However, as described below, the PDSI may
33 overestimate future soil moisture drying.

34 This projection is made “without attribution” (Ch. 4: Projections), but confidence that future
35 soils will generally be drier at the surface is *medium*, as the mechanisms leading to increased
36 evapotranspiration in a warmer climate are elementary scientific facts. However, the land surface
37 component models in the CMIP5 climate models vary greatly in their sophistication, causing the

1 projected magnitude of both the average soil moisture decrease and the increased risk for
2 agricultural drought to be less certain. The weighted projected seasonal decreases in surface soil
3 moisture are generally towards drier conditions, even in regions and seasons where precipitation
4 is projected to experience large increases (Figure 7.6) due to increases in the evapotranspiration
5 associated with higher temperature. Drying is assessed to be large relative to natural variations in
6 much of the CONUS region in the summer. Significant spring and fall drying is also projected in
7 the mountainous western states, with potential implications for forest and wildfire risk. Also, the
8 combination of significant summer and fall drying in the midwestern states has potential
9 agricultural implications. The largest percent changes are projected in the southwestern United
10 States and are consistent in magnitude with an earlier study of the Colorado River Basin using
11 more sophisticated macroscale hydrological models (Christensen and Lettenmaier 2007).

12 In this assessment, we limit the direct CMIP5 weighted multimodel projection of soil moisture
13 shown in Figure 8.1 to the surface (defined as the top 10 cm of the soil), as the land surface
14 component sub-models vary greatly in their representation of the total depth of the soil. A more
15 relevant projection to agricultural drought would be the soil moisture at the root depth of typical
16 U.S. crops. Cook et al. (2015) find that future drying at a depth of 30 cm will be less than at 2
17 cm, but still significant and comparable to a modified PDSI formulation. Few of the CMIP5 land
18 models have detailed ecological representations of evapotranspiration processes, causing the
19 simulation of the soil moisture budget to be less constrained than reality (Williams and Torn
20 2015). Over the western United States, unrealistically low elevations in the CMIP5 models due
21 to resolution constraints present a further challenge in interpreting evapotranspiration changes.
22 Nonetheless, Figure 8.1 shows a projected drying of surface soil moisture across nearly all of the
23 coterminous United States in all seasons, even in regions and seasons where precipitation is
24 projected to increase, consistent with increased evapotranspiration due to elevated temperatures
25 (Cook et al. 2015).

26 Widespread reductions in mean snowfall across North America are projected by the CMIP5
27 models (O’Gorman 2014). Together with earlier snowmelt at altitudes high enough for snow,
28 disruptions in western U.S. water delivery systems are expected to lead to more frequent
29 hydrological drought conditions (Barnett et al. 2008; Pierce et al. 2008; Barnett and Pierce 2009;
30 Cayan et al. 2010; Das et al. 2011). Due to resolution constraints, the elevation of mountains as
31 represented in the CMIP5 models is too low to adequately represent the effects of future
32 temperature on snowpacks. However, increased model resolution has been demonstrated to have
33 important impacts on future projections of snowpack water content in warmer climates and is
34 enabled by recent advances in high performance computing (Kapnick and Delworth 2013).
35 Figure 8.2 and Table 8.2 show a projection of changes in western U.S. mountain winter
36 (December, January, and February) hydrology obtained from a different high-resolution
37 atmospheric model at the middle and end of the 21st century under the RCP8.5 scenario. These
38 projections indicate dramatic reductions in all aspects of snow (Rhoades et al. 2017) and are
39 similar to previous statistically downscaled projections (Cayan et al. 2013; Klos et al. 2014).

1 Table 8.2 reveals that the reductions in snow water equivalent accelerate in the latter half of this
2 century under this emissions scenario and with substantial variations across the western United
3 States. Changes in snow residence time, an alternative measure of snowpack relevant to the
4 timing of runoff, is also shown to be sensitive to elevation, with widespread reductions across
5 this region (Luce et al. 2014). Given the larger projected increases in temperature at high
6 altitudes compared to adjacent lower altitudes (Pierce and Cayan 2013) and the resulting changes
7 in both snowpack depth and melt timing in very warm future scenarios such as RCP8.5, and
8 assuming no change to water resource management practices, several important western U.S.
9 snowpack reservoirs effectively disappear by 2100 in this dynamical projection, resulting in
10 chronic, long-lasting hydrological drought. This dramatic statement is also supported by two
11 climate model studies: a multimodel statistical downscaling of the CMIP5 RCP8.5 ensemble that
12 finds large areal reductions in snow dominated regions of the western United States by mid-
13 century and complete elimination of snow-dominated regions in certain watersheds (Klos et al.
14 2014), and a large ensemble simulation of a global climate model (Fyfe et al. 2017).

15 As earlier spring melt and reduced snow water equivalent has been formally attributed to human
16 induced warming, substantial reductions in western U.S. winter and spring snowpack are
17 projected (with attribution) to be *very likely* as the climate warms as the climate continues to
18 warm (*very high confidence*). Under higher emissions scenarios and assuming no change to
19 current water-resources management, chronic, long-duration hydrological drought is increasingly
20 possible by the end of this century (*very high confidence*).

21 **[INSERT FIGURES 8.1 AND 8.2 HERE]**

22 **8.2. Floods**

23 Flooding damage in the United States can come from flash floods of smaller rivers and creeks,
24 prolonged flooding along major rivers, urban flooding unassociated with proximity to a
25 riverway, coastal flooding from storm surge which may be exacerbated by sea level rise, and the
26 confluence of coastal storms and inland riverine flooding from the same precipitation event (Ch.
27 12: Sea Level Rise). Flash flooding is associated with extreme precipitation somewhere along the
28 river which may occur upstream of the regions at risk. Flooding of major rivers in the United
29 States with substantial winter snow accumulations usually occurs in the late winter or spring and
30 can result from an unusually heavy seasonal snowfall followed by a “rain on snow” event or
31 from a rapid onset of higher temperatures that leads to rapid snow melting within the river basin.
32 In the western coastal states, most flooding occurs in conjunction with extreme precipitation
33 events referred to as “atmospheric rivers” (see Ch. 9: Extreme Storms) (Ralph and Dettinger
34 2011; Neiman et al. 2011), with mountain snowpack being vulnerable to these typically warmer-
35 than-normal storms and their potential for rain on existing snow cover (Guan et al. 2016).
36 Hurricanes and tropical storms are an important driver of flooding events in the eastern United
37 States. Changes in streamflow rates depend on many factors, both human and natural, in
38 addition to climate change. Deforestation, urbanization, dams, floodwater management activities,

1 and changes in agricultural practices can all play a role in past and future changes in flood
2 statistics. Projection of future changes is thus a complex multivariate problem (Walsh et al.
3 2014).

4 The IPCC AR5 (Bindoff et al. 2013) did not attribute changes in flooding to anthropogenic
5 influence nor report detectable changes in flooding magnitude, duration or frequency. Trends in
6 extreme high values of streamflow are mixed across the United States (Walsh et al. 2014;
7 Archfield et al. 2016; EPA 2016). Analysis of 200 U.S. stream gauges indicates areas of both
8 increasing and decreasing flooding magnitude (Hirsch and Ryberg 2012) but does not provide
9 robust evidence that these trends are attributable to human influences. Significant increases in
10 flood frequency have been detected in about one-third of stream gauge stations examined for the
11 central United States, with a much stronger signal of frequency change than is found for changes
12 in flood magnitude in these gauges (Mallakpour and Villarini 2015). This apparent disparity with
13 ubiquitous increases in observed extreme precipitation (Figure 7.2) can be partly explained by
14 the seasonality of the two phenomena. Extreme precipitation events in the eastern half of the
15 CONUS are larger in the summer and fall when soil moisture and seasonal streamflow levels are
16 low and less favorable for flooding (Wehner 2013). By contrast, high streamflow events are
17 often larger in the spring and winter when soil moisture is high and snowmelt and frozen ground
18 can enhance runoff (Frei et al. 2015). Furthermore, floods may be poorly explained by daily
19 precipitation characteristics alone; the relevant mechanisms are more complex, involving
20 processes that are seasonally and geographically variable, including the seasonal cycles of soil
21 moisture content and snowfall/snowmelt (Berghuijs et al. 2016).

22 Recent analysis of annual maximum streamflow shows statistically significant trends in the
23 upper Mississippi River valley (increasing) and in the Northwest (decreasing) (McCabe and
24 Wolock 2014). In fact, across the midwestern United States, statistically significant increases in
25 flooding are well documented (Groisman et al. 2001; Novotny and Stefan 2007; Tomer and
26 Schilling 2009; Ryberg et al. 2014; Villarini and Strong 2014; Slater et al. 2015; Mallakpour and
27 Villarini 2015, 2016). These increases in flood risk and severity are not attributed to 20th century
28 changes in agricultural practices (Tomer and Schilling 2009; Frans et al. 2013) but instead are
29 attributed mostly to the observed increases in precipitation shown in Figures 7.1 through 7.4
30 (Novotny and Stefan 2007; Wang and Hejazi 2011; Frans et al. 2013; Mallakpour and Villarini
31 2015). Trends in maximum streamflow in the northeastern United States are less dramatic and
32 less spatially coherent (McCabe and Wolock 2014; Frei et al. 2015), although one study found
33 mostly increasing trends (Armstrong et al. 2014) in that region, consistent with the increasing
34 trends in observed extreme precipitation in the region (Ch. 6: Temperature Change; Walsh et al.
35 2014; Frei et al. 2015).

36 The nature of the proxy archives complicates the reconstruction of past flood events in a gridded
37 fashion as has been done with droughts. However, reconstructions of past river outflows do exist.
38 For instance, it has been suggested that the mid-20th century river allocations for the Colorado

1 River were made during one of the wettest periods of the past five centuries (Woodhouse et al.
2 2006). For the eastern United States, the Mississippi River has undergone century-scale
3 variability in flood frequency—perhaps linked to the moisture availability in the central United
4 States and the temperature structure of the Atlantic Ocean (Munoz et al. 2015).

5 The complex mix of processes complicates the formal attribution of observed flooding trends to
6 anthropogenic climate change and suggests that additional scientific rigor is needed in flood
7 attribution studies (Merz et al. 2012). As noted above, precipitation increases have been found to
8 strongly influence changes in flood statistics. However, in U.S. regions, no formal attribution of
9 precipitation changes to anthropogenic forcing has been made so far, so indirect attribution of
10 flooding changes is not possible. Hence, no formal attribution of observed flooding changes to
11 anthropogenic forcing has been claimed (Mallakpour and Villarini 2015).

12 A projection study based on coupling an ensemble of regional climate model output to a
13 hydrology model (Najafi and Moradkhani 2015) finds that the magnitude of future very extreme
14 runoff (which can lead to flooding) is decreased in most of the summer months in Washington
15 State, Oregon, Idaho, and western Montana but substantially increases in the other seasons.
16 Projected weighted increases in extreme runoff from the coast to the Cascade Mountains are
17 particularly large in that study during the fall and winter which are not evident in the weighted
18 seasonal averaged CMIP5 runoff projections (Collins et al. 2013). For the West Coast of the
19 United States, extremely heavy precipitation from intense atmospheric river storms is an
20 important factor in flood frequency and severity (Dettinger 2011; Dettinger et al. 2011).
21 Projections indicate greater frequency of heavy atmospheric rivers in the future (e.g., Dettinger et
22 al. 2011; Warner et al. 2015; Gao et al. 2015; see further discussion in Ch. 9: Extreme Storms).
23 Translating these increases in atmospheric river frequency to their impact on flood frequency
24 requires a detailed representation of western states topography in the global projection models
25 and/or via dynamic downscaling to regional models and is a rapidly developing science. In a
26 report prepared for the Federal Insurance and Mitigation Administration of the Federal
27 Emergency Management Agency, a regression-based approach of scaling river gauge data based
28 on seven commonly used climate change indices from the CMIP3 database (Tebaldi et al. 2006)
29 found that at the end of the 21st century the 1% annual chance floodplain area would increase in
30 area by about 30%, with larger changes in the Northeast and Great Lakes regions and smaller
31 changes in central part of the country and the Gulf Coast (AECOM 2013).

32 Urban flooding results from heavy precipitation events that overwhelm the existing sewer
33 infrastructure's ability to convey the resulting stormwater. Future increases in daily and sub-
34 daily extreme precipitation rates will require significant upgrades to many communities' storm
35 sewer systems, as will sea level rise in coastal cities and towns (SFPUC 2016; Winters et al.
36 2015).

37 No studies have formally attributed (see Ch. 3: Detection and Attribution) long-term changes in
38 observed flooding of major rivers in the United States to anthropogenic forcing. We conclude

1 that there is *medium confidence* that detectable (though not attributable to anthropogenic forcing
2 changes) increases in flood statistics have occurred in parts of the central United States. Key
3 Finding 3 of Chapter 7: Precipitation Change states that the frequency and intensity of heavy
4 precipitation events are projected to continue to increase over the 21st century with *high*
5 *confidence*. Given the connection between extreme precipitation and flooding, and the
6 complexities of other relevant factors, we concur with the IPCC Special Report on Extremes
7 (SREX) assessment of “medium confidence (based on physical reasoning) that projected
8 increases in heavy rainfall would contribute to increases in local flooding in some catchments or
9 regions” (IPCC 2012).

10 Existing studies of individual extreme flooding events are confined to changes in the locally
11 responsible precipitation event and have not included detailed analyses of the events’ hydrology.
12 Gochis et al. (2015) describes the massive floods of 2013 along the Colorado front range,
13 estimating that the streamflow amounts ranged from 50- to 500-year return values across the
14 region. Hoerling et al. (2014) analyzed the 2013 northeastern Colorado heavy multiday
15 precipitation event and resulting flood, finding little evidence of an anthropogenic influence on
16 its occurrence. However, Pall et al. (2017) challenge their event attribution methodology with a
17 more constrained study and find that the thermodynamic response of precipitation in this event
18 due to anthropogenic forcing was substantially increased. The Pall et al. (2017) approach does
19 not rule out that the likelihood of the extremely rare large-scale meteorological pattern
20 responsible for the flood may have changed.

21 **8.3 Wildfires**

22 A global phenomenon with natural (lightning) and human-caused ignition sources, wildfire
23 represents a critical ecosystem process. Recent decades have seen a profound increase in forest
24 fire activity over the western United States and Alaska (Westerling et al. 2006; Running 2006;
25 Higuera et al 2015; Abatzoglou and Williams 2016). The frequency of large wildfires is
26 influenced by a complex combination of natural and human factors. Temperature, soil moisture,
27 relative humidity, wind speed, and vegetation (fuel density) are important aspects of the
28 relationship between fire frequency and ecosystems. Forest management and fire suppression
29 practices can also alter this relationship from what it was in the preindustrial era. Changes in
30 these control parameters can interact with each other in complex ways with the potential for
31 tipping points—in both fire frequency and in ecosystem properties—that may be crossed as the
32 climate warms.

33 Figure 8.3 shows that the number of large fires has increased over the period 1984–2011, with
34 high statistical significance in 7 out of 10 western U.S. regions across a large variety of
35 vegetation, elevation, and climatic types (Dennison et al. 2014). State-level fire data over the
36 20th century (Littell et al. 2009) indicates that area burned in the western United States decreased
37 from 1916 to about 1940, was at low levels until the 1970s, then increased into the more recent
38 period. Modeled increases in temperatures and vapor pressure deficits due to anthropogenic

1 climate change has increased forest fire activity in the western United States by increasing the
2 aridity of forest fuels during the fire season (Abatzoglou and Williams 2016). Increases in these
3 relevant climatic drivers were found to be responsible for over half the observed increase in
4 western U.S. forest fuel aridity from 1979 to 2015 and doubled the forest fire area over the
5 period 1984–2015 (Abatzoglou and Williams 2016). Littell et al. (2009, 2010, 2016) find that
6 two climatic mechanisms affect fire in the western United States: increased fuel flammability
7 driven by warmer, drier conditions and increased fuel availability driven by antecedent moisture.
8 Littell et al. (2016) find a clear link between increased drought and increased fire risk. Yoon et
9 al. (2015) assessed the 2014 fire season, finding an increased risk of fire in California. While fire
10 suppression practices can also lead to a significant increase in fire risk in lower-elevation and
11 drier forest types, this is less important in higher-elevation and moister forests (Harvey 2016;
12 Stephens et al. 2013; Schoennagel et al. 2004). Increases in future forest fire extent, frequency,
13 and intensity depend strongly on local ecosystem properties and will vary greatly across the
14 United States. Westerling et al. (2011) project substantial increases in forest fire frequency in the
15 Greater Yellowstone ecosystem by mid-century under the older SRES A2 emissions scenario,
16 and further state that years without large fires in the region will become extremely rare. Stavros
17 et al. (2014) project increases in very large fires (greater than 50,000 acres) across the western
18 United States by mid-century under both the RCP4.5 and RCP8.5 emissions scenarios. Likewise,
19 Prestemon et al. (2016) project significant increases in lightning-ignited wildfire in the Southeast
20 by mid-century but with substantial differences between ecoregions. However, other factors,
21 related to climate change such as water scarcity or insect infestations may act to stifle future
22 forest fire activity by reducing growth or otherwise killing trees leading to fuel reduction (Littell
23 et al. 2010).

24 **[INSERT FIGURE 8.3 HERE]**

25 Historically, wildfires have been less frequent and of smaller extent in Alaska compared to the
26 rest of the globe (Flannigan et al. 2009; Hu et al. 2015). Shortened land snow cover seasons and
27 higher temperatures have made the Arctic more vulnerable to wildfire (Flannigan et al. 2009; Hu
28 et al. 2015; Young et al. 2016). Total area burned and the number of large fires (those with area
29 greater than 1,000 square km or 386 square miles) in Alaska exhibits significant interannual and
30 decadal scale variability from influences of atmospheric circulation patterns and controlled
31 burns, but have *likely* increased since 1959 (Kasischke and Turetsky 2006). The most recent
32 decade has seen an unusually large number of severe wildfire years in Alaska, for which the risk
33 of severe fires has *likely* increased by 33%–50% as a result of anthropogenic climate change
34 (Partain et al. 2016) and is projected to increase by up to a factor of four by the end of the
35 century under the moderate RCP6.0 scenario (Young et al. 2016). Historically less flammable
36 tundra and cooler boreal forest regions could shift into historically unprecedented fire risk
37 regimes as a consequence of temperatures increasing above the minimum thresholds required for
38 burning. Alaska's fire season is also *likely* lengthening—a trend expected to continue (Flannigan
39 et al. 2009; Sanford et al. 2015). Thresholds in temperature and precipitation shape Arctic fire

1 regimes, and projected increases in future lightning activity imply increased vulnerability to
2 future climate change (Flannigan et al. 2009; Young et al. 2016). Alaskan tundra and forest
3 wildfires will *likely* increase under warmer and drier conditions (Sanford et al. 2015; French et
4 al. 2015) and potentially result in a transition into a fire regime unprecedented in the last 10,000
5 years (Kelly et al. 2013). Total area burned is projected to increase between 25% and 53% by the
6 end of the century (Joly et al. 2012).

7 Boreal forests and tundra contain large stores of carbon, approximately 50% of the total global
8 soil carbon (McGuire et al. 2009). Increased fire activity could deplete these stores, releasing
9 them to the atmosphere to serve as an additional source of atmospheric CO₂ and alter the carbon
10 cycle if ecosystems change from higher to lower carbon densities (McGuire et al. 2009; Kelly et
11 al. 2013). Additionally, increased fires in Alaska may also enhance the degradation of Alaska's
12 permafrost, blackening the ground, reducing surface albedo, and removing protective vegetation.

13 Both anthropogenic climate change and the legacy of land use/management have an influence on
14 U.S. wildfires and are subtly and inextricably intertwined. Forest management practices have
15 resulted in higher fuel densities in most of U.S. forests, except in the Alaskan bush and the
16 higher mountainous regions of the western United States. Nonetheless, there is *medium*
17 *confidence* for a human-caused climate change contribution to increased forest fire activity in
18 Alaska in recent decades with a *likely* further increase as the climate continues to warm, and *low*
19 *to medium confidence* for a detectable human climate change contribution in the western United
20 States based on existing studies. Recent literature does not contain a complete robust detection
21 and attribution analysis of forest fires including estimates of natural decadal and multidecadal
22 variability, as described in Chapter 3: Detection and Attribution, nor separate the contributions to
23 observed trends from climate change and forest management. These assessment statements about
24 attribution to human-induced climate change are instead multistep attribution statements (Ch. 3:
25 Detection and Attribution) based on plausible model-based estimates of anthropogenic
26 contributions to observed trends. The modeled contributions, in turn, are based on climate
27 variables that are closely linked to fire risk and that, in most cases, have a detectable human
28 influence, such as surface air temperature and snow melt timing.

29

1 TRACEABLE ACCOUNTS

2 Key Message 1

3 Recent droughts and associated heat waves have reached record intensity in some regions of the
4 United States; however, by geographical scale and duration, the Dust Bowl era of the 1930s
5 remains the benchmark drought and extreme heat event in the historical record (*Very high*
6 *confidence*). While by some measures, drought has decreased over much of the continental
7 United States in association with long-term increases in precipitation, neither the precipitation
8 increases nor inferred drought decreases have been confidently attributed to anthropogenic
9 forcing.

10 Description of evidence base

11 Recent droughts are well characterized and described in the literature. The Dust Bowl is not as
12 well documented, but available observational records support the key finding. The last sentence
13 is an “absence of evidence” statement and does not imply “evidence of absence” of future
14 anthropogenic changes. The inferred decreases in some measures of U.S. drought or types of
15 drought (heat wave/flash droughts) are described in Andreadis and Lettenmaier (2006) and Mo
16 and Lettenmaier (2015).

17 Major uncertainties

18 Record breaking temperatures are well documented with low uncertainty (Meehl et al 2009). The
19 magnitude of the Dust Bowl relative to present times varies with location. Uncertainty in the key
20 finding is affected by the quality of pre-World War II observations but is relatively low.

21 Assessment of confidence based on evidence and agreement

22 Precipitation is well observed in the United States, leading to *very high confidence*.

23 Summary sentence or paragraph that integrates the above information

24 The key finding is a statement that recent U.S. droughts, while sometimes long and severe, are
25 not unprecedented in the historical record.

26

27 Key Message 2

28 The human effect on recent major U.S. droughts is complicated. Little evidence is found for a
29 human influence on observed precipitation deficits, but much evidence is found for a human
30 influence on surface soil moisture deficits due to increased evapotranspiration caused by higher
31 temperatures. (*High confidence*)

32

1 Description of evidence base

2 Observational records of meteorological drought are not long enough to detect statistically
3 significant trends. Additionally, paleoclimatic evidence suggests that major droughts have
4 occurred throughout the distant past. Surface soil moisture is not well observed throughout the
5 CONUS, but numerous event attribution studies attribute enhanced reduction of surface soil
6 moisture during dry periods to anthropogenic warming and enhanced evapotranspiration.
7 Sophisticated land surface models have been demonstrated to reproduce the available
8 observations and have allowed for century scale reconstructions.

9 Major uncertainties

10 Uncertainties stem from the length of precipitation observations and the lack of surface moisture
11 observations.

12 Assessment of confidence based on evidence and agreement

13 Confidence is *high* for widespread future surface soil moisture deficits, as little change is
14 projected for future summer and fall average precipitation. In the absence of increased
15 precipitation (and in some cases with it), evapotranspiration increases due to increased
16 temperatures will lead to less soil moisture overall, especially near the surface.

17 Summary sentence or paragraph that integrates the above information

18 The precipitation deficit portion of the key finding is a conservative statement reflecting the
19 conflicting and limited event attribution literature on meteorological drought. The soil moisture
20 portion of the key finding is limited to the surface and not the more relevant root depth and is
21 supported by the studies cited in this chapter.

23 Key Message 3

24 Future decreases in surface (top 10 cm) soil moisture from anthropogenic forcing over most of
25 the United States are *likely* as the climate warms under the higher emissions scenarios. (*Medium*
26 *confidence*)

27 Description of evidence base

28 First principles establish that evaporation is at least linearly dependent on temperatures and
29 accounts for much of the surface moisture decrease as temperature increases. Plant transpiration
30 for many non-desert species controls plant temperature and responds to increased temperature by
31 opening stomata to release more water vapor. This water comes from the soil at root depth as the
32 plant exhausts its stored water supply (*very high confidence*). Furthermore, nearly all CMIP5
33 models exhibit U.S. surface soil moisture drying at the end of the century under RCP8.5, and the

1 multimodel average exhibits no significant annual soil moisture increases anywhere on the planet
2 (Collins et al 2013).

3 **Major uncertainties**

4 While both evaporation and transpiration changes are of the same sign as temperature increases,
5 the relative importance of each as a function of depth is less well quantified. The amount of
6 transpiration varies considerably among plant species, and these are treated with widely varying
7 of sophistication in the land surface components of contemporary climate models. Uncertainty in
8 the sign of the anthropogenic change of root depth soil moisture is low in regions and seasons of
9 projected precipitation decreases (Ch. 7: Precipitation Changes). There is moderate to high
10 uncertainty in the magnitude of the change in soil moisture at all depths and all regions and
11 seasons. This key finding is a “projection without attribution” statement as such a drying is not
12 part of the observed record. Projections of summertime mean CONUS precipitation exhibit no
13 significant change. However, recent summertime precipitation trends are positive, leading to
14 reduced agricultural drought conditions overall (Andreadis and Lettenmaier 2006). While
15 statistically significant increases in precipitation have been identified over parts of the United
16 States, these trends have not been clearly attributed to anthropogenic forcing (Ch. 7:
17 Precipitation Change). Furthermore, North American summer temperature increases under
18 RCP8.5 at the end of the century are projected to be substantially more than the current observed
19 (and modeled) temperature increase. Because of the response of evapotranspiration to
20 temperature increases, the CMIP5 multimodel average projection is for drier surface soils even in
21 those high latitude regions (Alaska and Canada) that are confidently projected to experience
22 increases in precipitation. Hence, in the CONUS region, with little or no projected summertime
23 changes in precipitation, we conclude that surface soil moisture will likely decrease.

24 **Assessment of confidence based on evidence and agreement**

25 CMIP5 and regional models support the surface soil moisture key finding. Confidence is
26 assessed as “medium” as this key finding—despite the high level of agreement among model
27 projections—because of difficulties in observing long-term changes in this metric and because,
28 at present, there is no published evidence of detectable long-term decreases in surface soil
29 moisture across the United States.

30 **Summary sentence or paragraph that integrates the above information**

31 In the northern United States, surface soil moisture (top 10 cm) is *likely* to decrease as
32 evaporation outpaces increases in precipitation. In the Southwest, the combination of
33 temperature increases and precipitation decreases causes surface soil moisture decreases to be
34 *very likely*. In this region, decreases in soil moisture at the root depth are *likely*.

35

1 **Key Message 4**

2 Substantial reductions in western U.S. winter and spring snowpack are projected as the climate
3 warms. Earlier spring melt and reduced snow water equivalent have been formally attributed to
4 human induced warming (*high confidence*) and will *very likely* be exacerbated as the climate
5 continues to warm (*very high confidence*). Under higher emissions scenarios, and assuming no
6 change to current water resources management, chronic, long-duration hydrological drought is
7 increasingly possible by the end of this century (*very high confidence*).

8 **Description of evidence base**

9 First principles tell us that as temperatures rise, minimum snow levels also must rise. Certain
10 changes in western U.S. hydrology have already been attributed to human causes in several
11 papers following Barnett et al. (2008) and are cited in the text. The CMIP3/5 models project
12 widespread warming with future increases in atmospheric GHG concentrations, although these
13 are underestimated in the current generation of global climate models (GCMs) at the high
14 altitudes of the western United States due to constraints on orographic representation at current
15 GCM spatial resolutions.

16 CMIP5 models were not designed or constructed for direct projection of locally relevant
17 snowpack amounts. However, a high-resolution climate model, selected for its ability to simulate
18 western U.S. snowpack amounts and extent, projects devastating changes in the hydrology of this
19 region assuming constant water resource management practices (Rhoades et al 2017). This
20 conclusion is also supported by a statistical downscaling result shown in Figure 3.1 of Walsh et
21 al. 2014 and Cayan et al. 2013 and by the more recent statistical downscaling study of Klos et al.
22 2014.

23 **Major uncertainties**

24 The major uncertainty is not so much “if” but rather “how much” as changes to precipitation
25 phase (rain or snow) are sensitive to temperature increases that in turn depend on greenhouse gas
26 (GHG) forcing changes. Also, changes to the lower-elevation catchments will be realized prior to
27 those at higher elevations that, even at 25 km, is not adequately resolved. Uncertainty in the final
28 statement also stems from the usage of one model but is tempered by similar findings from
29 statistical downscaling studies. However, this simulation is a so-called “prescribed temperature”
30 experiment with the usual uncertainties about climate sensitivity wired in by the usage of one
31 particular ocean temperature change. Uncertainty in the equator-to-pole differential ocean
32 warming rate is also a factor.

33

1 **Assessment of confidence based on evidence and agreement**

2 All CMIP5 models project large-scale western U.S. warming as GHG forcing increases.
3 Warming is underestimated in most of the western United States due to elevation deficiencies
4 that are a consequence of coarse model resolution.

5 **Summary sentence or paragraph that integrates the above information**

6 Warmer temperatures lead to less snow and more rain if total precipitation remains unchanged.
7 Projected winter/spring precipitation changes are a mix of increases in northern states and
8 decreases in the Southwest. In the northern Rocky Mountains, snowpack is projected to decrease
9 even with a projected precipitation increase due to this phase change effect. This will lead to, at
10 the very least, profound changes to the seasonal and sub-seasonal timing of the western U.S.
11 hydrological cycle even where annual precipitation remains nearly unchanged with a strong
12 potential for water shortages.

13

14 **Key Message 5**

15 Detectable changes in some classes of flood frequency have occurred in parts of the United
16 States and are a mix of increases and decreases. Extreme precipitation, one of the controlling
17 factors in flood statistics, is observed to have generally increased and is projected to continue to
18 do so across the United States in a warming atmosphere. However, formal attribution approaches
19 have not established a significant connection of increased riverine flooding to human-induced
20 climate change and the timing of any emergence of a future detectable anthropogenic change in
21 flooding is unclear. (*Medium confidence*)

22 **Description of evidence base**

23 Observed changes are a mix of increases and decreases and are documented by Walsh et al. 2014
24 and other studies cited in the text. No attribution statements have been made.

25 **Major uncertainties**

26 Floods are highly variable both in space and time. The multivariate nature of floods complicates
27 detection and attribution.

28 **Assessment of confidence based on evidence and agreement**

29 Confidence is limited to *medium* due to both the lack of an attributable change in observed
30 flooding to date and the complicated multivariate nature of flooding. However, confidence is
31 *high* in the projections of increased future extreme precipitation, the principal driver (among
32 several) of many floods. It is unclear when an observed long-term increase in U.S. riverine

1 flooding will be attributed to anthropogenic climate change. Hence, confidence is *medium* in this
2 part of the key message at this time.

3 **Summary sentence or paragraph that integrates the above information**

4 The key finding is a relatively weak statement reflecting the lack of definitive detection and
5 attribution of anthropogenic changes in U.S. flooding intensity, duration, and frequency.

6

7 **Key Message 6**

8 The incidence of large forest fires in the western United States and Alaska has increased since
9 the early 1980s (*high confidence*) and is projected to further increase in those regions as the
10 climate warms with profound changes to certain ecosystems (*medium confidence*).

11 **Description of evidence base**

12 Studies by Dennison et al. 2014 (western U.S.) and Kasischke and Turetsky 2006 (Alaska)
13 document the observed increases in fire statistics. Projections of Westerling et al. (2011)
14 (western U.S.) and Young et al. 2016 and others (Alaska) indicate increased fire risk. These
15 observations and projections are consistent with drying due to warmer temperatures leading to
16 increased flammability and longer fire seasons.

17 **Major uncertainties**

18 Analyses of other regions of the United States, which also could be subject to increased fire risk
19 do not seem to be readily available. Likewise, projections of the western U.S. fire risk are of
20 limited areas. In terms of attribution, there is still some uncertainty on how well non-climatic
21 confounding factors such as forestry management and fire suppression practices have
22 been accounted for, particularly for the western United States. Other climate change factors, such
23 as increased water deficits and insect infestations could reduce fuel loads, tending towards
24 reducing fire frequency and/or intensity.

25 **Assessment of confidence based on evidence and agreement**

26 Confidence is *high* in the observations due to solid observational evidence. Confidence in
27 projections would be higher if there were more available studies covering a broader area of the
28 United States and a wider range of ecosystems.

29 **Summary sentence or paragraph that integrates the above information**

30 Wildfires have increased over parts of the western United States and Alaska in recent decades
31 and are projected to continue to increase as a result of climate change. As a result, shifts in
32 certain ecosystem types may occur.

1 **TABLES**

2 **Table 8.1:** A list of U.S. droughts for which attribution statements have been made. In the last
 3 column, “+” indicates that an attributable human induced increase in frequency and/or magnitude
 4 was found, “-“ indicates that an attributable human induced decrease in frequency and/or
 5 magnitude was found, “0” indicates no attributable human contribution was identified. As in
 6 tables 6.2 and 7.1, several of the events were originally examined in the *Bulletin of the American*
 7 *Meteorological Society’s (BAMS) State of the Climate Reports* and reexamined by Angélil et al.
 8 (2017). In these cases, both attribution statements are listed with the original authors first.
 9 Source: M. Wehner.

10

Authors	Event Year and Duration	Region or State	Type	Attribution Statement
Rupp and Mote 2012 / Angélil et al. 2017	MAMJJA 2011	Texas	Meteorological	+/+
Hoerling et al. 2013	2012	Texas	Meteorological	+
Rupp et al. 2013 / Angélil et al. 2017	MAMJJA 2012	CO, NE, KS, OK, IA, MO, AR & IL	Meteorological	0/0
Rupp et al. 2013 / Angélil et al. 2017	MAM 2012	CO, NE, KS, OK, IA, MO, AR & IL	Meteorological	0/0
Rupp et al. 2013 / Angélil et al. 2017	JJA 2012	CO, NE, KS, OK, IA, MO, AR & IL	Meteorological	0/+
Hoerling et al. 2014	MJJA 2012	Great Plains/Midwest	Meteorological	0
Swain et al. 2014 / Angélil et al. 2017	ANN 2013	California	Meteorological	+/+
Wang and Schubert 2014 / Angélil et al. 2017	JS 2013	California	Meteorological	0/+

Knutson et al. 2014 / Angélil et al. 2017	ANN 2013	California	Meteorological	0/+
Knutson et al. 2014 / Angélil et al. 2017	MAM 2013	U.S. Southern Plains region	Meteorological	0/+
Diffenbaugh et al. 2015	2012-2014	California	Agricultural	+
Seager et al. 2015	2012-2014	California	Agricultural	+
Cheng et al. 2016	2011-2015	California	Agricultural	-
Mote et al. 2016	2015	Washington, Oregon, California	Hydrological (snow water equivalent)	+

1

2

1 **Table 8.2:** Projected changes in western U.S. mountain range winter (DJF) snow-related
 2 hydrology variables at the middle and end of this century. Projections are for the RCP8.5
 3 scenario from a high-resolution version of the Community Atmospheric Model, CAM5 (Rhoades
 4 et al. 2017).

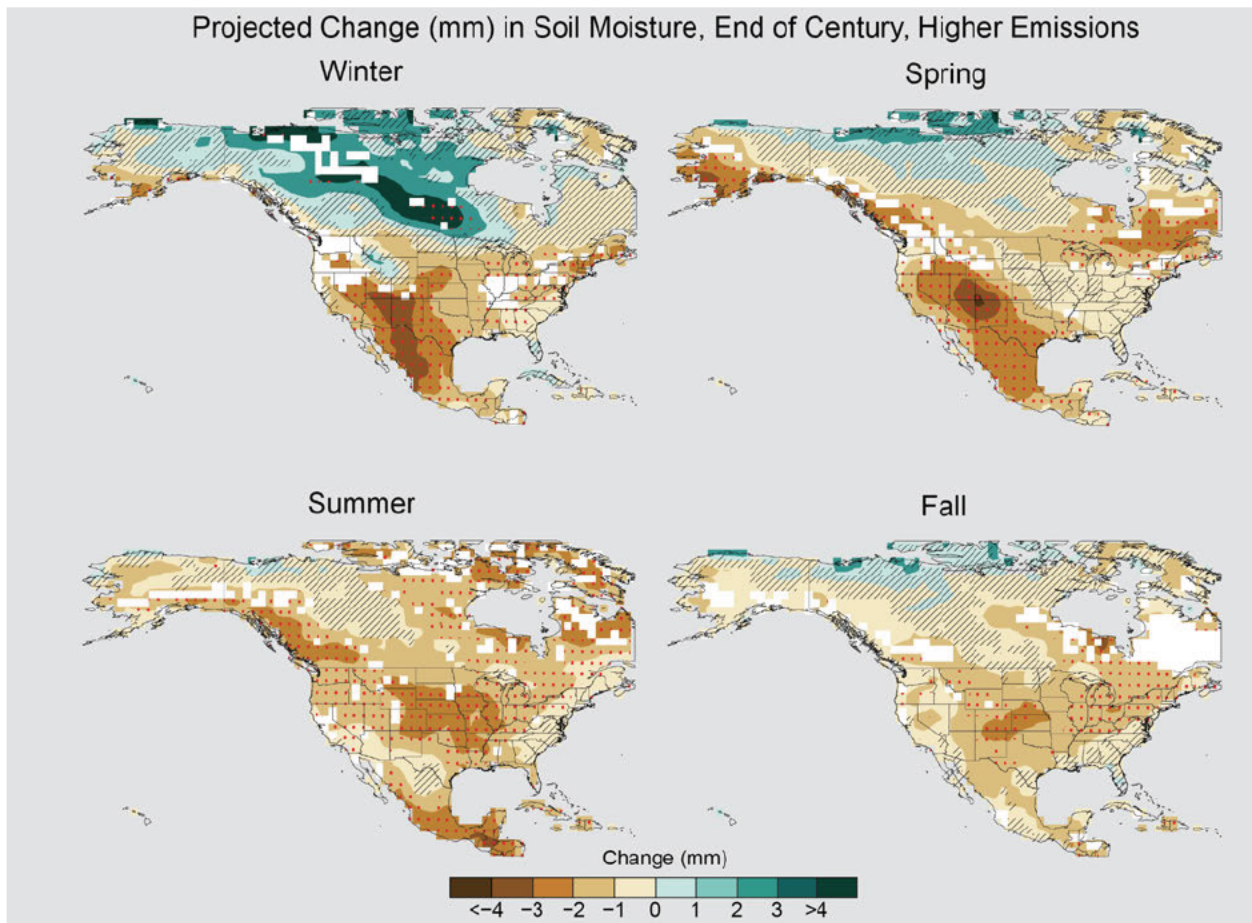
<i>Mountain Range</i>	<i>Snow Water Equivalent</i>		<i>Snow Cover</i>		<i>Snowfall</i>		<i>Surface Temperature</i>	
	<i>(% Change)</i>		<i>(% Change)</i>		<i>(% Change)</i>		<i>(Change in K)</i>	
	<i>2050</i>	<i>2100</i>	<i>2050</i>	<i>2100</i>	<i>2050</i>	<i>2100</i>	<i>2050</i>	<i>2100</i>
<i>Cascades</i>	-41.5	-89.9	-21.6	-72.9	-10.7	-50.0	0.9	4.1
<i>Klamath</i>	-50.7	-95.8	-38.6	-89.0	-23.1	-78.7	0.8	3.5
<i>Rockies</i>	-17.3	-65.1	-8.2	-43.1	1.7	-8.2	1.4	5.5
<i>Sierra Nevada</i>	-21.8	-89.0	-21.9	-77.7	-4.7	-66.6	1.1	4.5
<i>Wasatch and Uinta</i>	-18.9	-78.7	-14.2	-61.4	4.1	-34.6	1.8	6.1
<i>Western USA</i>	-22.3	-70.1	-12.7	-51.5	-1.6	-21.4	1.3	5.2

5
6

FINAL DRAFT

1 **FIGURES**

2

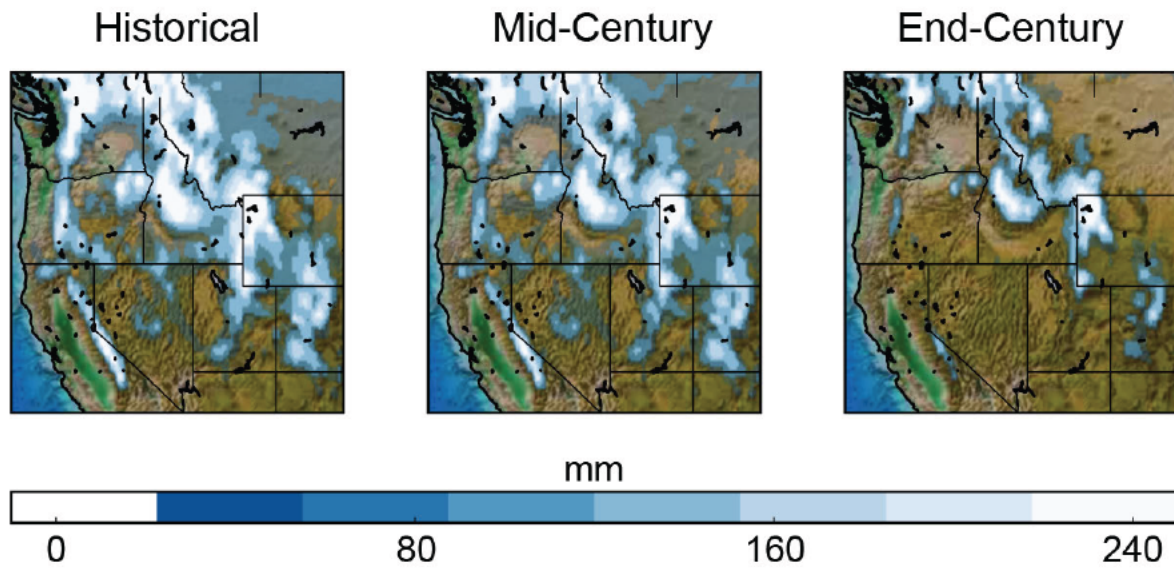


3

4 **Figure 8.1.** Projected end of the 21st century weighted CMIP5 multimodel average percent
 5 changes in near surface seasonal soil moisture (mrsos) under the RCP8.5 scenario. Stippling
 6 indicates that changes are assessed to be large compared to natural variations. Hashing indicates
 7 that changes are assessed to be small compared to natural variations. Blank regions (if any) are
 8 where projections are assessed to be inconclusive (Appendix B). (Figure source: NOAA NCEI /
 9 CICS-NC).

10

1

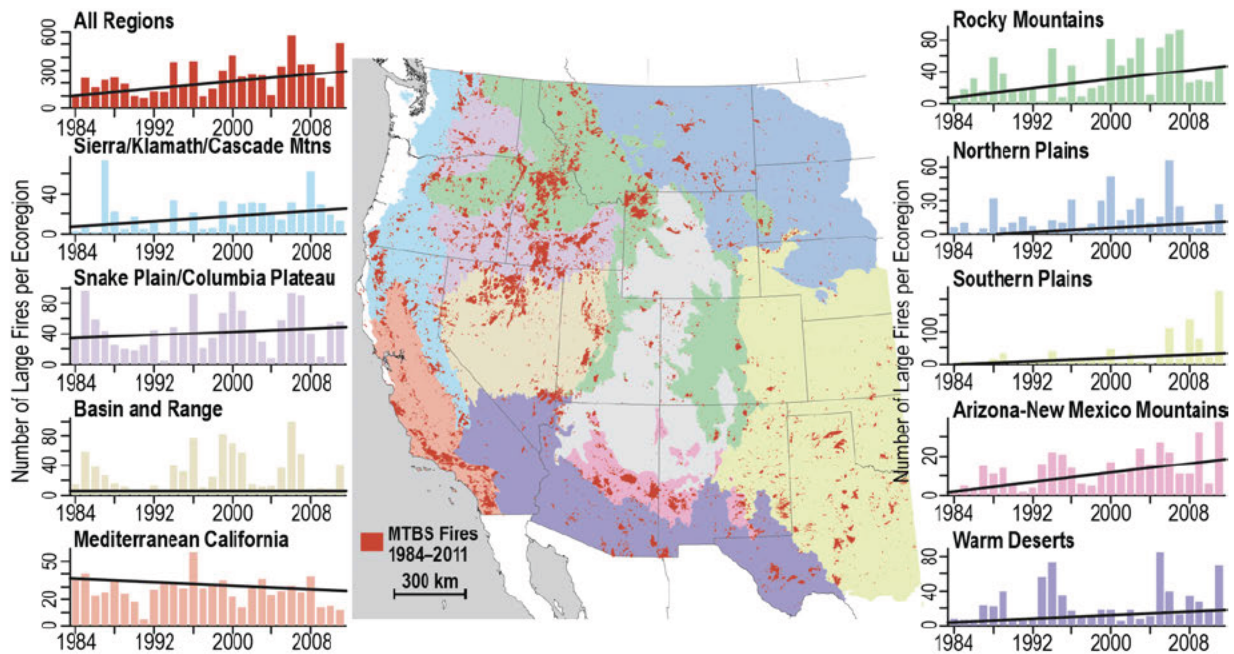


2

3 **Figure 8.2.** Projected changes in winter (DJF) snow water equivalent at the middle and end of
 4 this century under the RCP8.5 scenario from a high-resolution version of the Community
 5 Atmospheric Model, CAM5 (Rhoades et al. 2017). (Figure source: H. Krishnan, LBNL).

6

1



2

3 **Figure 8.3.** Trends in the annual number of large fires in the western United States for a variety
 4 of ecoregions. The black lines are fitted trend lines. Statistically significant at a 10% level for all
 5 regions except the Snake Plain/Columbian Plateau, Basin and Range, and Mediterranean
 6 California regions. (Figure source: Dennison et al. 2014).

FINAL

1 **REFERENCES**

- 2 Abatzoglou, J.T. and A.P. Williams, 2016: Impact of anthropogenic climate change on wildfire
3 across western US forests. *Proceedings of the National Academy of Sciences*, **113**, 11770-
4 11775. <http://dx.doi.org/10.1073/pnas.1607171113>
- 5 AECOM, 2013: The Impact of Climate Change and Population Growth on the National Flood
6 Insurance Program Through 2100. 257 pp.
7 http://www.acclimatise.uk.com/login/uploaded/resources/FEMA_NFIP_report.pdf
- 8 Andreadis, K.M. and D.P. Lettenmaier, 2006: Trends in 20th century drought over the
9 continental United States. *Geophysical Research Letters*, **33**, L10403.
10 <http://dx.doi.org/10.1029/2006GL025711>
- 11 Angélil, O., D. Stone, M. Wehner, C.J. Paciorek, H. Krishnan, and W. Collins, 2017: An
12 independent assessment of anthropogenic attribution statements for recent extreme
13 temperature and rainfall events. *Journal of Climate*, **30**, 5-16.
14 <http://dx.doi.org/10.1175/JCLI-D-16-0077.1>
- 15 Archfield, S.A., R.M. Hirsch, A. Viglione, and G. Blöschl. 2016. Fragmented patterns of flood
16 change across the United States. *Geophys. Res. Lett.* **43**, 10,232-10,239
- 17 Armstrong, W.H., M.J. Collins, and N.P. Snyder, 2014: Hydroclimatic flood trends in the
18 northeastern United States and linkages with large-scale atmospheric circulation patterns.
19 *Hydrological Sciences Journal*, **59**, 1636-1655.
20 <http://dx.doi.org/10.1080/02626667.2013.862339>
- 21 Barnett, T.P. and D.W. Pierce, 2009: Sustainable water deliveries from the Colorado River in a
22 changing climate. *Proceedings of the National Academy of Sciences*, **106**, 7334-7338.
23 <http://dx.doi.org/10.1073/pnas.0812762106>
- 24 Barnett, T.P., D.W. Pierce, H.G. Hidalgo, C. Bonfils, B.D. Santer, T. Das, G. Bala, A.W. Wood,
25 T. Nozawa, A.A. Mirin, D.R. Cayan, and M.D. Dettinger, 2008: Human-induced changes in
26 the hydrology of the western United States. *Science*, **319**, 1080-1083.
27 <http://dx.doi.org/10.1126/science.1152538>
- 28 Bennet, H.H., F.H. Fowler, F.C. Harrington, R.C. Moore, J.C. Page, M.L. Cooke, H.A. Wallace,
29 and R.G. Tugwell, 1936: *A Report of the Great Plains Area Drought Committee*. Hopkins
30 Papers Box 13. Franklin D. Roosevelt Library, New Deal Network (FERI), Hyde Park, NY.
31 <http://newdeal.feri.org/hopkins/hop27.htm>
- 32 Berg, A., J. Sheffield, and P. C. D. Milly (2017), Divergent surface and total soil moisture
33 projections under global warming, *Geophys. Res. Lett.*, **44**, 236–244,
34 [doi:10.1002/2016GL071921](https://doi.org/10.1002/2016GL071921).

- 1 Berghuijs, W.R., R.A. Woods, C.J. Hutton, and M. Sivapalan, 2016: Dominant flood generating
2 mechanisms across the United States. *Geophysical Research Letters*, **43**, 4382-4390.
3 <http://dx.doi.org/10.1002/2016GL068070>
- 4 Bindoff, N.L., P.A. Stott, K.M. AchutaRao, M.R. Allen, N. Gillett, D. Gutzler, K. Hansingo, G.
5 Hegerl, Y. Hu, S. Jain, I.I. Mokhov, J. Overland, J. Perlwitz, R. Sebbari, and X. Zhang, 2013:
6 Detection and attribution of climate change: From global to regional. *Climate Change 2013:*
7 *The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report*
8 *of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M.
9 Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds.
10 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 867–
11 952. <http://www.climatechange2013.org/report/full-report/>
- 12 Bond, N.A., M.F. Cronin, H. Freeland, and N. Mantua, 2015: Causes and impacts of the 2014
13 warm anomaly in the NE Pacific. *Geophysical Research Letters*, **42**, 3414-3420.
14 <http://dx.doi.org/10.1002/2015GL063306>
- 15 Bonfils, C., B.D. Santer, D.W. Pierce, H.G. Hidalgo, G. Bala, T. Das, T.P. Barnett, D.R. Cayan,
16 C. Doutriaux, A.W. Wood, A. Mirin, and T. Nozawa, 2008: Detection and attribution of
17 temperature changes in the mountainous western United States. *Journal of Climate*, **21**,
18 6404-6424. <http://dx.doi.org/10.1175/2008JCLI2397.1>
- 19 Brown, P.M., E.K. Heyerdahl, S.G. Kitchen, and M.H. Weber, 2008: Climate effects on
20 historical fires (1630–1900) in Utah. *International Journal of Wildland Fire*, **17**, 28-39.
21 <http://dx.doi.org/10.1071/WF07023>
- 22 Cayan, D.R., T. Das, D.W. Pierce, T.P. Barnett, M. Tyree, and A. Gershunov, 2010: Future
23 dryness in the southwest US and the hydrology of the early 21st century drought.
24 *Proceedings of the National Academy of Sciences*, **107**, 21271-21276.
25 <http://dx.doi.org/10.1073/pnas.0912391107>
- 26 Cayan, D., K. Kunkel, C. Castro, A. Gershunov, J. Barsugli, A. Ray, J. Overpeck, M. Anderson,
27 J. Russell, B. Rajagopalan, I. Rangwala, and P. Duffy, 2013: Ch. 6: Future climate: Projected
28 average. *Assessment of Climate Change in the Southwest United States: A Report Prepared*
29 *for the National Climate Assessment*. Garfin, G., A. Jardine, R. Merideth, M. Black, and S.
30 LeRoy, Eds. Island Press, Washington, D.C., 153-196.
31 <http://swccar.org/sites/all/themes/files/SW-NCA-color-FINALweb.pdf>
- 32 Cheng, L., M. Hoerling, A. AghaKouchak, B. Livneh, X.-W. Quan, and J. Eischeid, 2016: How
33 has human-induced climate change affected California drought risk? *Journal of Climate*, **29**,
34 111-120. <http://dx.doi.org/10.1175/JCLI-D-15-0260.1>

- 1 Christensen, N.S. and D.P. Lettenmaier, 2007: A multimodel ensemble approach to assessment
2 of climate change impacts on the hydrology and water resources of the Colorado River
3 Basin. *Hydrology and Earth System Sciences*, **11**, 1417-1434. [http://dx.doi.org/10.5194/hess-](http://dx.doi.org/10.5194/hess-11-1417-2007)
4 [11-1417-2007](http://dx.doi.org/10.5194/hess-11-1417-2007)
- 5 Coats, S., B.I. Cook, J.E. Smerdon, and R. Seager, 2015: North American pancontinental
6 droughts in model simulations of the last millennium. *Journal of Climate*, **28**, 2025-2043.
7 <http://dx.doi.org/10.1175/JCLI-D-14-00634.1>
- 8 Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J.
9 Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver, and M. Wehner,
10 2013: Long-term climate change: Projections, commitments and irreversibility. *Climate*
11 *Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth*
12 *Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D.
13 Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and
14 P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New
15 York, NY, USA, 1029–1136. <http://www.climatechange2013.org/report/full-report/>
- 16 Cook, B.I., T.R. Ault, and J.E. Smerdon, 2015: Unprecedented 21st century drought risk in the
17 American Southwest and Central Plains. *Science Advances*, **1**.
18 <http://dx.doi.org/10.1126/sciadv.1400082>
- 19 Cook, E.R., C.A. Woodhouse, C.M. Eakin, D.M. Meko, and D.W. Stahle, 2004: Long-term
20 aridity changes in the western United States. *Science*, **306**, 1015-1018.
21 <http://dx.doi.org/10.1126/science.1102586>
- 22 Dai, A., 2013: Increasing drought under global warming in observations and models. *Nature*
23 *Climate Change*, **3**, 52-58. <http://dx.doi.org/10.1038/nclimate1633>
- 24 Das, T., D.W. Pierce, D.R. Cayan, J.A. Vano, and D.P. Lettenmaier, 2011: The importance of
25 warm season warming to western U.S. streamflow changes. *Geophysical Research Letters*,
26 **38**, L23403. <http://dx.doi.org/10.1029/2011GL049660>
- 27 Dennison, P.E., S.C. Brewer, J.D. Arnold, and M.A. Moritz, 2014: Large wildfire trends in the
28 western United States, 1984–2011. *Geophysical Research Letters*, **41**, 2928-2933.
29 <http://dx.doi.org/10.1002/2014GL059576>
- 30 Dettinger, M., 2011: Climate change, atmospheric rivers, and floods in California—a multimodel
31 analysis of storm frequency and magnitude changes. *Journal of the American Water*
32 *Resources Association*, **47**, 514-523. <http://dx.doi.org/10.1111/j.1752-1688.2011.00546.x>
- 33 Dettinger, M.D., 2013: Atmospheric rivers as drought busters on the U.S. West Coast. *Journal of*
34 *Hydrometeorology*, **14**, 1721-1732. <http://dx.doi.org/10.1175/JHM-D-13-02.1>

- 1 Dettinger, M.D., F.M. Ralph, T. Das, P.J. Neiman, and D.R. Cayan, 2011: Atmospheric rivers,
2 floods and the water resources of California. *Water*, **3**, 445-478.
3 <http://dx.doi.org/10.3390/w3020445>
- 4 Diffenbaugh, N.S. and M. Scherer, 2013: Likelihood of July 2012 U.S. temperatures in pre-
5 industrial and current forcing regimes [in "Explaining Extreme Events of 2013 from a
6 Climate Perspective"]. *Bulletin of the American Meteorological Society*, **94** (9), S6-S9.
7 <http://dx.doi.org/10.1175/BAMS-D-13-00085.1>
- 8 Diffenbaugh, N.S., D.L. Swain, and D. Touma, 2015: Anthropogenic warming has increased
9 drought risk in California. *Proceedings of the National Academy of Sciences*, **112**, 3931-
10 3936. <http://dx.doi.org/10.1073/pnas.1422385112>
- 11 EPA, 2016: Climate Change Indicators in the United States, 2016. 4th edition. U.S.
12 Environmental Protection Agency, Washington, D.C., 96 pp.
13 https://www.epa.gov/sites/production/files/2016-08/documents/climate_indicators_2016.pdf
- 14 Flannigan, M., B. Stocks, M. Turetsky, and M. Wotton, 2009: Impacts of climate change on fire
15 activity and fire management in the circumboreal forest. *Global Change Biology*, **15**, 549-
16 560. <http://dx.doi.org/10.1111/j.1365-2486.2008.01660.x>
- 17 Frans, C., E. Istanbuluoglu, V. Mishra, F. Munoz-Arriola, and D.P. Lettenmaier, 2013: Are
18 climatic or land cover changes the dominant cause of runoff trends in the Upper Mississippi
19 River Basin? *Geophysical Research Letters*, **40**, 1104-1110.
20 <http://dx.doi.org/10.1002/grl.50262>
- 21 Frei, A., K.E. Kunkel, and A. Matonse, 2015: The seasonal nature of extreme hydrological
22 events in the northeastern United States. *Journal of Hydrometeorology*, **16**, 2065-2085.
23 <http://dx.doi.org/10.1175/JHM-D-14-0237.1>
- 24 French, N.H.F., L.K. Jenkins, T.V. Loboda, M. Flannigan, R. Jandt, L.L. Bourgeau-Chavez, and
25 M. Whitley, 2015: Fire in arctic tundra of Alaska: Past fire activity, future fire potential, and
26 significance for land management and ecology. *International Journal of Wildland Fire*, **24**,
27 1045-1061. <http://dx.doi.org/10.1071/WF14167>
- 28 Funk, C., A. Hoell, and D. Stone, 2014: Examining the contribution of the observed global
29 warming trend to the California droughts of 2012/13 and 2013/14 [in "Explaining Extreme
30 Events of 2013 from a Climate Perspective"]. *Bulletin of the American Meteorological
31 Society*, **95** (9), S11-S15. <http://dx.doi.org/10.1175/1520-0477-95.9.S1.1>
- 32 Fyfe, J.C., C. Derksen, L. Mudryk, G.M. Flato, B.D. Santer, N.C. Swart, N.P. Molotch, X.
33 Zhang, H. Wan, V.K. Arora, J. Scinocca, and Y. Jiao, 2017: Large near-term projected
34 snowpack loss over the western United States. *Nature Communications*, **8**, 14996.
35 <http://dx.doi.org/10.1038/ncomms14996>

- 1 Gao, Y., J. Lu, L.R. Leung, Q. Yang, S. Hagos, and Y. Qian, 2015: Dynamical and
2 thermodynamical modulations on future changes of landfalling atmospheric rivers over
3 western North America. *Geophysical Research Letters*, **42**, 7179-7186.
4 <http://dx.doi.org/10.1002/2015GL065435>
- 5 Gochis, D., R. Schumacher, K. Friedrich, N. Doesken, M. Kelsch, J. Sun, K. Ikeda, D. Lindsey,
6 A. Wood, B. Dolan, S. Matrosov, A. Newman, K. Mahoney, S. Rutledge, R. Johnson, P.
7 Kucera, P. Kennedy, D. Sempere-Torres, M. Steiner, R. Roberts, J. Wilson, W. Yu, V.
8 Chandrasekar, R. Rasmussen, A. Anderson, and B. Brown, 2015: The Great Colorado Flood
9 of September 2013. *Bulletin of the American Meteorological Society*, **96** (12), 1461-1487.
10 <http://dx.doi.org/10.1175/BAMS-D-13-00241.1>
- 11 Groisman, P.Y., R.W. Knight, and T.R. Karl, 2001: Heavy precipitation and high streamflow in
12 the contiguous United States: Trends in the twentieth century. *Bulletin of the American*
13 *Meteorological Society*, **82**, 219-246. [http://dx.doi.org/10.1175/1520-](http://dx.doi.org/10.1175/1520-0477(2001)082<0219:hpahsi>2.3.co;2)
14 [0477\(2001\)082<0219:hpahsi>2.3.co;2](http://dx.doi.org/10.1175/1520-0477(2001)082<0219:hpahsi>2.3.co;2)
- 15 Guan, B., N.P. Molotch, D.E. Waliser, E.J. Fetzer, and P.J. Neiman, 2013: The 2010/2011 snow
16 season in California's Sierra Nevada: Role of atmospheric rivers and modes of large-scale
17 variability. *Water Resources Research*, **49**, 6731-6743. <http://dx.doi.org/10.1002/wrcr.20537>
- 18 Guan, B., D.E. Waliser, F.M. Ralph, E.J. Fetzer, and P.J. Neiman, 2016: Hydrometeorological
19 characteristics of rain-on-snow events associated with atmospheric rivers. *Geophysical*
20 *Research Letters*, **43**, 2964-2973. <http://dx.doi.org/10.1002/2016GL067978>
- 21 Harvey, B.J., 2016: Human-caused climate change is now a key driver of forest fire activity in
22 the western United States. *Proceedings of the National Academy of Sciences*, **113**, 11649-
23 11650. <http://dx.doi.org/10.1073/pnas.1612926113>
- 24 Hegerl, G.C., F. W. Zwiers, P. Braconnot, N.P. Gillett, Y. Luo, J.A. Marengo Orsini, N.
25 Nicholls, J.E. Penner and P.A. Stott, 2007: Understanding and Attributing Climate Change.
26 In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to
27 the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon,
28 S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller
29 (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- 30 Hidalgo, H.G., T. Das, M.D. Dettinger, D.R. Cayan, D.W. Pierce, T.P. Barnett, G. Bala, A.
31 Mirin, A.W. Wood, C. Bonfils, B.D. Santer, and T. Nozawa, 2009: Detection and attribution
32 of streamflow timing changes to climate change in the western United States. *Journal of*
33 *Climate*, **22**, 3838-3855. <http://dx.doi.org/10.1175/2009jcli2470.1>

- 1 Higuera PE, Abatzoglou JT, Littell JS, Morgan P. 2015: The Changing Strength and Nature of
2 Fire-Climate Relationships in the Northern Rocky Mountains, U.S.A., 1902-2008. PLoS
3 ONE 10(6): e0127563. <https://doi.org/10.1371/journal.pone.0127563>
- 4 Hirsch, R.M. and K.R. Ryberg, 2012: Has the magnitude of floods across the USA changed with
5 global CO₂ levels? *Hydrological Sciences Journal*, **57**, 1-9.
6 <http://dx.doi.org/10.1080/02626667.2011.621895>
- 7 Hoerling, M., D. Lettenmaier, D. Cayan, and B. Udall, 2009: Reconciling future Colorado River
8 flows. *Southwest Hydrology*, **8**, 20-21.31.
9 http://www.swhydro.arizona.edu/archive/V8_N3/feature2.pdf
- 10 Hoerling, M., M. Chen, R. Dole, J. Eischeid, A. Kumar, J.W. Nielsen-Gammon, P. Pegion, J.
11 Perlwitz, X.-W. Quan, and T. Zhang, 2013: Anatomy of an extreme event. *Journal of*
12 *Climate*, **26**, 2811–2832. <http://dx.doi.org/10.1175/JCLI-D-12-00270.1>
- 13 Hoerling, M., J. Eischeid, A. Kumar, R. Leung, A. Mariotti, K. Mo, S. Schubert, and R. Seager,
14 2014: Causes and predictability of the 2012 Great Plains drought. *Bulletin of the American*
15 *Meteorological Society*, **95**, 269-282. <http://dx.doi.org/10.1175/BAMS-D-13-00055.1>
- 16 Hu, F.S., P.E. Higuera, P. Duffy, M.L. Chipman, A.V. Rocha, A.M. Young, R. Kelly, and M.C.
17 Dietze, 2015: Arctic tundra fires: Natural variability and responses to climate change.
18 *Frontiers in Ecology and the Environment*, **13**, 369-377. <http://dx.doi.org/10.1890/150063>
- 19 IPCC, 2012: Summary for Policymakers. In: *Managing the Risks of Extreme Events and*
20 *Disasters to Advance Climate Change Adaptation* [Field, C.B., V. Barros, T.F. Stocker, D.
21 Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M.
22 Tignor, and P.M. Midgley (eds.)]. A Special Report of Working Groups I and II of the
23 Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK,
24 and New York, NY, USA, pp. 3-21.
- 25 Joly, K., P.A. Duffy, and T.S. Rupp, 2012: Simulating the effects of climate change on fire
26 regimes in Arctic biomes: Implications for caribou and moose habitat. *Ecosphere*, **3**, 1-18.
27 <http://dx.doi.org/10.1890/ES12-00012.1>
- 28 Kapnick, S.B. and T.L. Delworth, 2013: Controls of global snow under a changed climate.
29 *Journal of Climate*, **26**, 5537-5562. <http://dx.doi.org/10.1175/JCLI-D-12-00528.1>
- 30 Karl, T.R., J.T. Melillo, and T.C. Peterson, eds., 2009: *Global Climate Change Impacts in the*
31 *United States*. ed. Karl, T.R., J.T. Melillo, and T.C. Peterson. Cambridge University Press:
32 New York, NY, 189 pp. [http://downloads.globalchange.gov/usimpacts/pdfs/climate-impacts-](http://downloads.globalchange.gov/usimpacts/pdfs/climate-impacts-report.pdf)
33 [report.pdf](http://downloads.globalchange.gov/usimpacts/pdfs/climate-impacts-report.pdf)

- 1 Kasischke, E.S. and M.R. Turetsky, 2006: Recent changes in the fire regime across the North
2 American boreal region—Spatial and temporal patterns of burning across Canada and
3 Alaska. *Geophysical Research Letters*, **33**, L09703.
4 <http://dx.doi.org/10.1029/2006GL025677>
- 5 Kelly, R., M.L. Chipman, P.E. Higuera, I. Stefanova, L.B. Brubaker, and F.S. Hu, 2013: Recent
6 burning of boreal forests exceeds fire regime limits of the past 10,000 years. *Proceedings of*
7 *the National Academy of Sciences*, **110**, 13055-13060.
8 <http://dx.doi.org/10.1073/pnas.1305069110>
- 9 Klos, P.Z., T.E. Link, and J.T. Abatzoglou, 2014: Extent of the rain–snow transition zone in the
10 western U.S. under historic and projected climate. *Geophysical Research Letters*, **41**, 4560-
11 4568. <http://dx.doi.org/10.1002/2014GL060500>
- 12 Knowles, N., M.D. Dettinger, and D.R. Cayan, 2006: Trends in snowfall versus rainfall in the
13 western United States. *Journal of Climate*, **19**, 4545-4559.
14 <http://dx.doi.org/10.1175/JCLI3850.1>
- 15 Knutson, Thomas R., Fanrong Zeng, and Andrew T Wittenberg, September 2014: Seasonal and
16 Annual Mean Precipitation Extremes Occurring During 2013: A U.S. Focused Analysis [in
17 "Explaining Extremes of 2013 from a Climate Perspective"]. *Bulletin of the American*
18 *Meteorological Society*, **95(9)**, S19-S23. <http://dx.doi.org/10.1175/1520-0477-95.9.S1.1>
- 19 Kormos, P.R., C.H. Luce, S.J. Wenger, and W.R. Berghuijs, 2016: Trends and sensitivities of
20 low streamflow extremes to discharge timing and magnitude in Pacific Northwest mountain
21 streams. *Water Resources Research*, **52**, 4990-5007.
22 <http://dx.doi.org/10.1002/2015WR018125>
- 23 Littell JS, McKenzie D, Peterson DL, Westerling AL (2009) Climate and wildfire area burned in
24 western US ecoprovinces, 1916–2003. *Ecological Applications*, **19**, 1003–1021.
- 25 Littell, J.S., E.E., Oneil, D. McKenzie, J. A. Hicke, J.A. Lutz, R.A. Norheim, M.M. Elsner, 2010:
26 Forest ecosystems, disturbance, and climatic change in Washington State, USA Climatic
27 Change 102: 129. doi:10.1007/s10584-010-9858-x
- 28 Littell, J.S., D. L. Peterson, K. L. Riley, Y. Liu, and C. H. Luce, 2016: Global Change Biology
29 **22**, 2353–2369, doi: 10.1111/gcb.13275
- 30 Livneh, B. and M.P. Hoerling, 2016: The physics of drought in the U.S. Central Great Plains.
31 *Journal of Climate*, **29**, 6783-6804. <http://dx.doi.org/10.1175/JCLI-D-15-0697.1>
- 32 Luce, C.H. and Z.A. Holden, 2009: Declining annual streamflow distributions in the Pacific
33 Northwest United States, 1948–2006. *Geophysical Research Letters*, **36**.
34 <http://dx.doi.org/10.1029/2009GL039407>

- 1 Luce, C.H., J.T. Abatzoglou, and Z.A. Holden, 2013: The missing mountain water: Slower
2 westerlies decrease orographic enhancement in the Pacific Northwest USA. *Science*, **342**,
3 1360-1364. <http://dx.doi.org/10.1126/science.1242335>
- 4 Luce, C.H., V. Lopez-Burgos, and Z. Holden, 2014: Sensitivity of snowpack storage to
5 precipitation and temperature using spatial and temporal analog models. *Water Resources*
6 *Research*, **50**, 9447-9462. <http://dx.doi.org/10.1002/2013WR014844>
- 7 Mallakpour, I. and G. Villarini, 2015: The changing nature of flooding across the central United
8 States. *Nature Climate Change*, **5**, 250-254. <http://dx.doi.org/10.1038/nclimate2516>
- 9 Mallakpour, I. and G. Villarini, 2016: Investigating the relationship between the frequency of
10 flooding over the central United States and large-scale climate. *Advances in Water*
11 *Resources*, **92**, 159-171. <http://dx.doi.org/10.1016/j.advwatres.2016.04.008>
- 12 Mao, Y., B. Nijssen, and D.P. Lettenmaier, 2015: Is climate change implicated in the 2013–2014
13 California drought? A hydrologic perspective. *Geophysical Research Letters*, **42**, 2805-2813.
14 <http://dx.doi.org/10.1002/2015GL063456>
- 15 Masson-Delmotte, V., M. Schulz, A. Abe-Ouchi, J. Beer, A. Ganopolski, J.F. González Rouco,
16 E. Jansen, K. Lambeck, J. Luterbacher, T. Naish, T. Osborn, B. Otto-Bliesner, T. Quinn, R.
17 Ramesh, M. Rojas, X. Shao, and A. Timmermann, 2013: Information from paleoclimate
18 archives. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group*
19 *I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker,
20 T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex,
21 and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New
22 York, NY, USA, 383–464. <http://www.climatechange2013.org/report/full-report/>
- 23 McCabe, G.J. and D.M. Wolock, 2014: Spatial and temporal patterns in conterminous United
24 States streamflow characteristics. *Geophysical Research Letters*, **41**, 6889-6897.
25 <http://dx.doi.org/10.1002/2014GL061980>
- 26 McGuire, A.D., L.G. Anderson, T.R. Christensen, S. Dallimore, L. Guo, D.J. Hayes, M.
27 Heimann, T.D. Lorenson, R.W. MacDonald, and N. Roulet, 2009: Sensitivity of the carbon
28 cycle in the Arctic to climate change. *Ecological Monographs*, **79**, 523-555.
29 <http://dx.doi.org/10.1890/08-2025.1>
- 30 Meehl, G.A., C. Tebaldi, G. Walton, D. Easterling, and L. McDaniel, 2009: Relative increase of
31 record high maximum temperatures compared to record low minimum temperatures in the
32 US. *Geophysical Research Letters*, **36**, L23701. <http://dx.doi.org/10.1029/2009GL040736>
- 33 Merz, B., S. Vorogushyn, S. Uhlemann, J. Delgado, and Y. Hundecha, 2012: HESS Opinions
34 "More efforts and scientific rigour are needed to attribute trends in flood time series".

- 1 *Hydrology and Earth System Sciences*, **16**, 1379-1387. [http://dx.doi.org/10.5194/hess-16-](http://dx.doi.org/10.5194/hess-16-1379-2012)
2 1379-2012
- 3 Milly, P.C.D. and K.A. Dunne, 2016: Potential evapotranspiration and continental drying.
4 *Nature Climate Change*, **6**, 946-969. <http://dx.doi.org/10.1038/nclimate3046>
- 5 Mo, K.C. and D.P. Lettenmaier, 2015: Heat wave flash droughts in decline. *Geophysical*
6 *Research Letters*, **42**, 2823-2829. <http://dx.doi.org/10.1002/2015GL064018>
- 7 Mo, K.C. and D.P. Lettenmaier, 2016: Precipitation deficit flash droughts over the United States.
8 *Journal of Hydrometeorology*, **17**, 1169-1184. <http://dx.doi.org/10.1175/jhm-d-15-0158.1>
- 9 Mote, P.W., 2003: Trends in snow water equivalent in the Pacific Northwest and their climatic
10 causes. *Geophysical Research Letters*, **30**, 1601. <http://dx.doi.org/10.1029/2003GL017258>
- 11 Mote, P.W., A.F. Hamlet, M.P. Clark, and D.P. Lettenmaier, 2005: Declining mountain
12 snowpack in western North America. *Bulletin of the American Meteorological Society*, **86**,
13 39-49. <http://dx.doi.org/10.1175/BAMS-86-1-39>
- 14 Mote, P.W., D.E. Rupp, S. Li, D.J. Sharp, F. Otto, P.F. Uhe, M. Xiao, D.P. Lettenmaier, H.
15 Cullen, and M.R. Allen, 2016: Perspectives on the causes of exceptionally low 2015
16 snowpack in the western United States. *Geophysical Research Letters*, **43**, 10,980-10,988.
17 <http://dx.doi.org/10.1002/2016GL069965>
- 18 Munoz, S.E., K.E. Gruley, A. Massie, D.A. Fike, S. Schroeder, and J.W. Williams, 2015:
19 Cahokia's emergence and decline coincided with shifts of flood frequency on the Mississippi
20 River. *Proceedings of the National Academy of Sciences*, **112**, 6319-6324.
21 <http://dx.doi.org/10.1073/pnas.1501904112>
- 22 Najafi, M.R. and H. Moradkhani, 2015: Multi-model ensemble analysis of runoff extremes for
23 climate change impact assessments. *Journal of Hydrology*, **525**, 352-361.
24 <http://dx.doi.org/10.1016/j.jhydrol.2015.03.045>
- 25 Neiman, P.J., L.J. Schick, F.M. Ralph, M. Hughes, and G.A. Wick, 2011: Flooding in western
26 Washington: The connection to atmospheric rivers. *Journal of Hydrometeorology*, **12**, 1337-
27 1358. <http://dx.doi.org/10.1175/2011JHM1358.1>
- 28 NOAA, 2008: Drought: Public Fact Sheet. National Oceanic and Atmospheric Administration,
29 National Weather Service, Washington, D.C.
30 <http://www.nws.noaa.gov/os/brochures/climate/DroughtPublic2.pdf>
- 31 Novotny, E.V. and H.G. Stefan, 2007: Stream flow in Minnesota: Indicator of climate change.
32 *Journal of Hydrology*, **334**, 319-333. <http://dx.doi.org/10.1016/j.jhydrol.2006.10.011>

- 1 O'Gorman, P.A., 2014: Contrasting responses of mean and extreme snowfall to climate change.
2 *Nature*, **512**, 416-418. <http://dx.doi.org/10.1038/nature13625>
- 3 Pall, P.C.M.P., M.F. Wehner, D.A. Stone, C.J. Paciorek, and W.D. Collins, To appear in:
4 Diagnosing anthropogenic contributions to heavy Colorado rainfall in September 2013.
5 *Weather and Climate Extremes*.
- 6 Partain, J.L., Jr., S. Alden, U.S. Bhatt, P.A. Bieniek, B.R. Brettschneider, R. Lader, P.Q. Olsson,
7 T.S. Rupp, H. Strader, R.L.T. Jr., J.E. Walsh, A.D. York, and R.H. Zieh, 2016: An
8 assessment of the role of anthropogenic climate change in the Alaska fire season of 2015 [in
9 "Explaining Extreme Events of 2015 from a Climate Perspective"]. *Bulletin of the American*
10 *Meteorological Society*, **97 (12)**, S14-S18. <http://dx.doi.org/10.1175/BAMS-D-16-0149.1>
- 11 Pierce, D.W. and D.R. Cayan, 2013: The uneven response of different snow measures to human-
12 induced climate warming. *Journal of Climate*, **26**, 4148-4167. [http://dx.doi.org/10.1175/jcli-
d-12-00534.1](http://dx.doi.org/10.1175/jcli-
13 d-12-00534.1)
- 14 Pierce, D.W., T.P. Barnett, H.G. Hidalgo, T. Das, C. Bonfils, B.D. Santer, G. Bala, M.D.
15 Dettinger, D.R. Cayan, A. Mirin, A.W. Wood, and T. Nozawa, 2008: Attribution of declining
16 western US snowpack to human effects. *Journal of Climate*, **21**, 6425-6444.
17 <http://dx.doi.org/10.1175/2008JCLI2405.1>
- 18 Prestemon, J.P., U. Shankar, A. Xiu, K. Talgo, D. Yang, E. Dixon, D. McKenzie, and K.L. Abt,
19 2016: Projecting wildfire area burned in the south-eastern United States, 2011–60.
20 *International Journal of Wildland Fire*, **25**, 715-729. <http://dx.doi.org/10.1071/WF15124>
- 21 Ralph, F.M. and M.D. Dettinger, 2011: Storms, floods, and the science of atmospheric rivers.
22 *Eos, Transactions American Geophysical Union*, **92**, 265-266.
23 <http://dx.doi.org/10.1029/2011EO320001>
- 24 Rhoades, A.M., P.A. Ullrich, and C.M. Zarzycki, 2017: Projecting 21st century snowpack trends
25 in western USA mountains using variable-resolution CESM. *Climate Dynamics*, **Online**
26 **First**, 1-28. <http://dx.doi.org/10.1007/s00382-017-3606-0>
- 27 Running, S.W., 2006: Is global warming causing more, larger wildfires? *Science*, **313**, 927-928.
28 <http://dx.doi.org/10.1126/science.1130370>
- 29 Rupp, D. E., and P. W. Mote, 2012: Did human influence on climate make the 2011 Texas
30 drought more probable? *Bull. Amer. Meteor. Soc.*, **93**, 1052–1054.
- 31 Rupp, D.E., P.W. Mote, N. Massey, F.E.L. Otto, and M.R. Allen, 2013: Human influence on the
32 probability of low precipitation in the central United States in 2012 [in "Explaining Extreme
33 Events of 2013 from a Climate Perspective"]. *Bulletin of the American Meteorological*
34 *Society*, **94 (9)**, S2-S6. <http://dx.doi.org/10.1175/BAMS-D-13-00085.1>

- 1 Ryberg, K.R., W. Lin, and A.V. Vecchia, 2014: Impact of climate variability on runoff in the
2 north-central United States. *Journal of Hydrologic Engineering*, **19**, 148-158.
3 [http://dx.doi.org/10.1061/\(ASCE\)HE.1943-5584.0000775](http://dx.doi.org/10.1061/(ASCE)HE.1943-5584.0000775)
- 4 Sanford, T., R. Wang, and A. Kenwa, 2015: *The Age of Alaskan Wildfires*. Climate Central,
5 Princeton, NJ, 32 pp. <http://assets.climatecentral.org/pdfs/AgeofAlaskanWildfires.pdf>
- 6 Schoennagel T, Veblen TT, and Romme WH. 2004. The interaction of fire, fuels, and climate
7 across Rocky Mountain forests. *BioScience* 54: 661–76.
- 8 Seager, R., M. Hoerling, D.S. Siegfried, h. Wang, B. Lyon, A. Kumar, J. Nakamura, and N.
9 Henderson, 2014: Causes and Predictability of the 2011-14 California Drought. National
10 Oceanic and Atmospheric Administration, Drought Task Force Narrative Team, 40 pp.
11 <http://dx.doi.org/10.7289/V58K771F>
- 12 Seager, R., M. Hoerling, S. Schubert, H. Wang, B. Lyon, A. Kumar, J. Nakamura, and N.
13 Henderson, 2015: Causes of the 2011–14 California drought. *Journal of Climate*, **28**, 6997-
14 7024. <http://dx.doi.org/10.1175/JCLI-D-14-00860.1>
- 15 SFPUC, 2016: Flood Resilience: Report, Task Order 57 (Draft: May 2016). San Francisco Public
16 Utilities Commission, San Francisco, CA. 302 pp.
17 <http://sfwater.org/modules/showdocument.aspx?documentid=9176>
- 18 Sheffield, J., E.F. Wood, and M.L. Roderick, 2012: Little change in global drought over the past
19 60 years. *Nature*, **491**, 435-438. <http://dx.doi.org/10.1038/nature11575>
- 20 Slater, L.J., M.B. Singer, and J.W. Kirchner, 2015: Hydrologic versus geomorphic drivers of
21 trends in flood hazard. *Geophysical Research Letters*, **42**, 370-376.
22 <http://dx.doi.org/10.1002/2014GL062482>
- 23 Stavros, E.N., J.T. Abatzoglou, D. McKenzie, and N.K. Larkin, 2014: Regional projections of
24 the likelihood of very large wildland fires under a changing climate in the contiguous
25 Western United States. *Climatic Change*, **126**, 455-468. [http://dx.doi.org/10.1007/s10584-](http://dx.doi.org/10.1007/s10584-014-1229-6)
26 [014-1229-6](http://dx.doi.org/10.1007/s10584-014-1229-6)
- 27 Stephens, S.L., J.K. Agee, P.Z. Fulé, M.P. North, W.H. Romme, T.W. Swetnam, and M.G.
28 Turner, 2013: Managing forests and fire in changing climates. *Science*, **342**, 41-42.
29 <http://dx.doi.org/10.1126/science.1240294>
- 30 Stewart, I.T., D.R. Cayan, and M.D. Dettinger, 2005: Changes toward earlier streamflow timing
31 across western North America. *Journal of Climate*, **18**, 1136-1155.
32 <http://dx.doi.org/10.1175/JCLI3321.1>

- 1 Swain, D., M. Tsiang, M. Haughen, D. Singh, A. Charland, B. Rajarthan, and N.S. Diffenbaugh,
2 2014: The extraordinary California drought of 2013/14: Character, context and the role of
3 climate change [in "Explaining Extreme Events of 2013 from a Climate Perspective"].
4 *Bulletin of the American Meteorological Society*, **95 (9)**, S3-S6.
5 <http://dx.doi.org/10.1175/1520-0477-95.9.S1.1>
- 6 Tebaldi, C., K. Hayhoe, J.M. Arblaster, and G.A. Meehl, 2006: Going to the extremes: An
7 intercomparison of model-simulated historical and future changes in extreme events.
8 *Climatic Change*, **79**, 185-211. <http://dx.doi.org/10.1007/s10584-006-9051-4>
- 9 Tomer, M.D. and K.E. Schilling, 2009: A simple approach to distinguish land-use and climate-
10 change effects on watershed hydrology. *Journal of Hydrology*, **376**, 24-33.
11 <http://dx.doi.org/10.1016/j.jhydrol.2009.07.029>
- 12 Trenberth, K.E., A. Dai, G. van der Schrier, P.D. Jones, J. Barichivich, K.R. Briffa, and J.
13 Sheffield, 2014: Global warming and changes in drought. *Nature Climate Change*, **4**, 17-22.
14 <http://dx.doi.org/10.1038/nclimate2067>
- 15 Villarini, G., and A. Strong, Roles of climate and agricultural practices in discharge
16 changes in an agricultural watershed in Iowa, *Agriculture, Ecosystems and Environment*,
17 188, 204-211, 2014.
- 18 Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, P. Thorne, R. Vose, M.
19 Wehner, J. Willis, D. Anderson, S. Doney, R. Feely, P. Hennon, V. Kharin, T. Knutson, F.
20 Landerer, T. Lenton, J. Kennedy, and R. Somerville, 2014: Ch. 2: Our changing climate.
21 *Climate Change Impacts in the United States: The Third National Climate Assessment*.
22 Melillo, J.M., T.C. Richmond, and G.W. Yohe, Eds. U.S. Global Change Research Program,
23 Washington, D.C., 19-67. <http://dx.doi.org/10.7930/J0KW5CXT>
- 24 Wang, D. and M. Hejazi, 2011: Quantifying the relative contribution of the climate and direct
25 human impacts on mean annual streamflow in the contiguous United States. *Water Resources*
26 *Research*, **47**, W00J12. <http://dx.doi.org/10.1029/2010WR010283>
- 27 Wang, H. and S. Schubert, 2014: Causes of the extreme dry conditions over California during
28 early 2013 [in "Explaining Extreme Events of 2013 from a Climate Perspective"]. *Bulletin of*
29 *the American Meteorological Society*, **95 (9)**, S7-S11. [http://dx.doi.org/10.1175/1520-0477-](http://dx.doi.org/10.1175/1520-0477-95.9.S1.1)
30 [95.9.S1.1](http://dx.doi.org/10.1175/1520-0477-95.9.S1.1)
- 31 Warner, M.D., C.F. Mass, and E.P. Salathé Jr., 2015: Changes in winter atmospheric rivers along
32 the North American West Coast in CMIP5 climate models. *Journal of Hydrometeorology*,
33 **16**, 118-128. <http://dx.doi.org/10.1175/JHM-D-14-0080.1>

- 1 Wehner, M.F., 2013: Very extreme seasonal precipitation in the NARCCAP ensemble: Model
2 performance and projections. *Climate Dynamics*, **40**, 59-80.
3 <http://dx.doi.org/10.1007/s00382-012-1393-1>
- 4 Wehner, M., D.R. Easterling, J.H. Lawrimore, R.R. Heim, Jr., R.S. Vose, and B.D. Santer, 2011:
5 Projections of future drought in the continental United States and Mexico. *Journal of*
6 *Hydrometeorology*, **12**, 1359-1377. <http://dx.doi.org/10.1175/2011JHM1351.1>
- 7 Westerling, A.L., H.G. Hidalgo, D.R. Cayan, and T.W. Swetnam, 2006: Warming and earlier
8 spring increase western U.S. forest wildfire activity. *Science*, **313**, 940-943.
9 <http://dx.doi.org/10.1126/science.1128834>
- 10 Westerling, A.L. M.G. Turner, E.A.H. Smithwick, W.H. Romme, and M.G. Ryan
11 2011:Continued warming could transform Greater Yellowstone fire regimes by mid-21st
12 century. *Proc. Nat. Acad. Sci.* 108 (32) 13165-13170; doi:10.1073/pnas.1110199108
- 13 Williams, A.P., R. Seager, J.T. Abatzoglou, B.I. Cook, J.E. Smerdon, and E.R. Cook, 2015:
14 Contribution of anthropogenic warming to California drought during 2012–2014.
15 *Geophysical Research Letters*, **42**, 6819-6828. <http://dx.doi.org/10.1002/2015GL064924>
- 16 Williams, I.N. and M.S. Torn, 2015: Vegetation controls on surface heat flux partitioning, and
17 land-atmosphere coupling. *Geophysical Research Letters*, **42**, 9416-9424.
18 <http://dx.doi.org/10.1002/2015GL066305>
- 19 Winters, B.A., J. Angel, C. Ballerine, J. Byard, A. Flegel, D. Gambill, E. Jenkins, S. McConkey,
20 M. Markus, B.A. Bender, and M.J. O’Toole, 2015: Report for the Urban Flooding Awareness
21 Act. Illinois Department of Natural Resources, Springfield, IL. 89 pp.
22 https://www.dnr.illinois.gov/WaterResources/Documents/Final_UFAA_Report.pdf
- 23 Woodhouse, C.A., S.T. Gray, and D.M. Meko, 2006: Updated streamflow reconstructions for the
24 Upper Colorado River Basin. *Water Resources Research*, **42**.
25 <http://dx.doi.org/10.1029/2005WR004455>
- 26 Yoon, J.-H., B. Kravitz, P.J. Rasch, S.-Y.S. Wang, R.R. Gillies, and L. Hipps, 2015: Extreme
27 fire season in California: A glimpse into the future? *Bulletin of the American Meteorological*
28 *Society*, **96 (12)**, S5-S9. <http://dx.doi.org/10.1175/bams-d-15-00114.1>
- 29 Young, A.M., P.E. Higuera, P.A. Duffy, and F.S. Hu, 2016: Climatic thresholds shape northern
30 high-latitude fire regimes and imply vulnerability to future climate change. *Ecography*,
31 **Early view**. <http://dx.doi.org/10.1111/ecog.02205>

32

9. Extreme Storms

KEY FINDINGS

1. Human activities have contributed substantially to observed ocean–atmosphere variability in the Atlantic Ocean (*medium confidence*), and these changes have contributed to the observed upward trend in North Atlantic hurricane activity since the 1970s (*medium confidence*).
2. Both theory and numerical modeling simulations (in general) indicate an increase in tropical cyclone (TC) intensity in a warmer world, and the models generally show an increase in the number of very intense TCs. For Atlantic and eastern North Pacific hurricanes and western North Pacific typhoons, increases are projected in precipitation rates (*high confidence*) and intensity (*medium confidence*). The frequency of the most intense of these storms is projected to increase in the Atlantic and western North Pacific (*low confidence*) and in the eastern North Pacific (*medium confidence*).
3. Tornado activity in the United States has become more variable, particularly over the 2000s, with a decrease in the number of days per year with tornadoes and an increase in the number of tornadoes on these days (*medium confidence*). Confidence in past trends for hail and severe thunderstorm winds, however, is *low*. Climate models consistently project environmental changes that would putatively support an increase in the frequency and intensity of severe thunderstorms (a category that combines tornadoes, hail, and winds), especially over regions that are currently prone to these hazards, but confidence in the details of this projected increase is *low*.
4. There has been a trend toward earlier snowmelt and a decrease in snowstorm frequency on the southern margins of climatologically snowy areas (*medium confidence*). Winter storm tracks have shifted northward since 1950 over the Northern Hemisphere (*medium confidence*). Projections of winter storm frequency and intensity over the United States vary from increasing to decreasing depending on region, but model agreement is poor and confidence is *low*. Potential linkages between the frequency and intensity of severe winter storms in the United States and accelerated warming in the Arctic have been postulated, but they are complex, and, to some extent, contested, and confidence in the connection is currently *low*.
5. The frequency and severity of landfalling “atmospheric rivers” on the U.S. West Coast (narrow streams of moisture that account for 30%–40% of precipitation and snowpack in the region and are associated with severe flooding events) will increase as a result of increasing evaporation and resulting higher atmospheric water vapor that occurs with increasing temperature. (*Medium confidence*)

1 **9.1 Introduction**

2 Extreme storms have numerous impacts on lives and property. Quantifying how broad-scale
3 average climate influences the behavior of extreme storms is particularly challenging, in part
4 because extreme storms are comparatively rare short-lived events and occur within an
5 environment of largely random variability. Additionally, because the physical mechanisms
6 linking climate change and extreme storms can manifest in a variety of ways, even the sign of the
7 changes in the extreme storms can vary in a warming climate. This makes detection and
8 attribution of trends in extreme storm characteristics more difficult than detection and attribution
9 of trends in the larger environment in which the storms evolve (e.g., Ch. 6: Temperature
10 Change). Projecting changes in severe storms is also challenging because of model constraints in
11 how they capture and represent small-scale, highly local physics. Despite the challenges, good
12 progress is being made for a variety of storm types, such as tropical cyclones, severe convective
13 storms (thunderstorms), winter storms, and atmospheric river events.

14 **9.2 Tropical Cyclones (Hurricanes and Typhoons)**

15 Detection and attribution (Ch. 3: Detection and Attribution) of past changes in tropical cyclone
16 (TC) behavior remain a challenge due to the nature of the historical data, which are highly
17 heterogeneous in both time and among the various regions that collect and analyze the data
18 (Kossin et al. 2013; Klotzbach and Landsea 2015; Walsh et al. 2016). While there are ongoing
19 efforts to reanalyze and homogenize the data (e.g., Landsea et al. 2015; Kossin et al. 2013), there
20 is still low confidence that any reported long-term (multidecadal to centennial) increases in TC
21 activity are robust, after accounting for past changes in observing capabilities (which is
22 unchanged from the Intergovernmental Panel on Climate Change Fifth Assessment Report
23 (IPCC AR5) assessment statement [Hartmann et al. 2013]). This is not meant to imply that no
24 such increases have occurred, but rather that the data are not of a high enough quality to
25 determine this with much confidence. Furthermore, it has been argued that within the period of
26 highest data quality (since around 1980), the globally observed changes in the environment
27 would not necessarily support a detectable trend in tropical cyclone intensity (Kossin et al.
28 2013). That is, the trend signal has not yet had time to rise above the background variability of
29 natural processes.

30 Both theory and numerical modeling simulations (in general) indicate an increase in TC intensity
31 in a warmer world, and the models generally show an increase in the number of very intense TCs
32 (Bindoff et al. 2013; Camargo 2013; Christensen et al. 2013; Walsh et al. 2015; Knutson et
33 al. 2015). In some cases, climate models can be used to make attribution statements about TCs
34 without formal detection (see also Ch. 3: Detection and Attribution). For example, there is
35 evidence that, in addition to the effects of El Niño, anthropogenic forcing made the extremely
36 active 2014 Hawaiian hurricane season substantially more likely, although no significant rising
37 trend in TC frequency near Hawai'i was detected (Murakami et al. 2015).

1 Changes in frequency and intensity are not the only measures of TC behavior that may be
2 affected by climate variability and change, and there is evidence that the locations where TCs
3 reach their peak intensity has migrated poleward over the past 30 years in the Northern and
4 Southern Hemispheres, apparently in concert with environmental changes associated with the
5 independently observed expansion of the tropics (Kossin et al. 2014). The poleward migration in
6 the western North Pacific (Kossin et al. 2016), which includes a number of U.S. territories,
7 appears particularly consistent among the various available TC datasets and remains significant
8 over the past 60–70 years after accounting for the known modes of natural variability in the
9 region (Figure 9.1). The migration, which can substantially change patterns of TC hazard
10 exposure and mortality risk, is also evident in 21st century Coupled Model Intercomparison
11 Project Phase 5 (CMIP5) projections following the RCP8.5 emissions trajectories, suggesting a
12 possible link to human activities. Further analysis comparing observed past TC behavior with
13 climate model historical forcing runs (and with model control runs simulating multidecadal
14 internal climate variability alone) are needed to better understand this process, but it is expected
15 that this will be an area of heightened future research.

16 **[INSERT FIGURE 9.1 HERE]**

17 In the Atlantic, observed multidecadal variability of the ocean and atmosphere, which TCs are
18 shown to respond to, has been ascribed (Ch. 3: Detection and Attribution) to natural internal
19 variability via meridional overturning ocean circulation changes (Delworth and Mann 2000),
20 natural external variability caused by volcanic eruptions (Thompson and Solomon 2009; Evan
21 2012) and Saharan dust outbreaks (Evan et al. 2009, 2011), and anthropogenic external forcing
22 via greenhouse gases and sulfate aerosols (Mann and Emanuel 2006; Booth et al. 2012;
23 Dunstone et al. 2013). Determining the relative contributions of each mechanism to the observed
24 multidecadal variability in the Atlantic, and even whether natural or anthropogenic factors have
25 dominated, is presently a very active area of research and debate, and no consensus has yet been
26 reached (Carslaw et al. 2013; Zhang et al. 2013; Tung and Zhao 2013; Mann et al. 2014; Stevens
27 2015; Sobel et al. 2016). Despite the level of disagreement about the relative magnitude of
28 human influences, there is broad agreement that human factors have had a measurable impact on
29 the observed oceanic and atmospheric variability in the North Atlantic, and there is *medium*
30 *confidence* that this has contributed to the observed increase in hurricane activity since the
31 1970s. This is essentially unchanged from the IPCC AR5 statement (Bindoff et al. 2013),
32 although the post-AR5 literature has only served to further support this statement (Kossin et
33 al. 2015). This is expected to remain an active research topic in the foreseeable future.

34 The IPCC AR5 consensus TC projections for the late 21st century (IPCC Figure 14.17;
35 Christensen et al. 2013) include an increase in global mean TC intensity, precipitation rate, and
36 frequency of very intense (Saffir-Simpson Category 4–5) TCs, and a decrease, or little change, in
37 global tropical cyclone frequency. Since the IPCC AR5, some studies have provided additional
38 support for this consensus, and some have challenged an aspect of it. For example, a recent study

1 (Knutson et al. 2015) projects increased mean hurricane intensities in the Atlantic Ocean basin
2 and in most, but not all, other TC-supporting basins (see Table 3 in Knutson et al. 2015). In their
3 study, the global occurrence of Saffir–Simpson Category 4–5 storms was projected to increase
4 significantly, with the most significant basin-scale changes projected for the Northeast Pacific
5 basin, potentially increasing intense hurricane risk to Hawai‘i (Figure 9.2) over the coming
6 century. However, another recent (post-AR5) study proposed that increased thermal stratification
7 of the upper ocean in CMIP5 climate warming scenarios should substantially reduce the
8 warming-induced intensification of TCs estimated in previous studies (Huang et al. 2015).
9 Follow-up studies, however, estimate that the effect of such increased stratification is relatively
10 small, reducing the projected intensification of TCs by only about 10%–15% (Emanuel 2015;
11 Tuleya et al. 2016).

12 Another recent study challenged the IPCC AR5 consensus projection of a decrease, or little
13 change, in global tropical cyclone frequency by simulating increased global TC frequency over
14 the 21st century under the RCP8.5 scenario (Emanuel 2013). However, another modeling study
15 has found that neither direct analysis of CMIP5-class simulations, nor indirect inferences from
16 the simulations (such as those of Emanuel 2013), could reproduce the decrease in TC frequency
17 projected in a warmer world by high-resolution TC-permitting climate models (Wehner et al.
18 2015), which adds uncertainty to the results of Emanuel (2013).

19 In summary, despite new research that challenges one aspect of the AR5 consensus for late 21st
20 century projected TC activity, it remains *likely* that global mean tropical cyclone maximum wind
21 speeds and precipitation rates will increase; and it is *more likely than not* that the global
22 frequency of occurrence of TCs will either decrease or remain essentially the same. Confidence
23 in projected global increases of intensity and tropical cyclone precipitation rates is *medium* and
24 *high*, respectively, as there is better model consensus. Confidence is further heightened,
25 particularly for projected increases in precipitation rates, by a robust physical understanding of
26 the processes that lead to these increases. Confidence in projected increases in the frequency of
27 very intense TCs is generally lower (*medium* in the eastern North Pacific and *low* in the western
28 North Pacific and Atlantic) due to comparatively fewer studies available and due to the
29 competing influences of projected reductions in overall storm frequency and increased mean
30 intensity on the frequency of the most intense storms. Both the magnitude and sign of projected
31 changes in individual ocean basins appears to depend on the large-scale pattern of changes to
32 atmospheric circulation and ocean surface temperature (e.g., Knutson et al. 2015). Projections of
33 these regional patterns of change—apparently critical for TC projections—are uncertain, leading
34 to uncertainty in regional TC projections.

35 **[INSERT FIGURE 9.2 HERE]**

36

1 ----- **START BOX 9.1 HERE** -----

2 **Box 9.1: U.S. Landfalling Major Hurricane “Drought”**

3 The last major hurricane (Saffir–Simpson Category 3 or higher) to make landfall in the
4 continental United States was Wilma in 2005. The current 11-year (2006–2016) absence of U.S.
5 major hurricane landfall events (sometimes colloquially referred to as a “hurricane drought”) is
6 unprecedented in the historical records dating back to the mid-19th century and has occurred in
7 tandem with average to above-average basin-wide major hurricane counts. Is the absence of U.S.
8 landfalling major hurricanes due to random luck, or are there systematic changes in climate
9 driving this?

10 One recent study indicates that the absence of U.S. landfalling major hurricanes cannot readily
11 be attributed to any sustained changes in the climate patterns that affect hurricanes (Hall and
12 Heried 2015). Based on a statistical analysis of the historical North Atlantic hurricane database,
13 the study found no evidence of a connection between the number of major U.S. landfalls from
14 one year to the next and concluded that the 11-year absence of U.S. landfalling major hurricanes
15 is random. A subsequent recent study did identify a systematic pattern of atmosphere/ocean
16 conditions that vary in such a way that conditions conducive to hurricane intensification in the
17 deep tropics occur in concert with conditions conducive to weakening near the U.S. coast
18 (Kossin 2017). This result suggests a possible relationship between climate and hurricanes;
19 increasing basin-wide hurricane counts are associated with a decreasing fraction of major
20 hurricanes making U.S. landfall, as major hurricanes approaching the U.S. coast are more likely
21 to weaken during active North Atlantic hurricane periods (such as the present period). It is
22 unclear to what degree this relationship has affected absolute hurricane landfall counts during the
23 recent active hurricane period from the mid-1990s, as the basin-wide number and landfalling
24 fraction are in opposition (that is, there are more major hurricanes but a smaller fraction make
25 landfall as major hurricanes). It is also unclear how this relationship may change as the climate
26 continues to warm. Other studies have identified systematic interdecadal hurricane track
27 variability that may affect landfalling hurricane and major hurricane frequency (Kossin and
28 Vimont 2007; Wang et al. 2011; Colbert and Soden 2012).

29 Another recent study (Hart et al. 2016) shows that the extent of the absence is sensitive to
30 uncertainties in the historical data and even small variations in the definition of a major
31 hurricane, which is somewhat arbitrary. It is also sensitive to the definition of U.S. landfall,
32 which is a geopolitical-border-based constraint and has no physical meaning. In fact, many areas
33 outside of the U.S. border have experienced major hurricane landfalls in the past 11 years. In this
34 sense, the frequency of U.S. landfalling major hurricanes is not a particularly robust metric with
35 which to study questions about hurricane activity and its relationship with climate variability.
36 Furthermore, the 11-year absence of U.S. landfalling major hurricanes is not a particularly
37 relevant metric in terms of coastal hazard exposure and risk. For example, Hurricanes Ike (2008),
38 Irene (2011), Sandy (2012), and most recently Hurricane Matthew (2016) brought severe impacts

1 to the U.S. coast despite not making landfall in the United States while classified as major
2 hurricanes. In the case of Hurricane Sandy, extreme rainfall and storm surge (see also Ch. 12:
3 Sea Level Rise) during landfall caused extensive destruction in and around the New York City
4 area, despite Sandy’s designation as a post-tropical cyclone at that time. In the case of Hurricane
5 Matthew, the center came within about 40 miles of the Florida coast while Matthew was a major
6 hurricane, which is close enough to significantly impact the coast but not close enough to break
7 the “drought” as it is defined.

8 In summary, the 11-year absence of U.S. landfalling major hurricanes is anomalous. There is
9 some evidence that systematic atmosphere/ocean variability has reduced the fraction of
10 hurricanes making U.S. landfall since the mid-1990s, but this is at least partly countered by
11 increased basin-wide numbers, and the net effect on landfall rates is unclear. Moreover, there is a
12 large random element, and the metric itself suffers from lack of physical basis due to the
13 arbitrary intensity threshold and geopolitically based constraints. Additionally, U.S. coastal risk,
14 particularly from storm surge and freshwater flooding, depends strongly on storm size,
15 propagation speed and direction, and rainfall rates. There is some danger, in the form of evoking
16 complacency, in placing too much emphasis on the recent absence of a specific subset of
17 hurricanes.

18 ----- **END BOX 9.1 HERE** -----

19 **9.3 Severe Convective Storms (Thunderstorms)**

20 Tornado and severe thunderstorm events cause significant loss of life and property: more than
21 one-third of the \$1 billion weather disasters in the United States during the past 25 years were
22 due to such events, and, relative to other extreme weather, the damages from convective weather
23 hazards have undergone the largest increase since 1980 (Smith and Katz 2013). A particular
24 challenge in quantifying the existence and intensity of these events arises from the data source:
25 rather than measurements, the occurrence of tornadoes and severe thunderstorms is determined
26 by visual sightings by eyewitnesses (such as “storm spotters” and law enforcement officials) or
27 post-storm damage assessments. The reporting has been susceptible to changes in population
28 density, modifications to reporting procedures and training, the introduction of video and social
29 media, and so on. These have led to systematic, non-meteorological biases in the long-term data
30 record.

31 Nonetheless, judicious use of the report database has revealed important information about
32 tornado trends. Since the 1970s, the United States has experienced a decrease in the number of
33 days per year on which tornadoes occur, but an increase in the number of tornadoes that form on
34 such days (Brooks et al. 2014). One important implication is that the frequency of days with
35 large numbers of tornadoes—tornado outbreaks—appears to be increasing (Figure 9.3). The
36 extent of the season over which such tornado activity occurs is increasing as well: although
37 tornadoes in the United States are observed in all months of the year, an earlier calendar-day start

1 to the season of high activity is emerging. In general, there is more interannual variability, or
2 volatility, in tornado occurrence (Tippett 2014; see also Elsner et al. 2015).

3 **[INSERT FIGURE 9.3 HERE]**

4 Evaluations of hail and (non-tornadic) thunderstorm wind reports have thus far been less
5 revealing. Although there is evidence of an increase in the number of hail days per year, the
6 inherent uncertainty in reported hail size reduces the confidence in such a conclusion (Allen and
7 Tippett 2015). Thunderstorm wind reports have proven to be even less reliable, because, as
8 compared to tornadoes and hail, there is less tangible visual evidence; thus, although the United
9 States has lately experienced several significant thunderstorm wind events (sometimes referred
10 to as “derechos”), the lack of studies that explore long-term trends in wind events and the
11 uncertainties in the historical data preclude any robust assessment.

12 It is possible to bypass the use of reports by exploiting the fact that the temperature, humidity,
13 and wind in the larger vicinity—or “environment”—of a developing thunderstorm ultimately
14 control the intensity, morphology, and hazardous tendency of the storm. Thus, the premise is that
15 quantifications of the vertical profiles of temperature, humidity, and wind can be used as a proxy
16 for actual severe thunderstorm occurrence. In particular, a thresholded product of convective
17 available potential energy (CAPE) and vertical wind shear over a surface-to-6 km layer (S06)
18 constitutes one widely used means of representing the frequency of severe thunderstorms
19 (Brooks et al. 2003). This environmental-proxy approach avoids the biases and other issues with
20 eyewitness storm reports and is readily evaluated using the relatively coarse global data sets and
21 global climate models. It has the disadvantage of assuming that a thunderstorm will necessarily
22 form and then realize its environmental potential.

23 Upon employing global climate models (GCMs) to evaluate CAPE and S06, a consistent finding
24 among a growing number of proxy-based studies is a projected increase in the frequency of
25 severe thunderstorm environments in the United States over the mid- to late 21st century (Van
26 Klooster and Roebber 2009; Diffenbaugh et al. 2013; Gensini et al. 2014; Seely and Romps
27 2015; Trapp et al. 2007, 2009). The most robust projected increases in frequency are over the
28 U.S. Midwest and Southern Great Plains, during March-April-May (MAM) (Diffenbaugh et al.
29 2013). Based on the increased frequency of very high CAPE, increases in storm intensity are also
30 projected over this same period (see also Del Genio et al. 2007).

31 Key limitations of the environmental proxy approach are being addressed through the
32 applications of high-resolution dynamical downscaling, wherein sufficiently fine model grids are
33 used so that individual thunderstorms are explicitly resolved, rather than implicitly represented
34 (as through environmental proxies). The individually modeled thunderstorms can then be
35 quantified and assessed in terms of severity (Trapp et al. 2011; Robinson et al. 2013; Gensini and
36 Mote 2014). The dynamical-downscaling results have thus far supported the basic findings of the
37 environmental proxy studies, particularly in terms of the seasons and geographical regions

1 projected to experience the largest increases in severe-thunderstorm occurrence (Diffenbaugh et
2 al. 2013).

3 The computational expense of high-resolution dynamical downscaling makes it difficult to
4 generate model ensembles over long time periods, and thus to assess the uncertainty of the
5 downscaled projections. Because these dynamical downscaling implementations focus on the
6 statistics of storm occurrence rather than on faithful representations of individual events, they
7 have generally been unconcerned with specific extreme convective events in history. So, for
8 example, such downscaling does not address whether the intensity of an event like the Joplin,
9 Missouri, tornado of May 22, 2011, would be amplified under projected future climates.
10 Recently, the “pseudo-global warming” (PGW) methodology (see Schär et al. 1996), which is a
11 variant of dynamical downscaling, has been adapted to address these and related questions. As an
12 example, when the parent “supercell” of select historical tornado events forms under the climate
13 conditions projected during the late 21st century, it does not evolve into a benign, unorganized
14 thunderstorm but instead maintains its supercellular structure (Trapp and Hoogewind 2016). As
15 measured by updraft strength, the intensity of these supercells under PGW is relatively higher,
16 although not in proportion to the theoretical intensity based on the projected higher levels of
17 CAPE. The adverse effects of enhanced precipitation loading under PGW has been offered as
18 one possible explanation for such shortfalls in projected updraft strength.

19 **9.4 Winter Storms**

20 The frequency of large snowfall years has decreased in the southern United States and Pacific
21 Northwest and increased in the northern United States (see Ch. 7: Precipitation Change). The
22 winters of 2013/2014 and 2014/2015 have contributed to this trend. They were characterized by
23 frequent storms and heavier-than-normal snowfalls in the Midwest and Northeast and drought in
24 the western United States. These were related to blocking (a large-scale pressure pattern with
25 little or no movement) of the wintertime circulation in the Pacific sector of the Northern
26 Hemisphere (e.g., Marinaro et al. 2015) that put the midwestern and northeastern United States
27 in the primary winter storm track, while at the same time reducing the number of winter storms
28 in California, causing severe drought conditions (Chang et al. 2015). While some observational
29 studies suggest a linkage between blocking affecting the U.S. climate and enhanced arctic
30 warming (arctic amplification), specifically for an increase in highly amplified jet stream
31 patterns in winter over the United States (Francis and Skific 2015), other studies show mixed
32 results (Barnes and Polvani 2015; Perlwitz et al. 2015; Screen et al. 2015). Therefore, a
33 definitive understanding of the effects of arctic amplification on midlatitude winter weather
34 remains elusive. Other explanations have been offered for the weather patterns of recent winters,
35 such as anomalously strong Pacific trade winds (Yang et al. 2015), but these have not been
36 linked to anthropogenic forcing (e.g., Delworth et al. 2015).

37 Analysis of storm tracks indicates that there has been an increase in winter storm frequency and
38 intensity since 1950, with a slight shift in tracks toward the poles (Wang et al. 2006, 2012; Vose

1 et al. 2014). Current global climate models (CMIP5) do in fact predict an increase in
2 extratropical cyclone (ETC) frequency over the eastern United States, including the most intense
3 ETCs, under the high RCP8.5 scenario (Colle et al. 2013). However, there are large model-to-
4 model differences in the realism of ETC simulations and in the projected changes. Moreover,
5 projected ETC changes have large regional variations, including a decreased total frequency in
6 the North Atlantic, further highlighting the complexity of the response to climate change.

7 **9.5 Atmospheric Rivers**

8 The term “atmospheric rivers” (ARs) refers to the relatively narrow streams of moisture transport
9 that often occur within and across midlatitudes (Zhu and Newell 1998) (Figure 9.4), in part
10 because they often transport as much water as in the Amazon River (Newell et al. 1992). While
11 ARs occupy less than 10% of the circumference of the Earth at any given time, they account for
12 90% of the poleward moisture transport across midlatitudes (a more complete discussion of
13 precipitation variability is found in Ch. 7: Precipitation Change). In many regions of the world,
14 they account for a substantial fraction of the precipitation (Guan and Waliser 2015), and thus
15 water supply, often delivered in the form of an extreme weather and precipitation event (Figure
16 9.4). For example, ARs account for 30%–40% of the typical snow pack in the Sierra Nevada
17 mountains and annual precipitation in the U.S. West Coast states (Guan et al. 2010; Dettinger et
18 al. 2011)—an essential summertime source of water for agriculture, consumption, and ecosystem
19 health. However, this vital source of water is also associated with severe flooding—with
20 observational evidence showing a close connection between historically high streamflow events
21 and floods with landfalling AR events—in the west and other sectors of the United States (Ralph
22 et al. 2006; Neiman et al. 2011; Moore et al. 2012). More recently, research has also
23 demonstrated that ARs are often found to be critical in ending droughts in the western United
24 States (Dettinger 2013).

25 **[INSERT FIGURE 9.4 HERE]**

26 Given the important role that ARs play in the water supply of the western United States and their
27 role in weather and water extremes in the west and occasionally other parts of the United States
28 (e.g., Rutz et al. 2014), it is critical to examine how climate change and the expected
29 intensification of the global water cycle and atmospheric transports (e.g., Held and Soden 2006;
30 Lavers et al. 2015) are projected to impact ARs (e.g., Dettinger and Ingram 2013). Under climate
31 change conditions, ARs may be altered in a number of ways, namely their frequency, intensity,
32 duration, and locations. In association with landfalling ARs, any of these would be expected to
33 result in impacts on hazards and water supply given the discussion above. Assessments of ARs in
34 climate change projections for the United States have been undertaken for central California
35 from CMIP3 (Dettinger et al. 2011) and a number of studies have been done for the West Coast
36 of North America (Warner et al. 2015; Payne and Magnusdottir 2015; Gao et al. 2015; Radić et
37 al. 2015; Hagos et al. 2016), and these studies have uniformly shown that ARs are likely to
38 become more frequent and intense in the future. For example, one recent study reveals a large

1 increase of AR days along the West Coast by the end of the 21st century in the RCP8.5 scenario,
2 with fractional increases between 50% and 600%, depending on the seasons and landfall
3 locations (Gao et al. 2015). Results from these studies (and Lavers et al. 2013 for ARs impacting
4 the United Kingdom) show that these AR changes were predominantly driven by increasing
5 atmospheric specific humidity, with little discernible change in the low-level winds. The higher
6 atmospheric water vapor content in a warmer climate is to be expected because of an increase in
7 saturation water vapor pressure with air temperature (Ch. 2: Physical Drivers of Climate
8 Change). While the thermodynamic effect appears to dominate the climate change impact on
9 ARs, leading to projected increases in ARs, there is evidence for a dynamical effect (that is,
10 location change) related to the projected poleward shift of the subtropical jet that diminished the
11 thermodynamic effect in the southern portion of the West Coast of North America (Gao et al.
12 2015).

13 Presently, there is no clear consensus on whether the consistently projected increases in AR
14 frequency and intensity will translate to increased precipitation in California. This is mostly
15 because previous studies did not examine this explicitly and because the model resolution is poor
16 and thus the topography is poorly represented, and the topography is a key aspect of forcing the
17 precipitation out of the systems (Pierce et al. 2013). The evidence for considerable increases in
18 the number and intensity of ARs depends (as do all climate variability studies based on
19 dynamical models) on the model fidelity in representing ARs and their interactions with the
20 global climate/circulation. Additional confidence comes from studies that show qualitatively
21 similar projected increases while also providing evidence that the models represent AR
22 frequency, transports, and spatial distributions relatively well compared to observations (Payne
23 and Magnusdottir 2015; Hagos et al. 2016). A caveat associated with drawing conclusions from
24 any given study or differences between two is that they typically use different detection
25 methodologies that are typically tailored to a regional setting (cf. Guan and Waliser 2015).
26 Additional research is warranted to examine these storms from a global perspective, with
27 additional and more in-depth, process-oriented diagnostics/metrics. Stepping away from the
28 sensitivities associated with defining atmospheric rivers, one study examined the intensification
29 of the integrated vapor transport (IVT), which is easily and unambiguously defined (Lavers et al.
30 2015). That study found that for the RCP8.5 scenario, multimodel mean IVT and the IVT
31 associated with extremes above 95% percentile increase by 30%–40% in the North Pacific.
32 These results, along with the uniform findings of the studies above examining projected changes
33 in ARs for western North America and the United Kingdom, give *high confidence* that the
34 frequency of AR storms will increase in association with rising global temperatures.

35

1 TRACEABLE ACCOUNTS

2 Key Finding 1

3 Human activities have contributed substantially to observed ocean–atmosphere variability in the
4 Atlantic Ocean (*medium confidence*), and these changes have contributed to the observed upward
5 trend in North Atlantic hurricane activity since the 1970s (*medium confidence*).

6 Description of evidence base

7 The Key Finding and supporting text summarizes extensive evidence documented in the climate
8 science literature and is similar to statements made in previous national (NCA3; Melillo et al.,
9 2014) and international (IPCC 2013) assessments. Data limitations are documented in Kossin et
10 al. 2013 and references therein. Contributions of natural and anthropogenic factors in observed
11 multidecadal variability are quantified in Carslaw et al. 2013; Zhang et al. 2013; Tung and Zhao
12 2013; Mann et al. 2014; Stevens 2015; Sobel et al. 2016; Walsh et al. 2015.

13 Major uncertainties

14 Key remaining uncertainties are due to known and substantial heterogeneities in the historical
15 tropical cyclone data and lack of robust consensus in determining the precise relative
16 contributions of natural and anthropogenic factors in past variability of the tropical environment.

17 Assessment of confidence based on evidence and agreement, including short description of 18 nature of evidence and level of agreement

19 Confidence in this finding is rated as *medium*. Although the range of estimates of natural versus
20 anthropogenic contributions in the literature is fairly broad, virtually all studies identify a
21 measurable, and generally substantial, anthropogenic influence. This does constitute a consensus
22 for human contribution to the increases in tropical cyclone activity since 1970.

23 Summary sentence or paragraph that integrates the above information

24 The key message and supporting text summarizes extensive evidence documented in the climate
25 science peer-reviewed literature. The uncertainties and points of consensus that were described
26 in the NCA3 and IPCC assessments have continued.

27

28 Key Finding 2

29 Both theory and numerical modeling simulations (in general) indicate an increase in tropical
30 cyclone (TC) intensity in a warmer world, and the models generally show an increase in the
31 number of very intense TCs. For Atlantic and eastern North Pacific hurricanes and western North
32 Pacific typhoons, increases are projected in precipitation rates (*high confidence*) and intensity

1 (*medium confidence*). The frequency of the most intense of these storms is projected to increase
2 in the Atlantic and western North Pacific (*low confidence*) and in the eastern North Pacific
3 (*medium confidence*).

4 **Description of evidence base**

5 The Key Finding and supporting text summarizes extensive evidence documented in the climate
6 science literature and is similar to statements made in previous national (NCA3; Melillo et al.
7 2014) and international (IPCC 2013) assessments. Since these assessments, more recent
8 downscaling studies have further supported these assessments (e.g., Knutson et al. 2015), though
9 pointing out that the changes (future increased intensity and tropical cyclone precipitation rates)
10 may not occur in all ocean basins.

11 **Major uncertainties**

12 A key uncertainty remains in the lack of a supporting detectable anthropogenic signal in the
13 historical data to add further confidence to these projections. As such, confidence in the
14 projections is based on agreement among different modeling studies and physical understanding
15 (for example, potential intensity theory for tropical cyclone intensities and the expectation of
16 stronger moisture convergence, and thus higher precipitation rates, in tropical cyclones in a
17 warmer environment containing greater amounts of environmental atmospheric moisture).
18 Additional uncertainty stems from uncertainty in both the projected pattern and magnitude of
19 future sea surface temperatures (Knutson et al. 2015).

20 **Assessment of confidence based on evidence and agreement, including short description of** 21 **nature of evidence and level of agreement**

22 Confidence is rated as *high* in tropical cyclone rainfall projections and *medium* in intensity
23 projections since there are a number of publications supporting these overall conclusions, fairly
24 well-established theory, general consistency among different studies, varying methods used in
25 studies, and still a fairly strong consensus among studies. However, a limiting factor for
26 confidence in the results is the lack of a supporting detectable anthropogenic contribution in
27 observed tropical cyclone data.

28 There is *low* to *medium confidence* for increased occurrence of the most intense tropical cyclones
29 for most ocean basins, as there are relatively few formal studies that focus on these changes, and
30 the change in occurrence of such storms would be enhanced by increased intensities, but reduced
31 by decreased overall frequency of tropical cyclones.

32 **Summary sentence or paragraph that integrates the above information**

33 Models are generally in agreement that tropical cyclones will be more intense and have higher
34 precipitation rates, at least in most ocean basins. Given the agreement between models and
35 support of theory and mechanistic understanding, there is *medium* to *high confidence* in the

1 overall projection, although there is some limitation on confidence levels due to the lack of a
2 supporting detectable anthropogenic contribution to tropical cyclone intensities or precipitation
3 rates.

4

5 **Key Finding 3**

6 Tornado activity in the United States has become more variable, particularly over the 2000s, with
7 a decrease in the number of days per year with tornadoes and an increase in the number of
8 tornadoes on these days (*medium confidence*). Confidence in past trends for hail and severe
9 thunderstorm winds, however, is *low*. Climate models consistently project environmental
10 changes that would putatively support an increase in the frequency and intensity of severe
11 thunderstorms (a category that combines tornadoes, hail, and winds), especially over regions that
12 are currently prone to these hazards, but confidence in the details of this projected increase is
13 *low*.

14 **Description of evidence base**

15 Evidence for the first and second statement comes from the U.S. database of tornado reports.
16 There are well known biases in this database, but application of an intensity threshold (greater
17 than or equal to a rating of 1 on the [Enhanced] Fujita scale) and the quantification of tornado
18 activity in terms of tornado days instead of raw numbers of reports are thought to reduce these
19 biases. It is not known at this time whether the variability and trends are necessarily due to
20 climate change.

21 The third statement is based on projections from a wide range of climate models, including
22 GCMs and RCMs, run over the past 10 years (e.g., see the review by Brooks 2013). The
23 evidence is derived from an “environmental-proxy” approach, which herein means that severe
24 thunderstorm occurrence is related to the occurrence of two key environmental parameters:
25 CAPE and vertical wind shear. A limitation of this approach is the assumption that the
26 thunderstorm will necessarily form and then realize its environmental potential. This assumption
27 is indeed violated, albeit at levels that vary by region and season.

28 **Major uncertainties**

29 Regarding the first and second statements, there is still some uncertainty in the database, even
30 when the data are filtered. The major uncertainty in the third statement equates to the
31 aforementioned limitation (that is, the thunderstorm will necessarily form and then realize its
32 environmental potential).

33

1 **Assessment of confidence based on evidence and agreement, including short description of**
2 **nature of evidence and level of agreement**

3 *Medium:* That the variability in tornado activity has increased.

4 *Medium:* That the severe-thunderstorm environmental conditions will change with a changing
5 climate, but

6 *Low:* on the precise (geographical and seasonal) realization of the environmental conditions as
7 actual severe thunderstorms.

8 **Summary sentence or paragraph that integrates the above information**

9 With an established understanding of the data biases, careful analysis provides useful
10 information about past changes in severe thunderstorm and tornado activity. This information
11 suggests that tornado variability has increased in the 2000s, with a concurrent decrease in the
12 number of days per year experiencing tornadoes and an increase in the number of tornadoes on
13 these days. Similarly, the development of novel applications of climate models provides
14 information about possible future severe storm and tornado activity, and although confidence in
15 these projections is low, they do suggest that the projected environments are at least consistent
16 with environments that would putatively support an increase in frequency and intensity of severe
17 thunderstorms.

18

19 **Key Finding 4**

20 There has been a trend toward earlier snowmelt and a decrease in snowstorm frequency on the
21 southern margins of climatologically snowy areas (*medium confidence*). Winter storm tracks
22 have shifted northward since 1950 over the Northern Hemisphere (*medium confidence*).
23 Projections of winter storm frequency and intensity over the United States vary from increasing
24 to decreasing depending on region, but model agreement is poor and confidence is *low*. Potential
25 linkages between the frequency and intensity of severe winter storms in the United States and
26 accelerated warming in the Arctic have been postulated, but they are complex, and, to some
27 extent, contested, and confidence in the connection is currently *low*.

28 **Description of evidence base**

29 The Key Finding and supporting text summarizes evidence documented in the climate science
30 literature.

31 Evidence for changes in winter storm track changes are documented in a small number of studies
32 (Wang et al. 2006, 2012). Future changes are documented in one study (Colle et al. 2013), but
33 there are large model-to-model differences. The effects of arctic amplification on U.S. winter
34 storms have been studied, but the results are mixed (Francis and Skific 2015; Barnes and Polvani
35 2015; Perlwitz et al. 2015; Screen et al. 2015), leading to considerable uncertainties.

1 **Major uncertainties**

2 Key remaining uncertainties relate to the sensitivity of observed snow changes to the spatial
3 distribution of observing stations and to historical changes in station location and observing
4 practices. There is conflicting evidence about the effects of arctic amplification on CONUS
5 winter weather.

6 **Assessment of confidence based on evidence and agreement, including short description of** 7 **nature of evidence and level of agreement**

8 There is *high confidence* that warming has resulted in earlier snowmelt and decreased snowfall
9 on the warm margins of areas with consistent snowpack based on a number of observational
10 studies. There is *medium confidence* that Northern Hemisphere storm tracks have shifted north
11 based on a small number of studies. There is *low confidence* in future changes in winter storm
12 frequency and intensity based on conflicting evidence from analysis of climate model
13 simulations.

14 **Summary sentence or paragraph that integrates the above information**

15 Decreases in snowfall on southern and low elevation margins of currently climatologically
16 snowy areas are likely but winter storm frequency and intensity changes are uncertain.

17

18 **Key Finding 5**

19 The frequency and severity of landfalling “atmospheric rivers” on the U.S. West Coast (narrow
20 streams of moisture that account for 30%–40% of precipitation and snowpack in the region and
21 are associated with severe flooding events) will increase as a result of increasing evaporation and
22 resulting higher atmospheric water vapor that occurs with increasing temperature. (*Medium*
23 *confidence*)

24 **Description of evidence base**

25 The Key Finding and supporting text summarizes evidence documented in the climate science
26 literature.

27 Evidence for the expectation of an increase in the frequency and severity of landfalling
28 atmospheric rivers on the U.S. West Coast comes from the CMIP-based climate change
29 projection studies of Dettinger et al. 2011; Warner et al. 2015; Payne and Magnúsdóttir 2015;
30 Gao et al. 2015; Radić et al. 2015; and Hagos et al. 2016. The close connection between
31 atmospheric rivers and water availability and flooding is based on the present-day observation
32 studies of Guan et al. 2010; Dettinger et al. 2011; Ralph et al. 2006; Neiman et al. 2011; Moore
33 et al. 2012; and Dettinger 2013.

1 **Major uncertainties**

2 A modest uncertainty remains in the lack of a supporting detectable anthropogenic signal in the
3 historical data to add further confidence to these projections. However, the overall increase in
4 atmospheric rivers projected/expected is based to a very large degree on the *very high confidence*
5 there is that the atmospheric water vapor will increase. Thus, increasing water vapor coupled
6 with little projected change in wind structure/intensity still indicates increases in the
7 frequency/intensity of atmospheric rivers. A modest uncertainty arises in quantifying the
8 expected change at a regional level (for example, northern Oregon vs. southern Oregon) given
9 that there are some changes expected in the position of the jet stream that might influence the
10 degree of increase for different locations along the West Coast. Uncertainty in the projections of
11 the number and intensity of ARs is introduced by uncertainties in the models' ability to represent
12 ARs and their interactions with climate.

13 **Assessment of confidence based on evidence and agreement, including short description of**
14 **nature of evidence and level of agreement**

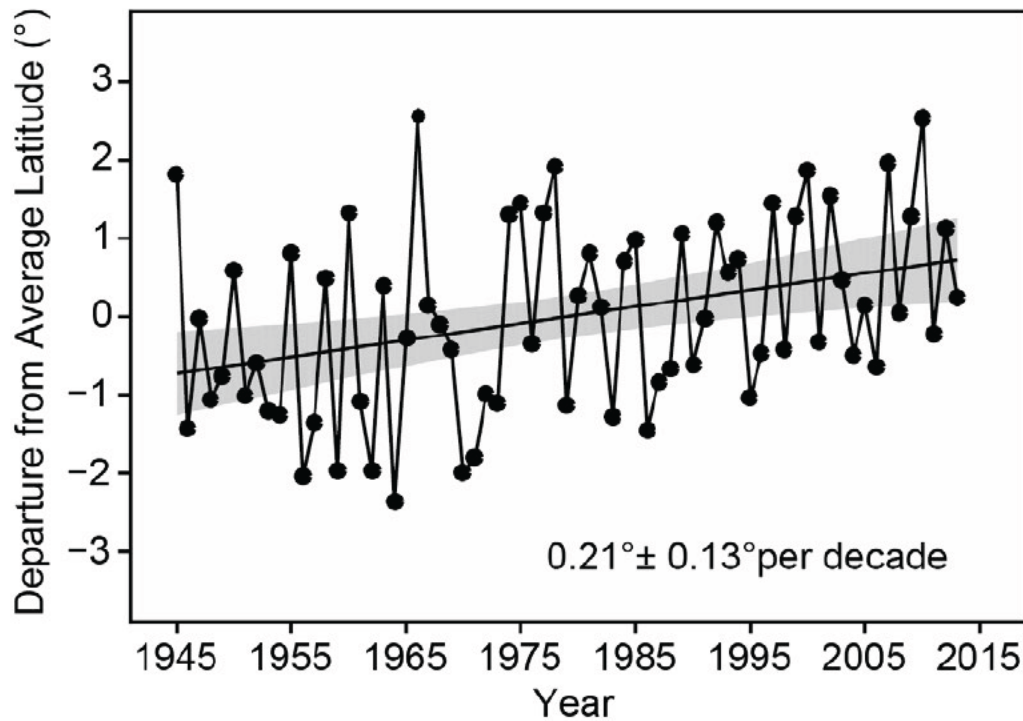
15 Confidence in this finding is rated as *medium* based on qualitatively similar projections among
16 different studies.

17 **Summary sentence or paragraph that integrates the above information**

18 Increases in atmospheric river frequency and intensity are expected along the U.S. West Coast,
19 leading to the likelihood of more frequent flooding conditions, with uncertainties remaining in
20 the details of the spatial structure of these along the coast (for example, northern vs. southern
21 California).

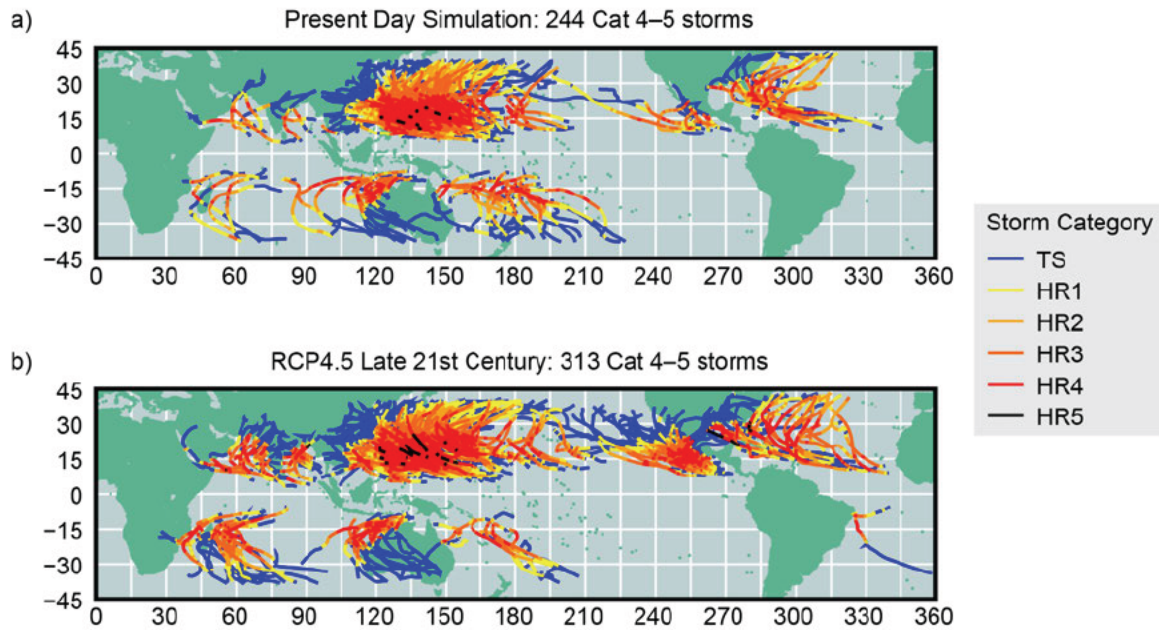
22

1 FIGURES



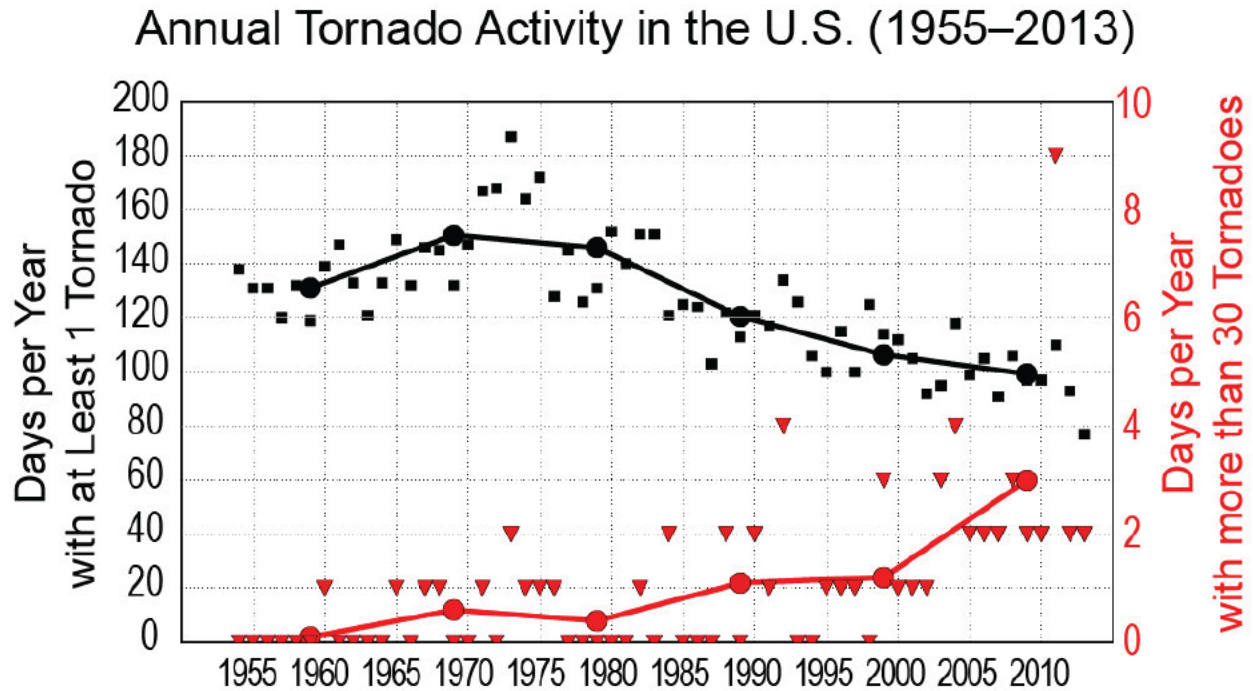
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3 **Figure 9.1:** Poleward migration, in degrees of latitude, of the location of annual mean tropical
 4 cyclone (TC) peak lifetime intensity in the western North Pacific Ocean, after accounting for the
 5 known regional modes of interannual (El Niño–Southern Oscillation; ENSO) and interdecadal
 6 (Pacific Decadal Oscillation; PDO) variability. The time series shows residuals of the
 7 multivariate regression of annually averaged latitude of TC peak lifetime intensity onto the mean
 8 Niño-3.4 and PDO indices. Data are taken from the Joint Typhoon Warning Center (JTWC).
 9 Shading shows 95% confidence bounds for the trend. Annotated values at lower right show the
 10 mean migration rate and its 95% confidence interval in degrees per decade for the period 1945–
 11 2013. (Figure source: adapted from Kossin et al. 2016; © American Meteorological Society.
 12 Used with permission.)



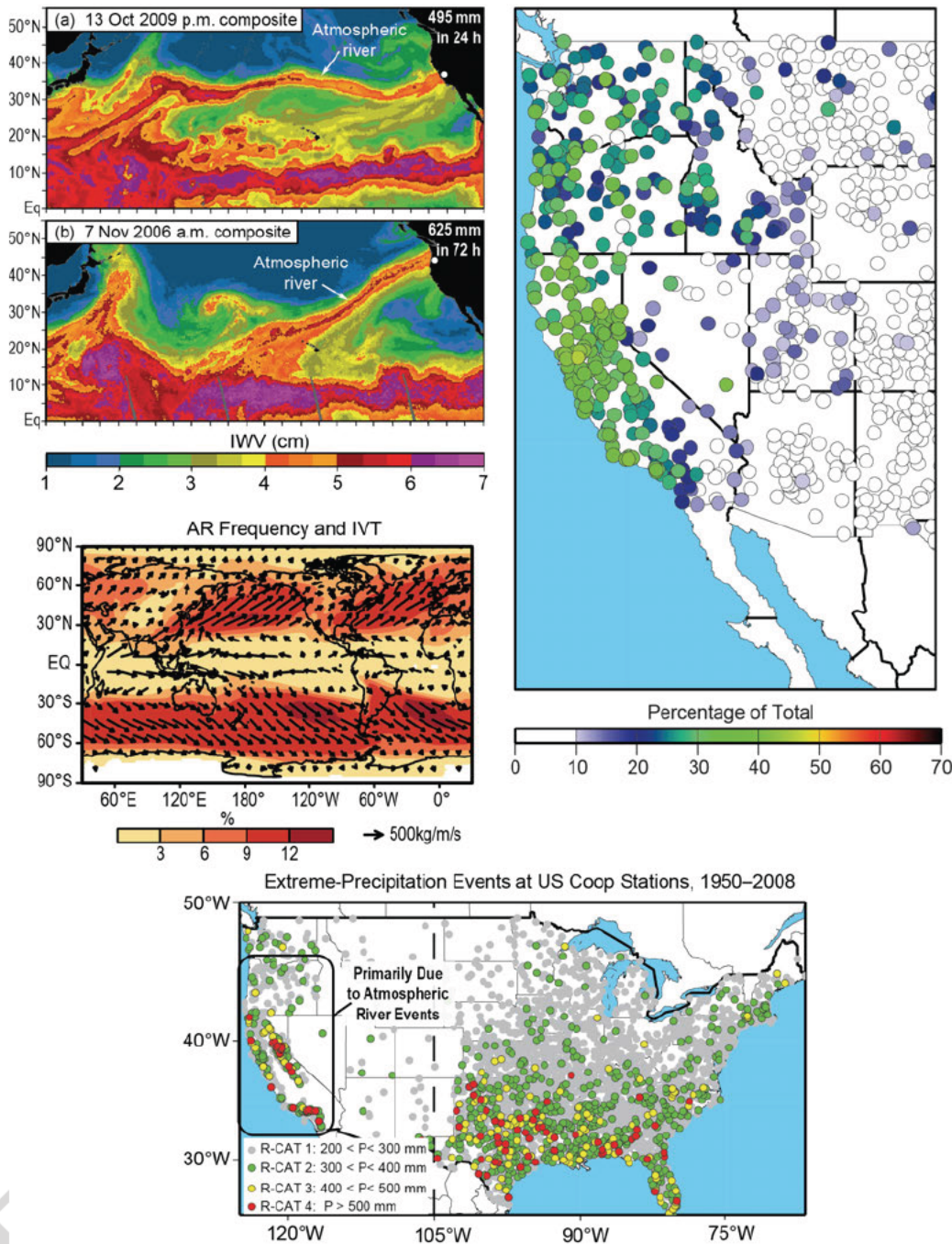
1
2 **Figure 9.2:** Tracks of simulated Saffir–Simpson Category 4–5 tropical cyclones for (a) present-
3 day or (b) late-21st-century conditions, based on dynamical downscaling of climate conditions
4 from the CMIP5 multimodel ensemble (RCP4.5 scenario). The tropical cyclones were initially
5 simulated using a 50-km grid global atmospheric model, but each individual tropical cyclone was
6 re-simulated at higher resolution using the GFDL hurricane model to provide more realistic
7 storm intensities and structure. Storm categories or intensities are shown over the lifetime of
8 each simulated storm, according to the Saffir–Simpson scale. The categories are depicted by the
9 track colors, varying from tropical storm (blue) to Category 5 (black; see legend). (Figure source:
10 Knutson et al. 2015; © American Meteorological Society. Used with permission.)

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Figure 9.3: Annual tornado activity in the United States over the period 1955–2013. The black squares indicate the number of days per year with at least one tornado rated (E)F1 or greater, and the black circles and line show the decadal mean line of such *tornado days*. The red triangles indicate the number of days per year with more than 30 tornadoes rated (E)F1 or greater, and the red circles and line show the decadal mean of these *tornado outbreaks*. (Figure source: redrawn from Brooks et al. 2014).



1

2 **Figure 9.4:** (upper left) Atmospheric rivers depicted in Special Sensor Microwave Imager
 3 (SSM/I) measurements of SSM/I total column water vapor leading to extreme precipitation
 4 events at landfall locations. (middle left) Annual mean frequency of atmospheric river
 5 occurrence (for example, 12% means about 1 every 8 days) and their integrated vapor transport
 6 (IVT) (Guan and Waliser 2015). (bottom) ARs are the dominant synoptic storms for the U.S.
 7 West Coast in terms of extreme precipitation (Ralph and Dettinger 2012) and (right) supply a
 8 large fraction of the annual precipitation in the U.S. West Coast states (Dettinger et al. 2011).
 9 (Figure source: [upper and middle left] Ralph et al. 2011, [upper right] Guan and Waliser 2015,

- 1 [lower left] Ralph and Dettinger 2012, [lower right], Dettinger et al. 2011; left panels, ©
- 2 American Meteorological Society. Used with permission.)
- 3

FINAL DRAFT

1 **REFERENCES**

- 2 Allen, J. T., and M. K. Tippett, 2015: The Characteristics of United States Hail Reports: 1955-
3 2014. *Electronic Journal of Severe Storms Meteorology*, 1-31.
- 4 Barnes, E. A., and L. M. Polvani, 2015: CMIP5 projections of arctic amplification, of the North
5 American/North Atlantic circulation, and of their relationship. *Journal of Climate*, **28** (13),
6 5254-5271, doi:10.1175/JCLI-D-14-00589.1.
- 7 Bindoff, N. L., and Coauthors, 2013: Detection and attribution of climate change: From global to
8 regional. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group
9 I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. F.
10 Stocker et al., Eds., Cambridge University Press, 867–952.
- 11 Booth, B. B. B., N. J. Dunstone, P. R. Halloran, T. Andrews, and N. Bellouin, 2012: Aerosols
12 implicated as a prime driver of twentieth-century North Atlantic climate variability. *Nature*,
13 **484**, 228-232, doi:10.1038/nature10946.
- 14 Brooks, H. E., 2013: Severe thunderstorms and climate change. *Atmospheric Research*, **123**,
15 129-138, doi:10.1016/j.atmosres.2012.04.002.
- 16 Brooks, H. E., J. W. Lee, and J. P. Craven, 2003: The spatial distribution of severe thunderstorm
17 and tornado environments from global reanalysis data. *Atmospheric Research*, **67–68**, 73-94,
18 doi:10.1016/S0169-8095(03)00045-0.
- 19 Brooks, H. E., G. W. Carbin, and P. T. Marsh, 2014: Increased variability of tornado occurrence
20 in the United States. *Science*, **346** (6207), 349-352, doi:10.1126/science.1257460.
- 21 Camargo, S. J., 2013: Global and regional aspects of tropical cyclone activity in the CMIP5
22 models, *Journal of Climate*, **26** (24), 9880–9902, doi:10.1175/JCLI-D-12-00549.1.
- 23 Carslaw, K. S., and Coauthors, 2013: Large contribution of natural aerosols to uncertainty in
24 indirect forcing. *Nature*, **503** (7474), 67-71, doi:10.1038/nature12674.
- 25 Chang, E. K. M., C. Zheng, P. Lanigan, A. M. W. Yau, and J. D. Neelin, 2015: Significant
26 modulation of variability and projected change in California winter precipitation by
27 extratropical cyclone activity. *Geophysical Research Letters*, **42** (14), 5983-5991,
28 doi:10.1002/2015GL064424.
- 29 Christensen, J. H., and Coauthors, 2013: Climate phenomena and their relevance for future
30 regional climate change. *Climate Change 2013: The Physical Science Basis. Contribution of
31 Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate
32 Change*, T. F. Stocker et al., Eds., Cambridge University Press, 1217–1308.

- 1 Colbert, A. J., and B. J. Soden, 2012: Climatological variations in North Atlantic tropical
2 cyclone tracks. *Journal of Climate*, **25** (2), 657-673, doi:10.1175/jcli-d-11-00034.1.
- 3 Colle, B. A., Z. Zhang, K. A. Lombardo, E. Chang, P. Liu, and M. Zhang, 2013: Historical
4 evaluation and future prediction of eastern North American and western Atlantic
5 extratropical cyclones in the CMIP5 models during the cool season. *Journal of Climate*, **26**
6 (18), 6882-6903, doi:10.1175/JCLI-D-12-00498.1.
- 7 Del Genio, A. D., M. S. Yao, and J. Jonas, 2007: Will moist convection be stronger in a warmer
8 climate? *Geophysical Research Letters*, **34** (16), 5, doi:10.1029/2007GL030525.
- 9 Delworth, L. T., and E. M. Mann, 2000: Observed and simulated multidecadal variability in the
10 Northern Hemisphere. *Climate Dynamics*, **16** (9), 661-676, doi:10.1007/s003820000075.
- 11 Delworth, T. L., F. Zeng, A. Rosati, G. A. Vecchi, and A. T. Wittenberg, 2015: A link between
12 the hiatus in global warming and North American drought. *Journal of Climate*, **28** (9), 3834-
13 3845, doi:10.1175/jcli-d-14-00616.1.
- 14 Dettinger, M. D., 2013: Atmospheric rivers as drought busters on the U.S. West Coast. *Journal*
15 *of Hydrometeorology*, **14** (6), 1721-1732, doi:10.1175/JHM-D-13-02.1.
- 16 Dettinger, M. D., and B. L. Ingram, 2013: The coming megafloods. *Scientific American*, **308**, 64-
17 71, doi:10.1038/scientificamerican0113-64.
- 18 Dettinger, M. D., F. M. Ralph, T. Das, P. J. Neiman, and D. R. Cayan, 2011: Atmospheric rivers,
19 floods and the water resources of California. *Water*, **3** (2), 445-478, doi:10.3390/w3020445.
- 20 N. S., M. Scherer, and R. J. Trapp, 2013: Robust increases in severe thunderstorm
21 environments in response to greenhouse forcing. *Proceedings of the National Academy of*
22 *Sciences*, **110** (41), 16361-16366, doi:10.1073/pnas.1307758110.
- 23 Dunstone, N. J., D. M. Smith, B. B. Booth, L. Hermanson, and R. Eade, 2013: Anthropogenic
24 aerosol forcing of Atlantic tropical storms. *Nature Geoscience*, **6** (7), 534-539,
25 doi:10.1038/ngeo1854.
- 26 Elsner, J. B., S. C. Elsner, and T. H. Jagger, 2015: The increasing efficiency of tornado days in
27 the United States. *Climate Dynamics*, **45** (3), 651-659, doi:10.1007/s00382-014-2277-3.
- 28 Emanuel, K. A., 2013: Downscaling CMIP5 climate models shows increased tropical cyclone
29 activity over the 21st century. *Proceedings of the National Academy of Sciences*, **110** (30),
30 12219-12224, doi:10.1073/pnas.1301293110.
- 31 Emanuel, K., 2015: Effect of upper-ocean evolution on projected trends in tropical cyclone
32 activity. *Journal of Climate*, **28** (20), 8165-8170, doi:10.1175/JCLI-D-15-0401.1.

- 1 Evan, A. T., 2012: Atlantic hurricane activity following two major volcanic eruptions. *Journal of*
2 *Geophysical Research*, **117** (D6), D06101, doi:10.1029/2011JD016716.
- 3 Evan, A. T., D. J. Vimont, A. K. Heidinger, J. P. Kossin, and R. Bennartz, 2009: The role of
4 aerosols in the evolution of tropical North Atlantic Ocean temperature anomalies. *Science*,
5 **324** (5928), 778-781, doi:10.1126/science.1167404.
- 6 Evan, A. T., G. R. Foltz, D. Zhang, and D. J. Vimont, 2011: Influence of African dust on ocean-
7 atmosphere variability in the tropical Atlantic. *Nature Geoscience*, **4** (11), 762-765,
8 doi:10.1038/ngeo1276.
- 9 Francis, J., and N. Skific, 2015: Evidence linking rapid Arctic warming to mid-latitude weather
10 patterns. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and*
11 *Engineering Sciences*, **373** (2045), doi:10.1098/rsta.2014.0170.
- 12 Gao, Y., J. Lu, L. R. Leung, Q. Yang, S. Hagos, and Y. Qian, 2015: Dynamical and
13 thermodynamical modulations on future changes of landfalling atmospheric rivers over
14 western North America. *Geophysical Research Letters*, **42** (17), 7179-7186,
15 doi:10.1002/2015GL065435.
- 16 Gensini, V. A., and T. L. Mote, 2014: Estimations of hazardous convective weather in the United
17 States using dynamical downscaling. *Journal of Climate*, **27** (17), 6581-6589,
18 doi:10.1175/JCLI-D-13-00777.1.
- 19 Gensini, V. A., C. Ramseyer, and T. L. Mote, 2014: Future convective environments using
20 NARCCAP. *International Journal of Climatology*, **34** (5), 1699-1705, doi:10.1002/joc.3769.
- 21 Guan, B., and D. E. Waliser, 2015: Detection of atmospheric rivers: Evaluation and application
22 of an algorithm for global studies. *Journal of Geophysical Research: Atmospheres*, **120** (24),
23 12514-12535, doi:10.1002/2015JD024257.
- 24 Guan, B., N. P. Molotch, D. E. Waliser, E. J. Fetzer, and P. J. Neiman, 2010: Extreme snowfall
25 events linked to atmospheric rivers and surface air temperature via satellite measurements.
26 *Geophysical Research Letters*, **37** (20), n/a-n/a, doi:10.1029/2010GL044696.
- 27 Hagos, S. M., L. R. Leung, J.-H. Yoon, J. Lu, and Y. Gao, 2016: A projection of changes in
28 landfalling atmospheric river frequency and extreme precipitation over western North
29 America from the Large Ensemble CESM simulations. *Geophysical Research Letters*, **43** (3),
30 1357-1363, doi:10.1002/2015GL067392.
- 31 Hall, T., and K. Hereid, 2015: The frequency and duration of U.S. hurricane droughts.
32 *Geophysical Research Letters*, **42** (9), 3482-3485, doi:10.1002/2015GL063652.

- 1 Hart, R. E., D. R. Chavas, and M. P. Guishard, 2016: The arbitrary definition of the current
2 Atlantic major hurricane landfall drought. *Bulletin of the American Meteorological Society*,
3 **97** (5), 713-722, doi:10.1175/BAMS-D-15-00185.1.
- 4 Hartmann, D. L., and Coauthors, 2013: Observations: Atmosphere and surface. *Climate Change*
5 *2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment*
6 *Report of the Intergovernmental Panel on Climate Change*, T. F. Stocker et al., Eds.,
7 Cambridge University Press, 159–254.
- 8 Held, I. M., and B. J. Soden, 2006: Robust responses of the hydrological cycle to global
9 warming. *Journal of Climate*, **19** (21), 5686-5699, doi:10.1175/jcli3990.1.
- 10 Huang, P., I. I. Lin, C. Chou, and R.-H. Huang, 2015: Change in ocean subsurface environment
11 to suppress tropical cyclone intensification under global warming. *Nature communications*,
12 **6**, 7188, doi:10.1038/ncomms8188.
- 13 IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group*
14 *I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. T. F.
15 Stocker et al., Eds. Cambridge University Press, 1535 pp.
- 16 Klotzbach, P. J., and C. W. Landsea, 2015: Extremely intense hurricanes: Revisiting Webster et
17 al. (2005) after 10 years. *Journal of Climate*, **28** (19), 7621-7629, doi:10.1175/JCLI-D-15-
18 0188.1.
- 19 Knutson, T. R., and Coauthors, 2015: Global projections of intense tropical cyclone activity for
20 the late twenty-first century from dynamical downscaling of CMIP5/RCP4.5 scenarios.
21 *Journal of Climate*, **28** (18), 7203-7224, doi:10.1175/JCLI-D-15-0129.1.
- 22 Kossin, J. P., 2017: Hurricane intensification along U. S. coast suppressed during active
23 hurricane periods. *Nature*, **541**, 390-393, doi:10.1038/nature20783.
- 24 Kossin, J. P., and D. J. Vimont, 2007: A more general framework for understanding Atlantic
25 hurricane variability and trends. *Bulletin of the American Meteorological Society*, **88** (11),
26 1767-1781, doi:10.1175/bams-88-11-1767.
- 27 Kossin, J. P., T. L. Olander, and K. R. Knapp, 2013: Trend analysis with a new global record of
28 tropical cyclone intensity. *Journal of Climate*, **26** (24), 9960-9976, doi:10.1175/JCLI-D-13-
29 00262.1.
- 30 Kossin, J. P., K. A. Emanuel, and G. A. Vecchi, 2014: The poleward migration of the location of
31 tropical cyclone maximum intensity. *Nature*, **509** (7500), 349-352, doi:10.1038/nature13278.
- 32 Kossin, J. P., T. R. Karl, T. R. Knutson, K. A. Emanuel, K. E. Kunkel, and J. J. O'Brien, 2015:
33 Reply to "Comments on 'Monitoring and understanding trends in extreme storms: State of

- 1 knowledge””. *Bulletin of the American Meteorological Society*, **96** (12) (7), 1177-1179,
2 doi:10.1175/BAMS-D-14-00261.1.
- 3 Kossin, J. P., K. A. Emanuel, and S. J. Camargo, 2016: Past and projected changes in western
4 North Pacific tropical cyclone exposure. *Journal of Climate*, **29** (16), 5725-5739,
5 doi:10.1175/JCLI-D-16-0076.1.
- 6 Landsea, C., J. Franklin, and J. Beven, 2015: The revised Atlantic hurricane database
7 (HURDAT2) 2ed., N. H. C. (NHC), Ed., NHC. [Available online at
8 [http://http://www.nhc.noaa.gov/data/hurdat/hurdat2-format-atlantic.pdf](http://www.nhc.noaa.gov/data/hurdat/hurdat2-format-atlantic.pdf).]
- 9 Lavers, D. A., R. P. Allan, G. Villarini, B. Lloyd-Hughes, D. J. Brayshaw, and A. J. Wade, 2013:
10 Future changes in atmospheric rivers and their implications for winter flooding in Britain.
11 *Environmental Research Letters*, **8** (3), 034010, doi:10.1088/1748-9326/8/3/034010.
- 12 Lavers, D. A., F. M. Ralph, D. E. Waliser, A. Gershunov, and M. D. Dettinger, 2015: Climate
13 change intensification of horizontal water vapor transport in CMIP5. *Geophysical Research*
14 *Letters*, **42** (13), 5617-5625, doi:10.1002/2015GL064672.
- 15 Mann, M. E., and K. A. Emanuel, 2006: Atlantic hurricane trends linked to climate change. *Eos*,
16 *Transactions, American Geophysical Union*, **87** (24), 233-244, doi:10.1029/2006EO240001.
- 17 Mann, M. E., B. A. Steinman, and S. K. Miller, 2014: On forced temperature changes, internal
18 variability, and the AMO. *Geophysical Research Letters*, **41** (9), 3211-3219,
19 doi:10.1002/2014GL059233.
- 20 Marinaro, A., S. Hilberg, D. Changnon, and J. R. Angel, 2015: The North Pacific–driven severe
21 Midwest winter of 2013/14. *Journal of Applied Meteorology and Climatology*, **54** (10), 2141-
22 2151, doi:10.1175/JAMC-D-15-0084.1.
- 23 Melillo, J. M., T. C. Richmond, and G. W. Yohe, Eds., 2014: *Climate Change Impacts in the*
24 *United States: The Third National Climate Assessment*. U.S. Global Change Research
25 Program, 842 pp.
- 26 Moore, B. J., P. J. Neiman, F. M. Ralph, and F. E. Barthold, 2012: Physical processes associated
27 with heavy flooding rainfall in Nashville, Tennessee, and vicinity during 1–2 May 2010: The
28 role of an atmospheric river and mesoscale convective systems. *Monthly Weather Review*,
29 **140** (2), 358-378, doi:10.1175/MWR-D-11-00126.1.
- 30 Murakami, H., G. A. Vecchi, T. L. Delworth, K. Paffendorf, L. Jia, R. Gudgel, and F. Zeng,
31 2015: Investigating the influence of anthropogenic forcing and natural variability on the 2014
32 Hawaiian hurricane season [in "Explaining Extreme Events of 2014 from a Climate
33 Perspective"]. *Bulletin of the American Meteorological Society*, **96** (12) (12), S115-S119,
34 doi:10.1175/BAMS-D-15-00119.1.

- 1 Neiman, P. J., L. J. Schick, F. M. Ralph, M. Hughes, and G. A. Wick, 2011: Flooding in western
2 Washington: The connection to atmospheric rivers. *Journal of Hydrometeorology*, **12** (6),
3 1337-1358, doi:10.1175/2011JHM1358.1.
- 4 Newell, R. E., N. E. Newell, Y. Zhu, and C. Scott, 1992: Tropospheric rivers? – A pilot study.
5 *Geophysical Research Letters*, **19** (24), 2401-2404, doi:10.1029/92GL02916.
- 6 Payne, A. E., and G. Magnusdottir, 2015: An evaluation of atmospheric rivers over the North
7 Pacific in CMIP5 and their response to warming under RCP 8.5. *Journal of Geophysical*
8 *Research: Atmospheres*, **120** (21), 11,173-111,190, doi:10.1002/2015JD023586.
- 9 Perlwitz, J., M. Hoerling, and R. Dole, 2015: Arctic tropospheric warming: Causes and linkages
10 to lower latitudes. *Journal of Climate*, **28** (6), 2154-2167, doi:10.1175/JCLI-D-14-00095.1.
- 11 Pierce, D. W., and Coauthors, 2013: The key role of heavy precipitation events in climate model
12 disagreements of future annual precipitation changes in California. *Journal of Climate*, **26**
13 (16), 5879-5896, doi:10.1175/jcli-d-12-00766.1.
- 14 Radić, V., A. J. Cannon, B. Menounos, and N. Gi, 2015: Future changes in autumn atmospheric
15 river events in British Columbia, Canada, as projected by CMIP5 global climate models.
16 *Journal of Geophysical Research: Atmospheres*, **120** (18), 9279-9302,
17 doi:10.1002/2015JD023279.
- 18 Ralph, F. M., and M. D. Dettinger, 2012: Historical and national perspectives on extreme West
19 Coast precipitation associated with atmospheric rivers during December 2010. *Bulletin of the*
20 *American Meteorological Society*, **93** (6), 783-790, doi:10.1175/BAMS-D-11-00188.1.
- 21 Ralph, F. M., P. J. Neiman, G. A. Wick, S. I. Gutman, M. D. Dettinger, D. R. Cayan, and A. B.
22 White, 2006: Flooding on California's Russian River: Role of atmospheric rivers.
23 *Geophysical Research Letters*, **33** (13), L13801, doi:10.1029/2006GL026689.
- 24 Ralph, F. M., P. J. Neiman, G. N. Kiladis, K. Weickmann, and D. W. Reynolds, 2011: A
25 multiscale observational case study of a Pacific atmospheric river exhibiting tropical–
26 extratropical connections and a mesoscale frontal wave. *Monthly Weather Review*, **139** (4),
27 1169-1189, doi:10.1175/2010mwr3596.1.
- 28 Robinson, E. D., R. J. Trapp, and M. E. Baldwin, 2013: The geospatial and temporal
29 distributions of severe thunderstorms from high-resolution dynamical downscaling. *Journal*
30 *of Applied Meteorology and Climatology*, **52** (9), 2147-2161, doi:10.1175/JAMC-D-12-
31 0131.1.
- 32 Rutz, J. J., W. J. Steenburgh, and F. M. Ralph, 2014: Climatological characteristics of
33 atmospheric rivers and their inland penetration over the western United States. *Monthly*
34 *Weather Review*, **142** (2), 905-921, doi:10.1175/MWR-D-13-00168.1.

- 1 Schär, C., C. Frei, D. Lüthi, and H. C. Davies, 1996: Surrogate climate-change scenarios for
2 regional climate models. *Geophysical Research Letters*, **23** (6), 669-672,
3 doi:10.1029/96GL00265.
- 4 Screen, J. A., C. Deser, and L. Sun, 2015: Projected changes in regional climate extremes arising
5 from Arctic sea ice loss. *Environmental Research Letters*, **10** (8), 084006, doi:10.1088/1748-
6 9326/10/8/084006.
- 7 Seeley, J. T., and D. M. Romps, 2015: The effect of global warming on severe thunderstorms in
8 the United States. *Journal of Climate*, **28** (6), 2443-2458, doi:10.1175/JCLI-D-14-00382.1.
- 9 Smith, A. B., and R. W. Katz, 2013: U.S. billion-dollar weather and climate disasters: Data
10 sources, trends, accuracy and biases. *Natural Hazards*, **67** (2), 387-410, doi:10.1007/s11069-
11 013-0566-5.
- 12 Sobel, A. H., S. J. Camargo, T. M. Hall, C.-Y. Lee, M. K. Tippett, and A. A. Wing, 2016:
13 Human influence on tropical cyclone intensity. *Science*, **353** (6296), 242-246,
14 doi:10.1126/science.aaf6574.
- 15 Stevens, B., 2015: Rethinking the lower bound on aerosol radiative forcing. *Journal of Climate*,
16 **28** (12), 4794-4819, doi:10.1175/JCLI-D-14-00656.1.
- 17 Thompson, D. W. J., and S. Solomon, 2009: Understanding recent stratospheric climate change.
18 *Journal of Climate*, **22** (8), 1934-1943, doi:10.1175/2008JCLI2482.1.
- 19 Tippett, M. K., 2014: Changing volatility of U.S. annual tornado reports. *Geophysical Research*
20 *Letters*, **41** (19), 6956-6961, doi:10.1002/2014GL061347.
- 21 Trapp, R. J., and K. A. Hoogewind, 2016: The realization of extreme tornadic storm events under
22 future anthropogenic climate change. *Journal of Climate*, **29** (14), 5251-5265,
23 doi:10.1175/JCLI-D-15-0623.1.
- 24 Trapp, R. J., N. S. Diffenbaugh, H. E. Brooks, M. E. Baldwin, E. D. Robinson, and J. S. Pal,
25 2007: Changes in severe thunderstorm environment frequency during the 21st century
26 caused by anthropogenically enhanced global radiative forcing. *Proceedings, National*
27 *Academy of Sciences*, **104**, 19719-19723, doi: 10.1073/pnas.0705494104.
- 28 Trapp, R. J., N. S. Diffenbaugh, and A. Gluhovsky, 2009: Transient response of severe
29 thunderstorm forcing to elevated greenhouse gas concentrations. *Geophysical Research*
30 *Letters*, **36**, L01703, doi:10.1029/2008GL036203.
- 31 Trapp, R. J., E. D. Robinson, M. E. Baldwin, N. S. Diffenbaugh, and B. R. J. Schwedler, 2011:
32 Regional climate of hazardous convective weather through high-resolution dynamical
33 downscaling. *Climate Dynamics*, **37** (3), 677-688, doi:10.1007/s00382-010-0826-y.

- 1 Tuleya, R. E., M. Bender, T. R. Knutson, J. J. Sirutis, B. Thomas, and I. Ginis, 2016: Impact of
2 upper-tropospheric temperature anomalies and vertical wind shear on tropical cyclone
3 evolution using an idealized version of the operational GFDL hurricane model. *Journal of the*
4 *Atmospheric Sciences*, **73** (10), 3803-3820, doi:10.1175/JAS-D-16-0045.1.
- 5 Tung, K.-K., and J. Zhou, 2013: Using data to attribute episodes of warming and cooling in
6 instrumental records. *Proceedings of the National Academy of Sciences*, **110** (6), 2058-2063,
7 doi:10.1073/pnas.1212471110.
- 8 Van Klooster, S. L., and P. J. Roebber, 2009: Surface-based convective potential in the
9 contiguous United States in a business-as-usual future climate. *Journal of Climate*, **22** (12),
10 3317-3330, doi:10.1175/2009JCLI2697.1.
- 11 Vose, R. S., and Coauthors, 2014: Monitoring and understanding changes in extremes:
12 Extratropical storms, winds, and waves. *Bulletin of the American Meteorological Society*, **95**
13 (3), 377-386, doi:10.1175/BAMS-D-12-00162.1.
- 14 Walsh, K. J. E., and Coauthors, 2016: Tropical cyclones and climate change. *Wiley*
15 *Interdisciplinary Reviews: Climate Change*, **7** (1), 65-89, doi:10.1002/wcc.371.
- 16 Walsh, K. J. E., and Coauthors, 2015: Hurricanes and climate: The U.S. CLIVAR Working
17 Group on Hurricanes. *Bulletin of the American Meteorological Society*, **96** (12) (6), 997-
18 1017, doi:10.1175/BAMS-D-13-00242.1.
- 19 Wang, C., H. Liu, S.-K. Lee, and R. Atlas, 2011: Impact of the Atlantic warm pool on United
20 States landfalling hurricanes. *Geophysical Research Letters*, **38** (19), L19702,
21 doi:10.1029/2011gl049265.
- 22 Wang, X. L., V. R. Swail, and F. W. Zwiers, 2006: Climatology and changes of extratropical
23 cyclone activity: Comparison of ERA-40 with NCEP-NCAR reanalysis for 1958-2001.
24 *Journal of Climate*, **19** (13), 3145-3166, doi:10.1175/JCLI3781.1.
- 25 Wang, X. L., Y. Feng, G. P. Compo, V. R. Swail, F. W. Zwiers, R. J. Allan, and P. D.
26 Sardeshmukh, 2012: Trends and low frequency variability of extra-tropical cyclone activity
27 in the ensemble of twentieth century reanalysis. *Climate Dynamics*, **40** (11-12), 2775-2800,
28 doi:10.1007/s00382-012-1450-9.
- 29 Warner, M. D., C. F. Mass, and E. P. Salathé, Jr., 2015: Changes in winter atmospheric rivers
30 along the North American West Coast in CMIP5 climate models. *Journal of*
31 *Hydrometeorology*, **16** (1), 118-128, doi:10.1175/JHM-D-14-0080.1.
- 32 Wehner, M., Prabhat, K. A. Reed, D. Stone, W. D. Collins, and J. Bacmeister, 2015: Resolution
33 dependence of future tropical cyclone projections of CAM5.1 in the U.S. CLIVAR Hurricane

- 1 Working Group idealized configurations. *Journal of Climate*, **28** (10), 3905-3925,
2 doi:10.1175/JCLI-D-14-00311.1.
- 3 Yang, X., and Coauthors, 2015: Extreme North America winter storm season of 2013/14: Roles
4 of radiative forcing and the global warming hiatus [in "Explaining Extreme Events of 2014
5 from a Climate Perspective"]. *Bulletin of the American Meteorological Society*, **96** (12) (12),
6 S25-S28, doi:10.1175/BAMS-D-15-00133.1.
- 7 Zhang, R., and Coauthors, 2013: Have aerosols caused the observed Atlantic multidecadal
8 variability? *Journal of the Atmospheric Sciences*, **70** (4), 1135-1144, doi:10.1175/jas-d-12-
9 0331.1.
- 10 Zhu, Y., and R. E. Newell, 1998: A proposed algorithm for moisture fluxes from atmospheric
11 rivers. *Monthly Weather Review*, **126** (3), 725-735, doi:10.1175/1520-
12 0493(1998)126<0725:APAFMF>2.0.CO;2.

13

10. Changes in Land Cover and Terrestrial Biogeochemistry

KEY FINDINGS

1. Changes in land use and land cover due to human activities produce physical changes in land surface albedo, latent and sensible heat, and atmospheric aerosol and greenhouse gas concentrations. The combined effects of these changes have recently been estimated to account for $40\% \pm 16\%$ of the human-caused global radiative forcing from 1850 to present day (*high confidence*). As a whole, the terrestrial biosphere (soil and plants) is a net “sink” for carbon (drawing down carbon from the atmosphere), and this sink has steadily increased since 1980 (*very high confidence*). Because of the uncertainty in the trajectory of land cover, the possibility of the land becoming a net carbon source cannot be excluded (*very high confidence*).
2. Climate change and induced changes in the frequency and magnitude of extreme events (e.g., droughts, floods, and heat waves) have led to large changes in plant community structure with subsequent effects on the biogeochemistry of terrestrial ecosystems. Uncertainties about how climate change will affect land cover change make it difficult to project the magnitude and sign of future climate feedbacks from land cover changes (*high confidence*).
3. Since 1901, regional averages of both the consecutive number of frost-free days and the length of the corresponding growing season have increased for the seven contiguous U.S. regions used in this assessment. However, there is important variability at smaller scales, with some locations actually showing decreases of a few days to as much as one to two weeks. Plant productivity has not increased commensurate with the increased number of frost-free days or with the longer growing season due to plant-specific temperature thresholds, plant–pollinator dependence, and seasonal limitations in water and nutrient availability (*very high confidence*). Future consequences of changes to the growing season for plant productivity are uncertain.
4. Recent studies confirm and quantify that surface temperatures are higher in urban areas than in surrounding rural areas for a number of reasons, including the concentrated release of heat from buildings, vehicles, and industry. In the United States, this urban heat island effect results in daytime temperatures 0.9° – 7.2° F (0.5° – 4.0° C) higher and nighttime temperatures 1.8° – 4.5° F (1.0° – 2.5° C) higher in urban areas, with larger temperature differences in humid regions (primarily in the eastern United States) and in cities with larger and denser populations. The urban heat island effect will strengthen in the future as the structure, spatial extent, and population density of urban areas change and grow (*high confidence*).

1 **10.1 Introduction**

2 Direct changes in land use by humans are contributing to radiative forcing by altering land cover
3 and therefore albedo, contributing to climate change (Ch. 2: Physical Drivers of Climate
4 Change). This forcing is spatially variable in both magnitude and sign; globally averaged, it is
5 negative (climate cooling; Figure 2.3). Climate changes, in turn, are altering the biogeochemistry
6 of land ecosystems through extended growing seasons, increased numbers of frost-free days,
7 altered productivity in agricultural and forested systems, longer fire seasons, and urban-induced
8 thunderstorms (Kunkel 2016; Galloway et al. 2014). Changes in land use and land cover interact
9 with local, regional, and global climate processes (Brown et al. 2014). The resulting ecosystem
10 responses alter Earth's albedo, the carbon cycle, and atmospheric aerosols, constituting a mix of
11 positive and negative feedbacks to climate change (Myhre et al. 2013; Ward et al. 2014; Figure
12 10.1 and Chapter 2, Section 2.6.2). Thus, changes to terrestrial ecosystems or land cover are a
13 direct driver of climate change and they are further altered by climate change in ways that affect
14 both ecosystem productivity and, through feedbacks, the climate itself. The following sections
15 describe advances since the Third National Climate Assessment (NCA3) (Melillo et al. 2014) in
16 scientific understanding of land cover and associated biogeochemistry and their impacts on the
17 climate system.

18 **[INSERT FIGURE 10.1 HERE]**

19 **10.2 Terrestrial Ecosystem Interactions with the Climate System**

20 Other chapters of this report discuss changes in temperature (Ch. 6: Temperature Change),
21 precipitation (Ch. 7: Precipitation Change), hydrology (Chapter 8: Droughts, Floods, and
22 Wildfires), and extreme events (Ch. 9: Extreme Storms). Collectively, these processes affect the
23 phenology, structure, productivity, and biogeochemical processes of all terrestrial ecosystems,
24 and as such, climate change will alter land cover and ecosystem services.

25 **10.2.1 Land Cover and Climate Forcing**

26 Changes in land cover and land use have long been recognized as important contributors to
27 global climate forcing (e.g., Feddema et al. 2005). Historically, studies that account for the
28 contribution of the land cover to radiative forcing have accounted for albedo forcings only and
29 not those from changes in land surface geophysical properties (e.g., plant transpiration,
30 evaporation from soils, plant community structure and function) or in aerosols. Physical climate
31 effects from land-cover or land-use change do not lend themselves directly to quantification
32 using the traditional radiative forcing concept. However, a framework to attribute the indirect
33 contributions of land cover to radiative forcing and the climate system—including effects on
34 seasonal and interannual soil moisture and latent/sensible heat, evapotranspiration,
35 biogeochemical cycle (CO₂) fluxes from soils and plants, aerosol and aerosol precursor
36 emissions, ozone precursor emissions, and snowpack—was reported in NRC (2005). Predicting

1 future consequences of changes in land cover on the climate system will require not only the
2 traditional calculations of surface albedo but also surface net radiation partitioning between
3 latent and sensible heat exchange and the effects of resulting changes in biogeochemical trace
4 gas and aerosol fluxes. Future trajectories of land use and land cover change are uncertain and
5 will depend on population growth, changes in agricultural yield driven by the competing
6 demands for production of fuel (i.e., bioenergy crops), food, feed, and fiber as well as urban
7 expansion. An example of the diversity of future land cover and land use changes is highlighted
8 through the Representative Concentration Pathway (RCPs) and their implementation of land
9 use/land cover to attain target goals of radiative forcing by 2100 (Hurtt et al. 2011). For example,
10 the highest scenario, RCP8.5 (Riahi et al. 2011), features an increase of cultivated land by about
11 185 million hectares from 2000 to 2050 and another 120 million hectares from 2050 to 2100. In
12 RCP6.0—the Asia Pacific Integrated Model (AIM) (Fujimori et al. 2014), urban land use
13 increases due to population and economic growth while cropland area expands due to increasing
14 food demand. Grassland areas decline while total forested area extent remains constant
15 throughout the century (Hurtt et al. 2011). The Global Change Assessment Model (GCAM),
16 RCP4.5, preserved and expanded forested areas throughout the 21st century. Agricultural land
17 declined slightly due to this afforestation, yet food demand is met through crop yield
18 improvements, dietary shifts, production efficiency, and international trade (Thomson et al.
19 2011; Hurtt et al. 2011). As with the highest scenario (RCP8.5), the lowest scenario (RCP2.6)
20 (van Vuuren et al. 2011a) reallocated agricultural production from developed to developing
21 countries, with increased bioenergy production (Hurtt et al. 2011). Continued land-use change is
22 projected across all RCPs (2.6, 4.5, 6.0, and 8.5) and is expected to contribute between 0.9 and
23 1.9 W/m^2 to direct radiative forcing by 2100 (Ward et al. 2014). The RCPs demonstrate that
24 land-use management and change combined with policy, demographic, energy technological
25 innovations and change, and lifestyle changes all contribute to future climate (van Vuuren et al.
26 2011b).

27 Traditional calculations of radiative forcing by land-cover change yield small forcing values (Ch.
28 2: Physical Drivers of Climate Change) because they account only for changes in surface albedo
29 (e.g., Myhre and Myhre 2003; Betts et al. 2007; Jones et al. 2015). Recent assessments (Myhre et
30 al. 2013 and references therein) are beginning to calculate the relative contributions of land-use
31 and land-cover change (LULCC) to radiative forcing in addition to albedo and/or aerosols (Ward
32 et al. 2014). Radiative forcing data reported in this chapter are largely from observations (see
33 Table 8.2 in Myhre et al. 2013). Ward et al. (2014) performed an independent modeling study to
34 partition radiative forcing from natural and anthropogenic land use and land cover change and
35 related land management activities into contributions from carbon dioxide (CO_2), methane (CH_4),
36 nitrous oxide (N_2O), aerosols, halocarbons, and ozone (O_3).

37 The more extended effects of land–atmosphere interactions from natural and anthropogenic land-
38 use and land-cover change (LULCC; Figure 10.1) described above have recently been reviewed
39 and estimated by atmospheric constituent (Myhre et al. 2013; Ward et al. 2014; Figure 10.2). The

1 combined albedo and greenhouse gas radiative forcing for land-cover change is estimated to
2 account for $40\% \pm 16\%$ of the human-caused global radiative forcing from 1850 to 2010 (Ward
3 et al. 2014; Figure 10.2). These calculations for total radiative forcing (from LULCC sources and
4 all other sources) are consistent with Myhre et al. (2013) (2.23 W/m^2 and 2.22 W/m^2 for Ward et
5 al. 2014 and Myhre et al. 2013, respectively). The contributions of CO_2 , CH_4 , N_2O and
6 aerosols/ O_3 /albedo effects to total LULCC radiative forcing are about 47%, 34%, 15% and 4%,
7 respectively, highlighting the importance of non-albedo contributions to LULCC and radiative
8 forcing. The net radiative forcing due specifically to fire—after accounting for short-lived
9 forcing agents (O_3 and aerosols), long-lived greenhouse gases, and land albedo change both now
10 and in the future—is estimated to be near zero due to regrowth of forests which offsets the
11 release of CO_2 from fire (Ward and Mahowald 2015).

12 **10.2.2 Land Cover and Climate Feedbacks**

13 Earth system models differ significantly in projections of terrestrial carbon uptake (Lovenduski
14 and Bonan 2017), with large uncertainties in the effects of increasing atmospheric CO_2
15 concentrations (i.e., CO_2 fertilization) and nutrient downregulation on plant productivity, as well
16 as the strength of carbon cycle feedbacks (Anav et al. 2013; Hoffman et al. 2014; Ch. 2: Physical
17 Drivers of Climate Change). When CO_2 effects on photosynthesis and transpiration are removed
18 from global gridded crop models, simulated response to climate across the models is comparable,
19 suggesting that model parameterizations representing these processes remain uncertain
20 (Rosenzweig et al. 2014).

21 A recent analysis shows large-scale greening in the Arctic and boreal regions of North America
22 and browning in the boreal forests of eastern Alaska for the period 1984–2012 (Ju and Masek
23 2016). Satellite observations and ecosystem models suggest that biogeochemical interactions of
24 carbon dioxide (CO_2) fertilization, nitrogen (N) deposition, and land-cover change are
25 responsible for 25%–50% of the global greening of the Earth and 4% of Earth's browning
26 between 1982 and 2009 (Zhu et al. 2016; Mao et al. 2016). While several studies have
27 documented significant increases in the rate of green-up periods, the lengthening of the growing
28 season (Section 10.3.1) also alters the timing of green-up (onset of growth) and brown-down
29 (senescence); however, where ecosystems become depleted of water resources as a result of
30 lengthening growing season, the actual period of productive growth can be truncated (Adams et
31 al. 2015).

32 Large-scale die-off and disturbances resulting from climate change have potential effects beyond
33 the biogeochemical and carbon cycle effects. Biogeophysical feedbacks can strengthen or reduce
34 climate forcing. The low albedo of boreal forests provides a positive feedback, but those albedo
35 effects are mitigated in tropical forests through evaporative cooling; for temperate forests, the
36 evaporative effects are less clear (Bonan 2008). Changes in surface albedo, evaporation, and
37 surface roughness can have feedbacks to local temperatures that are larger than the feedback due
38 to the change in carbon sequestration (Jackson et al. 2008). Forest management frameworks

1 (e.g., afforestation, deforestation, and avoided deforestation) that account for biophysical (e.g.,
2 land surface albedo and surface roughness) properties can be used as climate protection or
3 mitigation strategies (Anderson et al. 2011).

4 **[INSERT FIGURE 10.2 HERE]**

5 **10.2.3 Temperature Change**

6 Interactions between temperature changes, land cover, and biogeochemistry are more complex
7 than commonly assumed. Previous research suggested a fairly direct relationship between
8 increasing temperatures, longer growing seasons (see Section 10.3.1), increasing plant
9 productivity (e.g., Walsh et al. 2014), and therefore also an increase in CO₂ uptake. Without
10 water or nutrient limitations, increased CO₂ concentrations and warm temperatures have been
11 shown to extend the growing season, which may contribute to longer periods of plant activity
12 and carbon uptake, but do not affect reproduction rates (Reyes-Fox et al. 2014). However, there
13 are other processes that offset benefits of a longer growing season, such as changes in water
14 availability and demand for water (e.g., Georgakakos et al. 2014; Hibbard et al. 2014). For
15 instance, increased dry conditions can lead to wildfire (e.g., Hatfield et al. 2014; Joyce et al.
16 2014; Ch. 8: Droughts, Floods and Wildfires) and urban temperatures can contribute to urban-
17 induced thunderstorms in the southeastern United States (Ashley et al. 2012). Temperature
18 benefits of early onset of plant development in a longer growing season can be offset by 1)
19 freeze damage caused by late-season frosts; 2) limits to growth because of shortening of the
20 photoperiod later in the season; or 3) by shorter chilling periods required for leaf unfolding by
21 many plants (Fu et al. 2015; Gu et al. 2008). MODIS data provided insight into the coterminous
22 U.S. 2012 drought, when a warm spring reduced the carbon cycle impact of the drought by
23 inducing earlier carbon uptake (Wolf et al. 2016). New evidence points to longer temperature-
24 driven growing seasons for grasslands that may facilitate earlier onset of growth, but also that
25 senescence is typically earlier (Fridley et al. 2016). In addition to changing CO₂ uptake, higher
26 temperatures can also enhance soil decomposition rates, thereby adding more CO₂ to the
27 atmosphere. Similarly, temperature, as well as changes in the seasonality and intensity of
28 precipitation, can influence nutrient and water availability, leading to both shortages and
29 excesses, thereby influencing rates and magnitudes of decomposition (Galloway et al. 2014).

30 **10.2.4 Water Cycle Changes**

31 The global hydrological cycle is expected to intensify under climate change as a consequence of
32 increased temperatures in the troposphere. The consequences of the increased water-holding
33 capacity of a warmer atmosphere include longer and more frequent droughts and less frequent
34 but more severe precipitation events and cyclonic activity (see Ch. 9: Extreme Storms for an in-
35 depth discussion of extreme storms). More intense rain events and storms can lead to flooding
36 and ecosystem disturbances, thereby altering ecosystem function and carbon cycle dynamics. For

1 an extensive review of precipitation changes and droughts, floods, and wildfires, see Chapters 7
2 and 8 in this report, respectively.

3 From the perspective of the land biosphere, drought has strong effects on ecosystem productivity
4 and carbon storage by reducing photosynthesis and increasing the risk of wildfire, pest
5 infestation, and disease susceptibility. Thus, droughts of the future will affect carbon uptake and
6 storage, leading to feedbacks to the climate system (Chapter 2, Section 2.6.2; also see Chapter 11
7 for Arctic/climate/wildfire feedbacks; Schlesinger et al. 2016). Reduced productivity as a result
8 of extreme drought events can also extend for several years post-drought (i.e., drought legacy
9 effects; Frank et al. 2015; Reichstein et al. 2013; Anderegg et al. 2015). In 2011, the most severe
10 drought on record in Texas led to statewide regional tree mortality of 6.2%, or nearly nine times
11 greater than the average annual mortality in this region (approximately 0.7%) (Moore et al.
12 2016). The net effect on carbon storage was estimated to be a redistribution of 24–30 TgC from
13 the live to dead tree carbon pool, which is equal to 6%–7% of pre-drought live tree carbon
14 storage in Texas state forestlands (Moore et al. 2016). Another way to think about this
15 redistribution is that the single Texas drought event equals approximately 36% of annual global
16 carbon losses due to deforestation and land-use change (Ciais et al. 2013). The projected
17 increases in temperatures and in the magnitude and frequency of heavy precipitation events,
18 changes to snowpack, and changes in the subsequent water availability for agriculture and
19 forestry may lead to similar rates of mortality or changes in land cover. Increasing frequency and
20 intensity of drought across northern ecosystems reduces total observed organic matter export, has
21 led to oxidized wetland soils, and releases stored contaminants into streams after rain events
22 (Szkokan-Emilson et al. 2017).

23 **10.2.5 Biogeochemistry**

24 Terrestrial biogeochemical cycles play a key role in Earth's climate system, including by
25 affecting land-atmosphere fluxes of many aerosol precursors and greenhouse gases, including
26 carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O). As such, changes in the
27 terrestrial ecosphere can drive climate change. At the same time, biogeochemical cycles are
28 sensitive to changes in climate and atmospheric composition.

29 Historically, increased atmospheric CO₂ concentrations have led to increased plant production
30 (known as CO₂ fertilization) and longer-term storage of carbon in biomass and soils. Whether
31 increased atmospheric CO₂ will continue to lead to long-term storage of carbon in terrestrial
32 ecosystems depends on whether CO₂ fertilization simply intensifies the rate of short-term carbon
33 cycling (for example, by stimulating respiration, root exudation, and high turnover root growth)
34 or whether the additional carbon is used by plants to build more wood or tissues that, once
35 senesced, decompose into long-lived soil organic matter. Under increased CO₂ concentrations,
36 plants have been observed to optimize water use due to reduced stomatal conductance, thereby
37 increasing water-use efficiency (Keenan et al. 2013). This change in water-use efficiency can
38 affect plants' tolerance to stress and specifically to drought (Swann et al. 2016). Due to the

1 complex interactions of the processes that govern terrestrial biogeochemical cycling, terrestrial
2 ecosystem responses to increasing CO₂ levels remains one of the largest uncertainties in long-
3 term climate feedbacks and therefore in predicting longer-term climate change (Ch. 2: Physical
4 Drivers of Climate Change).

5 Nitrogen is a principal nutrient for plant growth and can limit or stimulate plant productivity (and
6 carbon uptake), depending on availability. As a result, increased nitrogen deposition and natural
7 nitrogen-cycle responses to climate change will influence the global carbon cycle. For example,
8 nitrogen limitation can inhibit the CO₂ fertilization response of plants to elevated atmospheric
9 CO₂ (e.g., Norby et al. 2005; Zaehle et al. 2010). Conversely, increased decomposition of soil
10 organic matter in response to climate warming increases nitrogen mineralization. This shift of
11 nitrogen from soil to vegetation can increase ecosystem carbon storage (Melillo et al. 2011; Ciais
12 et al. 2013). While the effects of increased nitrogen deposition may counteract some nitrogen
13 limitation on CO₂ fertilization, the importance of nitrogen in future carbon–climate interactions
14 is not clear. Nitrogen dynamics are being integrated into the simulation of land carbon cycle
15 modeling, but only two of the models in CMIP5 included coupled carbon–nitrogen interactions
16 (Knutti and Sedlacek 2013).

17 Many factors, including climate, atmospheric CO₂ concentrations, and nitrogen deposition rates
18 influence the structure of the plant community and therefore the amount and biochemical quality
19 of inputs into soils (Jandl et al. 2007; McLauchlan 2006; Smith et al. 2007). For example, though
20 CO₂ losses from soils may decrease with greater nitrogen deposition, increased emissions of
21 other greenhouse gases, such as methane (CH₄) and nitrous oxide (N₂O), can offset the reduction
22 in CO₂ (Liu and Greaver 2009). The dynamics of soil organic carbon under the influence of
23 climate change is poorly understood and therefore not well represented in models. As a result,
24 there is high uncertainty in soil carbon stocks in model simulations (Todd-Brown et al. 2013;
25 Tian et al. 2015).

26 Future emissions of many aerosol precursors are expected to be affected by a number of climate-
27 related factors, in part because of changes in aerosol and aerosol precursors from the terrestrial
28 biosphere. For example, volatile organic compounds (VOCs) are a significant source of
29 secondary organic aerosols, and biogenic sources of VOCs exceed emissions from the industrial
30 and transportation sectors (Guenther et al. 2006). Isoprene is one of the most important biogenic
31 VOCs, and isoprene emissions are strongly dependent on temperature and light, as well as other
32 factors like plant type and leaf age (Guenther et al. 2006). Higher temperatures are expected to
33 lead to an increase in biogenic VOC emissions. Atmospheric CO₂ concentration can also affect
34 isoprene emissions (e.g., Rosenstiel et al. 2003). Changes in biogenic VOC emissions can impact
35 aerosol formation and feedbacks with climate (Ch. 2: Physical Drivers of Climate Change,
36 Section 2.6.1; Feedbacks via changes in atmospheric composition). Increased biogenic VOC
37 emissions can also impact ozone and the atmospheric oxidizing capacity (Pyle et al. 2007).
38 Conversely, increases in nitrogen oxide (NO_x) pollution produce tropospheric ozone (O₃), which

1 has damaging effects on vegetation. For example, a recent study estimated yield losses for maize
2 and soybean production of up to 5% to 10% due to increases in O₃ (McGrath et al. 2015).

3 **10.2.6 Extreme Events and Disturbance**

4 This section builds on the physical overview provided in earlier chapters to frame how the
5 intersections of climate, extreme events, and disturbance affect regional land cover and
6 biogeochemistry. In addition to overall trends in temperature (Ch. 6: Temperature Change) and
7 precipitation (Ch. 7: Precipitation Change), changes in modes of variability such as the Pacific
8 Decadal Oscillation (PDO) and the El Niño–Southern Oscillation (ENSO) (Ch. 5: Circulation
9 and Variability) can contribute to drought in the United States, which leads to unanticipated
10 changes in disturbance regimes in the terrestrial biosphere (e.g., Kam et al. 2014). Extreme
11 climatic events can increase the susceptibility of ecosystems to invasive plants and plant pests by
12 promoting transport of propagules into affected regions, decreasing the resistance of native
13 communities to establishment, and by putting existing native species at a competitive
14 disadvantage (Diez et al. 2012). For example, drought may exacerbate the rate of plant invasions
15 by non-native species in rangelands and grasslands (Moore et al. 2016). Land-cover changes
16 such as encroachment and invasion of non-native species can in turn lead to increased frequency
17 of disturbance such as fire. Disturbance events alter soil moisture, which, in addition to being
18 affected by evapotranspiration and precipitation (Ch. 8: Droughts, Floods, and Wildfires), is
19 controlled by canopy and rooting architecture as well as soil physics. Invasive plants may be
20 directly responsible for changes in fire regimes through increased biomass, changes in the
21 distribution of flammable biomass, increased flammability, and altered timing of fuel drying,
22 while others may be “fire followers” whose abundances increase as a result of shortening the fire
23 return interval (e.g., Lambert et al. 2010). Changes in land cover resulting from alteration of fire
24 return intervals, fire severity, and historical disturbance regimes affect long-term carbon
25 exchange between the atmosphere and biosphere (e.g., Moore et al. 2016). Recent extensive
26 diebacks and changes in plant cover due to drought have interacted with regional carbon cycle
27 dynamics, including carbon release from biomass and reductions in carbon uptake from the
28 atmosphere; however, plant regrowth may offset emissions (Vose et al. 2016). The 2011–2015
29 meteorological drought in California (described in Ch. 8: Droughts, Floods, and Wildfires),
30 combined with future warming, will lead to long-term changes in land cover, leading to
31 increased probability of climate feedbacks (e.g., drought and wildfire) and in ecosystem shifts
32 (Diffenbaugh et al. 2015). California’s recent drought has also resulted in measureable canopy
33 water losses, posing long-term hazards to forest health and biophysical feedbacks to regional
34 climate (Anderegg et al. 2015; Asner et al. 2016; Mann and Gleick 2015). Multiyear or severe
35 meteorological and hydrological droughts (see Ch. 8: Droughts, Floods, and Wildfires for
36 definitions) can also affect stream biogeochemistry and riparian ecosystems by concentrating
37 sediments and nutrients (Vose et al. 2016).

1 Changes in the variability of hurricanes and winter storm events (Ch. 9: Extreme Storms) also
2 affect the terrestrial biosphere, as shown in studies comparing historic and future (projected)
3 extreme events in the western United States and how these translate into changes in regional
4 water balance, fire, and streamflow. Composited across 10 global climate models (GCMs)
5 summer (June–August) water-balance deficit in the future (2030–2059) increases compared to
6 that under historical (1916–2006) conditions. Portions of the Southwest that have significant
7 monsoon precipitation and some mountainous areas of the Pacific Northwest are exempt from
8 this deficit (Littell et al. 2016). Projections for 2030–2059 suggest that extremely low flows that
9 have historically occurred (1916–2006) in the Columbia Basin, upper Snake River, southeastern
10 California, and southwestern Oregon are less likely to occur. Given the historical relationships
11 between fire occurrence and drought indicators such as water-balance deficit and streamflow,
12 climate change can be expected to have significant effects on fire occurrence and area burned
13 (Littell et al. 2016, 2011; Elsner et al. 2010).

14 Climate change in the northern high latitudes is directly contributing to increased fire occurrence
15 (Ch. 11: Arctic Changes); in the coterminous United States, climate-induced changes in fires,
16 changes in direct human ignitions, and land-management practices all significantly contribute to
17 wildfire trends. Wildfires in the western United States are often ignited by lightning, but
18 management practices such as fire suppression contribute to fuels and amplify the intensity and
19 spread of wildfire. Fires initiated from unintentional ignition, such as by campfires, or intentional
20 human-caused ignitions are also intensified by increasingly dry and vulnerable fuels, which build
21 up with fire suppression or human settlements (See also Ch. 8: Droughts, Floods, and Wildfires).

22 **10.3 Climate Indicators and Agricultural and Forest Responses**

23 Recent studies indicate a correlation between the expansion of agriculture and the global
24 amplitude of CO₂ uptake and emissions (Zeng et al. 2014; Gray et al. 2014). Conversely,
25 agricultural production is increasingly disrupted by climate and extreme weather events, and
26 these effects are expected to be augmented by mid-century and beyond for most crops (Lobell
27 and Tebaldi 2014; Challinor et al. 2014). Precipitation extremes put pressure on agricultural soil
28 and water assets and lead to increased irrigation, shrinking aquifers, and ground subsidence.

29 **10.3.1 Changes in the Frost-Free and Growing Seasons**

30 The concept that longer growing seasons are increasing productivity in some agricultural and
31 forested ecosystems was discussed in the Third National Climate Assessment (NCA3; Melillo et
32 al. 2014). However, there are other consequences to a lengthened growing season that can offset
33 gains in productivity. Here we discuss these emerging complexities as well as other aspects of
34 how climate change is altering and interacting with terrestrial ecosystems. The growing season is
35 the part of the year in which temperatures are favorable for plant growth. A basic metric by
36 which this is measured is the frost-free period. The U.S. Department of Agriculture Natural
37 Resources Conservation Service defines the frost-free period using a range of thresholds. They

1 calculate the average date of the last day with temperature below 24°F (-4.4°C), 28°F (-2.2°C),
2 and 32°F (0°C) in the spring and the average date of the first day with temperature below 24°F,
3 28°F, and 32°F in the fall, at various probabilities. They then define the frost-free period at three
4 index temperatures (32°F, 28°F, and 24°F), also with a range of probabilities. A single
5 temperature threshold (for example, temperature below 32°F) is often used when discussing
6 growing season; however, different plant cover-types (e.g., forest, agricultural, shrub, and
7 tundra) have different temperature thresholds for growth, and different requirements/thresholds
8 for chilling (Zhang et al. 2011; Hatfield et al. 2014). For the purposes of this report, we use the
9 metric with a 32°F (0°C) threshold to define the change in the number of “frost-free” days, and a
10 temperature threshold of 41°F (5°C) as a first-order measure of how the growing season length
11 has changed over the observational record (Zhang et al. 2011).

12 The NCA3 reported an increase in the growing season length of as much as several weeks as a
13 result of higher temperatures occurring earlier and later in the year (e.g., Walsh et al. 2014;
14 Hatfield et al. 2014; Joyce et al. 2014). NCA3 used a threshold of 32°F (0°C) (i.e., the frost-free
15 period) to define the growing season. An update to this finding is presented in Figures 10.3 and
16 10.4, which show changes in the frost-free period and growing season, respectively, as defined
17 above. Overall, the length of the frost-free period has increased in the contiguous United States
18 during the past century (Figure 10.3). However, growing season changes are more variable:
19 growing season length increased until the late 1930s, declined slightly until the early 1970s,
20 increased again until about 1990, and remained quasi-stable thereafter (Figure 10.4). This
21 contrasts somewhat with changes in the length of the frost-free period presented in NCA3, which
22 showed a continuing increase after 1980. This difference is attributable to the temperature
23 thresholds used in each indicator to define the start and end of these periods. Specifically, there
24 are now more frost-free days (32°F threshold) in winter than the growing season (41°F
25 threshold).

26 The lengthening of the growing season has been somewhat greater in the northern and western
27 United States, which experienced increases of 1–2 weeks in many locations. In contrast, some
28 areas in the Midwest, Southern Great Plains, and the Southeast had decreases of a week or more
29 between the periods 1986–2015 and 1901–1960 (Kunkel 2016). These differences reflect the
30 more general pattern of warming and cooling nationwide (Ch. 6: Temperature Changes).
31 Observations and models have verified that the growing season has generally increased plant
32 productivity over most of the United States (Mao et al. 2016).

33 Consistent with increases in growing season length and the coldest temperature of the year, plant
34 hardiness zones have shifted northward in many areas (Daly et al. 2012). The widespread
35 increase in temperature has also impacted the distribution of other climate zones in parts of the
36 United States. For instance, there have been moderate changes in the range of the temperate and
37 continental climate zones of the eastern United States since 1950 (Chan and Wu 2015) as well as
38 changes in the coverage of some extreme climate zones in the western United States. In

1 particular, the spatial extent of the “alpine tundra” zone has decreased in high-elevation areas
2 (Diaz and Eischeid 2007), while the extent of the “hot arid” zone has increased in the Southwest
3 (Grundstein 2008).

4 The period over which plants are actually productive, that is, their true growing season, is a
5 function of multiple climate factors, including air temperature, number of frost-free days, and
6 rainfall, as well as biophysical factors, including soil physics, daylight hours, and the
7 biogeochemistry of ecosystems (EPA 2016). Temperature-induced changes in plant phenology,
8 like flowering or spring leaf onset, could result in a timing mismatch (phenological asynchrony)
9 with pollinator activity, affecting seasonal plant growth and reproduction and pollinator survival
10 (Yang and Rudolf 2010; Rafferty and Ives 2011; Kudo and Ida 2013; Forrest 2015). Further,
11 while growing season length is generally referred to in the context of agricultural productivity,
12 the factors that govern which plant types will grow in a given location are common to all plants
13 whether they are in agricultural, natural, or managed landscapes. Changes in both the length and
14 the seasonality of the growing season, in concert with local environmental conditions, can have
15 multiple effects on agricultural productivity and land cover.

16 In the context of agriculture, a longer growing season could allow for the diversification of
17 cropping systems or allow multiple harvests within a growing season. For example, shifts in cold
18 hardiness zones across the contiguous United States suggest widespread expansion of thermally
19 suitable areas for the cultivation of cold-intolerant perennial crops (Parker and Abatzoglou 2016)
20 as well as for biological invasion of non-native plants and plant pests (Hellmann et al. 2008).
21 However, changes in available water, conversion from dry to irrigated farming, and changes in
22 sensible and latent heat exchange associated with these shifts need to be considered. Increasingly
23 dry conditions under a longer growing season can alter terrestrial organic matter export and
24 catalyze oxidation of wetland soils, releasing stored contaminants (for example, copper and
25 nickel) into streamflow after rainfall (Szkokan-Emilson et al. 2017). Similarly, a longer growing
26 season, particularly in years where water is limited, is not due to warming alone, but is
27 exacerbated by higher atmospheric CO₂ concentrations that extend the active period of growth by
28 plants (Reyes-Fox et al. 2014). Longer growing seasons can also limit the types of crops that can
29 be grown, encourage invasive species encroachment or weed growth, or increase demand for
30 irrigation, possibly beyond the limits of water availability. They could also disrupt the function
31 and structure of a region’s ecosystems and could, for example, alter the range and types of
32 animal species in the area.

33 A longer and temporally shifted growing season also affects the role of terrestrial ecosystems in
34 the carbon cycle. Neither seasonality of growing season (spring and summer) nor carbon, water,
35 and energy fluxes should be interpreted separately when analyzing the impacts of climate
36 extremes such as drought (Sippel et al. 2016; Wolf et al. 2016; Ch. 8: Droughts, Floods, and
37 Wildfires). Observations and data-driven model studies suggest that losses in net terrestrial
38 carbon uptake during record warm springs followed by severely hot and dry summers can be

1 largely offset by carbon gains in record-exceeding warmth and early arrival of spring (Wolf et al.
2 2016). Depending on soil physics and land cover, a cool spring, however, can deplete soil water
3 resources less rapidly, making the subsequent impacts of precipitation deficits less severe (Sippel
4 et al. 2016). Depletion of soil moisture through early plant activity in a warm spring can
5 potentially amplify summer heating, a typical lagged direct effect of an extremely warm spring
6 (Frank et al. 2015). Ecosystem responses to the phenological changes of timing and extent of
7 growing season and subsequent biophysical feedbacks are therefore strongly dependent on the
8 timing of climate extremes (Sippel et al. 2016; Ch. 8: Droughts, Floods, and Wildfires; Ch. 9:
9 Extreme Storms).

10 The global Coupled Model Intercomparison Project Phase 5 (CMIP5) analyses did not explicitly
11 explore future changes to the growing season length. Many of the projected changes in North
12 American climate are generally consistent across CMIP5 models, but there is substantial inter-
13 model disagreement in projections of some metrics important to productivity in biophysical
14 systems, including the sign of regional precipitation changes and extreme heat events across the
15 northern United States (Maloney et al. 2014).

16 **[INSERT FIGURES 10.3 AND 10.4 HERE]**

17 **10.3.2 Water Availability and Drought**

18 Drought is generally parameterized in most agricultural models as limited water availability and
19 is an integrated response of both meteorological and agricultural drought, as described in Chapter
20 8: Droughts, Floods, and Wildfires. However, physiological as well as biophysical processes that
21 influence land cover and biogeochemistry interact with drought through stomatal closure induced
22 by elevated atmospheric CO₂ levels (Keenan et al. 2013; Swann et al. 2016). This has direct
23 impacts on plant transpiration, atmospheric latent heat fluxes, and soil moisture, thereby
24 influencing local and regional climate. Drought is often offset by management through
25 groundwater withdrawals, with increasing pressure on these resources to maintain plant
26 productivity. This results in indirect climate effects by altering land surface exchange of water
27 and energy with the atmosphere (Marston et al. 2015).

28 **10.3.3 Forestry Considerations**

29 Climate change and land-cover change in forested areas interact in many ways, such as through
30 changes in mortality rates driven by changes in the frequency and magnitude of fire, insect
31 infestations, and disease. In addition to the direct economic benefits of forestry, unquantified
32 societal benefits include ecosystem services, like protection of watersheds and wildlife habitat,
33 and recreation and human health value. United States forests and related wood products also
34 absorb and store the equivalent of 16% of all CO₂ emitted by fossil fuel burning in the United
35 States each year (Melillo et al., 2014). Climate change is expected to reduce the carbon sink
36 strength of forests overall.

1 Effective management of forests offers the opportunity to reduce future climate change—for
2 example, as given in proposals for Reduced Emissions from Deforestation and forest
3 Degradation (REDD+; <https://www.forestcarbonpartnership.org/what-redd>) in developing
4 countries and tropical ecosystems (see Ch. 14: Mitigation)—by capturing and storing carbon in
5 forest ecosystems and long-term wood products (Lippke et al. 2011). Afforestation in the United
6 States has the potential to capture and store 225 million tons of additional carbon per year from
7 2010 to 2110 (EPA 2005; King et al. 2006). However, the projected maturation of United States
8 forests (Wear and Coulston 2015) and land-cover change, driven in particular by the expansion
9 of urban and suburban areas along with projected increased demands for food and bioenergy,
10 threaten the extent of forests and their carbon storage potential (McKinley et al. 2011).

11 Changes in growing season length, combined with drought and accompanying wildfire are
12 reshaping California’s mountain ecosystems. The California drought led to the lowest snowpack
13 in 500 years, the largest wildfires in post-settlement history, greater than 23% stress mortality in
14 Sierra mid-elevation forests, and associated post-fire erosion (Asner et al., 2016). It is anticipated
15 that slow recovery, possibly to different ecosystem types, with numerous shifts to species’ ranges
16 will result in long-term changes to land surface biophysical as well as ecosystem structure and
17 function in this region (Asner et al. 2016; <http://www.fire.ca.gov/treetaskforce/>).

18 While changes in forest stocks, composition, and the ultimate use of forest products can
19 influence net emissions and climate, the future net changes in forest stocks remain uncertain
20 (Bonan 2008; Pan et al. 2011; Hurtt et al. 2011; Hansen et al. 2013; Williams et al. 2013).
21 This uncertainty is due to a combination of uncertainties in future population size, population
22 distribution and subsequent land-use change, harvest trends, wildfire management practices (for
23 example, large-scale thinning of forests), and the impact of maturing U.S. forests.

24 **10.4 Urban Environments and Climate Change**

25 Urban areas exhibit several characteristics that affect land-surface and geophysical attributes,
26 including building infrastructure (rougher, more uneven surfaces compared to rural or natural
27 systems), increased emissions and concentrations of aerosols and other greenhouse gasses, and
28 increased anthropogenic heat sources (Grimmond et al. 2016; Mitra and Shepherd 2016). The
29 understanding that urban areas modify their surrounding environment has been accepted for over
30 a century, but the mechanisms through which this occurs have only begun to be understood and
31 analyzed for more than 40 years (Landsberg 1970; Mitra and Shepherd 2016). Prior to the 1970s,
32 the majority of urban climate research was observational and descriptive (Mills 2007), but since
33 that time, more importance has been given to physical dynamics that are a function of land
34 surface (for example, built environment and change to surface roughness); hydrologic, aerosol,
35 and other greenhouse gas emissions; thermal properties of the built environment; and heat
36 generated from human activities (Seto et al. 2016 and references therein).

1 There is now strong evidence that urban environments modify local microclimates, with
2 implications for regional and global climate change (Mills 2007; Mitra and Shepherd 2016).
3 Urban systems affect various climate attributes, including temperature, rainfall intensity and
4 frequency, winter precipitation (snowfall), and flooding. New observational capabilities—
5 including NASA’s dual polarimetric radar, advanced satellite remote sensing (for example, the
6 Global Precipitation Measurement Mission-GPM), and regionalized, coupled land–surface–
7 atmospheric modeling systems for urban systems—are now available to evaluate aspects of
8 daytime and nighttime temperature fluctuations; urban precipitation; contribution of aerosols;
9 how the urban built environment impacts the seasonality and type of precipitation (rain or snow)
10 as well as the amount and distribution of precipitation; and the significance of the extent of urban
11 metropolitan areas (Shepherd 2013; Seto and Shepherd 2009; Grimmond et al. 2016; Mitra and
12 Shepherd 2016).

13 The urban heat island (UHI) is characterized by increased surface and canopy temperatures as a
14 result of heat-retaining asphalt and concrete, a lack of vegetation, and anthropogenic generation
15 of heat and greenhouse gasses (Shepherd 2013). The heat gain due to the storage capacity of
16 urban built structures, reductions in local evapotranspiration, and anthropogenically generated
17 heat alter the spatio-temporal pattern of temperature and leads to the UHI phenomenon. The UHI
18 physical processes that affect the climate system include generation of heat storage in buildings
19 during the day, nighttime release of latent heat storage by buildings, and sensible heat generated
20 by human activities, include heating of buildings, air conditioning, and traffic (Hidalgo et al.
21 2008).

22 The strength of the effect is correlated with the spatial extent and population density of urban
23 areas; however, because of varying definitions of urban vs. non-urban, impervious surface area is
24 a more objective metric for estimating the extent and intensity of urbanization (Imhoff et al.
25 2010). Based on land surface temperature measurements, on average, the UHI effect increases
26 urban temperature by 5.2°F (2.9°C), but it has been measured at 14.4°F (8°C) in cities built in
27 areas dominated by temperate forests (Imhoff et al. 2010). In arid regions, however, urban areas
28 can be more than 3.6°F (2°C) cooler than surrounding shrublands (Bounoua et al. 2015).
29 Similarly, urban settings lose up to 12% of precipitation through impervious surface runoff,
30 versus just over 3% loss to runoff in vegetated regions. Carbon losses from the biosphere to the
31 atmosphere through urbanization account for almost 2% of the continental terrestrial biosphere
32 total, a significant proportion given that urban areas only account for around 1% of land in the
33 United States (Bounoua et al. 2015). Similarly, statistical analyses of the relationship between
34 climate and urban land use suggest an empirical relationship between the patterns of urbanization
35 and precipitation deficits during the dry season. Causal factors for this reduction may include
36 changes to runoff (for example, impervious-surface versus natural-surface hydrology) that
37 extend beyond the urban heat island effect and energy-related aerosol emissions (Kaufmann et al.
38 2007).

1 The urban heat island effect is more significant during the night and during winter than during
2 the day, and it is affected by the shape, size, and geometry of buildings in urban centers as well
3 as by infrastructure along gradients from urban to rural settlements (Seto and Shepherd 2009;
4 Grimmond et al. 2016; Seto et al. 2016). Recent research points to mounting evidence that
5 urbanization also affects cycling of water, carbon, aerosols, and nitrogen in the climate system
6 (Seto and Shepherd 2009).

7 Coordinated modeling and observational studies have revealed other mechanisms by which the
8 physical properties of urban areas can influence local weather and climate. It has been suggested
9 that urban-induced wind convergence can determine storm initiation; aerosol concentrations and
10 composition then influence the amount of cloud water and ice present in the clouds. Aerosols can
11 also influence updraft and downdraft intensities, their life span, and surface precipitation totals
12 (Shepherd 2013). A pair of studies investigated rainfall efficiency in sea-breeze thunderstorms
13 and found that integrated moisture convergence in urban areas influenced storm initiation and
14 mid-level moisture, thereby affecting precipitation dynamics (Shepherd et al. 2001; van Den
15 Heever and Cotton 2007).

16 According to the World Bank, over 81% of the United States population currently resides in
17 urban settings (World Bank 2017). Climate mitigation efforts to offset UHI are often stalled by
18 the lack of quantitative data and understanding of the specific factors of urban systems that
19 contribute to UHI. A recent study set out to quantitatively determine contributors to the intensity
20 of UHI across North America (Zhao et al. 2014). The study found that population strongly
21 influenced nighttime UHI, but that daytime UHI varied spatially following precipitation
22 gradients. The model applied in this study indicated that the spatial variation in the UHI signal
23 was controlled most strongly by impacts on the atmospheric convection efficiency. Because of
24 the impracticality of managing convection efficiency, results from Zhao et al. (2014) support
25 albedo management as an efficient strategy to mitigate UHI on a large scale.

1 TRACEABLE ACCOUNTS

2 Key Finding 1

3 Changes in land use and land cover due to human activities produce physical changes in land
4 surface albedo, latent and sensible heat, and atmospheric aerosol and greenhouse gas
5 concentrations. The combined effects of these changes have recently been estimated to account
6 for 40% ± 16% of the human-caused global radiative forcing from 1850 to present day (*high*
7 *confidence*). As a whole, the terrestrial biosphere (soil and plants) is a net “sink” for carbon
8 (drawing down carbon from the atmosphere), and this sink has steadily increased since 1980
9 (*very high confidence*). Because of the uncertainty in the trajectory of land cover, the possibility
10 of the land becoming a net carbon source cannot be excluded (*very high confidence*).

11 Description of evidence base

12 Traditional methods that estimate albedo changes for calculating radiative forcing due to land-
13 use change were identified by NRC (2005). That report recommended that indirect contributions
14 of land-cover change to climate-relevant variables, such as soil moisture, greenhouse gas (e.g.,
15 CO₂ and water vapor) sources and sinks, snow cover, and aerosol and aerosol and ozone
16 precursor emissions also be considered. Several studies have documented physical land surface
17 processes such as albedo, surface roughness, sensible and latent heat exchange, and land-use and
18 land-cover change that interact with regional atmospheric processes (e.g., Marotz et al. 1975;
19 Barnston and Schickendanz 1984; Alpert and Mandel 1986; Pielke and Zeng 1989; Feddema et
20 al. 2005; Pielke et al. 2007), however, traditional calculations of radiative forcing by land-cover
21 change in global climate model simulations yield small forcing values (Ch. 2: Physical Drivers
22 of Climate Change) because they account only for changes in surface albedo (e.g., Myhre and
23 Myhre 2003; Betts et al. 2007; Jones et al. 2015).

24 Recent studies that account for the physical as well as biogeochemical changes in land cover and
25 land use radiative forcing estimated that these drivers contribute 40% of present radiative forcing
26 due to land-use/land-cover change (0.9 W/m²) (Ward et al. 2014; Myhre et al. 2013). These
27 studies utilized AR5 and follow-on model simulations to estimate changes in land-cover and
28 land-use climate forcing and feedbacks for the greenhouse gases—carbon dioxide, methane, and
29 nitrous oxide—that contribute to total anthropogenic radiative forcing from land-use and land-
30 cover change (Myhre et al., 2013; Ward et al., 2014). This research is grounded in long-term
31 observations that have been documented for over 40 years and recently implemented into global
32 Earth system models (Myhre et al. 2013; Anav et al 2013). For example, IPCC, 2013: Summary
33 for Policymakers states: “From 1750 to 2011, CO₂ emissions from fossil fuel combustion and
34 cement production have released 375 [345 to 405] GtC to the atmosphere, while deforestation
35 and other land-use changes are estimated to have released 180 [100 to 260] GtC. This results in
36 cumulative anthropogenic emissions of 555 [470 to 640] GtC.” (IPCC 2013). IPCC 2013,
37 Working Group 1, Chapter 14 states for North America: “In summary, it is very likely that by

1 mid-century the anthropogenic warming signal will be large compared to natural variability such
2 as that stemming from the NAO, ENSO, PNA, PDO, and the NAMS in all North America
3 regions throughout the year” (Christensen et al. 2013).

4 **Major uncertainties**

5 Uncertainty exists in the future land-cover and land-use change as well as uncertainties in
6 regional calculations of land-cover change and associated radiative forcing. The role of the land
7 as a current sink has *very high confidence*; however, future strength of the land sink is uncertain
8 (Wear and Coulston 2015; McKinley et al. 2011). The existing impact of land systems on
9 climate forcing has *high confidence* (Myhre et al. 2013). Based on current RCP scenarios for
10 future radiative forcing targets ranging from 2.6 to 8.5 W/m², the future forcing has lower
11 confidence because it is difficult to estimate changes in land cover and land use into the future
12 (van Vuuren et al. 2011b). Compared to 2000, the RCP8.5 CO₂-eq. emissions more than double
13 by 2050 and increase by three by 2100 (Riahi et al. 2011). About one quarter of this increase is
14 due to increasing use of fertilizers and intensification of agricultural production, giving rise to
15 the primary source of N₂O emissions. In addition, increases in livestock population, rice
16 production, and enteric fermentation processes increase CH₄ emissions (Riahi et al. 2011).
17 Therefore, if existing trends in land-use and land-cover change continue, the contribution of land
18 cover to forcing will increase with *high confidence*. Overall, future scenarios from the RCPs
19 suggest that land-cover change based on policy, bioenergy, and food demands could lead to
20 significantly different distribution of land cover types (forest, agriculture, urban) by 2100 (Hurtt
21 et al. 2011; Riahi et al. 2011; Thomson et al. 2011; van Vuuren et al. 2011a,b; Fujimori et al.
22 2014).

23 **Summary sentence or paragraph that integrates the above information**

24 The key finding is based on basic physics and biophysical models that have been well
25 established for decades with regards to the contribution of land albedo to radiative forcing (NRC
26 2005). Recent assessments specifically address additional biogeochemical contributions of land-
27 cover and land-use change to radiative forcing (NRC 2005; Myhre et al. 2013). The role of
28 current sink strength of the land is also uncertain (Wear and Coulston 2015; McKinley et al.
29 2011). The future distribution of land cover and contributions to total radiative forcing are
30 uncertain and depend on policy, energy demand and food consumption, dietary demands (van
31 Vuuren et al. 2011b).

32

33 **Key Finding 2**

34 Climate change and induced changes in the frequency and magnitude of extreme events (e.g.,
35 droughts, floods, and heat waves) have led to large changes in plant community structure with
36 subsequent effects on the biogeochemistry of terrestrial ecosystems. Uncertainties about how

1 climate change will affect land cover change make it difficult to project the magnitude and sign
2 of future climate feedbacks from land cover changes (*high confidence*).

3 **Description of evidence base**

4 From the perspective of the land biosphere, drought has strong effects on ecosystem productivity
5 and carbon storage by reducing microbial activity and photosynthesis and by increasing the risk
6 of wildfire, pest infestation, and disease susceptibility. Thus, future droughts will affect carbon
7 uptake and storage, leading to feedbacks to the climate system (Schlesinger et al. 2016). Reduced
8 productivity as a result of extreme drought events can also extend for several years post-drought
9 (i.e., drought legacy effects; Frank et al. 2015; Reichstein et al. 2013; Anderegg et al. 2015).
10 Under increased CO₂ concentrations, plants have been observed to optimize water use due to
11 reduced stomatal conductance, thereby increasing water-use efficiency (Keenan et al. 2013). This
12 change in water-use efficiency can affect plants' tolerance to stress and specifically to drought
13 (Swann et al. 2016).

14 Recent severe droughts in the western United States (Texas and California) have led to
15 significant mortality and carbon cycle dynamics. (Moore et al., 2016, Asner et al., 2016;
16 <http://www.fire.ca.gov/treetaskforce/>). Carbon redistribution through mortality in the Texas
17 drought was around 36% of global carbon losses due to deforestation and land use change (Ciais
18 et al. 2013).

19 **Major uncertainties**

20 Major uncertainties include how future land-use/land-cover changes will occur as a result of
21 policy and/or mitigation strategies in addition to climate change. Ecosystem responses to
22 phenological changes are strongly dependent on the timing of climate extremes (Sippel et al.
23 2016). Due to the complex interactions of the processes that govern terrestrial biogeochemical
24 cycling, terrestrial ecosystem response to increasing CO₂ levels remains one of the largest
25 uncertainties in long-term climate feedbacks and therefore in predicting longer-term climate
26 change effects on ecosystems (e.g., Swann et al. 2016).

27 **Summary sentence or paragraph that integrates the above information**

28 The timing, frequency, magnitude, and extent of climate extremes strongly influence plant
29 community structure and function, with subsequent effects on terrestrial biogeochemistry and
30 feedbacks to the climate system. Future interactions between land cover and the climate system
31 are uncertain and depend on human land-use decisions, the evolution of the climate system, and
32 the timing, frequency, magnitude, and extent of climate extremes

33

1 Key Finding 3

2 Since 1901, regional averages of both the consecutive number of frost-free days and the length of
3 the corresponding growing season have increased for the seven contiguous U.S. regions used in
4 this assessment. However, there is important variability at smaller scales, with some locations
5 actually showing decreases of a few days to as much as one to two weeks. Plant productivity has
6 not increased commensurate with the increased number of frost-free days or with the longer
7 growing season due to plant-specific temperature thresholds, plant–pollinator dependence, and
8 seasonal limitations in water and nutrient availability (*very high confidence*). Future
9 consequences of changes to the growing season for plant productivity are uncertain.

10 Description of evidence base

11 Data on the lengthening and regional variability of growing season since 1901 were updated by
12 Kunkel (2016). Many of these differences reflect the more general pattern of warming and
13 cooling nationwide (Ch. 6: Temperature Changes). Without nutrient limitations, increased CO₂
14 concentrations and warm temperatures have been shown to extend the growing season, which
15 may contribute to longer periods of plant activity and carbon uptake, but do not affect
16 reproduction rates (Reyes-Fox et al. 2014). However, other confounding variables that coincide
17 with climate change (for example, drought, increased ozone, and reduced photosynthesis due to
18 increased or extreme heat) can offset increased growth associated with longer growing seasons
19 (Adams et al. 2015) as well as changes in water availability and demand for water (e.g.,
20 Georgakakos et al. 2014; Hibbard et al. 2014). Increased dry conditions can lead to wildfire (e.g.,
21 Hatfield et al. 2014; Joyce et al. 2014; Ch. 8: Droughts, Floods and Wildfires) and urban
22 temperatures can contribute to urban-induced thunderstorms in the southeastern United States
23 (Ashley et al. 2012). Temperature benefits of early onset of plant development in a longer
24 growing season can be offset by 1) freeze damage caused by late-season frosts; 2) limits to
25 growth because of shortening of the photoperiod later in the season; or 3) by shorter chilling
26 periods required for leaf unfolding by many plants (Fu et al. 2015; Gu et al. 2008).

27 Major uncertainties

28 Uncertainties exist in future response of the climate system to anthropogenic forcings (land
29 use/land cover as well as fossil fuel emissions) and associated feedbacks among variables such as
30 temperature and precipitation interactions with carbon and nitrogen cycles as well as land-cover
31 change that impact the length of the growing season (Reyes-Fox et al. 2014, Hatfield et al. 2014,
32 Adams et al. 2015; Ch. 6: Temperature Changes and Ch. 8: Droughts, Floods and Wildfires).

33 Summary sentence or paragraph that integrates the above information

34 Changes in growing season length and interactions with climate, biogeochemistry and land cover
35 were covered in 12 chapters of NCA3 (Melillo et al. 2014), but with sparse assessment of how
36 changes in the growing season might offset plant productivity and subsequent feedbacks to the

1 climate system. This key finding provides an assessment of the current state of the complex
2 nature of the growing season.

3

4 **Key Finding 4**

5 Recent studies confirm and quantify higher surface temperatures in urban areas than in
6 surrounding rural areas, for a number of reasons including the concentrated release of heat from
7 buildings, vehicles, and industry. In the United States, this urban heat island effect results in
8 daytime temperatures 0.9°–7.2°F (0.5°–4.0°C) higher and nighttime temperatures 1.8°–4.5°F
9 (1.0°–2.5°C) higher in urban areas, with larger temperature differences in humid regions
10 (primarily in the eastern United States) and in cities with larger and denser populations. The
11 urban heat island effect will strengthen in the future as the structure, spatial extent, and
12 population density of urban areas change and grow (*high confidence*).

13 **Description of evidence base**

14 Urban interactions with the climate system have been investigated for more than 40 years
15 (Landsberg 1970; Mitra and Shepherd 2016). The heat gain due to the storage capacity of urban
16 built structures, reduction in local evapotranspiration, and anthropogenically generated heat alter
17 the spatio-temporal pattern of temperature and leads to the well-known urban heat island (UHI)
18 phenomenon (Seto and Shepherd 2009; Grimmond et al. 2016; Seto et al. 2016). The urban heat
19 island (UHI) effect is correlated with the extent of impervious surfaces, which alter albedo or the
20 saturation of radiation (Imhoff et al. 2010). The urban-rural difference that defines the UHI is
21 greatest for cities built in temperate forest ecosystems (Imhoff et al. 2010). The average
22 temperature increase is 2.9°C, except for urban areas in biomes with arid and semiarid climates
23 (Imhoff et al. 2010; Bounoua et al. 2015).

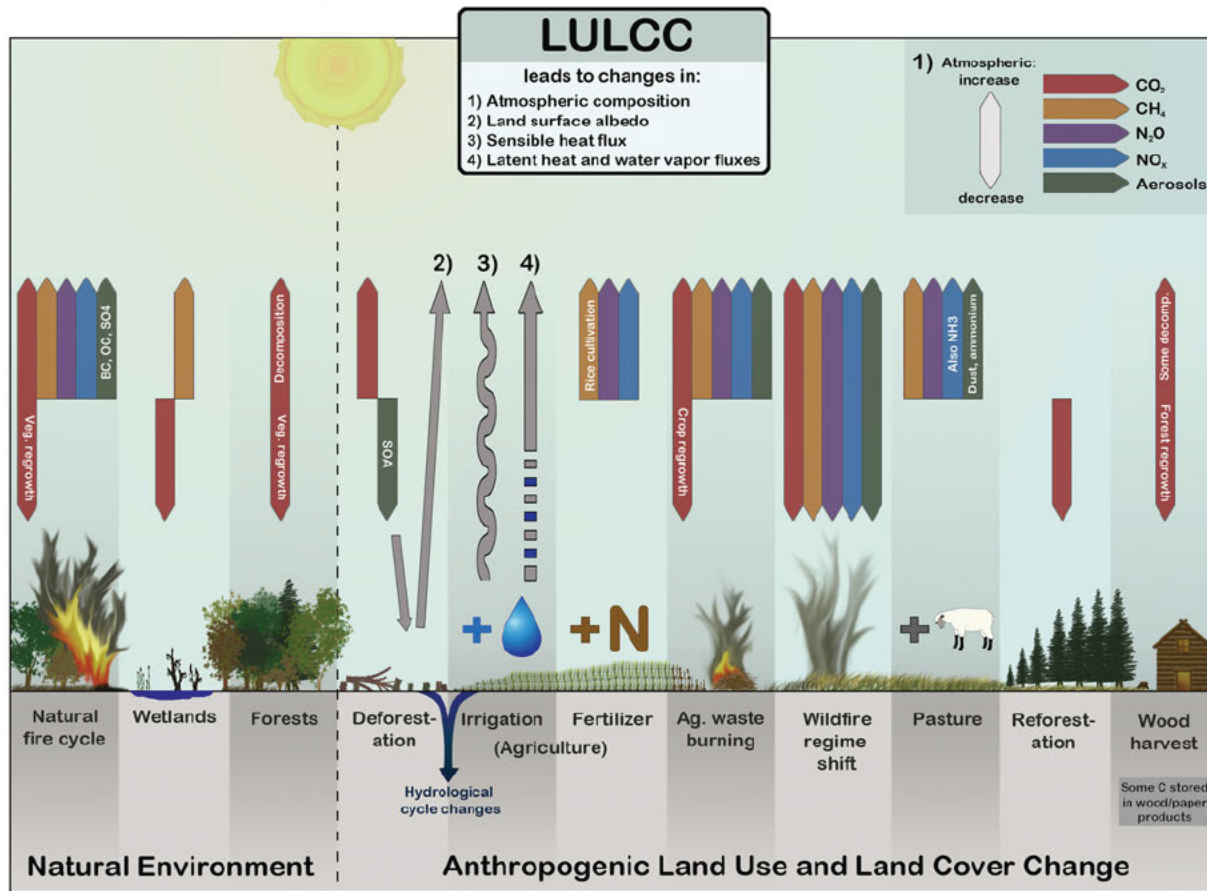
24 **Major uncertainties**

25 The largest uncertainties about urban forcings or feedbacks to the climate system are how urban
26 settlements will evolve and how energy consumption and efficiencies, and their interactions with
27 land cover and water, may change from present times (Riahi et al. 2011; van Vuuren et al.
28 2011b; Hibbard et al. 2014; Seto et al. 2016)

29 **Summary sentence or paragraph that integrates the above information**

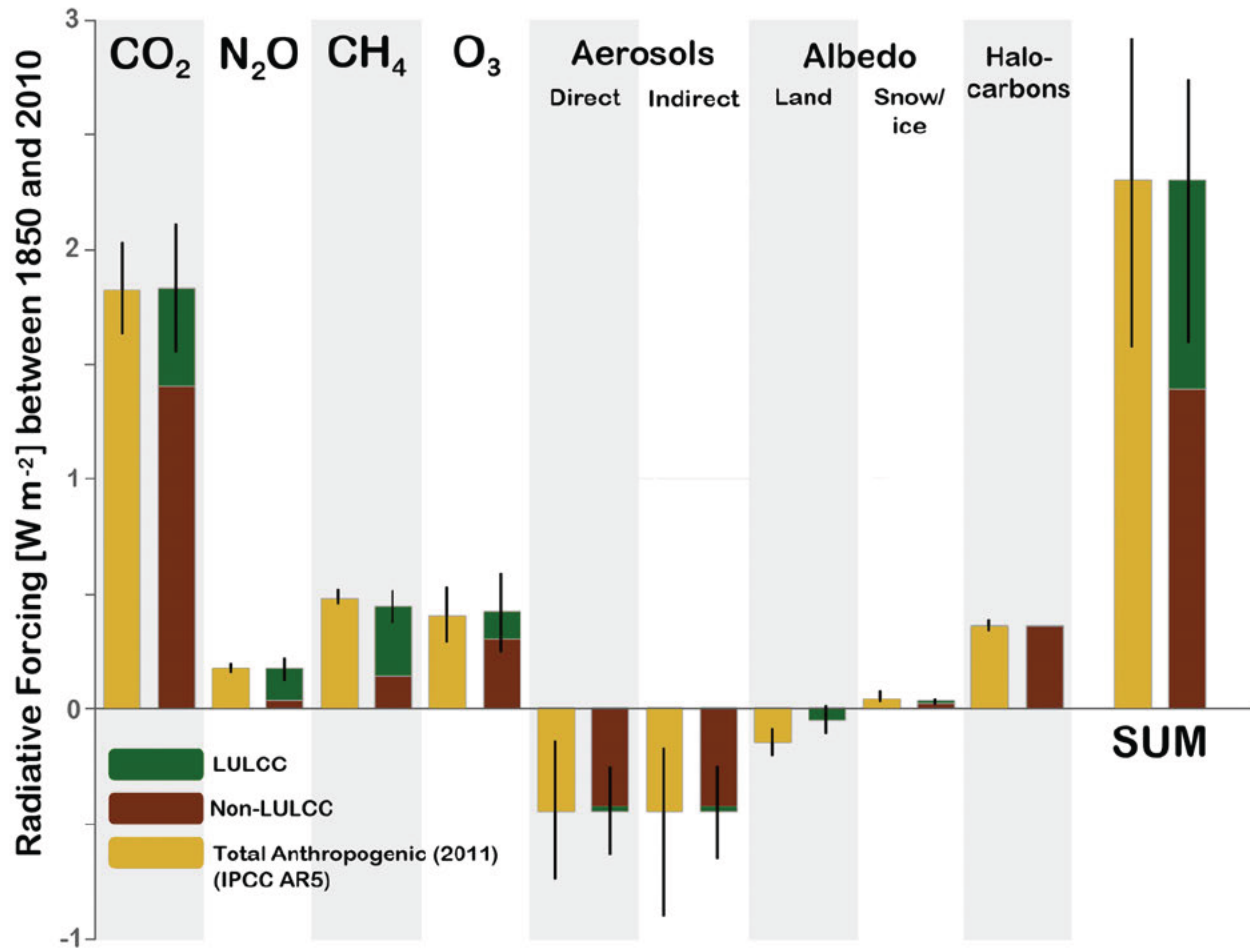
30 Key Finding 4 is based on simulated and satellite land surface measurements analyzed by Imhoff
31 et al. (2010). Bounoua et al. (2015), Shepherd (2013), Seto and Shepherd (2009), Grimmond et
32 al. (2016), Seto et al. (2016) provide specific references with regards to how building materials
33 and spatio-temporal patterns of urban settlements influence radiative forcing and feedbacks of
34 urban areas to the climate system.

1 FIGURES



2

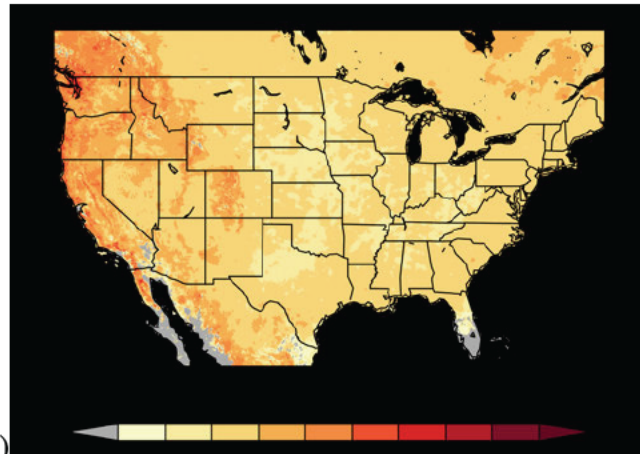
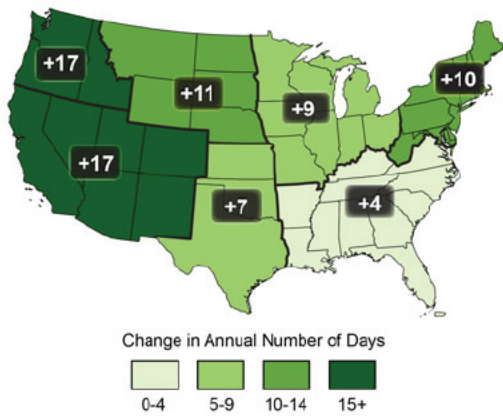
3 **Figure 10.1.** This graphical representation summarizes land–atmosphere interactions from
 4 natural and anthropogenic land-use and land-cover change (LULCC) contributions to radiative
 5 forcing. Emissions and sequestration of carbon and fluxes of nitrogen oxides, aerosols, and water
 6 shown here were used to calculate net radiative forcing from LULCC. (Figure source: Ward et
 7 al. 2014).



1

2 **Figure 10.2.** Anthropogenic radiative forcing (RF) contributions, separated by land-use and
 3 land-cover change (LULCC) and non-LULCC sources (green and maroon bars, respectively), are
 4 decomposed by atmospheric constituent to year 2010 in this diagram, using the year 1850 as the
 5 reference. Total anthropogenic RF contributions by atmospheric constituent (Myhre et al. 2013;
 6 see also Figure 2.3) are shown for comparison (yellow bars). Error bars represent uncertainties
 7 for total anthropogenic RF (yellow bars) and for the LULCC components (green bars; Ward et
 8 al. 2014). The SUM bars indicate the net RF when all anthropogenic forcing agents are
 9 combined. (Figure source: Ward et al. 2014).

Observed Increase in Frost-Free Season Length

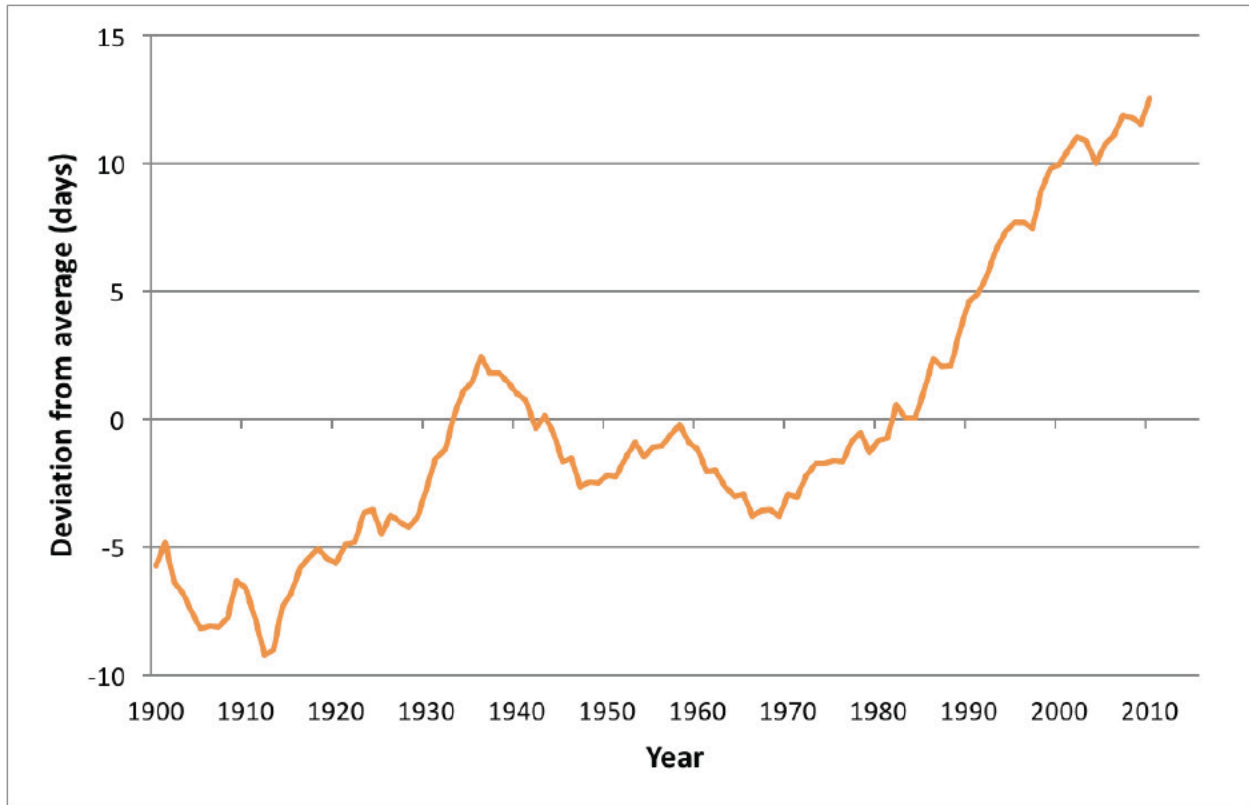


1 (a)

(b)

2 **Figure 10.3.** (a) Observed changes in the length of the frost-free season by region, where the
 3 frost-free season is defined as the number of days between the last spring occurrence and the first
 4 fall occurrence of a minimum temperature at or below 32°F. This change is expressed as the
 5 change in the average number of frost-free days in 1986–2015 compared to 1901–1960. (b)
 6 Projected changes in the length of the frost-free season at mid-century (2036–2065 as compared
 7 to 1976–2005) under the RCP8.5 scenario. Gray indicates areas that are not projected to
 8 experience a freeze in more than 10 of the 30 years (Figure source: (a) updated from Walsh et al.
 9 2014; (b) NOAA NCEI / CICS-NC, data source: LOCA dataset).

10



1

2 **Figure 10.4.** The length of the growing season in the contiguous 48 states compared with a long-
3 term average (1895–2015), where “growing season” is defined by a daily minimum temperature
4 threshold of 41°F. For each year, the line represents the number of days shorter or longer than
5 the long-term average. The line was smoothed using an 11-year moving average. Choosing a
6 different long-term average for comparison would not change the shape of the data over time.
7 (Figure source: Kunkel 2016).

8

1 **REFERENCES**

- 2 Adams, H.D., A.D. Collins, S.P. Briggs, M. Vennetier, L.T. Dickman, S.A. Sevanto, N. Garcia-
3 Forner, H.H. Powers, and N.G. McDowell, 2015: Experimental drought and heat can delay
4 phenological development and reduce foliar and shoot growth in semiarid trees. *Global*
5 *Change Biology*, **21**, 4210-4220. <http://dx.doi.org/10.1111/gcb.13030>
- 6 Alpert, P. and M. Mandel, 1986: Wind variability—An indicator for a mesoclimatic change in
7 Israel. *Journal of Climate and Applied Meteorology*, **25**, 1568-1576.
8 [http://dx.doi.org/10.1175/1520-0450\(1986\)025<1568:wwifam>2.0.co;2](http://dx.doi.org/10.1175/1520-0450(1986)025<1568:wwifam>2.0.co;2)
- 9 Anav, A., P. Friedlingstein, M. Kidston, L. Bopp, P. Ciais, P. Cox, C. Jones, M. Jung, R.
10 Myneni, and Z. Zhu, 2013: Evaluating the land and ocean components of the global carbon
11 cycle in the CMIP5 earth system models. *Journal of Climate*, **26**, 6801-6843.
12 <http://dx.doi.org/10.1175/jcli-d-12-00417.1>
- 13 Anderegg, W.R.L., C. Schwalm, F. Biondi, J.J. Camarero, G. Koch, M. Litvak, K. Ogle, J.D.
14 Shaw, E. Shevliakova, A.P. Williams, A. Wolf, E. Ziaco, and S. Pacala, 2015: Pervasive
15 drought legacies in forest ecosystems and their implications for carbon cycle models.
16 *Science*, **349**, 528-532. <http://dx.doi.org/10.1126/science.aab1833>
- 17 Anderson, R.G., J.G. Canadell, J.T. Randerson, R.B. Jackson, B.A. Hungate, D.D. Baldocchi,
18 G.A. Ban-Weiss, G.B. Bonan, K. Caldeira, L. Cao, N.S. Diffenbaugh, K.R. Gurney, L.M.
19 Kueppers, B.E. Law, S. Luysaert, and T.L. O'Halloran, 2011: Biophysical considerations in
20 forestry for climate protection. *Frontiers in Ecology and the Environment*, **9**, 174-182.
21 <http://dx.doi.org/10.1890/090179>
- 22 Ashley, W.S., M.L. Bentley, and J.A. Stallins, 2012: Urban-induced thunderstorm modification
23 in the southeast United States. *Climatic Change*, **113**, 481-498.
24 <http://dx.doi.org/10.1007/s10584-011-0324-1>
- 25 Asner, G.P., P.G. Brodrick, C.B. Anderson, N. Vaughn, D.E. Knapp, and R.E. Martin, 2016:
26 Progressive forest canopy water loss during the 2012–2015 California drought. *Proceedings*
27 *of the National Academy of Sciences*, **113**, E249-E255.
28 <http://dx.doi.org/10.1073/pnas.1523397113>
- 29 Barnston, A.G. and P.T. Schickedanz, 1984: The effect of irrigation on warm season
30 precipitation in the southern Great Plains. *Journal of Climate and Applied Meteorology*, **23**,
31 865-888. [http://dx.doi.org/10.1175/1520-0450\(1984\)023<0865:TEOIEW>2.0.CO;2](http://dx.doi.org/10.1175/1520-0450(1984)023<0865:TEOIEW>2.0.CO;2)
- 32 Betts, R.A., P.D. Falloon, K.K. Goldewijk, and N. Ramankutty, 2007: Biogeophysical effects of
33 land use on climate: Model simulations of radiative forcing and large-scale temperature
34 change. *Agricultural and Forest Meteorology*, **142**, 216-233.
35 <http://dx.doi.org/10.1016/j.agrformet.2006.08.021>

- 1 Bonan, G.B., 2008: Forests and climate change: Forcings, feedbacks, and the climate benefits of
2 forests. *Science*, **320**, 1444-1449. <http://dx.doi.org/10.1126/science.1155121>
- 3 Bounoua, L., P. Zhang, G. Mostovoy, K. Thome, J. Masek, M. Imhoff, M. Shepherd, D.
4 Quattrochi, J. Santanello, J. Silva, R. Wolfe, and A.M. Toure, 2015: Impact of urbanization
5 on US surface climate. *Environmental Research Letters*, **10**, 084010.
6 <http://dx.doi.org/10.1088/1748-9326/10/8/084010>
- 7 Brown, D.G., C. Polsky, P. Bolstad, S.D. Brody, D. Hulse, R. Kroh, T.R. Loveland, and A.
8 Thomson, 2014: Ch. 13: Land use and land cover change. *Climate Change Impacts in the*
9 *United States: The Third National Climate Assessment*. Melillo, J.M., Terese (T.C.)
10 Richmond, and G.W. Yohe, Eds. U.S. Global Change Research Program, Washington, DC,
11 318-332. <http://dx.doi.org/10.7930/J05Q4T1Q>
- 12 Challinor, A.J., J. Watson, D.B. Lobell, S.M. Howden, D.R. Smith, and N. Chhetri, 2014: A
13 meta-analysis of crop yield under climate change and adaptation. *Nature Climate Change*, **4**,
14 287-291. <http://dx.doi.org/10.1038/nclimate2153>
- 15 Chan, D. and Q. Wu, 2015: Significant anthropogenic-induced changes of climate classes since
16 1950. *Scientific Reports*, **5**, 13487. <http://dx.doi.org/10.1038/srep13487>
- 17 Christensen, J.H., K. Krishna Kumar, E. Aldrian, S.-I. An, I.F.A. Cavalcanti, M. de Castro, W.
18 Dong, P. Goswami, A. Hall, J.K. Kanyanga, A. Kitoh, J. Kossin, N.-C. Lau, J. Renwick, D.B.
19 Stephenson, S.-P. Xie, and T. Zhou, 2013: Climate phenomena and their relevance for future
20 regional climate change. *Climate Change 2013: The Physical Science Basis. Contribution of*
21 *Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate*
22 *Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A.
23 Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge,
24 United Kingdom and New York, NY, USA, 1217-1308.
25 <http://www.climatechange2013.org/report/full-report/>
- 26 Ciais, P., C. Sabine, G. Bala, L. Bopp, V. Brovkin, J. Canadell, A. Chhabra, R. DeFries, J.
27 Galloway, M. Heimann, C. Jones, C. Le Quéré, R.B. Myneni, S. Piao, and P. Thornton,
28 2013: Carbon and other biogeochemical cycles. *Climate Change 2013: The Physical Science*
29 *Basis. Contribution of Working Group I to the Fifth Assessment Report of the*
30 *Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M.
31 Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds.
32 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 465-
33 570. <http://www.climatechange2013.org/report/full-report/>
- 34 Daly, C., M.P. Widrlechner, M.D. Halbleib, J.I. Smith, and W.P. Gibson, 2012: Development of
35 a new USDA plant hardiness zone map for the United States. *Journal of Applied*
36 *Meteorology and Climatology*, **51**, 242-264. <http://dx.doi.org/10.1175/2010JAMC2536.1>

- 1 Diaz, H.F. and J.K. Eischeid, 2007: Disappearing “alpine tundra” Köppen climatic type in the
2 western United States. *Geophysical Research Letters*, **34**, L18707.
3 <http://dx.doi.org/10.1029/2007GL031253>
- 4 Diez, J.M., C.M. D’Antonio, J.S. Dukes, E.D. Grosholz, J.D. Olden, C.J.B. Sorte, D.M.
5 Blumenthal, B.A. Bradley, R. Early, I. Ibáñez, S.J. Jones, J.J. Lawler, and L.P. Miller, 2012:
6 Will extreme climatic events facilitate biological invasions? *Frontiers in Ecology and the*
7 *Environment*, **10**, 249-257. <http://dx.doi.org/10.1890/110137>
- 8 Diffenbaugh, N.S., D.L. Swain, and D. Touma, 2015: Anthropogenic warming has increased
9 drought risk in California. *Proceedings of the National Academy of Sciences*, **112**, 3931-
10 3936. <http://dx.doi.org/10.1073/pnas.1422385112>
- 11 Elsner, M.M., L. Cuo, N. Voisin, J.S. Deems, A.F. Hamlet, J.A. Vano, K.E.B. Mickelson, S.Y.
12 Lee, and D.P. Lettenmaier, 2010: Implications of 21st century climate change for the
13 hydrology of Washington State. *Climatic Change*, **102**, 225-260.
14 <http://dx.doi.org/10.1007/s10584-010-9855-0>
- 15 EPA, 2005: Greenhouse Gas Mitigation Potential in U.S. Forestry and Agriculture.
16 Environmental Protection Agency, Washington, D.C., 154 pp.
17 https://www3.epa.gov/climatechange/Downloads/ccs/ghg_mitigation_forestry_ag_2005.pdf
- 18 EPA, 2016: Climate Change Indicators in the United States, 2016. 4th edition. U.S.
19 Environmental Protection Agency, Washington, D.C., 96 pp.
20 https://www.epa.gov/sites/production/files/2016-08/documents/climate_indicators_2016.pdf
- 21 Feddema, J.J., K.W. Oleson, G.B. Bonan, L.O. Mearns, L.E. Buja, G.A. Meehl, and W.M.
22 Washington, 2005: The importance of land-cover change in simulating future climates.
23 *Science*, **310**, 1674-1678. <http://dx.doi.org/10.1126/science.1118160>
- 24 Forrest, J.R.K., 2015: Plant–pollinator interactions and phenological change: What can we learn
25 about climate impacts from experiments and observations? *Oikos*, **124**, 4-13.
26 <http://dx.doi.org/10.1111/oik.01386>
- 27 Frank, D., M. Reichstein, M. Bahn, K. Thonicke, D. Frank, M.D. Mahecha, P. Smith, M. van der
28 Velde, S. Vicca, F. Babst, C. Beer, N. Buchmann, J.G. Canadell, P. Ciais, W. Cramer, A.
29 Ibrom, F. Miglietta, B. Poulter, A. Rammig, S.I. Seneviratne, A. Walz, M. Wattenbach, M.A.
30 Zavala, and J. Zscheischler, 2015: Effects of climate extremes on the terrestrial carbon cycle:
31 Concepts, processes and potential future impacts. *Global Change Biology*, **21**, 2861-2880.
32 <http://dx.doi.org/10.1111/gcb.12916>
- 33 Fridley, J.D., J.S. Lynn, J.P. Grime, and A.P. Askew, 2016: Longer growing seasons shift
34 grassland vegetation towards more-productive species. *Nature Climate Change*, **6**, 865-868.
35 <http://dx.doi.org/10.1038/nclimate3032>

- 1 Fu, Y.H., H. Zhao, S. Piao, M. Peaucelle, S. Peng, G. Zhou, P. Ciais, M. Huang, A. Menzel, J.
2 Penuelas, Y. Song, Y. Vitasse, Z. Zeng, and I.A. Janssens, 2015: Declining global warming
3 effects on the phenology of spring leaf unfolding. *Nature*, **526**, 104-107.
4 <http://dx.doi.org/10.1038/nature15402>
- 5 Fujimori, S., T. Masui, and Y. Matsuoka, 2014: Development of a global computable general
6 equilibrium model coupled with detailed energy end-use technology. *Applied Energy*, **128**,
7 296–306. <https://dx.doi.org/10.1016/j.apenergy.2014.04.074>
- 8 Galloway, J.N., W.H. Schlesinger, C.M. Clark, N.B. Grimm, R.B. Jackson, B.E. Law, P.E.
9 Thornton, A.R. Townsend, and R. Martin, 2014: Ch. 15: Biogeochemical cycles. *Climate*
10 *Change Impacts in the United States: The Third National Climate Assessment*. Melillo, J.M.,
11 Terese (T.C.) Richmond, and G.W. Yohe, Eds. U.S. Global Change Research Program,
12 Washington, DC, 350-368. <http://dx.doi.org/10.7930/J0X63JT0>
- 13 Georgakakos, A., P. Fleming, M. Dettinger, C. Peters-Lidard, T.C. Richmond, K. Reckhow, K.
14 White, and D. Yates, 2014: Ch. 3: Water resources. *Climate Change Impacts in the United*
15 *States: The Third National Climate Assessment*. Melillo, J.M., T.C. Richmond, and G.W.
16 Yohe, Eds. U.S. Global Change Research Program, Washington, D.C., 69-112.
17 <http://dx.doi.org/10.7930/J0G44N6T>
- 18 Gray, J.M., S. Frohling, E.A. Kort, D.K. Ray, C.J. Kucharik, N. Ramankutty, and M.A. Friedl,
19 2014: Direct human influence on atmospheric CO₂ seasonality from increased cropland
20 productivity. *Nature*, **515**, 398-401. <http://dx.doi.org/10.1038/nature13957>
- 21 Grimmond, C.S.B., H.C. Ward, and S. Kotthaus, 2016: Effects of urbanization on local and
22 regional climate. *Routledge Handbook of Urbanization and Global Environment Change*.
23 Seto, K.C., W.D. Solecki, and C.A. Griffith, Eds. Routledge, London, 169-187.
- 24 Grundstein, A., 2008: Assessing climate change in the contiguous United States using a modified
25 Thornthwaite climate classification scheme. *The Professional Geographer*, **60**, 398-412.
26 <http://dx.doi.org/10.1080/00330120802046695>
- 27 Gu, L., P.J. Hanson, W. Mac Post, D.P. Kaiser, B. Yang, R. Nemani, S.G. Pallardy, and T.
28 Meyers, 2008: The 2007 eastern US spring freezes: Increased cold damage in a warming
29 world? *BioScience*, **58**, 253-262. <http://dx.doi.org/10.1641/b580311>
- 30 Guenther, A., T. Karl, P. Harley, C. Wiedinmyer, P.I. Palmer, and C. Geron, 2006: Estimates of
31 global terrestrial isoprene emissions using MEGAN (Model of Emissions of Gases and
32 Aerosols from Nature). *Atmospheric Chemistry and Physics*, **6**, 3181-3210.
33 <http://dx.doi.org/10.5194/acp-6-3181-2006>
- 34 Hansen, M. C., P. V. Potapov, R. Moore, M. Hancher, S. A. Turubanova, A. Tyukavina, D.
35 Thau, S. V. Stehman, S. J. Goetz, T. R. Loveland, A. Kommareddy, A. Egorov, L. Chini, C.

- 1 O. Justice, J. R. G. Townshend, 2013. High-resolution global maps of 21st-century forest
2 cover change, *Science*, 342(6160):850–853, doi:10.1126/science.1244693.
- 3 Hatfield, J., G. Takle, R. Grotjahn, P. Holden, R.C. Izaurralde, T. Mader, E. Marshall, and D.
4 Liverman, 2014: Ch. 6: Agriculture. *Climate Change Impacts in the United States: The Third*
5 *National Climate Assessment*. Melillo, J.M., Terese (T.C.) Richmond, and G.W. Yohe, Eds.
6 U.S. Global Change Research Program, Washington, DC, 150-174.
7 <http://dx.doi.org/10.7930/J02Z13FR>
- 8 Hellmann, J.J., J.E. Byers, B.G. Bierwagen, and J.S. Dukes, 2008: Five potential consequences
9 of climate change for invasive species. *Conservation Biology*, **22**, 534-543.
10 <http://dx.doi.org/10.1111/j.1523-1739.2008.00951.x>
- 11 Hibbard, K., T. Wilson, K. Averyt, R. Harriss, R. Newmark, S. Rose, E. Shevliakova, and V.
12 Tidwell, 2014: Ch. 10: Energy, water, and land use. *Climate Change Impacts in the United*
13 *States: The Third National Climate Assessment*. Melillo, J.M., Terese (T.C.) Richmond, and
14 G.W. Yohe, Eds. U.S. Global Change Research Program, Washington, DC, 257-281.
15 <http://dx.doi.org/10.7930/J0JW8BSF>
- 16 Hidalgo, J., V. Masson, A. Baklanov, G. Pigeon, and L. Gimeno, 2008: Advances in urban
17 climate modeling. *Annals of the New York Academy of Sciences*, **1146**, 354-374.
18 <http://dx.doi.org/10.1196/annals.1446.015>
- 19 Hoffman, F.M., J.T. Randerson, V.K. Arora, Q. Bao, P. Cadule, D. Ji, C.D. Jones, M.
20 Kawamiya, S. Khatiwala, K. Lindsay, A. Obata, E. Shevliakova, K.D. Six, J.F. Tjiputra,
21 E.M. Volodin, and T. Wu, 2014: Causes and implications of persistent atmospheric carbon
22 dioxide biases in Earth System Models. *Journal of Geophysical Research Biogeosciences*,
23 **119**, 141-162. <http://dx.doi.org/10.1002/2013JG002381>
- 24 Hurtt, G.C., L.P. Chini, S. Frolking, R.A. Betts, J. Feddema, G. Fischer, J.P. Fisk, K. Hibbard,
25 R.A. Houghton, A. Janetos, C.D. Jones, G. Kindermann, T. Kinoshita, K. Klein Goldewijk,
26 K. Riahi, E. Shevliakova, S. Smith, E. Stehfest, A. Thomson, P. Thornton, D.P. van Vuuren,
27 and Y.P. Wang, 2011: Harmonization of land-use scenarios for the period 1500–2100:
28 600 years of global gridded annual land-use transitions, wood harvest, and resulting
29 secondary lands. *Climatic Change*, **109**, 117. <http://dx.doi.org/10.1007/s10584-011-0153-2>
- 30 Imhoff, M.L., P. Zhang, R.E. Wolfe, and L. Bounoua, 2010: Remote sensing of the urban heat
31 island effect across biomes in the continental USA. *Remote Sensing of Environment*, **114**,
32 504-513. <http://dx.doi.org/10.1016/j.rse.2009.10.008>
- 33 IPCC, 2013: Summary for policymakers. *Climate Change 2013: The Physical Science Basis.*
34 *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental*
35 *Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J.

- 1 Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press,
2 Cambridge, United Kingdom and New York, NY, USA, 1–30.
3 <http://www.climatechange2013.org/report/>
- 4 Jackson, R.B., J.T. Randerson, J.G. Canadell, R.G. Anderson, R. Avissar, D.D. Baldocchi, G.B.
5 Bonan, K. Caldeira, N.S. Diffenbaugh, C.B. Field, B.A. Hungate, E.G. Jobbágy, L.M.
6 Kueppers, D.N. Marcelo, and D.E. Pataki, 2008: Protecting climate with forests.
7 *Environmental Research Letters*, **3**, 044006. <http://dx.doi.org/10.1088/1748-9326/3/4/044006>
- 8 Jandl, R., M. Lindner, L. Vesterdal, B. Bauwens, R. Baritz, F. Hagedorn, D.W. Johnson, K.
9 Minkinen, and K.A. Byrne, 2007: How strongly can forest management influence soil
10 carbon sequestration? *Geoderma*, **137**, 253-268.
11 <http://dx.doi.org/10.1016/j.geoderma.2006.09.003>
- 12 Jones, A.D., K.V. Calvin, W.D. Collins, and J. Edmonds, 2015: Accounting for radiative forcing
13 from albedo change in future global land-use scenarios. *Climatic Change*, **131**, 691-703.
14 <http://dx.doi.org/10.1007/s10584-015-1411-5>
- 15 Joyce, L.A., S.W. Running, D.D. Breshears, V.H. Dale, R.W. Malmshemer, R.N. Sampson, B.
16 Sohngen, and C.W. Woodall, 2014: Ch. 7: Forests. *Climate Change Impacts in the United*
17 *States: The Third National Climate Assessment*. Melillo, J.M., Terese (T.C.) Richmond, and
18 G.W. Yohe, Eds. U.S. Global Change Research Program, Washington, DC, 175-194.
19 <http://dx.doi.org/10.7930/JOZ60KZC>
- 20 Ju, J. and J.G. Masek, 2016: The vegetation greenness trend in Canada and US Alaska from
21 1984–2012 Landsat data. *Remote Sensing of Environment*, **176**, 1-16.
22 <http://dx.doi.org/10.1016/j.rse.2016.01.001>
- 23 Kam, J., J. Sheffield, and E.F. Wood, 2014: Changes in drought risk over the contiguous United
24 States (1901–2012): The influence of the Pacific and Atlantic Oceans. *Geophysical Research*
25 *Letters*, **41**, 5897-5903. <http://dx.doi.org/10.1002/2014GL060973>
- 26 Kaufmann, R.K., Seto, K.C., Schneider, A., Liu, A., Zhou, L., and W. Wang. 2007. Climate
27 response to rapid urban growth: Evidence of a human-induced precipitation deficit. *Journal*
28 *of Climate*. 20:2299-2306. doi: 10.1175/JCLI4109.1
- 29 Keenan, T.F., D.Y. Hollinger, G. Bohrer, D. Dragoni, J.W. Munger, H.P. Schmid, and A.D.
30 Richardson, 2013: Increase in forest water-use efficiency as atmospheric carbon dioxide
31 concentrations rise. *Nature*, **499**, 324-327. <http://dx.doi.org/10.1038/nature12291>
- 32 King, S.L., D.J. Twedt, and R.R. Wilson, 2006: The role of the wetland reserve program in
33 conservation efforts in the Mississippi River alluvial valley. *Wildlife Society Bulletin (1973-*
34 *2006)*, **34**, 914-920. [http://dx.doi.org/10.2193/0091-7648\(2006\)34\[914:TROTWR\]2.0.CO;2](http://dx.doi.org/10.2193/0091-7648(2006)34[914:TROTWR]2.0.CO;2)

- 1 Knutti, R. and J. Sedlacek, 2013: Robustness and uncertainties in the new CMIP5 climate model
2 projections. *Nature Climate Change*, **3**, 369-373. <http://dx.doi.org/10.1038/nclimate1716>
- 3 Kudo, G. and T.Y. Ida, 2013: Early onset of spring increases the phenological mismatch between
4 plants and pollinators. *Ecology*, **94**, 2311-2320. <http://dx.doi.org/10.1890/12-2003.1>
- 5 Kunkel, K.E., 2016: Update to data originally published in: Kunkel, K.E., D. R. Easterling, K.
6 Hubbard, K. Redmond, 2004: Temporal variations in frost-free season in the United States:
7 1895 - 2000. *Geophysical Research Letters*, **31**, L03201.
8 <http://dx.doi.org/10.1029/2003gl018624>
- 9 Lambert, A.M., C.M. D'Antonio, and T.L. Dudley, 2010: Invasive species and fire in California
10 ecosystems. *Fremontia*, **38**, 29-36.
- 11 Landsberg, H.E., 1970: Man-made climatic changes: Man's activities have altered the climate of
12 urbanized areas and may affect global climate in the future. *Science*, **170**, 1265-1274.
13 <http://dx.doi.org/10.1126/science.170.3964.1265>
- 14 Lippke, B., E. Oneil, R. Harrison, K. Skog, L. Gustavsson, and R. Sathre, 2011: Life cycle
15 impacts of forest management and wood utilization on carbon mitigation: Knowns and
16 unknowns. *Carbon management*, **2**, 303-333. <http://dx.doi.org/10.4155/CMT.11.24>
- 17 Littell, J.S., M.M. Elsner, G.S. Mauger, E.R. Lutz, A.F. Hamlet, and E.P. Salathé, 2011:
18 Regional Climate and Hydrologic Change in the Northern U.S. Rockies and Pacific
19 Northwest: Internally Consistent Projections of Future Climate for Resource Management.
20 University of Washington, Seattle. [https://cig.uw.edu/publications/regional-climate-and-
21 hydrologic-change-in-the-northern-u-s-rockies-and-pacific-northwest-internally-consistent-
22 projections-of-future-climate-for-resource-management/](https://cig.uw.edu/publications/regional-climate-and-hydrologic-change-in-the-northern-u-s-rockies-and-pacific-northwest-internally-consistent-projections-of-future-climate-for-resource-management/)
- 23 Littell, J.S., D.L. Peterson, K.L. Riley, Y.-Q. Liu, and C.H. Luce, 2016: Fire and drought. *Effects*
24 *of Drought on Forests and Rangelands in the United States: A comprehensive science*
25 *synthesis*. Vose, J., J.S. Clark, C. Luce, and T. Patel-Weynand, Eds. U.S. Department of
26 Agriculture, Forest Service, Washington Office, Washington, DC, 135-150.
27 <http://www.treesearch.fs.fed.us/pubs/50261>
- 28 Liu, L.L. and T.L. Greaver, 2009: A review of nitrogen enrichment effects on three biogenic
29 GHGs: The CO₂ sink may be largely offset by stimulated N₂O and CH₄ emission. *Ecology*
30 *Letters*, **12**, 1103-1117. <http://dx.doi.org/10.1111/j.1461-0248.2009.01351.x>
- 31 Lobell, D.B. and C. Tebaldi, 2014: Getting caught with our plants down: The risks of a global
32 crop yield slowdown from climate trends in the next two decades. *Environmental Research*
33 *Letters*, **9**, 074003. <http://dx.doi.org/10.1088/1748-9326/9/7/074003>

- 1 Lovenduski, N.S. and G.B. Bonan, 2017: Reducing uncertainty in projections of terrestrial
2 carbon uptake. *Environmental Research Letters*, **12**, 044020. [http://dx.doi.org/10.1088/1748-](http://dx.doi.org/10.1088/1748-9326/aa66b8)
3 [9326/aa66b8](http://dx.doi.org/10.1088/1748-9326/aa66b8)
- 4 Maloney, E.D., S.J. Camargo, E. Chang, B. Colle, R. Fu, K.L. Geil, Q. Hu, X. Jiang, N. Johnson,
5 K.B. Karnauskas, J. Kinter, B. Kirtman, S. Kumar, B. Langenbrunner, K. Lombardo, L.N.
6 Long, A. Mariotti, J.E. Meyerson, K.C. Mo, J.D. Neelin, Z. Pan, R. Seager, Y. Serra, A. Seth,
7 J. Sheffield, J. Stroeve, J. Thibeault, S.-P. Xie, C. Wang, B. Wyman, and M. Zhao, 2014:
8 North American climate in CMIP5 experiments: Part III: Assessment of twenty-first-century
9 projections. *Journal of Climate*, **27**, 2230-2270. [http://dx.doi.org/10.1175/JCLI-D-13-](http://dx.doi.org/10.1175/JCLI-D-13-00273.1)
10 [00273.1](http://dx.doi.org/10.1175/JCLI-D-13-00273.1)
- 11 Mann, M.E. and P.H. Gleick, 2015: Climate change and California drought in the 21st century.
12 *Proceedings of the National Academy of Sciences*, **112**, 3858-3859.
13 <http://dx.doi.org/10.1073/pnas.1503667112>
- 14 Mao, J., A. Ribes, B. Yan, X. Shi, P.E. Thornton, R. Seferian, P. Ciais, R.B. Myneni, H.
15 Douville, S. Piao, Z. Zhu, R.E. Dickinson, Y. Dai, D.M. Ricciuto, M. Jin, F.M. Hoffman, B.
16 Wang, M. Huang, and X. Lian, 2016: Human-induced greening of the northern extratropical
17 land surface. *Nature Climate Change*, **6**, 959-963. <http://dx.doi.org/10.1038/nclimate3056>
- 18 Marotz, G.A., J. Clark, J. Henry, and R. Standfast, 1975: Cloud fields over irrigated areas in
19 southwestern Kansas—Data and speculations. *The Professional Geographer*, **27**, 457-461.
20 <http://dx.doi.org/10.1111/j.0033-0124.1975.00457.x>
- 21 Marston, L., M. Konar, X. Cai, and T.J. Troy, 2015: Virtual groundwater transfers from
22 overexploited aquifers in the United States. *Proceedings of the National Academy of*
23 *Sciences*, **112**, 8561-8566. <http://dx.doi.org/10.1073/pnas.1500457112>
- 24 McGrath, J.M., A.M. Betzelberger, S. Wang, E. Shook, X.-G. Zhu, S.P. Long, and E.A.
25 Ainsworth, 2015: An analysis of ozone damage to historical maize and soybean yields in the
26 United States. *Proceedings of the National Academy of Sciences*, **112**, 14390-14395.
27 <http://dx.doi.org/10.1073/pnas.1509777112>
- 28 McKinley, D.C., M.G. Ryan, R.A. Birdsey, C.P. Giardina, M.E. Harmon, L.S. Heath, R.A.
29 Houghton, R.B. Jackson, J.F. Morrison, B.C. Murray, D.E. Pataki, and K.E. Skog, 2011: A
30 synthesis of current knowledge on forests and carbon storage in the United States. *Ecological*
31 *Applications*, **21**, 1902-1924. <http://dx.doi.org/10.1890/10-0697.1>
- 32 McLauchlan, K., 2006: The nature and longevity of agricultural impacts on soil carbon and
33 nutrients: A review. *Ecosystems*, **9**, 1364-1382. <http://dx.doi.org/10.1007/s10021-005-0135-1>
- 34 Melillo, J.M., S. Butler, J. Johnson, J. Mohan, P. Steudler, H. Lux, E. Burrows, F. Bowles, R.
35 Smith, L. Scott, C. Vario, T. Hill, A. Burton, Y.M. Zhou, and J. Tang, 2011: Soil warming,

- 1 carbon-nitrogen interactions, and forest carbon budgets. *Proceedings of the National*
2 *Academy of Sciences*, **108**, 9508-9512. <http://dx.doi.org/10.1073/pnas.1018189108>
- 3 Melillo, J.M., T.C. Richmond, and G.W. Yohe, eds., 2014: *Climate Change Impacts in the*
4 *United States: The Third National Climate Assessment*. U.S. Global Change Research
5 Program: Washington, D.C., 841 pp. <http://dx.doi.org/10.7930/J0Z31WJ2>
- 6 Mills, G., 2007: Cities as agents of global change. *International Journal of Climatology*, **27**,
7 1849-1857. <http://dx.doi.org/10.1002/joc.1604>
- 8 Mitra, C. and J.M. Shepherd, 2016: Urban precipitation: A global perspective. *Routledge*
9 *Handbook of Urbanization and Global Environment Change*. Seto, K.C., W.D. Solecki, and
10 C.A. Griffith, Eds. Routledge, London, 152-168.
- 11 Moore, G.W., C.B. Edgar, J.G. Vogel, R.A. Washington-Allen, Rosaleen G. March, and R.
12 Zehnder, 2016: Tree mortality from an exceptional drought spanning mesic to semiarid
13 ecoregions. *Ecological Applications*, **26**, 602-611. <http://dx.doi.org/10.1890/15-0330>
- 14 Myhre, G. and A. Myhre, 2003: Uncertainties in radiative forcing due to surface albedo changes
15 caused by land-use changes. *Journal of Climate*, **16**, 1511-1524.
16 [http://dx.doi.org/10.1175/1520-0442\(2003\)016<1511:uirfdt>2.0.co;2](http://dx.doi.org/10.1175/1520-0442(2003)016<1511:uirfdt>2.0.co;2)
- 17 Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F.
18 Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura, and H.
19 Zhang, 2013: Anthropogenic and natural radiative forcing. *Climate Change 2013: The*
20 *Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of*
21 *the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M.
22 Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds.
23 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 659–
24 740. <http://www.climatechange2013.org/report/full-report/>
- 25 Norby, R.J., E.H. DeLucia, B. Gielen, C. Calfapietra, C.P. Giardina, J.S. King, J. Ledford, H.R.
26 McCarthy, D.J.P. Moore, R. Ceulemans, P. De Angelis, A.C. Finzi, D.F. Karnosky, M.E.
27 Kubiske, M. Lukac, K.S. Pregitzer, G.E. Scarascia-Mugnozza, W.H. Schlesinger, and R.
28 Oren, 2005: Forest response to elevated CO₂ is conserved across a broad range of
29 productivity. *Proceedings of the National Academy of Sciences of the United States of*
30 *America*, **102**, 18052-18056. <http://dx.doi.org/10.1073/pnas.0509478102>
- 31 NRC, 2005: *Radiative Forcing of Climate Change: Expanding the Concept and Addressing*
32 *Uncertainties*. National Academies Press, Washington, D.C., 222 pp.
33 <http://dx.doi.org/10.17226/11175>
- 34 Pan, Y., R. A. Birdsey, J. Fang, R. Houghton, P. E. Kauppi, W. A. Kurz, O. L. Phillips, A.
35 Shvidenko, S. L. Lewis, J. G. Canadell, P. Ciais, R. B. Jackson, S. W. Pacala, A. D.

- 1 McGuire, S. Piao, A. Rautiainen, S. Sitch, D. Hayes, 2011. A large and persistent carbon sink
2 in the world's forests, *Science*, 333(6045):988–993, doi:10.1126/science.1201609.
- 3 Parker, L.E. and J.T. Abatzoglou, 2016: Projected changes in cold hardiness zones and suitable
4 overwinter ranges of perennial crops over the United States. *Environmental Research Letters*,
5 **11**, 034001. <http://dx.doi.org/10.1088/1748-9326/11/3/034001>
- 6 Pielke, R.A., Sr., J. Adegoke, A. Beltrán-Przekurat, C.A. Hiemstra, J. Lin, U.S. Nair, D. Niyogi,
7 and T.E. Nobis, 2007: An overview of regional land-use and land-cover impacts on rainfall.
8 *Tellus B*, **59**, 587-601. <http://dx.doi.org/10.1111/j.1600-0889.2007.00251.x>
- 9 Pielke, R.A., Sr. and X. Zeng, 1989: Influence on severe storm development of irrigated land.
10 *National Weather Digest* **14**, 16-17.
- 11 Pyle, J.A., N. Warwick, X. Yang, P.J. Young, and G. Zeng, 2007: Climate/chemistry feedbacks
12 and biogenic emissions. *Philosophical Transactions of the Royal Society A: Mathematical,*
13 *Physical and Engineering Sciences*, **365**, 1727-40. <http://dx.doi.org/10.1098/rsta.2007.2041>
- 14 Rafferty, N.E. and A.R. Ives, 2011: Effects of experimental shifts in flowering phenology on
15 plant–pollinator interactions. *Ecology Letters*, **14**, 69-74. <http://dx.doi.org/10.1111/j.1461->
16 [0248.2010.01557.x](http://dx.doi.org/10.1111/j.1461-0248.2010.01557.x)
- 17 Reichstein, M., M. Bahn, P. Ciais, D. Frank, M.D. Mahecha, S.I. Seneviratne, J. Zscheischler, C.
18 Beer, N. Buchmann, D.C. Frank, D. Papale, A. Rammig, P. Smith, K. Thonicke, M. van der
19 Velde, S. Vicca, A. Walz, and M. Wattenbach, 2013: Climate extremes and the carbon cycle.
20 *Nature*, **500**, 287-295. <http://dx.doi.org/10.1038/nature12350>
- 21 Reyes-Fox, M., H. Steltzer, M.J. Trlica, G.S. McMaster, A.A. Andales, D.R. LeCain, and J.A.
22 Morgan, 2014: Elevated CO₂ further lengthens growing season under warming conditions.
23 *Nature*, **510**, 259-262. <http://dx.doi.org/10.1038/nature13207>
- 24 Riahi, K., S. Rao, V. Krey, C. Cho, V. Chirkov, G. Fischer, G. Kindermann, N. Nakicenovic, and
25 P. Rafaj, 2011: RCP 8.5—A scenario of comparatively high greenhouse gas emissions.
26 *Climatic Change*, **109**, 33. <http://dx.doi.org/10.1007/s10584-011-0149-y>
- 27 Rosenstiel, T.N., M.J. Potosnak, K.L. Griffin, R. Fall, and R.K. Monson, 2003: Increased CO₂
28 uncouples growth from isoprene emission in an agriforest ecosystem. *Nature*, **421**, 256-259.
29 <http://dx.doi.org/10.1038/nature01312>
- 30 Rosenzweig, C., J. Elliott, D. Deryng, A.C. Ruane, C. Müller, A. Arneth, K.J. Boote, C.
31 Folberth, M. Glotter, N. Khabarov, K. Neumann, F. Piontek, T.A.M. Pugh, E. Schmid, E.
32 Stehfest, H. Yang, and J.W. Jones, 2014: Assessing agricultural risks of climate change in the
33 21st century in a global gridded crop model intercomparison. *Proceedings of the National*
34 *Academy of Sciences*, **111**, 3268-3273. <http://dx.doi.org/10.1073/pnas.1222463110>

- 1 Schlesinger, W.H., M.C. Dietze, R.B. Jackson, R.P. Phillips, C.C. Rhoads, L.E. Rustad, and J.M.
2 Vose, 2016: Forest biogeochemistry in response to drought. *Effects of Drought on Forests*
3 *and Rangelands in the United States: A comprehensive science synthesis*. Vose, J., J.S. Clark,
4 C. Luce, and T. Patel-Weynand, Eds. U.S. Department of Agriculture, Forest Service,
5 Washington Office, Washington, DC, 97-106. <http://www.treesearch.fs.fed.us/pubs/50261>
- 6 Seto, K.C. and J.M. Shepherd, 2009: Global urban land-use trends and climate impacts. *Current*
7 *Opinion in Environmental Sustainability*, **1**, 89-95.
8 <http://dx.doi.org/10.1016/j.cosust.2009.07.012>
- 9 Seto, K.C., W.D. Solecki, and C.A. Griffith, eds., 2016: *Routledge Handbook on Urbanization*
10 *and Global Environmental Change*. Routledge: London, 582 pp.
- 11 Shepherd, J.M., 2013: Impacts of urbanization on precipitation and storms: Physical insights and
12 vulnerabilities *Climate Vulnerability: Understanding and Addressing Threats to Essential*
13 *Resources*. Academic Press, Oxford, 109-125. [http://dx.doi.org/10.1016/B978-0-12-384703-](http://dx.doi.org/10.1016/B978-0-12-384703-4.00503-7)
14 [4.00503-7](http://dx.doi.org/10.1016/B978-0-12-384703-4.00503-7)
- 15 Shepherd, J.M., B.S. Ferrier, and P.S. Ray, 2001: Rainfall morphology in Florida convergence
16 zones: A numerical study. *Monthly Weather Review*, **129**, 177-197.
17 [http://dx.doi.org/10.1175/1520-0493\(2001\)129<0177:rmifcz>2.0.co;2](http://dx.doi.org/10.1175/1520-0493(2001)129<0177:rmifcz>2.0.co;2)
- 18 Sippel, S., J. Zscheischler, and M. Reichstein, 2016: Ecosystem impacts of climate extremes
19 crucially depend on the timing. *Proceedings of the National Academy of Sciences*, **113**, 5768-
20 5770. <http://dx.doi.org/10.1073/pnas.1605667113>
- 21 Smith, P., S.J. Chapman, W.A. Scott, H.I.J. Black, M. Wattenbach, R. Milne, C.D. Campbell, A.
22 Lilly, N. Ostle, P.E. Levy, D.G. Lumsdon, P. Millard, W. Towers, S. Zaehle, and J.U. Smith,
23 2007: Climate change cannot be entirely responsible for soil carbon loss observed in England
24 and Wales, 1978–2003. *Global Change Biology*, **13**, 2605-2609.
25 <http://dx.doi.org/10.1111/j.1365-2486.2007.01458.x>
- 26 Swann, A.L.S., F.M. Hoffman, C.D. Koven, and J.T. Randerson, 2016: Plant responses to
27 increasing CO2 reduce estimates of climate impacts on drought severity. *Proceedings of the*
28 *National Academy of Sciences*, **113**, 10019-10024.
29 <http://dx.doi.org/10.1073/pnas.1604581113>
- 30 Szkokan-Emilson, E.J., B.W. Kielstra, S.E. Arnott, S.A. Watmough, J.M. Gunn, and A.J.
31 Tanentzap, 2017: Dry conditions disrupt terrestrial–aquatic linkages in northern catchments.
32 *Global Change Biology*, **23**, 117-126. <http://dx.doi.org/10.1111/gcb.13361>
- 33 Tian, H., C. Lu, J. Yang, K. Banger, D.N. Huntzinger, C.R. Schwalm, A.M. Michalak, R. Cook,
34 P. Ciais, D. Hayes, M. Huang, A. Ito, A.K. Jain, H. Lei, J. Mao, S. Pan, W.M. Post, S. Peng,
35 B. Poulter, W. Ren, D. Ricciuto, K. Schaefer, X. Shi, B. Tao, W. Wang, Y. Wei, Q. Yang, B.

- 1 Zhang, and N. Zeng, 2015: Global patterns and controls of soil organic carbon dynamics as
2 simulated by multiple terrestrial biosphere models: Current status and future directions.
3 *Global Biogeochemical Cycles*, **29**, 775-792. <http://dx.doi.org/10.1002/2014GB005021>
- 4 Todd-Brown, K.E.O., J.T. Randerson, W.M. Post, F.M. Hoffman, C. Tarnocai, E.A.G. Schuur,
5 and S.D. Allison, 2013: Causes of variation in soil carbon simulations from CMIP5 Earth
6 system models and comparison with observations. *Biogeosciences*, **10**, 1717-1736.
7 <http://dx.doi.org/10.5194/bg-10-1717-2013>
- 8 Thomson, A.M., K. V. Calvin, S. J. Smith, P. Kyle, A. Volke, P. Patel, S. Delgado-Arias, Ben
9 Bond-Lamberty, M. A. Wise, L. E. Clarke, and J. A. Edmonds, 2011: RCP4.5: A pathway for
10 stabilization of radiative forcing by 2100. *Climatic Change*, **109**, 77.
11 <https://dx.doi.org/10.1007/s10584-011-0151-4>
- 12 van den Heever, S.C. and W.R. Cotton, 2007: Urban aerosol impacts on downwind convective
13 storms. *Journal of Applied Meteorology and Climatology*, **46**, 828-850.
14 <http://dx.doi.org/10.1175/jam2492.1>
- 15 van Vuuren, D.P., S. Deetman, M.G.J. den Elzen, A. Hof, M. Isaac, K. Klein Goldewijk, T.
16 Kram, A. Mendoza Beltran, E. Stehfest, and J. van Vliet, 2011a: RCP2.6: Exploring the
17 possibility to keep global mean temperature increase below 2°C. *Climatic Change*, **109**, 95-
18 116. <http://dx.doi.org/10.1007/s10584-011-0152-3>
- 19 van Vuuren, D.P., J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G.C. Hurtt, T.
20 Kram, V. Krey, and J.F. Lamarque, 2011b: The representative concentration pathways: An
21 overview. *Climatic Change*, **109**, 5-31. <http://dx.doi.org/10.1007/s10584-011-0148-z>
- 22 Vose, J., J.S. Clark, C. Luce, and T. Patel-Weynand, eds., 2016: *Effects of Drought on Forests*
23 *and Rangelands in the United States: A Comprehensive Science Synthesis*. U.S. Department
24 of Agriculture, Forest Service, Washington Office: Washington, DC, 289 pp.
25 <http://www.treesearch.fs.fed.us/pubs/50261>
- 26 Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, P. Thorne, R. Vose, M.
27 Wehner, J. Willis, D. Anderson, S. Doney, R. Feely, P. Hennon, V. Kharin, T. Knutson, F.
28 Landerer, T. Lenton, J. Kennedy, and R. Somerville, 2014: Ch. 2: Our changing climate.
29 *Climate Change Impacts in the United States: The Third National Climate Assessment*.
30 Melillo, J.M., T.C. Richmond, and G.W. Yohe, Eds. U.S. Global Change Research Program,
31 Washington, D.C., 19-67. <http://dx.doi.org/10.7930/J0KW5CXT>
- 32 Ward, D.S. and N.M. Mahowald, 2015: Local sources of global climate forcing from different
33 categories of land use activities. *Earth System Dynamics*, **6**, 175-194.
34 <http://dx.doi.org/10.5194/esd-6-175-2015>

- 1 Ward, D.S., N.M. Mahowald, and S. Kloster, 2014: Potential climate forcing of land use and
2 land cover change. *Atmospheric Chemistry and Physics*, **14**, 12701-12724.
3 <http://dx.doi.org/10.5194/acp-14-12701-2014>
- 4 Wear, D.N. and J.W. Coulston, 2015: From sink to source: Regional variation in U.S. forest
5 carbon futures. *Scientific Reports*, **5**, 16518. <http://dx.doi.org/10.1038/srep16518>
- 6 Williams, A. P., C. D. Allen, A. K. Macalady, D. Griffin, C. A. Woodhouse, D. M. Meko, T. W.
7 Swetnam, S. A. Rauscher, R. Seager, H. D. Grissino-Mayer, J. S. Dean, E. R. Cook, C.
8 Gangodagamage, M. Cai, and N. G. McDowell, 2013. Temperature as a potent driver of
9 regional forest drought stress and tree mortality, *Nature Clim. Change*, 3:292–297,
10 [doi:10.1038/nclimate1693](https://doi.org/10.1038/nclimate1693).
- 11 Wolf, S., T.F. Keenan, J.B. Fisher, D.D. Baldocchi, A.R. Desai, A.D. Richardson, R.L. Scott,
12 B.E. Law, M.E. Litvak, N.A. Brunsell, W. Peters, and I.T. van der Laan-Luijkx, 2016: Warm
13 spring reduced carbon cycle impact of the 2012 US summer drought. *Proceedings of the*
14 *National Academy of Sciences*, **113**, 5880-5885. <http://dx.doi.org/10.1073/pnas.1519620113>
- 15 World Bank, 2017: Urban population (% of total): United States (1960-2015). World Bank Open
16 Data. <http://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS?locations=US>
- 17 Yang, L.H. and V.H.W. Rudolf, 2010: Phenology, ontogeny and the effects of climate change on
18 the timing of species interactions. *Ecology Letters*, **13**, 1-10.
19 <http://dx.doi.org/10.1111/j.1461-0248.2009.01402.x>
- 20 Zaehle, S., P. Friedlingstein, and A.D. Friend, 2010: Terrestrial nitrogen feedbacks may
21 accelerate future climate change. *Geophysical Research Letters*, **37**, L01401.
22 <http://dx.doi.org/10.1029/2009GL041345>
- 23 Zeng, N., F. Zhao, G.J. Collatz, E. Kalnay, R.J. Salawitch, T.O. West, and L. Guanter, 2014:
24 Agricultural green revolution as a driver of increasing atmospheric CO2 seasonal amplitude.
25 *Nature*, **515**, 394-397. <http://dx.doi.org/10.1038/nature13893>
- 26 Zhang, X., L. Alexander, G.C. Hegerl, P. Jones, A.K. Tank, T.C. Peterson, B. Trewin, and F.W.
27 Zwiers, 2011: Indices for monitoring changes in extremes based on daily temperature and
28 precipitation data. *Wiley Interdisciplinary Reviews: Climate Change*, **2**, 851-870.
29 <http://dx.doi.org/10.1002/wcc.147>
- 30 Zhao, L., X. Lee, R.B. Smith, and K. Oleson, 2014: Strong contributions of local background
31 climate to urban heat islands. *Nature*, **511**, 216-219. <http://dx.doi.org/10.1038/nature13462>
- 32 Zhu, Z., S. Piao, R.B. Myneni, M. Huang, Z. Zeng, J.G. Canadell, P. Ciais, S. Sitch, P.
33 Friedlingstein, A. Arneth, C. Cao, L. Cheng, E. Kato, C. Koven, Y. Li, X. Lian, Y. Liu, R.
34 Liu, J. Mao, Y. Pan, S. Peng, J. Penuelas, B. Poulter, T.A.M. Pugh, B.D. Stocker, N. Viogy,

- 1 X. Wang, Y. Wang, Z. Xiao, H. Yang, S. Zaehle, and N. Zeng, 2016: Greening of the Earth
- 2 and its drivers. *Nature Climate Change*, **6**, 791-795. <http://dx.doi.org/10.1038/nclimate3004>.

FINAL DRAFT

11. Arctic Changes and their Effects on Alaska and the Rest of the United States

KEY FINDINGS

1. Annual average near-surface air temperatures across Alaska and the Arctic have increased over the last 50 years at a rate more than twice as fast as the global average temperature. (*Very high confidence*)
2. Rising Alaskan permafrost temperatures are causing permafrost to thaw and become more discontinuous; this process releases additional CO₂ and methane, resulting in an amplifying feedback and additional warming (*high confidence*). The overall magnitude of the permafrost–carbon feedback is uncertain; however, it is clear that these emissions have the potential to complicate the ability to meet policy goals for the reduction of greenhouse gas concentrations.
3. Arctic land and sea ice loss observed in the last three decades continues, in some cases accelerating (*very high confidence*). It is *virtually certain* that Alaska glaciers have lost mass over the last 50 years, with each year since 1984 showing an annual average ice mass less than the previous year. Based on gravitational data from satellites, average ice mass loss from Greenland was –269 Gt per year between April 2002 and April 2016, accelerating in recent years (*high confidence*). Since the early 1980s, annual average Arctic sea ice has decreased in extent between 3.5% and 4.1% per decade, become thinner by between 4.3 and 7.5 feet, and began melting at least 15 more days each year. September sea ice extent has decreased between 10.7% and 15.9% per decade (*very high confidence*). Arctic-wide ice loss is expected to continue through the 21st century, *very likely* resulting in nearly sea ice-free late summers by the 2040s (*very high confidence*).
4. It is *virtually certain* that human activities have contributed to Arctic surface temperature warming, sea ice loss since 1979, glacier mass loss, and northern hemisphere snow extent decline observed across the Arctic (*very high confidence*). Human activities have *likely* contributed to more than half of the observed Arctic surface temperature rise and September sea ice decline since 1979 (*high confidence*).
5. Atmospheric circulation patterns connect the climates of the Arctic and the contiguous United States. Evidenced by recent record warm temperatures in the Arctic and emerging science, the midlatitude circulation has influenced observed Arctic temperatures and sea ice (*high confidence*). However, confidence is *low* regarding whether or by what mechanisms observed Arctic warming may have influenced the midlatitude circulation and weather patterns over the continental United States. The influence of Arctic changes on U.S. weather over the coming decades remains an open question with the potential for significant impact.

1 **11.1. Introduction**

2 Climate changes in Alaska and across the Arctic continue to outpace changes occurring across
3 the globe. The Arctic, defined as the area north of the Arctic Circle, is a vulnerable and complex
4 system integral to Earth's climate. The vulnerability stems in part from the extensive cover of ice
5 and snow, where the freezing point marks a critical threshold that when crossed has the potential
6 to transform the region. Because of its high sensitivity to radiative forcing and its role in
7 amplifying warming (Manabe and Wetherald 1975), the Arctic cryosphere is a key indicator of
8 the global climate state. Accelerated melting of multiyear sea ice, mass loss from the Greenland
9 Ice Sheet (GrIS), reduction of terrestrial snow cover, and permafrost degradation are stark
10 examples of the rapid Arctic-wide response to global warming. These local Arctic changes
11 influence global sea level, ocean salinity, the carbon cycle, and potentially atmospheric and
12 oceanic circulation patterns. Arctic climate change has altered the global climate in the past
13 (Knies et al. 2014) and will influence climate in the future.

14 As an Arctic nation, United States' adaptation, mitigation, and policy decisions depend on
15 projections of future Alaskan and Arctic climate. Aside from uncertainties due to natural
16 variability, scientific uncertainty, and greenhouse gas emissions uncertainty (see Ch. 4:
17 Projections), additional unique uncertainties in our understanding of Arctic processes thwart
18 projections, including mixed-phase cloud processes (Wyser et al. 2008); boundary layer
19 processes (Bourassa et al. 2013); sea ice mechanics (Bourassa et al. 2013); and ocean currents,
20 eddies, and tides that affect the advection of heat into and around the Arctic Ocean (Maslowski
21 et al. 2012, 2014). The inaccessibility of the Arctic has made it difficult to sustain the high-
22 quality observations of the atmosphere, ocean, land, and ice required to improve physically-
23 based models. Improved data quality and increased observational coverage would help address
24 societally relevant Arctic science questions.

25 Despite these challenges, our scientific knowledge is sufficiently advanced to effectively inform
26 policy. This chapter documents significant scientific progress and knowledge about how the
27 Alaskan and Arctic climate has changed and will continue to change.

28 **11.2. Arctic Changes**

29 **11.2.1. Alaska and Arctic Temperature**

30 Surface temperature—an essential component of the Arctic climate system—drives and signifies
31 change, fundamentally controlling the melting of ice and snow. Further, the vertical profile of
32 boundary layer temperature modulates the exchange of mass, energy, and momentum between
33 the surface and atmosphere, influencing other components such as clouds (Kay and Gettelman
34 2009; Taylor et al. 2015). Arctic temperatures exhibit spatial and interannual variability due to
35 interactions and feedbacks between sea ice, snow cover, atmospheric heat transports, vegetation,
36 clouds, water vapor, and the surface energy budget (Overland et al. 2015b; Johannessen et al.

1 2016; Overland and Wang 2016). Interannual variations in Alaskan temperatures are strongly
2 influenced by decadal variability like the Pacific Decadal Oscillation (Hartmann and Wendler
3 2005; McAfee 2014; Ch. 5: Circulation and Variability). However, observed temperature trends
4 exceed this variability.

5 Arctic surface and atmospheric temperatures have substantially increased in the observational
6 record. Multiple observation sources, including land-based surface stations since at least 1950
7 and available meteorological reanalysis datasets, provide evidence that Arctic near-surface air
8 temperatures have increased more than twice as fast as the global average (Serreze et al. 2009;
9 Bekryaev et al. 2010; Screen and Simmonds 2010; Hartmann et al. 2013; Overland et al. 2014).
10 Showing enhanced Arctic warming since 1981, satellite-observed Arctic average surface skin
11 temperatures have increased by $1.08 \pm 0.13^\circ\text{F}$ ($+0.60 \pm 0.07^\circ\text{C}$) per decade (Comiso and Hall
12 2014). As analyzed in Chapter 6: Temperature Change (Figure 6.1), strong near-surface air
13 temperature warming has occurred across Alaska exceeding 1.5°F (0.8°C) over the last 30 years.
14 Especially strong warming has occurred over Alaska's North Slope during autumn. For example,
15 Utqiagvik's (formally Barrow) warming since 1979 exceeds 7°F (3.8°C) in September, 12°F
16 (6.6°C) in October, and 10°F (5.5°C) in November (Wendler et al. 2014).

17 Enhanced Arctic warming is a robust feature of the climate response to anthropogenic forcing
18 (Collins et al. 2013; Taylor et al. 2013). An anthropogenic contribution to Arctic and Alaskan
19 surface temperature warming over the past 50 years is *virtually certain* and *likely* amounting to
20 more than 50% of observed warming (Gillett et al. 2008; Bindoff et al. 2013). One study argues
21 that the natural forcing has not contributed to the long-term Arctic warming in a discernable way
22 (Najafi et al. 2015). Also, other anthropogenic forcings (mostly aerosols) have *likely* offset up to
23 60% of the high-latitude greenhouse gas warming since 1913 (Najafi et al. 2015), suggesting that
24 Arctic warming to date would have been larger without the offsetting aerosols influence. It is
25 *virtually certain* that Arctic surface temperatures will continue to increase faster than the global
26 mean through the 21st century (Christensen et al. 2013).

27 **11.2.2. Arctic Sea Ice Change**

28 Arctic sea ice strongly influences Alaskan, Arctic, and global climate by modulating exchanges
29 of mass, energy, and momentum between the ocean and the atmosphere. Variations in Arctic sea
30 ice cover also influence atmospheric temperature and humidity, wind patterns, clouds, ocean
31 temperature, thermal stratification, and ecosystem productivity (Kay and Gettelman 2009; Kay et
32 al. 2011a; Pavelsky et al. 2011; Taylor et al. 2011a; Boisvert et al. 2013; Vaughan et al. 2013;
33 Solomon et al. 2014; Boisvert et al. 2015a,b; Johannessen et al. 2016). Arctic sea ice exhibits
34 significant interannual, spatial, and seasonal variability driven by atmospheric wind patterns and
35 cyclones, atmospheric temperature and humidity structure, clouds, radiation, sea ice dynamics,
36 and the ocean (Ogi and Wallace 2007; Kwok and Untersteiner 2011; Taylor et al. 2011b; Stroeve
37 et al. 2012a,b; Ogi and Rigor 2013; Carmack et al. 2015).

1 Overwhelming evidence indicates that the character of Arctic sea ice is rapidly changing.
2 Observational evidence shows Arctic-wide sea ice decline since 1979, accelerating ice loss since
3 2000, and some of the fastest loss along the Alaskan coast (Stroeve et al. 2014a,b; Comiso and
4 Hall 2014; Wendler et al. 2014). Although sea ice loss is found in all months, satellite
5 observations show the fastest loss in late summer and autumn (Stroeve et al. 2014a). Since 1979,
6 the annual average Arctic sea ice extent has *very likely* decreased at a rate of 3.5%–4.1% per
7 decade (Vaughan et al. 2013; Comiso and Hall 2014). Regional sea ice melt along the Alaskan
8 coasts exceeds the Arctic average rates with declines in the Beaufort and Chukchi Seas of –4.1%
9 and –4.7% per decade, respectively (Wendler et al. 2014). The annual minimum and maximum
10 sea ice extent have decreased over the last 35 years by $-13.3 \pm 2.6\%$ and $-2.7 \pm 0.5\%$ per decade,
11 respectively (Perovich et al. 2016). The ten lowest September sea ice extents over the satellite
12 period have all occurred in the last ten years, the lowest in 2012. The 2016 September sea ice
13 minimum tied with 2007 for the second lowest on record, but rapid refreezing resulted in the
14 2016 September monthly average extent being the fifth lowest. Despite the rapid initial
15 refreezing, sea ice extent was again in record low territory during fall–winter 2016/2017 due to
16 anomalously warm temperatures in the marginal seas around Alaska (Perovich et al. 2016),
17 contributing to a new record low in winter ice-volume (See:
18 <http://psc.apl.uw.edu/research/projects/arctic-sea-ice-volume-anomaly>, Schweiger et al. 2011).

19 Other important characteristics of Arctic sea ice have also changed, including thickness, age, and
20 volume. Sea ice thickness is monitored using an array of satellite, aircraft, and vessel
21 measurements (Vaughan et al. 2013; Stroeve et al. 2014a). The mean thickness of the Arctic sea
22 ice during winter between 1980 and 2008 has decreased between 4.3 and 7.5 feet (1.3 and 2.3
23 meters) (Vaughan et al. 2013). The age distribution of sea ice has become younger since 1988. In
24 March 2016, first-year (multi-year) sea ice accounted for 78% (22%) of the total extent, whereas
25 in the 1980s first-year (multi-year) sea ice accounted for 55% (45%) (Perovich et al. 2016).
26 Moreover, ice older than four years accounted for 16% of the March 1985 icepack but accounted
27 for only 1.2% of the icepack in March 2016, indicating significant changes in sea ice volume
28 (Perovich et al. 2016). The top two panels in Figure 11.1 show the September sea ice extent and
29 age in 1984 and 2016, illustrating significant reductions in sea ice age (Tschudi et al. 2016).
30 While these panels show only two years (beginning point and ending point) of the complete time
31 series, these two years are representative of the overall trends discussed and shown in the
32 September sea ice extent time series in the bottom panel of Fig 11.1. Younger, thinner sea ice is
33 more susceptible to melt, therefore reductions in age and thickness imply a larger interannual
34 variability of extent.

35 **[INSERT FIGURE 11.1 HERE]**

36 Sea ice melt season—defined as the number of days between spring melt onset and fall freeze-
37 up—has lengthened Arctic-wide by at least five days per decade since 1979, with larger regional
38 changes (Stroeve et al. 2014b; Parkinson 2014). Some of the largest observed changes in sea ice

1 melt season (Figure 11.2) are found along Alaska's northern and western coasts, lengthening the
2 melt season by 20–30 days per decade and increasing the annual number of ice-free days by
3 more than 90 (Parkinson 2014). Summer sea ice retreat along coastal Alaska has led to longer
4 open water seasons, making the Alaskan coastline more vulnerable to erosion (Chapin et al.
5 2014; Gibbs and Richmond 2015). Increased melt season length corresponds to increased
6 absorption of solar radiation by the Arctic Ocean during summer and increases upper ocean
7 temperature delaying fall freeze-up. Overall, this process significantly contributes to reductions
8 in Arctic sea ice (Stroeve et al. 2012a; Stroeve et al. 2014b). Wind-driven sea ice export through
9 the Fram Strait has not increased over the last 80 years (Vaughn et al. 2013), however one recent
10 study suggests that it may have increased since 1979 (Smedsrud et al. 2017).

11 **[INSERT FIGURE 11.2 HERE]**

12 It is *virtually certain* that there is an anthropogenic contribution to the observed Arctic sea ice
13 decline since 1979. A range of modeling studies analyzing the September sea ice extent trends in
14 simulations with and without anthropogenic forcing conclude that these declines cannot be
15 explained by natural variability alone (Vinnikov et al. 1999; Stroeve et al. 2007; Min et al. 2008;
16 Kay et al. 2011b; Day et al. 2012; Wang and Overland 2012). Further, observational-based
17 analyses considering a range of anthropogenic and natural forcing mechanisms for September
18 sea ice loss reach the same conclusion (Notz and Marotzke 2012). Considering the occurrence of
19 individual September sea ice anomalies, internal climate variability alone *very likely* could not
20 have caused recently observed record low Arctic sea ice extents, such as in September 2012
21 (Zhang and Knutson 2013; Kirchmeyer-Young et al. 2017). The potential contribution of natural
22 variability to Arctic sea ice trends is significant (Kay et al. 2011b; Jahn et al. 2016; Swart et al.
23 2015). One recent study (Ding et al. 2017) indicates that internal variability dominates Arctic
24 atmospheric circulation trends, accounting for 30%–50% of the sea ice reductions since 1979,
25 and up to 60% in September. However, previous studies indicate that the contributions from
26 internal variability are smaller than 50% (Kay et al. 2011b; Day et al. 2012). This apparent
27 significant contribution of natural variability to sea ice decline is consistent with the statement
28 that *likely* more than half of the observed sea ice loss since 1979 has an anthropogenic
29 contribution.

30 Continued sea ice loss is expected across the Arctic, which is *very likely* to result in late summers
31 becoming nearly ice-free (areal extent less than 10^6 km² or approximately 3.9×10^5 mi²) by mid-
32 century (Collins et al. 2013; Snape and Forster 2014). Natural variability (Wettstein and Deser
33 2014), future emissions, and model uncertainties (Gagné et al. 2015; Stroeve and Notz 2015;
34 Swart et al. 2015) all influence sea ice projections. One study suggests that internal variability
35 alone accounts for a 20-year prediction uncertainty in the timing of the first occurrence of an ice-
36 free summer, whereas emissions scenario differences between RCP8.5 and RCP4.5 add only 5
37 years (Jahn et al. 2016). Projected September sea ice reductions by 2081–2100 range from 43%
38 for RCP2.6 to 94% for RCP8.5 (Collins et al. 2013). However, September sea ice projections

1 over the next few decades are similar for the different anthropogenic forcing associated with
2 these scenarios; scenario dependent sea ice loss only becomes apparent after 2050. Another study
3 (Notz and Stroeve 2016) indicates that the total sea ice loss scales roughly linearly with CO₂
4 emissions, such that an additional 1,000 GtC from present day levels corresponds to ice-free
5 conditions in September. A key message from the Third National Climate Assessment (NCA3;
6 Melillo et al. 2014) was that Arctic sea ice is disappearing. The fundamental conclusion of this
7 assessment is unchanged; additional research corroborates the NCA3 statement.

8 **11.2.3. Arctic Ocean and Marginal Seas**

9 **SEA SURFACE TEMPERATURE**

10 Arctic Ocean sea surface temperatures (SSTs) have increased since comprehensive records
11 became available in 1982. Satellite-observed Arctic Ocean SSTs, poleward of 60°N, exhibit a
12 trend of $0.16 \pm 0.02^{\circ}\text{F}$ ($0.09 \pm 0.01^{\circ}\text{C}$) per decade (Comiso and Hall 2014). Arctic Ocean SST is
13 controlled by a combination of factors, including solar radiation and energy transport from ocean
14 currents and atmospheric winds. Summertime Arctic Ocean SST trends and patterns strongly
15 couple with sea ice extent; however, clouds, ocean color, upper-ocean thermal structure, and
16 atmospheric circulation also play a role (Ogi and Rigor 2013; Rhein et al. 2013). Along coastal
17 Alaska, SSTs in the Chukchi Sea exhibit a statistically significant (95% confidence) trend of 0.9
18 $\pm 0.5^{\circ}\text{F}$ ($0.5 \pm 0.3^{\circ}\text{C}$) per decade (Timmermans and Proshutinsky 2015).

19 Arctic Ocean temperatures also increased at depth (Polyakov et al. 2012; Rhein et al. 2013).
20 Since 1970, Arctic Ocean Intermediate Atlantic Water—located between 150 and 900 meters—
21 has warmed by $0.86 \pm 0.09^{\circ}\text{F}$ ($0.48 \pm 0.05^{\circ}\text{C}$) per decade; the most recent decade being the
22 warmest (Polyakov et al. 2012). The observed temperature level is unprecedented in the last
23 1,150 years for which proxy indicators provide records (Spielhagen et al. 2011; Jungclaus et al.
24 2014). The influence of Intermediate Atlantic Water warming on future Alaska and Arctic sea
25 ice loss is unclear (Döscher et al. 2014; Carmack et al. 2015).

26 **ALASKAN SEA LEVEL RISE**

27 The Alaskan coastline is vulnerable to sea level rise (SLR); however, strong regional variability
28 exists in current trends and future projections. Some regions are experiencing relative sea level
29 fall, whereas others are experiencing relative sea level rise, as measured by tide gauges that are
30 part of NOAA's National Water Level Observation Network. These tide gauge data show sea
31 levels rising fastest along the northern coast of Alaska but still slower than the global average,
32 due to isostatic rebound (Church et al. 2013; Ch. 12: Sea Level Rise). However, considerable
33 uncertainty in relative sea level rise exists to due to a lack of tide gauges; for example, no tide
34 gauges are located between Bristol Bay and Norton Sound or between Cape Lisburne and
35 Prudhoe Bay. Under almost all future scenarios, SLR along most of the Alaskan coastline is
36 projected to be less than the global average (Ch. 12: Sea Level Rise).

1 SALINITY

2 Arctic Ocean salinity influences the freezing temperature of sea ice (less salty water freezes more
3 readily) and the density profile representing the integrated effects of freshwater transport, river
4 runoff, evaporation, and sea ice processes. Arctic Ocean salinity exhibits multidecadal
5 variability, hampering the assessment of long-term trends (Rawlins et al. 2010). Emerging
6 evidence suggests that the Arctic Ocean and marginal sea salinity has decreased in recent years
7 despite short-lived regional salinity increases between 2000 and 2005 (Rhein et al. 2013).
8 Increased river runoff, rapid melting of sea and land ice, and changes in freshwater transport
9 have influenced observed Arctic Ocean salinity (Rhein et al. 2013; Köhl and Serra 2014).

10 OCEAN ACIDIFICATION

11 Arctic Ocean acidification is occurring at a faster rate than the rest of the globe (Mathis et al.
12 2015; see also Ch. 13: Ocean Changes). Coastal Alaska and its ecosystems are especially
13 vulnerable to ocean acidification because of the high sensitivity of Arctic Ocean water chemistry
14 to changes in sea ice, respiration of organic matter, upwelling, and increasing river runoff
15 (Mathis et al. 2015). Sea ice loss and a longer melt season contribute to increased vulnerability of
16 the Arctic Ocean to acidification by lowering total alkalinity, permitting greater upwelling, and
17 influencing the primary production characteristics in coastal Alaska (Arrigo et al. 2008; Cai et al.
18 2010; Hunt et al. 2011; Stabeno et al. 2012; Mathis et al. 2012; Bates et al. 2014). Global-scale
19 modeling studies suggest that the largest and most rapid changes in pH will continue along
20 Alaska's coast, indicating that ocean acidification may increase enough by the 2030s to
21 significantly influence coastal ecosystems (Mathis et al. 2015).

22 11.2.4. Boreal Wildfires

23 Alaskan wildfire activity has increased in recent decades. This increase has occurred both in the
24 boreal forest (Flannigan et al. 2009) and in the Arctic tundra (Hu et al. 2015), where fires
25 historically were smaller and less frequent. A shortened snow cover season and higher
26 temperatures over the last 50 years (Derksen et al. 2015) make the Arctic more vulnerable to
27 wildfire (Flannigan et al. 2009; Hu et al. 2015; Young et al. 2016). Total area burned and the
28 number of large fires (those with area greater than 1000 km² or 386 mi²) in Alaska exhibit
29 significant interannual and decadal variability, from influences of atmospheric circulation
30 patterns and controlled burns, but have *likely* increased since 1959 (Kasischke and Turetsky
31 2006). The most recent decade has seen an unusually large number of years with anomalously
32 large wildfires in Alaska (Sanford et al. 2015). Studies indicate that anthropogenic climate
33 change has *likely* lengthened the wildfire season and increased the risk of severe fires (Partain et
34 al. 2016). Further, wildfire risks are expected to increase through the end of the century due to
35 warmer, drier conditions (French et al. 2015; Young et al. 2017). Using climate simulations to
36 force an ecosystem model over Alaska (Alaska Frame-Based Ecosystem Code, ALFRESCO),
37 the total area burned is projected to increase between 25% and 53% by 2100 (Joly et al. 2012). A

1 transition into a regime of fire activity unprecedented in the last 10,000 years is possible (Kelly
2 et al. 2013). We conclude that there is *medium confidence* for a human-caused climate change
3 contribution to increased forest fire activity in Alaska in recent decades. See Chapter 8: Drought,
4 Floods, and Wildfires for more details.

5 A significant amount of the total global soil carbon is found in the boreal forest and tundra
6 ecosystems, including permafrost (McGuire et al. 2009; Mishra and Riley 2012; Mishra et al.
7 2013). Increased fire activity could deplete these stores, releasing them to the atmosphere to
8 serve as an additional source of atmospheric CO₂ (McGuire et al. 2009; Kelly et al. 2016).
9 Increased fires may also enhance the degradation of Alaska's permafrost by blackening the
10 ground, reducing surface albedo, and removing protective vegetation (Swanson 1996;
11 Yoshikawa et al. 2003; Myers-Smith et al. 2008; Brown et al. 2015).

12 **11.2.5. Snow Cover**

13 Snow cover extent has significantly decreased across the Northern Hemisphere and Alaska over
14 the last decade (Derksen and Brown 2012; Kunkel et al. 2016; see also Ch. 7: Precipitation
15 Change and Ch. 10: Land Cover). Northern Hemisphere June snow cover decreased by more
16 than 65% between 1967 and 2012 (Brown and Robinson 2011; Vaughan et al. 2013), at a trend
17 of -17.2% per decade since 1979 (Derksen et al. 2015). June snow cover dipped below 3 million
18 square km (approximately 1.16 million square miles) for the fifth time in six years between 2010
19 and 2015, a threshold not crossed in the previous 43 years of record (Derksen et al. 2015). Early
20 season snow cover in May, which affects the accumulation of solar insolation through the
21 summer, has also declined at -7.3% per decade, due to reduced winter accumulation from
22 warmer temperatures. Regional trends in snow cover duration vary, with some showing earlier
23 onsets while others show later onsets (Derksen et al. 2015). In Alaska, the 2016 May statewide
24 snow coverage of 595,000 square km (approximately 372,000 square miles) was the lowest on
25 record dating back to 1967; the snow coverage of 2015 was the second lowest, and 2014 was the
26 fourth lowest.

27 Human activities have contributed to observed snow cover declines over the last 50 years.
28 Attribution studies indicate that observed trends in Northern Hemisphere snow cover cannot be
29 explained by natural forcing alone, but instead require anthropogenic forcing (Rupp et al. 2013;
30 Bindoff et al. 2013; Kunkel et al. 2016). Declining snow cover is expected to continue and will
31 be affected by both the anthropogenic forcing and evolution of Arctic ecosystems. The observed
32 tundra shrub expansion and greening (Myers-Smith et al. 2011; Mao et al. 2016) affects melt by
33 influencing snow depth, melt dynamics, and the local surface energy budget. Nevertheless,
34 model simulations show that future reductions in snow cover influence biogeochemical
35 feedbacks and warming more strongly than changes in vegetation cover and fire in the North
36 American Arctic (Euskirchen et al. 2016).

37

1 11.2.6. Continental Ice Sheets and Mountain Glaciers

2 Mass loss from ice sheets and glaciers influences sea level rise, the oceanic thermohaline
3 circulation, and the global energy budget. Moreover, the relative contribution of GrIS to global
4 sea level rise continues to increase, exceeding the contribution from thermal expansion (see Ch.
5 12: Sea Level Rise). Observational and modeling studies indicate that GrIS and glaciers in
6 Alaska are out of mass balance with current climate conditions and are rapidly losing mass
7 (Vaughan et al. 2013; Zemp et al. 2015). In recent years, mass loss has accelerated and is
8 expected to continue (Zemp et al. 2015; Harig and Simons 2016).

9 Dramatic changes have occurred across GrIS, particularly at its margins. GrIS average annual
10 mass loss from January 2003 to May 2013 was -244 ± 6 Gt per year (approximately 0.26 inches
11 per decade sea level equivalent) (Harig and Simons 2016). One study indicates that ice mass loss
12 from Greenland was -269 Gt per year between April 2002 and April 2016 (Perovich et al. 2016).
13 Increased surface melt, runoff, and increased outlet glacier discharge from warmer air
14 temperatures are primary contributing factors (Howat et al. 2008; van den Broeke et al. 2009;
15 Rignot et al. 2010; Straneo et al. 2011; Khan et al. 2014). The effects of warmer air and ocean
16 temperatures on GrIS can be amplified by ice dynamical feedbacks, such as faster sliding, greater
17 calving, and increased submarine melting (Joughin et al. 2008; Holland et al. 2008; Rignot et al.
18 2010; Bartholomew et al. 2011). Shallow ocean warming and regional ocean and atmospheric
19 circulation changes also contribute to mass loss (Dupont and Alley 2005; Lim et al. 2016;
20 Tedesco et al. 2016). The underlying mechanisms of the recent discharge speed-up remain
21 unclear (Straneo et al. 2010; Johannessen et al. 2011); however, warmer subsurface ocean and
22 atmospheric temperatures (Velicogna 2009; van den Broeke et al. 2009; Andresen et al. 2012)
23 and meltwater penetration to the glacier bed (Johannessen et al. 2011; Mernild et al. 2012) *very*
24 *likely* contribute.

25 Annual average ice mass from Arctic-wide glaciers has decreased every year since 1984 (AMAP
26 2011; Pelto 2015; Zemp et al. 2015), with significant losses in Alaska, especially over the past
27 two decades (Figure 11.3; Vaughan et al. 2013; Sharp et al. 2015). Figure 11.4 illustrates
28 observed changes from U.S. Geological Survey repeat photography of Alaska's Muir Glacier,
29 retreating more than 4 miles between 1941 and 2004, and its tributary the Riggs Glacier. Total
30 glacial ice mass in the Gulf of Alaska region has declined steadily since 2003 (Harig and Simons
31 2016). NASA's Gravity Recovery and Climate Experiment (GRACE) indicates mass loss from
32 the northern and southern parts of the Gulf of Alaska region of -36 ± 4 Gt per year and -4 ± 3 Gt
33 per year, respectively (Harig and Simons 2016). Studies show imbalances in Alaskan glaciers,
34 indicating that melt will continue through the 21st century (Zemp et al. 2015; Mengel et al.
35 2016). Multiple datasets indicate that it is *extremely likely* that Alaskan glaciers have lost mass
36 over the last 50 years and will continue to do so (Larsen et al. 2015).

37 **[INSERT FIGURES 11.3 AND 11.4 HERE]**

1 **11.3. Arctic Feedbacks on the Lower 48 and Globally**

2 **11.3.1. Linkages between Arctic Warming and Lower Latitudes**

3 Midlatitude circulation influences Arctic climate and climate change (Rigor et al. 2002;
4 Graversen 2006; Perlwitz et al. 2015; Francis et al. 2017; Screen et al. 2012; Park et al. 2015;
5 Lee 2014; Lee et al. 2011; Ding et al. 2014; Screen and Francis 2016; Overland and Wang 2016).
6 Record warm Arctic temperatures in winter 2016 resulted primarily from the transport of
7 midlatitude air into the Arctic, demonstrating the significant midlatitude influence (Overland et
8 al. 2016). Emerging science demonstrates that warm, moist air intrusions from midlatitudes
9 results in increased downwelling longwave radiation, warming the Arctic surface and hindering
10 wintertime sea ice growth (Liu and Key 2014; Lee 2014; Park et al. 2015; Woods and Caballero
11 2016).

12 The extent to which enhanced Arctic surface warming and sea ice loss influence the large-scale
13 atmospheric circulation and midlatitude weather and climate extremes has become an active
14 research area (Overland et al. 2016; Francis et al. 2017). Several pathways have been proposed
15 (see reference in Cohen et al. 2014 and Barnes and Screen 2015): reduced meridional
16 temperature gradient, a more sinuous jet-stream, trapped atmospheric waves, modified storm
17 tracks, weakened stratospheric polar vortex. While modeling studies link a reduced meridional
18 temperature gradient to fewer cold temperature extremes in the continental United States
19 (Ayarzagüena and Screen 2016; Sun et al. 2016; Screen et al. 2015a,b), other studies hypothesize
20 that a slower jet stream may amplify Rossby waves and increase the frequency of atmospheric
21 blocking, causing more persistent and extreme weather in midlatitudes (Francis and Vavrus
22 2012).

23 Multiple observational studies suggest that the concurrent changes in the Arctic and Northern
24 Hemisphere large-scale circulation since the 1990s did not occur by chance, but were caused by
25 arctic amplification (Cohen et al. 2014; Vihma 2014; Barnes and Screen 2015). Reanalysis data
26 suggest a relationship between arctic amplification and observed changes in persistent circulation
27 phenomena like blocking and planetary wave amplitude (Francis and Skific 2015; Francis and
28 Vavrus 2012, 2015). The recent multi-year California drought serves as an example of an event
29 caused by persistent circulation phenomena (Swain et al. 2014; Seager et al. 2015; Teng and
30 Branstator 2017; see Ch. 5: Circulation and Variability and Ch. 8: Drought, Floods, and
31 Wildfires). Robust empirical evidence is lacking because the Arctic sea ice observational record
32 is too short (Overland et al. 2015a) or because the atmospheric response to arctic amplification
33 depends on the prior state of the atmospheric circulation, reducing detectability (Overland et al.
34 2016). Furthermore, it is not possible to draw conclusions regarding the direction of the
35 relationship between Arctic warming and midlatitude circulation based on empirical correlation
36 and covariance analyses alone. Observational analyses have been combined with modeling
37 studies to test causality statements.

1 Studies with simple models and Atmospheric General Circulation Models (AGCMs) provide
2 evidence that Arctic warming can affect midlatitude jet streams and location of storm tracks
3 (Barnes and Screen 2015; Overland et al. 2016; Francis et al. 2017). In addition, analysis of
4 CMIP5 models forced with increasing greenhouse gases suggests that the magnitude of arctic
5 amplification affects the future midlatitude jet position, specifically during boreal winter (Barnes
6 and Polvani 2015). However, the effect of arctic amplification on blocking is not clear (Hoskins
7 and Woollings 2015; Ch. 5: Circulation and Variability).

8 Regarding attribution, AGCM simulations forced with observed changes in Arctic sea ice
9 suggest that the sea ice loss effect on observed recent midlatitude circulation changes and winter
10 climate in the continental United States is small compared to natural large-scale atmospheric
11 variability (Screen et al. 2012; Perlwitz et al. 2015; Sigmond and Fyfe 2016; Sun et al. 2016). It
12 is argued, however, that climate models do not properly reproduce the linkages between arctic
13 amplification and lower latitude climate due to model errors, including incorrect sea ice–
14 atmosphere coupling and poor representation of stratospheric processes (Cohen et al. 2013;
15 Francis et al. 2017)

16 In summary, emerging science demonstrates a strong influence of the midlatitude circulation on
17 the Arctic, affecting temperatures and sea ice (*high confidence*). The influence of Arctic changes
18 on the midlatitude circulation and weather patterns are an area of active research. Currently,
19 confidence is *low* regarding whether or by what mechanisms observed Arctic warming may have
20 influenced midlatitude circulation and weather patterns over the continental United States. The
21 nature and magnitude of arctic amplification’s influence on U.S. weather over the coming
22 decades remains an open question.

23 **11.3.2. Freshwater Effects on Ocean Circulation**

24 The addition of freshwater to the Arctic Ocean from melting sea ice and land ice can influence
25 important Arctic climate system characteristics, including ocean salinity, altering ocean
26 circulation, density stratification, and sea ice characteristics. Observations indicate that river
27 runoff is increasing, driven by land ice melt, adding freshwater to the Arctic Ocean (Nummelin
28 et al. 2016). Melting Arctic sea and land ice combined with time-varying atmospheric forcing
29 (Giles et al. 2012; Köhl and Serra 2014) control Arctic Ocean freshwater export to the North
30 Atlantic. Large-scale circulation variability in the central Arctic not only controls the
31 redistribution and storage of freshwater in the Arctic (Köhl and Serra 2014) but also the export
32 volume (Morison et al. 2012). Increased freshwater fluxes can weaken open ocean convection
33 and deep water formation in the Labrador and Irminger seas, weakening the Atlantic meridional
34 overturning circulation (AMOC; Rahmstorf et al. 2015; Yang et al. 2016). AMOC-associated
35 poleward heat transport substantially contributes to North American and continental European
36 climate; any AMOC slow-down could have implications for global climate change as well
37 (Smeed et al. 2014; Liu et al. 2017; see Ch. 15: Potential Surprises). Connections to subarctic

1 ocean variations and the Atlantic Meridional Overturning Circulation have not been conclusively
2 established and require further investigation (see Ch. 13: Ocean Changes).

3 **11.3.3. Permafrost–Carbon Feedback**

4 Alaska and Arctic permafrost characteristics have responded to increased temperatures and
5 reduced snow cover in most regions since the 1980s (AMAP 2011). The permafrost warming
6 rate varies regionally; however, colder permafrost is warming faster than warmer permafrost
7 (Vaughan et al. 2013; Romanovsky et al. 2015). This feature is most evident across Alaska,
8 where permafrost on the North Slope is warming more rapidly than in the interior. Permafrost
9 temperatures across the North Slope at various depths ranging from 39 to 65 feet (12 to 20
10 meters) have warmed between 0.3° and 1.3°F (0.2° and 0.7°C) per decade over the observational
11 period (Figure 11.5; Romanovsky et al. 2016). Permafrost active layer thickness increased across
12 much of the Arctic while showing strong regional variations (AMAP 2011; Shiklomanov et al.
13 2012; Vaughan et al. 2013). Further, recent geologic survey data indicate significant permafrost
14 thaw slumping in northwestern Canada and across the circumpolar Arctic that indicate
15 significant ongoing permafrost thaw, potentially priming the region for more rapid thaw in the
16 future (Kokelj et al. 2017). Continued degradation of permafrost and a transition from
17 continuous to discontinuous permafrost is expected over the 21st century (Vaughan et al. 2013;
18 Schuur et al. 2015; Grosse et al. 2016).

19 **[INSERT FIGURE 11.5 HERE]**

20 Permafrost contains large stores of carbon. Though the total contribution of these carbon stores
21 to global methane emission is uncertain, Alaska’s permafrost contains rich and vulnerable
22 organic carbon soils (Tarnocai et al. 2009; Mishra and Riley 2012; Schuur et al. 2015). Thus,
23 warming Alaska permafrost is a concern for the global carbon cycle as it provides a possibility
24 for a significant and potentially uncontrollable release of carbon, complicating the ability to meet
25 global policy goals. Current methane emissions from Alaskan Arctic tundra and boreal forests
26 contribute a small fraction of the global methane (CH₄) budget (Chang et al. 2014). However,
27 gas flux measurements have directly measured the release of CO₂ and CH₄ from Arctic
28 permafrost (Schuur et al. 2009). Recent measurement indicate that cold season methane
29 emissions (after snowfall) are greater than summer emissions in Alaska, and methane emissions
30 in upland tundra are greater than in wetland tundra (Zona et al. 2016).

31 The permafrost–carbon feedback represents the additional release of CO₂ and CH₄ from thawing
32 permafrost soils providing additional radiative forcing, a source of a potential surprise (Treat et
33 al. 2015; Ch. 15: Potential Surprises). Thawing permafrost makes previously frozen organic
34 matter available for microbial decomposition, producing CO₂ and CH₄. The specific condition
35 under which microbial decomposition occurs, aerobic or anaerobic, determines the proportion of
36 CO₂ and CH₄ released. This distinction has potentially significant implications, as CH₄ has a 100-
37 year global warming potential 35 times that of CO₂ (Myhre et al. 2013). Emerging science

1 indicates that 3.4 times more carbon is released under aerobic conditions than anaerobic
2 conditions, and 2.3 times more carbon after accounting for the stronger greenhouse effect of CH₄
3 (Schädel et al. 2016). Additionally, CO₂ and CH₄ production strongly depends on vegetation and
4 soil properties (Treat et al. 2015).

5 Combined data and modeling studies indicate a positive permafrost–carbon feedback with a
6 global sensitivity between –14 and –19 GtC per °C (approximately –25 to –34 GtC per °F) soil
7 carbon loss (Koven et al. 2015a,b) resulting in a total 120 ± 85 GtC release from permafrost by
8 2100 and an additional global temperature increase of 0.52 ± 0.38°F (0.29 ± 0.21°C) by the
9 permafrost–carbon feedback (Schaefer et al. 2014). More recently, Chadburn et al. (2017) infer a
10 –4 million km² per °C (or approximately 858,000 mi² per °F) reduction in permafrost area to
11 globally averaged warming at stabilization by constraining climate models with the observed
12 spatial distribution of permafrost; this sensitivity is 20% higher than previous studies. In the
13 coming decades, enhanced high-latitude plant growth and its associated CO₂ sink should partially
14 offset the increased emissions from permafrost thaw (Friedlingstein et al. 2006; Schaefer et al.
15 2014; Schuur et al. 2015); thereafter, decomposition is expected to dominate uptake. Permafrost
16 thaw is occurring faster than models predict due to poorly understood deep soil, ice wedge, and
17 thermokarst processes (Fisher et al. 2014; Koven et al. 2015a; Liljedahl et al. 2016). Additional,
18 uncertainty stems from the surprising uptake of methane from mineral soils (Oh et al. 2016).
19 There is *high confidence* in the positive sign of the permafrost–carbon feedback, but *low*
20 *confidence* in the feedback magnitude.

21 **11.3.4. Methane Hydrate Instability**

22 Significant stores of CH₄, in the form of methane hydrates (also called clathrates), lie below
23 permafrost and under the global ocean. The estimated total global inventory of methane hydrates
24 ranges from 500 to 3,000 GtC (Archer 2007; Ruppel 2011; Piñero et al. 2013) with a central
25 estimate of 1800 GtC (Ruppel and Kessler 2017). Methane hydrates are solid compounds formed
26 at high pressures and cold temperatures trapping methane gas within the crystalline structure of
27 water. In the Arctic Ocean and along the shallow coastal Alaskan seas, methane hydrates form
28 on shallow but cold continental shelves and may be vulnerable to small increases in ocean
29 temperature (Bollman et al. 2010; Ruppel 2011; Ruppel and Kessler 2017).

30 Rising sea levels and warming oceans have a competing influence on methane hydrate stability
31 (Bollman et al. 2010; Hunter et al. 2013). Studies indicate that the temperature effect dominates
32 and that the overall influence is *likely* a destabilizing effect. Projected warming rates for the 21st
33 century Arctic Ocean are not expected to lead to sudden or catastrophic destabilization of sea
34 floor methane hydrates (Kretschmer et al. 2015). Recent observations indicate increased CH₄
35 emission from the Arctic sea floor near Svalbard; however, these emissions are not reaching the
36 atmosphere (Graves et al. 2015; Ruppel and Kessler 2017). It is likely that most of the methane
37 hydrate deposits will remain stable for the foreseeable future (the next few thousand years).

1 However, deposits off of coastal Alaska are among the most vulnerable and are expected to
2 continue to release CH₄ during the 21st century (Archer 2007; Kretschmer et al. 2015).

3

FINAL DRAFT

1 TRACEABLE ACCOUNTS

2 Key Finding 1

3 Annual average near-surface air temperatures across Alaska and the Arctic have increased over
4 the last 50 years at a rate more than twice as fast as the global average temperature. (*Very high*
5 *confidence*)

6 Description of evidence base

7 The Key Finding is supported by observational evidence from ground-based observing stations,
8 satellites, and data-model temperature analyses from multiple sources and independent analysis
9 techniques (Serrreze et al. 2009; Bekryaev et al. 2010; Screen and Simmonds 2010; Hartmann et
10 al. 2013; Overland et al. 2014; Comiso and Hall 2014; Wendler et al. 2014). For more than 40
11 years, climate models have predicted enhanced Arctic warming, indicating a solid grasp on the
12 underlying physics and positive feedbacks driving the accelerated Arctic warming (Manabe and
13 Wetherald 1975; Collins et al. 2013; Taylor et al. 2013). Lastly, similar statements have been
14 made in NCA3 (Melillo et al. 2014), IPCC AR5 (Hartmann et al. 2013), and in other Arctic-
15 specific assessments such as the Arctic Climate Impacts Assessment (ACIA 2005) and Snow,
16 Water, Ice and Permafrost in the Arctic (AMAP 2011).

17 Major Uncertainties

18 The lack of high quality and restricted spatial resolution of surface and ground temperature data
19 over many Arctic land regions and essentially no measurements over the Central Arctic Ocean
20 hampers the ability to better refine the rate of Arctic warming and completely restricts our ability
21 to quantify and detect regional trends, especially over the sea ice. Climate models generally
22 produce an Arctic warming between two to three times the global mean warming. A key
23 uncertainty is our quantitative knowledge of the contributions from individual feedback
24 processes in driving the accelerated Arctic warming. Reducing this uncertainty will help
25 constrain projections of future Arctic warming.

26 Assessment of confidence based on evidence and agreement, including short description of 27 nature of evidence and level of agreement

28 *Very high confidence* that the Arctic surface and air temperatures have warmed across Alaska
29 and the Arctic at a much faster rate than the global average is provided by the multiple datasets
30 analyzed by multiple independent groups indicating the same conclusion. Additionally, climate
31 models capture the enhanced warming in the Arctic indicating a solid understanding of the
32 underlying physical mechanisms.

33

1 **If appropriate, estimate likelihood of impact or consequence, including short description of**
2 **basis of estimate**

3 It is *very likely* that the accelerated rate of Arctic warming will have a significant consequence
4 for the United States due to accelerated land and sea ice melt driving changes in the ocean
5 including sea level rise threatening our coastal communities and freshening of sea water that is
6 influencing marine ecology.

7 **Summary sentence or paragraph that integrates the above information**

8 Annual average near-surface air temperatures across Alaska and the Arctic have increased over
9 the last 50 years at a rate more than twice the global average. Observational studies using
10 ground-based observing stations and satellites analyzed by multiple independent groups support
11 this finding. The enhanced sensitivity of the Arctic climate system to anthropogenic forcing is
12 also supported by climate modeling evidence, indicating a solid grasp on the underlying physics.
13 These multiple lines of evidence provide *very high confidence* of enhanced Arctic warming with
14 potentially significant impacts on coastal communities and marine ecosystems.

15

16 **Key Finding 2**

17 Rising Alaskan permafrost temperatures are causing permafrost to thaw and become more
18 discontinuous; this process releases additional CO₂ and methane, resulting in an amplifying
19 feedback and additional warming (*high confidence*). The overall magnitude of the permafrost–
20 carbon feedback is uncertain; however, it is clear that these emissions have the potential to
21 complicate the ability to meet policy goals for the reduction of greenhouse gas concentrations.

22 **Description of evidence base**

23 The Key Finding is supported by observational evidence of warming permafrost temperatures
24 and a deepening active layer, in situ gas measurements and laboratory incubation experiments of
25 CO₂ and CH₄ release, and model studies (Vaughan et al. 2013; Fisher et al. 2014; Schuur et al.
26 2015; Koven et al. 2015a,b; Schädel et al. 2016; Liljedahl et al. 2016). Alaska and Arctic
27 permafrost characteristics have responded to increased temperatures and reduced snow cover in
28 most regions since the 1980s, with colder permafrost warming faster than warmer permafrost
29 (AMAP 2011; Vaughan et al. 2013; Romanovsky et al. 2016). Large carbon soil pools (more
30 than 50% of the global below-ground organic carbon pool) are locked up in the permafrost soils
31 (Tarnocai et al. 2009), with the potential to be released. Thawing permafrost makes previously
32 frozen organic matter available for microbial decomposition. In situ gas flux measurements have
33 directly measured the release of CO₂ and CH₄ from Arctic permafrost (Schuur et al. 2009; Zona
34 et al. 2016). The specific conditions of microbial decomposition, aerobic or anaerobic,
35 determines the relative production of CO₂ and CH₄. This distinction is significant as CH₄ is a

1 much more powerful greenhouse gas than CO₂ (Myhre et al. 2013). However, incubation studies
2 indicate that 3.4 times more carbon is released under aerobic conditions than anaerobic
3 conditions, leading to a 2.3 times the stronger radiative forcing under aerobic conditions
4 (Schädel et al. 2016). Combined data and modeling studies suggest a global sensitivity of the
5 permafrost–carbon feedback warming global temperatures in 2100 by 0.52 ± 0.38°F (0.29 ±
6 0.21°C) alone (Schaefer et al. 2014). Chadburn et al. (2017) infer the sensitivity of permafrost
7 area to globally averaged warming to be 4 million km² by constraining a group of climate models
8 with the observed spatial distribution of permafrost; this sensitivity is 20% higher than previous
9 studies. Permafrost thaw is occurring faster than models predict due to poorly understood deep
10 soil, ice wedge, and thermokarst processes (Fisher et al. 2014; Koven et al. 2015a; Hollesen et al.
11 2015; Liljedahl et al. 2016). Additional uncertainty stems from the surprising uptake of methane
12 from mineral soils (Oh et al. 2016) and dependence of emissions on vegetation and soil
13 properties (Treat et al. 2015). The observational and modeling evidence supports the Key
14 Finding that the permafrost–carbon cycle is positive.

15 **Major uncertainties**

16 A major limiting factor is the sparse observations of permafrost in Alaska and remote areas
17 across the Arctic. Major uncertainties are related to deep soil, ice wedging, and thermokarst
18 processes and the dependence of CO₂ and CH₄ uptake and production on vegetation and soil
19 properties. Uncertainties also exist in relevant soil processes during and after permafrost thaw,
20 especially those that control unfrozen soil carbon storage and plant carbon uptake and net
21 ecosystem exchange. Many processes with the potential to drive rapid permafrost thaw (such as
22 thermokarst) are not included in current earth system models.

23 **Assessment of confidence based on evidence and agreement, including short description of 24 nature of evidence and level of agreement**

25 There is *high confidence* that permafrost is thawing, becoming discontinuous, and releasing CO₂
26 and CH₄. Physically-based arguments and observed increases in CO₂ and CH₄ emissions as
27 permafrost thaws indicate that the feedback is positive. This confidence level is justified based
28 on observations of rapidly changing permafrost characteristics.

29 **If appropriate, estimate likelihood of impact or consequence, including short description of 30 basis of estimate**

31 Thawing permafrost *very likely* has significant impacts to the global carbon cycle and serves as a
32 source of CO₂ and CH₄ emission that complicates the ability to meet policy goals

33 **Summary sentence or paragraph that integrates the above information**

34 Permafrost is thawing, becoming more discontinuous, and releasing CO₂ and CH₄. Observational
35 and modeling evidence indicates that permafrost has thawed and released additional CO₂ and

1 CH₄ indicating that the permafrost–carbon cycle feedback is positive accounting for additional
2 warming of approximately 0.08°C to 0.50°C on top of climate model projections. Although the
3 magnitude of the permafrost–carbon feedback is uncertain due to a range of poorly understood
4 processes (deep soil and ice wedge processes, plant carbon uptake, dependence of uptake and
5 emissions on vegetation and soil type, and the role of rapid permafrost thaw processes, such as
6 thermokarst), emerging science and the newest estimates continue to indicate that this feedback
7 is more likely on the larger side of the range. Impacts of permafrost thaw and the permafrost
8 carbon feedback complicates our ability to meet policy goals by adding a currently unconstrained
9 radiative forcing to the climate system.

10

11 **Key Finding 3**

12 Arctic land and sea ice loss observed in the last three decades continues, in some cases
13 accelerating (*very high confidence*). It is *virtually certain* that Alaska glaciers have lost mass
14 over the last 50 years, with each year since 1984 showing an annual average ice mass less than
15 the previous year. Based on gravitational data from satellites, average ice mass loss from
16 Greenland was –269 Gt per year between April 2002 and April 2016, accelerating in recent years
17 (*high confidence*). Since the early 1980s, annual average Arctic sea ice has decreased in extent
18 between 3.5% and 4.1% per decade, become thinner by between 4.3 and 7.5 feet, and began
19 melting at least 15 more days each year. September sea ice extent has decreased between 10.7%
20 and 15.9% per decade (*very high confidence*). Arctic-wide ice loss is expected to continue
21 through the 21st century, *very likely* resulting in nearly sea ice-free late summers by the 2040s
22 (*very high confidence*).

23 **Description of evidence base**

24 The Key Finding is supported by observational evidence from multiple ground-based and
25 satellite-based observational techniques (including passive microwave, laser and radar altimetry,
26 and gravimetry) analyzed by independent groups using different techniques reaching similar
27 conclusions (Vaughan et al. 2013; Comiso and Hall 2014; Stroeve et al. 2014a; Larsen et al.
28 2015; Zemp et al. 2015; Larsen et al. 2015; Harig and Simons 2016; Mengel et al. 2016;
29 Perovich et al. 2016). Additionally, the U.S. Geological Survey repeat photography database
30 shows the glacier retreat for many Alaskan glaciers (Figure 11.4: Muir Glacier). Several
31 independent model analysis studies using a wide array of climate models and different analysis
32 techniques indicate that sea ice loss will continue across the Arctic, *very likely* resulting in late
33 summers becoming nearly ice-free by mid-century (Wang and Overland 2012; Collins et al.
34 2013; Snape and Forster 2014).

35

1 **Major uncertainties**

2 Key uncertainties remain in the quantification and modeling of key physical processes that
3 contribute to the acceleration of land and sea ice melting. Climate models are unable to capture
4 the rapid pace of observed sea and land ice melt over the last 15 years; a major factor is our
5 inability to quantify and accurately model the physical processes driving the accelerated melting.
6 The interactions between atmospheric circulation, ice dynamics and thermodynamics, clouds,
7 and specifically the influence on the surface energy budget are key uncertainties. Mechanisms
8 controlling marine-terminating glacier dynamics—specifically the roles of atmospheric warming,
9 seawater intrusions under floating ice shelves, and the penetration of surface meltwater to the
10 glacier bed—are key uncertainties in projecting Greenland Ice Sheet melt.

11 **Assessment of confidence based on evidence and agreement, including short description of**
12 **nature of evidence and level of agreement**

13 There is *very high confidence* that Arctic sea and land ice melt is accelerating and mountain
14 glacier ice mass is declining given the multiple observational sources and analysis technique
15 documented in the peer reviewed climate science literature.

16 **If appropriate, estimate likelihood of impact or consequence, including short description of**
17 **basis of estimate**

18 It is *very likely* that accelerating Arctic land and sea ice melt impacts the United States.
19 Accelerating Arctic Ocean sea ice melt increases coastal erosion in Alaska and makes Alaskan
20 fisheries more susceptible to ocean acidification by changing Arctic Ocean chemistry. Greenland
21 Ice Sheet and Alaska mountain glacier melt drives sea level rise threatening coastal communities
22 in the United State and worldwide, influencing marine ecology, and potentially altering the
23 thermohaline circulation.

24 **Summary sentence or paragraph that integrates the above information**

25 Arctic land and sea ice loss observed in the last three decades continues, in some cases
26 accelerating. A diverse range of observational evidence from multiple data sources and
27 independent analysis techniques provide consistent evidence of substantial declines in Arctic sea
28 ice extent, thickness, and volume since at least 1979, mountain glacier melt over the last 50
29 years, and accelerating mass loss from Greenland. An array of different models and independent
30 analyses indicate that future declines in ice across the Arctic are expected resulting in late
31 summers in the Arctic becoming ice free by midcentury.

32

1 Key Finding 4

2 It is *virtually certain* that human activities have contributed to Arctic surface temperature
3 warming, sea ice loss since 1979, glacier mass loss, and northern hemisphere snow extent
4 decline observed across the Arctic (*very high confidence*). Human activities have *likely*
5 contributed to more than half of the observed Arctic surface temperature rise and September sea
6 ice decline since 1979 (*high confidence*).

7 Description of evidence base

8 The Key Finding is supported by many attribution studies including a wide array of climate
9 models documenting the anthropogenic influence on Arctic temperature, sea ice, mountain
10 glaciers and snow extent (Vinnikov et al. 1999; Stroeve et al. 2007; Gillett et al. 2008; Min et al.
11 2008; Kay et al. 2011b; Day et al. 2012; Wang and Overland 2012; Bindoff et al. 2013;
12 Christensen et al. 2013; Najafi et al. 2015). Observation-based analyses also support an
13 anthropogenic influence (Notz and Marotzke 2012; Notz and Stroeve 2015). Emerging science
14 indicates it is *very likely* that natural variability alone could not have caused the recently
15 observed record low Arctic sea ice extents, such as in September 2012 (Zhang and Knutson
16 2013; Kirchmeyer-Young et al. 2017). Natural variability in the Arctic is significant (Swart et al.
17 2015; Jahn et al. 2016), however the majority of studies indicate that the contribution from
18 internal variability to observed trends in Arctic temperature and sea ice are less than 50% (Kay et
19 al. 2011b; Day et al. 2012; Ding et al. 2017), therefore human activities have *likely* contributed to
20 more than half of the observed sea ice loss since 1979. Multiple lines evidence, independent
21 analysis techniques, models, and studies support the Key Finding.

22 Major uncertainties

23 A major limiting factor in our ability to attribute Arctic sea ice and glacier melt to human
24 activities is the significant natural climate variability in the Arctic. Longer data records and a
25 better understanding of the physical mechanisms that drive natural climate variability in the
26 Arctic are required to reduce this uncertainty. Another major uncertainty is the ability of climate
27 models to capture the relevant physical processes and climate changes at a fine spatial scale,
28 especially those at the land and ocean surface in the Arctic.

**29 Assessment of confidence based on evidence and agreement, including short description of
30 nature of evidence and level of agreement**

31 There is *very high confidence* that human activities have contributed to Arctic surface
32 temperature warming, sea ice loss since 1979, glacier mass loss, and northern hemisphere snow
33 extent given multiple independent analysis techniques from independent groups using many
34 different climate models indicate the same conclusion.

35

1 **If appropriate, estimate likelihood of impact or consequence, including short description of**
2 **basis of estimate**

3 Arctic sea ice and glacier mass loss impacts the United States by affecting coastal erosion in
4 Alaska and key Alaskan fisheries through an increased vulnerability to ocean acidification.
5 Glacier mass loss is a significant driver of sea level rise threatening coastal communities in the
6 United States and worldwide, influencing marine ecology, and potentially altering the Atlantic
7 Meridional Overturning Circulation (Liu et al. 2017).

8 **Summary sentence or paragraph that integrates the above information**

9 Evidenced by the multiple independent studies, analysis techniques, and the array of different
10 climate models used over the last 20 years, it is *virtually certain* that human activities have
11 contributed to Arctic surface temperature warming, sea ice loss since 1979, glacier mass loss,
12 and Northern Hemisphere snow extent decline observed across the Arctic. Key uncertainties
13 remain in the understanding and modeling of Arctic climate variability; however, the majority of
14 studies indicate that contribution from internal variability to observed trends in Arctic
15 temperature and sea ice are less than 50%. This suggests that it is also *likely* that human activities
16 have contributed to more than half of the observed September sea ice decline since 1979.

17

18 **Key Finding 5**

19 Atmospheric circulation patterns connect the climates of the Arctic and the contiguous United
20 States. Evidenced by recent record warm temperatures in the Arctic and emerging science, the
21 midlatitude circulation has influenced observed Arctic temperatures and sea ice (*high*
22 *confidence*). However, confidence is *low* regarding whether or by what mechanisms observed
23 Arctic warming may have influenced the midlatitude circulation and weather patterns over the
24 continental United States. The influence of Arctic changes on U.S. weather over the coming
25 decades remains an open question with the potential for significant impact.

26 **Description of evidence base**

27 The midlatitude circulation influences the Arctic through the transport of warm, moist air,
28 altering the Arctic surface energy budget (Rigor et al. 2002; Graverson et al. 2006; Screen et al.
29 2012; Perlwitz et al. 2015). The intrusion of warm, moist air from midlatitudes increases
30 downwelling longwave radiation, warming the Arctic surface and hindering wintertime sea ice
31 growth (Lee 2014; Liu and Key 2014). Emerging research provides a new understanding of the
32 importance of synoptic time scales and the episodic nature of midlatitude air intrusions (Lee
33 2014; Park et al. 2015; Woods and Caballero 2016). The combination of recent observational and
34 model-based evidence as well as the physical understanding of the mechanisms of midlatitude
35 circulation effects on Arctic climate supports this Key Finding.

1 In addition, research on the impact of Arctic climate on midlatitude circulation is rapidly
2 evolving, including observational analysis and modeling studies. Multiple observational studies
3 provide evidence for concurrent changes in the Arctic and Northern Hemisphere large-scale
4 circulation changes (Cohen et al. 2014; Vihma 2014; Barnes and Screen 2015). Further,
5 modeling studies demonstrate that Arctic warming can influence the midlatitude jet stream and
6 storm track (Barnes and Screen 2015; Barnes and Polvani 2015; Overland et al. 2016; Francis et
7 al. 2017). However, attribution studies indicate that the observed midlatitude circulation changes
8 over the continental United States are smaller than natural variability and are therefore not
9 detectable in the observational record (Screen et al. 2012; Perlwitz et al. 2015; Sigmund and Fyfe
10 2016; Sun et al. 2016). This disagreement between independent studies using different analysis
11 techniques and the lack of understanding of the physical mechanism(s) support this Key Finding.

12 **Major uncertainties**

13 A major limiting factor is our understanding and modeling of natural climate variability in the
14 Arctic. Longer data records and a better understanding of the physical mechanisms that drive
15 natural climate variability in the Arctic are required to reduce this uncertainty. The inability of
16 climate models to accurately capture interactions between sea ice and the atmospheric circulation
17 and polar stratospheric processes limits our current understanding.

18 **Assessment of confidence based on evidence and agreement, including short description of 19 nature of evidence and level of agreement**

20 *High confidence* in the impact of midlatitude circulation on Arctic changes from the consistency
21 between observations and models as well as a solid physical understanding.

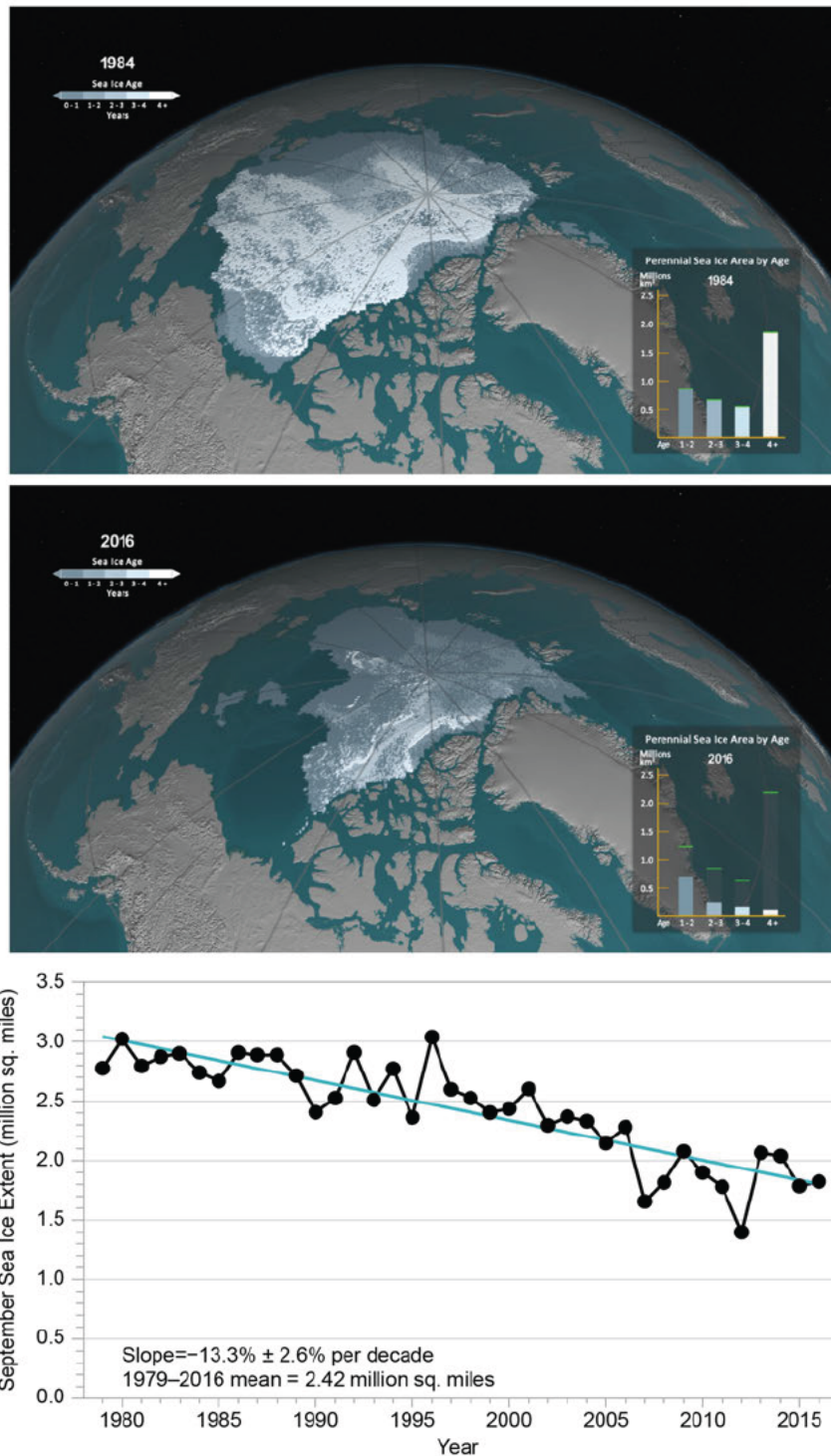
22 *Low confidence* on the detection of an impact of Arctic warming on midlatitude climate is based
23 on short observational data record, model uncertainty, and lack of physical understanding.

24 **Summary sentence or paragraph that integrates the above information**

25 The midlatitude circulation has influenced observed Arctic temperatures, supported by recent
26 observational and model-based evidence as well as the physical understanding from emerging
27 science. In turn, confidence is low regarding the mechanisms by which observed Arctic warming
28 has influenced the midlatitude circulation and weather patterns over the continental United
29 States, due to the disagreement between numerous studies and a lack of understanding of the
30 physical mechanism(s). Resolving the remaining questions requires longer data records and
31 improved understanding and modeling of physics in the Arctic. The influence of Arctic changes
32 on U.S. weather over the coming decades remains an open question with the potential for
33 significant impact.

34

1 FIGURES



2

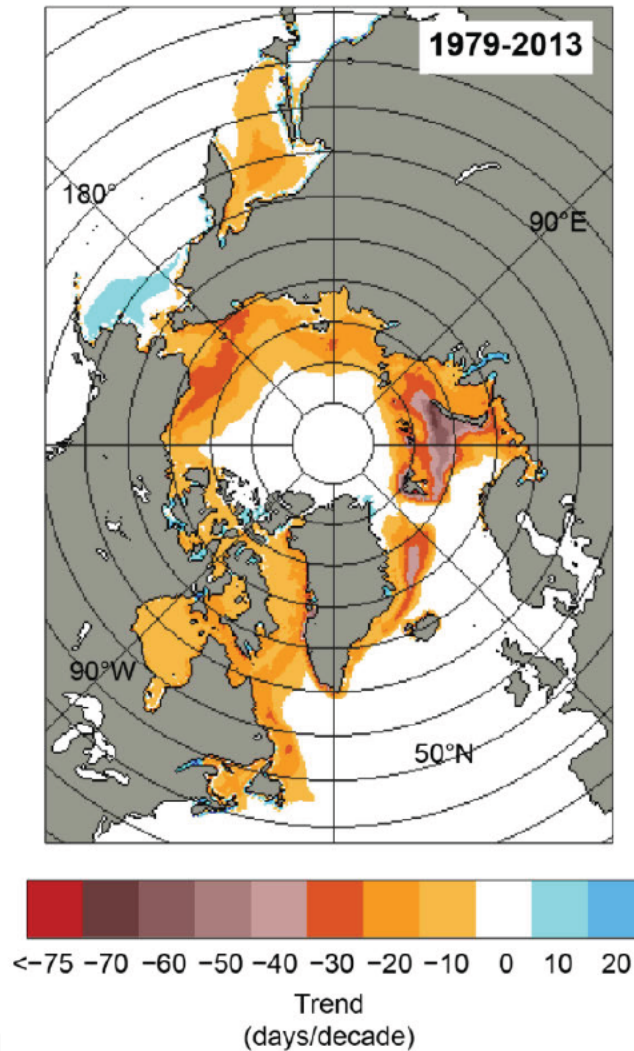
3 **Figure 11.1:** September sea ice extent and age shown for (a) 1984 and (b) 2016, illustrating
 4 significant reductions in sea ice extent and age (thickness). Bar graph in the lower right of each
 5 panel illustrates the sea ice area (unit: million km²) covered within each age category (> 1 year),

1 and the green bars represent the maximum value for each age range during the record. The year
2 1984 is representative of September sea ice characteristics during the 1980s. The years 1984 and
3 2016 are selected as endpoints in the time series; a movie of the complete time series is available
4 at <http://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=4489>. (c) Shows the satellite-era Arctic sea ice
5 areal extent trend from 1979 to 2016 for September (unit: million mi²). (Figure source: Panel
6 (a,b): NASA Science Visualization Studio; data: Tschudi et al. 2016; Panel (c) data: Fetterer et
7 al. 2016).

8

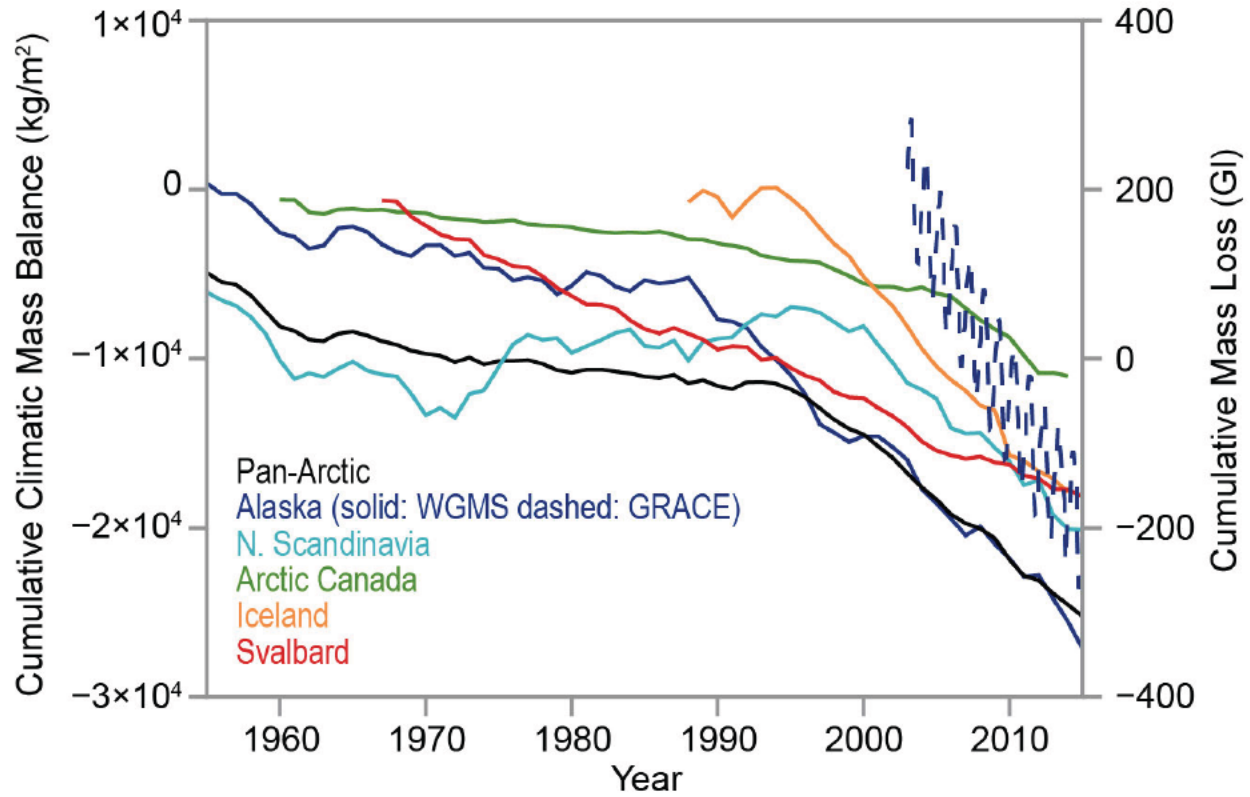
FINAL DRAFT

Trends in Sea Ice Melt Season



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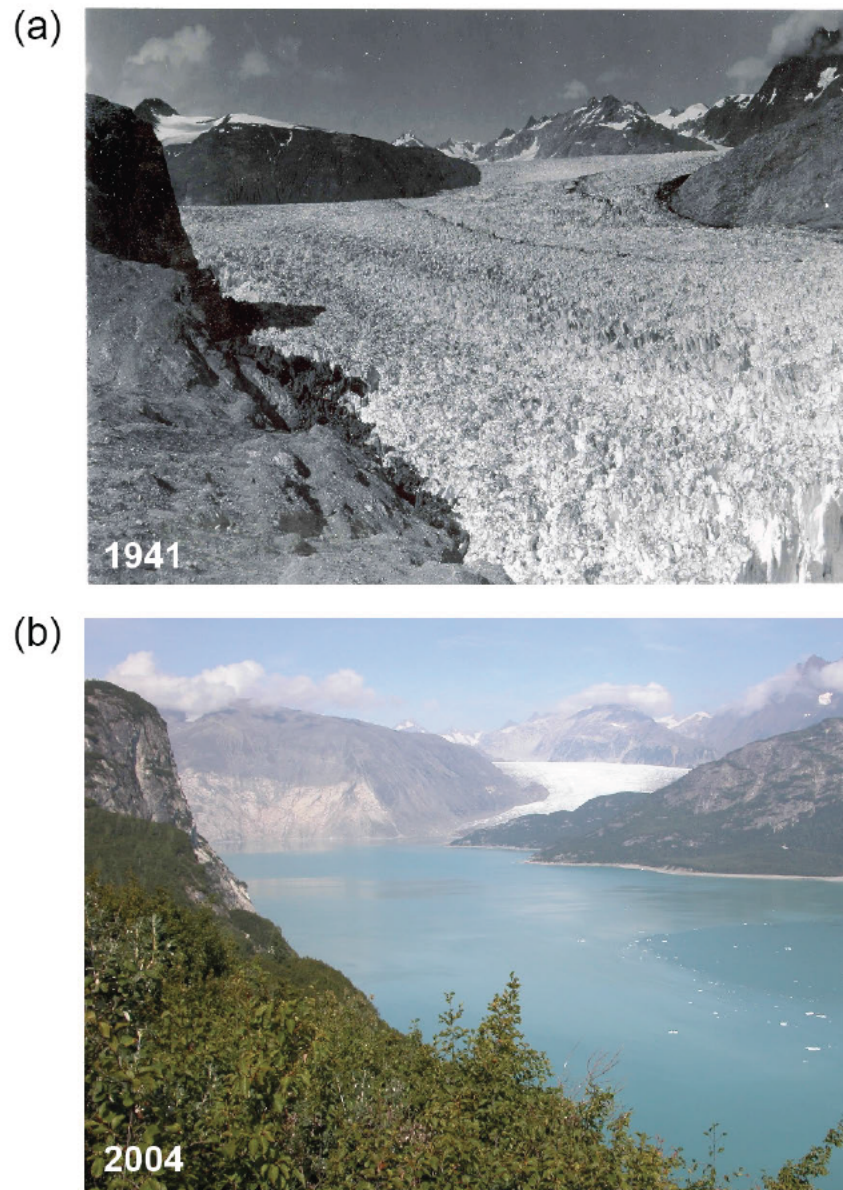
Figure 11.2: 35-year trend in Arctic sea ice melt season length, in days per decade, from passive microwave satellite observations, illustrating that the sea ice season has shortened by more than 60 days in coastal Alaska over the last 30 years. (Figure source: adapted from Parkinson 2014).



1

2 **Figure 11.3:** Time series of the cumulative climatic mass balance (units: kg/m²) in five Arctic
 3 regions and for the Pan-Arctic from the World Glacier Monitoring Service (WGMS 2016;
 4 Wolken et al. 2016; solid lines, left y-axis), plus Alaskan glacial mass loss observed from NASA
 5 GRACE (Harig and Simons 2016; dashed blue line, right y-axis). (Figure source: Harig and
 6 Simons 2016 and Wolken et al. 2016; © American Meteorological Society, used with
 7 permission).

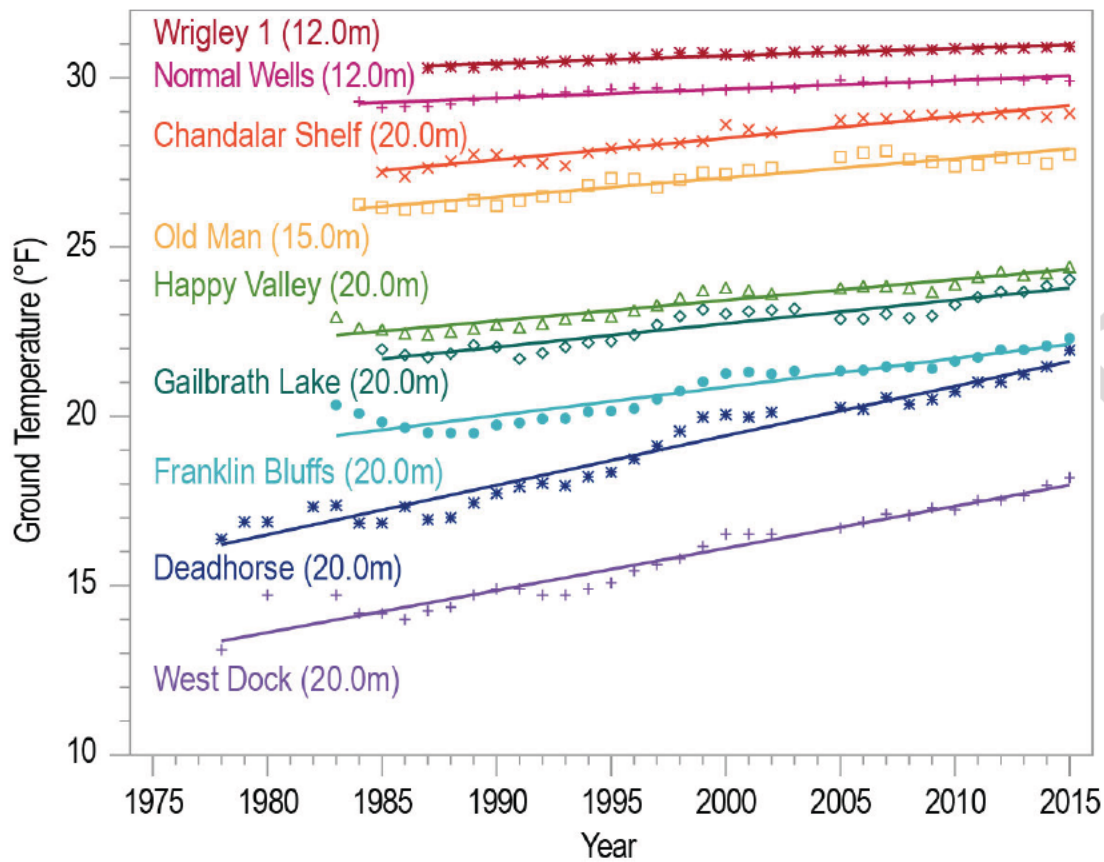
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2 **Figure 11.4:** Two northeast-looking photographs of the Muir Glacier located in southeastern
3 Alaska are shown taken from a Glacier Bay Photo station in (a) 1941 and (b) 2004. U.S.
4 Geological Survey repeat photography allows the tracking of glacier changes, illustrating that
5 between 1941 and 2004 the Muir Glacier has retreated more than 4 miles to the northwest and
6 out of view. Riggs Glacier (in view) is a tributary to Muir Glacier and has retreated by as much
7 as 0.37 miles and thinned by more than 0.16 miles. The photographs also illustrate a significant
8 change in the surface type between 1941 and 2004 as bare rock in the foreground has been
9 replaced by dense vegetation (Figure source: USGS 2004).

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Figure 11.5: Time series of annual mean permafrost temperatures (units: °F) at various depths from 39 to 65 feet (12 to 20 meters) from 1977 through 2015 at several sites across Alaska, including the North Slope continuous permafrost region (purple/blue/green shades), and the discontinuous permafrost (orange/pink/red shades) in Alaska and northwestern Canada. Solid lines represent the linear trends drawn to highlight that permafrost temperatures are warming faster in the colder, coastal permafrost regions than the warmer interior regions. (Figure Source: adapted from Romanovsky et al. 2016; © American Meteorological Society, used with permission).

1 **REFERENCES**

- 2 ACIA, 2005: Arctic Climate Impact Assessment. ACIA Secretariat and Cooperative Institute for
3 Arctic Research, 1042 pp. <http://www.acia.uaf.edu/pages/scientific.html>
- 4 AMAP, 2011: Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the
5 Cryosphere. Oslo, Norway. 538 pp. <http://www.amap.no/documents/download/1448>
- 6 Andresen, C.S., F. Straneo, M.H. Ribergaard, A.A. Bjork, T.J. Andersen, A. Kuijpers, N.
7 Norgaard-Pedersen, K.H. Kjaer, F. Schjoth, K. Weckstrom, and A.P. Ahlstrom, 2012: Rapid
8 response of Helheim Glacier in Greenland to climate variability over the past century. *Nature*
9 *Geoscience*, **5**, 37-41. <http://dx.doi.org/10.1038/ngeo1349>
- 10 Archer, D., 2007: Methane hydrate stability and anthropogenic climate change. *Biogeosciences*,
11 **4**, 521-544. <http://dx.doi.org/10.5194/bg-4-521-2007>
- 12 Arrigo, K.R., G. van Dijken, and S. Pabi, 2008: Impact of a shrinking Arctic ice cover on marine
13 primary production. *Geophysical Research Letters*, **35**, L19603.
14 <http://dx.doi.org/10.1029/2008GL035028>
- 15 Ayarzagüena, B. and J.A. Screen, 2016: Future Arctic sea ice loss reduces severity of cold air
16 outbreaks in midlatitudes. *Geophysical Research Letters*, **43**, 2801-2809.
17 <http://dx.doi.org/10.1002/2016GL068092>
- 18 Barnes, E.A. and L.M. Polvani, 2015: CMIP5 projections of arctic amplification, of the North
19 American/North Atlantic circulation, and of their relationship. *Journal of Climate*, **28**, 5254-
20 5271. <http://dx.doi.org/10.1175/JCLI-D-14-00589.1>
- 21 Barnes, E.A. and J.A. Screen, 2015: The impact of Arctic warming on the midlatitude jet-stream:
22 Can it? Has it? Will it? *Wiley Interdisciplinary Reviews: Climate Change*, **6**, 277-286.
23 <http://dx.doi.org/10.1002/wcc.337>
- 24 Bartholomew, I.D., P. Nienow, A. Sole, D. Mair, T. Cowton, M.A. King, and S. Palmer, 2011:
25 Seasonal variations in Greenland Ice Sheet motion: Inland extent and behaviour at higher
26 elevations. *Earth and Planetary Science Letters*, **307**, 271-278.
27 <http://dx.doi.org/10.1016/j.epsl.2011.04.014>
- 28 Bates, N.R., R. Garley, K.E. Frey, K.L. Shake, and J.T. Mathis, 2014: Sea-ice melt CO₂-
29 carbonate chemistry in the western Arctic Ocean: Meltwater contributions to air-sea CO₂ gas
30 exchange, mixed-layer properties and rates of net community production under sea ice.
31 *Biogeosciences*, **11**, 6769-6789. <http://dx.doi.org/10.5194/bg-11-6769-2014>

- 1 Bekryaev, R.V., I.V. Polyakov, and V.A. Alexeev, 2010: Role of polar amplification in long-
2 term surface air temperature variations and modern Arctic warming. *Journal of Climate*, **23**,
3 3888-3906. <http://dx.doi.org/10.1175/2010jcli3297.1>
- 4 Bindoff, N.L., P.A. Stott, K.M. AchutaRao, M.R. Allen, N. Gillett, D. Gutzler, K. Hansingo, G.
5 Hegerl, Y. Hu, S. Jain, I.I. Mokhov, J. Overland, J. Perlwitz, R. Sebbari, and X. Zhang, 2013:
6 Detection and attribution of climate change: From global to regional. *Climate Change 2013:*
7 *The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report*
8 *of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M.
9 Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds.
10 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 867–
11 952. <http://www.climatechange2013.org/report/full-report/>
- 12 Boisvert, L.N., T. Markus, and T. Vihma, 2013: Moisture flux changes and trends for the entire
13 Arctic in 2003–2011 derived from EOS Aqua data. *Journal of Geophysical Research:*
14 *Oceans*, **118**, 5829-5843. <http://dx.doi.org/10.1002/jgrc.20414>
- 15 Boisvert, L.N., D.L. Wu, and C.L. Shie, 2015: Increasing evaporation amounts seen in the Arctic
16 between 2003 and 2013 from AIRS data. *Journal of Geophysical Research: Atmospheres*,
17 **120**, 6865-6881. <http://dx.doi.org/10.1002/2015JD023258>
- 18 Boisvert, L.N., D.L. Wu, T. Vihma, and J. Susskind, 2015: Verification of air/surface humidity
19 differences from AIRS and ERA-Interim in support of turbulent flux estimation in the Arctic.
20 *Journal of Geophysical Research: Atmospheres*, **120**, 945-963.
21 <http://dx.doi.org/10.1002/2014JD021666>
- 22 Bollmann, M., T. Bosch, F. Colijn, R. Ebinghaus, R. Froese, K. Güssow, S. Khalilian, S. Krastel,
23 A. Körtzinger, M. Langenbuch, M. Latif, B. Matthiessen, F. Melzner, A. Oeschies, S.
24 Petersen, A. Proelß, M. Quaas, J. Reichenbach, T. Requate, T. Reusch, P. Rosenstiel, J.O.
25 Schmidt, K. Schrottke, H. Sichelschmidt, U. Siebert, R. Soltwedel, U. Sommer, K.
26 Stattegger, H. Sterr, R. Sturm, T. Treude, A. Vafeidis, C.v. Bernem, J.v. Beusekom, R. Voss,
27 M. Visbeck, M. Wahl, K. Wallmann, and F. Weinberger, 2010: *World Ocean Review: Living*
28 *With the Oceans*. maribus gGmbH, 232 pp. [http://worldoceanreview.com/wp-](http://worldoceanreview.com/wp-content/downloads/wor1/WOR1_english.pdf)
29 [content/downloads/wor1/WOR1_english.pdf](http://worldoceanreview.com/wp-content/downloads/wor1/WOR1_english.pdf)
- 30 Bourassa, M.A., S.T. Gille, C. Bitz, D. Carlson, I. Cerovecki, C.A. Clayson, M.F. Cronin, W.M.
31 Drennan, C.W. Fairall, R.N. Hoffman, G. Magnusdottir, R.T. Pinker, I.A. Renfrew, M.
32 Serreze, K. Speer, L.D. Talley, and G.A. Wick, 2013: High-latitude ocean and sea ice surface
33 fluxes: Challenges for climate research. *Bulletin of the American Meteorological Society*, **94**,
34 403-423. <http://dx.doi.org/10.1175/BAMS-D-11-00244.1>

- 1 Brown, R.D. and D.A. Robinson, 2011: Northern Hemisphere spring snow cover variability and
2 change over 1922–2010 including an assessment of uncertainty. *The Cryosphere*, **5**, 219–229.
3 <http://dx.doi.org/10.5194/tc-5-219-2011>
- 4 Brown, D. R. N., M. T. Jorgenson, T. A. Douglas, V. E. Romanovsky, K. Kielland, C.
5 Hiemstra, E. S. Euskirchen, and R. W. Ruess, 2015: Interactive effects of wildfire and
6 climate on permafrost degradation in Alaskan lowland forests. *J. Geophys. Res.*
7 *Biogeosci.*, **120**, 1619–1637.
8 <http://dx.doi.org/10.1002/2015JG003033>
9
- 10 Cai, W.-J., L. Chen, B. Chen, Z. Gao, S.H. Lee, J. Chen, D. Pierrot, K. Sullivan, Y. Wang, X.
11 Hu, W.-J. Huang, Y. Zhang, S. Xu, A. Murata, J.M. Grebmeier, E.P. Jones, and H. Zhang,
12 2010: Decrease in the CO₂ uptake capacity in an ice-free Arctic Ocean basin. *Science*, **329**,
13 556–559. <http://dx.doi.org/10.1126/science.1189338>
- 14 Carmack, E., I. Polyakov, L. Padman, I. Fer, E. Hunke, J. Hutchings, J. Jackson, D. Kelley, R.
15 Kwok, C. Layton, H. Melling, D. Perovich, O. Persson, B. Ruddick, M.-L. Timmermans, J.
16 Toole, T. Ross, S. Vavrus, and P. Winsor, 2015: Toward quantifying the increasing role of
17 oceanic heat in sea ice loss in the new Arctic. *Bulletin of the American Meteorological*
18 *Society*, **96** (12), 2079–2105. <http://dx.doi.org/10.1175/BAMS-D-13-00177.1>
- 19 Chadburn, S.E., E.J. Burke, P.M. Cox, P. Friedlingstein, G. Hugelius, and S. Westermann, 2017:
20 An observation-based constraint on permafrost loss as a function of global warming. *Nature*
21 *Climate Change*, **7**, 340–344. <http://dx.doi.org/10.1038/nclimate3262>
- 22 Chang, R.Y.-W., C.E. Miller, S.J. Dinardo, A. Karion, C. Sweeney, B.C. Daube, J.M.
23 Henderson, M.E. Mountain, J. Eluszkiewicz, J.B. Miller, L.M.P. Bruhwiler, and S.C. Wofsy,
24 2014: Methane emissions from Alaska in 2012 from CARVE airborne observations.
25 *Proceedings of the National Academy of Sciences*, **111**, 16694–16699.
26 <http://dx.doi.org/10.1073/pnas.1412953111>
- 27 Chapin III, F.S., S.F. Trainor, P. Cochran, H. Huntington, C. Markon, M. McCammon, A.D.
28 McGuire, and M. Serreze, 2014: Ch. 22: Alaska. *Climate Change Impacts in the United*
29 *States: The Third National Climate Assessment*. Melillo, J.M., Terese (T.C.) Richmond, and
30 G.W. Yohe, Eds. U.S. Global Change Research Program, Washington, DC, 514–536.
31 <http://dx.doi.org/10.7930/J00Z7150>
- 32 Christensen, J.H., K. Krishna Kumar, E. Aldrian, S.-I. An, I.F.A. Cavalcanti, M. de Castro, W.
33 Dong, P. Goswami, A. Hall, J.K. Kanyanga, A. Kitoh, J. Kossin, N.-C. Lau, J. Renwick, D.B.
34 Stephenson, S.-P. Xie, and T. Zhou, 2013: Climate phenomena and their relevance for future
35 regional climate change. *Climate Change 2013: The Physical Science Basis. Contribution of*
36 *Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate*
37 *Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A.

- 1 Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge,
2 United Kingdom and New York, NY, USA, 1217–1308.
3 <http://www.climatechange2013.org/report/full-report/>
- 4 Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A.
5 Merrifield, G.A. Milne, R.S. Nerem, P.D. Nunn, A.J. Payne, W.T. Pfeffer, D. Stammer, and
6 A.S. Unnikrishnan, 2013: Sea level change. *Climate Change 2013: The Physical Science
7 Basis. Contribution of Working Group I to the Fifth Assessment Report of the
8 Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M.
9 Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds.
10 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1137–
11 1216. <http://www.climatechange2013.org/report/full-report/>
- 12 Cohen, J., J. Jones, J.C. Furtado, and E. Tzipermam, 2013: Warm Arctic, cold continents: A
13 common pattern related to Arctic sea ice melt, snow advance, and extreme winter weather.
14 *Oceanography*, **26**, 150-160. <http://dx.doi.org/10.5670/oceanog.2013.70>
- 15 Cohen, J., J.A. Screen, J.C. Furtado, M. Barlow, D. Whittleston, D. Coumou, J. Francis, K.
16 Dethloff, D. Entekhabi, J. Overland, and J. Jones, 2014: Recent Arctic amplification and
17 extreme mid-latitude weather. *Nature Geoscience*, **7**, 627-637.
18 <http://dx.doi.org/10.1038/ngeo2234>
- 19 Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J.
20 Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver, and M. Wehner,
21 2013: Long-term climate change: Projections, commitments and irreversibility. *Climate
22 Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth
23 Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D.
24 Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and
25 P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New
26 York, NY, USA, 1029–1136. <http://www.climatechange2013.org/report/full-report/>
- 27 Comiso, J.C. and D.K. Hall, 2014: Climate trends in the Arctic as observed from space. *Wiley
28 Interdisciplinary Reviews: Climate Change*, **5**, 389-409. <http://dx.doi.org/10.1002/wcc.277>
- 29 Day, J.J., J.C. Hargreaves, J.D. Annan, and A. Abe-Ouchi, 2012: Sources of multi-decadal
30 variability in Arctic sea ice extent. *Environmental Research Letters*, **7**, 034011.
31 <http://dx.doi.org/10.1088/1748-9326/7/3/034011>
- 32 Derksen, C. and R. Brown, 2012: Snow [in Arctic Report Card 2012].
33 ftp://ftp.oar.noaa.gov/arctic/documents/ArcticReportCard_full_report2012.pdf

- 1 Derksen, C., R. Brown, L. Mudryk, and K. Luojus, 2015: Terrestrial snow cover [in Arctic
2 Report Card 2015].
3 ftp://ftp.oar.noaa.gov/arctic/documents/ArcticReportCard_full_report2015.pdf
- 4 Ding, Q., A. Schweiger, M. Lheureux, D.S. Battisti, S. Po-Chedley, N.C. Johnson, E. Blanchard-
5 Wrigglesworth, K. Harnos, Q. Zhang, R. Eastman, and E.J. Steig, 2017: Influence of high-
6 latitude atmospheric circulation changes on summertime Arctic sea ice. *Nature Climate*
7 *Change*, **7**, 289-295. <http://dx.doi.org/10.1038/nclimate3241>
- 8 Ding, Q., J.M. Wallace, D.S. Battisti, E.J. Steig, A.J.E. Gallant, H.-J. Kim, and L. Geng, 2014:
9 Tropical forcing of the recent rapid Arctic warming in northeastern Canada and Greenland.
10 *Nature*, **509**, 209-212. <http://dx.doi.org/10.1038/nature13260>
- 11 Döscher, R., T. Vihma, and E. Maksimovich, 2014: Recent advances in understanding the Arctic
12 climate system state and change from a sea ice perspective: A review. *Atmospheric*
13 *Chemistry and Physics*, **14**, 13571-13600. <http://dx.doi.org/10.5194/acp-14-13571-2014>
- 14 Dupont, T.K. and R.B. Alley, 2005: Assessment of the importance of ice-shelf buttressing to ice-
15 sheet flow. *Geophysical Research Letters*, **32**, n/a-n/a.
16 <http://dx.doi.org/10.1029/2004GL022024>
- 17 Euskirchen, E.S., A.P. Bennett, A.L. Breen, H. Genet, M.A. Lindgren, T.A. Kurkowski, A.D.
18 McGuire, and T.S. Rupp, 2016: Consequences of changes in vegetation and snow cover for
19 climate feedbacks in Alaska and northwest Canada. *Environmental Research Letters*, **11**,
20 105003. <http://dx.doi.org/10.1088/1748-9326/11/10/105003>
- 21 Fetterer, F., K. Knowles, W. Meier, and M. Savoie, 2016, updated daily: Sea Ice Index, Version
22 2. National Snow and Ice Data Center, Boulder, CO.
- 23 Fisher, J.B., M. Sikka, W.C. Oechel, D.N. Huntzinger, J.R. Melton, C.D. Koven, A. Ahlström,
24 M.A. Arain, I. Baker, J.M. Chen, P. Ciais, C. Davidson, M. Dietze, B. El-Masri, D. Hayes, C.
25 Huntingford, A.K. Jain, P.E. Levy, M.R. Lomas, B. Poulter, D. Price, A.K. Sahoo, K.
26 Schaefer, H. Tian, E. Tomelleri, H. Verbeeck, N. Viovy, R. Wania, N. Zeng, and C.E. Miller,
27 2014: Carbon cycle uncertainty in the Alaskan Arctic. *Biogeosciences*, **11**, 4271-4288.
28 <http://dx.doi.org/10.5194/bg-11-4271-2014>
- 29 Flannigan, M., B. Stocks, M. Turetsky, and M. Wotton, 2009: Impacts of climate change on fire
30 activity and fire management in the circumboreal forest. *Global Change Biology*, **15**, 549-
31 560. <http://dx.doi.org/10.1111/j.1365-2486.2008.01660.x>
- 32 Francis, J. and N. Skific, 2015: Evidence linking rapid Arctic warming to mid-latitude weather
33 patterns. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and*
34 *Engineering Sciences*, **373**. <http://dx.doi.org/10.1098/rsta.2014.0170>

- 1 Francis, J.A. and S.J. Vavrus, 2012: Evidence linking Arctic amplification to extreme weather in
2 mid-latitudes. *Geophysical Research Letters*, **39**, L06801.
3 <http://dx.doi.org/10.1029/2012GL051000>
- 4 Francis, J.A. and S.J. Vavrus, 2015: Evidence for a wavier jet stream in response to rapid Arctic
5 warming. *Environmental Research Letters*, **10**, 014005. [http://dx.doi.org/10.1088/1748-](http://dx.doi.org/10.1088/1748-9326/10/1/014005)
6 [9326/10/1/014005](http://dx.doi.org/10.1088/1748-9326/10/1/014005)
- 7 Francis, J.A., S.J. Vavrus, and J. Cohen, 2017: Amplified Arctic warming and mid-latitude
8 weather: New perspectives on emerging connections. *WIREs Climate Change*, e474.
9 <http://dx.doi.org/10.1002/wcc.474>
- 10 French, N.H.F., L.K. Jenkins, T.V. Loboda, M. Flannigan, R. Jandt, L.L. Bourgeau-Chavez, and
11 M. Whitley, 2015: Fire in arctic tundra of Alaska: Past fire activity, future fire potential, and
12 significance for land management and ecology. *International Journal of Wildland Fire*, **24**,
13 1045-1061. <http://dx.doi.org/10.1071/WF14167>
- 14 Friedlingstein, P., P. Cox, R. Betts, L. Bopp, W.v. Bloh, V. Brovkin, P. Cadule, S. Doney, M.
15 Eby, I. Fung, G. Bala, J. John, C. Jones, F. Joos, T. Kato, M. Kawamiya, W. Knorr, K.
16 Lindsay, H.D. Matthews, T. Raddatz, P. Rayner, C. Reick, E. Roeckner, K.-G. Schnitzler, R.
17 Schnur, K. Strassmann, A.J. Weaver, C. Yoshikawa, and N. Zeng, 2006: Climate–carbon
18 cycle feedback analysis: Results from the C⁴MIP model intercomparison. *Journal of Climate*,
19 **19**, 3337-3353. <http://dx.doi.org/10.1175/JCLI3800.1>
- 20 Gagné, M.È., N.P. Gillett, and J.C. Fyfe, 2015: Impact of aerosol emission controls on future
21 Arctic sea ice cover. *Geophysical Research Letters*, **42**, 8481-8488.
22 <http://dx.doi.org/10.1002/2015GL065504>
- 23 Gibbs, A.E. and B.M. Richmond, 2015: National Assessment of Shoreline Change: Historical
24 Shoreline Change Along the North Coast of Alaska, U.S.–Canadian Border to Icy Cape. U.S.
25 Geological Survey Open-File Report 2015–1048. U.S. Geological Survey, 96 pp.
26 <http://dx.doi.org/10.3133/ofr20151048>
- 27 Giles, K.A., S.W. Laxon, A.L. Ridout, D.J. Wingham, and S. Bacon, 2012: Western Arctic
28 Ocean freshwater storage increased by wind-driven spin-up of the Beaufort Gyre. *Nature*
29 *Geoscience*, **5**, 194-197. <http://dx.doi.org/10.1038/ngeo1379>
- 30 Gillett, N.P., D.A. Stone, P.A. Stott, T. Nozawa, A.Y. Karpechko, G.C. Hegerl, M.F. Wehner,
31 and P.D. Jones, 2008: Attribution of polar warming to human influence. *Nature Geoscience*,
32 **1**, 750-754. <http://dx.doi.org/10.1038/ngeo338>
- 33 Graverson, R.G., 2006: Do changes in the midlatitude circulation have any impact on the Arctic
34 surface air temperature trend? *Journal of Climate*, **19**, 5422-5438.
35 <http://dx.doi.org/10.1175/JCLI3906.1>

- 1 Graves, C.A., L. Steinle, G. Rehder, H. Niemann, D.P. Connelly, D. Lowry, R.E. Fisher, A.W.
2 Stott, H. Sahling, and R.H. James, 2015: Fluxes and fate of dissolved methane released at the
3 seafloor at the landward limit of the gas hydrate stability zone offshore western Svalbard.
4 *Journal of Geophysical Research: Oceans*, **120**, 6185-6201.
5 <http://dx.doi.org/10.1002/2015JC011084>
- 6 Grosse, G., S. Goetz, A.D. McGuire, V.E. Romanovsky, and E.A.G. Schuur, 2016: Changing
7 permafrost in a warming world and feedbacks to the Earth system. *Environmental Research*
8 *Letters*, **11**, 040201. <http://dx.doi.org/10.1088/1748-9326/11/4/040201>
- 9 Harig, C. and F.J. Simons, 2016: Ice mass loss in Greenland, the Gulf of Alaska, and the
10 Canadian Archipelago: Seasonal cycles and decadal trends. *Geophysical Research Letters*,
11 **43**, 3150-3159. <http://dx.doi.org/10.1002/2016GL067759>
- 12 Hartmann, B. and G. Wendler, 2005: The significance of the 1976 Pacific climate shift in the
13 climatology of Alaska. *Journal of Climate*, **18**, 4824-4839.
14 <http://dx.doi.org/10.1175/JCLI3532.1>
- 15 Hartmann, D.L., A.M.G. Klein Tank, M. Rusticucci, L.V. Alexander, S. Brönnimann, Y.
16 Charabi, F.J. Dentener, E.J. Dlugokencky, D.R. Easterling, A. Kaplan, B.J. Soden, P.W.
17 Thorne, M. Wild, and P.M. Zhai, 2013: Observations: Atmosphere and surface. *Climate*
18 *Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth*
19 *Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D.
20 Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and
21 P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New
22 York, NY, USA, 159–254. <http://www.climatechange2013.org/report/full-report/>
- 23 Holland, D.M., R.H. Thomas, B. de Young, M.H. Ribergaard, and B. Lyberth, 2008:
24 Acceleration of Jakobshavn Isbrae triggered by warm subsurface ocean waters. *Nature*
25 *Geoscience*, **1**, 659-664. <http://dx.doi.org/10.1038/ngeo316>
- 26 Hollesen, J., H. Matthiesen, A.B. Møller, and B. Elberling, 2015: Permafrost thawing in organic
27 Arctic soils accelerated by ground heat production. *Nature Climate Change*, **5**, 574-578.
28 <http://dx.doi.org/10.1038/nclimate2590>
- 29 Hoskins, B. and T. Woollings, 2015: Persistent extratropical regimes and climate extremes.
30 *Current Climate Change Reports*, **1**, 115-124. <http://dx.doi.org/10.1007/s40641-015-0020-8>
- 31 Howat, I.M., I. Joughin, M. Fahnestock, B.E. Smith, and T.A. Scambos, 2008: Synchronous
32 retreat and acceleration of southeast Greenland outlet glaciers 2000–06: Ice dynamics and
33 coupling to climate. *Journal of Glaciology*, **54**, 646-660.
34 <http://dx.doi.org/10.3189/002214308786570908>

- 1 Hu, F.S., P.E. Higuera, P. Duffy, M.L. Chipman, A.V. Rocha, A.M. Young, R. Kelly, and M.C.
2 Dietze, 2015: Arctic tundra fires: Natural variability and responses to climate change.
3 *Frontiers in Ecology and the Environment*, **13**, 369-377. <http://dx.doi.org/10.1890/150063>
- 4 Hunt, G.L., Jr., K.O. Coyle, L.B. Eisner, E.V. Farley, R.A. Heintz, F. Mueter, J.M. Napp, J.E.
5 Overland, P.H. Ressler, S. Salo, and P.J. Stabeno, 2011: Climate impacts on eastern Bering
6 Sea foodwebs: A synthesis of new data and an assessment of the Oscillating Control
7 Hypothesis. *ICES Journal of Marine Science*, **68**, 1230-1243.
8 <http://dx.doi.org/10.1093/icesjms/fsr036>
- 9 Hunter, S.J., D.S. Goldobin, A.M. Haywood, A. Ridgwell, and J.G. Rees, 2013: Sensitivity of
10 the global submarine hydrate inventory to scenarios of future climate change. *Earth and
11 Planetary Science Letters*, **367**, 105-115. <http://dx.doi.org/10.1016/j.epsl.2013.02.017>
- 12 Jahn, A., J.E. Kay, M.M. Holland, and D.M. Hall, 2016: How predictable is the timing of a
13 summer ice-free Arctic? *Geophysical Research Letters*, **43**, 9113-9120.
14 <http://dx.doi.org/10.1002/2016GL070067>
- 15 Johannessen, O.M., A. Korablev, V. Miles, M.W. Miles, and K.E. Solberg, 2011: Interaction
16 between the warm subsurface Atlantic water in the Sermilik Fjord and Helheim Glacier in
17 southeast Greenland. *Surveys in Geophysics*, **32**, 387-396. [http://dx.doi.org/10.1007/s10712-
18 011-9130-6](http://dx.doi.org/10.1007/s10712-011-9130-6)
- 19 Johannessen, O.M., S.I. Kuzmina, L.P. Bobylev, and M.W. Miles, 2016: Surface air temperature
20 variability and trends in the Arctic: New amplification assessment and regionalisation. *Tellus
21 A*, **68**. <http://dx.doi.org/10.3402/tellusa.v68.28234>
- 22 Joly, K., P.A. Duffy, and T.S. Rupp, 2012: Simulating the effects of climate change on fire
23 regimes in Arctic biomes: Implications for caribou and moose habitat. *Ecosphere*, **3**, 1-18.
24 <http://dx.doi.org/10.1890/ES12-00012.1>
- 25 Joughin, I., S.B. Das, M.A. King, B.E. Smith, I.M. Howat, and T. Moon, 2008: Seasonal speedup
26 along the western flank of the Greenland Ice Sheet. *Science*, **320**, 781-783.
27 <http://dx.doi.org/10.1126/science.1153288>
- 28 Jungclauss, J.H., K. Lohmann, and D. Zanchettin, 2014: Enhanced 20th-century heat transfer to
29 the Arctic simulated in the context of climate variations over the last millennium. *Climate of
30 the Past*, **10**, 2201-2213. <http://dx.doi.org/10.5194/cp-10-2201-2014>
- 31 Kasischke, E.S. and M.R. Turetsky, 2006: Recent changes in the fire regime across the North
32 American boreal region—Spatial and temporal patterns of burning across Canada and
33 Alaska. *Geophysical Research Letters*, **33**, n/a-n/a. <http://dx.doi.org/10.1029/2006GL025677>

- 1 Kay, J.E. and A. Gettelman, 2009: Cloud influence on and response to seasonal Arctic sea ice
2 loss. *Journal of Geophysical Research*, **114**, D18204.
3 <http://dx.doi.org/10.1029/2009JD011773>
- 4 Kay, J.E., K. Raeder, A. Gettelman, and J. Anderson, 2011a: The boundary layer response to
5 recent Arctic sea ice loss and implications for high-latitude climate feedbacks. *Journal of*
6 *Climate*, **24**, 428-447. <http://dx.doi.org/10.1175/2010JCLI3651.1>
- 7 Kay, J.E., M.M. Holland, and A. Jahn, 2011b: Inter-annual to multi-decadal Arctic sea ice extent
8 trends in a warming world. *Geophysical Research Letters*, **38**, L15708.
9 <http://dx.doi.org/10.1029/2011GL048008>
- 10 Kelly, R., M.L. Chipman, P.E. Higuera, I. Stefanova, L.B. Brubaker, and F.S. Hu, 2013: Recent
11 burning of boreal forests exceeds fire regime limits of the past 10,000 years. *Proceedings of*
12 *the National Academy of Sciences*, **110**, 13055-13060.
13 <http://dx.doi.org/10.1073/pnas.1305069110>
- 14 Kelly, R., H. Genet, A.D. McGuire, and F.S. Hu, 2016: Palaeodata-informed modelling of large
15 carbon losses from recent burning of boreal forests. *Nature Climate Change*, **6**, 79-82.
16 <http://dx.doi.org/10.1038/nclimate2832>
- 17 Khan, S.A., K.H. Kjaer, M. Bevis, J.L. Bamber, J. Wahr, K.K. Kjeldsen, A.A. Bjork, N.J.
18 Korsgaard, L.A. Stearns, M.R. van den Broeke, L. Liu, N.K. Larsen, and I.S. Muresan, 2014:
19 Sustained mass loss of the northeast Greenland ice sheet triggered by regional warming.
20 *Nature Climate Change*, **4**, 292-299. <http://dx.doi.org/10.1038/nclimate2161>
- 21 Kirchmeier-Young, M.C., F.W. Zwiers, and N.P. Gillett, 2017: Attribution of extreme events in
22 Arctic sea ice extent. *Journal of Climate*, **30**, 553-571. [http://dx.doi.org/10.1175/jcli-d-16-](http://dx.doi.org/10.1175/jcli-d-16-0412.1)
23 [0412.1](http://dx.doi.org/10.1175/jcli-d-16-0412.1)
- 24 Knies, J., P. Cabedo-Sanz, S.T. Belt, S. Baranwal, S. Fietz, and A. Rosell-Melé, 2014: The
25 emergence of modern sea ice cover in the Arctic Ocean. *Nature Communications*, **5**, 5608.
26 <http://dx.doi.org/10.1038/ncomms6608>
- 27 Köhl, A. and N. Serra, 2014: Causes of decadal changes of the freshwater content in the Arctic
28 Ocean. *Journal of Climate*, **27**, 3461-3475. <http://dx.doi.org/10.1175/JCLI-D-13-00389.1>
- 29 Kokelj, S.V., T.C. Lantz, J. Tunnicliffe, R. Segal, and D. Lacelle, 2017: Climate-driven thaw of
30 permafrost preserved glacial landscapes, northwestern Canada. *Geology*, **45**, 371-374.
31 <http://dx.doi.org/10.1130/g38626.1>
- 32 Koven, C.D., D.M. Lawrence, and W.J. Riley, 2015: Permafrost carbon–climate feedback is
33 sensitive to deep soil carbon decomposability but not deep soil nitrogen dynamics.

- 1 *Proceedings of the National Academy of Sciences*, **112**, 3752-3757.
2 <http://dx.doi.org/10.1073/pnas.1415123112>
- 3 Koven, C.D., E.A.G. Schuur, C. Schädel, T.J. Bohn, E.J. Burke, G. Chen, X. Chen, P. Ciais, G.
4 Grosse, J.W. Harden, D.J. Hayes, G. Hugelius, E.E. Jafarov, G. Krinner, P. Kuhry, D.M.
5 Lawrence, A.H. MacDougall, S.S. Marchenko, A.D. McGuire, S.M. Natali, D.J. Nicolsky, D.
6 Olefeldt, S. Peng, V.E. Romanovsky, K.M. Schaefer, J. Strauss, C.C. Treat, and M. Turetsky,
7 2015: A simplified, data-constrained approach to estimate the permafrost carbon–climate
8 feedback. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and*
9 *Engineering Sciences*, **373**. <http://dx.doi.org/10.1098/rsta.2014.0423>
- 10 Kretschmer, K., A. Biastoch, L. Rüpke, and E. Burwicz, 2015: Modeling the fate of methane
11 hydrates under global warming. *Global Biogeochemical Cycles*, **29**, 610–625.
12 <http://dx.doi.org/10.1002/2014GB005011>
- 13 Kunkel, K.E., D.A. Robinson, S. Champion, X. Yin, T. Estilow, and R.M. Frankson, 2016:
14 Trends and extremes in Northern Hemisphere snow characteristics. *Current Climate Change*
15 *Reports*, **2**, 65-73. <http://dx.doi.org/10.1007/s40641-016-0036-8>
- 16 Kwok, R. and N. Untersteiner, 2011: The thinning of Arctic sea ice. *Physics Today*, **64**, 36-41.
17 <http://dx.doi.org/10.1063/1.3580491>
- 18 Larsen, C.F., E. Burgess, A.A. Arendt, S. O'Neel, A.J. Johnson, and C. Kienholz, 2015: Surface
19 melt dominates Alaska glacier mass balance. *Geophysical Research Letters*, **42**, 5902-5908.
20 <http://dx.doi.org/10.1002/2015GL064349>
- 21 Lee, S., 2014: A theory for polar amplification from a general circulation perspective. *Asia-*
22 *Pacific Journal of Atmospheric Sciences*, **50**, 31-43. [http://dx.doi.org/10.1007/s13143-014-](http://dx.doi.org/10.1007/s13143-014-0024-7)
23 [0024-7](http://dx.doi.org/10.1007/s13143-014-0024-7)
- 24 Lee, S., T. Gong, N. Johnson, S.B. Feldstein, and D. Pollard, 2011: On the possible link between
25 tropical convection and the Northern Hemisphere Arctic surface air temperature change
26 between 1958 and 2001. *Journal of Climate*, **24**, 4350-4367.
27 <http://dx.doi.org/10.1175/2011JCLI4003.1>
- 28 Liljedahl, A.K., J. Boike, R.P. Daanen, A.N. Fedorov, G.V. Frost, G. Grosse, L.D. Hinzman, Y.
29 Iijma, J.C. Jorgenson, N. Matveyeva, M. Necsoiu, M.K. Raynolds, V.E. Romanovsky, J.
30 Schulla, K.D. Tape, D.A. Walker, C.J. Wilson, H. Yabuki, and D. Zona, 2016: Pan-Arctic
31 ice-wedge degradation in warming permafrost and its influence on tundra hydrology. *Nature*
32 *Geoscience*, **9**, 312-318. <http://dx.doi.org/10.1038/ngeo2674>
- 33 Lim, Y.-K., D.S. Siegfried, M.J.N. Sophie, N.L. Jae, M.M. Andrea, I.C. Richard, Z. Bin, and V.
34 Isabella, 2016: Atmospheric summer teleconnections and Greenland Ice Sheet surface mass

- 1 variations: Insights from MERRA-2. *Environmental Research Letters*, **11**, 024002.
2 <http://dx.doi.org/10.1088/1748-9326/11/2/024002>
- 3 Liu, W., S.-P. Xie, Z. Liu, and J. Zhu, 2017: Overlooked possibility of a collapsed Atlantic
4 Meridional Overturning Circulation in warming climate. *Science Advances*, **3**, e1601666.
5 <http://dx.doi.org/10.1126/sciadv.1601666>
- 6 Liu, Y. and J.R. Key, 2014: Less winter cloud aids summer 2013 Arctic sea ice return from 2012
7 minimum. *Environmental Research Letters*, **9**, 044002. [http://dx.doi.org/10.1088/1748-](http://dx.doi.org/10.1088/1748-9326/9/4/044002)
8 [9326/9/4/044002](http://dx.doi.org/10.1088/1748-9326/9/4/044002)
- 9 Manabe, S. and R.T. Wetherald, 1975: The effects of doubling the CO₂ concentration on the
10 climate of a General Circulation Model. *Journal of the Atmospheric Sciences*, **32**, 3-15.
11 [http://dx.doi.org/10.1175/1520-0469\(1975\)032<0003:teodtc>2.0.co;2](http://dx.doi.org/10.1175/1520-0469(1975)032<0003:teodtc>2.0.co;2)
- 12 Mao, J., A. Ribes, B. Yan, X. Shi, P.E. Thornton, R. Seferian, P. Ciais, R.B. Myneni, H.
13 Douville, S. Piao, Z. Zhu, R.E. Dickinson, Y. Dai, D.M. Ricciuto, M. Jin, F.M. Hoffman, B.
14 Wang, M. Huang, and X. Lian, 2016: Human-induced greening of the northern extratropical
15 land surface. *Nature Climate Change*, **6**, 959-963. <http://dx.doi.org/10.1038/nclimate3056>
- 16 Maslowski, W., J. Clement Kinney, M. Higgins, and A. Roberts, 2012: The future of Arctic sea
17 ice. *Annual Review of Earth and Planetary Sciences*, **40**, 625-654.
18 <http://dx.doi.org/10.1146/annurev-earth-042711-105345>
- 19 Maslowski, W., J. Clement Kinney, S.R. Okkonen, R. Osinski, A.F. Roberts, and W.J. Williams,
20 2014: The large scale ocean circulation and physical processes controlling Pacific-Arctic
21 interactions. *The Pacific Arctic Region: Ecosystem Status and Trends in a Rapidly Changing*
22 *Environment*. Grebmeier, M.J. and W. Maslowski, Eds. Springer Netherlands, Dordrecht,
23 101-132. http://dx.doi.org/10.1007/978-94-017-8863-2_5
- 24 Mathis, J.T., J.N. Cross, W. Evans, and S.C. Doney, 2015: Ocean acidification in the surface
25 waters of the Pacific–Arctic boundary regions. *Oceanography*, **28**, 122-135.
26 <http://dx.doi.org/10.5670/oceanog.2015.36>
- 27 Mathis, J.T., R.S. Pickart, R.H. Byrne, C.L. McNeil, G.W.K. Moore, L.W. Juranek, X. Liu, J.
28 Ma, R.A. Easley, M.M. Elliot, J.N. Cross, S.C. Reisdorph, F. Bahr, J. Morison, T.
29 Lichendorf, and R.A. Feely, 2012: Storm-induced upwelling of high pCO₂ waters onto the
30 continental shelf of the western Arctic Ocean and implications for carbonate mineral
31 saturation states. *Geophysical Research Letters*, **39**, L16703.
32 <http://dx.doi.org/10.1029/2012GL051574>
- 33 McAfee, S.A., 2014: Consistency and the lack thereof in Pacific decadal oscillation impacts on
34 North American winter climate. *Journal of Climate*, **27**, 7410-7431.
35 <http://dx.doi.org/10.1175/JCLI-D-14-00143.1>

- 1 McGuire, A.D., L.G. Anderson, T.R. Christensen, S. Dallimore, L. Guo, D.J. Hayes, M.
2 Heimann, T.D. Lorenson, R.W. MacDonald, and N. Roulet, 2009: Sensitivity of the carbon
3 cycle in the Arctic to climate change. *Ecological Monographs*, **79**, 523-555.
4 <http://dx.doi.org/10.1890/08-2025.1>
- 5 Melillo, J.M., T.C. Richmond, and G.W. Yohe, eds., 2014: *Climate Change Impacts in the*
6 *United States: The Third National Climate Assessment*. U.S. Global Change Research
7 Program: Washington, D.C., 842 pp. <http://dx.doi.org/10.7930/JOZ31WJ2>
- 8 Melillo, J.M., T.C. Richmond, and G.W. Yohe, eds., 2014: *Highlights of Climate Change*
9 *Impacts in the United States: The Third National Climate Assessment*. U.S. Global Change
10 Research Program: Washington, DC, 148 pp. <http://dx.doi.org/10.7930/JOH41PB6>
- 11 Mengel, M., A. Levermann, K. Frieler, A. Robinson, B. Marzeion, and R. Winkelmann, 2016:
12 Future sea level rise constrained by observations and long-term commitment. *Proceedings of*
13 *the National Academy of Sciences*, **113**, 2597-2602.
14 <http://dx.doi.org/10.1073/pnas.1500515113>
- 15 Mernild, S.H., J.K. Malmros, J.C. Yde, and N.T. Knudsen, 2012: Multi-decadal marine- and
16 land-terminating glacier recession in the Ammassalik region, southeast Greenland. *The*
17 *Cryosphere*, **6**, 625-639. <http://dx.doi.org/10.5194/tc-6-625-2012>
- 18 Min, S.-K., X. Zhang, F.W. Zwiers, and T. Agnew, 2008: Human influence on Arctic sea ice
19 detectable from early 1990s onwards. *Geophysical Research Letters*, **35**, L21701.
20 <http://dx.doi.org/10.1029/2008GL035725>
- 21 Mishra, U., J.D. Jastrow, R. Matamala, G. Hugelius, C.D. Koven, J.W. Harden, C.L. Ping, G.J.
22 Michaelson, Z. Fan, R.M. Miller, A.D. McGuire, C. Tarnocai, P. Kuhry, W.J. Riley, K.
23 Schaefer, E.A.G. Schuur, M.T. Jorgenson, and L.D. Hinzman, 2013: Empirical estimates to
24 reduce modeling uncertainties of soil organic carbon in permafrost regions: A review of
25 recent progress and remaining challenges. *Environmental Research Letters*, **8**, 035020.
26 <http://dx.doi.org/10.1088/1748-9326/8/3/035020>
- 27 Mishra, U. and W.J. Riley, 2012: Alaskan soil carbon stocks: Spatial variability and dependence
28 on environmental factors. *Biogeosciences*, **9**, 3637-3645. [http://dx.doi.org/10.5194/bg-9-](http://dx.doi.org/10.5194/bg-9-3637-2012)
29 [3637-2012](http://dx.doi.org/10.5194/bg-9-3637-2012)
- 30 Morison, J., R. Kwok, C. Peralta-Ferriz, M. Alkire, I. Rigor, R. Andersen, and M. Steele, 2012:
31 Changing Arctic Ocean freshwater pathways. *Nature*, **481**, 66-70.
32 <http://dx.doi.org/10.1038/nature10705>
- 33 Myers-Smith, I. H., J. W. Harden, M. Wilmsking, C. C. Fuller, A. D. McGuire, and F. S.
34 Chapin III, 2008. Wetland succession in a permafrost collapse: Interactions between fire
35 and thermokarst. *Biogeosciences* **5**, 1273–1286. <http://dx.doi.org/10.5194/bg-5-1273-2008>

- 1 Myers-Smith, I.H., B.C. Forbes, M. Wilking, M. Hallinger, T. Lantz, D. Blok, K.D. Tape, M.
2 Macias-Fauria, U. Sass-Klaassen, E. Lévesque, S. Boudreau, P. Ropars, L. Hermanutz, A.
3 Trant, L.S. Collier, S. Weijers, J. Rozema, S.A. Rayback, N.M. Schmidt, G. Schaeppman-
4 Strub, S. Wipf, C. Rixen, C.B. Ménard, S. Venn, S. Goetz, L. Andreu-Hayles, S. Elmendorf,
5 V. Ravolainen, J. Welker, P. Grogan, H.E. Epstein, and D.S. Hik, 2011: Shrub expansion in
6 tundra ecosystems: Dynamics, impacts and research priorities. *Environmental Research*
7 *Letters*, **6**, 045509. <http://dx.doi.org/10.1088/1748-9326/6/4/045509>
- 8 Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestedt, J. Huang, D. Koch, J.-F.
9 Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura, and H.
10 Zhang, 2013: Anthropogenic and natural radiative forcing. *Climate Change 2013: The*
11 *Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of*
12 *the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M.
13 Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds.
14 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 659–
15 740. <http://www.climatechange2013.org/report/full-report/>
- 16 Najafi, M.R., F.W. Zwiers, and N.P. Gillett, 2015: Attribution of Arctic temperature change to
17 greenhouse-gas and aerosol influences. *Nature Climate Change*, **5**, 246-249.
18 <http://dx.doi.org/10.1038/nclimate2524>
- 19 Notz, D. and J. Marotzke, 2012: Observations reveal external driver for Arctic sea-ice retreat.
20 *Geophysical Research Letters*, **39**, L08502. <http://dx.doi.org/10.1029/2012GL051094>
- 21 Notz, D. and J. Stroeve, 2016: Observed Arctic sea-ice loss directly follows anthropogenic CO₂
22 emission. *Science*, 354, 747-750. <http://dx.doi.org/10.1126/science.aag2345>
- 23 Nummelin, A., M. Ilicak, C. Li, and L.H. Smedsrud, 2016: Consequences of future increased
24 Arctic runoff on Arctic Ocean stratification, circulation, and sea ice cover. *Journal of*
25 *Geophysical Research: Oceans*, **121**, 617-637. <http://dx.doi.org/10.1002/2015JC011156>
- 26 Ogi, M. and I.G. Rigor, 2013: Trends in Arctic sea ice and the role of atmospheric circulation.
27 *Atmospheric Science Letters*, **14**, 97-101. <http://dx.doi.org/10.1002/asl2.423>
- 28 Ogi, M. and J.M. Wallace, 2007: Summer minimum Arctic sea ice extent and the associated
29 summer atmospheric circulation. *Geophysical Research Letters*, **34**, L12705.
30 <http://dx.doi.org/10.1029/2007GL029897>
- 31 Oh, Y., B. Stackhouse, M.C.Y. Lau, X. Xu, A.T. Trugman, J. Moch, T.C. Onstott, C.J.
32 Jørgensen, L. D'Imperio, B. Elberling, C.A. Emmerton, V.L. St. Louis, and D. Medvigy,
33 2016: A scalable model for methane consumption in Arctic mineral soils. *Geophysical*
34 *Research Letters*, **43**, 5143-5150. <http://dx.doi.org/10.1002/2016GL069049>

- 1 Overland, J., J.A. Francis, R. Hall, E. Hanna, S.-J. Kim, and T. Vihma, 2015: The melting Arctic
2 and midlatitude weather patterns: Are they connected? *Journal of Climate*, **28**, 7917-7932.
3 <http://dx.doi.org/10.1175/JCLI-D-14-00822.1>
- 4 Overland, J., E. Hanna, I. Hanssen-Bauer, S.-J. Kim, J. Walsh, M. Wang, and U. Bhatt, 2014: Air
5 temperature [in Arctic Report Card 2014].
6 ftp://ftp.oar.noaa.gov/arctic/documents/ArcticReportCard_full_report2014.pdf
- 7 Overland, J., E. Hanna, I. Hanssen-Bauer, S.-J. Kim, J. Walsh, M. Wang, U. Bhatt, and R.L.
8 Thoman, 2016: Surface air temperature [in Arctic Report Card 2016].
9 [http://arctic.noaa.gov/Report-Card/Report-Card-2016/ArtMID/5022/ArticleID/271/Surface-](http://arctic.noaa.gov/Report-Card/Report-Card-2016/ArtMID/5022/ArticleID/271/Surface-Air-Temperature)
10 [Air-Temperature](http://arctic.noaa.gov/Report-Card/Report-Card-2016/ArtMID/5022/ArticleID/271/Surface-Air-Temperature)
- 11 Overland, J., E. Hanna, I. Hanssen-Bauer, S.-J. Kim, J. Wlsh, M. Wang, and U.S. Bhatt, 2015:
12 [The Arctic] Arctic air temperature [in "State of the Climate in 2014"]. *Bulletin of the*
13 *American Meteorological Society*, **96 (12)**, S128-S129.
14 <http://dx.doi.org/10.1175/2015BAMSSStateoftheClimate.1>
- 15 Overland, J.E. and M. Wang, 2016: Recent extreme Arctic temperatures are due to a split polar
16 vortex. *Journal of Climate*, **29**, 5609-5616. <http://dx.doi.org/10.1175/JCLI-D-16-0320.1>
- 17 Park, H.-S., S. Lee, S.-W. Son, S.B. Feldstein, and Y. Kosaka, 2015: The impact of poleward
18 moisture and sensible heat flux on Arctic winter sea ice variability. *Journal of Climate*, **28**,
19 5030-5040. <http://dx.doi.org/10.1175/JCLI-D-15-0074.1>
- 20 Parkinson, C.L., 2014: Spatially mapped reductions in the length of the Arctic sea ice season.
21 *Geophysical Research Letters*, **41**, 4316-4322. <http://dx.doi.org/10.1002/2014GL060434>
- 22 Partain, J.L., Jr., S. Alden, U.S. Bhatt, P.A. Bieniek, B.R. Brettschneider, R. Lader, P.Q. Olsson,
23 T.S. Rupp, H. Strader, R.L.T. Jr., J.E. Walsh, A.D. York, and R.H. Zieh, 2016: An
24 assessment of the role of anthropogenic climate change in the Alaska fire season of 2015 [in
25 "Explaining Extreme Events of 2015 from a Climate Perspective"]. *Bulletin of the American*
26 *Meteorological Society*, **97 (12)**, S14-S18. <http://dx.doi.org/10.1175/BAMS-D-16-0149.1>
- 27 Pavelsky, T.M., J. Boé, A. Hall, and E.J. Fetzer, 2011: Atmospheric inversion strength over polar
28 oceans in winter regulated by sea ice. *Climate Dynamics*, **36**, 945-955.
29 <http://dx.doi.org/10.1007/s00382-010-0756-8>
- 30 Pelto, M.S., 2015: [Global Climate] Alpine glaciers [in "State of the Climate in 2014"]. *Bulletin*
31 *of the American Meteorological Society*, **96 (12)**, S19-S20.
32 <http://dx.doi.org/10.1175/2015BAMSSStateoftheClimate.1>

- 1 Perlwitz, J., M. Hoerling, and R. Dole, 2015: Arctic tropospheric warming: Causes and linkages
2 to lower latitudes. *Journal of Climate*, **28**, 2154-2167. [http://dx.doi.org/10.1175/JCLI-D-14-](http://dx.doi.org/10.1175/JCLI-D-14-00095.1)
3 [00095.1](http://dx.doi.org/10.1175/JCLI-D-14-00095.1)
- 4 Perovich, D., W. Meier, M. Tschudi, S. Farrell, S. Gerland, S. Hendricks, T. Krumpen, and C.
5 Hass, 2016: Sea ice [in Arctic Report Card 2016]. [http://www.arctic.noaa.gov/Report-](http://www.arctic.noaa.gov/Report-Card/Report-Card-2016/ArtMID/5022/ArticleID/286/Sea-Ice)
6 [Card/Report-Card-2016/ArtMID/5022/ArticleID/286/Sea-Ice](http://www.arctic.noaa.gov/Report-Card/Report-Card-2016/ArtMID/5022/ArticleID/286/Sea-Ice)
- 7 Piñero, E., M. Marquardt, C. Hensen, M. Haeckel, and K. Wallmann, 2013: Estimation of the
8 global inventory of methane hydrates in marine sediments using transfer functions.
9 *Biogeosciences*, **10**, 959-975. <http://dx.doi.org/10.5194/bg-10-959-2013>
- 10 Polyakov, I.V., A.V. Pnyushkov, and L.A. Timokhov, 2012: Warming of the intermediate
11 Atlantic water of the Arctic Ocean in the 2000s. *Journal of Climate*, **25**, 8362-8370.
12 <http://dx.doi.org/10.1175/JCLI-D-12-00266.1>
- 13 Rahmstorf, S., J.E. Box, G. Feulner, M.E. Mann, A. Robinson, S. Rutherford, and E.J.
14 Schaffernicht, 2015: Exceptional twentieth-century slowdown in Atlantic Ocean overturning
15 circulation. *Nature Climate Change*, **5**, 475-480. <http://dx.doi.org/10.1038/nclimate2554>
- 16 Rawlins, M.A., M. Steele, M.M. Holland, J.C. Adam, J.E. Cherry, J.A. Francis, P.Y. Groisman,
17 L.D. Hinzman, T.G. Huntington, D.L. Kane, J.S. Kimball, R. Kwok, R.B. Lammers, C.M.
18 Lee, D.P. Lettenmaier, K.C. McDonald, E. Podest, J.W. Pundsack, B. Rudels, M.C. Serreze,
19 A. Shiklomanov, Ø. Skagseth, T.J. Troy, C.J. Vörösmarty, M. Wensnahan, E.F. Wood, R.
20 Woodgate, D. Yang, K. Zhang, and T. Zhang, 2010: Analysis of the Arctic system for
21 freshwater cycle intensification: Observations and expectations. *Journal of Climate*, **23**,
22 [5715-5737](http://dx.doi.org/10.1175/2010JCLI3421.1). <http://dx.doi.org/10.1175/2010JCLI3421.1>
- 23 Rhein, M., S.R. Rintoul, S. Aoki, E. Campos, D. Chambers, R.A. Feely, S. Gulev, G.C. Johnson,
24 S.A. Josey, A. Kostianoy, C. Mauritzen, D. Roemmich, L.D. Talley, and F. Wang, 2013:
25 Observations: Ocean. *Climate Change 2013: The Physical Science Basis. Contribution of*
26 *Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate*
27 *Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A.
28 Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge,
29 United Kingdom and New York, NY, USA, 255–316.
30 <http://www.climatechange2013.org/report/full-report/>
- 31 Rignot, E., M. Koppes, and I. Velicogna, 2010: Rapid submarine melting of the calving faces of
32 West Greenland glaciers. *Nature Geoscience*, **3**, 187-191. <http://dx.doi.org/10.1038/ngeo765>
- 33 Rigor, I.G., J.M. Wallace, and R.L. Colony, 2002: Response of sea ice to the Arctic oscillation.
34 *Journal of Climate*, **15**, 2648-2663. [http://dx.doi.org/10.1175/1520-](http://dx.doi.org/10.1175/1520-0442(2002)015<2648:ROSITT>2.0.CO;2)
35 [0442\(2002\)015<2648:ROSITT>2.0.CO;2](http://dx.doi.org/10.1175/1520-0442(2002)015<2648:ROSITT>2.0.CO;2)

- 1 Romanovsky, V.E., S.L. Smith, H.H. Christiansen, N.I. Shiklomanov, D.A. Streletskiy, D.S.
2 Drozdov, G.V. Malkova, N.G. Oberman, A.L. Kholodov, and S.S. Marchenko, 2015: [The
3 Arctic] Terrestrial permafrost [in “State of the Climate in 2014”]. *Bulletin of the American*
4 *Meteorological Society*, **96** (12), S139-S141.
5 <http://dx.doi.org/10.1175/2015BAMSStateoftheClimate.1>
- 6 Romanovsky, V.E., S.L. Smith, K. Isaksen, N.I. Shiklomanov, D.A. Streletskiy, A.L. Kholodov,
7 H.H. Christiansen, D.S. Drozdov, G.V. Malkova, and S.S. Marchenko, 2016: [The Arctic]
8 Terrestrial permafrost [in “State of the Climate in 2015”]. *Bulletin of the American*
9 *Meteorological Society*, **97**, S149-S152.
10 <http://dx.doi.org/10.1175/2016BAMSStateoftheClimate.1>
- 11 Rupp, D.E., P.W. Mote, N.L. Bindoff, P.A. Stott, and D.A. Robinson, 2013: Detection and
12 attribution of observed changes in Northern Hemisphere spring snow cover. *Journal of*
13 *Climate*, **26**, 6904-6914. <http://dx.doi.org/10.1175/JCLI-D-12-00563.1>
- 14 Ruppel, C.D. *Methane hydrates and contemporary climate change*. Nature Education
15 Knowledge, 2011. **3**.
- 16 Ruppel, C.D. and J.D. Kessler, 2017: The interaction of climate change and methane hydrates.
17 *Reviews of Geophysics*, **55**, 126-168. <http://dx.doi.org/10.1002/2016RG000534>
- 18 Sanford, T., R. Wang, and A. Kenwa, 2015: *The Age of Alaskan Wildfires*. Climate Central,
19 Princeton, NJ, 32 pp. <http://assets.climatecentral.org/pdfs/AgeofAlaskanWildfires.pdf>
- 20 Schädel, C., M.K.F. Bader, E.A.G. Schuur, C. Biasi, R. Bracho, P. Capek, S. De Baets, K.
21 Diakova, J. Ernakovich, C. Estop-Aragones, D.E. Graham, I.P. Hartley, C.M. Iversen, E.
22 Kane, C. Knoblauch, M. Lupascu, P.J. Martikainen, S.M. Natali, R.J. Norby, J.A. O'Donnell,
23 T.R. Chowdhury, H. Santruckova, G. Shaver, V.L. Sloan, C.C. Treat, M.R. Turetsky, M.P.
24 Waldrop, and K.P. Wickland, 2016: Potential carbon emissions dominated by carbon dioxide
25 from thawed permafrost soils. *Nature Climate Change*, **6**, 950-953.
26 <http://dx.doi.org/10.1038/nclimate3054>
- 27 Schaefer, K., H. Lantuit, E.R. Vladimir, E.A.G. Schuur, and R. Witt, 2014: The impact of the
28 permafrost carbon feedback on global climate. *Environmental Research Letters*, **9**, 085003.
29 <http://dx.doi.org/10.1088/1748-9326/9/8/085003>
- 30 Schuur, E.A.G., A.D. McGuire, C. Schadel, G. Grosse, J.W. Harden, D.J. Hayes, G. Hugelius,
31 C.D. Koven, P. Kuhry, D.M. Lawrence, S.M. Natali, D. Olefeldt, V.E. Romanovsky, K.
32 Schaefer, M.R. Turetsky, C.C. Treat, and J.E. Vonk, 2015: Climate change and the
33 permafrost carbon feedback. *Nature*, **520**, 171-179. <http://dx.doi.org/10.1038/nature14338>

- 1 Schuur, E.A.G., J.G. Vogel, K.G. Crummer, H. Lee, J.O. Sickman, and T.E. Osterkamp, 2009:
2 The effect of permafrost thaw on old carbon release and net carbon exchange from tundra.
3 *Nature*, **459**, 556-559. <http://dx.doi.org/10.1038/nature08031>
- 4 Schweiger, A., R. Lindsay, J. Zhang, M. Steele, H. Stern, 2011: Uncertainty in modeled arctic
5 sea ice volume. *J. Geophys. Res.* 116, C00D06, <http://dx.doi.org/10.1029/2011JC007084>
- 6 Screen, J.A., C. Deser, and I. Simmonds, 2012: Local and remote controls on observed Arctic
7 warming. *Geophysical Research Letters*, **39**, L10709.
8 <http://dx.doi.org/10.1029/2012GL051598>
- 9 Screen, J.A., C. Deser, and L. Sun, 2015: Reduced risk of North American cold extremes due to
10 continued Arctic sea ice loss. *Bulletin of the American Meteorological Society*, **96** (12),
11 1489-1503. <http://dx.doi.org/10.1175/BAMS-D-14-00185.1>
- 12 Screen, J.A., C. Deser, and L. Sun, 2015: Projected changes in regional climate extremes arising
13 from Arctic sea ice loss. *Environmental Research Letters*, **10**, 084006.
14 <http://dx.doi.org/10.1088/1748-9326/10/8/084006>
- 15 Screen, J.A. and J.A. Francis, 2016: Contribution of sea-ice loss to Arctic amplification is
16 regulated by Pacific Ocean decadal variability. *Nature Climate Change*, **6**, 856-860.
17 <http://dx.doi.org/10.1038/nclimate3011>
- 18 Screen, J.A. and I. Simmonds, 2010: The central role of diminishing sea ice in recent Arctic
19 temperature amplification. *Nature*, **464**, 1334-1337. <http://dx.doi.org/10.1038/nature09051>
- 20 Seager, R., M. Hoerling, S. Schubert, H. Wang, B. Lyon, A. Kumar, J. Nakamura, and N.
21 Henderson, 2015: Causes of the 2011–14 California drought. *Journal of Climate*, **28**, 6997-
22 7024. <http://dx.doi.org/10.1175/JCLI-D-14-00860.1>
- 23 Serreze, M.C., A.P. Barrett, J.C. Stroeve, D.N. Kindig, and M.M. Holland, 2009: The emergence
24 of surface-based Arctic amplification. *The Cryosphere*, **3**, 11-19.
25 <http://dx.doi.org/10.5194/tc-3-11-2009>
- 26 Sharp, M., G. Wolken, D. Burgess, J.G. Cogley, L. Copland, L. Thomson, A. Arendt, B.
27 Wouters, J. Kohler, L.M. Andreassen, S. O’Neel, and M. Pelto, 2015: [Global Climate]
28 Glaciers and ice caps outside Greenland [in “State of the Climate in 2014”]. *Bulletin of the*
29 *American Meteorological Society*, **96** (12), S135-S137.
30 <http://dx.doi.org/10.1175/2015BAMSSStateoftheClimate.1>
- 31 Shiklomanov, N.E., D.A. Streletskiy, and F.E. Nelson, 2012: Northern Hemisphere component
32 of the global Circumpolar Active Layer Monitory (CALM) program. In *Proceedings of the*
33 *10th International Conference on Permafrost*, Salekhard, Russia. Kane, D.L. and K.M.
34 Hinkel, Eds., 377-382. http://research.iarc.uaf.edu/NICOP/proceedings/10th/TICOP_vol1.pdf

- 1 Sigmond, M. and J.C. Fyfe, 2016: Tropical Pacific impacts on cooling North American winters.
2 *Nature Climate Change*, **6**, 970-974. <http://dx.doi.org/10.1038/nclimate3069>
- 3 Smedsrud, L.H., M.H. Halvorsen, J.C. Stroeve, R. Zhang, and K. Kloster, 2017: Fram Strait sea
4 ice export variability and September Arctic sea ice extent over the last 80 years. *The*
5 *Cryosphere*, **11**, 65-79. <http://dx.doi.org/10.5194/tc-11-65-2017>
- 6 Smeed, D.A., G.D. McCarthy, S.A. Cunningham, E. Frajka-Williams, D. Rayner, W.E. Johns,
7 C.S. Meinen, M.O. Baringer, B.I. Moat, A. Ducez, and H.L. Bryden, 2014: Observed
8 decline of the Atlantic meridional overturning circulation 2004–2012. *Ocean Science*, **10**, 29-
9 38. <http://dx.doi.org/10.5194/os-10-29-2014>
- 10 Snape, T.J. and P.M. Forster, 2014: Decline of Arctic sea ice: Evaluation and weighting of
11 CMIP5 projections. *Journal of Geophysical Research: Atmospheres*, **119**, 546-554.
12 <http://dx.doi.org/10.1002/2013JD020593>
- 13 Solomon, A., M.D. Shupe, O. Persson, H. Morrison, T. Yamaguchi, P.M. Caldwell, and G.d.
14 Boer, 2014: The sensitivity of springtime Arctic mixed-phase stratocumulus clouds to
15 surface-layer and cloud-top inversion-layer moisture sources. *Journal of the Atmospheric*
16 *Sciences*, **71**, 574-595. <http://dx.doi.org/10.1175/JAS-D-13-0179.1>
- 17 Spielhagen, R.F., K. Werner, S.A. Sørensen, K. Zamelczyk, E. Kandiano, G. Budeus, K. Husum,
18 T.M. Marchitto, and M. Hald, 2011: Enhanced modern heat transfer to the Arctic by warm
19 Atlantic water. *Science*, **331**, 450-453. <http://dx.doi.org/10.1126/science.1197397>
- 20 Stabeno, P.J., E.V. Farley, Jr., N.B. Kachel, S. Moore, C.W. Mordy, J.M. Napp, J.E. Overland,
21 A.I. Pinchuk, and M.F. Sigler, 2012: A comparison of the physics of the northern and
22 southern shelves of the eastern Bering Sea and some implications for the ecosystem. *Deep*
23 *Sea Research Part II: Topical Studies in Oceanography*, **65-70**, 14-30.
24 <http://dx.doi.org/10.1016/j.dsr2.2012.02.019>
- 25 Straneo, F., R.G. Curry, D.A. Sutherland, G.S. Hamilton, C. Cenedese, K. Vage, and L.A.
26 Stearns, 2011: Impact of fjord dynamics and glacial runoff on the circulation near Helheim
27 Glacier. *Nature Geoscience*, **4**, 322-327. <http://dx.doi.org/10.1038/ngeo1109>
- 28 Straneo, F., G.S. Hamilton, D.A. Sutherland, L.A. Stearns, F. Davidson, M.O. Hammill, G.B.
29 Stenson, and A. Rosing-Asvid, 2010: Rapid circulation of warm subtropical waters in a
30 major glacial fjord in East Greenland. *Nature Geoscience*, **3**, 182-186.
31 <http://dx.doi.org/10.1038/ngeo764>
- 32 Stroeve, J., A. Barrett, M. Serreze, and A. Schweiger, 2014: Using records from submarine,
33 aircraft and satellites to evaluate climate model simulations of Arctic sea ice thickness. *The*
34 *Cryosphere*, **8**, 1839-1854. <http://dx.doi.org/10.5194/tc-8-1839-2014>

- 1 Stroeve, J., M.M. Holland, W. Meier, T. Scambos, and M. Serreze, 2007: Arctic sea ice decline:
2 Faster than forecast. *Geophysical Research Letters*, **34**, L09501.
3 <http://dx.doi.org/10.1029/2007GL029703>
- 4 Stroeve, J. and D. Notz, 2015: Insights on past and future sea-ice evolution from combining
5 observations and models. *Global and Planetary Change*, **135**, 119-132.
6 <http://dx.doi.org/10.1016/j.gloplacha.2015.10.011>
- 7 Stroeve, J.C., V. Kattsov, A. Barrett, M. Serreze, T. Pavlova, M. Holland, and W.N. Meier,
8 2012: Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations. *Geophysical*
9 *Research Letters*, **39**, L16502. <http://dx.doi.org/10.1029/2012GL052676>
- 10 Stroeve, J.C., T. Markus, L. Boisvert, J. Miller, and A. Barrett, 2014: Changes in Arctic melt
11 season and implications for sea ice loss. *Geophysical Research Letters*, **41**, 1216-1225.
12 <http://dx.doi.org/10.1002/2013GL058951>
- 13 Stroeve, J.C., M.C. Serreze, M.M. Holland, J.E. Kay, J. Malanik, and A.P. Barrett, 2012: The
14 Arctic's rapidly shrinking sea ice cover: A research synthesis. *Climatic Change*, **110**, 1005-
15 1027. <http://dx.doi.org/10.1007/s10584-011-0101-1>
- 16 Sun, L., J. Perlwitz, and M. Hoerling, 2016: What caused the recent "Warm Arctic, Cold
17 Continents" trend pattern in winter temperatures? *Geophysical Research Letters*, **43**, 5345-
18 5352. <http://dx.doi.org/10.1002/2016GL069024>
- 19 Swain, D., M. Tsiang, M. Haughen, D. Singh, A. Charland, B. Rajarthan, and N.S. Diffenbaugh,
20 2014: The extraordinary California drought of 2013/14: Character, context and the role of
21 climate change [in "Explaining Extreme Events of 2013 from a Climate Perspective"].
22 *Bulletin of the American Meteorological Society*, **95** (9), S3-S6.
23 <http://dx.doi.org/10.1175/1520-0477-95.9.S1.1>
- 24 Swanson, D. K., 1996: Susceptibility of permafrost soils to deep thaw after forest fires in
25 Interior Alaska, USA, and some ecological implications. *Arct Antarct Alp Res.*, **28**, 217-
26 227. <http://dx.doc.org/10.2307/1551763>.
- 27 Swart, N.C., J.C. Fyfe, E. Hawkins, J.E. Kay, and A. Jahn, 2015: Influence of internal variability
28 on Arctic sea-ice trends. *Nature Climate Change*, **5**, 86-89.
29 <http://dx.doi.org/10.1038/nclimate2483>
- 30 Tarnocai, C., J.G. Canadell, E.A.G. Schuur, P. Kuhry, G. Mazhitova, and S. Zimov, 2009: Soil
31 organic carbon pools in the northern circumpolar permafrost region. *Global Biogeochemical*
32 *Cycles*, **23**, GB2023. <http://dx.doi.org/10.1029/2008GB003327>

- 1 Taylor, P.C., M. Cai, A. Hu, J. Meehl, W. Washington, and G.J. Zhang, 2013: A decomposition
2 of feedback contributions to polar warming amplification. *Journal of Climate*, **26**, 7023-
3 7043. <http://dx.doi.org/10.1175/JCLI-D-12-00696.1>
- 4 Taylor, P.C., R.G. Ellingson, and M. Cai, 2011: Geographical distribution of climate feedbacks
5 in the NCAR CCSM3.0. *Journal of Climate*, **24**, 2737-2753.
6 <http://dx.doi.org/10.1175/2010JCLI3788.1>
- 7 Taylor, P.C., R.G. Ellingson, and M. Cai, 2011: Seasonal variations of climate feedbacks in the
8 NCAR CCSM3. *Journal of Climate*, **24**, 3433-3444.
9 <http://dx.doi.org/10.1175/2011jcli3862.1>
- 10 Taylor, P.C., S. Kato, K.-M. Xu, and M. Cai, 2015: Covariance between Arctic sea ice and
11 clouds within atmospheric state regimes at the satellite footprint level. *Journal of*
12 *Geophysical Research: Atmospheres*, **120**, 12656-12678.
13 <http://dx.doi.org/10.1002/2015JD023520>
- 14 Tedesco, M., T. Mote, X. Fettweis, E. Hanna, J. Jeyaratnam, J.F. Booth, R. Datta, and K. Briggs,
15 2016: Arctic cut-off high drives the poleward shift of a new Greenland melting record.
16 *Nature Communications*, **7**, 11723. <http://dx.doi.org/10.1038/ncomms11723>
- 17 Teng, H. and G. Branstator, 2017: Causes of extreme ridges that induce California droughts.
18 *Journal of Climate*, **30**, 1477-1492. <http://dx.doi.org/10.1175/jcli-d-16-0524.1>
- 19 Timmermans, M.-L. and A. Proshutinsky, 2015: [The Arctic] Sea surface temperature [in “State
20 of the Climate in 2014”]. *Bulletin of the American Meteorological Society*, **96** (12), S147-
21 S148. <http://dx.doi.org/10.1175/2015BAMSStateoftheClimate.1>
- 22 Treat, C.C., S.M. Natali, J. Ernakovich, C.M. Iversen, M. Lupascu, A.D. McGuire, R.J. Norby,
23 T. Roy Chowdhury, A. Richter, H. Šantrůčková, C. Schädel, E.A.G. Schuur, V.L. Sloan,
24 M.R. Turetsky, and M.P. Waldrop, 2015: A pan-Arctic synthesis of CH₄ and CO₂ production
25 from anoxic soil incubations. *Global Change Biology*, **21**, 2787-2803.
26 <http://dx.doi.org/10.1111/gcb.12875>
- 27 Tschudi, M., C. Fowler, J. Maslanik, J.S. Stewart, and W. Meier, 2016: EASE-Grid Sea Ice Age,
28 Version 3. In: NASA (ed.). National Snow and Ice Data Center Distributed Active Archive
29 Center, Boulder, CO.
- 30 USGS 2004, Department of the Interior, U.S. Geological Survey, photo by Bruce F. Molnia.
31 https://www2.usgs.gov/climate_landuse/glaciers/repeat_photography.asp
- 32 van den Broeke, M., J. Bamber, J. Ettema, E. Rignot, E. Schrama, W.J. van de Berg, E. van
33 Meijgaard, I. Velicogna, and B. Wouters, 2009: Partitioning recent Greenland mass loss.
34 *Science*, **326**, 984-986. <http://dx.doi.org/10.1126/science.1178176>

- 1 Vaughan, D.G., J.C. Comiso, I. Allison, J. Carrasco, G. Kaser, R. Kwok, P. Mote, T. Murray, F.
2 Paul, J. Ren, E. Rignot, O. Solomina, K. Steffen, and T. Zhang, 2013: Observations:
3 Cryosphere. *Climate Change 2013: The Physical Science Basis. Contribution of Working*
4 *Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.*
5 Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia,
6 V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom
7 and New York, NY, USA, 317–382. <http://www.climatechange2013.org/report/full-report/>
- 8 Velicogna, I., 2009: Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets
9 revealed by GRACE. *Geophysical Research Letters*, **36**, L19503.
10 <http://dx.doi.org/10.1029/2009GL040222>
- 11 Vihma, T., 2014: Effects of Arctic sea ice decline on weather and climate: A review. *Surveys in*
12 *Geophysics*, **35**, 1175-1214. <http://dx.doi.org/10.1007/s10712-014-9284-0>
- 13 Vinnikov, K.Y., A. Robock, R.J. Stouffer, J.E. Walsh, C.L. Parkinson, D.J. Cavalieri, J.F.B.
14 Mitchell, D. Garrett, and V.F. Zakharov, 1999: Global warming and Northern Hemisphere
15 sea ice extent. *Science*, **286**, 1934-1937. <http://dx.doi.org/10.1126/science.286.5446.1934>
- 16 Wang, M. and J.E. Overland, 2012: A sea ice free summer Arctic within 30 years: An update
17 from CMIP5 models. *Geophysical Research Letters*, **39**, L18501.
18 <http://dx.doi.org/10.1029/2012GL052868>
- 19 Wendler, G., B. Moore, and K. Galloway, 2014: Strong temperature increase and shrinking sea
20 ice in Arctic Alaska. *The Open Atmospheric Science Journal*, **8**, 7-15.
21 <http://dx.doi.org/10.2174/1874282301408010007>
- 22 Wettstein, J.J. and C. Deser, 2014: Internal variability in projections of twenty-first-century
23 Arctic sea ice loss: Role of the large-scale atmospheric circulation. *Journal of Climate*, **27**,
24 527-550. <http://dx.doi.org/10.1175/JCLI-D-12-00839.1>
- 25 WGMS, 2016: Fluctuations of Glaciers Database. World Glacier Monitoring Service, Zurich,
26 Switzerland.
- 27 Wolken, G., M. Sharp, L.M. Andreassen, A. Arendt, D. Burgess, J.G. Cogley, L. Copland, J.
28 Kohler, S. O’Neel, M. Pelto, L. Thomson, and B. Wouters, 2016: [The Arctic] Glaciers and
29 ice caps outside Greenland [in “State of the Climate in 2015”]. *Bulletin of the American*
30 *Meteorological Society*, **97**, S142-S145.
31 <http://dx.doi.org/10.1175/2016BAMSSStateoftheClimate.1>
- 32 Woods, C. and R. Caballero, 2016: The role of moist intrusions in winter Arctic warming and sea
33 ice decline. *Journal of Climate*, **29**, 4473-4485. <http://dx.doi.org/10.1175/jcli-d-15-0773.1>

- 1 Wyser, K., C.G. Jones, P. Du, E. Girard, U. Willén, J. Cassano, J.H. Christensen, J.A. Curry, K.
2 Dethloff, J.-E. Haugen, D. Jacob, M. Køltzow, R. Laprise, A. Lynch, S. Pfeifer, A. Rinke, M.
3 Serreze, M.J. Shaw, M. Tjernström, and M. Zagar, 2008: An evaluation of Arctic cloud and
4 radiation processes during the SHEBA year: Simulation results from eight Arctic regional
5 climate models. *Climate Dynamics*, **30**, 203-223. [http://dx.doi.org/10.1007/s00382-007-](http://dx.doi.org/10.1007/s00382-007-0286-1)
6 [0286-1](http://dx.doi.org/10.1007/s00382-007-0286-1)
- 7 Yang, Q., T.H. Dixon, P.G. Myers, J. Bonin, D. Chambers, and M.R. van den Broeke, 2016:
8 Recent increases in Arctic freshwater flux affects Labrador Sea convection and Atlantic
9 overturning circulation. *Nature Communications*, **7**, 10525.
10 <http://dx.doi.org/10.1038/ncomms10525>
- 11 Yoshikawa, K., W. R. Bolton, V. E. Romanovsky, M. Fukuda, and L. D. Hinzman, 2003:
12 Impacts of wildfire on the permafrost in the boreal forests of Interior Alaska. *J. Geophys.*
13 *Res.*, **107**, 8148. <http://dx.doi.org/10.1029/2001JD000438> 2002.
- 14 Young, A.M., P.E. Higuera, P.A. Duffy, and F.S. Hu, 2016: Climatic thresholds shape northern
15 high-latitude fire regimes and imply vulnerability to future climate change. *Ecography*,
16 **Early view**. <http://dx.doi.org/10.1111/ecog.02205>
- 17 Zemp, M., H. Frey, I. Gärtner-Roer, S.U. Nussbaumer, M. Hoelzle, F. Paul, W. Haeberli, F.
18 Denzinger, A.P. Ahlstrøm, B. Anderson, S. Bajracharya, C. Baroni, L.N. Braun, B.E.
19 Cáceres, G. Casassa, G. Cobos, L.R. Dávila, H. Delgado Granados, M.N. Demuth, L.
20 Espizua, A. Fischer, K. Fujita, B. Gadek, A. Ghazanfar, J.O. Hagen, P. Holmlund, N. Karimi,
21 Z. Li, M. Pelto, P. Pitte, V.V. Popovnin, C.A. Portocarrero, R. Prinz, C.V. Sangewar, I.
22 Severskiy, O. Sigurdsson, A. Soruco, R. Usubaliev, and C. Vincent, 2015: Historically
23 unprecedented global glacier decline in the early 21st century. *Journal of Glaciology*, **61**,
24 745-762. <http://dx.doi.org/10.3189/2015JoG15J017>
- 25 Zhang, R. and T.R. Knutson, 2013: The role of global climate change in the extreme low
26 summer Arctic sea ice extent in 2012 [in "Explaining Extreme Events of 2012 from a
27 Climate Perspective"]. *Bulletin of the American Meteorological Society*, **94** (9), S23-S26.
28 <http://dx.doi.org/10.1175/BAMS-D-13-00085.1>
- 29 Zona, D., B. Gioli, R. Commane, J. Lindaas, S.C. Wofsy, C.E. Miller, S.J. Dinardo, S. Dengel,
30 C. Sweeney, A. Karion, R.Y.-W. Chang, J.M. Henderson, P.C. Murphy, J.P. Goodrich, V.
31 Moreaux, A. Liljedahl, J.D. Watts, J.S. Kimball, D.A. Lipson, and W.C. Oechel, 2016: Cold
32 season emissions dominate the Arctic tundra methane budget. *Proceedings of the National*
33 *Academy of Sciences*, **113**, 40-45. <http://dx.doi.org/10.1073/pnas.1516017113>
- 34

12. Sea Level Rise

KEY FINDINGS

1. Global mean sea level (GMSL) has risen by about 7–8 inches (about 16–21 cm) since 1900, with about 3 of those inches (about 7 cm) occurring since 1993 (*very high confidence*). Human-caused climate change has made a substantial contribution to GMSL rise since 1900 (*high confidence*), contributing to a rate of rise that is greater than during any preceding century in at least 2,800 years (*medium confidence*).
2. Relative to the year 2000, GMSL is *very likely* to rise by 0.3–0.6 feet (9–18 cm) by 2030, 0.5–1.2 feet (15–38 cm) by 2050, and 1 to 4 feet (30–130 cm) by 2100 (*very high confidence in lower bounds; medium confidence in upper bounds for 2030 and 2050; low confidence in upper bounds for 2100*). Future emissions pathways have little effect on projected GMSL rise in the first half of the century, but significantly affect projections for the second half of the century (*high confidence*). Emerging science regarding Antarctic ice sheet stability suggests that, for high emission scenarios, a GMSL rise exceeding 8 feet (2.4 m) by 2100 is physically possible, although the probability of such an extreme outcome cannot currently be assessed. Regardless of emissions pathway, it is *extremely likely* that GMSL rise will continue beyond 2100 (*high confidence*).
3. Relative sea level (RSL) rise in this century will vary along U.S. coastlines due, in part, to changes in Earth’s gravitational field and rotation from melting of land ice, changes in ocean circulation, and vertical land motion (*very high confidence*). For almost all future GMSL rise scenarios, RSL rise is *likely* to be greater than the global average in the U.S. Northeast and the western Gulf of Mexico. In intermediate and low GMSL rise scenarios, RSL rise is *likely* to be less than the global average in much of the Pacific Northwest and Alaska. For high GMSL rise scenarios, RSL rise is *likely* to be higher than the global average along all U.S. coastlines outside Alaska. Almost all U.S. coastlines experience more than global mean sea level rise in response to Antarctic ice loss, and thus would be particularly affected under extreme GMSL rise scenarios involving substantial Antarctic mass loss (*high confidence*).
4. As sea levels have risen, the number of tidal floods each year that cause minor impacts (also called “nuisance floods”) have increased 5- to 10-fold since the 1960s in several U.S. coastal cities (*very high confidence*). Rates of increase are accelerating in over 25 Atlantic and Gulf Coast cities (*very high confidence*). Tidal flooding will continue increasing in depth, frequency, and extent this century (*very high confidence*).
5. Assuming storm characteristics do not change, sea level rise will increase the frequency and extent of extreme flooding associated with coastal storms, such as hurricanes and nor’easters (*very high confidence*). A projected increase in the intensity of hurricanes in the North Atlantic could increase the probability of extreme flooding along most of the U.S. Atlantic

1 and Gulf Coast states beyond what would be projected based solely on RSL rise. However,
2 there is *low confidence* in the magnitude of the increase in intensity and the associated flood
3 risk amplification, and these effects could be offset or amplified by other factors, such as
4 changes in storm frequency or tracks.

5 **12.1 Introduction**

6 Sea level rise is closely linked to increasing global temperatures. Thus, even as uncertainties
7 remain about just how much sea level may rise this century, it is virtually certain that sea level
8 rise this century and beyond will pose a growing challenge to coastal communities,
9 infrastructure, and ecosystems from increased (permanent) inundation, more frequent and
10 extreme coastal flooding, erosion of coastal landforms, and saltwater intrusion within coastal
11 rivers and aquifers. Assessment of vulnerability to rising sea levels requires consideration of
12 physical causes, historical evidence, and projections. A risk-based perspective on sea level rise
13 points to the need for emphasis on how changing sea levels alter the coastal zone and interact
14 with coastal flood risk at local scales.

15 This chapter reviews the physical factors driving global and regional sea level changes. It
16 presents geological and instrumental observations of historical sea level changes and an
17 assessment of the human contribution to sea level change. It then describes a range of scenarios
18 for future levels and rates of sea level change, and the relationship of these scenarios to the
19 Representative Concentration Pathways (RCPs). Finally, it assesses the impact of changes in sea
20 level on extreme water levels.

21 While outside the scope of this chapter, it is important to note the myriad of other potential
22 impacts associated with relative sea level (RSL) rise, wave action, and increases in coastal
23 flooding. These impacts include loss of life, damage to infrastructure and the built environment,
24 salinization of coastal aquifers, mobilization of pollutants, changing sediment budgets, coastal
25 erosion, and ecosystem changes such as marsh loss and threats to endangered flora and fauna
26 (Wong et al. 2014). While all of these impacts are inherently important, some also have the
27 potential to influence local rates of RSL rise and the extent of wave-driven and coastal flooding
28 impacts. For example, there is evidence that wave action and flooding of beaches and marshes
29 can induce changes in coastal geomorphology, such as sediment build up, that may iteratively
30 modify the future flood risk profile of communities and ecosystems (Lentz et al. 2016).

31 **12.2 Physical Factors Contributing to Sea Level Rise**

32 Sea level change is driven by a variety of mechanisms operating at different spatial and temporal
33 scales (see Kopp et al. 2015a for a review). Global mean sea level (GMSL) rise is primarily
34 driven by two factors: 1) increased volume of seawater due to thermal expansion of the ocean as
35 it warms, and 2) increased mass of water in the ocean due to melting ice from mountain glaciers
36 and the Antarctic and Greenland ice sheets (Church et al. 2013). The overall amount (mass) of
37 ocean water, and thus sea level, is also affected to a lesser extent by changes in global land-water

1 storage, which reflects changes in the impoundment of water in dams and reservoirs and river
2 runoff from groundwater extraction, inland sea and wetland drainage, and global precipitation
3 patterns, such as occurs during phases of the El Niño–Southern Oscillation (ENSO) (Church et
4 al. 2013; Reager et al. 2016; Rietbroek et al. 2016; Wada et al. 2016, 2017).

5 Sea level and its changes are not uniform globally for several reasons. First, atmosphere–ocean
6 dynamics—driven by ocean circulation, winds, and other factors—are associated with
7 differences in the height of the sea surface, as are differences in density arising from the
8 distribution of heat and salinity in the ocean. Changes in any of these factors will affect sea
9 surface height. For example, a weakening of the Gulf Stream transport in the mid-to-late 2000s
10 may have contributed to enhanced sea level rise in the ocean environment extending to the
11 northeastern U.S. coast (Boon 2012; Sallenger et al. 2012; Ezer 2013), a trend that many models
12 project will continue into the future (Yin and Goddard 2013).

13 Second, the locations of land ice melting and land water reservoir changes impart distinct
14 regional “static-equilibrium fingerprints” on sea level, based on gravitational, rotational, and
15 crustal deformation effects (Mitrovica et al. 2011) (Figure 12.1a–d). For example, sea level falls
16 near a melting ice sheet because of the reduced gravitational attraction of the ocean toward the
17 ice sheet; reciprocally, it rises by greater than the global average far from the melting ice sheet.

18 Third, the Earth’s mantle is still moving in response to the loss of the great North American
19 (Laurentide) and European ice sheets of the Last Glacial Maximum; the associated changes in
20 the height of the land, the shape of the ocean basin, and the Earth’s gravitational field give rise to
21 glacial-isostatic adjustment (Figure 12.1e). For example, in areas once covered by the thickest
22 parts of the great ice sheets of the Last Glacial Maximum, such as in Hudson Bay and in
23 Scandinavia, post-glacial rebound of the land is causing relative sea level (RSL) to fall. Along
24 the flanks of the ice sheets, such as along most of the east coast of the United States, subsidence
25 of the bulge that flanked the ice sheet is causing RSL to rise.

26 Finally, a variety of other factors can cause local vertical land movement. These include natural
27 sediment compaction, compaction caused by local extraction of groundwater and fossil fuels, and
28 processes related to plate tectonics, such as earthquakes and more gradual seismic creep (Zervas
29 et al. 2013; Wöppelmann and Marcos 2016) (Figure 12.1f).

30 Compared to many climate variables, the trend signal for sea level change tends to be large
31 relative to natural variability. However, at interannual timescales, changes in ocean dynamics,
32 density, and wind can cause substantial sea level variability in some regions. For example, there
33 has been a multidecadal suppression of sea level rise off the Pacific coast (Bromirski et al. 2011)
34 and large year-to-year variations in sea level along the Northeast U.S. coast (Goddard et al.
35 2015). Local rates of land height change have also varied dramatically on decadal timescales in
36 some locations, such as along the western Gulf Coast, where rates of subsurface extraction of
37 fossil fuels and groundwater have varied over time (Galloway et al. 1999).

1 **[INSERT FIGURE 12.1 HERE]**

2 **12.3 Paleo Sea Level**

3 Geological records of temperature and sea level indicate that during past warm periods over the
4 last several millions of years, GMSL was higher than it is today (Miller et al. 2005; Dutton et al.
5 2015). During the Last Interglacial stage, about 125,000 years ago, global average sea surface
6 temperature was about $0.5^{\circ} \pm 0.3^{\circ}\text{C}$ ($0.9^{\circ} \pm 0.5^{\circ}\text{F}$) above the preindustrial level [that is,
7 comparable to the average over 1995–2014, when global mean temperature was about 0.8°C
8 (1.4°F) above the preindustrial levels] (Hoffman et al. 2017). Polar temperatures were
9 comparable to those projected for 1°C – 2°C (1.8°F – 3.6°F) of global mean warming above the
10 preindustrial level. At this time, GMSL was about 6–9 meters (about 20–30 feet) higher than
11 today (Dutton and Lambeck 2012; Kopp et al. 2009) (Figure 12.2a). This geological benchmark
12 may indicate the probable long-term response of GMSL to the minimum magnitude of
13 temperature change projected for the current century.

14 Similarly, during the mid-Pliocene warm period, about 3 million years ago, global mean
15 temperature was about 1.8° – 3.6°C (3.2° – 6.5°F) above the preindustrial level (Haywood et al.
16 2013). Estimates of GMSL are less well constrained than during the Last Interglacial, due to the
17 smaller number of local geological sea level reconstruction and the possibility of significant
18 vertical land motion over millions of years (Dutton et al. 2015). Some reconstructions place mid-
19 Pliocene GMSL at about 10–30 meters (about 30–100 feet) higher than today (Miller et al.
20 2012). Sea levels this high would require a significantly reduced Antarctic ice sheet, highlighting
21 the risk of significant Antarctic ice sheet loss under such levels of warming (Figure 12.2a).

22 For the period since the Last Glacial Maximum, about 26,000 to 19,000 years ago (Clark et al.
23 2009), geologists can produce detailed reconstructions of sea levels as well as rates of sea level
24 change. To do this, they use proxies such as the heights of fossil coral reefs and the populations
25 of different salinity-sensitive microfossils within salt marsh sediments (Shennan et al. 2015).
26 During the main portion of the deglaciation, from about 17,000 to 8,000 years ago, GMSL rose
27 at an average rate of about 12 mm/year (0.5 inches/year) (Lambeck et al. 2014). However, there
28 were periods of faster rise. For example, during Meltwater Pulse 1a, lasting from about 14,600 to
29 14,300 years ago, GMSL may have risen at an average rate about 50 mm/year (2 inches/year)
30 (Deschamps et al. 2012).

31 Since the disappearance of the last remnants of the North American (Laurentide) Ice Sheet about
32 7,000 years ago (Carlson et al. 2008) to about the start of the 20th century, however, GMSL has
33 been relatively stable. During this period, total GMSL rise is estimated to have been about 4
34 meters (about 13 feet), most of which occurred between 7,000 and 4,000 years ago (Lambeck et
35 al. 2014). The Third National Climate Assessment (NCA3) noted, based on a geological data set
36 from North Carolina (Kemp et al. 2011), that the 20th century GMSL rise was much faster than
37 at any time over the past 2,000 years. Since NCA3, high-resolution sea level reconstructions

1 have been developed for multiple locations, and a new global analysis of such reconstructions
2 strengthens this finding (Kopp et al. 2016). Over the last 2,000 years, prior to the industrial era,
3 GMSL exhibited small fluctuations of about ± 8 cm (3 inches), with a significant decline of about
4 8 cm (3 inches) between the years 1000 and 1400 CE coinciding with about 0.2°C (0.4°F) of
5 global mean cooling (Kopp et al. 2016). The rate of rise in the last century, about 14 cm/century
6 (5.5 inches/century), was greater than during any preceding century in at least 2,800 years (Kopp
7 et al. 2016; Figure 12.2b).

8 **[INSERT FIGURE 12.2 HERE]**

9 **12.4 Recent Past Trends (20th and 21st Centuries)**

10 **12.4.1 Global Tide Gauge Network and Satellite Observations**

11 A global tide gauge network provides the century-long observations of local RSL, whereas
12 satellite altimetry provides broader coverage of sea surface heights outside the polar regions
13 starting in 1993. GMSL can be estimated through statistical analyses of either data set. GMSL
14 trends over the 1901–1990 period vary slightly (Hay et al. 2015: 1.2 ± 0.2 mm/year [0.05
15 inches/year]; Church and White 2011: 1.5 ± 0.2 mm/year [0.06 inches/year]) with differences
16 amounting to about 1 inch over 90 years. Thus, these results indicate about 11–14 cm (4–5
17 inches) of GMSL rise from 1901 to 1990.

18 Tide gauge analyses indicate that GMSL rose at a considerably faster rate of about 3 mm/year
19 (0.12 inches/year) since 1993 (Hay et al. 2015; Church and White 2011), a result supported by
20 satellite data indicating a trend of 3.4 ± 0.4 mm/year (0.13 ± 0.02 inches/year) over 1993–2015
21 (update to Nerem et al. 2010). These results indicate an additional GMSL rise of about 7 cm (3
22 inches) since 1990 (Figure 12.2b, Figure 12.3a) and 18–21 cm (7–8 inches) since 1900. Satellite
23 (altimetry and gravity) and in situ water column (Argo floats) measurements show that, since
24 2005, about one third of GMSL rise has been from steric changes (primarily thermal expansion)
25 and about two thirds from the addition of mass to the ocean, which represents a growing land-ice
26 contribution (compared to steric) and a departure from the relative contributions earlier in the
27 20th century (Church et al. 2013; Llovel et al. 2014; Leuliette 2015; Merrifield et al. 2015;
28 Chambers et al. 2017; Leuliette and Nerem 2016) (Figure 12.3a).

29 In addition to land ice, the mass-addition contribution also includes net changes in global land-
30 water storage. This term varied in sign over the course of the last century, with human-induced
31 changes in land-water storage being negative (perhaps as much as about -0.6 mm/year [-0.02
32 inches/year]) during the period of heavy dam construction in the middle of the last century, and
33 turning positive in the 1990s as groundwater withdrawal came to dominate (Wada et al. 2017).
34 On decadal timescales, precipitation variability can dominate human-induced changes in land
35 water storage; recent satellite-gravity estimates suggest that, over 2002–2014, a human-caused
36 land-water contribution to GMSL of 0.4 mm/year (0.02 inches/year) was more than offset by
37 -0.7 mm/year (-0.03 inches/year) due to natural variability (Reager et al. 2016).

1 Comparison of results from a variety of approaches supports the conclusion that a substantial
2 fraction of GMSL rise since 1900 is attributable to human-caused climate change (Kopp et al.
3 2016; Slangen et al. 2016; Jevrejeva et al. 2009; Dangendorf et al. 2015; Becker et al. 2014;
4 Marcos and Amores 2014; Slangen et al. 2014a; Marzeion et al. 2014; Marcos et al. 2017). For
5 example, based on the long term historical relationship between temperature and rate of GMSL
6 change, Kopp et al. (2016) found that GMSL rise would *extremely likely* have been less than
7 59% of observed in the absence of 20th century global warming, and that it is *very likely* that
8 GMSL has been higher since 1960 than it would have been without 20th century global warming
9 (Figure 12.3b). Similarly, using a variety of models for individual components, Slangen et al.
10 (2016) found that about 80% of the GMSL rise they simulated for 1970–2005 and about half of
11 that which they simulated for 1900–2005 was attributable to anthropogenic forcing.

12 Over timescales of a few decades, ocean–atmosphere dynamics drive significant variability in
13 sea surface height, as can be observed by satellite (Figure 12.3c) and in tide gauge records that
14 have been adjusted to account for background rates of rise due to long term factors like glacio-
15 isostatic adjustments. For example, the U.S. Pacific Coast experienced a slower-than-global
16 increase between about 1980 and 2011, while the western tropical Pacific experienced a faster-
17 than-global increase in the 1990s and 2000s. This pattern was associated with changes in average
18 winds linked to the Pacific Decadal Oscillation (PDO) (Bromirski et al. 2011; Zhang and Church
19 2012; Merrifield 2011) and appears to have reversed since about 2012 (Hamlington et al. 2016).
20 Along the Atlantic coast, the U.S. Northeast has experienced a faster-than-global increase since
21 the 1970s, while the U.S. Southeast has experienced a slower-than-global increase since the
22 1970s. This pattern appears to be tied to changes in the Gulf Stream (Yin and Goddard 2013;
23 Ezer 2013; Kopp 2013; Kopp et al. 2015b), although whether these changes represent natural
24 variability or a long term trend remains uncertain (Rahmstorf et al. 2015).

25 **[INSERT FIGURE 12.3 HERE]**

26 **12.4.2 Ice Sheet Gravity and Altimetry and Visual Observations**

27 Since NCA3, Antarctica and Greenland have continued to lose ice mass, with mounting evidence
28 accumulating that mass loss is accelerating. Studies using repeat gravimetry (GRACE satellites),
29 repeat altimetry, GPS monitoring, and mass balance calculations generally agree on accelerating
30 mass loss in Antarctica (Shepherd et al. 2012; Scambos and Shuman 2016; Seo et al. 2015;
31 Martín-Español et al. 2016). Together, these indicate a mass loss of roughly 100 Gt/year
32 (gigatonnes/year) over the last decade (a contribution to GMSL of about 0.3 mm/year [0.01
33 inches/year]). Positive accumulation rate anomalies in East Antarctica, especially in Dronning
34 Maud Land (Helm et al. 2014), have contributed to the trend of slight growth there (e.g., Seo et
35 al. 2015; Martín-Español et al. 2016), but this is more than offset by mass loss elsewhere,
36 especially in West Antarctica along the coast facing the Amundsen Sea (Sutterley et al. 2014;
37 Mouginit et al. 2014), Totten Glacier in East Antarctica (Khazendar et al. 2013; Li et al. 2015),
38 and along the Antarctic Peninsula (Seo et al. 2015; Wouters et al. 2015; Martín-Español et al.

1 2016). Floating ice shelves around Antarctica are losing mass at an accelerating rate (Paolo et al.
2 2015). Mass loss from floating ice shelves does not directly affect GMSL, but does allow faster
3 flow of ice from the ice sheet into the ocean.

4 Estimates of mass loss in Greenland based on mass balance from input-output, repeat
5 gravimetry, repeat altimetry, and aerial imagery as discussed in Chapter 11: Arctic Changes
6 reveal a recent acceleration (Khan et al. 2014). Mass loss averaged approximately 75 Gt/year
7 (about 0.2 mm/year [0.01 inches/year] GMSL rise) from 1900 to 1983, continuing at a similar
8 rate of approximately 74 Gt/year through 2003 before accelerating to 186 Gt/year (0.5 mm/year
9 [0.02 inches/year] GMSL rise) from 2003 to 2010 (Kjeldsen et al. 2015). Strong interannual
10 variability does exist (see Ch. 11: Arctic Changes), such as during the exceptional melt year from
11 April 2012 to April 2013, which resulted in mass loss of approximately 560 Gt (1.6 mm/year
12 [0.06 inches/year]) (Tedesco et al. 2013). More recently (April 2014–April 2015), annual mass
13 losses have resumed the accelerated rate of 186 Gt/year (Kjeldsen et al. 2015; Tedesco et al.
14 2016). Mass loss over the last century has reversed the long-term trend of slow thickening linked
15 to the continuing evolution of the ice sheet from the end of the last ice age (MacGregor et al.
16 2016).

17 **12.5 Projected Sea Level Rise**

18 **12.5.1 Scenarios of Global Mean Sea Level Rise**

19 No single physical model is capable of accurately representing all of the major processes
20 contributing to GMSL and regional/local RSL rise. Accordingly, the U.S. Interagency Sea Level
21 Rise Task Force (Sweet et al. 2017; henceforth referred to as “Interagency”) has revised the
22 GMSL rise scenarios for the United States and now provides six scenarios that can be used for
23 assessment and risk-framing purposes (Figure 12.4a; Table 12.1). The low scenario of 30 cm
24 (about 1 foot) GMSL rise by 2100 is consistent with a continuation of the recent approximately 3
25 mm/year (0.12 inches/year) rate of rise through to 2100 (Table 12.2), while the five other
26 scenarios span a range of GMSL rise between 50 and 250 cm (1.6 and 8.2 feet) in 2100, with
27 corresponding rise rates between 5 mm/year (0.2 inches/year) to 44 mm/year (1.7 inches/year)
28 towards the end of this century (Table 12.2). The highest scenario of 250 cm is consistent with
29 several literature estimates of the maximum physically plausible level of 21st century sea level
30 rise (e.g., Pfeffer et al. 2008, updated with Srivier et al. 2012 estimates of thermal expansion and
31 Bamber and Aspinall 2013 estimates of Antarctic contribution, and incorporating land water
32 storage, as discussed in Miller et al. 2013; Kopp et al. 2014). It is also consistent with the high
33 end of recent projections of Antarctic ice sheet melt discussed below (DeConto and Pollard
34 2016). The Interagency GMSL scenario interpretations are shown in Table 12.3.

35 **[INSERT FIGURE 12.4 HERE]**

36 The Interagency scenario approach is similar to local RSL rise scenarios of Hall et al. (2016)
37 used for all coastal U.S. Department of Defense installations worldwide. The Interagency

1 approach starts with a probabilistic projection framework to generate time series and regional
 2 projections consistent with each GMSL rise scenario for 2100 (Kopp et al. 2014). That
 3 framework combines probabilistic estimates of contributions to GMSL and regional RSL rise
 4 from ocean processes, cryospheric processes, geological processes, and anthropogenic land-
 5 water storage. Pooling the Kopp et al. (2014) projections across RCP2.6, 4.5, and 8.5, the
 6 probabilistic projections are filtered to identify pathways consistent with each of these 2100
 7 levels with median (and 17th and 83rd percentiles) picked from each of the filtered subsets.

8 **Table 12.1.** The Interagency GMSL rise scenarios in meters (feet) relative to 2000. All values
 9 are 19-year averages of GMSL centered at the identified year. To convert from a 1991–2009
 10 tidal datum to the 1983–2001 tidal datum, add 2.4 cm (0.9 inches).

Scenario	2020	2030	2050	2100
Low	0.06 (0.2)	0.09 (0.3)	0.16 (0.5)	0.30 (1.0)
Intermediate-Low	0.08 (0.3)	0.13 (0.4)	0.24 (0.8)	0.50 (1.6)
Intermediate	0.10 (0.3)	0.16 (0.5)	0.34 (1.1)	1.0 (3.3)
Intermediate-High	0.10 (0.3)	0.19 (0.6)	0.44 (1.4)	1.5 (4.9)
High	0.11 (0.4)	0.21 (0.7)	0.54 (1.8)	2.0 (6.6)
Extreme	0.11 (0.4)	0.24 (0.8)	0.63 (2.1)	2.5 (8.2)

11

12 **Table 12.2.** Rates of GMSL rise in the Interagency scenarios in mm/year (inches/year). All
 13 values represent 19-year average rates of change, centered at the identified year.

Scenario	2020	2030	2050	2090
Low	3 (0.1)	3 (0.1)	3 (0.1)	3 (0.1)

Intermediate-Low	5 (0.2)	5 (0.2)	5 (0.2)	5 (0.2)
Intermediate	6 (0.2)	7 (0.3)	10 (0.4)	15 (0.6)
Intermediate-High	7 (0.3)	10 (0.4)	15 (0.6)	24 (0.9)
High	8 (0.3)	13 (0.5)	20 (0.8)	35 (1.4)
Extreme	10 (0.4)	15 (0.6)	25 (1.0)	44 (1.7)

1

2 **Table 12.3.** Interpretations of the Interagency GMSL rise scenarios

Scenario	Interpretation
Low	Continuing current rate of GMSL rise, as calculated since 1993 Low end of <i>very likely</i> range under RCP2.6
Intermediate-Low	Modest increase in rate Middle of <i>likely</i> range under RCP2.6 Low end of <i>likely</i> range under RCP4.5 Low end of <i>very likely</i> range under RCP8.5
Intermediate	High end of <i>very likely</i> range under RCP4.5 High end of <i>likely</i> range under RCP8.5 Middle of <i>likely</i> range under RCP4.5 when accounting for possible ice cliff instabilities
Intermediate-High	Slightly above high end of <i>very likely</i> range

	under RCP8.5 Middle of <i>likely</i> range under RCP8.5 when accounting for possible ice cliff instabilities
High	High end of <i>very likely</i> range under RCP8.5 when accounting for possible ice cliff instabilities
Extreme	Consistent with estimates of physically possible “worst case”

1

2 **12.5.2 Probabilities of Different Sea Level Rise Scenarios**

3 Several studies have estimated the probabilities of different amounts of GMSL rise under
4 different emissions pathways (e.g., Church et al. 2013; Kopp et al. 2014; Slangen et al. 2014b;
5 Jevrejeva et al. 2014; Grinsted et al. 2015; Kopp et al. 2016; Mengel et al. 2016; Jackson and
6 Jevrejeva 2016) using a variety of methods, including both statistical and physical models. Most
7 of these studies are in general agreement that GMSL rise by 2100 is *very likely* to be between
8 about 25–80 cm (0.8–2.6 feet) under RCP2.6, 35–95 cm (1.1–3.1 feet) under RCP4.5, and 50–
9 130 cm (1.6–4.3 feet) under RCP8.5, although some projections extend the *very likely* range for
10 RCP8.5 as high as 160–180 cm (5–6 feet) (Kopp et al. 2014, sensitivity study; Jevrejeva et al.
11 2014; Jackson and Jevrejeva 2016). Based on Kopp et al. (2014), the probability of exceeding the
12 amount of GMSL in 2100 under the Interagency scenarios is shown in Table 12.4.

13 The Antarctic projections of Kopp et al. (2014), the GMSL projections of which underlie Table
14 12.4, are consistent with a statistical-physical model of the onset of marine ice sheet instability
15 calibrated to observations of ongoing retreat in the Amundsen Embayment sector of West
16 Antarctica (Ritz et al. 2015). Ritz et al. (2015)’s 95th percentile Antarctic contribution to GMSL
17 of 30 cm by 2100 is comparable to Kopp et al. (2014)’s 95th percentile projection of 33 cm
18 under RCP8.5. However, emerging science suggests that these projections may understate the
19 probability of faster-than-expected ice sheet melt, particularly for high-end warming scenarios.
20 While these probability estimates are consistent with the assumption that the relationship
21 between global temperature and GMSL in the coming century will be similar to that observed
22 over the last two millennia (Rahmstorf 2007; Kopp et al. 2016), emerging positive feedbacks
23 (self-amplifying cycles) in the Antarctic Ice Sheet especially (Rignot et al. 2014; Joughin et al.
24 2014) may invalidate that assumption. Physical feedbacks that until recently were not
25 incorporated into ice sheet models (Pollard et al. 2015) could add about 0–10 cm (0–0.3 feet),
26 20–50 cm (0.7–1.6 feet) and 60–110 cm (2.0–3.6 feet) to central estimates of current century sea

1 level rise under RCP2.6, RCP4.5 and RCP8.5, respectively (DeConto and Pollard 2016). In
 2 addition to marine ice sheet instability, examples of these interrelated processes include ice cliff
 3 instability and ice shelf hydrofracturing. Processes underway in Greenland may also be leading
 4 to accelerating high-end melt risk. Much of the research has focused on changes in surface
 5 albedo driven by the melt-associated unmasking and concentration of impurities in snow and ice
 6 (Tedesco et al. 2016). However, ice dynamics at the bottom of the ice sheet may be important as
 7 well, through interactions with surface runoff or a warming ocean. As an example of the latter,
 8 Jakobshavn Isbræ, Kangerdlugssuaq Glacier, and the Northeast Greenland ice stream may be
 9 vulnerable to marine ice sheet instability (Khan et al. 2014).

10 **Table 12.4.** Probability of exceeding the Interagency GMSL scenarios in 2100 per Kopp et al.
 11 (2014). New evidence regarding the Antarctic ice sheet, if sustained, may significantly increase
 12 the probability of the intermediate-high, high and extreme scenarios, particularly for RCP8.5, but
 13 these results have not yet been incorporated into a probabilistic analysis.

Scenario	RCP2.6	RCP4.5	RCP8.5
Low	94%	98%	100%
Intermediate-Low	49%	73%	96%
Intermediate	2%	3%	17%
Intermediate-High	0.4%	0.5%	1.3%
High	0.1%	0.1%	0.3%
Extreme	0.05%	0.05%	0.1%

14

15 12.5.3 Sea Level Rise after 2100

16 GMSL rise will not stop in 2100, and so it is useful to consider extensions of GMSL rise
 17 projections beyond this point. By 2200, the 0.3–2.5 meters (1.0–8.2 feet) range spanned by the
 18 six Interagency GMSL scenarios in year 2100 increases to about 0.4–9.7 meters (1.3–31.8 feet),
 19 as shown in Table 12.5. These six scenarios imply average rates of GMSL rise over the first half
 20 of the next century of 1.4 mm/year (0.06 inch/year), 4.6 mm/yr (0.2 inch/year), 16 mm/year (0.6
 21 inch/year), 32 mm/year (1.3 inches/year), 46 mm/yr (1.8 inches/year) and 60 mm/year (2.4

1 inches/year), respectively. Excluding the possible effects of still emerging science regarding ice
 2 cliffs and ice shelves, it is very likely that by 2200 GMSL will have risen by 0.3–2.4 meters
 3 (1.0–7.9 feet) under RCP2.6, 0.4–2.7 meters (1.3–8.9 feet) under RCP4.5, and 1.0–3.7 meters
 4 (3.3–12 feet) under RCP8.5 (Kopp et al. 2014).

5 Under most projections, GMSL rise will also not stop in 2200. The concept of a “sea level rise
 6 commitment” refers to the long-term projected sea level rise were the planet’s temperature to be
 7 stabilized at a given level (e.g., Levermann et al. 2013; Golledge et al. 2015). The paleo sea level
 8 record suggests that even 2°C (3.6°F) of global average warming above the preindustrial
 9 temperature may represent a commitment to several meters of rise. One modeling study
 10 suggesting a 2,000-year commitment of 2.3 m/°C (4.2 feet/°F) (Levermann et al. 2013) indicates
 11 that emissions through to 2100 would lock in a likely 2,000-year GMSL rise commitment of
 12 about 0.7–4.2 meters (2.3–14 feet) under RCP2.6, about 1.7–5.6 meters (5.6–19 feet) under
 13 RCP4.5, and about 4.3–9.9 meters (14–33 feet) under RCP8.5 (Strauss et al. 2015). However, as
 14 with the 21st century projections, emerging science regarding the sensitivity of the Antarctic Ice
 15 Sheet may increase the estimated sea level rise over the next millennium, especially for high
 16 emissions pathways (DeConto and Pollard 2016). Large-scale climate geoengineering might
 17 reduce these commitments (Irvine et al. 2009; Applegate and Keller 2015), but may not be able
 18 to avoid lock-in of significant change (Lenton 2011; Barrett et al. 2014; Markusson et al. 2014;
 19 Sillmann et al. 2015). Once changes are realized, they will be effectively irreversible for many
 20 millennia, even if humans artificially accelerate the removal of CO₂ from the atmosphere
 21 (DeConto and Pollard 2016).

22 The 2,000-year commitment understates the full sea level rise commitment, due to the long
 23 response time of the polar ice sheets. Paleo sea level records (Figure 12.2a) suggest that 1°C of
 24 warming may already represent a long-term commitment to more than 6 meters (20 feet) of
 25 GMSL rise (Dutton and Lambeck 2012; Kopp et al. 2009; Dutton et al. 2015). A 10,000-year
 26 modeling study (Clark et al. 2016) suggests that 2°C warming represents a 10,000-year
 27 commitment to about 25 meters (80 feet) of GMSL rise, driven primarily by a loss of about one-
 28 third of the Antarctic ice sheet and three-fifths of the Greenland ice sheet, while the 21st century
 29 RCP8.5 emissions represent a 10,000-year commitment to about 38 meters (125 feet) of GMSL
 30 rise, including a complete loss of the Greenland ice sheet over about 6,000 years.

31 **Table 12.5.** Post-2100 extensions of the Interagency GMSL rise scenarios in meters (feet)

Scenario	2100	2120	2150	2200
Low	0.30 (1.0)	0.34 (1.1)	0.37 (1.2)	0.39 (1.3)
Intermediate-Low	0.50 (1.6)	0.60 (2.0)	0.73 (2.4)	0.95 (3.1)

Intermediate	1.0 (3.3)	1.3 (4.3)	1.8 (5.9)	2.8 (9.2)
Intermediate-High	1.5 (4.9)	2.0 (6.6)	3.1 (10)	5.1 (17)
High	2.0 (6.6)	2.8 (9.2)	4.3 (14)	7.5 (25)
Extreme	2.5 (8.2)	3.6 (12)	5.5 (18)	9.7 (32)

1

2 **12.5.4 Regional Projections of Sea Level Change**

3 Because the different factors contributing to sea level change give rise to different spatial
 4 patterns, projecting future RSL change at specific locations requires not just an estimate of
 5 GMSL change but estimates of the different processes contributing to GMSL change—each of
 6 which has a different associated spatial pattern—as well as of the processes contributing
 7 exclusively to regional or local change. Based on the process-level projections of the Interagency
 8 GMSL scenarios, several key regional patterns are apparent in future U.S. RSL rise as shown for
 9 the Intermediate (1 meter [3.3 feet] GMSL rise by 2100 scenario) in Figure 12.4b.

- 10 (1) RSL rise due to Antarctic Ice Sheet melt is greater than GMSL rise along all U.S.
 11 coastlines due to static-equilibrium effects.
- 12 (2) RSL rise due to Greenland Ice Sheet melt is less than GMSL rise in the continental U.S.
 13 due to static-equilibrium effects. This effect is especially strong in the Northeast.
- 14 (3) RSL rise is additionally augmented in the Northeast by the effects of glacial isostatic
 15 adjustment.
- 16 (4) The Northeast is also exposed to rise due to changes in the Gulf Stream and reductions in
 17 the Atlantic meridional overturning circulation (AMOC). Were the AMOC to collapse
 18 entirely—an outcome viewed as unlikely in the 21st century—it could result in as much
 19 as approximately 0.5 meters (1.6 feet) of additional regional sea level rise (Gregory and
 20 Lowe 2000; Levermann et al. 2005; see Ch. 15: Potential Surprises for further
 21 discussion).
- 22 (5) The western Gulf of Mexico and parts of the U.S. Atlantic Coast south of New York are
 23 currently experiencing significant RSL rise caused by the withdrawal of groundwater
 24 (along the Atlantic Coast) and of both fossil fuels and groundwater (along the Gulf
 25 Coast). Continuation of these practices will further amplify RSL rise.

1 (6) The presence of glaciers in Alaska and their proximity to the Pacific Northwest reduces
2 RSL rise in these regions, due to both the ongoing glacial isostatic adjustment to past
3 glacier shrinkage and to the static-equilibrium effects of projected future losses.

4 (7) Because they are far from all glaciers and ice sheets, RSL rise in Hawai‘i and other
5 Pacific islands due to any source of melting land ice is amplified by the static-equilibrium
6 effects.

7 **12.6 Extreme Water Levels**

8 **12.6.1 Observations**

9 Coastal flooding during extreme high-water events has become deeper due to local RSL rise and
10 more frequent from a fixed-elevation perspective (Menéndez and Woodworth 2010; Kemp and
11 Horton 2013; Sweet et al. 2013; Hall et al. 2016). Trends in annual frequencies surpassing local
12 emergency preparedness thresholds for minor tidal flooding (i.e., “nuisance” levels of about 30–
13 60 cm [1–2 feet]) that begin to flood infrastructure and trigger coastal flood “advisories” by
14 NOAA’s National Weather Service have increased 5- to 10-fold or more since the 1960s along
15 the U.S. coastline (Sweet et al. 2014), as shown in Figure 12.5a. Locations experiencing such
16 trend changes (based upon fits of flood days per year of Sweet and Park 2014) include Atlantic
17 City and Sandy Hook, NJ; Philadelphia, PA; Baltimore and Annapolis, MD; Norfolk, VA;
18 Wilmington, NC; Charleston, SC; Savannah, GA; Mayport and Key West, FL; Port Isabel, TX,
19 La Jolla, CA; and Honolulu, HI. In fact, over the last several decades, minor tidal flood rates
20 have been accelerating within several (more than 25) East and Gulf Coast cities with established
21 elevation thresholds for minor (nuisance) flood impacts, fastest where elevation thresholds are
22 lower, local RSL rise is higher, and extreme variability less (Ezer and Atkinson 2014; Sweet et
23 al. 2014; Sweet and Park 2014).

24 Trends in extreme water levels (for example, monthly maxima) in excess of mean sea levels (for
25 example, monthly means) exist, but are not commonplace (Menéndez and Woodworth 2010;
26 Talke et al. 2014; Wahl and Chambers 2015; Reed et al. 2015; Marcos et al. 2017). More
27 common are regional time dependencies in high-water probabilities, which can co-vary on an
28 interannual basis with climatic and other patterns (Menéndez and Woodworth 2010; Grinstead et
29 al. 2013; Marcos et al. 2015; Woodworth and Menéndez 2015; Wahl and Chambers 2016;
30 Mawdsley and Haigh 2016; Sweet et al. 2016). These patterns are often associated with
31 anomalous oceanic and atmospheric conditions (Feser et al. 2015; Colle et al. 2015). For
32 instance, the probability of experiencing minor tidal flooding is compounded during El Niño
33 periods along portions of the West and Mid-Atlantic Coasts (Sweet and Park 2014) from a
34 combination of higher sea levels and enhanced synoptic forcing and storm surge frequency
35 (Sweet and Zervas 2011; Thompson et al. 2013; Hamlington et al. 2015; Woodworth and
36 Menéndez 2015).

37

1 **12.6.2 Influence of Projected Sea Level Rise on Coastal Flood Frequencies**

2 The extent and depth of minor-to-major coastal flooding during high-water events will continue
3 to increase in the future as local RSL rises (Tebaldi et al. 2012; Horton et al. 2011; Woodruff et
4 al. 2013; Kopp et al. 2014; Sweet and Park 2014; Buchanan et al. 2016; Hall et al. 2016; Dahl et
5 al. 2017; Sweet et al. 2017). Relative to fixed elevations, the frequency of high-water events will
6 increase the fastest where extreme variability is less and the rate of local RSL rise is higher
7 (Hunter 2012; Tebaldi et al. 2012; Kopp et al. 2014; Sweet and Park 2014; Buchanan et al. 2016;
8 Sweet et al. 2017). Under the RCP-based probabilistic RSL projections of Kopp et al. 2014, at
9 tide gauge locations along the contiguous U.S. coastline, a median 8-fold increase (range of 1.1-
10 to 430-fold increase) is expected by 2050 in the annual number of floods exceeding the elevation
11 of the current 100-year flood event (measured with respect to a 1991–2009 baseline sea level)
12 (Buchanan et al. 2016). Under the same forcing, the frequency of minor tidal flooding (with
13 contemporary recurrence intervals generally <1 year [Sweet et al. 2014]) will increase even more
14 so in the coming decades (Sweet and Park 2014; Moftakhari et al. 2015) and eventually occur on
15 a daily basis (Figure 12.5b). With only about 0.35 m (<14 inches) of additional local RSL rise
16 (with respect to the year 2000), annual frequencies of moderate level flooding—those locally
17 with a 5-year recurrence interval (Figure 12.5c) and associated with a NOAA coastal flood
18 warning of serious risk to life and property—will increase 25-fold at the majority of NOAA tide
19 gauge locations along the U.S. coastline (outside of Alaska) by or about (± 5 years) 2080, 2060,
20 2040, and 2030 under the Interagency Low, Intermediate-Low, Intermediate, and Intermediate-
21 High GMSL scenarios, respectively (Sweet et al. 2017). Figure 12.5d, which shows the decade in
22 which the frequency of such moderate level flooding will increase 25-fold under the Interagency
23 Intermediate Scenario, highlights that the mid- and Southeast Atlantic, western Gulf of Mexico,
24 California, and the Island States and Territories are most susceptible to rapid changes in
25 potentially damaging flood frequencies.

26 **[INSERT FIGURE 12.5 HERE]**

27 **12.6.3 Waves and Impacts**

28 The combination of a storm surge at high tide with additional dynamic effects from waves
29 (Stockdon et al. 2006; Sweet et al. 2015) creates the most damaging coastal hydraulic conditions
30 (Moritz et al. 2015). Simply with higher-than-normal sea levels, wave action increases the
31 likelihood for extensive coastal erosion (Barnard et al. 2011; Theuerkauf et al. 2014; Serafin and
32 Ruggiero 2014) and low-island overwash (Hoeke et al. 2013). Wave runup is often the largest
33 water level component during extreme events especially along island coastlines where storm
34 surge is constrained by bathymetry (Tebaldi et al. 2012; Woodruff et al. 2013; Hall et al. 2016).
35 On an interannual basis, wave impacts are correlated across the Pacific Ocean with phases of
36 ENSO (Stopa and Cheung 2014; Barnard et al. 2015). Over the last half century, there has been
37 an increasing trend in wave height and power within the North Pacific Ocean (Bromirski et al.
38 2013; Erikson et al. 2015) that is modulated by the PDO (Aucan et al. 2012; Bromirski et al.

1 2013). Resultant increases in wave run-up have been more of a factor than RSL rise in terms of
2 impacts along the U.S. Northwest Pacific Coast over the last several decades (Ruggiero 2013). In
3 the Northwest Atlantic Ocean, no long-term trends in wave power have been observed over the
4 last half century (Bromirski and Cayan 2015), though hurricane activity drives interannual
5 variability (Bromirski and Kossin 2008). In terms of future conditions this century, increases in
6 mean and maximum seasonal wave heights are projected within parts of the northeast Pacific,
7 northwest Atlantic, and Gulf of Mexico (Graham et al. 2013; Wang et al. 2014; Erikson et al.
8 2015; Shope et al. 2016).

9 **12.6.4 Sea Level Rise, Changing Storm Characteristics, and Their Interdependencies**

10 Future probabilities of extreme coastal floods will depend upon the amount of local RSL rise,
11 changes in coastal storm characteristics, and their interdependencies. For instance, there have
12 been more storms producing concurrent locally extreme storm surge and rainfall (not captured in
13 tide gauge data) along the U.S. East and Gulf Coasts over the last 65 years, with flooding further
14 compounded by local RSL rise (Wahl et al. 2015). Hemispheric-scale extratropical cyclones may
15 experience a northward shift this century, with some studies projecting an overall decrease in
16 storm number (Colle et al. 2015 and references therein). The research is mixed about strong
17 extratropical storms; studies find potential increases in frequency and intensity in some regions,
18 like within the Northeast (Colle et al. 2013), whereas others project decreases in strong
19 extratropical storms in some regions (e.g., Zappa et al. 2013).

20 For tropical cyclones, model projections for the North Atlantic mostly agree that intensities and
21 precipitation rates will increase this century (see Ch. 9: Extreme Storms), although some model
22 evidence suggests that track changes could dampen the effect in the U.S. Mid-Atlantic and
23 Northeast (Hall and Yonekura 2013). Assuming other storm characteristics do not change, sea
24 level rise will increase the frequency and extent of extreme flooding associated with coastal
25 storms, such as hurricanes and nor'easters. A projected increase in the intensity of hurricanes in
26 the North Atlantic could increase the probability of extreme flooding along most of the U.S.
27 Atlantic and Gulf Coast States beyond what would be projected based solely on RSL rise
28 (Grinsted et al. 2013; Lin et al. 2012; Little et al. 2015; Lin et al. 2016). In addition, RSL
29 increases are projected to cause a nonlinear increase in storm surge heights in shallow
30 bathymetry environments (Smith et al. 2010; Atkinson et al. 2013; Bilskie et al. 2014; Passeri et
31 al. 2015; Bilskie et al. 2016) and extend wave propagation and impacts landward (Smith et al.
32 2010; Atkinson et al. 2013). However, there is low confidence in the magnitude of the increase
33 in intensity and the associated flood risk amplification, and it could be offset or amplified by
34 other factors, such as changes in storm frequency or tracks (e.g., Knutson et al. 2013, 2015)

35

1 TRACEABLE ACCOUNTS

2 Key Finding 1

3 Global mean sea level (GMSL) has risen by about 7–8 inches (about 16–21 cm) since 1900, with
4 about 3 of those inches (about 7 cm) occurring since 1993 (*very high confidence*). Human-caused
5 climate change has made a substantial contribution to GMSL rise since 1900 (*high confidence*),
6 contributing to a rate of rise that is greater than during any preceding century in at least 2,800
7 years (*medium confidence*).

8 Description of evidence base

9 Multiple researchers, using different statistical approaches, have integrated tide gauge records to
10 estimate GMSL rise since the late nineteenth century (e.g., Church and White 2006, 2011; Hay et
11 al. 2015; Jevrejeva et al. 2009). The most recent published rate estimates are 1.2 ± 0.2 (Hay et al.
12 2015) or 1.5 ± 0.2 (Church and White 2011) mm/year over 1901–1990. Thus, these results
13 indicate about 11–14 cm (4–5 inches) of GMSL rise from 1901 to 1990. Tide gauge analyses
14 indicate that GMSL rose at a considerably faster rate of about 3 mm/year (0.12 inches/year) since
15 1993 (Hay et al. 2015; Church and White 2011), a result supported by satellite data indicating a
16 trend of 3.4 ± 0.4 mm/year (0.13 inches/year) over 1993–2015 (update to Nerem et al. 2010)
17 (Figure 12.3a). These results indicate an additional GMSL rise of about 7 cm (3 inches) rise
18 since 1990. Thus, total GMSL rise since 1900 is about 18–21 cm (7–8 inches).

19 The finding regarding the historical context of the 20th century change is based upon Kopp et al.
20 (2016), who conducted a meta-analysis of geological RSL reconstructions spanning the last
21 3,000 years from 24 locations around the world as well as tide gauge data from 66 sites and the
22 tide gauge based GMSL reconstruction of Hay et al. (2015). By constructing a spatio-temporal
23 statistical model of these data sets, they identified the common global sea level signal over the
24 last three millennia and its uncertainties. They found a 95% probability that the average rate of
25 GMSL change over 1900–2000 was greater than during any preceding century in at least 2,800
26 years.

27 The finding regarding the substantial human contribution is based upon several lines of evidence.
28 Kopp et al. (2016), based on the long term historical relationship between temperature and the
29 rate of sea level change, found that it is *extremely likely* that GMSL rise would have been <59%
30 of observed in the absence of 20th century global warming, and that it is *very likely* that GMSL
31 has been higher since 1960 than it would have been without 20th century global warming. Using
32 a variety of models for individual components, Slangen et al. (2016) found that $69\% \pm 31\%$ out
33 of the $87\% \pm 20\%$ of GMSL rise over 1970–2005 that their models simulated was attributable to
34 anthropogenic forcing, and that $37\% \pm 38\%$ out of $74\% \pm 22\%$ simulated was attributable over
35 1900–2005. Jevrejeva et al. (2009), using the relationship between forcing and GMSL over 1850
36 and 2001 and CMIP3 models, found that ~75% of GMSL rise in the 20th century is attributable
37 to anthropogenic forcing. Marcos and Amores (2014), using CMIP5 models, found that ~87% of

1 ocean heat uptake since 1970 in the top 700 m of the ocean has been due to anthropogenic
2 forcing. Slangen et al. (2014a), using CMIP5, found that anthropogenic forcing was required to
3 explain observed thermosteric SLR over 1957–2005. Marzeion et al. (2014) found that $25\% \pm$
4 35% of glacial loss over 1851–2010, and $69\% \pm 24\%$ over 1991–2010, was attributable to
5 anthropogenic forcing. Dangendorf et al (2015), based on time series analysis, found that $>45\%$
6 of observed GMSL trend since 1900 cannot (with 99% probability) be explained by multi-
7 decadal natural variability. Becker et al. (2014), based on time series analysis, found a 99%
8 probability that at least 1.0 or 1.3 mm/year of GMSL rise over 1880–2010 is anthropogenic.

9 **Major uncertainties**

10 Uncertainties in reconstructed GMSL change relate to the sparsity of tide gauge records,
11 particularly before the middle of the twentieth century, and to different statistical approaches for
12 estimating GMSL change from these sparse records. Uncertainties in reconstructed GMSL
13 change before the twentieth century also relate to the sparsity of geological proxies for sea level
14 change, the interpretation of these proxies, and the dating of these proxies. Uncertainty in
15 attribution relates to the reconstruction of past changes and the magnitude of unforced
16 variability.

17 **Assessment of confidence based on evidence and agreement, including short description of** 18 **nature of evidence and level of agreement**

19 Confidence is *very high* in the rate of GMSL rise since 1900, based on multiple different
20 approaches to estimating GMSL rise from tide gauges and satellite altimetry. Confidence is *high*
21 in the substantial human contribution to GMSL rise since 1900, based on both statistical and
22 physical modeling evidence. It is *medium* that the magnitude of the observed rise since 1900 is
23 unprecedented in the context of the previous 2,700 years, based on meta-analysis of geological
24 proxy records.

25 **Summary sentence or paragraph that integrates the above information**

26 This key finding is based upon multiple analyses of tide gauge and satellite altimetry records, on
27 a meta-analysis of multiple geological proxies for pre-instrumental sea level change, and on both
28 statistical and physical analyses of the human contribution to GMSL rise since 1900.

29

30 **Key Finding 2**

31 Relative to the year 2000, GMSL is *very likely* to rise by 0.3–0.6 feet (9–18 cm) by 2030, 0.5–1.2
32 feet (15–38 cm) by 2050, and 1 to 4 feet (30–130 cm) by 2100 (*very high confidence in lower*
33 *bounds; medium confidence in upper bounds for 2030 and 2050; low confidence in upper bounds*
34 *for 2100*). Future emissions pathways have little effect on projected GMSL rise in the first half
35 of the century, but significantly affect projections for the second half of the century (*high*

1 *confidence*). Emerging science regarding Antarctic ice sheet stability suggests that, for high
 2 emission scenarios, a GMSL rise exceeding 8 feet (2.4 m) by 2100 is physically possible,
 3 although the probability of such an extreme outcome cannot currently be assessed. Regardless of
 4 emissions pathway, it is *extremely likely* that GMSL rise will continue beyond 2100 (*high*
 5 *confidence*).

6 **Description of evidence base**

7 The lower bound of the *very likely* range is based on a continuation of the observed
 8 approximately 3 mm/year rate of GMSL rise. The upper end of the *very likely* range is based
 9 upon estimates for RCP8.5 from three studies producing fully probabilistic projections across
 10 multiple RCPs. Kopp et al. (2014) fused multiple sources of information accounting for the
 11 different individual process contributing to GMSL rise. Kopp et al. (2016) constructed a semi-
 12 empirical sea level model calibrated to the Common Era sea level reconstruction. Mengel et al.
 13 (2016) constructed a set of semi-empirical models of the different contributing processes. All
 14 three studies show negligible RCP dependence in the first half of this century, becoming more
 15 prominent in the second half of the century. A sensitivity study by Kopp et al. (2014), as well as
 16 studies by Jevrejeva et al. (2014) and by Jackson and Jevrejeva (2016), used frameworks similar
 17 to Kopp et al. (2016) but incorporated directly an expert elicitation study on ice sheet stability
 18 (Bamber and Aspinall 2013). (This study was incorporated in Kopp et al. [2014]’s main results
 19 with adjustments for consistency with Church et al. 2013). These studies extend the *very likely*
 20 range for RCP8.5 as high as 160–180 cm (5–6 feet) (Kopp et al. 2014, sensitivity study;
 21 Jevrejeva et al. 2014; Jackson and Jevrejeva 2016).

22 To estimate the effect of incorporating the DeConto and Pollard (2016) projections of Antarctic
 23 ice sheet melt, we note that Kopp et al. (2014)’s median projection of Antarctic melt in 2100 is 4
 24 cm (1.6 inches) (RCP2.6), 5 cm (2 inches) (RCP4.5), or 6 cm (2.4 inches) (RCP8.5). By contrast,
 25 DeConto and Pollard (2016)’s ensemble mean projections are (varying the assumptions for the
 26 size of Pliocene mass loss and the bias correction in the Amundsen Sea) 2–14 cm (0.1–0.5 foot)
 27 for RCP2.6, 26–58 cm (0.9–1.9 feet) for RCP4.5, and 64–114 cm (2.1–3.7 ft) for RCP8.5. Thus,
 28 we conclude that DeConto and Pollard (2016)’s projection would lead to a –10 cm (–0.1–0.3 ft)
 29 increase in median RCP2.6 projections, a 21–53 cm (0.7–1.7 feet) increase in median RCP4.5
 30 projections, and a 58–108 cm (1.9–3.5 feet) increase in median RCP8.5 projections.

31 **Very likely ranges, 2030 relative to 2000 in cm (feet)**

	Kopp et al. (2014)	Kopp et al. (2016)	Mengel et al. (2016)
RCP8.5	11–18 (0.4–0.6)	8–15 (0.3–0.5)	7–12 (0.2–0.4)

RCP4.5	10–18 (0.3–0.6)	8–15 (0.3–0.5)	7–12 (0.2–0.4)
RCP2.6	10–18 (0.3–0.6)	8–15 (0.3–0.5)	7–12 (0.2–0.4)

1

2 Very likely ranges, 2050 relative to 2000 in cm (feet)

	Kopp et al. (2014)	Kopp et al. (2016)	Mengel et al. (2016)
RCP8.5	21–38 (0.7–1.2)	16–34 (0.5–1.1)	15–28 (0.5–0.9)
RCP4.5	18–35 (0.6–1.1)	15–31 (0.5–1.0)	14–25 (0.5–0.8)
RCP2.6	18–33 (0.6–1.1)	14–29 (0.5–1.0)	13–23 (0.4–0.8)

3

4 Very likely ranges, 2100 relative to 2000 in cm (feet)

	Kopp et al. (2014)	Kopp et al. (2016)	Mengel et al. (2016)
RCP8.5	55–121 (1.8–4.0)	52–131 (1.7–4.3)	57–131 (1.9–4.3)
RCP4.5	36–93 (1.2–3.1)	33–85 (1.1–2.8)	37–77 (1.2–2.5)
RCP2.6	29–82 (1.0–2.7)	24–61 (0.8–2.0)	28–56 (0.9–1.8)

5

6 Major uncertainties

7 Since NCA3, multiple different approaches have been used to generate probabilistic projections
 8 of GMSL rise, conditional upon the RCPs. These approaches are in general agreement. However,
 9 emerging results indicate that marine-based sectors of the Antarctic Ice Sheet are more unstable
 10 than previous modeling indicated. The rate of ice sheet mass changes remains challenging to
 11 project.

12

1 **Assessment of confidence based on evidence and agreement, including short description of**
2 **nature of evidence and level of agreement**

3 There is *very high* confidence that future GMSL rise over the next several decades will be at
4 least as fast as a continuation of the historical trend over the last quarter century would indicate.
5 There is *medium* confidence in the upper end of very likely ranges for 2030 and 2050. Due to
6 possibly large ice sheet contributions, there is *low* confidence in the upper end of very likely
7 ranges for 2100. Based on multiple projection methods, there is *high confidence* that differences
8 between emission scenarios are small before 2050 but significant beyond 2050.

9 **Summary sentence or paragraph that integrates the above information**

10 This key finding is based upon multiple methods for estimating the probability of future sea level
11 change and on new modeling results regarding the stability of marine based ice in Antarctica.
12

13 **Key Finding 3**

14 Relative sea level (RSL) rise in this century will vary along U.S. coastlines due, in part, to
15 changes in Earth's gravitational field and rotation from melting of land ice, changes in ocean
16 circulation, and vertical land motion (*very high confidence*). For almost all future GMSL rise
17 scenarios, RSL rise is *likely* to be greater than the global average in the U.S. Northeast and the
18 western Gulf of Mexico. In intermediate and low GMSL rise scenarios, RSL rise is *likely* to be
19 less than the global average in much of the Pacific Northwest and Alaska. For high GMSL rise
20 scenarios, RSL rise is *likely* to be higher than the global average along all U.S. coastlines outside
21 Alaska. Almost all U.S. coastlines experience more than global-mean sea-level rise in response
22 to Antarctic ice loss, and thus would be particularly affected under extreme GMSL rise scenarios
23 involving substantial Antarctic mass loss (*high confidence*).

24 **Description of evidence base**

25 The processes that cause geographic variability in RSL change are reviewed by Kopp et al.
26 (2015a). Long tide gauge data sets show the RSL rise caused by vertical land motion due to
27 glacio-isostatic adjustment and fluid withdrawal along many U.S. coastlines (PSMSL 2016;
28 Holgate et al. 2013). These observations are corroborated by glacio-isostatic adjustment models,
29 by GPS observations, and by geological data (e.g., Engelhart and Horton 2012). The physics of
30 the gravitational, rotational and flexural "static-equilibrium fingerprint" response of sea level to
31 redistribution of mass from land ice to the oceans is well established (Farrell and Clark 1976;
32 Mitrovica et al. 2011). GCM studies indicate the potential for a Gulf Stream contribution to sea
33 level rise in the U.S. Northeast (Yin et al. 2009; Yin and Goddard 2013). Kopp et al. (2014) and
34 Slangen et al. (2014a) accounted for land motion (only glacial isostatic adjustment for Slangen et
35 al.), fingerprint, and ocean dynamic responses. Comparing projections of local RSL change and

1 GMSL change in these studies indicate that local rise is likely to be greater than the global
2 average along the U.S. Atlantic and Gulf Coasts and less than the global average in most of the
3 Pacific Northwest. Sea level rise projections in this report are developed by an Interagency Sea
4 Level Rise Task Force (Sweet et al. 2017).

5 **Major uncertainties**

6 Since NCA3, multiple authors have produced global or regional studies synthesizing the major
7 process that causes global and local sea level change to diverge. The largest sources of
8 uncertainty in the geographic variability of sea level change are ocean dynamic sea level change
9 and, for those regions where sea level fingerprints for Greenland and Antarctica differ from the
10 global mean in different directions, the relative contributions of these two sources to projected
11 sea level change.

12 **Assessment of confidence based on evidence and agreement, including short description of** 13 **nature of evidence and level of agreement**

14 Because of the enumerated physical processes, there is *very high* confidence that RSL change
15 will vary across U.S. coastlines. There is *high* confidence in the likely differences of RSL change
16 from GMSL change under different levels of GMSL change, based on projections incorporating
17 the different relevant processes.

18 **Summary sentence or paragraph that integrates the above information**

19 The part of the key finding regarding the existence of geographic variability is based upon a
20 broader observational, modeling, and theoretical literature. The specific differences are based
21 upon the scenarios described by the Interagency Sea Level Rise Task Force (Sweet et al. 2017)

22

23 **Key Finding 4**

24 As sea levels have risen, the number of tidal floods each year that cause minor impacts (also
25 called “nuisance floods”) have increased 5- to 10-fold since the 1960s in several U.S. coastal
26 cities (*very high confidence*). Rates of increase are accelerating in over 25 Atlantic and Gulf
27 Coast cities (*very high confidence*). Tidal flooding will continue increasing in depth, frequency,
28 and extent this century (*very high confidence*).

29 **Description of evidence base**

30 Sweet et al. (2014) examined 45 NOAA tide gauge locations with hourly data since 1980 and
31 Sweet and Park (2014) examined a subset of these (27 locations) with hourly data prior to 1950,
32 all with a National Weather Service elevation threshold established for minor “nuisance” flood
33 impacts. Using linear or quadratic fits of annual number of days exceeding the minor thresholds,

1 Sweet and Park (2014) find increases in trend-derived values between 1960 and 2010 greater
2 than 10-fold at 8 locations, greater than 5-fold at 6 locations, and greater than 3-fold at 7
3 locations. Sweet et al. (2014), Sweet and Park (2014), and Ezer and Atkinson (2014) find that
4 annual minor tidal flood frequencies since 1980 are accelerating along locations on the East and
5 Gulf Coasts (>25 locations, Sweet et al. 2014) due to continued exceedance of a typical high-
6 water distribution above elevation thresholds for minor impacts.

7 Historical changes over the last 60 years in flood probabilities have occurred most rapidly where
8 RSL rates were highest and where tide ranges and extreme variability is less (Sweet and Park
9 2014). In terms of future rates of changes in extreme event probabilities relative to fixed
10 elevations, Hunter (2012), Tebaldi et al. (2012), Kopp et al. (2014), Sweet and Park (2014) and
11 Sweet et al. (2017) all find that locations with less extreme variability and higher RSL rise rates
12 are most prone.

13 **Major uncertainties**

14 Minor flooding probabilities have been only assessed where a tide gauge is present with >30
15 years of data and where a NOAA National Weather Service elevation threshold for impacts has
16 been established. There are likely many other locations experiencing similar flooding patterns,
17 but an expanded assessment is not possible at this time.

18 **Assessment of confidence based on evidence and agreement, including short description of** 19 **nature of evidence and level of agreement**

20 There is *very high* confidence that exceedance probabilities of high tide flooding at dozens of
21 local-specific elevation thresholds have significantly increased over the last half century, often in
22 an accelerated fashion, and that exceedance probabilities will continue to increase this century.

23 **Summary sentence or paragraph that integrates the above information**

24 This key finding is based upon several studies finding historic and projecting future changes in
25 high-water probabilities for local-specific elevation thresholds for flooding.

26

27 **Key Finding 5**

28 Assuming storm characteristics do not change, sea level rise will increase the frequency and
29 extent of extreme flooding associated with coastal storms, such as hurricanes and nor'easters
30 (*very high confidence*). A projected increase in the intensity of hurricanes in the North Atlantic
31 could increase the probability of extreme flooding along most of the U.S. Atlantic and Gulf
32 Coast states beyond what would be projected based solely on RSL rise. However, there is *low*
33 *confidence* in the magnitude of the increase in intensity and the associated flood risk

1 amplification, and these effects could be offset or amplified by other factors, such as changes in
2 storm frequency or tracks.

3 **Description of evidence base**

4 The frequency, extent, and depth of extreme event-driven (for example, 5 to 100 year event
5 probabilities) coastal flooding relative to existing infrastructure will continue to increase in the
6 future as local RSL rises (Tebaldi et al. 2012; Horton et al. 2011; Woodruff et al. 2013; Sweet et
7 al. 2013; Kopp et al. 2014; Buchanan et al. 2016; Hall et al. 2016; Sweet et al. 2017). Extreme
8 flood probabilities will increase regardless of change in storm characteristics, which may
9 exacerbate such changes. Model-based projections of tropical storms and related major storm
10 surges within the North Atlantic mostly agree that intensities and frequencies of the most intense
11 storms will increase this century (Grinsted et al. 2013; Lin et al. 2012; Little et al. 2015; Knutson
12 et al. 2013; Lin et al. 2016). However, the projection of increased hurricane intensity is more
13 robust across models than the projection of increased frequency of the most intense storms, since
14 a number of models project a decrease in the overall number of tropical storms and hurricanes in
15 the North Atlantic, although high-resolution models generally project increased mean hurricane
16 intensity (e.g., Knutson et al. 2013). In addition, there is model evidence for a change in tropical
17 cyclone tracks in warm years that minimizes the increase in landfalling hurricanes in the U.S.
18 Mid-Atlantic or Northeast (Hall and Yonekura 2013).

19 **Major uncertainties**

20 Uncertainties remain large with respect to the precise change in future risk of a major coastal
21 impact at a specific location from changes in the most intense tropical cyclone characteristics and
22 tracks beyond changes imposed from local sea level rise.

23 **Assessment of confidence based on evidence and agreement, including short description of 24 nature of evidence and level of agreement**

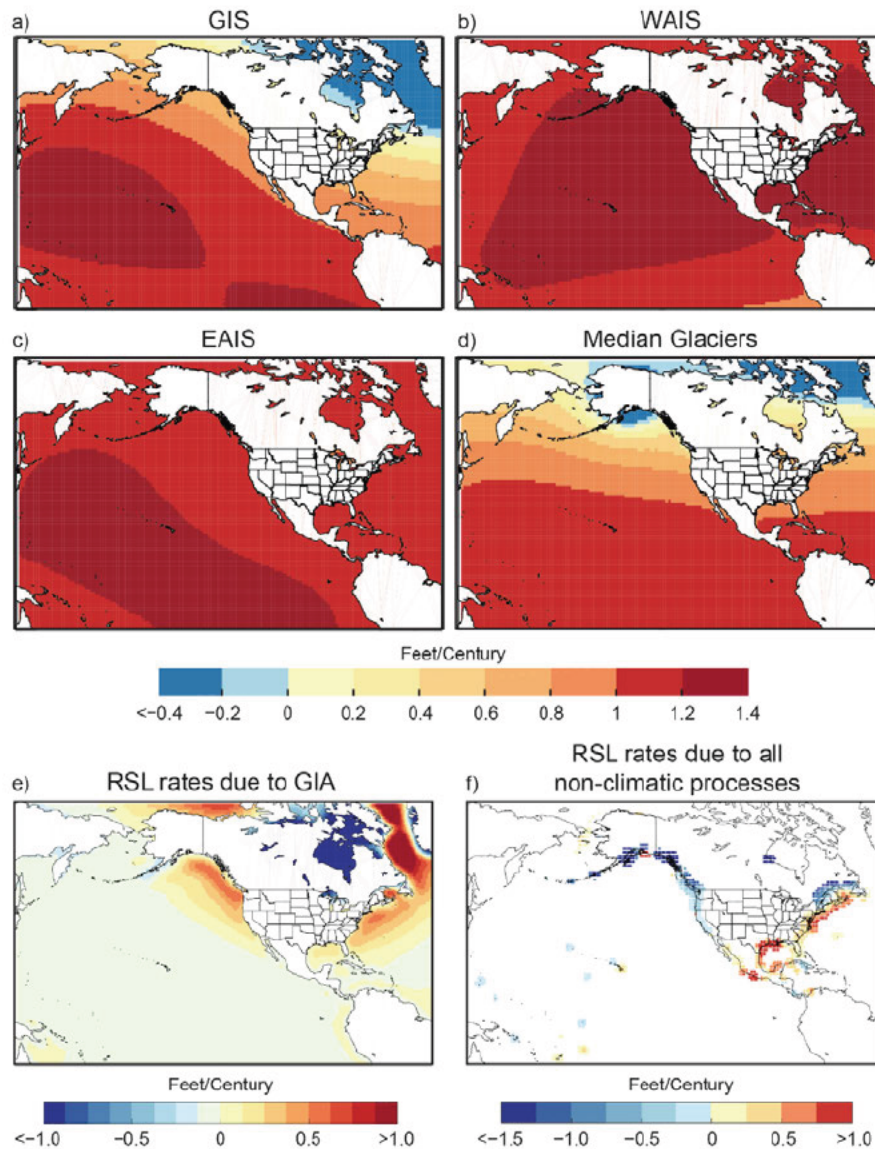
25 There is *low confidence* that the flood risk at specific locations will be amplified from a major
26 tropical storm this century.

27 **Summary sentence or paragraph that integrates the above information**

28 This key finding is based upon several modeling studies of future hurricane characteristics and
29 associated increases in major storm surge risk amplification.

30

1 **FIGURES**

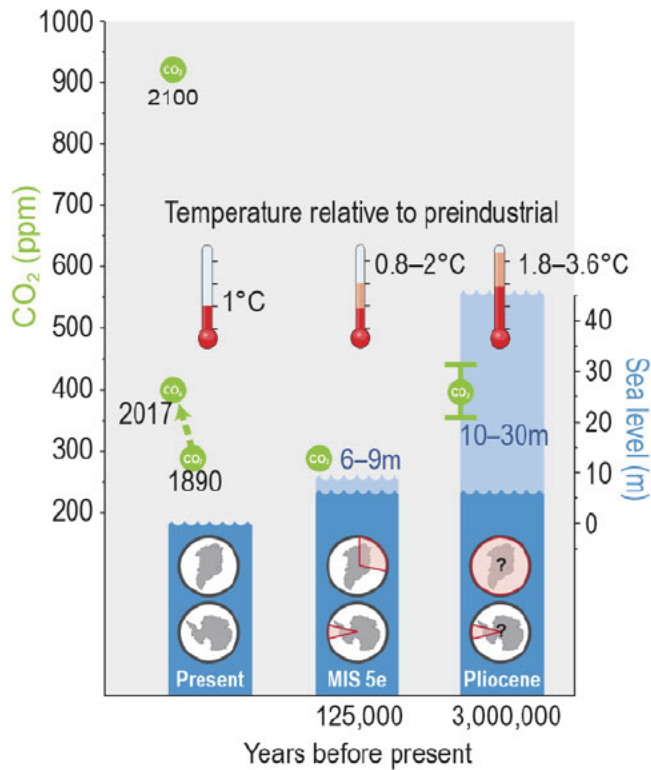


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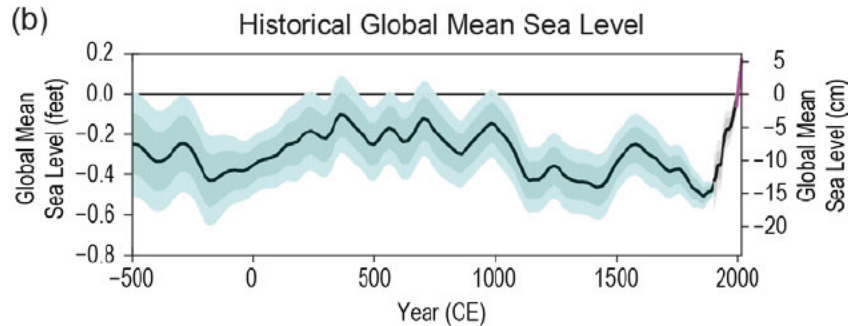
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4 **Figure 12.1:** (a–d) Static-equilibrium fingerprints of the relative sea level (RSL) effect of land
 5 ice melt, in units of feet of RSL change per feet of global mean sea level (GMSL) change, for
 6 mass loss from (a) Greenland, (b) West Antarctica, (c) East Antarctica, and (d) the median
 7 projected combination of melting glaciers, after Kopp et al. (2014, 2015a). (e) Model projections
 8 of the rate of RSL rise due to glacial-isostatic adjustment (units of feet/century), after Kopp et al.
 9 (2015a). (f) Tide gauge-based estimates of the non-climatic, long term contribution to RSL rise,
 10 including the effects of glacial isostatic adjustment, tectonics, and sediment compaction (units of
 11 feet/century) (Kopp et al. 2014). [Figure source: (a)–(d) Kopp et al. 2015a, (e) adapted from
 12 Kopp et al. 2015a; (f) adapted from Sweet et al. 2017].

(a)



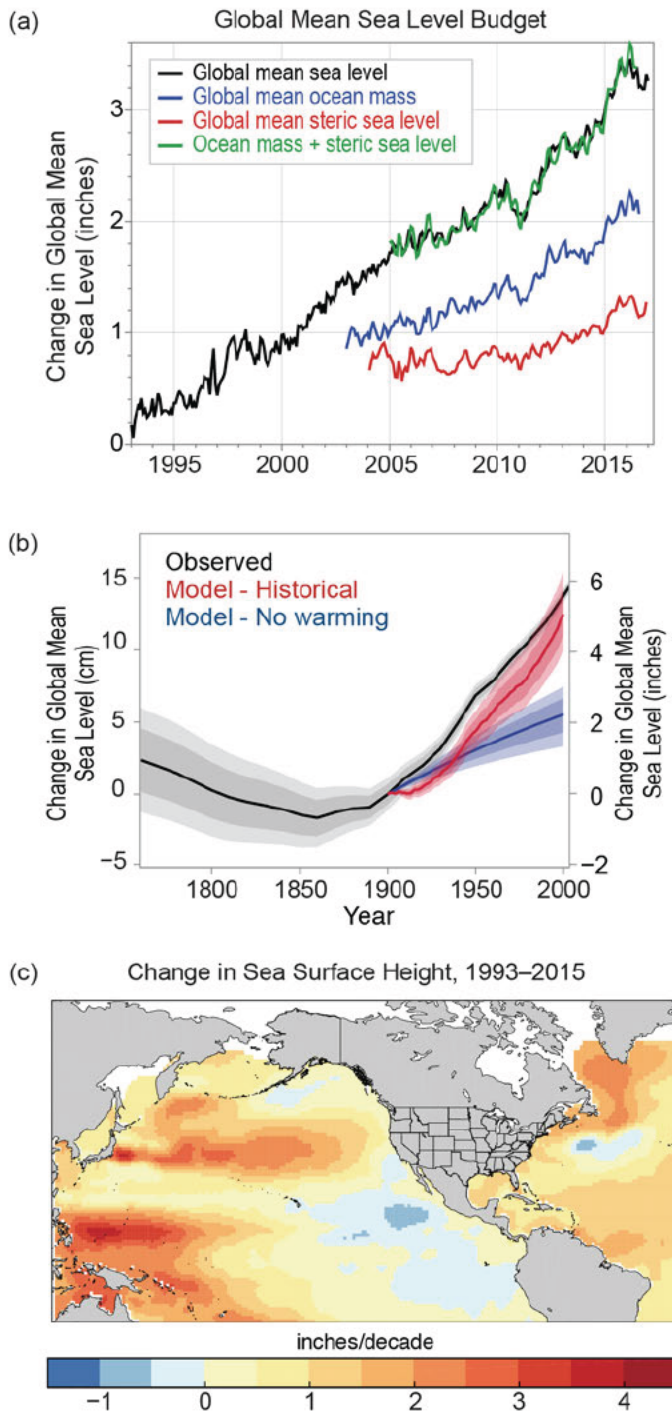
(b)



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Figure 12.2: (a) The relationship between peak global mean temperature, maximum global mean sea level (GMSL), and source(s) of meltwater over three periods in the past with global mean temperature comparable to or warmer than present. Light blue shading indicates uncertainty of GMSL maximum. Red pie charts over Greenland and Antarctica denote fraction, not location, of ice retreat. (b) GMSL rise from -500 to 1900 CE, from Kopp et al. 2016’s geological and tide gauge-based reconstruction (blue), from 1900 to 2010 from Hay et al. 2015’s tide gauge-based reconstruction (black), and from 1992 to 2015 from the satellite-based reconstruction updated from Nerem et al. 2010 (magenta). [Figure source: (a) adapted from Dutton et al. 2015 and (b) Sweet et al. 2017].

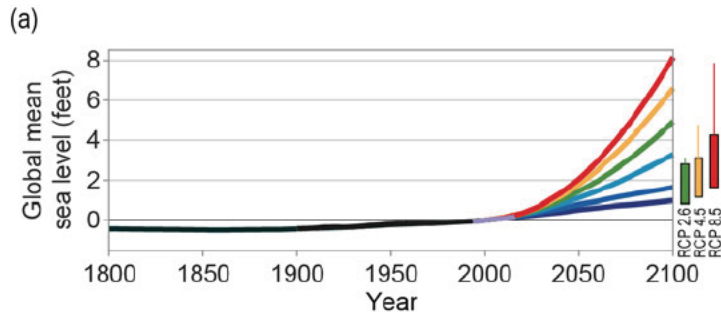


2 **Figure 12.3:** (a) Contributions of ocean mass changes from land ice and land water storage
 3 (measured by satellite gravimetry) and ocean volume changes (or steric, primarily from thermal
 4 expansion measured by in situ ocean profilers) and their comparison to global mean sea level
 5 (GMSL) change (measured by satellite altimetry) since 1993. (b) An estimate of modeled GMSL
 6 rise in the absence of 20th century warming (blue) and from the same model with observed
 7 warming (red), compared to observed GMSL change (black). Heavy/light shading indicates the

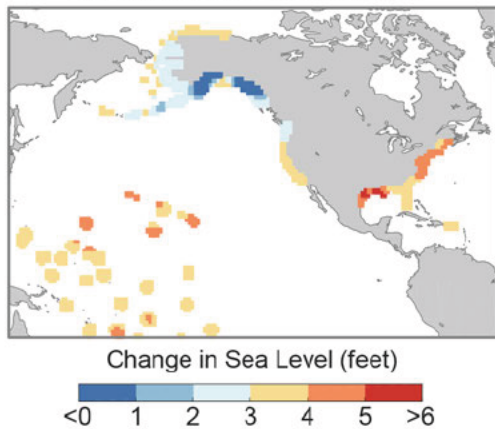
1 17th–83rd and 5th–95th percentiles. (c) Rates of change from 1993 to 2015 in sea surface height
2 from satellite altimetry data; updated from Kopp et al. 2015a using data updated from Church
3 and White 2011. [Figure source: (a) adapted and updated from Leuliette and Nerem 2016, (b)
4 adapted from Kopp et al. (2016) and (c) adapted and updated from Kopp et al. 2015a].

5

FINAL DRAFT



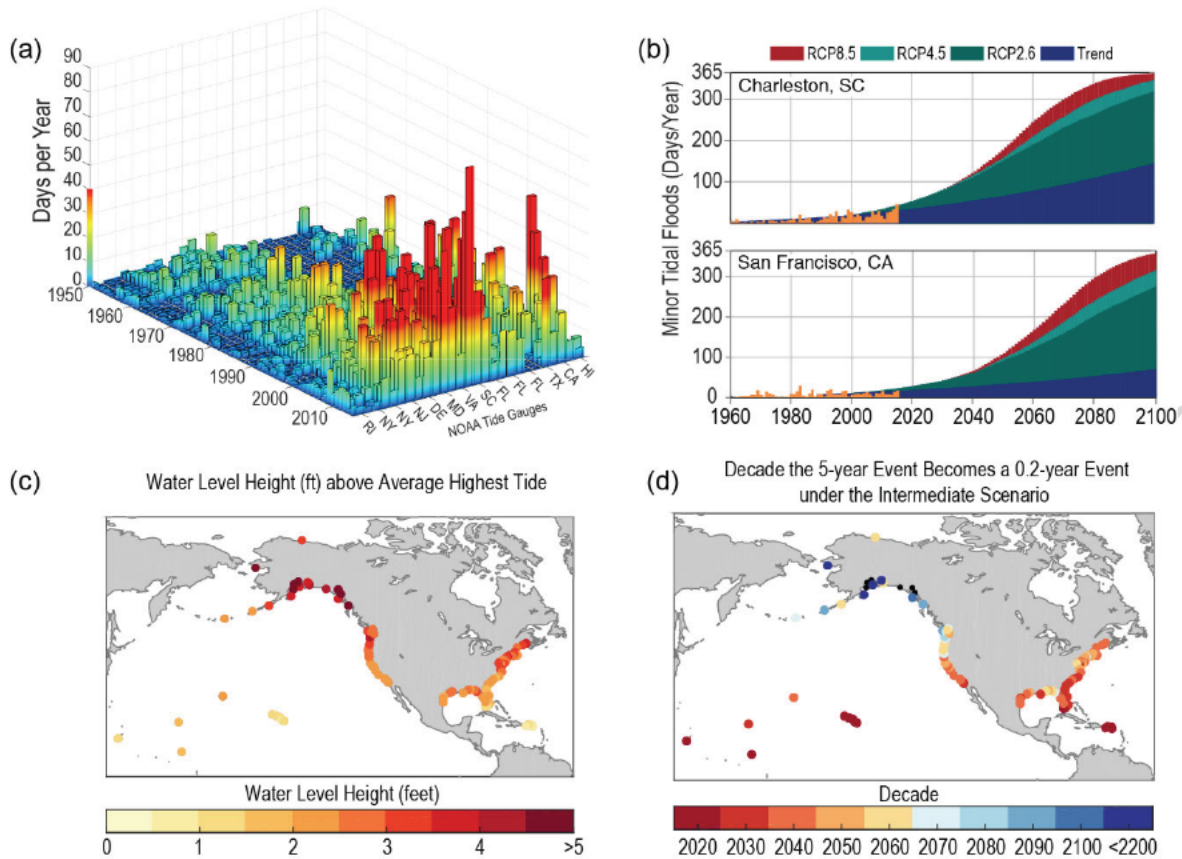
(b) Projected Relative Sea Level Change for 2100 under the Intermediate Scenario



1

2 **Figure 12.4:** (a) Global mean sea level (GMSL) rise from 1800 to 2100, based on Figure 12.2b
 3 from 1800 to 2015, the six Interagency (Sweet et al. 2017) GMSL scenarios (navy blue, royal
 4 blue, cyan, green, orange and red curves), the *very likely* ranges in 2100 for different RCPs from
 5 this chapter (colored boxes), and lines augmenting the *very likely* ranges by the difference
 6 between the median Antarctic contribution of Kopp et al. 2014 and the various median Antarctic
 7 projections of DeConto and Pollard (2016). (b) Relative sea level (RSL) rise (feet) in 2100
 8 projected for the Interagency Intermediate Scenario (1-meter [3.3 feet] GMSL rise by 2100)
 9 (Figure source: Sweet et al. 2017).

10



1
 2 Figure 12.5: (a) Tidal floods (days per year) exceeding NOAA thresholds for minor impacts at
 3 28 NOAA tide gauges through 2015 showing (b) historical exceedances (orange) for two of the
 4 locations—Charleston, SC and San Francisco, CA—and future projections through 2100 based
 5 upon the continuation of the historical trend (blue) and under median RCP2.6, 4.5 and 8.5
 6 conditions. (c) Water level heights above average highest tide associated with a local 5-year
 7 recurrence probability and (d) the future decade when the 5-year event becomes a 0.2-year (5 or
 8 more times a year) event under the Interagency Intermediate scenario; black dots imply that a 5-
 9 year to 0.2-year frequency change does not unfold by 2200 under the Intermediate scenario.
 10 [Figure source: (a) adapted from Sweet and Marra 2016, (b) adapted from Sweet and Park 2014,
 11 (c) and (d) Sweet et al. 2017]

12

1 **REFERENCES**

- 2 Applegate, P.J. and K. Keller, 2015: How effective is albedo modification (solar radiation
3 management geoen지니어ing) in preventing sea-level rise from the Greenland Ice Sheet?
4 *Environmental Research Letters*, **10**, 084018. [http://dx.doi.org/10.1088/1748-](http://dx.doi.org/10.1088/1748-9326/10/8/084018)
5 [9326/10/8/084018](http://dx.doi.org/10.1088/1748-9326/10/8/084018)
- 6 Atkinson, J., J.M. Smith, and C. Bender, 2013: Sea-level rise effects on storm surge and
7 nearshore waves on the Texas coast: Influence of landscape and storm characteristics.
8 *Journal of Waterway, Port, Coastal, and Ocean Engineering*, **139**, 98-117.
9 [http://dx.doi.org/10.1061/\(ASCE\)WW.1943-5460.0000187](http://dx.doi.org/10.1061/(ASCE)WW.1943-5460.0000187)
- 10 Aucan, J., R. Hoeke, and M.A. Merrifield, 2012: Wave-driven sea level anomalies at the Midway
11 tide gauge as an index of North Pacific storminess over the past 60 years. *Geophysical*
12 *Research Letters*, **39**, L17603. <http://dx.doi.org/10.1029/2012GL052993>
- 13 Bamber, J.L. and W.P. Aspinall, 2013: An expert judgement assessment of future sea level rise
14 from the ice sheets. *Nature Climate Change*, **3**, 424-427.
15 <http://dx.doi.org/10.1038/nclimate1778>
- 16 Barnard, P.L., J. Allan, J.E. Hansen, G.M. Kaminsky, P. Ruggiero, and A. Doria, 2011: The
17 impact of the 2009–10 El Niño Modoki on U.S. West Coast beaches. *Geophysical Research*
18 *Letters*, **38**, L13604. <http://dx.doi.org/10.1029/2011GL047707>
- 19 Barnard, P.L., A.D. Short, M.D. Harley, K.D. Splinter, S. Vitousek, I.L. Turner, J. Allan, M.
20 Banno, K.R. Bryan, A. Doria, J.E. Hansen, S. Kato, Y. Kuriyama, E. Randall-Goodwin, P.
21 Ruggiero, I.J. Walker, and D.K. Heathfield, 2015: Coastal vulnerability across the Pacific
22 dominated by El Niño/Southern Oscillation. *Nature Geoscience*, **8**, 801-807.
23 <http://dx.doi.org/10.1038/ngeo2539>
- 24 Barrett, S., T.M. Lenton, A. Millner, A. Tavoni, S. Carpenter, J.M. Anderies, F.S. Chapin, III,
25 A.-S. Crepin, G. Daily, P. Ehrlich, C. Folke, V. Galaz, T. Hughes, N. Kautsky, E.F. Lambin,
26 R. Naylor, K. Nyborg, S. Polasky, M. Scheffer, J. Wilen, A. Xepapadeas, and A. de Zeeuw,
27 2014: Climate engineering reconsidered. *Nature Climate Change*, **4**, 527-529.
28 <http://dx.doi.org/10.1038/nclimate2278>
- 29 Becker, M., M. Karpytchev, and S. Lennartz-Sassinek, 2014: Long-term sea level trends: Natural
30 or anthropogenic? *Geophysical Research Letters*, **41**, 5571-5580.
31 <http://dx.doi.org/10.1002/2014GL061027>
- 32 Bilskie, M.V., S.C. Hagen, S.C. Medeiros, and D.L. Passeri, 2014: Dynamics of sea level rise
33 and coastal flooding on a changing landscape. *Geophysical Research Letters*, **41**, 927-934.
34 <http://dx.doi.org/10.1002/2013GL058759>

- 1 Bilskie, M.V., S.C. Hagen, K. Alizad, S.C. Medeiros, D.L. Passeri, H.F. Needham, and A. Cox,
2 2016: Dynamic simulation and numerical analysis of hurricane storm surge under sea level
3 rise with geomorphologic changes along the northern Gulf of Mexico. *Earth's Future*, **4**, 177-
4 193. <http://dx.doi.org/10.1002/2015EF000347>
- 5 Boon, J.D., 2012: Evidence of sea level acceleration at U.S. and Canadian tide stations, Atlantic
6 Coast, North America. *Journal of Coastal Research*, 1437-1445.
7 <http://dx.doi.org/10.2112/JCOASTRES-D-12-00102.1>
- 8 Bromirski, P.D. and D.R. Cayan, 2015: Wave power variability and trends across the North
9 Atlantic influenced by decadal climate patterns. *Journal of Geophysical Research: Oceans*,
10 **120**, 3419-3443. <http://dx.doi.org/10.1002/2014JC010440>
- 11 Bromirski, P.D. and J.P. Kossin, 2008: Increasing hurricane wave power along the U.S. Atlantic
12 and Gulf coasts. *Journal of Geophysical Research*, **113**, C07012.
13 <http://dx.doi.org/10.1029/2007JC004706>
- 14 Bromirski, P.D., A.J. Miller, R.E. Flick, and G. Auad, 2011: Dynamical suppression of sea level
15 rise along the Pacific coast of North America: Indications for imminent acceleration. *Journal*
16 *of Geophysical Research*, **116**, C07005. <http://dx.doi.org/10.1029/2010JC006759>
- 17 Bromirski, P.D., D.R. Cayan, J. Helly, and P. Wittmann, 2013: Wave power variability and
18 trends across the North Pacific. *Journal of Geophysical Research: Oceans*, **118**, 6329-6348.
19 <http://dx.doi.org/10.1002/2013JC009189>
- 20 Buchanan, M.K., R.E. Kopp, M. Oppenheimer, and C. Tebaldi, 2016: Allowances for evolving
21 coastal flood risk under uncertain local sea-level rise. *Climatic Change*, **137**, 347-362.
22 <http://dx.doi.org/10.1007/s10584-016-1664-7>
- 23 Carlson, A.E., A.N. LeGrande, D.W. Oppo, R.E. Came, G.A. Schmidt, F.S. Anslow, J.M.
24 Licciardi, and E.A. Obbink, 2008: Rapid early Holocene deglaciation of the Laurentide ice
25 sheet. *Nature Geoscience*, **1**, 620-624. <http://dx.doi.org/10.1038/ngeo285>
- 26 Chambers, D.P., A. Cazenave, N. Champollion, H. Dieng, W. Llovel, R. Forsberg, K. von
27 Schuckmann, and Y. Wada, 2017: Evaluation of the global mean sea level budget between
28 1993 and 2014. *Surveys in Geophysics*, **38**, 309-327. [http://dx.doi.org/10.1007/s10712-016-](http://dx.doi.org/10.1007/s10712-016-9381-3)
29 [9381-3](http://dx.doi.org/10.1007/s10712-016-9381-3)
- 30 Church, J.A. and N.J. White, 2006: A 20th century acceleration in global sea-level rise.
31 *Geophysical Research Letters*, **33**, L01602. <http://dx.doi.org/10.1029/2005GL024826>
- 32 Church, J.A. and N.J. White, 2011: Sea-level rise from the late 19th to the early 21st century.
33 *Surveys in Geophysics*, **32**, 585-602. <http://dx.doi.org/10.1007/s10712-011-9119-1>

- 1 Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A.
2 Merrifield, G.A. Milne, R.S. Nerem, P.D. Nunn, A.J. Payne, W.T. Pfeffer, D. Stammer, and
3 A.S. Unnikrishnan, 2013: Sea level change. *Climate Change 2013: The Physical Science*
4 *Basis. Contribution of Working Group I to the Fifth Assessment Report of the*
5 *Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M.
6 Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds.
7 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1137–
8 1216. <http://www.climatechange2013.org/report/full-report/>
- 9 Clark, P.U., A.S. Dyke, J.D. Shakun, A.E. Carlson, J. Clark, B. Wohlfarth, J.X. Mitrovica, S.W.
10 Hostetler, and A.M. McCabe, 2009: The last glacial maximum. *Science*, **325**, 710-714.
11 <http://dx.doi.org/10.1126/science.1172873>
- 12 Clark, P.U., J.D. Shakun, S.A. Marcott, A.C. Mix, M. Eby, S. Kulp, A. Levermann, G.A. Milne,
13 P.L. Pfister, B.D. Santer, D.P. Schrag, S. Solomon, T.F. Stocker, B.H. Strauss, A.J. Weaver,
14 R. Winkelmann, D. Archer, E. Bard, A. Goldner, K. Lambeck, R.T. Pierrehumbert, and G.-
15 K. Plattner, 2016: Consequences of twenty-first-century policy for multi-millennial climate
16 and sea-level change. *Nature Climate Change*, **6**, 360-369.
17 <http://dx.doi.org/10.1038/nclimate2923>
- 18 Colle, B.A., Z. Zhang, K.A. Lombardo, E. Chang, P. Liu, and M. Zhang, 2013: Historical
19 evaluation and future prediction of eastern North American and western Atlantic
20 extratropical cyclones in the CMIP5 models during the cool season. *Journal of Climate*, **26**,
21 6882-6903. <http://dx.doi.org/10.1175/JCLI-D-12-00498.1>
- 22 Colle, B.A., J.F. Booth, and E.K.M. Chang, 2015: A review of historical and future changes of
23 extratropical cyclones and associated impacts along the US East Coast. *Current Climate*
24 *Change Reports*, **1**, 125-143. <http://dx.doi.org/10.1007/s40641-015-0013-7>
- 25 Dahl, K.A., M.F. Fitzpatrick, and E. Spanger-Siegfried, 2017: Sea level rise drives increased
26 tidal flooding frequency at tide gauges along the U.S. East and Gulf Coasts: Projections for
27 2030 and 2045. *PLOS ONE*, **12**, e0170949. <http://dx.doi.org/10.1371/journal.pone.0170949>
- 28 Dangendorf, S., M. Marcos, A. Müller, E. Zorita, R. Riva, K. Berk, and J. Jensen, 2015:
29 Detecting anthropogenic footprints in sea level rise. *Nature Communications*, **6**, 7849.
30 <http://dx.doi.org/10.1038/ncomms8849>
- 31 DeConto, R.M. and D. Pollard, 2016: Contribution of Antarctica to past and future sea-level rise.
32 *Nature*, **531**, 591-597. <http://dx.doi.org/10.1038/nature17145>
- 33 Deschamps, P., N. Durand, E. Bard, B. Hamelin, G. Camoin, A.L. Thomas, G.M. Henderson, J.i.
34 Okuno, and Y. Yokoyama, 2012: Ice-sheet collapse and sea-level rise at the Bolling warming
35 14,600[thinsp]years ago. *Nature*, **483**, 559-564. <http://dx.doi.org/10.1038/nature10902>

- 1 Dutton, A., A.E. Carlson, A.J. Long, G.A. Milne, P.U. Clark, R. DeConto, B.P. Horton, S.
2 Rahmstorf, and M.E. Raymo, 2015: Sea-level rise due to polar ice-sheet mass loss during
3 past warm periods. *Science*, **349**. <http://dx.doi.org/10.1126/science.aaa4019>
- 4 Dutton, A. and K. Lambeck, 2012: Ice volume and sea level during the Last Interglacial. *Science*,
5 **337**, 216-219. <http://dx.doi.org/10.1126/science.1205749>
- 6 Engelhart, S.E. and B.P. Horton, 2012: Holocene sea level database for the Atlantic coast of the
7 United States. *Quaternary Science Reviews*, **54**, 12-25.
8 <http://dx.doi.org/10.1016/j.quascirev.2011.09.013>
- 9 Erikson, L.H., C.A. Hegermiller, P.L. Barnard, P. Ruggiero, and M. van Ormondt, 2015:
10 Projected wave conditions in the Eastern North Pacific under the influence of two CMIP5
11 climate scenarios. *Ocean Modelling*, **96 (12), Part 1**, 171-185.
12 <http://dx.doi.org/10.1016/j.ocemod.2015.07.004>
- 13 Ezer, T., 2013: Sea level rise, spatially uneven and temporally unsteady: Why the U.S. East
14 Coast, the global tide gauge record, and the global altimeter data show different trends.
15 *Geophysical Research Letters*, **40**, 5439-5444. <http://dx.doi.org/10.1002/2013GL057952>
- 16 Ezer, T. and L.P. Atkinson, 2014: Accelerated flooding along the U.S. East Coast: On the impact
17 of sea-level rise, tides, storms, the Gulf Stream, and the North Atlantic Oscillations. *Earth's*
18 *Future*, **2**, 362-382. <http://dx.doi.org/10.1002/2014EF000252>
- 19 Farrell, W.E. and J.A. Clark, 1976: On postglacial sea level. *Geophysical Journal International*,
20 **46**, 647-667. <http://dx.doi.org/10.1111/j.1365-246X.1976.tb01252.x>
- 21 Feser, F., M. Barcikowska, O. Krueger, F. Schenk, R. Weisse, and L. Xia, 2015: Storminess over
22 the North Atlantic and northwestern Europe—A review. *Quarterly Journal of the Royal*
23 *Meteorological Society*, **141**, 350-382. <http://dx.doi.org/10.1002/qj.2364>
- 24 Galloway, D., D.R. Jones, and S.E. Ingebritsen, 1999: Land Subsidence in the United States.
25 USGS Circular 1182. U.S. Geological Survey, Reston, VA. 6 pp.
26 <https://pubs.usgs.gov/circ/circ1182/>
- 27 Goddard, P.B., J. Yin, S.M. Griffies, and S. Zhang, 2015: An extreme event of sea-level rise
28 along the Northeast coast of North America in 2009–2010. *Nature Communications*, **6**, 6346.
29 <http://dx.doi.org/10.1038/ncomms7346>
- 30 Gollidge, N.R., D.E. Kowalewski, T.R. Naish, R.H. Levy, C.J. Fogwill, and E.G.W. Gasson,
31 2015: The multi-millennial Antarctic commitment to future sea-level rise. *Nature*, **526**, 421-
32 425. <http://dx.doi.org/10.1038/nature15706>

- 1 Graham, N.E., D.R. Cayan, P.D. Bromirski, and R.E. Flick, 2013: Multi-model projections of
2 twenty-first century North Pacific winter wave climate under the IPCC A2 scenario. *Climate*
3 *Dynamics*, **40**, 1335-1360. <http://dx.doi.org/10.1007/s00382-012-1435-8>
- 4 Gregory, J. M., and J. A. Lowe, 2000: Predictions of global and regional sea-level rise using
5 AOGCMs with and without flux adjustment. *Geophysical Research Letters*, **27** (19), 3069-
6 3072, doi:10.1029/1999GL011228.
- 7 Grinsted, A., J.C. Moore, and S. Jevrejeva, 2013: Projected Atlantic hurricane surge threat from
8 rising temperatures. *Proceedings of the National Academy of Sciences*, **110**, 5369-5373.
9 <http://dx.doi.org/10.1073/pnas.1209980110>
- 10 Grinsted, A., S. Jevrejeva, R.E.M. Riva, and D. Dahl-Jensen, 2015: Sea level rise projections for
11 northern Europe under RCP8.5. *Climate Research*, **64**, 15-23.
12 <http://dx.doi.org/10.3354/cr01309>
- 13 Hall, J.A., S. Gill, J. Obeysekera, W. Sweet, K. Knuuti, and J. Marburger, 2016: Regional Sea
14 Level Scenarios for Coastal Risk Management: Managing the Uncertainty of Future Sea
15 Level Change and Extreme Water Levels for Department of Defense Coastal Sites
16 Worldwide. U.S. Department of Defense, Strategic Environmental Research and
17 Development Program, Alexandria VA. 224 pp.
18 <https://www.usfsp.edu/icar/files/2015/08/CARSWG-SLR-FINAL-April-2016.pdf>
- 19 Hall, T. and E. Yonekura, 2013: North American tropical cyclone landfall and SST: A statistical
20 model study. *Journal of Climate*, **26**, 8422-8439. <http://dx.doi.org/10.1175/jcli-d-12-00756.1>
- 21 Hamlington, B.D., R.R. Leben, K.Y. Kim, R.S. Nerem, L.P. Atkinson, and P.R. Thompson,
22 2015: The effect of the El Niño–Southern Oscillation on U.S. regional and coastal sea level.
23 *Journal of Geophysical Research: Oceans*, **120**, 3970-3986.
24 <http://dx.doi.org/10.1002/2014JC010602>
- 25 Hamlington, B.D., S.H. Cheon, P.R. Thompson, M.A. Merrifield, R.S. Nerem, R.R. Leben, and
26 K.Y. Kim, 2016: An ongoing shift in Pacific Ocean sea level. *Journal of Geophysical*
27 *Research: Oceans*, **121**, 5084-5097. <http://dx.doi.org/10.1002/2016JC011815>
- 28 Hay, C.C., E. Morrow, R.E. Kopp, and J.X. Mitrovica, 2015: Probabilistic reanalysis of
29 twentieth-century sea-level rise. *Nature*, **517**, 481-484. <http://dx.doi.org/10.1038/nature14093>
- 30 Haywood, A.M., D.J. Hill, A.M. Dolan, B.L. Otto-Bliesner, F. Bragg, W.L. Chan, M.A.
31 Chandler, C. Contoux, H.J. Dowsett, A. Jost, Y. Kamae, G. Lohmann, D.J. Lunt, A. Abe-
32 Ouchi, S.J. Pickering, G. Ramstein, N.A. Rosenbloom, U. Salzmann, L. Sohl, C. Stepanek,
33 H. Ueda, Q. Yan, and Z. Zhang, 2013: Large-scale features of Pliocene climate: Results from
34 the Pliocene Model Intercomparison Project. *Climate of the Past*, **9**, 191-209.
35 <http://dx.doi.org/10.5194/cp-9-191-2013>

- 1 Helm, V., A. Humbert, and H. Miller, 2014: Elevation and elevation change of Greenland and
2 Antarctica derived from CryoSat-2. *The Cryosphere*, **8**, 1539-1559.
3 <http://dx.doi.org/10.5194/tc-8-1539-2014>
- 4 Hoeke, R.K., K.L. McInnes, J.C. Kruger, R.J. McNaught, J.R. Hunter, and S.G. Smithers, 2013:
5 Widespread inundation of Pacific islands triggered by distant-source wind-waves. *Global
6 and Planetary Change*, **108**, 128-138. <http://dx.doi.org/10.1016/j.gloplacha.2013.06.006>
- 7 Hoffman, J.S., P.U. Clark, A.C. Parnell, and F. He, 2017: Regional and global sea-surface
8 temperatures during the last interglaciation. *Science*, **355**, 276-279.
9 <http://dx.doi.org/10.1126/science.aai8464>
- 10 Holgate, S.J., A. Matthews, P.L. Woodworth, L.J. Rickards, M.E. Tamisiea, E. Bradshaw, P.R.
11 Foden, K.M. Gordon, S. Jevrejeva, and J. Pugh, 2013: New data systems and products at the
12 Permanent Service for Mean Sea Level. *Journal of Coastal Research*, **29**, 493-504.
13 <http://dx.doi.org/10.2112/JCOASTRES-D-12-00175.1>
- 14 Horton, R.M., V. Gornitz, D.A. Bader, A.C. Ruane, R. Goldberg, and C. Rosenzweig, 2011:
15 Climate hazard assessment for stakeholder adaptation planning in New York City. *Journal of
16 Applied Meteorology and Climatology*, **50**, 2247-2266.
17 <http://dx.doi.org/10.1175/2011JAMC2521.1>
- 18 Hunter, J., 2012: A simple technique for estimating an allowance for uncertain sea-level rise.
19 *Climatic Change*, **113**, 239-252. <http://dx.doi.org/10.1007/s10584-011-0332-1>
- 20 Irvine, P.J., D.J. Lunt, E.J. Stone, and A. Ridgwell, 2009: The fate of the Greenland Ice Sheet in
21 a geoengineered, high CO₂ world. *Environmental Research Letters*, **4**, 045109.
22 <http://dx.doi.org/10.1088/1748-9326/4/4/045109>
- 23 Jackson, L.P. and S. Jevrejeva, 2016: A probabilistic approach to 21st century regional sea-level
24 projections using RCP and High-end scenarios. *Global and Planetary Change*, **146**, 179-189.
25 <http://dx.doi.org/10.1016/j.gloplacha.2016.10.006>
- 26 Jevrejeva, S., A. Grinsted, and J.C. Moore, 2009: Anthropogenic forcing dominates sea level rise
27 since 1850. *Geophysical Research Letters*, **36**, L20706.
28 <http://dx.doi.org/10.1029/2009GL040216>
- 29 Jevrejeva, S., A. Grinsted, and J.C. Moore, 2014: Upper limit for sea level projections by 2100.
30 *Environmental Research Letters*, **9**, 104008. [http://dx.doi.org/10.1088/1748-
31 9326/9/10/104008](http://dx.doi.org/10.1088/1748-9326/9/10/104008)
- 32 Joughin, I., B.E. Smith, and B. Medley, 2014: Marine ice sheet collapse potentially under way
33 for the Thwaites Glacier Basin, West Antarctica. *Science*, **344**, 735-738.
34 <http://dx.doi.org/10.1126/science.1249055>

- 1 Kemp, A.C. and B.P. Horton, 2013: Contribution of relative sea-level rise to historical hurricane
2 flooding in New York City. *Journal of Quaternary Science*, **28**, 537-541.
3 <http://dx.doi.org/10.1002/jqs.2653>
- 4 Kemp, A.C., B.P. Horton, J.P. Donnelly, M.E. Mann, M. Vermeer, and S. Rahmstorf, 2011:
5 Climate related sea-level variations over the past two millennia. *Proceedings of the National*
6 *Academy of Sciences*, **108**, 11017-11022. <http://dx.doi.org/10.1073/pnas.1015619108>
- 7 Khan, S.A., K.H. Kjaer, M. Bevis, J.L. Bamber, J. Wahr, K.K. Kjeldsen, A.A. Bjork, N.J.
8 Korsgaard, L.A. Stearns, M.R. van den Broeke, L. Liu, N.K. Larsen, and I.S. Muresan, 2014:
9 Sustained mass loss of the northeast Greenland ice sheet triggered by regional warming.
10 *Nature Climate Change*, **4**, 292-299. <http://dx.doi.org/10.1038/nclimate2161>
- 11 Khazendar, A., M.P. Schodlok, I. Fenty, S.R.M. Ligtenberg, E. Rignot, and M.R. van den
12 Broeke, 2013: Observed thinning of Totten Glacier is linked to coastal polynya variability.
13 *Nature Communications*, **4**, 2857. <http://dx.doi.org/10.1038/ncomms3857>
- 14 Kjeldsen, K.K., N.J. Korsgaard, A.A. Bjørk, S.A. Khan, J.E. Box, S. Funder, N.K. Larsen, J.L.
15 Bamber, W. Colgan, M. van den Broeke, M.-L. Siggaard-Andersen, C. Nuth, A.
16 Schomacker, C.S. Andresen, E. Willerslev, and K.H. Kjær, 2015: Spatial and temporal
17 distribution of mass loss from the Greenland Ice Sheet since AD 1900. *Nature*, **528**, 396-400.
18 <http://dx.doi.org/10.1038/nature16183>
- 19 Knutson, T.R., J.J. Sirutis, M. Zhao, R.E. Tuleya, M. Bender, G.A. Vecchi, G. Villarini, and D.
20 Chavas, 2015: Global projections of intense tropical cyclone activity for the late twenty-first
21 century from dynamical downscaling of CMIP5/RCP4.5 scenarios. *Journal of Climate*, **28**,
22 7203-7224. <http://dx.doi.org/10.1175/JCLI-D-15-0129.1>
- 23 Knutson, T.R., J.J. Sirutis, G.A. Vecchi, S. Garner, M. Zhao, H.-S. Kim, M. Bender, R.E.
24 Tuleya, I.M. Held, and G. Villarini, 2013: Dynamical downscaling projections of twenty-
25 first-century Atlantic hurricane activity: CMIP3 and CMIP5 model-based scenarios. *Journal*
26 *of Climate*, **27**, 6591-6617. <http://dx.doi.org/10.1175/jcli-d-12-00539.1>
- 27 Kopp, R.E., 2013: Does the mid-Atlantic United States sea level acceleration hot spot reflect
28 ocean dynamic variability? *Geophysical Research Letters*, **40**, 3981-3985.
29 <http://dx.doi.org/10.1002/grl.50781>
- 30 Kopp, R.E., F.J. Simons, J.X. Mitrovica, A.C. Maloof, and M. Oppenheimer, 2009: Probabilistic
31 assessment of sea level during the last interglacial stage. *Nature*, **462**, 863-867.
32 <http://dx.doi.org/10.1038/nature08686>
- 33 Kopp, R.E., R.M. Horton, C.M. Little, J.X. Mitrovica, M. Oppenheimer, D.J. Rasmussen, B.H.
34 Strauss, and C. Tebaldi, 2014: Probabilistic 21st and 22nd century sea-level projections at a

- 1 global network of tide-gauge sites. *Earth's Future*, **2**, 383-406.
2 <http://dx.doi.org/10.1002/2014EF000239>
- 3 Kopp, R.E., C.C. Hay, C.M. Little, and J.X. Mitrovica, 2015: Geographic variability of sea-level
4 change. *Current Climate Change Reports*, **1**, 192-204. <http://dx.doi.org/10.7282/T37W6F4P>
- 5 Kopp, R.E., B.P. Horton, A.C. Kemp, and C. Tebaldi, 2015: Past and future sea-level rise along
6 the coast of North Carolina, USA. *Climatic Change*, **132**, 693-707.
7 <http://dx.doi.org/10.1007/s10584-015-1451-x>
- 8 Kopp, R.E., A.C. Kemp, K. Bittermann, B.P. Horton, J.P. Donnelly, W.R. Gehrels, C.C. Hay,
9 J.X. Mitrovica, E.D. Morrow, and S. Rahmstorf, 2016: Temperature-driven global sea-level
10 variability in the Common Era. *Proceedings of the National Academy of Sciences*, **113**,
11 E1434-E1441. <http://dx.doi.org/10.1073/pnas.1517056113>
- 12 Lambeck, K., H. Rouby, A. Purcell, Y. Sun, and M. Sambridge, 2014: Sea level and global ice
13 volumes from the Last Glacial Maximum to the Holocene. *Proceedings of the National*
14 *Academy of Sciences*, **111**, 15296-15303. <http://dx.doi.org/10.1073/pnas.1411762111>
- 15 Lenton, T.M., 2011: Early warning of climate tipping points. *Nature Climate Change*, **1**, 201-
16 209. <http://dx.doi.org/10.1038/nclimate1143>
- 17 Lentz, E.E., E.R. Thieler, N.G. Plant, S.R. Stippa, R.M. Horton, and D.B. Gesch, 2016:
18 Evaluation of dynamic coastal response to sea-level rise modifies inundation likelihood.
19 *Nature Climate Change*, **6**, 696-700. <http://dx.doi.org/10.1038/nclimate2957>
- 20 Leuliette, E.W., 2015: The balancing of the sea-level budget. *Current Climate Change Reports*,
21 **1**, 185-191. <http://dx.doi.org/10.1007/s40641-015-0012-8>
- 22 Leuliette, E.W. and R.S. Nerem, 2016: Contributions of Greenland and Antarctica to global and
23 regional sea level change. *Oceanography*, **29**, 154-159.
24 <http://dx.doi.org/10.5670/oceanog.2016.107>
- 25 Levermann, A., A. Griesel, M. Hofmann, M. Montoya, and S. Rahmstorf, 2005: Dynamic sea
26 level changes following changes in the thermohaline circulation. *Climate Dynamics*, **24** (4),
27 347-354, doi:10.1007/s00382-004-0505-y.
- 28 Levermann, A., P.U. Clark, B. Marzeion, G.A. Milne, D. Pollard, V. Radic, and A. Robinson,
29 2013: The multimillennial sea-level commitment of global warming. *Proceedings of the*
30 *National Academy of Sciences*, **110**, 13745-13750.
31 <http://dx.doi.org/10.1073/pnas.1219414110>

- 1 Li, X., E. Rignot, M. Morlighem, J. Mouginot, and B. Scheuchl, 2015: Grounding line retreat of
2 Totten Glacier, East Antarctica, 1996 to 2013. *Geophysical Research Letters*, **42**, 8049-8056.
3 <http://dx.doi.org/10.1002/2015GL065701>
- 4 Lin, N., K. Emanuel, M. Oppenheimer, and E. Vanmarcke, 2012: Physically based assessment of
5 hurricane surge threat under climate change. *Nature Climate Change*, **2**, 462-467.
6 <http://dx.doi.org/10.1038/nclimate1389>
- 7 Lin, N., R.E. Kopp, B.P. Horton, and J.P. Donnelly, 2016: Hurricane Sandy's flood frequency
8 increasing from year 1800 to 2100. *Proceedings of the National Academy of Sciences*, **113**,
9 12071-12075. <http://dx.doi.org/10.1073/pnas.1604386113>
- 10 Little, C.M., R.M. Horton, R.E. Kopp, M. Oppenheimer, and S. Yip, 2015: Uncertainty in
11 twenty-first-century CMIP5 sea level projections. *Journal of Climate*, **28**, 838-852.
12 <http://dx.doi.org/10.1175/JCLI-D-14-00453.1>
- 13 Llovel, W., J.K. Willis, F.W. Landerer, and I. Fukumori, 2014: Deep-ocean contribution to sea
14 level and energy budget not detectable over the past decade. *Nature Climate Change*, **4**,
15 1031-1035. <http://dx.doi.org/10.1038/nclimate2387>
- 16 MacGregor, J.A., W.T. Colgan, M.A. Fahnestock, M. Morlighem, G.A. Catania, J.D. Paden, and
17 S.P. Gogineni, 2016: Holocene deceleration of the Greenland Ice Sheet. *Science*, **351**, 590-
18 593. <http://dx.doi.org/10.1126/science.aab1702>
- 19 Marcos, M. and A. Amores, 2014: Quantifying anthropogenic and natural contributions to
20 thermosteric sea level rise. *Geophysical Research Letters*, **41**, 2502-2507.
21 <http://dx.doi.org/10.1002/2014GL059766>
- 22 Marcos, M., F.M. Calafat, Á. Berihuete, and S. Dangendorf, 2015: Long-term variations in
23 global sea level extremes. *Journal of Geophysical Research: Oceans*, **120**, 8115-8134.
24 <http://dx.doi.org/10.1002/2015JC011173>
- 25 Marcos, M., B. Marzeion, S. Dangendorf, A.B.A. Slangen, H. Palanisamy, and L. Fenoglio-
26 Marc, 2017: Internal variability versus anthropogenic forcing on sea level and its
27 components. *Surveys in Geophysics*, **38**, 329-348. <http://dx.doi.org/10.1007/s10712-016-9373-3>
28
- 29 Markusson, N., F. Ginn, N. Singh Ghaleigh, and V. Scott, 2014: 'In case of emergency press
30 here': Framing geoengineering as a response to dangerous climate change. *Wiley*
31 *Interdisciplinary Reviews: Climate Change*, **5**, 281-290. <http://dx.doi.org/10.1002/wcc.263>
- 32 Martín-Español, A., A. Zammit-Mangion, P.J. Clarke, T. Flament, V. Helm, M.A. King, S.B.
33 Luthcke, E. Petrie, F. Rémy, N. Schön, B. Wouters, and J.L. Bamber, 2016: Spatial and
34 temporal Antarctic Ice Sheet mass trends, glacio-isostatic adjustment, and surface processes

- 1 from a joint inversion of satellite altimeter, gravity, and GPS data. *Journal of Geophysical*
2 *Research: Earth Surface*, **121**, 182-200. <http://dx.doi.org/10.1002/2015JF003550>
- 3 Marzeion, B., J.G. Cogley, K. Richter, and D. Parkes, 2014: Attribution of global glacier mass
4 loss to anthropogenic and natural causes. *Science*, **345**, 919-921.
5 <http://dx.doi.org/10.1126/science.1254702>
- 6 Mawdsley, R.J. and I.D. Haigh, 2016: Spatial and temporal variability and long-term trends in
7 skew surges globally. *Frontiers in Marine Science*, **3**.
8 <http://dx.doi.org/10.3389/fmars.2016.00029>
- 9 Menéndez, M. and P.L. Woodworth, 2010: Changes in extreme high water levels based on a
10 quasi-global tide-gauge data set. *Journal of Geophysical Research*, **115**, C10011.
11 <http://dx.doi.org/10.1029/2009JC005997>
- 12 Mengel, M., A. Levermann, K. Frieler, A. Robinson, B. Marzeion, and R. Winkelmann, 2016:
13 Future sea level rise constrained by observations and long-term commitment. *Proceedings of*
14 *the National Academy of Sciences*, **113**, 2597-2602.
15 <http://dx.doi.org/10.1073/pnas.1500515113>
- 16 Merrifield, M.A., 2011: A shift in western tropical Pacific sea level trends during the 1990s.
17 *Journal of Climate*, **24**, 4126-4138. <http://dx.doi.org/10.1175/2011JCLI3932.1>
- 18 Merrifield, M.A., P. Thompson, E. Leuliette, G.T. Mitchum, D.P. Chambers, S. Jevrejeva, R.S.
19 Nerem, M. Menéndez, W. Sweet, B. Hamlington, and J.J. Marra, 2015: [Global Oceans] Sea
20 level variability and change [in “State of the Climate in 2014”]. *Bulletin of the American*
21 *Meteorological Society*, **96 (12)**, S82-S85.
22 <http://dx.doi.org/10.1175/2015BAMSStateoftheClimate.1>
- 23 Miller, K.G., M.A. Kominz, J.V. Browning, J.D. Wright, G.S. Mountain, M.E. Katz, P.J.
24 Sugarman, B.S. Cramer, N. Christie-Blick, and S.F. Pekar, 2005: The Phanerozoic record of
25 global sea-level change. *Science*, **310**, 1293-1298. <http://dx.doi.org/10.1126/science.1116412>
- 26 Miller, K.G., J.D. Wright, J.V. Browning, A. Kulpecz, M. Kominz, T.R. Naish, B.S. Cramer, Y.
27 Rosenthal, W.R. Peltier, and S. Sossdian, 2012: High tide of the warm Pliocene: Implications
28 of global sea level for Antarctic deglaciation. *Geology*, **40**, 407-410.
29 <http://dx.doi.org/10.1130/g32869.1>
- 30 Miller, K.G., R.E. Kopp, B.P. Horton, J.V. Browning, and A.C. Kemp, 2013: A geological
31 perspective on sea-level rise and its impacts along the U.S. mid-Atlantic coast. *Earth's*
32 *Future*, **1**, 3-18. <http://dx.doi.org/10.1002/2013EF000135>

- 1 Mitrovica, J.X., N. Gomez, E. Morrow, C. Hay, K. Letychev, and M.E. Tamisiea, 2011: On the
2 robustness of predictions of sea level fingerprints. *Geophysical Journal International*, **187**,
3 729-742. <http://dx.doi.org/10.1111/j.1365-246X.2011.05090.x>
- 4 Moftakhari, H.R., A. AghaKouchak, B.F. Sanders, D.L. Feldman, W. Sweet, R.A. Matthew, and
5 A. Luke, 2015: Increased nuisance flooding along the coasts of the United States due to sea
6 level rise: Past and future. *Geophysical Research Letters*, **42**, 9846-9852.
7 <http://dx.doi.org/10.1002/2015GL066072>
- 8 Moritz, H., K. White, B. Gouldby, W. Sweet, P. Ruggiero, M. Gravens, P. O'Brien, H. Moritz, T.
9 Wahl, N.C. Nadal-Caraballo, and W. Veatch, 2015: USACE adaptation approach for future
10 coastal climate conditions. *Proceedings of the Institution of Civil Engineers - Maritime*
11 *Engineering*, **168**, 111-117. <http://dx.doi.org/10.1680/jmaen.15.00015>
- 12 Mouginot, J., E. Rignot, and B. Scheuchl, 2014: Sustained increase in ice discharge from the
13 Amundsen Sea Embayment, West Antarctica, from 1973 to 2013. *Geophysical Research*
14 *Letters*, **41**, 1576-1584. <http://dx.doi.org/10.1002/2013GL059069>
- 15 Nerem, R.S., D.P. Chambers, C. Choe, and G.T. Mitchum, 2010: Estimating mean sea level
16 change from the TOPEX and Jason altimeter missions. *Marine Geodesy*, **33**, 435-446.
17 <http://dx.doi.org/10.1080/01490419.2010.491031>
- 18 Paolo, F.S., H.A. Fricker, and L. Padman, 2015: Volume loss from Antarctic ice shelves is
19 accelerating. *Science*, **348**, 327-331. <http://dx.doi.org/10.1126/science.aaa0940>
- 20 Passeri, D.L., S.C. Hagen, S.C. Medeiros, M.V. Bilskie, K. Alizad, and D. Wang, 2015: The
21 dynamic effects of sea level rise on low-gradient coastal landscapes: A review. *Earth's*
22 *Future*, **3**, 159-181. <http://dx.doi.org/10.1002/2015EF000298>
- 23 Pfeffer, W.T., J.T. Harper, and S. O'Neel, 2008: Kinematic constraints on glacier contributions to
24 21st-century sea-level rise. *Science*, **321**, 1340-1343.
25 <http://dx.doi.org/10.1126/science.1159099>
- 26 Pollard, D., R.M. DeConto, and R.B. Alley, 2015: Potential Antarctic Ice Sheet retreat driven by
27 hydrofracturing and ice cliff failure. *Earth and Planetary Science Letters*, **412**, 112-121.
28 <http://dx.doi.org/10.1016/j.epsl.2014.12.035>
- 29 PSMSL, 2016: Obtaining tide gauge data. Permanent Service for Mean Sea Level.
30 <http://www.psmsl.org/data/obtaining/>
- 31 Rahmstorf, S., 2007: A semi-empirical approach to projecting future sea-level rise. *Science*, **315**,
32 368-370. <http://dx.doi.org/10.1126/science.1135456>

- 1 Rahmstorf, S., J.E. Box, G. Feulner, M.E. Mann, A. Robinson, S. Rutherford, and E.J.
2 Schaffernicht, 2015: Exceptional twentieth-century slowdown in Atlantic Ocean overturning
3 circulation. *Nature Climate Change*, **5**, 475-480. <http://dx.doi.org/10.1038/nclimate2554>
- 4 Reager, J.T., A.S. Gardner, J.S. Famiglietti, D.N. Wiese, A. Eicker, and M.-H. Lo, 2016: A
5 decade of sea level rise slowed by climate-driven hydrology. *Science*, **351**, 699-703.
6 <http://dx.doi.org/10.1126/science.aad8386>
- 7 Reed, A.J., M.E. Mann, K.A. Emanuel, N. Lin, B.P. Horton, A.C. Kemp, and J.P. Donnelly,
8 2015: Increased threat of tropical cyclones and coastal flooding to New York City during the
9 anthropogenic era. *Proceedings of the National Academy of Sciences*, **112**, 12610-12615.
10 <http://dx.doi.org/10.1073/pnas.1513127112>
- 11 Rietbroek, R., S.-E. Brunnabend, J. Kusche, J. Schröter, and C. Dahle, 2016: Revisiting the
12 contemporary sea-level budget on global and regional scales. *Proceedings of the National
13 Academy of Sciences*, **113**, 1504-1509. <http://dx.doi.org/10.1073/pnas.1519132113>
- 14 Rignot, E., J. Mouginot, M. Morlighem, H. Seroussi, and B. Scheuchl, 2014: Widespread, rapid
15 grounding line retreat of Pine Island, Thwaites, Smith, and Kohler Glaciers, West Antarctica,
16 from 1992 to 2011. *Geophysical Research Letters*, **41**, 3502-3509.
17 <http://dx.doi.org/10.1002/2014GL060140>
- 18 Ritz, C., T.L. Edwards, G. Durand, A.J. Payne, V. Peyaud, and R.C.A. Hindmarsh, 2015:
19 Potential sea-level rise from Antarctic ice-sheet instability constrained by observations.
20 *Nature*, **528**, 115-118. <http://dx.doi.org/10.1038/nature16147>
- 21 Ruggiero, P., 2013: Is the intensifying wave climate of the U.S. Pacific Northwest increasing
22 flooding and erosion risk faster than sea-level rise? *Journal of Waterway, Port, Coastal, and
23 Ocean Engineering*, **139**, 88-97. [http://dx.doi.org/10.1061/\(ASCE\)WW.1943-5460.0000172](http://dx.doi.org/10.1061/(ASCE)WW.1943-5460.0000172)
- 24 Sallenger, A.H., K.S. Doran, and P.A. Howd, 2012: Hotspot of accelerated sea-level rise on the
25 Atlantic coast of North America. *Nature Climate Change*, **2**, 884-888.
26 <http://dx.doi.org/10.1038/nclimate1597>
- 27 Scambos, T. and C. Shuman, 2016: Comment on 'Mass gains of the Antarctic ice sheet exceed
28 losses' by H. J. Zwally and others. *Journal of Glaciology*, **62**, 599-603.
29 <http://dx.doi.org/10.1017/jog.2016.59>
- 30 Seo, K.-W., C.R. Wilson, T. Scambos, B.-M. Kim, D.E. Waliser, B. Tian, B.-H. Kim, and J.
31 Eom, 2015: Surface mass balance contributions to acceleration of Antarctic ice mass loss
32 during 2003–2013. *Journal of Geophysical Research: Solid Earth*, **120**, 3617-3627.
33 <http://dx.doi.org/10.1002/2014JB011755>

- 1 Serafin, K.A. and P. Ruggiero, 2014: Simulating extreme total water levels using a time-
2 dependent, extreme value approach. *Journal of Geophysical Research: Oceans*, **119**, 6305-
3 6329. <http://dx.doi.org/10.1002/2014JC010093>
- 4 Shennan, I., A.J. Long, and B.P. Horton, eds., 2015: *Handbook of Sea-Level Research*. John
5 Wiley & Sons, Ltd, 581 pp. <http://dx.doi.org/10.1002/9781118452547>
- 6 Shepherd, A., E.R. Ivins, A. Geruo, V.R. Barletta, M.J. Bentley, S. Bettadpur, K.H. Briggs, D.H.
7 Bromwich, R. Forsberg, N. Galin, M. Horwath, S. Jacobs, I. Joughin, M.A. King, J.T.M.
8 Lenaerts, J. Li, S.R.M. Ligtenberg, A. Luckman, S.B. Luthcke, M. McMillan, R. Meister, G.
9 Milne, J. Mouginot, A. Muir, J.P. Nicolas, J. Paden, A.J. Payne, H. Pritchard, E. Rignot, H.
10 Rott, L. Sandberg Sørensen, T.A. Scambos, B. Scheuchl, E.J.O. Schrama, B. Smith, A.V.
11 Sundal, J.H. van Angelen, W.J. van de Berg, M.R. van den Broeke, D.G. Vaughan, I.
12 Velicogna, J. Wahr, P.L. Whitehouse, D.J. Wingham, D. Yi, D. Young, and H.J. Zwally,
13 2012: A reconciled estimate of ice-sheet mass balance. *Science*, **338**, 1183-1189.
14 <http://dx.doi.org/10.1126/science.1228102>
- 15 Shope, J.B., C.D. Storlazzi, L.H. Erikson, and C.A. Hegermiller, 2016: Changes to extreme wave
16 climates of islands within the western tropical Pacific throughout the 21st century under RCP
17 4.5 and RCP 8.5, with implications for island vulnerability and sustainability. *Global and
18 Planetary Change*, **141**, 25-38. <http://dx.doi.org/10.1016/j.gloplacha.2016.03.009>
- 19 Sillmann, J., T.M. Lenton, A. Levermann, K. Ott, M. Hulme, F. Benduhn, and J.B. Horton, 2015:
20 Climate emergencies do not justify engineering the climate. *Nature Climate Change*, **5**, 290-
21 292. <http://dx.doi.org/10.1038/nclimate2539>
- 22 Slangen, A.B.A., M. Carson, C.A. Katsman, R.S.W. van de Wal, A. Köhl, L.L.A. Vermeersen,
23 and D. Stammer, 2014: Projecting twenty-first century regional sea-level changes. *Climatic
24 Change*, **124**, 317-332. <http://dx.doi.org/10.1007/s10584-014-1080-9>
- 25 Slangen, A.B.A., J.A. Church, X. Zhang, and D. Monselesan, 2014: Detection and attribution of
26 global mean thermosteric sea level change. *Geophysical Research Letters*, **41**, 5951-5959.
27 <http://dx.doi.org/10.1002/2014GL061356>
- 28 Slangen, A.B.A., J.A. Church, C. Agosta, X. Fettweis, B. Marzeion, and K. Richter, 2016:
29 Anthropogenic forcing dominates global mean sea-level rise since 1970. *Nature Climate
30 Change*, **6**, 701-705. <http://dx.doi.org/10.1038/nclimate2991>
- 31 Smith, J.M., M.A. Cialone, T.V. Wamsley, and T.O. McAlpin, 2010: Potential impact of sea
32 level rise on coastal surges in southeast Louisiana. *Ocean Engineering*, **37**, 37-47.
33 <http://dx.doi.org/10.1016/j.oceaneng.2009.07.008>

- 1 Sriver, R.L., N.M. Urban, R. Olson, and K. Keller, 2012: Toward a physically plausible upper
2 bound of sea-level rise projections. *Climatic Change*, **115**, 893-902.
3 <http://dx.doi.org/10.1007/s10584-012-0610-6>
- 4 Stockdon, H.F., R.A. Holman, P.A. Howd, and A.H. Sallenger, Jr., 2006: Empirical
5 parameterization of setup, swash, and runup. *Coastal Engineering*, **53**, 573-588.
6 <http://dx.doi.org/10.1016/j.coastaleng.2005.12.005>
- 7 Stopa, J.E. and K.F. Cheung, 2014: Periodicity and patterns of ocean wind and wave climate.
8 *Journal of Geophysical Research: Oceans*, **119**, 5563-5584.
9 <http://dx.doi.org/10.1002/2013JC009729>
- 10 Strauss, B.H., S. Kulp, and A. Levermann, 2015: Carbon choices determine US cities committed
11 to futures below sea level. *Proceedings of the National Academy of Sciences*, **112**, 13508-
12 13513. <http://dx.doi.org/10.1073/pnas.1511186112>
- 13 Sutterley, T.C., I. Velicogna, E. Rignot, J. Mouginot, T. Flament, M.R. van den Broeke, J.M.
14 van Wessem, and C.H. Reijmer, 2014: Mass loss of the Amundsen Sea embayment of West
15 Antarctica from four independent techniques. *Geophysical Research Letters*, **41**, 8421-8428.
16 <http://dx.doi.org/10.1002/2014GL061940>
- 17 Sweet, W.V. and J.J. Marra, 2016: State of U.S. Nuisance Tidal Flooding. Supplement to State of
18 the Climate: National Overview for May 2016. National Oceanic and Atmospheric
19 Administration, National Centers for Environmental Information, 5 pp.
20 [http://www.ncdc.noaa.gov/monitoring-content/sotc/national/2016/may/sweet-marra-
21 nuisance-flooding-2015.pdf](http://www.ncdc.noaa.gov/monitoring-content/sotc/national/2016/may/sweet-marra-nuisance-flooding-2015.pdf)
- 22 Sweet, W.V. and J. Park, 2014: From the extreme to the mean: Acceleration and tipping points
23 of coastal inundation from sea level rise. *Earth's Future*, **2**, 579-600.
24 <http://dx.doi.org/10.1002/2014EF000272>
- 25 Sweet, W.V. and C. Zervas, 2011: Cool-season sea level anomalies and storm surges along the
26 U.S. East Coast: Climatology and comparison with the 2009/10 El Niño. *Monthly Weather
27 Review*, **139**, 2290-2299. <http://dx.doi.org/10.1175/MWR-D-10-05043.1>
- 28 Sweet, W.V., C. Zervas, S. Gill, and J. Park, 2013: Hurricane Sandy inundation probabilities of
29 today and tomorrow [in "Explaining Extreme Events of 2012 from a Climate Perspective"].
30 *Bulletin of the American Meteorological Society*, **94** (9), S17-S20.
31 <http://dx.doi.org/10.1175/BAMS-D-13-00085.1>
- 32 Sweet, W., J. Park, J. Marra, C. Zervas, and S. Gill, 2014: Sea Level Rise and Nuisance Flood
33 Frequency Changes around the United States. NOAA Technical Report NOS CO-OPS 073.
34 National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring,
35 MD. 58 pp.

- 1 [http://tidesandcurrents.noaa.gov/publications/NOAA_Technical_Report_NOS_COOPS_073.](http://tidesandcurrents.noaa.gov/publications/NOAA_Technical_Report_NOS_COOPS_073.pdf)
2 pdf
- 3 Sweet, W.V., J. Park, S. Gill, and J. Marra, 2015: New ways to measure waves and their effects
4 at NOAA tide gauges: A Hawaiian-network perspective. *Geophysical Research Letters*, **42**,
5 9355-9361. <http://dx.doi.org/10.1002/2015GL066030>
- 6 Sweet, W., M. Menendez, A. Genz, J. Obeysekera, J. Park, and J. Marra, 2016: In tide's way:
7 Southeast Florida's September 2015 sunny-day flood [in "Explaining Extreme Events of
8 2015 from a Climate Perspective"]. *Bulletin of the American Meteorological Society*, **97** (12),
9 S25-S30. <http://dx.doi.org/10.1175/BAMS-D-16-0117.1>
- 10 Sweet, W.V., R.E. Kopp, C.P. Weaver, J. Obeysekera, R.M. Horton, E.R. Thieler, and C. Zervas,
11 2017: Global and Regional Sea Level Rise Scenarios for the United States. NOAA Tech.
12 Rep. NOS CO-OPS 083. National Oceanic and Atmospheric Administration, National Ocean
13 Service, Silver Spring, MD. 75 pp.
14 [https://tidesandcurrents.noaa.gov/publications/techrpt83_Global_and_Regional_SLR_Scenar](https://tidesandcurrents.noaa.gov/publications/techrpt83_Global_and_Regional_SLR_Scenarios_for_the_US_final.pdf)
15 [ios_for_the_US_final.pdf](https://tidesandcurrents.noaa.gov/publications/techrpt83_Global_and_Regional_SLR_Scenarios_for_the_US_final.pdf)
- 16 Talke, S.A., P. Orton, and D.A. Jay, 2014: Increasing storm tides in New York Harbor, 1844–
17 2013. *Geophysical Research Letters*, **41**, 3149-3155.
18 <http://dx.doi.org/10.1002/2014GL059574>
- 19 Tebaldi, C., B.H. Strauss, and C.E. Zervas, 2012: Modelling sea level rise impacts on storm
20 surges along US coasts. *Environmental Research Letters*, **7**, 014032.
21 <http://dx.doi.org/10.1088/1748-9326/7/1/014032>
- 22 Tedesco, M., X. Fettweis, T. Mote, J. Wahr, P. Alexander, J.E. Box, and B. Wouters, 2013:
23 Evidence and analysis of 2012 Greenland records from spaceborne observations, a regional
24 climate model and reanalysis data. *The Cryosphere*, **7**, 615-630. [http://dx.doi.org/10.5194/tc-](http://dx.doi.org/10.5194/tc-7-615-2013)
25 [7-615-2013](http://dx.doi.org/10.5194/tc-7-615-2013)
- 26 Tedesco, M., S. Doherty, X. Fettweis, P. Alexander, J. Jeyaratnam, and J. Stroeve, 2016: The
27 darkening of the Greenland ice sheet: Trends, drivers, and projections (1981–2100). *The*
28 *Cryosphere*, **10**, 477-496. <http://dx.doi.org/10.5194/tc-10-477-2016>
- 29 Theuerkauf, E.J., A.B. Rodriguez, S.R. Fegley, and R.A. Luettich, 2014: Sea level anomalies
30 exacerbate beach erosion. *Geophysical Research Letters*, **41**, 5139-5147.
31 <http://dx.doi.org/10.1002/2014GL060544>
- 32 Thompson, P.R., G.T. Mitchum, C. Vonesch, and J. Li, 2013: Variability of winter storminess in
33 the eastern United States during the twentieth century from tide gauges. *Journal of Climate*,
34 **26**, 9713-9726. <http://dx.doi.org/10.1175/JCLI-D-12-00561.1>

- 1 Wada, Y., M.-H. Lo, P.J.F. Yeh, J.T. Reager, J.S. Famiglietti, R.-J. Wu, and Y.-H. Tseng, 2016:
2 Fate of water pumped from underground and contributions to sea-level rise. *Nature Climate*
3 *Change*, **6**, 777-780. <http://dx.doi.org/10.1038/nclimate3001>
- 4 Wada, Y., J.T. Reager, B.F. Chao, J. Wang, M.-H. Lo, C. Song, Y. Li, and A.S. Gardner, 2017:
5 Recent changes in land water storage and its contribution to sea level variations. *Surveys in*
6 *Geophysics*, **38**, 131-152. <http://dx.doi.org/10.1007/s10712-016-9399-6>
- 7 Wahl, T. and D.P. Chambers, 2015: Evidence for multidecadal variability in US extreme sea
8 level records. *Journal of Geophysical Research: Oceans*, **120**, 1527-1544.
9 <http://dx.doi.org/10.1002/2014JC010443>
- 10 Wahl, T. and D.P. Chambers, 2016: Climate controls multidecadal variability in U. S. extreme
11 sea level records. *Journal of Geophysical Research: Oceans*, **121**, 1274-1290.
12 <http://dx.doi.org/10.1002/2015JC011057>
- 13 Wang, X.L., Y. Feng, and V.R. Swail, 2014: Changes in global ocean wave heights as projected
14 using multimodel CMIP5 simulations. *Geophysical Research Letters*, **41**, 1026-1034.
15 <http://dx.doi.org/10.1002/2013GL058650>
- 16 Wong, P.P., I.J. Losada, J.-P. Gattuso, J. Hinkel, A. Khattabi, K.L. McInnes, Y. Saito, and A.
17 Sallenger, 2014: Coastal systems and low-lying areas. *Climate Change 2014:*
18 *Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of*
19 *Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate*
20 *Change*. Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M.
21 Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S.
22 MacCracken, P.R. Mastrandrea, and L.L. White, Eds. Cambridge University Press,
23 Cambridge, United Kingdom and New York, NY, USA, 361-409.
24 <http://www.ipcc.ch/report/ar5/wg2/>
- 25 Woodruff, J.D., J.L. Irish, and S.J. Camargo, 2013: Coastal flooding by tropical cyclones and
26 sea-level rise. *Nature*, **504**, 44-52. <http://dx.doi.org/10.1038/nature12855>
- 27 Woodworth, P.L. and M. Menéndez, 2015: Changes in the mesoscale variability and in extreme
28 sea levels over two decades as observed by satellite altimetry. *Journal of Geophysical*
29 *Research: Oceans*, **120**, 64-77. <http://dx.doi.org/10.1002/2014JC010363>
- 30 Wöppelmann, G. and M. Marcos, 2016: Vertical land motion as a key to understanding sea level
31 change and variability. *Reviews of Geophysics*, **54**, 64-92.
32 <http://dx.doi.org/10.1002/2015RG000502>
- 33 Wouters, B., A. Martín-Español, V. Helm, T. Flament, J.M. van Wessem, S.R.M. Ligtenberg,
34 M.R. van den Broeke, and J.L. Bamber, 2015: Dynamic thinning of glaciers on the Southern
35 Antarctic Peninsula. *Science*, **348**, 899-903. <http://dx.doi.org/10.1126/science.aaa5727>

- 1 Yin, J. and P.B. Goddard, 2013: Oceanic control of sea level rise patterns along the East Coast of
2 the United States. *Geophysical Research Letters*, **40**, 5514-5520.
3 <http://dx.doi.org/10.1002/2013GL057992>
- 4 Yin, J., M.E. Schlesinger, and R.J. Stouffer, 2009: Model projections of rapid sea-level rise on
5 the northeast coast of the United States. *Nature Geoscience*, **2**, 262-266.
6 <http://dx.doi.org/10.1038/ngeo462>
- 7 Zappa, G., L.C. Shaffrey, K.I. Hodges, P.G. Sansom, and D.B. Stephenson, 2013: A multimodel
8 assessment of future projections of North Atlantic and European extratropical cyclones in the
9 CMIP5 climate models. *Journal of Climate*, **26**, 5846-5862. [http://dx.doi.org/10.1175/jcli-d-](http://dx.doi.org/10.1175/jcli-d-12-00573.1)
10 [12-00573.1](http://dx.doi.org/10.1175/jcli-d-12-00573.1)
- 11 Zervas, C., S. Gill, and W.V. Sweet, 2013: Estimating Vertical Land Motion From Long-term
12 Tide Gauge Records. NOAA Tech. Rep. NOS CO-OPS 65. National Oceanic and
13 Atmospheric Administration, National Ocean Service, 22 pp.
14 https://tidesandcurrents.noaa.gov/publications/Technical_Report_NOS_CO-OPS_065.pdf
- 15 Zhang, X. and J.A. Church, 2012: Sea level trends, interannual and decadal variability in the
16 Pacific Ocean. *Geophysical Research Letters*, **39**, L21701.
17 <http://dx.doi.org/10.1029/2012GL053240>

1 **13. Ocean Acidification and Other Ocean Changes**

2 **KEY FINDINGS**

- 3 1. The world's oceans have absorbed about 93% of the excess heat caused by greenhouse
4 gas warming since the mid-20th century, making them warmer and altering global and
5 regional climate feedbacks. Ocean heat content has increased at all depths since the 1960s
6 and surface waters have warmed by about $1.3^{\circ} \pm 0.1^{\circ}\text{F}$ ($0.7^{\circ} \pm 0.08^{\circ}\text{C}$) per century
7 globally since 1900 to 2016. Under a high emissions scenario, a global increase in
8 average sea surface temperature of $4.9^{\circ} \pm 1.3^{\circ}\text{F}$ ($2.7^{\circ} \pm 0.7^{\circ}\text{C}$) by 2100 is projected, with
9 even higher changes in some U.S. coastal regions. (*Very high confidence*)
- 10 2. The potential slowing of the Atlantic Meridional Overturning Circulation (AMOC) (of
11 which the Gulf Stream is one component)—as a result of increasing ocean heat content
12 and freshwater driven buoyancy changes—could have dramatic climate feedbacks as the
13 ocean absorbs less heat and CO_2 from the atmosphere. This slowing would also affect the
14 climates of North America and Europe. Any slowing documented to date cannot be
15 directly tied to anthropogenic forcing primarily due to lack of adequate observational data
16 and to challenges in modeling ocean circulation changes. Under a high emissions
17 scenario (RCP8.5) in CMIP5 simulations, it is likely that the AMOC will weaken over
18 the 21st century by 12% to 54%. (*Low confidence*)
- 19 3. The world's oceans are currently absorbing more than a quarter of the CO_2 emitted to the
20 atmosphere annually from human activities, making them more acidic (*very high*
21 *confidence*), with potential detrimental impacts to marine ecosystems. In particular,
22 higher-latitude systems typically have a lower buffering capacity against pH change,
23 exhibiting seasonally corrosive conditions sooner than low-latitude systems.
24 Acidification is regionally increasing along U.S. coastal systems as a result of upwelling
25 (for example, in the Pacific Northwest) (*high confidence*), changes in freshwater inputs
26 (for example, in the Gulf of Maine) (*medium confidence*), and nutrient input (for
27 example, in urbanized estuaries) (*high confidence*). The rate of acidification is
28 unparalleled in at least the past 66 million years (*medium confidence*). Under RCP8.5, the
29 global average surface ocean acidity is projected to increase by 100% to 150% (*high*
30 *confidence*).
- 31 4. Increasing sea surface temperatures, rising sea levels, and changing patterns of
32 precipitation, winds, nutrients, and ocean circulation are contributing to overall declining
33 oxygen concentrations at intermediate depths in various ocean locations and in many
34 coastal areas. Over the last half century, major oxygen losses have occurred in inland
35 seas, estuaries, and in the coastal and open ocean (*high confidence*). Ocean oxygen levels
36 are projected to decrease by as much as 3.5% under the RCP8.5 scenario by 2100 relative
37 to preindustrial values (*high confidence*).

1 **13.0 A Changing Ocean**

2 Anthropogenic perturbations to the global Earth system have included important alterations in
3 the nutrient composition, temperature, and circulation of the oceans. Some of these changes will
4 be distinguishable from the background natural variability in nearly half of the global open ocean
5 within a decade, with important consequences for marine ecosystems and their services (Gattuso
6 et al. 2015). However, the timeframe for detection will vary depending on the parameter featured
7 (Henson et al 2010; Henson et al 2016).

8 **13.1 Ocean Warming**

9 **13.1.1 General Background**

10 Approximately 93% of excess heat energy trapped since the 1970s has been absorbed into the
11 oceans, lessening atmospheric warming and leading to a variety of changes in ocean conditions,
12 including sea level rise and ocean circulation (see Ch. 2: Physical Drivers of Climate Change,
13 Ch. 6: Temperature Change, and Ch. 12: Sea Level Rise in this report; Rhein et al. 2013; Gattuso
14 et al. 2015). This is the result of the high heat capacity of seawater relative to the atmosphere, the
15 relative area of the ocean compared to the land, and the ocean circulation that enables the
16 transport of heat into deep waters. This large heat absorption by the oceans moderates the effects
17 of increased anthropogenic greenhouse emissions on terrestrial climates while altering the
18 fundamental physical properties of the ocean and indirectly impacting chemical properties such
19 as the biological pump through increased stratification (Gattuso et al. 2015; Rossby 1959).
20 Although upper ocean temperature varies over short- and medium timescales (for example,
21 seasonal and regional patterns), there are clear long-term increases in surface temperature and
22 ocean heat content over the past 65 years (Cheng et al. 2017; Rhein et al. 2013; Levitus et al.
23 2012).

24 **13.1.2 Ocean Heat Content**

25 Ocean heat content (OHC) is an ideal variable to monitor changing climate as it is calculated
26 using the entire water column, so ocean warming can be documented and compared between
27 particular regions, ocean basins, and depths. However, for years prior to the 1970s, estimates of
28 ocean uptake are confined to the upper ocean due to sparse spatial and temporal coverage and
29 limited vertical capabilities of many of the instruments in use. Ocean heat content estimates are
30 improved for time periods after 1970 with increased sampling coverage and depth (Abraham et
31 al. 2013; Rhein et al. 2013). Estimates of OHC have been calculated going back to the 1950s
32 using averages over longer time intervals (i.e., decadal or 5-year intervals) to compensate for
33 sparse data distributions, allowing for clear long-term trends to emerge (e.g., Levitus et al. 2012).

34 From 1960 to 2015, ocean heat content (OHC) significantly increased for both 0–700 and 700–
35 2,000 m depths, for a total ocean warming of $33.5 \pm 7.0 \times 10^{22}$ J (a net heating of 0.37 ± 0.08
36 W/m^2), although there is some uncertainty with global ocean heat estimates (Figure 13.1; Cheng

1 et al. 2017). During this period, there is evidence of an acceleration of ocean warming beginning
2 in 1998 (Lee et al. 2015), with a total heat increase of about 15.2×10^{22} J (Cheng et al. 2017).
3 Robust ocean warming occurs in the upper 700 m and is slow to penetrate into the deep ocean.
4 However, the 700–2,000 m depths constitute an increasing portion of the total ocean energy
5 budget as compared to the surface ocean (Figure 13.1; Cheng et al. 2017). The role of the deep
6 ocean (below 2,000 m [6,600 ft]) in ocean heat uptake remains uncertain, both in the magnitude
7 but also the sign of the uptake (Purkey and Johnson 2010; Llovel et al. 2014). Penetration of
8 surface waters to the deep ocean is a slow process, which means that while it takes only about a
9 decade for near-surface temperatures to respond to increased heat energy, the deep ocean will
10 continue to warm, and as a result sea levels will rise for centuries to millennia even if all further
11 emissions cease (Rhein et al. 2013).

12 **[INSERT FIGURE 13.1 HERE]**

13 Several sources have documented warming in all ocean basins from 0–2,000 m depths over the
14 past 50 years (Figure 13.2; Boyer et al. 2016; Cheng et al. 2017; Levitus et al. 2012). Annual
15 fluctuations in surface temperatures and OHC are attributed to the combination of a long-term
16 secular trend and decadal and smaller time scale variations, such as the Pacific Decadal
17 Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO) (Ch. 5: Large-Scale
18 Circulation and Climate Variability; Ch. 12: Sea Level Rise; Trenberth et al. 2014; Steinman et
19 al. 2015). The transport of heat to the deep ocean is likely linked to the strength of the Atlantic
20 Meridional Overturning Circulation (see Section 13.2.1), where the Atlantic and Southern Ocean
21 accounts for the dominant portion of total OHC at the 700–2,000 m depth (Figure 13.2; Cheng et
22 al. 2017; Lee et al. 2015; Roemmich et al. 2015; Abraham et al. 2013). Decadal variability in
23 ocean heat uptake is mostly attributed to ENSO phases (with El Niños warming and La Niñas
24 cooling). For instance, La Niña conditions over the past decade have led to colder ocean
25 temperatures in the eastern tropical Pacific (Abraham et al. 2013; Cheng et al. 2017; Lee et al.
26 2015; Kosaka and Xie 2013). For the Pacific and Indian Oceans, the decadal shifts are primarily
27 observed in the upper 350 m depth, likely due to shallow subtropical circulation, leading to an
28 abrupt increase of OHC in the Indian Ocean carried by the Indonesian throughflow from the
29 Pacific Ocean over the last decade (Lee et al. 2015). Although there is natural variability in
30 ocean temperature, there remain clear increasing trends due to anthropogenic influences.

31 **[INSERT FIGURE 13.2 HERE]**

32 **13.1.3 Sea Surface Temperature and U.S. Regional Warming**

33 In addition to OHC, sea surface temperature (SST) measurements are widely available. SST
34 measurements are useful because 1) the measurements have been taken over 150 years (albeit
35 using different platforms, instruments, and depths through time); 2) SST reflects the lower
36 boundary condition of the atmosphere; and 3) SST can be used to predict specific regional
37 impacts of global warming on terrestrial and coastal systems (Roemmich et al. 2015; Yan et al.

1 2016; Matthews 2013). Globally, surface ocean temperatures have increased by $1.3^{\circ} \pm 0.1^{\circ}\text{F}$
2 ($0.70^{\circ} \pm 0.08^{\circ}\text{C}$) per century from 1900 to 2016 for the Extended Reconstructed Sea Surface
3 Temperature version 4 (ERSST v4) record (Huang et al. 2015). All U.S. coastal waters have
4 warmed by more than 0.7°F (0.4°C) over this period as shown in both Table 13.1 and Chapter 6:
5 Temperature Change, Figure 6.6. During the past century, the rates of increase of SSTs for the
6 coastal waters of three U.S. regions were above the global average rate. These included the
7 waters around Alaska, the Caribbean, and the Southwest (Table 13.1). Over the last decade,
8 some regions have experienced increased high ocean temperature anomalies. For instance, due to
9 a resilient ridge of high pressure over the North American west coast, storm activity and mixing
10 was suppressed and heat in the upper ocean intensified in 2013 in a phenomenon known as “The
11 Blob” (Bond et al. 2015). These anomalously warm waters persisted in the coastal waters of the
12 Alaskan and Pacific Northwest until 2015. Under a higher emissions pathway (RCP8.5), ocean
13 SST are projected to increase by an additional 4.9°F (2.7°C) by 2100 (Figure 13.3), whereas for
14 a lower emissions scenario (RCP4.5) the SST increase would be 2.3°F (1.3°C ; Bopp et al. 2013).
15 In all U.S. coastal regions, the warming since 1901 is detectable compared to natural variability
16 and attributable to anthropogenic forcing, according to an analysis of the CMIP5 models (Ch. 6:
17 Temperature Change, Figure 6.5).

18 **[INSERT TABLE 13.1 AND FIGURE 13.3 HERE]**

19 **13.1.4 Ocean Heat Feedback**

20 The residual heat not taken up by the oceans increases land surface temperatures (approximately
21 3%) and atmospheric temperatures (approximately 1%), and melts both land and sea ice
22 (approximately 3%), leading to sea level rise (see Ch. 12: Sea Level Rise; Cheng et al. 2017;
23 Rhein et al. 2013; Nieves et al. 2015). The meltwater from land and sea ice amplifies further
24 subsurface ocean warming and ice shelf melting, primarily due to increased thermal
25 stratification, which reduces the ocean’s efficiency in transporting heat to deep waters (Rhein et
26 al. 2013). Surface ocean stratification has increased by about 4% during the period 1971–2010
27 (Ciais et al. 2013) due to thermal heating and freshening from increased freshwater inputs
28 (precipitation and evaporation changes and land and sea ice melting). The increase of ocean
29 stratification will contribute to further feedback of ocean warming and, indirectly, mean sea
30 level. In addition, increases in stratification are associated with suppression of tropical cyclone
31 intensification (Mei et al. 2015), retreat of the polar ice sheets (Straneo and Heimbach 2013), and
32 reductions of the convective mixing at higher latitudes that transports heat to the deep ocean
33 through the Atlantic Meridional Overturning Circulation (AMOC) (Rahmstorf et al. 2015).
34 Ocean heat uptake therefore represents an important feedback that will have a significant
35 influence on future shifts in climate (see Ch. 2: Physical Drivers of Climate Change).

36

1 **13.2 Ocean Circulation**

2 **13.2.1 Atlantic Meridional Overturning Circulation**

3 The Atlantic Meridional Overturning Circulation (AMOC) refers to the three-dimensional, time-
4 dependent circulation of the Atlantic Ocean, which has been a high priority topic of study in
5 recent decades. The AMOC plays an important role in climate through its transport of heat,
6 freshwater, and carbon (e.g., Johns et al. 2011; McDonagh et al. 2015; Talley et al. 2016).
7 AMOC-associated poleward heat transport substantially contributes to North American and
8 continental European climate (see Ch. 5: Circulation and Variability). The Gulf Stream, in
9 contrast to other western boundary currents, is expected to slow down because of the weakening
10 of the AMOC, which would impact the European climate (Yang et al. 2016). Variability in the
11 AMOC has been attributed to wind forcing on intra-annual time scales and to geostrophic forces
12 on interannual to decadal timescales (Buckley and Marshall 2016). Increased freshwater fluxes
13 from melting arctic sea and land ice can weaken open ocean convection and deep-water
14 formation in the Labrador and Irminger Seas, which could weaken the AMOC (Ch. 11: Arctic
15 Changes; Rahmstorf et al. 2015; Yang et al. 2016; Also see Chapter 5, Section 5.2.3: North
16 Atlantic Oscillation and Northern Annular Mode).

17 While one recent study has suggested that the AMOC has slowed since preindustrial times
18 (Rahmstorf et al. 2015) and another suggested slowing on faster time scales (Smeed et al. 2014),
19 there is at present insufficient observational evidence to support a finding of long term slowdown
20 of AMOC strength over the 20th century (Rhein et al. 2013) or within the last 50 years (Buckley
21 and Marshall 2016) as decadal ocean variability can obscure long-term trends. Some studies
22 show long-term trends (Longworth et al. 2011; Bryden et al. 2005), but the combination of
23 sparse data and large seasonal variability may also lead to incorrect interpretations (e.g., Kanzow
24 et al. 2010). Several recent high resolution modeling studies constrained with the limited existing
25 observational data (Jackson et al. 2016) and/or with reconstructed freshwater fluxes (Böning et
26 al. 2016) suggest that the recently observed AMOC slowdown at 26°N (off the Florida coast)
27 since 2004 (e.g., as described in Smeed et al. 2014) is mainly due to natural variability, and that
28 anthropogenic forcing has not yet caused a significant AMOC slowdown. In addition, direct
29 observations of the AMOC in the South Atlantic fail to unambiguously demonstrate
30 anthropogenic trends (e.g., Dong et al. 2015; Garzoli et al. 2013).

31 Under a high emissions future scenario (RCP8.5) in CMIP5 simulations, it is very likely that the
32 AMOC will weaken over the 21st century. The projected decline ranges from 12% to 54%
33 (Collins et al. 2013), with the range width reflecting substantial uncertainty in quantitative
34 projections of AMOC behavior. In RCP4.5 scenarios, CMIP5 models predict a 20% weakening
35 of the AMOC during the first half of the 21st century and a stabilization and slight recovery after
36 that (Cheng et al. 2013). The projected slowdown of the AMOC will be counteracted by the
37 warming of the deep ocean (below 700 m [2,300 ft]), which will tend to strengthen the AMOC
38 (Patara and Böning 2014). The situation is further complicated due to the known bias in coupled

1 climate models related to the direction of the salinity transport in models versus observations,
2 which is an indicator of AMOC stability (e.g., Drijhout et al. 2011; Bryden et al. 2011; Garzoli et
3 al. 2013). Some argue that coupled climate models should be corrected for this known bias and
4 that AMOC variations could be even larger than the gradual decrease most models predict if the
5 AMOC were to shut down completely and “flip states” (Liu et al. 2017). Any AMOC slowdown
6 will result in less heat and CO₂ absorbed by the ocean from the atmosphere, which is a positive
7 feedback to climate change (also see Ch. 2: Physical Drivers of Climate Change).

8 **13.2.2 Changes in Salinity Structure**

9 As a response to warming, increased atmospheric moisture leads to stronger evaporation or
10 precipitation in terrestrial and oceanic environments and melting of land and sea ice.
11 Approximately 80% of precipitation/evaporation events occur over the ocean, leading to patterns
12 of higher salt content or freshwater anomalies and changes in ocean circulation (see Ch. 2:
13 Physical Drivers of Climate Change and Ch. 6: Temperature Change; Durack and Wijffels
14 2010). Over 1950–2010, average global amplification of the surface salinity pattern amounted to
15 5.3%; where fresh regions in the ocean became fresher and salty regions became saltier (Skiriris
16 et al. 2014). However, the long-term trends of these physical and chemical changes to the ocean
17 are difficult to isolate from natural large-scale variability. In particular, ENSO displays particular
18 salinity and precipitation/evaporation patterns that skew the trends. More research and data are
19 necessary to better model changes to ocean salinity. Several models have shown a similar spatial
20 structure of surface salinity changes, including general salinity increases in the subtropical gyres,
21 a strong basin-wide salinity increase in the Atlantic Ocean, and reduced salinity in the western
22 Pacific warm pools and the North Pacific subpolar regions (Durack and Wijffels 2010; Skiriris et
23 al. 2014). There is also a stronger distinction between the upper salty thermocline and fresh
24 intermediate depth through the century. The regional changes in salinity to ocean basins will
25 have an overall impact on ocean circulation and net primary production, leading to
26 corresponding carbon export (see Ch. 2: Physical Drivers of Climate Change). In particular, the
27 freshening of the Arctic Ocean due to melting of land and sea ice can lead to buoyancy changes
28 which could slow down the AMOC (see Section 13.2.1).

29 **13.2.3 Changes in Upwelling**

30 Significant changes to ocean stratification and circulation can also be observed regionally, along
31 the eastern ocean boundaries and at the equator. In these areas, wind-driven upwelling brings
32 colder, nutrient- and carbon-rich water to the surface; this upwelled water is more efficient in
33 heat and CO₂ uptake. There is some evidence that coastal upwelling in mid- to high-latitude
34 eastern boundary regions has increased in intensity and/or frequency (García-Reyes et al. 2015),
35 but in more tropical areas of the western Atlantic, such as in the Caribbean Sea, it has decreased
36 between 1990 and 2010 (Taylor et al. 2012; Astor et al. 2013). This has led to a decrease in
37 primary productivity in the southern Caribbean Sea (Taylor et al. 2012). Within the continental
38 United States, the California Current is experiencing fewer (by about 23%–40%) but stronger

1 upwelling events (Hoegh-Guldberg et al. 2014; Sydeman et al. 2014; Jacox et al. 2014). Stronger
2 offshore upwelling combined with cross-shelf advection brings nutrients from the deeper ocean
3 but also increased offshore transport (Bakun et al. 2015). The net nutrient load in the coastal
4 regions is responsible for increased productivity and ecosystem function.

5 IPCC 2013 concluded that there is low confidence in the current understanding of how eastern
6 upwelling systems will be altered under future climate change because of the obscuring role of
7 multidecadal climate variability (Ciais et al. 2013). However, subsequent studies show that by
8 2100, upwelling is predicted to start earlier, end later, and intensify in three of the four major
9 eastern boundary upwelling systems (not in the California Current; Wang et al. 2015). Southern
10 Ocean upwelling will intensify while the Atlantic equatorial upwelling systems will weaken
11 (Hoegh-Guldberg et al. 2014; Wang et al. 2015). The intensification is attributed to the
12 strengthening of regional coastal winds as observations already show (Sydeman et al. 2014), and
13 RCP8.5 model projection scenarios estimate wind intensifying near poleward boundaries
14 (including northern California current system [CCS]) and weakening near equatorward
15 boundaries (including southern CCS) for the 21st century (Rykaczewski et al. 2015; Wang et al.
16 2015).

17 **13.3 Ocean Acidification**

18 **13.3.1 General Background**

19 In addition to causing changes in climate, increasing atmospheric levels of carbon dioxide (CO₂)
20 from the burning of fossil fuels and other human activities, including changes in land use, have a
21 direct effect on ocean chemistry (Orr et al. 2005; Feely et al. 2009). Ocean acidification refers to
22 a change in ocean chemistry in response to the uptake of increasing CO₂ in the atmosphere.

23 Ocean acidification causes a variety of chemical changes in seawater: an increase in the partial
24 pressure of CO₂ (pCO_{2,sw}), dissolved inorganic carbon (DIC), and an increase in the
25 concentration of hydrogen and bicarbonate ions and a decrease in the concentration of carbonate
26 ions (Figure 13.4). In brief, CO₂ is an acid gas that combines with water to form carbonic acid,
27 which then dissociates to hydrogen and bicarbonate ions. Increasing concentrations of seawater
28 hydrogen ions result in a decrease of carbonate ions through their conversion to bicarbonate ions.
29 Ocean acidity refers to the concentration of hydrogen ions in ocean seawater regardless of ocean
30 pH, which is fundamentally basic (e.g., pH > 7). Ocean surface waters have become 30% more
31 acidic over the last 150 years as they have absorbed large amounts of CO₂ from the atmosphere
32 (Feely et al. 2004), and anthropogenically sourced CO₂ is gradually invading into oceanic deep
33 waters. Since the preindustrial period, the oceans have absorbed approximately 27% of all CO₂
34 emitted to the atmosphere. Oceans currently absorb about 26% of the human-caused CO₂
35 anthropogenically emitted into the atmosphere (Le Quéré et al. 2016).

36 **[INSERT FIGURE 13.4 HERE]**

1 **13.3.2 Open Ocean Acidification**

2 Surface waters in the open ocean experience changes in carbonate chemistry reflective of large-
3 scale physical oceanic processes (see Ch. 2: Physical Drivers of Climate Change). These
4 processes include both the global uptake of atmospheric CO₂ and the shoaling of naturally
5 acidified subsurface waters due to vertical mixing and upwelling. In general, the rate of ocean
6 acidification in open ocean surface waters at a decadal time-scale closely approximates the rate
7 of atmospheric CO₂ increase (Bates et al. 2014). Large, multidecadal phenomena such as the
8 Atlantic Multidecadal Oscillation and Pacific Decadal Oscillation can add variability to the
9 observed rate of change (Bates et al. 2014).

10 **13.3.3 Coastal Acidification**

11 Coastal shelf and nearshore waters are influenced by the same processes as open ocean surface
12 waters such as absorption of atmospheric CO₂ and upwelling, as well as a number of additional,
13 local-level processes, including freshwater and nutrient input (Duarte et al. 2013). Coastal
14 acidification generally exhibits higher-frequency variability and short-term episodic events
15 relative to open-ocean acidification (Borges and Gypens 2010; Waldbusser and Salisbury 2014;
16 Hendriks et al. 2015; Sutton et al. 2016). Upwelling is of particular importance in coastal waters,
17 especially along the Pacific Coast. Deep waters that shoal with upwelling are enriched in CO₂
18 due to uptake of anthropogenic atmospheric CO₂ when last in contact with the atmosphere,
19 coupled with deep water respiration processes and lack of gas exchange with the atmosphere
20 (Feely et al. 2009; Harris et al. 2013). Freshwater inputs to coastal waters change seawater
21 chemistry in ways that make it more susceptible to acidification, largely by freshening ocean
22 waters and contributing varying amounts of dissolved inorganic carbon (DIC), total alkalinity
23 (TA), dissolved and particulate organic carbon, and nutrients from riverine and estuarine sources.
24 Coastal waters of the East Coast and mid-Atlantic are far more influenced by freshwater inputs
25 than are Pacific Coast waters (Gledhill et al. 2015). Coastal waters can episodically experience
26 riverine and glacial melt plumes that create conditions in which seawater can dissolve calcium
27 carbonate structures (Evans et al. 2014; Salisbury et al. 2008). While these processes have
28 persisted historically, climate-induced increases in glacial melt and high-intensity precipitation
29 events can yield larger freshwater plumes than have occurred in the past. Nutrient runoff can
30 increase coastal acidification by creating conditions that enhance biological respiration. In brief,
31 nutrient loading typically promotes phytoplankton blooms, which, when they die, are consumed
32 by bacteria. Bacteria respire CO₂ and thus bacterial blooms can result in acidification events
33 whose intensity depends on local hydrographic conditions, including water column stratification
34 and residence time (Waldbusser and Salisbury 2014). Long-term changes in nutrient loading,
35 precipitation, and/or ice melt may also impart long-term, secular changes in the magnitude of
36 coastal acidification.

37

1 **13.3.4 Latitudinal Variation**

2 Ocean carbon chemistry is highly influenced by water temperature, largely because the solubility
3 of CO₂ in seawater increases as water temperature declines. Thus, cold, high-latitude waters can
4 absorb more CO₂ than warm, lower-latitude waters (Gledhill et al. 2015; Bates and Mathis 2009).
5 Because carbonate minerals also more readily dissolve in colder waters, these waters can more
6 regularly become undersaturated with respect to calcium carbonate whereby mineral dissolution
7 is energetically favored. This chemical state, often referred to as seawater being “corrosive” to
8 calcium carbonate, is important when considering the ecological implications of ocean
9 acidification as many species make structures such as shells and skeletons from calcium
10 carbonate. Some high-latitude waters already experience such corrosive conditions, which are
11 rarely documented in low-latitude systems. For example, corrosive conditions have been
12 documented in the Arctic and northeastern Pacific Oceans (Bates and Mathis 2009; Feely et al.
13 2008; Qi et al. 2017; Sutton et al. 2016). It is important to note that low-latitude waters are
14 experiencing a greater absolute rate of change in calcium carbonate saturation state than higher
15 latitudes, though these low-latitude waters are not approaching the undersaturated state except
16 within near-shore or some benthic habitats (Friedrich et al. 2012).

17 **13.3.5 Paleo Evidence**

18 Evidence suggests that the current rate of ocean acidification is the fastest in the last 66 million
19 years (the K-Pg boundary) and possibly even the last 300 million years (when the first pelagic
20 calcifiers evolved providing proxy information and also a strong carbonate buffer, characteristic
21 of the modern ocean) (Hönisch et al. 2012; Zeebe et al. 2016). The Paleo-Eocene Thermal
22 Maximum (PETM; around 56 million years ago) is often referenced as the closest analogue to
23 the present, although the overall rate of change in CO₂ conditions during that event (estimated
24 between 0.6 and 1.1 GtC/year) was much lower than the current increase in atmospheric CO₂ of
25 10 GtC/year (Wright and Schaller 2013; Zeebe et al. 2016). The relatively slower rate of
26 atmospheric CO₂ increase at the PETM likely led to relatively small changes in carbonate ion
27 concentration in seawater compared with the contemporary acidification rate, due to the ability
28 of rock weathering to buffer the change over the longer time period (Zeebe et al. 2016). Some of
29 the presumed acidification events in Earth’s history have been linked to selective extinction
30 events suggestive of how guilds of species may respond to the current acidification event
31 (Hönisch et al. 2012).

32 **13.3.6 Projected Changes**

33 Projections indicate that by the end of the century under higher emissions pathways, such as
34 SRES A1f1 or RCP8.5, open-ocean surface pH will decline from the current average level of 8.1
35 to a possible average of 7.8 (Figure 13.5; Gattuso et al. 2015). When the entire ocean volume is
36 considered under the same scenario, the volume of waters undersaturated with respect to calcium
37 carbonate could expand from 76% in the 1990s to 91% in 2100. As discussed above, for a

1 variety of reasons, not all ocean and coastal regions will experience acidification in the same way
2 depending on other compounding factors. For instance, recent observational data from the Arctic
3 Basin show that the Beaufort Sea became undersaturated, for part of the year, with respect to
4 aragonite in 2001, while other continental shelf seas in the Arctic Basin are projected to do so
5 closer to the middle of the century (e.g., the Chukchi Sea in about 2033 and Bering Sea in about
6 2062; Mathis et al. 2015). Deviation from the global average rate of acidification will be
7 especially true in coastal and estuarine areas where the rate of acidification is influenced by other
8 drivers than atmospheric CO₂, some of which are under the control of local management
9 decisions (for example, nutrient pollution loads).

10 **[INSERT FIGURE 13.5 HERE]**

11 **13.4 Ocean Deoxygenation**

12 **13.4.1 General Background**

13 Oxygen is essential to most life in the ocean, governing a host of biogeochemical and biological
14 processes. Oxygen influences metabolic, physiological, reproductive, behavioral, and ecological
15 processes, ultimately shaping the composition, diversity, abundance, and distribution of
16 organisms from microbes to whales. Increasingly, climate-induced oxygen loss (deoxygenation)
17 associated with ocean warming and reduced ventilation to deep waters has become evident
18 locally, regionally, and globally. Deoxygenation can also be attributed to anthropogenic nutrient
19 input, especially in the coastal regions, where the nutrients can lead to the proliferation of
20 primary production and, consequently, enhanced drawdown of dissolved oxygen by microbes
21 (Altieri and Gedan 2015). In addition, acidification (Section 13.2) can co-occur with
22 deoxygenation as a result of warming-enhanced biological respiration (Breitburg et al. 2015). As
23 aerobic organisms respire, O₂ is consumed and CO₂ is produced. Understanding the combined
24 effect of both low O₂ and low pH on marine ecosystems is an area of active research (Gobler et
25 al. 2014). Warming also raises biological metabolic rates which, in combination with intensified
26 coastal and estuarine stratification, exacerbates eutrophication-induced hypoxia. We now see
27 earlier onset and longer periods of seasonal hypoxia in many eutrophic sites, most of which
28 occur in areas that are also warming (Altieri and Gedan 2015).

29 **13.4.2 Climate Drivers of Ocean Deoxygenation**

30 Global ocean deoxygenation is a direct effect of warming. Ocean warming reduces the solubility
31 of oxygen (that is, warmer water can hold less oxygen) and changes physical mixing (for
32 example, upwelling and circulation) of oxygen in the oceans. The increased temperature of
33 global oceans accounts for about 15% of current global oxygen loss (Helm et al. 2011), although
34 changes in temperature and oxygen are not uniform throughout the ocean (Roemmich et al.
35 2015). Warming also exerts direct influence on thermal stratification and enhances salinity
36 stratification through ice melt and climate change-associated precipitation effects. Intensified

1 stratification leads to reduced ventilation (mixing of oxygen into the ocean interior) and accounts
2 for up to 85% of global ocean oxygen loss (Helm et al. 2011). Effects of ocean temperature
3 change and stratification on oxygen loss are strongest in intermediate or mode waters at bathyal
4 depths (in general, 200–3,000 m) and also nearshore and in the open ocean; these changes are
5 especially evident in tropical and subtropical waters globally, in the Eastern Pacific (Stramma et
6 al. 2010), and in the Southern Ocean (Helm et al. 2011).

7 There are also other, less direct effects of global temperature increase. Warming on land reduces
8 terrestrial plant water efficiency (through effects on stomata; see Ch. 8: Drought, Floods, and
9 Wildfires, Key Message 3), leading to greater runoff, on average, into coastal zones (see Ch. 8:
10 Drought, Floods, and Wildfires for other hydrological effects of warming) and further enhancing
11 hypoxia potential because greater runoff means more nutrient transport (See Ch. 2: Physical
12 Drivers of Climate Change; Reay et al. 2008; Rabalais et al. 2009). Estuaries, especially ones
13 with minimal tidal mixing, are particularly vulnerable to oxygen-depleted dead zones from the
14 enhanced runoff and stratification. Warming can induce dissociation of frozen methane in gas
15 hydrates buried on continental margins, leading to further drawdown of oxygen through aerobic
16 methane oxidation in the water column (Boetius and Wenzhöfer 2013). On eastern ocean
17 boundaries, warming can enhance the land–sea temperature differential, causing increased
18 upwelling due to higher winds with (a) greater nutrient input leading to production, sinking,
19 decay, and biochemical drawdown of oxygen and (b) upwelling of naturally low-oxygen, high-
20 CO₂ waters onto the upper slope and shelf environments (Sydeman et al. 2014; Feely et al.
21 2009). However, in the California Current Ecosystem, upwelling intensification has occurred
22 only in the poleward regions (north of San Francisco), and the drivers may not be associated with
23 land–sea temperature differences (Rykaczewski et al. 2015). Taken together, the effects of
24 warming are manifested as low-oxygen water in open oceans are transported to and upwelled
25 along coastal regions. These low-oxygen upwelled waters are then coupled with eutrophication-
26 induced hypoxia, further reducing oxygen content in coastal areas.

27 Changes in precipitation, winds, circulation, airborne nutrients, and sea level can also contribute
28 to ocean deoxygenation. Projected increases in precipitation in some regions will intensify
29 stratification, reducing vertical mixing and ventilation, and intensify nutrient input to coastal
30 waters through excess runoff, which leads to increased algal biomass and concurrent dissolved
31 oxygen consumption via community respiration (Lee et al. 2016). Coastal wetlands that might
32 remove these nutrients before they reach the ocean may be lost through rising sea level, further
33 exacerbating hypoxia (Rabalais et al. 2009). Some observations of oxygen decline are linked to
34 regional changes in circulation involving low-oxygen water masses. Enhanced fluxes of airborne
35 iron and nitrogen are interacting with natural climate variability and contributing to fertilization,
36 enhanced respiration, and oxygen loss in the tropical Pacific (Ito et al. 2016). In contrast to the
37 many sources of climate-induced oxygen loss, the projected increase in incidence and intensity
38 of cyclones and hurricanes will induce mixing, which can ameliorate hypoxia locally (Rabalais et
39 al. 2009).

1 **13.4.3 Biogeochemical Feedbacks of Deoxygenation to Climate and Elemental Cycles**

2 Climate patterns and ocean circulation have a large effect on global nitrogen and oxygen cycles,
3 which in turn affect phosphorus and trace metal availability and generate feedbacks to the
4 atmosphere and oceanic production. Global ocean productivity may be affected by climate-
5 driven changes below the tropical and subtropical thermocline which control the volume of
6 suboxic waters (< 5 micromolar O_2), and consequently the loss of fixed nitrogen through
7 denitrification (Codispoti et al. 2001; Deutsch et al. 2011). The extent of suboxia in the open
8 ocean also regulates the production of the greenhouse gas nitrous oxide (N_2O); as oxygen
9 declines, greater N_2O production may intensify global warming, as N_2O is about 310 times more
10 effective at trapping heat than CO_2 (see Ch. 2: Physical Drivers of Climate Change, Section
11 2.3.2; Gruber 2008; EPA 2017). Production of hydrogen sulfide (H_2S , which is highly toxic) and
12 intensified phosphorus recycling can occur at low oxygen levels (Wallmann 2003). Other
13 feedbacks may emerge as oxygen minimum zone (OMZ) shoaling diminishes the depths of
14 diurnal vertical migrations by fish and invertebrates, and as their huge biomass and associated
15 oxygen consumption deplete oxygen (Bianchi et al. 2013).

16 **13.4.4 Past Trends**

17 Over hundreds of millions of years, oxygen has varied dramatically in the atmosphere and ocean
18 and has been linked to biodiversity gains and losses (Knoll and Carroll 1999; McFall-Ngai et al.
19 2013). Variation in oxygenation in the paleo record is very sensitive to climate—with clear links
20 to temperature and often CO_2 variation (Falkowski et al. 2011). OMZs expand and contract in
21 synchrony with warming and cooling events, respectively (Robinson et al. 2007). Episodic
22 climate events that involve rapid temperature increases over decades, followed by a cool period
23 lasting a few hundred years, lead to major fluctuations in the intensity of Pacific and Indian
24 Ocean OMZs (i.e., DO of $< 20 \mu M$). These events are associated with rapid variations in North
25 Atlantic deep water formation (Schmittner et al. 2007). Ocean oxygen fluctuates on glacial-
26 interglacial timescales of thousands of years in the Eastern Pacific (Galbraith et al. 2004; Moffitt
27 et al. 2015).

28 **13.4.5 Modern Observations (last 50+ years)**

29 Long-term oxygen records made over the last 50 years reflect oxygen declines in inland seas
30 (Justić et al. 1987; Zaitzev 1992; Conley et al. 2011), in estuaries (Brush 2009; Gilbert et al.
31 2005), and in coastal waters (Rabalais et al. 2007, 2010; Booth et al. 2012; Baden et al. 1990).
32 The number of coastal, eutrophication-induced hypoxic sites in the United States has grown
33 dramatically over the past 40 years (Diaz and Rosenberg 2008). Over larger scales, global
34 syntheses show hypoxic waters have expanded by 4.5 million km^2 at a depth of 200 m (Stramma
35 et al. 2010), with widespread loss of oxygen in the Southern Ocean (Helm et al. 2011), Western
36 Pacific (Takatani et al. 2012), and North Atlantic (Stendardo and Gruber 2012). Overall oxygen
37 declines have been greater in coastal ocean than in the open ocean (Gilbert et al. 2010) and often

1 greater inshore than offshore (Bograd et al. 2015). The emergence of a deoxygenation signal in
2 regions with naturally high oxygen variability will unfold over longer time periods (20–50 years
3 from now) (Long et al. 2016).

4 **13.4.6 Projected Changes**

5 **GLOBAL MODELS**

6 Global models generally agree that ocean deoxygenation is occurring; this finding is also
7 reflected in in situ observations from past 50 years. Compilations of 10 Earth System models
8 predict a global average loss of oxygen of –3.5% (RCP8.5) to –2.4% (RCP4.5) by 2100, but
9 much stronger losses regionally, and in intermediate and mode waters (Bopp et al. 2013) (Figure
10 13.6). The North Pacific, North Atlantic, Southern Ocean, subtropical South Pacific, and South
11 Indian Oceans all are expected to experience deoxygenation, with O₂ decreases of as much as
12 17% in the North Pacific by 2100 for the RCP8.5 pathway. However, the tropical Atlantic and
13 tropical Indian Oceans show increasing O₂ concentrations. In the many areas where oxygen is
14 declining, high natural variability makes it difficult to identify anthropogenically forced trends
15 (Long et al. 2016).

16 **[INSERT FIGURE 13.6 HERE]**

17 **REGIONAL MODELS**

18 Regional models are critical because many oxygen drivers are local, influenced by bathymetry,
19 winds, circulation, and fresh water and nutrient inputs. Most eastern boundary upwelling areas
20 are predicted to experience intensified upwelling to 2100 (Wang et al. 2015), although on the
21 West Coast projections for increasing upwelling for the northern California Current occur only
22 north of San Francisco (see Section 13.2.3).

23 Particularly notable for the western United States, variation in trade winds in the eastern Pacific
24 Ocean can affect nutrient inputs, leading to centennial periods of oxygen decline or oxygen
25 increase distinct from global oxygen decline (Deutsch et al. 2014). Oxygen dynamics in the
26 Eastern Tropical Pacific are highly sensitive to equatorial circulation changes (Montes et al.
27 2014).

28 Regional modeling also shows that year-to-year variability in precipitation in the central United
29 States affects the nitrate–N flux by the Mississippi River and the extent of hypoxia in the Gulf of
30 Mexico (Donner and Scavia 2007). A host of climate influences linked to warming and increased
31 precipitation are predicted to lower dissolved oxygen in Chesapeake Bay (Najjar et al. 2010).

32

1 **13.5 Other Coastal Changes**

2 **13.5.1 Sea Level Rise**

3 Sea level is an important variable that affects coastal ecosystems. Global sea level rose very
4 rapidly at the end of the last glaciation, as glaciers and the polar ice sheets thinned and melted at
5 their fringes. On average around the globe, sea level is estimated to have risen at rates exceeding
6 2.5 mm/year between about 8,000 and 6,000 years before present. These rates steadily decreased
7 to less than 2.0 mm/year through about 4,000 years ago and stabilized at less than 0.4 mm/year
8 through the late 1800s. Global sea level rise has accelerated again within the last 100 years, and
9 now averages about 1 to 2 mm/year (Thompson et al. 2016). See Chapter 12: Sea Level Rise for
10 more thorough analysis of how sea level rise has already and will affect the U.S. coasts.

11 **13.5.2 Wet and Dry Deposition**

12 Dust transported from continental desert regions to the marine environment deposits nutrients
13 such as iron, nitrogen, phosphorus, and trace metals that stimulate growth of phytoplankton and
14 increase marine productivity (Jickells and Moore 2015). U.S. continental and coastal regions
15 experience large dust deposition fluxes originating from the Saharan desert to the East and from
16 Central Asia and China to the Northwest (Chiapello 2014). Changes in drought frequency or
17 intensity resulting from anthropogenically forced climate change, as well as other anthropogenic
18 activities such as agricultural practices and land-use changes may play an important role in the
19 future viability and strength of these dust sources (e.g., Mulitza et al. 2010).

20 Additionally, oxidized nitrogen, released during high-temperature combustion over land, and
21 reduced nitrogen, released from intensive agriculture, are emitted in high population areas in
22 North America and are carried away and deposited through wet or dry deposition over coastal
23 and open ocean ecosystems via local wind circulation. Wet deposition of pollutants produced in
24 urban areas is known to play an important role in changes of ecosystem structure in coastal and
25 open ocean systems through intermediate changes in the biogeochemistry, for instance in
26 dissolved oxygen or various forms of carbon (Paerl et al. 2002).

27 **13.5.3 Primary Productivity**

28 Marine phytoplankton represent about half of the global net primary production (NPP)
29 (approximately 50 ± 28 GtC/year), fixing atmospheric CO₂ into a bioavailable form for
30 utilization by higher trophic levels (see also Ch. 2: Physical Drivers of Climate Change; Carr et
31 al. 2006; Franz et al. 2016). As such, NPP represents a critical component in the role of the
32 oceans in climate feedback. The effect of climate change on primary productivity varies across
33 the coasts depending on local conditions. For instance, nutrients that stimulate phytoplankton
34 growth are impacted by various climate conditions, such as increased stratification which limits
35 the transport of nutrient-rich deep water to the surface, changes in circulation leading to
36 variability in dry and wet deposition of nutrients to coasts, and altered precipitation/evaporation

1 which changes runoff of nutrients from coastal communities. The effect of the multiple physical
2 factors on NPP is complex and leads to model uncertainties (Chavez et al. 2011). There is
3 considerable variation in model projections for NPP, from estimated decreases or no changes, to
4 the potential increase by 2100 (Frölicher et al. 2016; Fu et al. 2016; Laufkötter et al. 2015).
5 Simulations from nine Earth system models projected total NPP in 2090 to decrease by 2%–16%
6 and export production (that is, particulate flux to the deep ocean) to drop by 7%–18% as
7 compared to 1990 (RCP8.5; Fu et al. 2016). More information on phytoplankton species
8 response and associated ecosystem dynamics is needed as any reduction of NPP would have a
9 strong impact on atmospheric CO₂ levels and marine ecosystems in general.

10 **13.5.4 Estuaries**

11 Estuaries are critical ecosystems of biological, economic, and social importance in the United
12 States. They are highly dynamic, influenced by the interactions of atmospheric, freshwater,
13 terrestrial, oceanic, and benthic components. Of the 28 national estuarine research reserves in the
14 United States and Puerto Rico, all are being impacted by climate change to varying levels
15 (Robinson et al. 2013). In particular, sea level rise, saltwater intrusion, and the degree of
16 freshwater discharge influence the forces and processes within these estuaries (Monbaliu et al.
17 2014). Sea level rise and subsidence are leading to drowning of existing salt marshes and/or
18 subsequent changes in the relative area of the marsh plain, if adaptive upslope movement is
19 impeded due to urbanization along shorelines. Several model scenarios indicate a decline in salt
20 marsh habitat quality and an accelerated degradation as the rate of sea level rise increases in the
21 latter half of the century (Schile et al. 2014; Swanson et al. 2015). The increase in sea level as
22 well as alterations to oceanic and atmospheric circulation can result in extreme wave conditions
23 and storm surges, impacting coastal communities (Robinson et al. 2013). Additional climate
24 change impacts to the physical and chemical estuarine processes include more extreme sea
25 surface temperatures (higher highs and lower lows compared to the open ocean due to shallower
26 depths and influence from land temperatures), changes in flow rates due to changes in
27 precipitation, and potentially greater extents of salinity intrusion.

1 TRACEABLE ACCOUNTS

2 Key Finding 1

3 The world's oceans have absorbed about 93% of the excess heat caused by greenhouse gas
4 warming since the mid-20th century, making them warmer and altering global and regional
5 climate feedbacks. Ocean heat content has increased at all depths since the 1960s and surface
6 waters have warmed by about $1.3^{\circ} \pm 0.1^{\circ}\text{F}$ ($0.7^{\circ} \pm 0.08^{\circ}\text{C}$) per century globally since 1900 to
7 2016. Under a high emissions scenario, a global increase in average sea surface temperature of
8 $4.9^{\circ} \pm 1.3^{\circ}\text{F}$ ($2.7^{\circ} \pm 0.7^{\circ}\text{C}$) by 2100 is projected, with even higher changes in some U.S. coastal
9 regions. (*Very high confidence*)

10 Description of evidence base

11 The key finding and supporting text summarizes the evidence documented in climate science
12 literature, including Rhein et al. 2013 and thereafter. Oceanic warming has been documented in a
13 variety of data sources, most notably the WOCE (<http://www.nodc.noaa.gov/woce/wdiu/>),
14 ARGO database (<https://www.nodc.noaa.gov/argo/>), and ERSSTv4
15 ([https://www.ncdc.noaa.gov/data-access/marineocean-data/extended-reconstructed-sea-surface-
16 temperature-ersst-v4](https://www.ncdc.noaa.gov/data-access/marineocean-data/extended-reconstructed-sea-surface-temperature-ersst-v4)). There is particular confidence in calculated warming for the time period
17 since 1971 due to increased spatial and depth coverage and the level of agreement among
18 independent SST observations from satellites, surface drifters and ships, and independent studies
19 using differing analyses, bias corrections, and data sources (Cheng et al. 2017; Levitus et al.
20 2012; Llovel et al. 2014). Other observations such as the increase in mean sea level rise (see Ch.
21 12: Sea Level Rise) and reduced Arctic/Antarctic ice sheets (see Ch. 11: Arctic Changes) further
22 confirm the increase in thermal expansion. For the purpose of extending the selected time
23 periods back from 1900 to 2016 and analyzing U.S. regional SSTs, the Extended Reconstructed
24 Sea Surface Temperature version 4 (ERSSTv4; Huang et al. 2015) is used. For the centennial
25 time scale changes over 1900–2016, warming trends in all regions are statistically significant
26 with the 95% confidence level. U.S. regional SST warming is similar between calculations using
27 ERSSTv4 in this report and those published by Belkin (2016), suggesting confidence in these
28 findings. The projected increase in SST is based on evidence from the latest generation of Earth
29 System Models (CMIP5).

30 Major uncertainties

31 Uncertainties in the magnitude of ocean warming stem from the disparate measurements of
32 ocean temperature over the last century. There is low uncertainty in warming trends of the upper
33 ocean temperature from 0–700 m depth, whereas there is more uncertainty for deeper ocean
34 depths of 700–2,000 m due to the short record of measurements from those areas. Data on
35 warming trends at depths greater than 2,000 m are even more sparse. There are also uncertainties
36 in the timing and reasons for particular decadal and interannual variations in ocean heat content
37 and the contributions that different ocean basins play in the overall ocean heat uptake.

1 Summary sentence or paragraph that integrates the above information

2 There is *very high confidence* in measurements that show increases in the ocean heat content and
3 warming of the ocean, based on the agreement of different methods. However, long-term data in
4 total ocean heat uptake in the deep ocean are sparse leading to limited knowledge of the transport
5 of heat between and within ocean basins.

6

7 Key Finding 2

8 The potential slowing of the Atlantic Meridional Overturning Circulation (AMOC) (of which the
9 Gulf Stream is one component)—as a result of increasing ocean heat content and freshwater
10 driven buoyancy changes—could have dramatic climate feedbacks as the ocean absorbs less heat
11 and CO₂ from the atmosphere. This slowing would also affect the climates of North America and
12 Europe. Any slowing documented to date cannot be directly tied to anthropogenic forcing
13 primarily due to lack of adequate observational data and to challenges in modeling ocean
14 circulation changes. Under a high emissions scenario (RCP8.5) in CMIP5 simulations, it is likely
15 that the AMOC will weaken over the 21st century by 12% to 54%. (*Low confidence*)

16 Description of evidence base

17 Investigations both through direct observations and models since 2013 (Rhein et al. 2013) have
18 raised significant concerns about whether there is enough evidence to determine the existence of
19 an overall slowdown in the AMOC. As a result, more robust international observational
20 campaigns are underway currently to measure AMOC circulation. Direct observations have
21 determined a statistically significant slowdown at the 95% confidence level at 26°N (off Florida;
22 see Baringer et al. 2016), but modeling studies constrained with observations cannot attribute
23 this to anthropogenic forcing (Jackson et al. 2016). The study (Rahmstorf et al. 2015) which
24 seemed to indicate broad-scale slowing has since been discounted due to its heavy reliance on
25 sea surface temperature cooling as proxy for slowdown rather than actual direct observations.
26 Since Rhein et al. 2013, more observations have led to increased statistical confidence in the
27 measurement of the AMOC. Current observation trends indicate the AMOC slowing down at the
28 95% confidence level at 26°N and 41°N but a more limited in situ estimate at 35°S shows an
29 increase in the AMOC (Smeed et al. 2014; Baringer et al. 2016). There is no one collection spot
30 for AMOC-related data, but the U.S. Climate Variability and Predictability Program (US
31 CLIVAR) has a U.S. AMOC priority focus area and a webpage with relevant data sites
32 (<https://usclivar.org/amoc/amoc-time-series>).

33 The IPCC 2013 WG1 projections indicate a high likelihood of AMOC slowdown in the next 100
34 years, however overall understanding is limited by both a lack of direct observations (which is
35 being remedied) and a lack of model skill to resolve deep ocean dynamics. As a result, this key
36 finding was given an overall assessment of *low confidence*.

1 **Major uncertainties**

2 As noted, uncertainty about the overall trend of the AMOC is high given opposing trends in
3 northern and southern ocean time series observations. Although earth system models do indicate
4 a high likelihood of AMOC slowdown as a result of a warming, climate projections are subject
5 to high uncertainty. This uncertainty stems from intermodel differences, internal variability that
6 is different in each model, uncertainty in stratification changes, and most importantly uncertainty
7 in both future freshwater input at high latitudes as well as the strength of the subpolar gyre
8 circulation.

9 **Summary sentence or paragraph that integrates the above information**

10 The increased focus on direct measurements of the AMOC should lead to a better understanding
11 of 1) how it is changing and its variability by region, and 2) whether those changes are
12 attributable to climate drivers through both model improvements and incorporation of those
13 expanded observations into the models.

14

15 **Key Finding 3**

16 The world's oceans are currently absorbing more than a quarter of the CO₂ emitted to the
17 atmosphere annually from human activities, making them more acidic (*very high confidence*),
18 with potential detrimental impacts to marine ecosystems. In particular, higher-latitude systems
19 typically have a lower buffering capacity against pH change, exhibiting seasonally corrosive
20 conditions sooner than low-latitude systems. Acidification is regionally increasing along U.S.
21 coastal systems as a result of upwelling (for example, in the Pacific Northwest) (*high*
22 *confidence*), changes in freshwater inputs (for example, in the Gulf of Maine) (*medium*
23 *confidence*), and nutrient input (for example, in urbanized estuaries) (*high confidence*). The rate
24 of acidification is unparalleled in at least the past 66 million years (*medium confidence*). Under
25 RCP8.5, the global average surface ocean acidity is projected to increase by 100% to 150% (*high*
26 *confidence*).

27 **Description of evidence base**

28 Evidence on the magnitude of the ocean sink is obtained from multiple biogeochemical and
29 transport ocean models and two observation-based estimates from the 1990s for the uptake of the
30 anthropogenic CO₂. Estimates of the carbonate system (DIC and alkalinity) were based on
31 multiple survey cruises in the global ocean in the 1990s (WOCE, JGOFS). Coastal carbon and
32 acidification surveys have been executed along the U.S. coastal large marine ecosystem since at
33 least 2007, documenting significantly elevated pCO₂ and low pH conditions relative to oceanic
34 waters. The data is available from the National Centers for Environmental Information
35 (<https://www.ncei.noaa.gov/>). Other sources of biogeochemical bottle data can be found from

1 HOT-DOGS ALOHA (<http://hahana.soest.hawaii.edu/hot/hot-dogs>) or ERSL/GFM Data Finder
2 (<https://www.esrl.noaa.gov/gmd/dv/data>). Rates of change associated with the Palaeocene-
3 Eocene Thermal Maximum (PETM, 56 million years ago) were derived using stable carbon and
4 oxygen isotope records preserved in the sedimentary record from the New Jersey shelf using
5 time series analysis and carbon cycle–climate modelling. This evidence supports a carbon release
6 during the onset of the PETM over no less than 4,000 years, yielding a maximum sustained
7 carbon release rate of less than 1.1 GtC per year (Zeebe et al. 2016). The projected increase in
8 global surface ocean acidity is based on evidence from ten of the latest generation earth system
9 models which include six distinct biogeochemical models that were included in the latest IPCC
10 AR5 2013.

11 **Major uncertainties**

12 In 2014 the ocean sink was 2.6 ± 0.5 GtC (9.5 GtCO₂), equivalent to 26% of the total emissions
13 attributed to fossil fuel use and land use changes (Le Quéré et al. 2016). Estimates of the PETM
14 ocean acidification event evidenced in the geological record remains a matter of some debate
15 within the community. Evidence for the 1.1 GtC per year cited by Zeebe et al. (2016), could be
16 biased as a result of brief pulses of carbon input above average rates of emissions were they to
17 transpire over timescales ≤ 40 years.

18 **Summary sentence or paragraph that integrates the above information**

19 There is *very high confidence* in evidence that the oceans absorb about a quarter of the carbon
20 dioxide emitted in the atmosphere and hence become more acidic. The magnitude of the ocean
21 carbon sink is known at a *high confidence* level because it is estimated using a series of disparate
22 data sources and analysis methods, while the magnitude of the interannual variability is based
23 only on model studies. There is medium confidence that the current rate of climate acidification
24 is unprecedented in the past 66 million years. There is also *high confidence* that oceanic pH will
25 continue to decrease.

26

27 **Key Finding 4**

28 Increasing sea surface temperatures, rising sea levels, and changing patterns of precipitation,
29 winds, nutrients, and ocean circulation are contributing to overall declining oxygen
30 concentrations at intermediate depths in various ocean locations and in many coastal areas. Over
31 the last half century, major oxygen losses have occurred in inland seas, estuaries, and in the
32 coastal and open ocean (*high confidence*). Ocean oxygen levels are projected to decrease by as
33 much as 3.5% under the RCP8.5 scenario by 2100 relative to preindustrial values (*high*
34 *confidence*).

35

1 Description of evidence base

2 The key finding and supporting text summarizes the evidence documented in climate science
3 literature including Rhein et al. 2013, Bopp et al. 2013, and Schmidtko et al. 2017. Evidence
4 arises from extensive global measurements of the World Ocean Circulation Experiment (WOCE)
5 after 1989 and individual profiles before that (Helm et al. 2011). The first basin-wide dissolved
6 oxygen surveys were performed in the 1920s (Schmidtko et al. 2017). The confidence level is
7 based on globally integrated O₂ distributions in a variety of ocean models. Although the global
8 mean exhibits low interannual variability, regional contrasts are large.

9 Major uncertainties

10 Uncertainties (as estimated from the intermodel spread) in the global mean are moderate mainly
11 because ocean oxygen content exhibits low interannual variability when globally averaged.
12 Uncertainties in long-term decreases of the global averaged oxygen concentration amount to
13 25% in the upper 1,000 m for the 1970–1992 period and 28% for the 1993–2003 period.
14 Remaining uncertainties relate to regional variability driven by mesoscale eddies and intrinsic
15 climate variability such as ENSO.

16 Summary sentence or paragraph that integrates the above information

17 Major ocean deoxygenation is taking place in bodies of water inland, at estuaries, and in the
18 coastal and the open ocean (*high confidence*). Regionally, the phenomenon is exacerbated by
19 local changes in weather, ocean circulation, and continental inputs to the oceans.

20

1 **TABLE**

2 **Table 13.1.** Historical sea surface temperature trends (°C per century) and projected trends by
 3 2080 (°C) for eight U.S. coastal regions and globally. Historical temperature trends are presented
 4 for the 1900–2016 and 1950–2016 periods with 95% confidence level, observed using the
 5 Extended Reconstructed Sea Surface Temperature version 4 (ERSSTv4; Huang et al. 2015).
 6 Global and regional predictions are calculated for RCP4.5 and RCP8.5 emission levels with 80%
 7 spread of all the CMIP5 members compared to the 1976–2005 period (Scott et al. 2016). The
 8 historical trends were analyzed for the latitude and longitude in the table, while the projected
 9 trends were analyzed for the California current instead of the Northwest and Southwest
 10 separately and for the Bering Sea in Alaska (NOAA).

Region	latitude and longitude	Historical Trend (°C/100 years)		Projected Trend by 2080 (relative to 1976-2005 climate) (°C)	
		1900–2016	1950–2016	RCP4.5	RCP8.5
Global		0.70 ± 0.08	1.00 ± 0.11	1.3 ± 0.6	2.7 ± 0.7
Alaska	50°–66°N, 150°–170°W	0.82 ± 0.26	1.22 ± 0.59	2.5 ± 0.6	3.7 ± 1.0
Northwest (NW)	40°–50°N, 120°–132°W	0.64 ± 0.30	0.68 ± 0.70	1.7 ± 0.4	2.8 ± 0.6
Southwest (SW)	30°–40°N, 116°–126°W	0.73 ± 0.33	1.02 ± 0.79		
Hawaii (HI)	18°–24°N, 152°–162°W	0.58 ± 0.19	0.46 ± 0.39	1.6 ± 0.4	2.8 ± 0.6
Northeast (NE)	36°–46°N, 64°–76°W	0.63 ± 0.31	1.10 ± 0.71	2.0 ± 0.3	3.2 ± 0.6

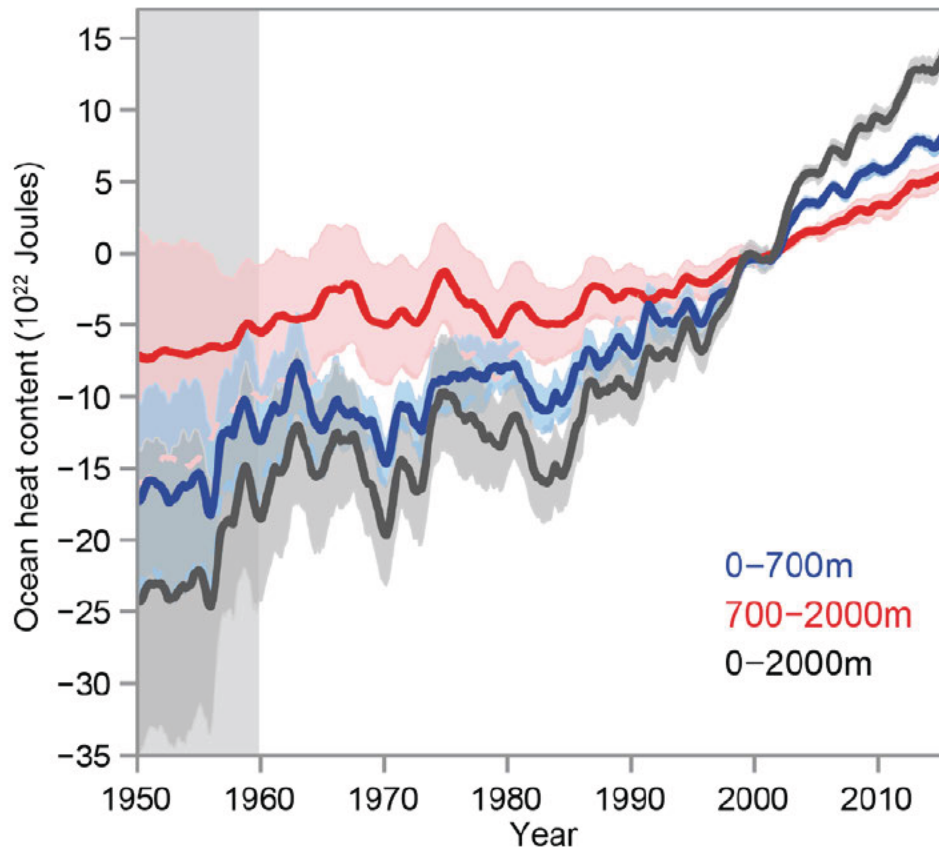
Southeast (SE)	24°–34°N, 64°–80°W	0.40 ± 0.18	0.13 ± 0.34	1.6 ± 0.3	2.7 ± 0.4
Gulf of Mexico (GOM)	20°–30°N, 80°–96°W	0.52 ± 0.14	0.37 ± 0.27	1.6 ± 0.3	2.8 ± 0.3
Caribbean	10°–20°N, 66°–86°W	0.76 ± 0.15	0.77 ± 0.32	1.5 ± 0.4	2.6 ± 0.3

1

2

FINAL DRAFT

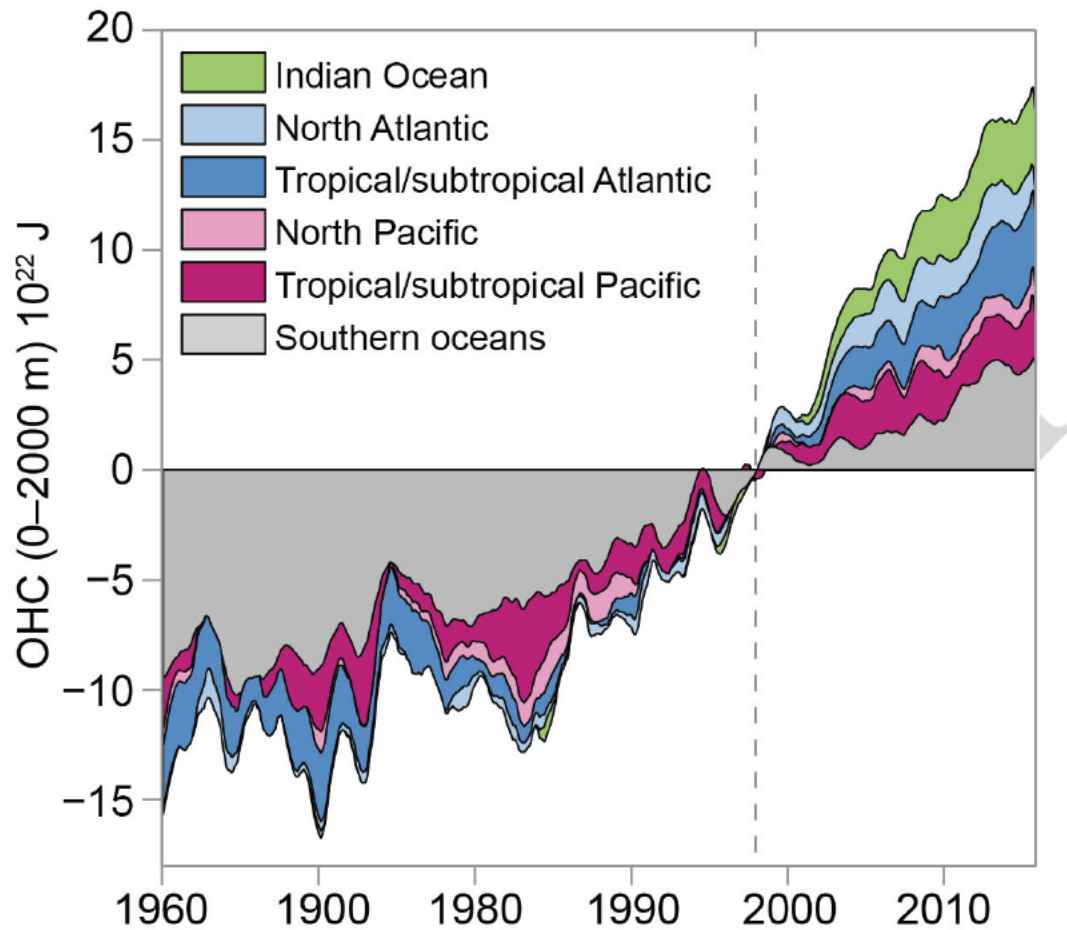
1 FIGURES



2

3 **Figure 13.1:** Global Ocean heat content change time series. Ocean heat content from 0 to 700 m
4 (blue), 700 to 2,000 m (red), and 0 to 2,000 m (dark gray) from 1955 to 2015 with an uncertainty
5 interval of ± 2 standard deviations shown in shading. All time series of the analysis performed by
6 Cheng et al. (2017) are smoothed by a 12-month running mean filter, relative to the 1997–2005
7 base period. (Figure source: Cheng et al. 2017).

8

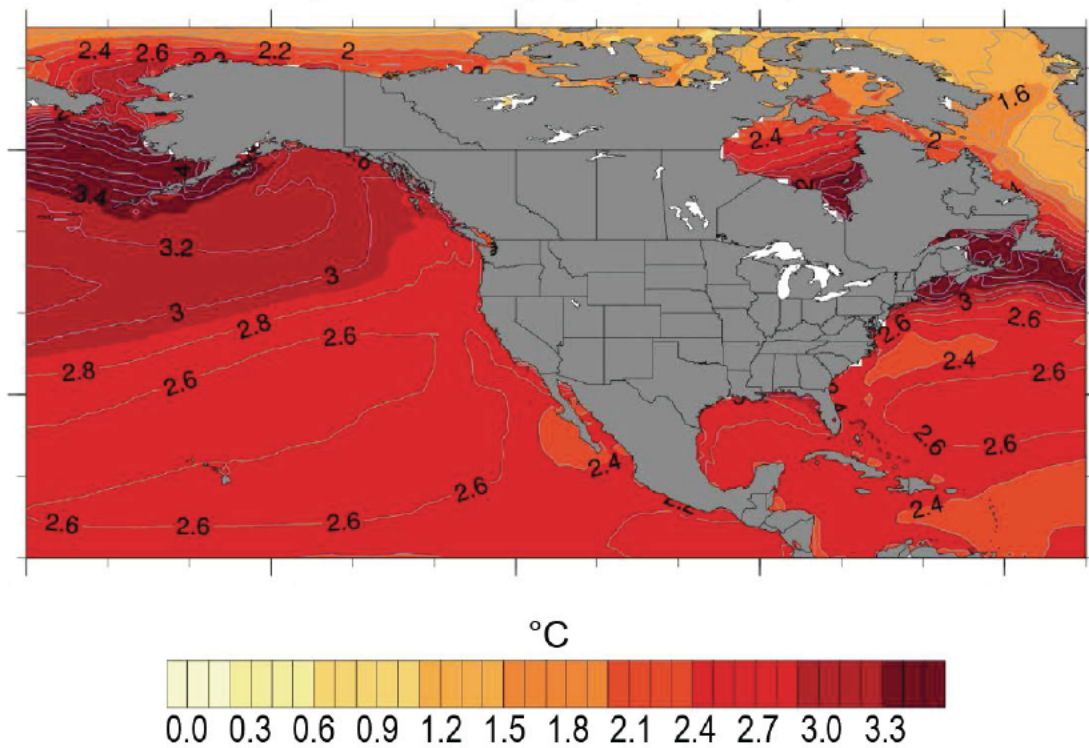


1

2 **Figure 13.2:** Ocean heat content changes from 1960 to 2015 for different ocean basins for 0 to
 3 2,000 m depths. Time series is relative to the 1997–1999 base period and smoothed by a 12-
 4 month running filter by Cheng et al. (2017). The curves are additive, and the ocean heat content
 5 changes in different ocean basins are shaded in different colors (Figure source: Cheng et al.
 6 2017).

7

CMIP5 ENSMN RCP8.5 Anomaly (2050–2099)–(1956–2005)

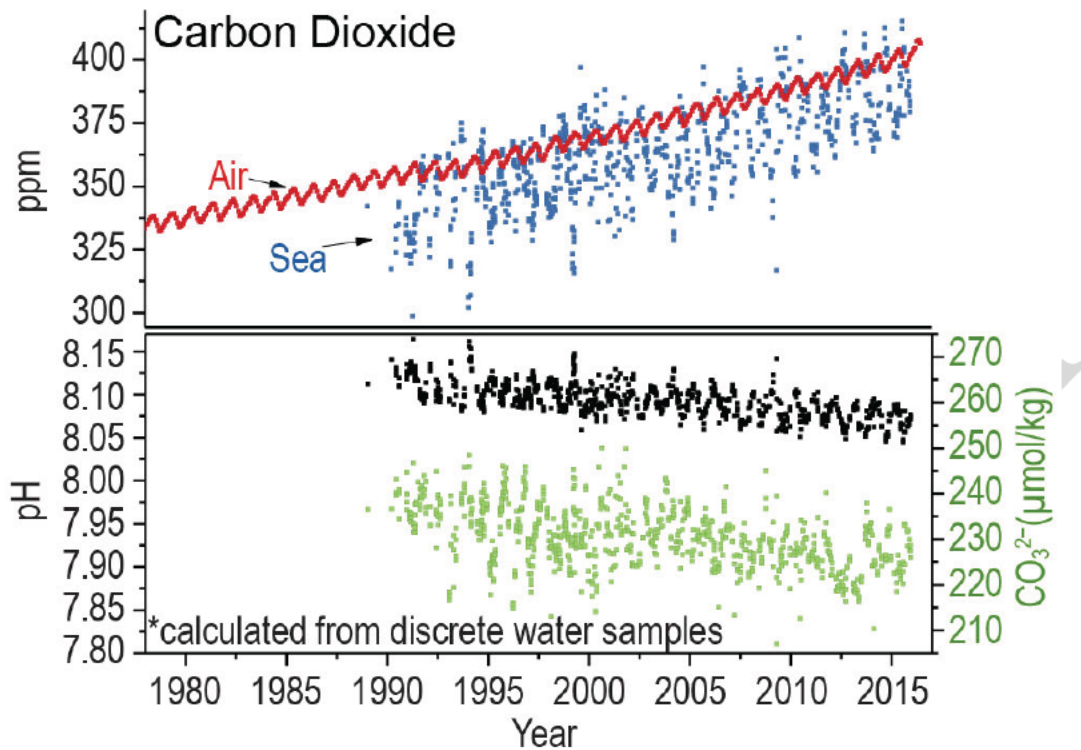


1

2 **Figure 13.3:** Projected changes in sea surface temperature (°C) for the coastal United States
 3 under emission scenario RCP8.5. Projected anomalies for the 2050–2099 period are calculated
 4 using a comparison from the average sea surface temperatures over 1956–2005. Projected
 5 changes are examined using the Coupled Model Intercomparison Project Phase 5 (CMIP5) suite
 6 of model simulations. (Figure source: NOAA).

7

1

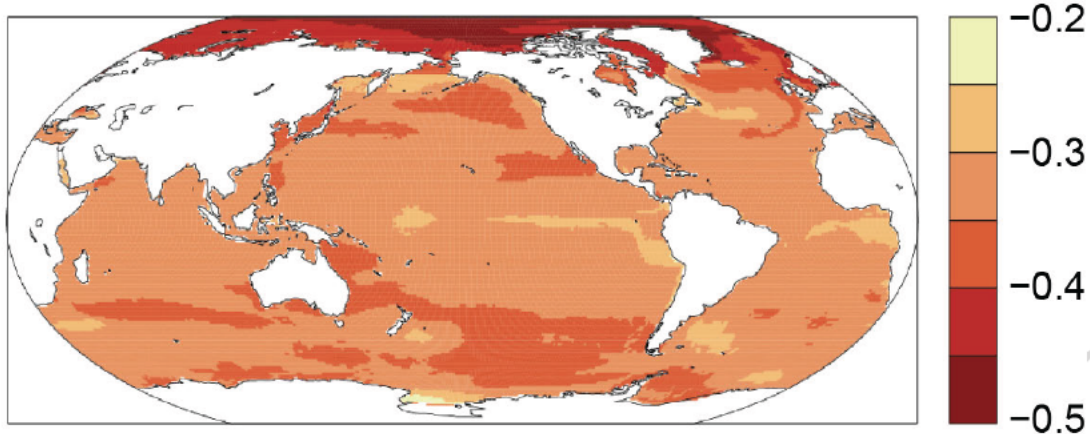


2

3 **Figure 13.4:** Trends in surface (< 50 m) ocean carbonate chemistry calculated from observations
 4 obtained at the Hawai'i Ocean Time-series (HOT) Program in the North Pacific over 1988–2015.
 5 The upper panel shows the linked increase in atmospheric (red points) and seawater (blue points)
 6 CO₂ concentrations. The bottom panels shows a decline in seawater pH (black points, primary y-
 7 axis) and carbonate ion concentration (green points, secondary y-axis). Ocean chemistry data
 8 were obtained from the Hawai'i Ocean Time-series Data Organization & Graphical System
 9 (HOT-DOGS, <http://hahana.soest.hawaii.edu/hot/hot-dogs/index.html>). (Figure source: NOAA).

10

Surface pH in 2090s (RCP8.5, changes from 1990s)

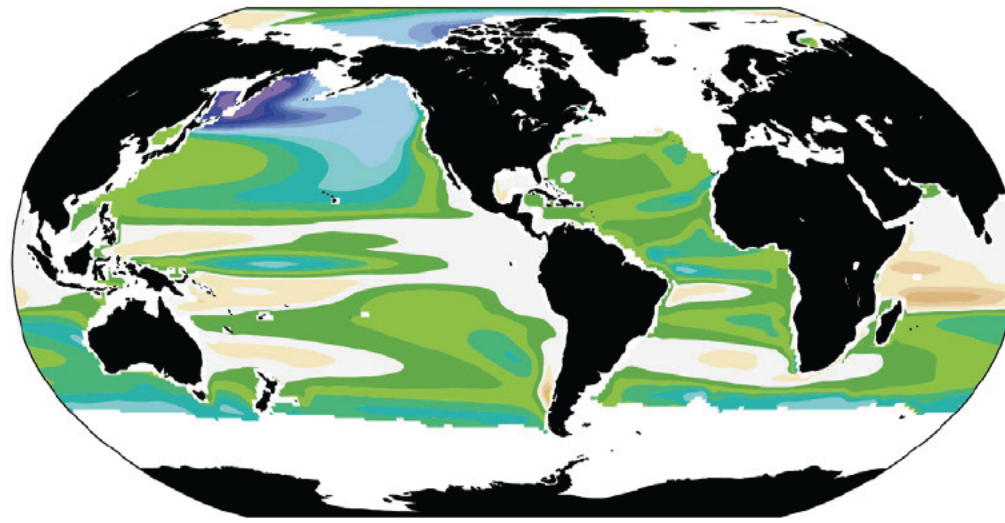
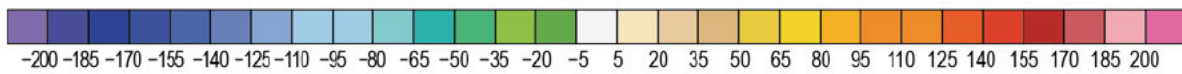


1

2 **Figure 13.5** Predicted change in sea surface pH in 2090–2099 relative to 1990–1999 under
3 RCP8.5, based on the Community Earth System Models–Large Ensemble Experiments CMIP5
4 (Figure source: adapted from Bopp et al. 2013).

5

Projected Change in Dissolved Oxygen

mmol/m³

1

2

3

4

5

6

Figure 13.6: Predicted change in dissolved oxygen on the $\sigma_{\theta} = 26.5$ (average depth of approximately 290 m) potential density surface, between the 1981–2000 and 2081–2100, based on the Community Earth System Models–Large Ensemble Experiments (Figure source: redrawn from Long et al. 2016).

1 **REFERENCES**

- 2 Abraham, J.P., M. Baringer, N.L. Bindoff, T. Boyer, L.J. Cheng, J.A. Church, J.L. Conroy, C.M.
3 Domingues, J.T. Fasullo, J. Gilson, G. Goni, S.A. Good, J.M. Gorman, V. Gouretski, M.
4 Ishii, G.C. Johnson, S. Kizu, J.M. Lyman, A.M. Macdonald, W.J. Minkowycz, S.E. Moffitt,
5 M.D. Palmer, A.R. Piola, F. Reseghetti, K. Schuckmann, K.E. Trenberth, I. Velicogna, and
6 J.K. Willis, 2013: A review of global ocean temperature observations: Implications for ocean
7 heat content estimates and climate change. *Reviews of Geophysics*, **51**, 450–483.
8 <http://dx.doi.org/10.1002/rog.20022>
- 9 Altieri, A.H. and K.B. Gedan, 2015: Climate change and dead zones. *Global Change Biology*,
10 **21**, 1395–1406. <http://dx.doi.org/10.1111/gcb.12754>
- 11 Astor, Y.M., L. Lorenzoni, R. Thunell, R. Varela, F. Muller-Karger, L. Troccoli, G.T. Taylor,
12 M.I. Scranton, E. Tappa, and D. Rueda, 2013: Interannual variability in sea surface
13 temperature and $f\text{CO}_2$ changes in the Cariaco Basin. *Deep Sea Research Part II: Topical*
14 *Studies in Oceanography*, **93**, 33–43. <http://dx.doi.org/10.1016/j.dsr2.2013.01.002>
- 15 Baden, S.P., L.O. Loo, L. Pihl, and R. Rosenberg, 1990: Effects of eutrophication on benthic
16 communities including fish — Swedish west coast. *Ambio*, **19**, 113-122.
17 www.jstor.org/stable/4313676
- 18 Bakun, A., B.A. Black, S.J. Bograd, M. García-Reyes, A.J. Miller, R.R. Rykaczewski, and W.J.
19 Sydeman, 2015: Anticipated effects of climate change on coastal upwelling ecosystems.
20 *Current Climate Change Reports*, **1**, 85-93. <http://dx.doi.org/10.1007/s40641-015-0008-4>
- 21 Baringer, M.O., M. Lankhorst, D. Volkov, S. Garzoli, S. Dong, U. Send, and C. Meinen, 2016:
22 Meridional oceanic overturning circulation and heat transport in the Atlantic Ocean [in "State
23 of the Climate in 2015"]. *Bulletin of the American Meteorological Society*, **97**, S84–S87.
24 <http://dx.doi.org/10.1175/2015BAMSStateoftheClimate.1>
- 25 Bates, N.R. and J.T. Mathis, 2009: The Arctic Ocean marine carbon cycle: Evaluation of air-sea
26 CO_2 exchanges, ocean acidification impacts and potential feedbacks. *Biogeosciences*, **6**,
27 2433-2459. <http://dx.doi.org/10.5194/bg-6-2433-2009>
- 28 Bates, N.R., Y.M. Astor, M.J. Church, K. Currie, J.E. Dore, M. González-Dávila, L. Lorenzoni,
29 F. Muller-Karger, J. Olafsson, and J.M. Santana-Casiano, 2014: A time-series view of
30 changing ocean chemistry due to ocean uptake of anthropogenic CO_2 and ocean
31 acidification. *Oceanography*, **27**, 126–141. <http://dx.doi.org/10.5670/oceanog.2014.16>
- 32 Belkin, I., 2016: Chapter 5.2: Sea surface temperature trends in large marine ecosystems. *Large*
33 *Marine Ecosystems: Status and Trends*. United Nations Environment Programme, Nairobi,
34 101-109.
35 wedocs.unep.org/bitstream/handle/20.500.11822/13456/UNEP_DEWA_TWAP%20VOLUM

- 1 E%204%20REPORT_FINAL_4_MAY.pdf?sequence=1&isAllowed=y,%20English%20-
2 %20Summary
- 3 Bianchi, D., E.D. Galbraith, D.A. Carozza, K.A.S. Mislan, and C.A. Stock, 2013: Intensification
4 of open-ocean oxygen depletion by vertically migrating animals. *Nature Geoscience*, **6**, 545-
5 548. <http://dx.doi.org/10.1038/ngeo1837>
- 6 Boetius, A. and F. Wenzhofer, 2013: Seafloor oxygen consumption fuelled by methane from
7 cold seeps. *Nature Geoscience*, **6**, 725-734. <http://dx.doi.org/10.1038/ngeo1926>
- 8 Bograd, S.J., M.P. Buil, E.D. Lorenzo, C.G. Castro, I.D. Schroeder, R. Goericke, C.R. Anderson,
9 C. Benitez-Nelson, and F.A. Whitney, 2015: Changes in source waters to the Southern
10 California Bight. *Deep Sea Research Part II: Topical Studies in Oceanography*, **112**, 42-52.
11 <http://dx.doi.org/10.1016/j.dsr2.2014.04.009>
- 12 Bond, N.A., M.F. Cronin, H. Freeland, and N. Mantua, 2015: Causes and impacts of the 2014
13 warm anomaly in the NE Pacific. *Geophysical Research Letters*, **42**, 3414-3420.
14 <http://dx.doi.org/10.1002/2015GL063306>
- 15 Böning, C.W., E. Behrens, A. Biastoch, K. Getzlaff, and J.L. Bamber, 2016: Emerging impact of
16 Greenland meltwater on deepwater formation in the North Atlantic Ocean. *Nature*
17 *Geoscience*, **9**, 523-527. <http://dx.doi.org/10.1038/ngeo2740>
- 18 Booth, J.A.T., E.E. McPhee-Shaw, P. Chua, E. Kingsley, M. Denny, R. Phillips, S.J. Bograd,
19 L.D. Zeidberg, and W.F. Gilly, 2012: Natural intrusions of hypoxic, low pH water into
20 nearshore marine environments on the California coast. *Continental Shelf Research*, **45**, 108-
21 115. <http://dx.doi.org/10.1016/j.csr.2012.06.009>
- 22 Bopp, L., L. Resplandy, J.C. Orr, S.C. Doney, J.P. Dunne, M. Gehlen, P. Halloran, C. Heinze, T.
23 Ilyina, R. Séférian, J. Tjiputra, and M. Vichi, 2013: Multiple stressors of ocean ecosystems in
24 the 21st century: Projections with CMIP5 models. *Biogeosciences*, **10**, 6225-6245.
25 <http://dx.doi.org/10.5194/bg-10-6225-2013>
- 26 Borges, A.V. and N. Gypens, 2010: Carbonate chemistry in the coastal zone responds more
27 strongly to eutrophication than ocean acidification. *Limnology and Oceanography*, **55**, 346-
28 353. <http://dx.doi.org/10.4319/lo.2010.55.1.0346>
- 29 Boyer, T., C.M. Domingues, S.A. Good, G.C. Johnson, J.M. Lyman, M. Ishii, V. Gouretski, J.K.
30 Willis, J. Antonov, S. Wijffels, J.A. Church, R. Cowley, and N.L. Bindoff, 2016: Sensitivity
31 of global upper-ocean heat content estimates to mapping methods, XBT bias corrections, and
32 baseline climatologies. *Journal of Climate*, **29**, 4817-4842. <http://dx.doi.org/10.1175/jcli-d-15-0801.1>
33

- 1 Breitburg, D.L., J. Salisbury, J.M. Bernhard, W.-J. Cai, S. Dupont, S.C. Doney, K.J. Kroeker,
2 L.A. Levin, W.C. Long, L.M. Milke, S.H. Miller, B. Phelan, U. Passow, B.A. Seibel, A.E.
3 Todgham, and A.M. Tarrant, 2015: And on top of all that... Coping with ocean acidification
4 in the midst of many stressors. *Oceanography*, **28**, 48-61.
5 <http://dx.doi.org/10.5670/oceanog.2015.31>
- 6 Brush, G.S., 2009: Historical land use, nitrogen, and coastal eutrophication: A paleoecological
7 perspective. *Estuaries and Coasts*, **32**, 18-28. <http://dx.doi.org/10.1007/s12237-008-9106-z>
- 8 Bryden, H.L., H.R. Longworth, and S.A. Cunningham, 2005: Slowing of the Atlantic meridional
9 overturning circulation at 25[deg][thinsp]N. *Nature*, **438**, 655-657.
10 <http://dx.doi.org/10.1038/nature04385>
- 11 Bryden, H.L., B.A. King, and G.D. McCarthy, 2011: South Atlantic overturning circulation at
12 24°S. *Journal of Marine Research*, **69**, 38-55.
13 <http://dx.doi.org/10.1357/002224011798147633>
- 14 Buckley, M.W. and J. Marshall, 2016: Observations, inferences, and mechanisms of the Atlantic
15 Meridional Overturning Circulation: A review. *Reviews of Geophysics*, **54**, 5-63.
16 <http://dx.doi.org/10.1002/2015RG000493>
- 17 Carr, M.-E., M.A.M. Friedrichs, M. Schmeltz, M. Noguchi Aita, D. Antoine, K.R. Arrigo, I.
18 Asanuma, O. Aumont, R. Barber, M. Behrenfeld, R. Bidigare, E.T. Buitenhuis, J. Campbell,
19 A. Ciotti, H. Dierssen, M. Dowell, J. Dunne, W. Esaias, B. Gentili, W. Gregg, S. Groom, N.
20 Hoepffner, J. Ishizaka, T. Kameda, C. Le Quéré, S. Lohrenz, J. Marra, F. Mélin, K. Moore,
21 A. Morel, T.E. Reddy, J. Ryan, M. Scardi, T. Smyth, K. Turpie, G. Tilstone, K. Waters, and
22 Y. Yamanaka, 2006: A comparison of global estimates of marine primary production from
23 ocean color. *Deep Sea Research Part II: Topical Studies in Oceanography*, **53**, 741-770.
24 <http://dx.doi.org/10.1016/j.dsr2.2006.01.028>
- 25 Chavez, F.P., M. Messié, and J.T. Pennington, 2011: Marine primary production in relation to
26 climate variability and change. *Annual Review of Marine Science*, **3**, 227-260.
27 <http://dx.doi.org/10.1146/annurev.marine.010908.163917>
- 28 Cheng, L., K.E. Trenberth, J. Fasullo, T. Boyer, J. Abraham, and J. Zhu, 2017: Improved
29 estimates of ocean heat content from 1960 to 2015. *Science Advances*, **3**, e1601545.
30 <http://dx.doi.org/10.1126/sciadv.1601545>
- 31 Cheng, W., J.C.H. Chiang, and D. Zhang, 2013: Atlantic Meridional Overturning Circulation
32 (AMOC) in CMIP5 models: RCP and historical simulations. *Journal of Climate*, **26**, 7187-
33 7197. <http://dx.doi.org/10.1175/jcli-d-12-00496.1>

- 1 Chiapello, I., 2014: Dust observations and climatology. *Mineral Dust: A Key Player in the Earth*
2 *System*. Knippertz, P. and J.-B.W. Stuut, Eds. Springer Netherlands, Dordrecht, 149-177.
3 http://dx.doi.org/10.1007/978-94-017-8978-3_7
- 4 Ciais, P., C. Sabine, G. Bala, L. Bopp, V. Brovkin, J. Canadell, A. Chhabra, R. DeFries, J.
5 Galloway, M. Heimann, C. Jones, C. Le Quéré, R.B. Myneni, S. Piao, and P. Thornton,
6 2013: Carbon and other biogeochemical cycles. *Climate Change 2013: The Physical Science*
7 *Basis. Contribution of Working Group I to the Fifth Assessment Report of the*
8 *Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M.
9 Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds.
10 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 465–
11 570. <http://www.climatechange2013.org/report/full-report/>
- 12 Codispoti, L.A., J.A. Brandes, J.P. Christensen, A.H. Devol, S.W.A. Naqvi, H.W. Paerl, and T.
13 Yoshinari, 2001: The oceanic fixed nitrogen and nitrous oxide budgets: Moving targets as we
14 enter the anthropocene? *Scientia Marina*, **65**, 85-105.
15 <http://dx.doi.org/10.3989/scimar.2001.65s285>
- 16 Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J.
17 Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver, and M. Wehner,
18 2013: Long-term climate change: Projections, commitments and irreversibility. *Climate*
19 *Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth*
20 *Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D.
21 Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and
22 P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New
23 York, NY, USA, 1029–1136. <http://www.climatechange2013.org/report/full-report/>
- 24 Conley, D.J., J. Carstensen, J. Aigars, P. Axe, E. Bonsdorff, T. Eremina, B.-M. Haahti, C.
25 Humborg, P. Jonsson, J. Kotta, C. Lännegren, U. Larsson, A. Maximov, M.R. Medina, E.
26 Lysiak-Pastuszak, N. Remeikaitė-Nikiėnė, J. Walve, S. Wilhelms, and L. Zillén, 2011:
27 Hypoxia is increasing in the coastal zone of the Baltic Sea. *Environmental Science &*
28 *Technology*, **45**, 6777-6783. <http://dx.doi.org/10.1021/es201212r>
- 29 Deutsch, C., H. Brix, T. Ito, H. Frenzel, and L. Thompson, 2011: Climate-forced variability of
30 ocean hypoxia. *Science*, **333**, 336-339. <http://dx.doi.org/10.1126/science.1202422>
- 31 Deutsch, C., W. Berelson, R. Thunell, T. Weber, C. Tems, J. McManus, J. Crusius, T. Ito, T.
32 Baumgartner, V. Ferreira, J. Mey, and A. van Geen, 2014: Centennial changes in North
33 Pacific anoxia linked to tropical trade winds. *Science*, **345**, 665-668.
34 <http://dx.doi.org/10.1126/science.1252332>
- 35 Diaz, R.J. and R. Rosenberg, 2008: Spreading dead zones and consequences for marine
36 ecosystems. *Science*, **321**, 926-929. <http://dx.doi.org/10.1126/science.1156401>

- 1 Dong, S., G. Goni, and F. Bringas, 2015: Temporal variability of the South Atlantic Meridional
2 Overturning Circulation between 20°S and 35°S. *Geophysical Research Letters*, **42**, 7655-
3 7662. <http://dx.doi.org/10.1002/2015GL065603>
- 4 Donner, S.D. and D. Scavia, 2007: How climate controls the flux of nitrogen by the Mississippi
5 River and the development of hypoxia in the Gulf of Mexico. *Limnology and Oceanography*,
6 **52**, 856-861. <http://dx.doi.org/10.4319/lo.2007.52.2.0856>
- 7 Drijfhout, S.S., S.L. Weber, and E. van der Swaluw, 2011: The stability of the MOC as
8 diagnosed from model projections for pre-industrial, present and future climates. *Climate*
9 *Dynamics*, **37**, 1575-1586. <http://dx.doi.org/10.1007/s00382-010-0930-z>
- 10 Duarte, C.M., Hendriks, I.E., Moore, T.S., Olsen, Y.S., Steckbauer, A., Ramajo, L., Carstensen,
11 J., Trotter, J.A. and McCulloch, M., 2013. Is ocean acidification an open-ocean syndrome?
12 Understanding anthropogenic impacts on seawater pH. *Estuaries and Coasts*, 36(2), pp.221-
13 236. DOI: 10.1007/s12237-013-9594-3
- 14 Durack, P.J. and S.E. Wijffels, 2010: Fifty-year trends in global ocean salinities and their
15 relationship to broad-scale warming. *Journal of Climate*, **23**, 4342-4362.
16 <http://dx.doi.org/10.1175/2010jcli3377.1>
- 17 EPA. 2017: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2015.
18 https://www.epa.gov/sites/production/files/2017-02/documents/2017_complete_report.pdf
- 19 Evans, W., J.T. Mathis, and J.N. Cross, 2014: Calcium carbonate corrosivity in an Alaskan
20 inland sea. *Biogeosciences*, **11**, 365-379. <http://dx.doi.org/10.5194/bg-11-365-2014>
- 21 Falkowski, P.G., T. Algeo, L. Codispoti, C. Deutsch, S. Emerson, B. Hales, R.B. Huey, W.J.
22 Jenkins, L.R. Kump, L.A. Levin, T.W. Lyons, N.B. Nelson, O.S. Schofield, R. Summons,
23 L.D. Talley, E. Thomas, F. Whitney, and C.B. Pilcher, 2011: Ocean deoxygenation: Past,
24 present, and future. *Eos, Transactions, American Geophysical Union*, **92**, 409-410.
25 <http://dx.doi.org/10.1029/2011EO460001>
- 26 Fasullo, J.T., R.S. Nerem, and B. Hamlington, 2016: Is the detection of accelerated sea level rise
27 imminent? *Scientific Reports*, **6**, 31245. <http://dx.doi.org/10.1038/srep31245>
- 28 Feely, R.A., C.L. Sabine, K. Lee, W. Berelson, J. Kleypas, V.J. Fabry, and F.J. Millero, 2004:
29 Impact of anthropogenic CO₂ on the CaCO₃ system in the oceans. *Science*, **305**, 362-366.
30 <http://dx.doi.org/10.1126/science.1097329>
- 31 Feely, R.A., C.L. Sabine, J.M. Hernandez-Ayon, D. Ianson, and B. Hales, 2008: Evidence for
32 upwelling of corrosive "acidified" water onto the continental shelf. *Science*, **320**, 1490-1492.
33 <http://dx.doi.org/10.1126/science.1155676>

- 1 Feely, R.A., S.C. Doney, and S.R. Cooley, 2009: Ocean acidification: Present conditions and
2 future changes in a high-CO₂ world. *Oceanography*, **22**, 36-47.
3 <http://dx.doi.org/10.5670/oceanog.2009.95>
- 4 Franz, B.A., M.J. Behrenfeld, D.A. Siegel, and S.R. Signorini, 2016: Global ocean
5 phytoplankton [in "State of the Climate in 2015"]. *Bulletin of the American Meteorological*
6 *Society*, **97**, S87–S89. <http://dx.doi.org/10.1175/2016BAMSStateoftheClimate.1>
- 7 Friedrich, T., A. Timmermann, A. Abe-Ouchi, N.R. Bates, M.O. Chikamoto, M.J. Church, J.E.
8 Dore, D.K. Gledhill, M. Gonzalez-Davila, M. Heinemann, T. Ilyina, J.H. Jungclaus, E.
9 McLeod, A. Mouchet, and J.M. Santana-Casiano, 2012: Detecting regional anthropogenic
10 trends in ocean acidification against natural variability. *Nature Climate Change*, **2**, 167-171.
11 <http://dx.doi.org/10.1038/nclimate1372>
- 12 Frölicher, T.L., K.B. Rodgers, C.A. Stock, and W.W.L. Cheung, 2016: Sources of uncertainties
13 in 21st century projections of potential ocean ecosystem stressors. *Global Biogeochemical*
14 *Cycles*, **30**, 1224-1243. <http://dx.doi.org/10.1002/2015GB005338>
- 15 Fu, W., J.T. Randerson, and J.K. Moore, 2016: Climate change impacts on net primary
16 production (NPP) and export production (EP) regulated by increasing stratification and
17 phytoplankton community structure in the CMIP5 models. *Biogeosciences*, **13**, 5151-5170.
18 <http://dx.doi.org/10.5194/bg-13-5151-2016>
- 19 Galbraith, E.D., M. Kienast, T.F. Pedersen, and S.E. Calvert, 2004: Glacial-interglacial
20 modulation of the marine nitrogen cycle by high-latitude O₂ supply to the global
21 thermocline. *Paleoceanography*, **19**, n/a-n/a. <http://dx.doi.org/10.1029/2003PA001000>
- 22 García-Reyes, M., W.J. Sydeman, D.S. Schoeman, R.R. Rykaczewski, B.A. Black, A.J. Smit,
23 and S.J. Bograd, 2015: Under pressure: Climate change, upwelling, and eastern boundary
24 upwelling ecosystems. *Frontiers in Marine Science*, **2**.
25 <http://dx.doi.org/10.3389/fmars.2015.00109>
- 26 Garzoli, S.L., M.O. Baringer, S. Dong, R.C. Perez, and Q. Yao, 2013: South Atlantic meridional
27 fluxes. *Deep Sea Research Part I: Oceanographic Research Papers*, **71**, 21-32.
28 <http://dx.doi.org/10.1016/j.dsr.2012.09.003>
- 29 Gattuso, J.-P., A. Magnan, R. Billé, W.W.L. Cheung, E.L. Howes, F. Joos, D. Allemand, L.
30 Bopp, S.R. Cooley, C.M. Eakin, O. Hoegh-Guldberg, R.P. Kelly, H.-O. Pörtner, A.D.
31 Rogers, J.M. Baxter, D. Laffoley, D. Osborn, A. Rankovic, J. Rochette, U.R. Sumaila, S.
32 Treyer, and C. Turley, 2015: Contrasting futures for ocean and society from different
33 anthropogenic CO₂ emissions scenarios. *Science*, **349**.
34 <http://dx.doi.org/10.1126/science.aac4722>

- 1 Gilbert, D., B. Sundby, C. Gobeil, A. Mucci, and G.-H. Tremblay, 2005: A seventy-two-year
2 record of diminishing deep-water oxygen in the St. Lawrence estuary: The northwest Atlantic
3 connection. *Limnology and Oceanography*, **50**, 1654-1666.
4 <http://dx.doi.org/10.4319/lo.2005.50.5.1654>
- 5 Gilbert, D., N.N. Rabalais, R.J. Díaz, and J. Zhang, 2010: Evidence for greater oxygen decline
6 rates in the coastal ocean than in the open ocean. *Biogeosciences*, **7**, 2283-2296.
7 <http://dx.doi.org/10.5194/bg-7-2283-2010>
- 8 Gledhill, D.K., M.M. White, J. Salisbury, H. Thomas, I. Mlsna, M. Liebman, B. Mook, J. Grear,
9 A.C. Candelmo, R.C. Chambers, C.J. Gobler, C.W. Hunt, A.L. King, N.N. Price, S.R.
10 Signorini, E. Stancioff, C. Stymiest, R.A. Wahle, J.D. Waller, N.D. Rebeck, Z.A. Wang, T.L.
11 Capson, J.R. Morrison, S.R. Cooley, and S.C. Doney, 2015: Ocean and coastal acidification
12 off New England and Nova Scotia. *Oceanography*, **28**, 182-197.
13 <http://dx.doi.org/10.5670/oceanog.2015.41>
- 14 Gobler, C.J., E.L. DePasquale, A.W. Griffith, and H. Baumann, 2014: Hypoxia and acidification
15 have additive and synergistic negative effects on the growth, survival, and metamorphosis of
16 early life stage bivalves. *PLoS ONE*, **9**, e83648.
17 <http://dx.doi.org/10.1371/journal.pone.0083648>
- 18 Gruber, N., 2008: Chapter 1 - The marine nitrogen cycle: Overview and challenges. *Nitrogen in*
19 *the Marine Environment (2nd Edition)*. Academic Press, San Diego, 1-50.
20 <http://dx.doi.org/10.1016/B978-0-12-372522-6.00001-3>
- 21 Harris, K.E., M.D. DeGrandpre, and B. Hales, 2013: Aragonite saturation state dynamics in a
22 coastal upwelling zone. *Geophysical Research Letters*, **40**, 2720-2725.
23 <http://dx.doi.org/10.1002/grl.50460>
- 24 Helm, K.P., N.L. Bindoff, and J.A. Church, 2011: Observed decreases in oxygen content of the
25 global ocean. *Geophysical Research Letters*, **38**, n/a-n/a.
26 <http://dx.doi.org/10.1029/2011GL049513>
- 27 Hendriks, I.E., C.M. Duarte, Y.S. Olsen, A. Steckbauer, L. Ramajo, T.S. Moore, J.A. Trotter,
28 and M. McCulloch, 2015: Biological mechanisms supporting adaptation to ocean
29 acidification in coastal ecosystems. *Estuarine, Coastal and Shelf Science*, **152**, A1-A8.
30 <http://dx.doi.org/10.1016/j.ecss.2014.07.019>
- 31 Henson, S.A., Sarmiento, J.L., Dunne, J.P., Bopp, L., Lima, I.D., Doney, S.C., John, J.G. and
32 Beaulieu, C., 2010. Detection of anthropogenic climate change in satellite records of ocean
33 chlorophyll and productivity. *Biogeosciences* 7: 621-640, doi:10.5194/bg-7-621-2010

- 1 Henson, S.A., Beaulieu, C. and Lampitt, R., 2016. Observing climate change trends in ocean
2 biogeochemistry: when and where. *Global change biology*, 22(4), pp.1561-1571. DOI:
3 10.1111/gcb.13152
- 4 Hoegh-Guldberg, O., R. Cai, E.S. Poloczanska, P.G. Brewer, S. Sundby, K. Hilmi, V.J. Fabry,
5 and S. Jung, 2014: The Ocean--Supplementary material. *Climate Change 2014: Impacts,*
6 *Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II*
7 *to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change*. Barros,
8 V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L.
9 Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R.
10 Mastrandrea, and L.L. White, Eds. Cambridge University Press, Cambridge, United
11 Kingdom and New York, NY, USA, 1655-1731. [ipcc.ch/pdf/assessment-](http://ipcc.ch/pdf/assessment-report/ar5/wg2/supplementary/WGIIAR5-Chap30_OLSM.pdf)
12 [report/ar5/wg2/supplementary/WGIIAR5-Chap30_OLSM.pdf](http://ipcc.ch/pdf/assessment-report/ar5/wg2/supplementary/WGIIAR5-Chap30_OLSM.pdf)
- 13 Hönisch, B., A. Ridgwell, D.N. Schmidt, E. Thomas, S.J. Gibbs, A. Sluijs, R. Zeebe, L. Kump,
14 R.C. Martindale, S.E. Greene, W. Kiessling, J. Ries, J.C. Zachos, D.L. Royer, S. Barker,
15 T.M. Marchitto, Jr., R. Moyer, C. Pelejero, P. Ziveri, G.L. Foster, and B. Williams, 2012:
16 The geological record of ocean acidification. *Science*, **335**, 1058-1063.
17 <http://dx.doi.org/10.1126/science.1208277>
- 18 Huang, B., V.F. Banzon, E. Freeman, J. Lawrimore, W. Liu, T.C. Peterson, T.M. Smith, P.W.
19 Thorne, S.D. Woodruff, and H.-M. Zhang, 2015: Extended Reconstructed Sea Surface
20 Temperature Version 4 (ERSST.v4). Part I: Upgrades and intercomparisons. *Journal of*
21 *Climate*, **28**, 911-930. <http://dx.doi.org/10.1175/JCLI-D-14-00006.1>
- 22 IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group*
23 *I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.
24 Cambridge University Press, Cambridge, UK and New York, NY, 1535 pp.
25 <http://www.climatechange2013.org/report/>
- 26 Ito, T., A. Nenes, M.S. Johnson, N. Meskhidze, and C. Deutsch, 2016: Acceleration of oxygen
27 decline in the tropical Pacific over the past decades by aerosol pollutants. *Nature Geoscience*,
28 **9**, 443-447. <http://dx.doi.org/10.1038/ngeo2717>
- 29 Jackson, L.C., K.A. Peterson, C.D. Roberts, and R.A. Wood, 2016: Recent slowing of Atlantic
30 overturning circulation as a recovery from earlier strengthening. *Nature Geoscience*, **9**, 518-
31 522. <http://dx.doi.org/10.1038/ngeo2715>
- 32 Jacox, M.G., A.M. Moore, C.A. Edwards, and J. Fiechter, 2014: Spatially resolved upwelling in
33 the California Current System and its connections to climate variability. *Geophysical*
34 *Research Letters*, **41**, 3189-3196. <http://dx.doi.org/10.1002/2014GL059589>

- 1 Jickells, T. and C.M. Moore, 2015: The importance of atmospheric deposition for ocean
2 productivity. *Annual Review of Ecology, Evolution, and Systematics*, **46**, 481-501.
3 <http://dx.doi.org/10.1146/annurev-ecolsys-112414-054118>
- 4 Johns, W.E., M.O. Baringer, L.M. Beal, S.A. Cunningham, T. Kanzow, H.L. Bryden, J.J.M.
5 Hirschi, J. Marotzke, C.S. Meinen, B. Shaw, and R. Curry, 2011: Continuous, array-based
6 estimates of Atlantic ocean heat transport at 26.5°N. *Journal of Climate*, **24**, 2429-2449.
7 <http://dx.doi.org/10.1175/2010jcli3997.1>
- 8 Justić, D., T. Legović, and L. Rottini-Sandrini, 1987: Trends in oxygen content 1911–1984 and
9 occurrence of benthic mortality in the northern Adriatic Sea. *Estuarine, Coastal and Shelf*
10 *Science*, **25**, 435-445. [http://dx.doi.org/10.1016/0272-7714\(87\)90035-7](http://dx.doi.org/10.1016/0272-7714(87)90035-7)
- 11 Kanzow, T., S.A. Cunningham, W.E. Johns, J.J.-M. Hirschi, J. Marotzke, M.O. Baringer, C.S.
12 Meinen, M.P. Chidichimo, C. Atkinson, L.M. Beal, H.L. Bryden, and J. Collins, 2010:
13 Seasonal variability of the Atlantic meridional overturning circulation at 26.5°N. *Journal of*
14 *Climate*, **23**, 5678-5698. <http://dx.doi.org/10.1175/2010jcli3389.1>
- 15 Knoll, A.H. and S.B. Carroll, 1999: Early animal evolution: Emerging views from comparative
16 biology and geology. *Science*, **284**, 2129-2137.
17 <http://dx.doi.org/10.1126/science.284.5423.2129>
- 18 Kosaka, Y. and Xie, S.P., 2013. Recent global-warming hiatus tied to equatorial Pacific surface cooling.
19 *Nature*, 501(7467), pp.403-407. doi:10.1038/nature12534
- 20 Laufkötter, C., M. Vogt, N. Gruber, M. Aita-Noguchi, O. Aumont, L. Bopp, E. Buitenhuis, S.C.
21 Doney, J. Dunne, T. Hashioka, J. Hauck, T. Hirata, J. John, C. Le Quéré, I.D. Lima, H.
22 Nakano, R. Seferian, I. Totterdell, M. Vichi, and C. Völker, 2015: Drivers and uncertainties
23 of future global marine primary production in marine ecosystem models. *Biogeosciences*, **12**,
24 6955-6984. <http://dx.doi.org/10.5194/bg-12-6955-2015>
- 25 Le Quéré, C., R.M. Andrew, J.G. Canadell, S. Sitch, J.I. Korsbakken, G.P. Peters, A.C. Manning,
26 T.A. Boden, P.P. Tans, R.A. Houghton, R.F. Keeling, S. Alin, O.D. Andrews, P. Anthoni, L.
27 Barbero, L. Bopp, F. Chevallier, L.P. Chini, P. Ciais, K. Currie, C. Delire, S.C. Doney, P.
28 Friedlingstein, T. Gkritzalis, I. Harris, J. Hauck, V. Haverd, M. Hoppema, K. Klein
29 Goldewijk, A.K. Jain, E. Kato, A. Körtzinger, P. Landschützer, N. Lefèvre, A. Lenton, S.
30 Lienert, D. Lombardozi, J.R. Melton, N. Metzl, F. Millero, P.M.S. Monteiro, D.R. Munro,
31 J.E.M.S. Nabel, S.I. Nakaoka, K. O'Brien, A. Olsen, A.M. Omar, T. Ono, D. Pierrot, B.
32 Poulter, C. Rödenbeck, J. Salisbury, U. Schuster, J. Schwinger, R. Séférian, I. Skjelvan, B.D.
33 Stocker, A.J. Sutton, T. Takahashi, H. Tian, B. Tilbrook, I.T. van der Laan-Luijkx, G.R. van
34 der Werf, N. Viogy, A.P. Walker, A.J. Wiltshire, and S. Zaehle, 2016: Global carbon budget
35 2016. *Earth System Science Data*, **8**, 605-649. <http://dx.doi.org/10.5194/essd-8-605-2016>

- 1 Lee, M., E. Shevliakova, S. Malyshev, P.C.D. Milly, and P.R. Jaffé, 2016: Climate variability
2 and extremes, interacting with nitrogen storage, amplify eutrophication risk. *Geophysical*
3 *Research Letters*, **43**, 7520-7528. <http://dx.doi.org/10.1002/2016GL069254>
- 4 Lee, S.-K., W. Park, M.O. Baringer, A.L. Gordon, B. Huber, and Y. Liu, 2015: Pacific origin of
5 the abrupt increase in Indian Ocean heat content during the warming hiatus. *Nature*
6 *Geoscience*, **8**, 445-449. <http://dx.doi.org/10.1038/ngeo2438>
- 7 Levitus, S., J.I. Antonov, T.P. Boyer, O.K. Baranova, H.E. Garcia, R.A. Locarnini, A.V.
8 Mishonov, J.R. Reagan, D. Seidov, E.S. Yarosh, and M.M. Zweng, 2012: World ocean heat
9 content and thermosteric sea level change (0–2000 m), 1955–2010. *Geophysical Research*
10 *Letters*, **39**, L10603. <http://dx.doi.org/10.1029/2012GL051106>
- 11 Liu, W., S.-P. Xie, Z. Liu, and J. Zhu, 2017: Overlooked possibility of a collapsed Atlantic
12 Meridional Overturning Circulation in warming climate. *Science Advances*, **3**, e1601666.
13 <http://dx.doi.org/10.1126/sciadv.1601666>
- 14 Llovel, W., J.K. Willis, F.W. Landerer, and I. Fukumori, 2014: Deep-ocean contribution to sea
15 level and energy budget not detectable over the past decade. *Nature Climate Change*, **4**,
16 1031-1035. <http://dx.doi.org/10.1038/nclimate2387>
- 17 Long, M.C., C. Deutsch, and T. Ito, 2016: Finding forced trends in oceanic oxygen. *Global*
18 *Biogeochemical Cycles*, **30**, 381-397. <http://dx.doi.org/10.1002/2015GB005310>
- 19 Longworth, H.R., H.L. Bryden, and M.O. Baringer, 2011: Historical variability in Atlantic
20 meridional baroclinic transport at 26.5°N from boundary dynamic height observations. *Deep*
21 *Sea Research Part II: Topical Studies in Oceanography*, **58**, 1754-1767.
22 <http://dx.doi.org/10.1016/j.dsr2.2010.10.057>
- 23 Mathis, J.T., S.R. Cooley, N. Lucey, S. Colt, J. Ekstrom, T. Hurst, C. Hauri, W. Evans, J.N.
24 Cross, and R.A. Feely, 2015: Ocean acidification risk assessment for Alaska's fishery sector.
25 *Progress in Oceanography*, **136**, 71-91. <http://dx.doi.org/10.1016/j.pocean.2014.07.001>
- 26 Matthews, J. B. R. "Comparing historical and modern methods of sea surface temperature
27 measurement—Part 1: Review of methods, field comparisons and dataset adjustments." *Ocean*
28 *Science* 9.4 (2013): 683-694. doi:10.5194/os-9-683-2013
- 29 McDonagh, E.L., B.A. King, H.L. Bryden, P. Courtois, Z. Szuts, M. Baringer, S.A. Cunningham,
30 C. Atkinson, and G. McCarthy, 2015: Continuous estimate of Atlantic oceanic freshwater
31 flux at 26.5°N. *Journal of Climate*, **28**, 8888-8906. [http://dx.doi.org/10.1175/jcli-d-14-](http://dx.doi.org/10.1175/jcli-d-14-00519.1)
32 00519.1
- 33 McFall-Ngai, M., M.G. Hadfield, T.C.G. Bosch, H.V. Carey, T. Domazet-Lošo, A.E. Douglas,
34 N. Dubilier, G. Eberl, T. Fukami, S.F. Gilbert, U. Hentschel, N. King, S. Kjelleberg, A.H.

- 1 Knoll, N. Kremer, S.K. Mazmanian, J.L. Metcalf, K. Nealson, N.E. Pierce, J.F. Rawls, A.
2 Reid, E.G. Ruby, M. Rumpho, J.G. Sanders, D. Tautz, and J.J. Wernegreen, 2013: Animals
3 in a bacterial world, a new imperative for the life sciences. *Proceedings of the National*
4 *Academy of Sciences*, **110**, 3229-3236. <http://dx.doi.org/10.1073/pnas.1218525110>
- 5 Mei, W., S.-P. Xie, F. Primeau, J.C. McWilliams, and C. Pasquero, 2015: Northwestern Pacific
6 typhoon intensity controlled by changes in ocean temperatures. *Science Advances*, **1**.
7 <http://dx.doi.org/10.1126/sciadv.1500014>
- 8 Moffitt, S.E., R.A. Moffitt, W. Sauthoff, C.V. Davis, K. Hewett, and T.M. Hill, 2015:
9 Paleoceanographic insights on recent oxygen minimum zone expansion: Lessons for modern
10 oceanography. *PLoS ONE*, **10**, e0115246. <http://dx.doi.org/10.1371/journal.pone.0115246>
- 11 Monbaliu, J., Z. Chen, D. Felts, J. Ge, F. Hissel, J. Kappenberg, S. Narayan, R.J. Nicholls, N.
12 Ohle, D. Schuster, J. Sothmann, and P. Willems, 2014: Risk assessment of estuaries under
13 climate change: Lessons from Western Europe. *Coastal Engineering*, **87**, 32-49.
14 <http://dx.doi.org/10.1016/j.coastaleng.2014.01.001>
- 15 Montes, I., B. Dewitte, E. Gutknecht, A. Paulmier, I. Dadou, A. Oeschies, and V. Garçon, 2014:
16 High-resolution modeling of the eastern tropical Pacific oxygen minimum zone: Sensitivity
17 to the tropical oceanic circulation. *Journal of Geophysical Research: Oceans*, **119**, 5515-
18 5532. <http://dx.doi.org/10.1002/2014JC009858>
- 19 Mulitza, S., D. Heslop, D. Pittauerova, H.W. Fischer, I. Meyer, J.-B. Stuut, M. Zabel, G.
20 Mollenhauer, J.A. Collins, H. Kuhnert, and M. Schulz, 2010: Increase in African dust flux at
21 the onset of commercial agriculture in the Sahel region. *Nature*, **466**, 226-228.
22 <http://dx.doi.org/10.1038/nature09213>
- 23 Najjar, R.G., C.R. Pyke, M.B. Adams, D. Breitburg, C. Hershner, M. Kemp, R. Howarth, M.R.
24 Mulholland, M. Paolisso, D. Secor, K. Sellner, D. Wardrop, and R. Wood, 2010: Potential
25 climate-change impacts on the Chesapeake Bay. *Estuarine, Coastal and Shelf Science*, **86**, 1-
26 20. <http://dx.doi.org/10.1016/j.ecss.2009.09.026>
- 27 Nieves, V., J.K. Willis, and W.C. Patzert, 2015: Recent hiatus caused by decadal shift in Indo-
28 Pacific heating. *Science*, **349**, 532-535. <http://dx.doi.org/10.1126/science.aaa4521>
- 29 Orr, J.C., V.J. Fabry, O. Aumont, L. Bopp, S.C. Doney, R.A. Feely, A. Gnanadesikan, N.
30 Gruber, A. Ishida, F. Joos, R.M. Key, K. Lindsay, E. Maier-Reimer, R. Matear, P. Monfray,
31 A. Mouchet, R.G. Najjar, G.-K. Plattner, K.B. Rodgers, C.L. Sabine, J.L. Sarmiento, R.
32 Schlitzer, R.D. Slater, I.J. Totterdell, M.-F. Weirig, Y. Yamanaka, and A. Yool, 2005:
33 Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying
34 organisms. *Nature*, **437**, 681-686. <http://dx.doi.org/10.1038/nature04095>

- 1 Paerl, H.W., R.L. Dennis, and D.R. Whitall, 2002: Atmospheric deposition of nitrogen:
2 Implications for nutrient over-enrichment of coastal waters. *Estuaries*, **25**, 677-693.
3 <http://dx.doi.org/10.1007/bf02804899>
- 4 Patara, L. and C.W. Böning, 2014: Abyssal ocean warming around Antarctica strengthens the
5 Atlantic overturning circulation. *Geophysical Research Letters*, **41**, 3972-3978.
6 <http://dx.doi.org/10.1002/2014GL059923>
- 7 Purkey, S.G. and G.C. Johnson, 2010: Warming of global abyssal and deep Southern Ocean
8 waters between the 1990s and 2000s: Contributions to global heat and sea level rise budgets.
9 *Journal of Climate*, **23**, 6336-6351. <http://dx.doi.org/10.1175/2010JCLI3682.1>
- 10 Qi, D., L. Chen, B. Chen, Z. Gao, W. Zhong, R.A. Feely, L.G. Anderson, H. Sun, J. Chen, M.
11 Chen, L. Zhan, Y. Zhang, and W.-J. Cai, 2017: Increase in acidifying water in the western
12 Arctic Ocean. *Nature Climate Change*, **7**, 195-199. <http://dx.doi.org/10.1038/nclimate3228>
- 13 Rabalais, N.N., R.E. Turner, B.K. Sen Gupta, D.F. Boesch, P. Chapman, and M.C. Murrell,
14 2007: Hypoxia in the northern Gulf of Mexico: Does the science support the plan to reduce,
15 mitigate, and control hypoxia? *Estuaries and Coasts*, **30**, 753-772.
16 <http://dx.doi.org/10.1007/bf02841332>
- 17 Rabalais, N.N., R.E. Turner, R.J. Díaz, and D. Justić, 2009: Global change and eutrophication of
18 coastal waters. *ICES Journal of Marine Science: Journal du Conseil*, **66**, 1528-1537.
19 <http://dx.doi.org/10.1093/icesjms/fsp047>
- 20 Rabalais, N.N., R.J. Díaz, L.A. Levin, R.E. Turner, D. Gilbert, and J. Zhang, 2010: Dynamics
21 and distribution of natural and human-caused hypoxia. *Biogeosciences*, **7**, 585-619.
22 <http://dx.doi.org/10.5194/bg-7-585-2010>
- 23 Rahmstorf, S., J.E. Box, G. Feulner, M.E. Mann, A. Robinson, S. Rutherford, and E.J.
24 Schaffernicht, 2015: Exceptional twentieth-century slowdown in Atlantic Ocean overturning
25 circulation. *Nature Climate Change*, **5**, 475-480. <http://dx.doi.org/10.1038/nclimate2554>
- 26 Reay, D.S., F. Dentener, P. Smith, J. Grace, and R.A. Feely, 2008: Global nitrogen deposition
27 and carbon sinks. *Nature Geoscience*, **1**, 430-437. <http://dx.doi.org/10.1038/ngeo230>
- 28 Rhein, M., S.R. Rintoul, S. Aoki, E. Campos, D. Chambers, R.A. Feely, S. Gulev, G.C. Johnson,
29 S.A. Josey, A. Kostianoy, C. Mauritzen, D. Roemmich, L.D. Talley, and F. Wang, 2013:
30 Observations: Ocean. *Climate Change 2013: The Physical Science Basis. Contribution of*
31 *Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate*
32 *Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A.
33 Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge,
34 United Kingdom and New York, NY, USA, 255–316.
35 <http://www.climatechange2013.org/report/full-report/>

- 1 Robinson, P., A.K. Leight, D.D. Trueblood, and B. Wood, 2013: Climate sensitivity of the
2 National Estuarine Research Reserve System. NERRS, NOAA National Ocean Service,
3 Silver Spring, Maryland. 79 pp.
4 https://coast.noaa.gov/data/docs/nerrs/Research_DataSyntheses_130725_climate%20sensitivity%20of%20nerrs_Final-Rpt-in-Layout_FINAL.pdf
5
- 6 Robinson, R.S., A. Mix, and P. Martinez, 2007: Southern Ocean control on the extent of
7 denitrification in the southeast Pacific over the last 70 ka. *Quaternary Science Reviews*, **26**,
8 201-212. <http://dx.doi.org/10.1016/j.quascirev.2006.08.005>
- 9 Roemmich, D., J. Church, J. Gilson, D. Monselesan, P. Sutton, and S. Wijffels, 2015: Unabated
10 planetary warming and its ocean structure since 2006. *Nature Climate Change*, **5**, 240-245.
11 <http://dx.doi.org/10.1038/nclimate2513>
- 12 Rossby, C.-G., 1959: Current problems in meteorology. *The Atmosphere and the Sea in Motion*.
13 Bolin, B., Ed. Rockefeller Institute Press, New York, 9-50.
- 14 Rykaczewski, R.R., J.P. Dunne, W.J. Sydeman, M. García-Reyes, B.A. Black, and S.J. Bograd,
15 2015: Poleward displacement of coastal upwelling-favorable winds in the ocean's eastern
16 boundary currents through the 21st century. *Geophysical Research Letters*, **42**, 6424-6431.
17 <http://dx.doi.org/10.1002/2015GL064694>
- 18 Salisbury, J., M. Green, C. Hunt, and J. Campbell, 2008: Coastal acidification by rivers: A threat
19 to shellfish? *Eos, Transactions, American Geophysical Union*, **89**, 513-513.
20 <http://dx.doi.org/10.1029/2008EO500001>
- 21 Schile, L.M., J.C. Callaway, J.T. Morris, D. Stralberg, V.T. Parker, and M. Kelly, 2014:
22 Modeling tidal marsh distribution with sea-level rise: Evaluating the role of vegetation,
23 sediment, and upland habitat in marsh resiliency. *PLOS ONE*, **9**, e88760.
24 <http://dx.doi.org/10.1371/journal.pone.0088760>
- 25 Schmidtko, S., L. Stramma, and M. Visbeck, 2017: Decline in global oceanic oxygen content
26 during the past five decades. *Nature*, **542**, 335-339. <http://dx.doi.org/10.1038/nature21399>
- 27 Schmittner, A., E.D. Galbraith, S.W. Hostetler, T.F. Pedersen, and R. Zhang, 2007: Large
28 fluctuations of dissolved oxygen in the Indian and Pacific oceans during Dansgaard–
29 Oeschger oscillations caused by variations of North Atlantic Deep Water subduction.
30 *Paleoceanography*, **22**, n/a-n/a. <http://dx.doi.org/10.1029/2006PA001384>
- 31 Scott, J.D., Alexander, M.A., Murray, D.R., Swales, D. and Eischeid, J., 2016. The Climate
32 Change Web Portal: a system to access and display climate and Earth system model output
33 from the CMIP5 archive. *Bulletin of the American Meteorological Society*, **97**(4), 523-530.
34 <https://doi.org/10.1175/BAMS-D-15-00035.1>

- 1 Skliris, N., R. Marsh, S.A. Josey, S.A. Good, C. Liu, and R.P. Allan, 2014: Salinity changes in
2 the World Ocean since 1950 in relation to changing surface freshwater fluxes. *Climate*
3 *Dynamics*, **43**, 709-736. <http://dx.doi.org/10.1007/s00382-014-2131-7>
- 4 Smeed, D.A., G.D. McCarthy, S.A. Cunningham, E. Frajka-Williams, D. Rayner, W.E. Johns,
5 C.S. Meinen, M.O. Baringer, B.I. Moat, A. Ducez, and H.L. Bryden, 2014: Observed
6 decline of the Atlantic meridional overturning circulation 2004–2012. *Ocean Science*, **10**, 29-
7 38. <http://dx.doi.org/10.5194/os-10-29-2014>
- 8 Steinman, B.A., M.E. Mann, and S.K. Miller, 2015: Atlantic and Pacific multidecadal
9 oscillations and Northern Hemisphere temperatures. *Science*, **347**, 988-991.
10 <http://dx.doi.org/10.1126/science.1257856>
- 11 Stendardo, I. and N. Gruber, 2012: Oxygen trends over five decades in the North Atlantic.
12 *Journal of Geophysical Research*, **117**, C11004. <http://dx.doi.org/10.1029/2012JC007909>
- 13 Stramma, L., S. Schmidtko, L.A. Levin, and G.C. Johnson, 2010: Ocean oxygen minima
14 expansions and their biological impacts. *Deep Sea Research Part I: Oceanographic Research*
15 *Papers*, **57**, 587-595. <http://dx.doi.org/10.1016/j.dsr.2010.01.005>
- 16 Straneo, F. and P. Heimbach, 2013: North Atlantic warming and the retreat of Greenland's outlet
17 glaciers. *Nature*, **504**, 36-43. <http://dx.doi.org/10.1038/nature12854>
- 18 Sutton, A.J., C.L. Sabine, R.A. Feely, W.J. Cai, M.F. Cronin, M.J. McPhaden, J.M. Morell, J.A.
19 Newton, J.H. Noh, S.R. Ólafsdóttir, J.E. Salisbury, U. Send, D.C. Vandemark, and R.A.
20 Weller, 2016: Using present-day observations to detect when anthropogenic change forces
21 surface ocean carbonate chemistry outside preindustrial bounds. *Biogeosciences*, **13**, 5065-
22 5083. <http://dx.doi.org/10.5194/bg-13-5065-2016>
- 23 Swanson, K.M., J.Z. Drexler, C.C. Fuller, and D.H. Schoellhamer, 2015: Modeling tidal
24 freshwater marsh sustainability in the Sacramento–San Joaquin delta under a broad suite of
25 potential future scenarios. *San Francisco Estuary and Watershed Science*, **13**, 21.
26 <http://dx.doi.org/10.15447/sfews.2015v13iss1art3>
- 27 Sydeman, W.J., M. García-Reyes, D.S. Schoeman, R.R. Rykaczewski, S.A. Thompson, B.A.
28 Black, and S.J. Bograd, 2014: Climate change and wind intensification in coastal upwelling
29 ecosystems. *Science*, **345**, 77-80. <http://dx.doi.org/10.1126/science.1251635>
- 30 Takatani, Y., D. Sasano, T. Nakano, T. Midorikawa, and M. Ishii, 2012: Decrease of dissolved
31 oxygen after the mid-1980s in the western North Pacific subtropical gyre along the 137°E
32 repeat section. *Global Biogeochemical Cycles*, **26**, n/a-n/a.
33 <http://dx.doi.org/10.1029/2011GB004227>

- 1 Talley, L.D., R.A. Feely, B.M. Sloyan, R. Wanninkhof, M.O. Baringer, J.L. Bullister, C.A.
2 Carlson, S.C. Doney, R.A. Fine, E. Firing, N. Gruber, D.A. Hansell, M. Ishii, G.C. Johnson,
3 K. Katsumata, R.M. Key, M. Kramp, C. Langdon, A.M. Macdonald, J.T. Mathis, E.L.
4 McDonagh, S. Mecking, F.J. Millero, C.W. Mordy, T. Nakano, C.L. Sabine, W.M. Smethie,
5 J.H. Swift, T. Tanhua, A.M. Thurnherr, M.J. Warner, and J.-Z. Zhang, 2016: Changes in
6 ocean heat, carbon content, and ventilation: A review of the first decade of GO-SHIP global
7 repeat hydrography. *Annual Review of Marine Science*, **8**, 185-215.
8 <http://dx.doi.org/10.1146/annurev-marine-052915-100829>
- 9 Taylor, G.T., F.E. Muller-Karger, R.C. Thunell, M.I. Scranton, Y. Astor, R. Varela, L.T.
10 Ghinaglia, L. Lorenzoni, K.A. Fanning, S. Hameed, and O. Doherty, 2012: Ecosystem
11 responses in the southern Caribbean Sea to global climate change. *Proceedings of the*
12 *National Academy of Sciences*, **109**, 19315-19320.
13 <http://dx.doi.org/10.1073/pnas.1207514109>
- 14 Thompson, P.R., B.D. Hamlington, F.W. Landerer, and S. Adhikari, 2016: Are long tide gauge
15 records in the wrong place to measure global mean sea level rise? *Geophysical Research*
16 *Letters*, **43**, 10,403-10,411. <http://dx.doi.org/10.1002/2016GL070552>
- 17 Trenberth, K.E., J.T. Fasullo, and M.A. Balmaseda, 2014: Earth's energy imbalance. *Journal of*
18 *Climate*, **27**, 3129-3144. <http://dx.doi.org/10.1175/jcli-d-13-00294.1>
- 19 Waldbusser, G.G. and J.E. Salisbury, 2014: Ocean acidification in the coastal zone from an
20 organism's perspective: Multiple system parameters, frequency domains, and habitats.
21 *Annual Review of Marine Science*, **6**, 221-247. [http://dx.doi.org/10.1146/annurev-marine-](http://dx.doi.org/10.1146/annurev-marine-121211-172238)
22 [121211-172238](http://dx.doi.org/10.1146/annurev-marine-121211-172238)
- 23 Wallmann, K., 2003: Feedbacks between oceanic redox states and marine productivity: A model
24 perspective focused on benthic phosphorus cycling. *Global Biogeochemical Cycles*, **17**, n/a-
25 n/a. <http://dx.doi.org/10.1029/2002GB001968>
- 26 Wang, D., T.C. Gouhier, B.A. Menge, and A.R. Ganguly, 2015: Intensification and spatial
27 homogenization of coastal upwelling under climate change. *Nature*, **518**, 390-394.
28 <http://dx.doi.org/10.1038/nature14235>
- 29 Wright, J.D. and M.F. Schaller, 2013: Evidence for a rapid release of carbon at the Paleocene-
30 Eocene thermal maximum. *Proceedings of the National Academy of Sciences*, **110**, 15908-
31 15913. <http://dx.doi.org/10.1073/pnas.1309188110>
- 32 Yan, X.-H., T. Boyer, K. Trenberth, T.R. Karl, S.-P. Xie, V. Nieves, K.-K. Tung, and D.
33 Roemmich, 2016: The global warming hiatus: Slowdown or redistribution? *Earth's Future*, **4**,
34 472-482. <http://dx.doi.org/10.1002/2016EF000417>

- 1 Yang, H., G. Lohmann, W. Wei, M. Dima, M. Ionita, and J. Liu, 2016: Intensification and
2 poleward shift of subtropical western boundary currents in a warming climate. *Journal of*
3 *Geophysical Research: Oceans*, **121**, 4928-4945. <http://dx.doi.org/10.1002/2015JC011513>
- 4 Zaitsev, Y.P., 1992: Recent changes in the trophic structure of the Black Sea. *Fisheries*
5 *Oceanography*, **1**, 180-189. <http://dx.doi.org/10.1111/j.1365-2419.1992.tb00036.x>
- 6 Zeebe, R.E., A. Ridgwell, and J.C. Zachos, 2016: Anthropogenic carbon release rate
7 unprecedented during the past 66 million years. *Nature Geoscience*, **9**, 325-329.
8 <http://dx.doi.org/10.1038/ngeo2681>

FINAL DRAFT

14. Perspectives on Climate Change Mitigation

KEY FINDINGS

1. Warming and associated climate effects from CO₂ emissions persist for decades to millennia. In the near-term, changes in climate are determined by past and present greenhouse gas emissions modified by natural variability. Reducing the total concentration of atmospheric CO₂ is necessary to limit near-term climate change and stay below long-term warming targets (such as the oft-cited 3.6°F [2°C] goal). Other greenhouse gases (for example, methane) and black carbon aerosols exert stronger warming effects than CO₂ on a per ton basis, but they do not persist as long in the atmosphere; therefore, mitigation of non-CO₂ species contributes substantially to near-term cooling benefits but cannot be relied upon for ultimate stabilization goals. (*Very high confidence*)
2. Stabilizing global mean temperature below long-term warming targets requires an upper limit on the accumulation of CO₂ in the atmosphere. The relationship between cumulative CO₂ emissions and global temperature response is estimated to be nearly linear. Nevertheless, in evaluating specific temperature targets, there are uncertainties about the exact amount of compatible anthropogenic CO₂ emissions due to uncertainties in climate sensitivity, the response of the carbon cycle including feedbacks, the amount of past CO₂ emissions, and the influence of past and future non-CO₂ species. (*Very high confidence*)
3. Stabilizing global mean temperature below 3.6°F (2°C) or lower relative to preindustrial levels requires significant reductions in net global CO₂ emissions relative to present-day values before 2040 and likely requires net emissions to become zero or possibly negative later in the century. Accounting for the temperature effects of non-CO₂ species, cumulative CO₂ emissions are required to stay below about 800 GtC in order to provide a two-thirds likelihood of preventing 3.6°F (2°C) of warming, meaning approximately 230 GtC more could be emitted globally. Assuming global emissions follow the range between the RCP8.5 and RCP4.5 scenarios, emissions could continue for approximately two decades before this cumulative carbon threshold is exceeded. (*High confidence*)
4. Successful implementation of the first round of Nationally Determined Contributions associated with the Paris Agreement will provide some likelihood of meeting the long-term temperature goal of limiting global warming to “well below” 3.6°F (2°C) above preindustrial levels; the likelihood depends strongly on the magnitude of global emission reductions after 2030. (*High confidence*)
5. Climate intervention or geoengineering strategies such as solar radiation management are measures that attempt to limit or reduce global temperature increases. If interest in geoengineering increases with observed impacts and/or projected risks of climate change,

1 interest will also increase in assessments of the technical feasibilities, costs, risks, co-
2 benefits, and governance challenges of these additional measures, which are as yet
3 unproven at scale. These assessments are a necessary step before judgments about the
4 benefits and risks of these approaches can be made with high confidence. (*High*
5 *confidence*)

6 **Introduction**

7 This chapter provides scientific context for key issues regarding the long-term mitigation of
8 climate change. As such, this chapter first addresses the science underlying the timing of
9 when and how CO₂ and other greenhouse gas (GHG) mitigation activities that occur in the
10 present affect the climate of the future. When do we see the benefits of a GHG emission
11 reduction activity? Chapter 4: Projections provides further context for this topic. Relatedly,
12 the present chapter discusses the significance of the relationship between cumulative CO₂
13 emissions and eventual global warming levels. The chapter reviews studies of the climate
14 effects of the first round of national contributions associated with the Paris Agreement if
15 fully implemented. Looking beyond the first round of national contributions (which do not
16 set emission reduction targets past 2030), what global-scale emissions pathways are
17 estimated to be necessary by mid-century and beyond in order to have a high likelihood of
18 preventing 3.6°F (2°C) or 2.7°F (1.5°C) of warming relative to preindustrial times? In
19 response to this question, this chapter briefly reviews the status of climate intervention
20 proposals and how these types of mitigation actions could possibly play a role in avoiding
21 future climate change.

22 **14.1 The Timing of Benefits from Mitigation Actions**

23 **14.1.1 Lifetime of Greenhouse Gases and Inherent Delays in the Climate System**

24 Carbon dioxide (CO₂) concentrations in the atmosphere are directly affected by human
25 activities in the form of CO₂ emissions. Atmospheric CO₂ concentrations adjust to human
26 emissions of CO₂ over long time scales, spanning from decades to millennia (Ciais et al.
27 2013; Joos et al. 2013). The IPCC estimated that 15% to 40% of CO₂ emitted until 2100 will
28 remain in the atmosphere longer than 1,000 years (Ciais et al. 2013). The persistence of
29 warming is longer than the atmospheric lifetime of CO₂ and other GHGs, owing in large part
30 to the thermal inertia of the ocean (Collins et al. 2013). Climate change resulting from
31 anthropogenic CO₂ emissions, and any associated risks to the environment, human health and
32 society, are thus essentially irreversible on human timescales (Solomon et al. 2009). The
33 world is committed to some degree of irreversible warming and associated climate change
34 resulting from emissions to date.

35 The long lifetime in the atmosphere of CO₂ (Joos et al. 2013) and some other key GHGs,
36 coupled with the time lag in the response of the climate system to atmospheric forcing

1 (Tebaldi and Friedlingstein 2013), has timing implications for the benefits (i.e., avoided
2 warming or risk) of mitigation actions. Large reductions in emissions of the long-lived GHGs
3 are estimated to have modest temperature effects in the *near term* (e.g., over one to two
4 decades), because total atmospheric concentration levels require long periods to adjust
5 (Prather et al. 2009), but are necessary in the *long term* to achieve any objective of
6 preventing warming of any desired magnitude. Near-term projections of global mean surface
7 air temperature are therefore not strongly influenced by changes in emissions but rather
8 dominated by natural variability, the Earth system response to past and current GHG
9 emissions, and by model spread (i.e., the different climate outcomes associated with different
10 models using the same emissions scenario) (Kirtman et al. 2013). Long-term projections of
11 global surface temperature (after mid-century), on the other hand, show that emissions
12 scenario choice, and thus the mitigation pathway, is the dominant source of future
13 uncertainty in climate outcomes (Paltsev et al. 2015; Collins et al. 2013).

14 Some studies have nevertheless shown the potential for some near-term benefits of
15 mitigation. For example, one study found that, even at the regional scale, heat waves would
16 already be significantly more severe by the 2030s in a non-mitigation scenario compared to a
17 moderate mitigation scenario (Tebaldi and Wehner 2016). The mitigation of non-CO₂ GHGs
18 with short atmospheric lifetimes (such as methane, some hydrofluorocarbons [HFCs], and
19 ozone) and black carbon (an aerosol that absorbs solar radiation; see Ch. 2: Physical Drivers
20 of Climate Change), collectively referred to as short-lived climate pollutants (SLCPs), has
21 been highlighted as a particular way to achieve more rapid climate benefits (e.g., Zaelke and
22 Borgford-Parnell 2015). SLCPs are substances that not only have an atmospheric lifetime
23 shorter (for example, weeks to a decade) than CO₂ but also exert a stronger radiative forcing
24 (and hence temperature effect) compared to CO₂ on a per ton basis (Myhre et al. 2013). For
25 these reasons, mitigation of SLCP emissions produces more rapid radiative responses. In the
26 case of black carbon, with an atmospheric lifetime of a few days to weeks (Bond et al. 2013),
27 emissions (and therefore reductions of those emissions) produce strong regional effects.
28 Mitigation of black carbon and methane also generate direct health co-benefits (Anenberg et
29 al. 2012; Rao et al. 2016). Reductions and/or avoidances of SLCP emissions could be a
30 significant contribution to staying at or below a 3.6°F (2°C) or any other chosen global mean
31 temperature increase (Hayhoe et al. 1998; Shah et al. 2015; Shindell et al. 2012; Rogelj et al.
32 2015). The recent Kigali Amendment to the Montreal Protocol seeks to phase down global
33 HFC production and consumption in order to avoid substantial GHG emissions in coming
34 decades. Stringent near-term SLCP mitigation could potentially increase allowable CO₂
35 budgets for avoiding warming beyond any desired future level, by up to 25% under certain
36 scenarios (Rogelj et al. 2015). However, given that economic and technological factors tend
37 to couple CO₂ and many SLCP emissions to varying degrees, significant SLCP emissions
38 reduction would be a co-benefit of CO₂ mitigation.

39

1 14.1.2 Stock and Stabilization: Cumulative CO₂ and the Role of Other Greenhouse 2 Gases

3 Cumulative CO₂ emissions in the industrial era will largely determine long-term, global mean
4 temperature change. A robust feature of model climate change simulations is a nearly linear
5 relationship between cumulative CO₂ emissions and global mean temperature increases,
6 irrespective of the details and exact timing of the emissions pathway (see Figure 14.1; see
7 also Ch. 4: Projections). Limiting and stabilizing warming to any level implies that there is
8 an upper limit to the cumulative amount of CO₂ that can be added to the atmosphere (Collins
9 et al. 2013). Eventually stabilizing the global temperature requires CO₂ emissions to
10 approach zero (NRC 2011). Thus, for a 3.6°F (2°C) or any desired global mean temperature
11 target, an estimated range of allowable cumulative CO₂ emissions from the current period
12 onward can be calculated. The key sources of uncertainty for any compatible, forward
13 looking CO₂ budget associated with a given future warming objective include the climate
14 sensitivity, the response of the carbon cycle including feedbacks (for example, the release of
15 GHGs from permafrost thaw), the amount of past CO₂ emissions, and the influence of past
16 and future non-CO₂ species (Collins et al. 2013; NRC 2011). Increasing the probability that
17 any given temperature target be reached therefore implies tighter constraints on cumulative
18 CO₂ emissions. Relatedly, for any given cumulative CO₂ budget, higher emissions in the near
19 term imply the need for steeper reductions in the long term.

20 **[INSERT FIGURE 14.1 HERE]**

21 Between 1870 and 2015, human activities, primarily the burning of fossil fuels and
22 deforestation, emitted about 560 GtC in the form of CO₂ into the atmosphere (Le Quéré et al.
23 2016). According to best estimates in the literature, 1,000 GtC is the total cumulative amount
24 of CO₂ that could be emitted yet still provide a two-thirds likelihood of preventing 3.6°F
25 (2°C) of global mean warming since pre-industrial times (Collins et al. 2013; Allen et al.
26 2009). That estimate, however, ignores the additional radiative forcing effects of non-CO₂
27 species (that is, the net positive forcing resulting from the forcing of other well-mixed GHGs,
28 including halocarbons, plus the other ozone precursor gases and aerosols). Considering both
29 historic and projected non-CO₂ effects reduces the estimated cumulative CO₂ budget
30 compatible with any future warming target (Rogelj et al. 2015), and in the case of 3.6°F
31 (2°C) it reduces the aforementioned estimate to 790 GtC (Collins et al. 2013). Given this
32 more comprehensive estimate, meeting the 3.6°F (2°C) target means approximately 230 GtC
33 more CO₂ could be emitted globally. To illustrate, if one assumes future global emissions
34 follow the RCP4.5 scenario, this cumulative carbon threshold is exceeded by around 2037,
35 while under the RCP8.5 scenario this occurs by around 2033. To meet a 2.7°F (1.5°C) target,
36 the estimated cumulative CO₂ budget is about 590 GtC (assuming linear scaling with the
37 compatible 3.6°F (2°C) budget that also considers non-CO₂ effects), meaning only about 30

1 GtC more of CO₂ could be emitted. Further emissions of 30 GtC (in the form of CO₂) are
2 projected to occur in the next few years (Table 14.1).

3 **[INSERT TABLE 14.1 HERE]**

4 **14.2 Pathways Centered Around 3.6°F (2°C)**

5 In December of 2015 in Paris, the Parties to the United Nations Framework Convention on
6 Climate Change (UNFCCC) adopted the Paris Agreement, under which all Parties committed
7 to prepare and communicate successive Nationally Determined Contributions (NDCs) to
8 mitigate climate change. The first NDCs extend to 2025 or 2030 and take a wide range of
9 forms. The Agreement contains the long-term goal of “holding the increase in the global
10 average temperature to well below 2°C above pre-industrial levels and pursuing efforts to
11 limit the temperature increase to 1.5°C above pre-industrial levels.”

12 Estimates of global emissions and temperature implications from a successful
13 implementation of the first round of NDCs (Rogelj et al. 2016; Sanderson et al. 2016;
14 Climate Action Tracker 2016; Fawcett et al. 2015; UNFCCC 2015) generally find that: 1) the
15 first round of NDCs reduces GHG emissions growth by 2030 relative to a situation where
16 these goals did not exist, though emissions are still not expected to be lower in 2030 than in
17 2015; and 2) the NDCs are a step towards meeting a 3.6°F (2°C) target, but the NDCs are, by
18 themselves, insufficient to achieve this ambitious target. According to one study, the NDCs
19 imply a median warming of 4.7°–5.6°F (2.6°–3.1°C) by 2100, though year 2100 temperature
20 estimates depend on assumed emissions between 2030 and 2100 (Rogelj et al. 2016). For
21 example, Climate Action Tracker, using alternative post-2030 assumptions, put the range at
22 5.9°–7.0°F (3.3°–3.9°C).

23 Emissions pathways consistent with the NDCs have been evaluated in the context of the
24 likelihood of global mean surface temperature change (Figure 14.2). It was found that the
25 likelihood of meeting the 3.6°F (2°C) or less target was enhanced by the NDCs, but
26 depended strongly on subsequent policies and measures. The chief finding was that even
27 without additional emission reductions after 2030, if implemented successfully, the NDCs
28 provide some likelihood (less than 10%) of preventing a global mean surface temperature
29 change of 3.6°F (2°C) relative to preindustrial levels (Fawcett et al. 2015). Greater emissions
30 reductions beyond 2030 (here, based on assumed higher decarbonization rates past 2030)
31 increase the likelihood of achieving the 3.6°F (2°C) or lower target to about 30%, and almost
32 eliminate the likelihood of a global mean temperature increase greater than 7°F (4°C).
33 Scenarios that assume even greater emissions reductions past 2030 would be necessary to
34 have at least a 50% probability of limiting warming to 3.6°F (2°C) (Fawcett et al. 2015), as
35 discussed and illustrated further below.

36 **[INSERT FIGURE 14.2 HERE]**

1 There are only a limited number of pathways which enable the world to remain below 3.6°F
2 (2°C) of warming (see Figure 14.3), and almost all but the most rapid near-term mitigation
3 pathways are heavily reliant on the implementation of CO₂ removal from the atmosphere
4 later in the century or other climate intervention, discussed below. If global emissions are in
5 line with the first round of NDCs by 2030, then the world likely needs to reduce effective
6 GHG emissions to zero by 2080, and be significantly net negative by the end of the century
7 (relying on as yet unproven technologies to remove GHGs from the atmosphere) in order to
8 stay below 3.6°F (2°C) of warming. Avoiding 2.7°F (1.5°C) of warming requires more
9 aggressive action still, with net zero emissions achieved by 2050 and net negative emissions
10 thereafter. In either case, faster near-term action significantly decreases the requirements for
11 negative emissions in the future.

12 **[INSERT FIGURE 14.3 HERE]**

13 **14.3 The Role of Climate Intervention in Meeting Ambitious Climate** 14 **Targets**

15 Achieving a 3.6°F (2°C) target through emissions reductions or adapting to the impacts
16 of a greater-than-3.6°F (2°C) world have been acknowledged as severely challenging
17 tasks by the international science and policy communities. Consequently, there is
18 increased interest by some scientists and policy makers in exploring additional measures
19 designed to reduce net radiative forcing through other, as yet untested actions, which are
20 often referred to as geoengineering or climate intervention (CI) actions. CI approaches
21 are generally divided into two categories: CO₂ removal (CDR) (NAS 2015a) and solar
22 radiation management (SRM) (NAS 2015b). CDR and SRM methods may have future
23 roles in helping meet global temperature targets. Both methods would reduce global
24 average temperature by reducing net global radiative forcing: CDR through reducing
25 atmospheric CO₂ concentrations and SRM through increasing Earth's albedo.

26 The evaluation of the suitability and advisability of potential CI actions requires a
27 decision framework that includes important dimensions beyond scientific and technical
28 considerations. Among these dimensions to be considered are the potential development
29 of global and national governance and oversight procedures, geopolitical relations, legal
30 considerations, environmental, economic and societal impacts, ethical considerations, and
31 the relationships to global climate policy and current GHG mitigation and adaptation
32 actions. It is clear that these social science and other non-physical science dimensions are
33 likely to be the major part of the decision framework and ultimately control the adoption
34 and effectiveness of CI actions. This report only acknowledges these mostly non-physical
35 scientific dimensions and must forego a detailed discussion.

36 By removing CO₂ from the atmosphere, CDR directly addresses the principal cause of
37 climate change. Potential CDR approaches include point-source CO₂ capture, direct air

1 capture, currently well-understood biological methods on land (for example,
2 afforestation), less well-understood and potentially risky methods in the ocean (for
3 example, ocean fertilization), and accelerated weathering (for example, forming calcium
4 carbonate on land or in the oceans). While CDR is technically possible, the primary
5 challenge is achieving the required scale of removal in a cost-effective manner, which in
6 part presumes a comparison to the costs of other, more traditional GHG mitigation
7 options. In principle, at large scale, CDR could measurably reduce CO₂ concentrations
8 (that is, cause negative emissions). Point-source capture (as opposed to CO₂ capture from
9 ambient air) and removal of CO₂ is a particularly effective CDR method. The climate
10 value of avoided CO₂ emissions is essentially equivalent to that of the atmospheric
11 removal of the same amount. To realize sustained climate benefits from CDR, however,
12 the removal of CO₂ from the atmosphere must be essentially permanent—at least several
13 centuries to millennia. In addition to high costs, CDR has the additional limitation of long
14 implementation times.

15 By contrast, SRM approaches offer the only known CI methods of cooling Earth within a
16 few years after inception. An important limitation of SRM is that it would not address
17 damage to ocean ecosystems from increasing ocean acidification due to continued CO₂
18 uptake. SRM could theoretically have a significant global impact even if implemented by
19 a small number of nations, and by nations that are not also the major emitters of GHGs;
20 this could be viewed either as a benefit or risk of SRM.

21 Proposed SRM concepts increase Earth's albedo through injection of sulfur gases or
22 aerosols into the stratosphere (thereby simulating the effects of explosive volcanic
23 eruptions) or marine cloud brightening through aerosol injection near the ocean surface.
24 Injection of solid particles is an alternative to sulfur and yet other SRM methods could be
25 deployed in space. Studies have evaluated the expected effort and effectiveness of
26 various SRM methods (NAS 2015b; Keith et al. 2014). For example, model runs were
27 performed in the GeoMIP project using the full CMIP5 model suite to illustrate the effect
28 of reducing top-of-the-atmosphere insolation to offset climate warming from CO₂
29 (Kravitz et al. 2013). The idealized runs, which assumed an abrupt, globally-uniform
30 insolation reduction in a 4 × CO₂ atmosphere, show that temperature increases are largely
31 offset, most sea-ice loss is avoided, average precipitation changes are small, and net
32 primary productivity increases. However, important regional changes in climate variables
33 are likely in SRM scenarios as discussed below.

34 As global ambitions increase to avoid or remove CO₂ emissions, probabilities of large
35 increases in global temperatures by 2100 are proportionately reduced (Fawcett et al.
36 2015). Scenarios in which large-scale CDR is used to meet a 3.6°F (2°C) limit while
37 allowing business-as-usual consumption of fossil fuels are likely not feasible with present
38 technologies. Model SRM scenarios have been developed that show reductions in

1 radiative forcing up to 1 W/m^2 with annual stratospheric injections of 1 Mt of sulfur from
2 aircraft or other platforms (Pierce et al. 2010; Tilmes et al. 2016). Preliminary studies
3 suggest that this could be accomplished at a cost as low as a few billion dollars per year
4 using current technology, enabling an individual country or subnational entity to conduct
5 activities having significant global climate impacts.

6 SRM scenarios could in principle be designed to follow a particular radiative forcing
7 trajectory, with adjustments made in response to monitoring of the climate effects (Keith
8 and MacMartin 2015). SRM could be used as an interim measure to avoid peaks in global
9 average temperature and other climate parameters. The assumption is often made that
10 SRM measures, once implemented, must continue indefinitely in order to avoid the rapid
11 climate change that would occur if the measures were abruptly stopped. SRM could be
12 used, however, as an interim measure to buy time for the implementation of emissions
13 reductions and/or CDR, and SRM could be phased out as emission reductions and CDR
14 are phased in, to avoid abrupt changes in radiative forcing (Keith and MacMartin 2015).

15 SRM via marine cloud brightening derives from changes in cloud albedo from injection
16 of aerosol into low-level clouds, primarily over the oceans. Clouds with smaller and more
17 numerous droplets reflect more sunlight than clouds with fewer and larger droplets.
18 Current models provide more confidence in the effects of stratospheric injection than in
19 marine cloud brightening and in achieving scales large enough to reduce global forcing
20 (NAS 2015b).

21 CDR and SRM have substantial uncertainties regarding their effectiveness and
22 unintended consequences. For example, CDR on a large scale may disturb natural
23 systems and have important implications for land use changes. For SRM actions, even if
24 the reduction in global average radiative forcing from SRM was exactly equal to the
25 radiative forcing from GHGs, the regional and temporal patterns of these forcings would
26 have important differences. While SRM could rapidly lower global mean temperatures,
27 the effects on precipitation patterns, light availability, crop yields, acid rain, pollution
28 levels, temperature gradients, and atmospheric circulation in response to such actions are
29 less well understood. Also, the reduction in sunlight from SRM may have effects on
30 agriculture and ecosystems. In general, restoring regional preindustrial temperature and
31 precipitation conditions through SRM actions is not expected to be possible based on
32 ensemble modeling studies (Ricke et al. 2010). As a consequence, optimizing the climate
33 and geopolitical value of SRM actions would likely involve tradeoffs between regional
34 temperature and precipitation changes (MacMartin et al. 2013). Alternatively,
35 intervention options have been proposed to address particular regional impacts
36 (MacCracken 2016).

37 GHG forcing has the potential to push the climate farther into unprecedented states for
38 human civilization and increase the likelihood of “surprises” (see Ch. 15: Potential

1 Surprises). CI could prevent climate change from reaching a state with more
2 unpredictable consequences. The potential for rapid changes upon initiation (or ceasing)
3 of a CI action would require adaptation on timescales significantly more rapid than what
4 would otherwise be necessary. The NAS (2015a, b) and the Royal Society (Shepherd et
5 al. 2009) recognized that research on the feasibilities and consequences of CI actions is
6 incomplete and call for continued research to improve knowledge of the feasibility, risks,
7 and benefits of CI techniques.

8

FINAL DRAFT

1 TRACEABLE ACCOUNTS

2 **Key Finding 1**

3 Warming and associated climate effects from CO₂ emissions persist for decades to millennia.
4 In the near-term, changes in climate are determined by past and present greenhouse gas
5 emissions modified by natural variability. Reducing the total concentration of atmospheric
6 CO₂ is necessary to limit near-term climate change and stay below long-term warming
7 targets (such as the oft-cited 3.6°F [2°C] goal). Other greenhouse gases (for example,
8 methane) and black carbon aerosols exert stronger warming effects than CO₂ on a per ton
9 basis, but they do not persist as long in the atmosphere; therefore, mitigation of non-CO₂
10 species contributes substantially to near-term cooling benefits but cannot be relied upon for
11 ultimate stabilization goals. (*Very high confidence*)

12 **Description of evidence base**

13 The first statement is supported in the literature, including by Joos et al. (2013) and Ciais et
14 al. (2013) (see Box 6.1 in particular), describing the climate response of CO₂ pulse
15 emissions, and further by Solomon et al. (2009), NRC (2011), and Collins et al. (2013),
16 describing the long-term warming and other climate effects associated with CO₂ emissions.
17 Paltsev et al. (2015) and Collins et al. (2013) describe the near-term vs. long-term nature of
18 climate outcomes resulting from GHG mitigation. Myhre et al. (2013) synthesize numerous
19 studies detailing information about the radiative forcing effects and atmospheric lifetimes of
20 all GHGs and aerosols (see in particular Appendix 8A therein). A recent body of literature
21 has emerged highlighting the particular role that non-CO₂ mitigation can play in providing
22 near-term cooling benefits (e.g., Shindell et al. 2012; Zaelke and Borgford-Parnell 2015;
23 Rogelj et al. 2015). For each of the individual statements made in Key Finding 1, there are
24 numerous literature sources that provide consistent grounds on which to make these
25 statements with very high confidence.

26 **Major uncertainties**

27 The Key Finding is comprised of qualitative statements that are traceable to the literature
28 described above and in this chapter. Uncertainties affecting estimates of the exact timing and
29 magnitude of the climate response following emissions (or avoidance of those emissions) of
30 CO₂ and other GHGs involve the quantity of emissions, climate sensitivity, some uncertainty
31 about the removal time or atmospheric lifetime of CO₂ and other GHGs, and the choice of
32 model carrying out future simulations. The role of black carbon in climate change is more
33 uncertain compared to the role of the well-mixed GHGs (see Bond et al. 2013).

34

1 **Assessment of confidence based on evidence and agreement, including short description**
2 **of nature of evidence and level of agreement**

3 Key Finding 1 is comprised of qualitative statements based on a body of literature for which
4 there is a high level of agreement. There is a well-established understanding, based in the
5 literature, of the atmospheric lifetime and warming effects of CO₂ vs. other GHGs after
6 emission, and in turn how atmospheric concentration levels respond following the emission
7 of CO₂ and other GHGs.

8 **Summary sentence or paragraph that integrates the above information**

9 The qualitative statements contained in Key Finding 1 reflect aspects of fundamental
10 scientific understanding, well grounded in the literature, that provide a relevant framework
11 for considering the role of CO₂ and non-CO₂ species in mitigating climate change.

12

13 **Key Finding 2**

14 Stabilizing global mean temperature below long-term warming targets requires an upper limit
15 on the accumulation of CO₂ in the atmosphere. The relationship between cumulative CO₂
16 emissions and global temperature response is estimated to be nearly linear. Nevertheless, in
17 evaluating specific temperature targets, there are uncertainties about the exact amount of
18 compatible anthropogenic CO₂ emissions due to uncertainties in climate sensitivity, the
19 response of carbon cycle including feedbacks, the amount of past CO₂ emissions, and the
20 influence of past and future non-CO₂ species. (*Very high confidence*)

21 **Description of evidence base**

22 The qualitative statements made in Key Finding 2 are based on evidence synthesized, most
23 notably, by both the National Academy of Sciences (NRC 2011) and by the IPCC (Collins et
24 al. 2013).

25 **Major uncertainties**

26 The NRC (2011) and IPCC (Collins et al. 2013) discuss the uncertainties associated with the
27 Key Finding 2 statement, “The relationship between cumulative CO₂ emissions and global
28 temperature response is estimated to be nearly linear.” The ratio of global mean temperature
29 response to cumulative emissions is relatively constant over time and independent of
30 scenario, but the exact magnitude still depends on key assumptions in the future such as
31 climate sensitivity. The IPCC also points out that a constant ratio of cumulative CO₂
32 emissions to global mean temperature does not hold for stabilization scenarios on millennial
33 time scales and that it is unknown if this constant ratio would hold for scenarios exceeding
34 2,000 GtC of cumulative CO₂. The other major uncertainties are identified in Key Finding 2.

1 **Assessment of confidence based on evidence and agreement, including short description**
2 **of nature of evidence and level of agreement**

3 Key Finding 2 is made with *very high* confidence because it consists of qualitative statements
4 that represent fundamental elements of scientific understanding, supported by different
5 literature sources for which there is high agreement.

6 **Summary sentence or paragraph that integrates the above information**

7 The qualitative statements contained in Key Finding 2 reflect aspects of fundamental
8 scientific understanding, grounded in the literature, that provide a relevant framework for
9 considering the role of CO₂ in mitigating climate change.

10

11 **Key Finding 3**

12 Stabilizing global mean temperature below 3.6°F (2°C) or lower relative to pre-industrial
13 levels requires significant reductions in net global CO₂ emissions relative to present-day
14 values before 2040, and likely requires net emissions to become zero or possibly negative
15 later in the century. Accounting for the temperature effects of non-CO₂ species, cumulative
16 CO₂ emissions are required to stay below about 800 GtC in order to provide a two-thirds
17 likelihood of preventing 3.6°F (2°C) of warming, meaning approximately 230 GtC more
18 could be emitted globally. Assuming global emissions follow the range between the RCP8.5
19 and RCP4.5 scenarios, emissions could continue for approximately two decades before this
20 cumulative carbon threshold is exceeded. (*High confidence*)

21 **Description of evidence base**

22 Key Finding 3 is a case study, focused on a pathway associated with 3.6°F (2°C) of warming,
23 based on the more general concepts described in Key Finding 2. As such, the evidence for the
24 relationship between cumulative CO₂ emissions and global mean temperature response (NRC
25 2011; Collins et al. 2013; Allen et al. 2009) also supports key finding 3.

26 Numerous studies have provided best estimates of cumulative CO₂ compatible with 3.6°F
27 (2°C) of warming above preindustrial levels, including a synthesis by the IPCC (Collins et al.
28 2013). Sanderson et al. (2016) provide further recent evidence to support the statement that
29 net CO₂ emissions would need to approach zero or become negative later in the century in
30 order to avoid this level of warming. Rogelj et al. 2015 and the IPCC (Collins et al. 2013)
31 demonstrate that the consideration of non-CO₂ species has the effect of further constraining
32 the amount of cumulative CO₂ emissions compatible with 3.6°F (2°C).

33

1 Table 14.1 shows the IPCC estimates associated with different probabilities (>66% [the one
2 highlighted in Key Finding 3], >50%, and >33%) of cumulative CO₂ emissions compatible
3 with warming of 3.6°F (2°C) above preindustrial levels, and the cumulative CO₂ emissions
4 compatible with 2.7°F (1.5°C) are in turn linearly derived from those, based on the
5 understanding that cumulative emissions scale linearly with global mean temperature
6 response (as stated in Key Finding 2). The IPCC estimates take into account the additional
7 radiative forcing effects—past and future—of non-CO₂ species based on the RCP emission
8 scenarios (available here:
9 <https://tntcat.iiasa.ac.at/RcpDb/dsd?Action=htmlpage&page=about#descript>).

10 The authors calculated the dates shown in Table 14.1, which supports the last statement in
11 Key Finding 3, based on Le Quéré et al. (2016) and the publicly available RCP database. Le
12 Quéré et al. (2016) provide the widely used reference for historical global, annual CO₂
13 emissions from 1870 to 2015 (land-use change emissions were estimated up to year 2010 so
14 are assumed to be constant between 2010 and 2015). Future CO₂ emissions are based on the
15 RCP4.5 and RCP8.5 scenarios; annual numbers between model-projected years (e.g., 2020,
16 2030, 2040, etc.) are linearly interpolated.

17 **Major uncertainties**

18 There are large uncertainties about the course of future CO₂ and non-CO₂ emissions, but the
19 fundamental point that CO₂ emissions need to eventually approach zero or possibly become
20 net negative to stabilize warming below 3.6°F (2°C) holds regardless of future emissions
21 scenario. There are also large uncertainties about the magnitude of past (since 1870 in this
22 case) CO₂ and non-CO₂ emissions, which in turn influence the uncertainty about compatible
23 cumulative emissions from the present day forward. Further uncertainties regarding non-CO₂
24 species, including aerosols, include their radiative forcing effects. The uncertainty in
25 achieving the temperature targets for a given emissions pathway is in large part reflected by
26 the range of probabilities shown in Table 14.1.

27 **Assessment of confidence based on evidence and agreement, including short description 28 of nature of evidence and level of agreement**

29 There is *very high* confidence in the first statement of Key Finding 3 because it is based on a
30 number of sources with a high level of agreement. The role of non-CO₂ species in particular
31 introduces uncertainty in the second statement of Key Finding 3 regarding compatible
32 cumulative CO₂ emissions that take into account past and future radiative forcing effects of
33 non-CO₂ species; though this estimate is based on a synthesis of numerous studies by the
34 IPCC. The last statement of Key Finding 3 is straightforward based on the best available
35 estimates of historic emissions in combination with the widely used future projections of the
36 RCP scenarios.

1 **Summary sentence or paragraph that integrates the above information**

2 Fundamental scientific understanding of the climate system provides a framework for
3 considering potential pathways for achieving a target of preventing 3.6°F (2°C) of warming.
4 There are uncertainties about cumulative CO₂ emissions compatible with this target, in large
5 part because of uncertainties about the role of non-CO₂ species, but it appears, based on past
6 emissions and future projections, that the cumulative carbon threshold for this target could be
7 reached or exceeded in about two decades.

8

9 **Key Finding 4**

10 Successful implementation of the first round of Nationally Determined Contributions
11 associated with the Paris Agreement will provide some likelihood of meeting the long-term
12 temperature goal of limiting global warming to “well below” 3.6°F (2°C) above preindustrial
13 levels; the likelihood depends strongly on the magnitude of global emission reductions after
14 2030. (*High confidence*)

15 **Description of evidence base**

16 The primary source supporting this key finding is Fawcett et al. (2015); it is also supported
17 by Rogelj et al. (2016), Sanderson et al. (2016), and the Climate Action Tracker. Each of
18 these analyses evaluated the global climate implications of the aggregation of the individual
19 country contributions thus far put forward under the Paris Agreement.

20 **Major uncertainties**

21 The largest uncertainty lies in the assumption of “successful implementation” of the first
22 round of NDCs; these are assumed to be fully successful but could either over- or
23 underachieve. This in turn creates uncertainty about the extent of emission reductions that
24 would be needed after the first round of NDCs in order to achieve the 2°C or any other target.
25 The response of the climate system, the climate sensitivity, is also a source of uncertainty;
26 the Fawcett et al. analysis used the IPCC AR5 range, 1.5° to 4.5°C.

27 **Assessment of confidence based on evidence and agreement, including short description
28 of nature of evidence and level of agreement**

29 There is *high* confidence in this key finding because a number of analyses have examined the
30 implications of the first round of NDCs under the Paris Agreement and have come to similar
31 conclusions, as captured in this key finding.

32 **Summary sentence or paragraph that integrates the above information**

1 Different analyses have estimated the implications for global mean temperature of the first
2 round of NDCs associated with the Paris Agreement and have reached similar conclusions.
3 Assuming successful implementation of this first round of NDCs, along with a range of
4 climate sensitivities, these contributions provide some likelihood of meeting the long-term
5 goal of limiting global warming to well below 2°C about pre-industrial levels, but much
6 depends on assumptions about what happens after 2030.

7

8 **Key Finding 5**

9 Climate intervention or geoengineering strategies such as solar radiation management are
10 measures that attempt to limit or reduce global temperature increases. If interest in
11 geoengineering increases with observed impacts and/or projected risks of climate change,
12 interest will also increase in assessments of the technical feasibilities, costs, risks, co-
13 benefits, and governance challenges of these additional measures, which are as yet unproven
14 at scale. These assessments are a necessary step before judgments about the benefits and
15 risks of these approaches can be made with high confidence. (*High confidence*)

16 **Description of evidence base**

17 Key Finding 5 contains qualitative statements based on the growing literature addressing this
18 topic, including from such bodies as the National Academy of Sciences and the Royal
19 Society, coupled with judgment by the authors about the future interest level in this topic.

20 **Major uncertainties**

21 The major uncertainty is how public perception and interest among policymakers in climate
22 intervention may change over time, even independently from the perceived level of progress
23 made towards reducing CO₂ and other GHG emissions over time.

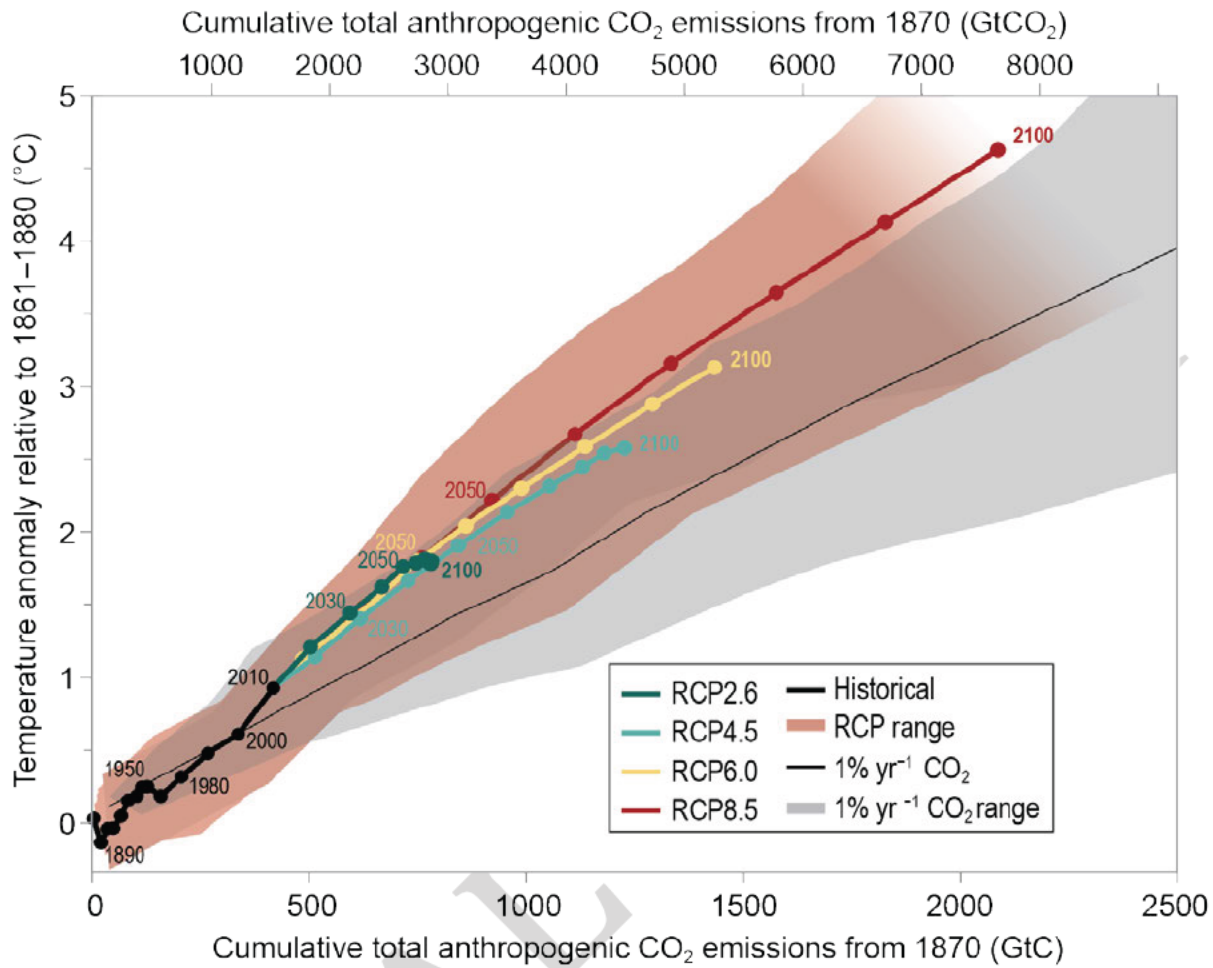
24 **Assessment of confidence based on evidence and agreement, including short description 25 of nature of evidence and level of agreement**

26 There is *high* confidence that climate intervention strategies may gain greater attention,
27 especially if efforts to slow the buildup of atmospheric CO₂ and other GHGs are considered
28 inadequate by many in the scientific and policy communities.

29 **Summary sentence or paragraph that integrates the above information**

30 The key finding is a qualitative statement based on the growing literature on this topic. The
31 uncertainty moving forward is the comfort level and desire among numerous stakeholders to
32 research and potentially carry out these climate intervention strategies, particularly in light of
33 how progress by the global community to reduce GHG emissions is perceived.

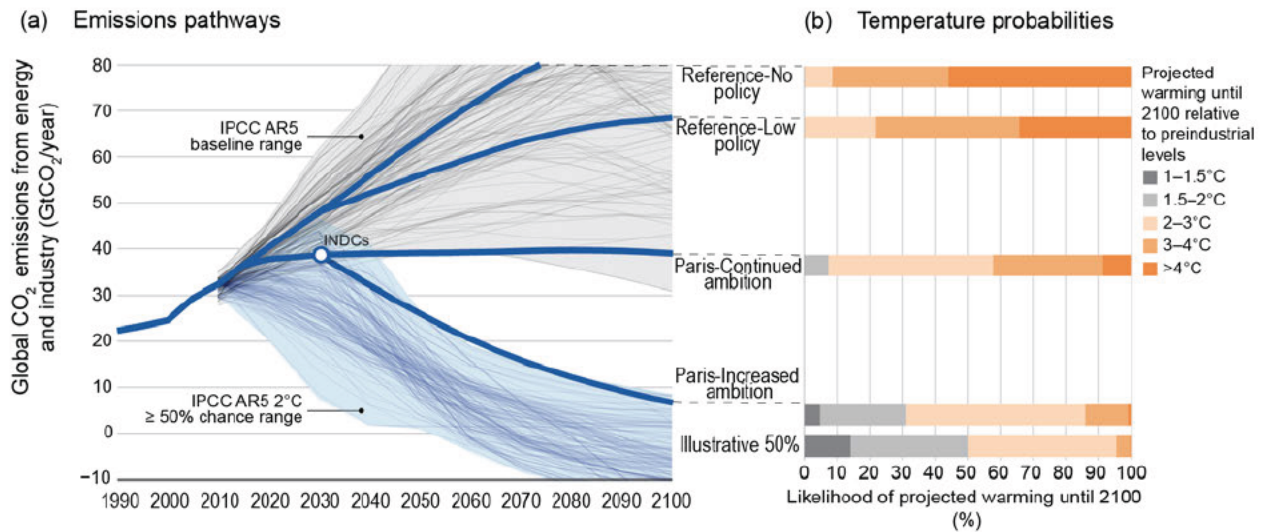
1 **FIGURES**



2

3 **Figure 14.1:** Global mean temperature change for a number of scenarios as a function of
 4 cumulative CO₂ emissions from preindustrial conditions, with time progressing along each
 5 individual line for each scenario. (Figure source: IPCC 2013; ©IPCC. Used with
 6 permission).

7



1

2 **Figure 14.2:** Global CO₂ emissions and probabilistic temperature outcomes of Paris. (a)

3 Global CO₂ emissions from energy and industry (includes CO₂ emissions from all fossil fuel

4 production and use and industrial processes such as cement manufacture that also produce

5 CO₂ as a byproduct) for emissions scenarios following no policy, current policy, meeting the

6 NDCs with no increased future ambition and meeting the NDCs with continually increasing

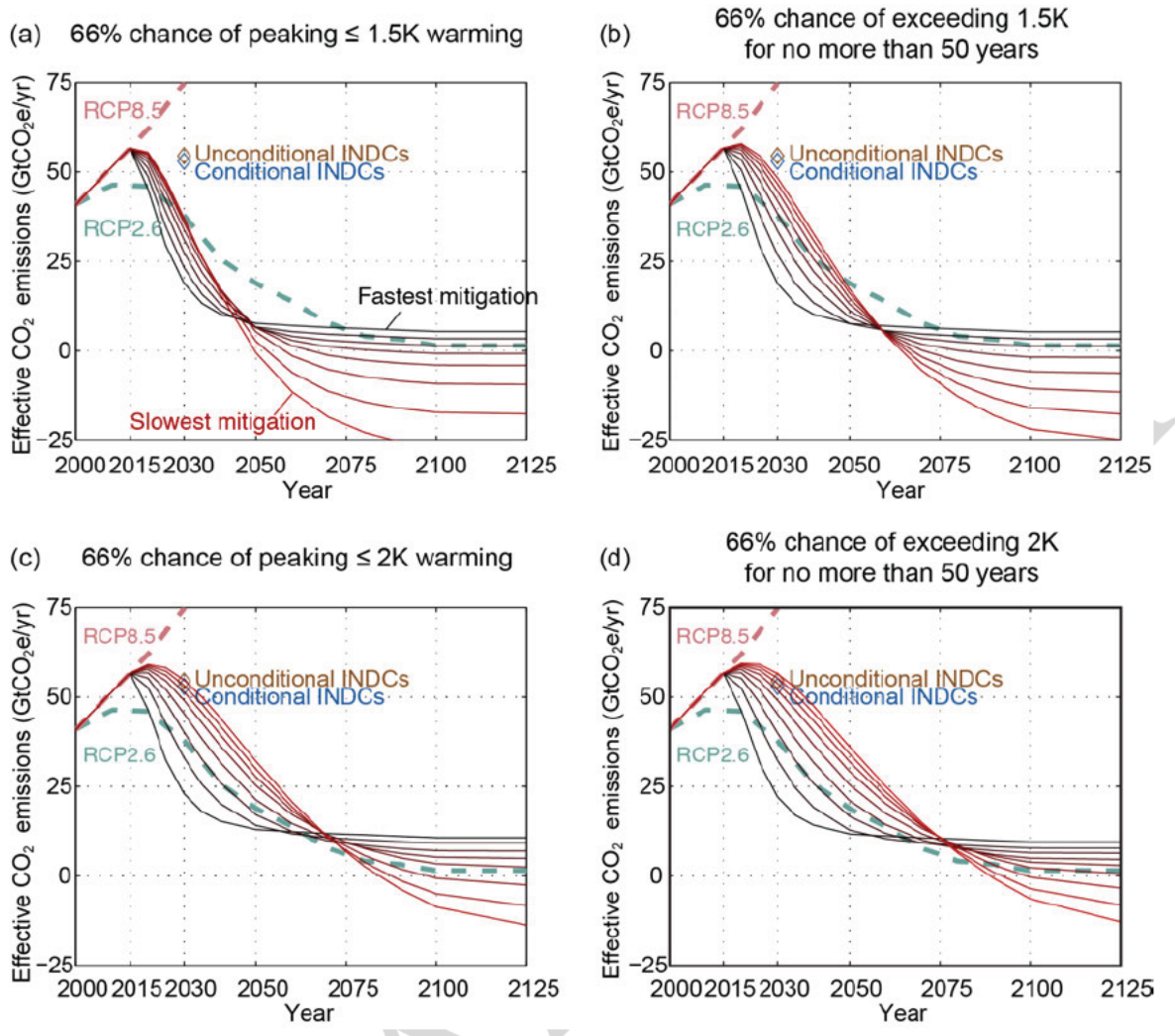
7 ambition. (b) Likelihoods of different levels of increase in global mean surface temperature

8 during the 21st century relative to preindustrial levels for the four scenarios. Although (a)

9 shows only CO₂ emissions from energy and industry, temperature outcomes are based on the

10 full suite of GHG, aerosol, and short-lived species emissions across the full set of human

11 activities and physical Earth systems. (Figure source: Fawcett et al. 2015).



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Figure 14.3: Global emission pathways for GHGs, expressed as CO₂-equivalent emissions, which would be consistent with different temperature targets (relative to preindustrial temperatures). (a) shows a set of pathways where global mean temperatures would likely (66%) not exceed 2.7°F (1.5°C). A number of pathways are consistent with the target, ranging from the red curve (slowest near-term mitigation with large negative emission requirements in the future) to the black curve with rapid near-term mitigation and less future negative emissions. (b) shows similar pathways with a 66% chance of exceeding 2.7°F (1.5°C) for only 50 years, where (c) and (d) show similar emission pathways for 3.6°F (2°C). (Figure source: Sanderson et al. 2016).

	Dates by when cumulative carbon emissions (GtC) since 1870 reach amount commensurate with 3.6F (2C), when accounting for non-CO2 forcings:		
	>66% = 790 GtC	>50% = 820 GtC	>33% = 900 GtC
RCP4.5	2037	2040	2047
RCP8.5	2033	2035	2040

1

2

	Dates by when cumulative carbon emissions (GtC) since 1870 reach amount commensurate with 2.7F (1.5C), when accounting for non-CO2 forcings:		
	>66% = 593 GtC	>50% = 615 GtC	>33% = 675 GtC
RCP4.5	2019	2021	2027
RCP8.5	2019	2021	2025

3

4

5 **Table 14.1:** Dates illustrating when cumulative CO₂ emission thresholds associated with
 6 eventual warming of 3.6°F or 2.7°F above preindustrial levels might be reached. RCP4.5 and
 7 RCP8.5 refer, respectively, to the low and high emission scenarios used throughout this
 8 report. The estimated cumulative CO₂ emissions (measured in Gigatons (Gt) of carbon)
 9 associated with different probabilities (e.g., >66%) of preventing 3.6°F (2°C) of warming are
 10 from the IPCC (Collins et al. 2013). The cumulative emissions compatible with 2.7°F (1.5°C)
 11 are linearly derived from the estimates associated with 3.6°F (2°C). The cumulative CO₂
 12 estimates take into account the additional net warming effects associated with past and future
 13 non-CO₂ emissions according to the RCP scenarios. Historic CO₂ emissions from 1870–2015
 14 (including fossil fuel combustion, land use change, and cement manufacturing) are from Le
 15 Quéré et al. 2016. See Traceable Accounts for further details.

1 **REFERENCES**

- 2 Allen, M.R., D.J. Frame, C. Huntingford, C.D. Jones, J.A. Lowe, M. Meinshausen, and N.
3 Meinshausen, 2009: Warming caused by cumulative carbon emissions towards the
4 trillionth tonne. *Nature*, **458**, 1163-1166. <http://dx.doi.org/10.1038/nature08019>
- 5 Anenberg, S.C., J. Schwartz, D. Shindell, M. Amann, G. Faluvegi, Z. Klimont, G. Janssens-
6 Maenhout, L. Pozzoli, R. Van Dingenen, E. Vignati, L. Emberson, N.Z. Muller, J.J.
7 West, M. Williams, V. Demkine, W.K. Hicks, J. Kuylenstierna, F. Raes, and V.
8 Ramanathan, 2012: Global air quality and health co-benefits of mitigating near-term
9 climate change through methane and black carbon emission controls. *Environmental*
10 *Health Perspectives*, **120**, 831-839. <http://dx.doi.org/10.1289/ehp.1104301>
- 11 Bond, T.C., S.J. Doherty, D.W. Fahey, P.M. Forster, T. Berntsen, B.J. DeAngelo, M.G.
12 Flanner, S. Ghan, B. Kärcher, D. Koch, S. Kinne, Y. Kondo, P.K. Quinn, M.C. Sarofim,
13 M.G. Schultz, M. Schulz, C. Venkataraman, H. Zhang, S. Zhang, N. Bellouin, S.K.
14 Guttikunda, P.K. Hopke, M.Z. Jacobson, J.W. Kaiser, Z. Klimont, U. Lohmann, J.P.
15 Schwarz, D. Shindell, T. Storelvmo, S.G. Warren, and C.S. Zender, 2013: Bounding the
16 role of black carbon in the climate system: A scientific assessment. *Journal of*
17 *Geophysical Research: Atmospheres*, **118**, 5380-5552.
18 <http://dx.doi.org/10.1002/jgrd.50171>
- 19 Ciais, P., C. Sabine, G. Bala, L. Bopp, V. Brovkin, J. Canadell, A. Chhabra, R. DeFries, J.
20 Galloway, M. Heimann, C. Jones, C. Le Quéré, R.B. Myneni, S. Piao, and P. Thornton,
21 2013: Carbon and other biogeochemical cycles. *Climate Change 2013: The Physical*
22 *Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the*
23 *Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M.
24 Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds.
25 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA,
26 465–570. <http://www.climatechange2013.org/report/full-report/>
- 27 Climate Action Tracker, 2016: Climate Action Tracker.
28 <http://climateactiontracker.org/global.html>
- 29 Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao,
30 W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver, and M.
31 Wehner, 2013: Long-term climate change: Projections, commitments and irreversibility.
32 *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to*
33 *the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker,
34 T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V.
35 Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom
36 and New York, NY, USA, 1029–1136. [http://www.climatechange2013.org/report/full-](http://www.climatechange2013.org/report/full-report/)
37 [report/](http://www.climatechange2013.org/report/full-report/)

- 1 Fawcett, A.A., G.C. Iyer, L.E. Clarke, J.A. Edmonds, N.E. Hultman, H.C. McJeon, J. Rogelj,
2 R. Schuler, J. Alsalam, G.R. Asrar, J. Creason, M. Jeong, J. McFarland, A. Mundra, and
3 W. Shi, 2015: Can Paris pledges avert severe climate change? *Science*, **350**, 1168-1169.
4 <http://dx.doi.org/10.1126/science.aad5761>
- 5 Hayhoe, K.A.S., H.S. Kheshgi, A.K. Jain, and D.J. Wuebbles, 1998: Tradeoffs in fossil fuel
6 use: The effects of CO₂, CH₄, and SO₂ aerosol emissions on climate. *World Resources*
7 *Review*, **10**.
- 8 IPCC, 2013: Summary for policymakers. *Climate Change 2013: The Physical Science Basis.*
9 *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental*
10 *Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J.
11 Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University
12 Press, Cambridge, UK and New York, NY, 1-30.
13 <http://www.climatechange2013.org/report/>
- 14 Joos, F., R. Roth, J.S. Fuglestedt, G.P. Peters, I.G. Enting, W. von Bloh, V. Brovkin, E.J.
15 Burke, M. Eby, N.R. Edwards, T. Friedrich, T.L. Frölicher, P.R. Halloran, P.B. Holden,
16 C. Jones, T. Kleinen, F.T. Mackenzie, K. Matsumoto, M. Meinshausen, G.K. Plattner, A.
17 Reisinger, J. Segschneider, G. Shaffer, M. Steinacher, K. Strassmann, K. Tanaka, A.
18 Timmermann, and A.J. Weaver, 2013: Carbon dioxide and climate impulse response
19 functions for the computation of greenhouse gas metrics: A multi-model analysis.
20 *Atmospheric Chemistry and Physics*, **13**, 2793-2825. [http://dx.doi.org/10.5194/acp-13-](http://dx.doi.org/10.5194/acp-13-2793-2013)
21 [2793-2013](http://dx.doi.org/10.5194/acp-13-2793-2013)
- 22 Keith, D.W. and D.G. MacMartin, 2015: A temporary, moderate and responsive scenario for
23 solar geoengineering. *Nature Climate Change*, **5**, 201-206.
24 <http://dx.doi.org/10.1038/nclimate2493>
- 25 Keith, D.W., R. Duren, and D.G. MacMartin, 2014: Field experiments on solar
26 geoengineering: Report of a workshop exploring a representative research portfolio.
27 *Philosophical Transactions of the Royal Society A: Mathematical, Physical and*
28 *Engineering Sciences*, **372**. <http://dx.doi.org/10.1098/rsta.2014.0175>
- 29 Kirtman, B., S.B. Power, J.A. Adedoyin, G.J. Boer, R. Bojariu, I. Camilloni, F.J. Doblas-
30 Reyes, A.M. Fiore, M. Kimoto, G.A. Meehl, M. Prather, A. Sarr, C. Schär, R. Sutton,
31 G.J. van Oldenborgh, G. Vecchi, and H.J. Wang, 2013: Near-term climate change:
32 Projections and predictability. *Climate Change 2013: The Physical Science Basis.*
33 *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental*
34 *Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J.
35 Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University
36 Press, Cambridge, UK and New York, NY, USA, 953–1028.
37 <http://www.climatechange2013.org/report/full-report/>

- 1 Kravitz, B., K. Caldeira, O. Boucher, A. Robock, P.J. Rasch, K. Alterskjær, D.B. Karam,
2 J.N.S. Cole, C.L. Curry, J.M. Haywood, P.J. Irvine, D. Ji, A. Jones, J.E. Kristjánsson,
3 D.J. Lunt, J.C. Moore, U. Niemeier, H. Schmidt, M. Schulz, B. Singh, S. Tilmes, S.
4 Watanabe, S. Yang, and J.-H. Yoon, 2013: Climate model response from the
5 Geoengineering Model Intercomparison Project (GeoMIP). *Journal of Geophysical*
6 *Research: Atmospheres*, **118**, 8320-8332. <http://dx.doi.org/10.1002/jgrd.50646>
- 7 Le Quéré, C., R.M. Andrew, J.G. Canadell, S. Sitch, J.I. Korsbakken, G.P. Peters, A.C.
8 Manning, T.A. Boden, P.P. Tans, R.A. Houghton, R.F. Keeling, S. Alin, O.D. Andrews,
9 P. Anthoni, L. Barbero, L. Bopp, F. Chevallier, L.P. Chini, P. Ciais, K. Currie, C. Delire,
10 S.C. Doney, P. Friedlingstein, T. Gkritzalis, I. Harris, J. Hauck, V. Haverd, M. Hoppema,
11 K. Klein Goldewijk, A.K. Jain, E. Kato, A. Körtzinger, P. Landschützer, N. Lefèvre, A.
12 Lenton, S. Lienert, D. Lombardozzi, J.R. Melton, N. Metzl, F. Millero, P.M.S. Monteiro,
13 D.R. Munro, J.E.M.S. Nabel, S.I. Nakaoka, K. O'Brien, A. Olsen, A.M. Omar, T. Ono, D.
14 Pierrot, B. Poulter, C. Rödenbeck, J. Salisbury, U. Schuster, J. Schwinger, R. Séférian, I.
15 Skjelvan, B.D. Stocker, A.J. Sutton, T. Takahashi, H. Tian, B. Tilbrook, I.T. van der
16 Laan-Luijkx, G.R. van der Werf, N. Viovy, A.P. Walker, A.J. Wiltshire, and S. Zaehle,
17 2016: Global carbon budget 2016. *Earth System Science Data*, **8**, 605-649.
18 <http://dx.doi.org/10.5194/essd-8-605-2016>
- 19 MacCracken, M.C., 2016: The rationale for accelerating regionally focused climate
20 intervention research. *Earth's Future*, **4**, 649-657.
21 <http://dx.doi.org/10.1002/2016EF000450>
- 22 MacMartin, D.G., D.W. Keith, B. Kravitz, and K. Caldeira, 2013: Management of trade-offs
23 in geoengineering through optimal choice of non-uniform radiative forcing. *Nature*
24 *Climate Change*, **3**, 365-368. <http://dx.doi.org/10.1038/nclimate1722>
- 25 Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestedt, J. Huang, D. Koch, J.-F.
26 Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura, and
27 H. Zhang, 2013: Anthropogenic and natural radiative forcing. *Climate Change 2013: The*
28 *Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report*
29 *of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner,
30 M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds.
31 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA,
32 659–740. <http://www.climatechange2013.org/report/full-report/>
- 33 NAS, 2015: *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration*. The
34 National Academies Press, Washington, DC, 154 pp. <http://dx.doi.org/10.17226/18805>
- 35 NAS, 2015: *Climate Intervention: Reflecting Sunlight to Cool Earth*. The National
36 Academies Press, Washington, DC, 260 pp. <http://dx.doi.org/10.17226/18988>

- 1 NRC, 2011: *Climate Stabilization Targets: Emissions, Concentrations, and Impacts over*
2 *Decades to Millennia*. National Research Council. The National Academies Press,
3 Washington, D.C., 298 pp. <http://dx.doi.org/10.17226/12877>
- 4 Paltsev, S., E. Monier, J. Scott, A. Sokolov, and J. Reilly, 2015: Integrated economic and
5 climate projections for impact assessment. *Climatic Change*, **131**, 21-33.
6 <http://dx.doi.org/10.1007/s10584-013-0892-3>
- 7 Pierce, J.R., D.K. Weisenstein, P. Heckendorn, T. Peter, and D.W. Keith, 2010: Efficient
8 formation of stratospheric aerosol for climate engineering by emission of condensible
9 vapor from aircraft. *Geophysical Research Letters*, **37**, L18805.
10 <http://dx.doi.org/10.1029/2010GL043975>
- 11 Prather, M.J., J.E. Penner, J.S. Fuglestedt, A. Kurosawa, J.A. Lowe, N. Höhne, A.K. Jain,
12 N. Andronova, L. Pinguelli, C. Pires de Campos, S.C.B. Raper, R.B. Skeie, P.A. Stott, J.
13 van Aardenne, and F. Wagner, 2009: Tracking uncertainties in the causal chain from
14 human activities to climate. *Geophysical Research Letters*, **36**, L05707.
15 <http://dx.doi.org/10.1029/2008GL036474>
- 16 Rao, S., Z. Klimont, J. Leita, K. Riahi, R. van Dingenen, L.A. Reis, K. Calvin, F. Dentener,
17 L. Drouet, S. Fujimori, M. Harmsen, G. Luderer, C. Heyes, J. Strefler, M. Tavoni, and
18 D.P. van Vuuren, 2016: A multi-model assessment of the co-benefits of climate
19 mitigation for global air quality. *Environmental Research Letters*, **11**, 124013.
20 <http://dx.doi.org/10.1088/1748-9326/11/12/124013>
- 21 Ricke, K.L., M.G. Morgan, and M.R. Allen, 2010: Regional climate response to solar-
22 radiation management. *Nature Geoscience*, **3**, 537-541.
23 <http://dx.doi.org/10.1038/ngeo915>
- 24 Rogelj, J., M. Meinshausen, M. Schaeffer, R. Knutti, and K. Riahi, 2015: Impact of short-
25 lived non-CO₂ mitigation on carbon budgets for stabilizing global warming.
26 *Environmental Research Letters*, **10**, 075001. [http://dx.doi.org/10.1088/1748-](http://dx.doi.org/10.1088/1748-9326/10/7/075001)
27 [9326/10/7/075001](http://dx.doi.org/10.1088/1748-9326/10/7/075001)
- 28 Rogelj, J., M. den Elzen, N. Höhne, T. Fransen, H. Fekete, H. Winkler, R. Schaeffer, F. Sha,
29 K. Riahi, and M. Meinshausen, 2016: Paris Agreement climate proposals need a boost to
30 keep warming well below 2 °C. *Nature*, **534**, 631-639.
31 <http://dx.doi.org/10.1038/nature18307>
- 32 Sanderson, B.M., B.C. O'Neill, and C. Tebaldi, 2016: What would it take to achieve the Paris
33 temperature targets? *Geophysical Research Letters*, **43**, 7133-7142.
34 <http://dx.doi.org/10.1002/2016GL069563>

- 1 Shah, N., M. Wei, E.L. Virginie, and A.A. Phadke, 2015: Benefits of Leapfrogging to
2 Superefficiency and Low Global Warming Potential Refrigerants in Room Air
3 Conditioning. LBNL-1003671. Lawrence Berkeley National Laboratory, Energy
4 Technology Area, Berkeley, CA. 39 pp. [https://eetd.lbl.gov/publications/benefits-of-](https://eetd.lbl.gov/publications/benefits-of-leapfrogging-to-superef-0)
5 [leapfrogging-to-superef-0](https://eetd.lbl.gov/publications/benefits-of-leapfrogging-to-superef-0)
- 6 Shepherd, J.G., K. Caldeira, P. Cox, J. Haigh, D. Keith, B. Launder, G. Mace, G.
7 MacKerron, J. Pyle, S. Rayner, C. Redgwell, and A. Watson, 2009: *Geoengineering the*
8 *Climate: Science, Governance and Uncertainty*. Royal Society, 82 pp.
9 http://eprints.soton.ac.uk/156647/1/Geoengineering_the_climate.pdf
- 10 Shindell, D., J.C.I. Kuylenstierna, E. Vignati, R. van Dingenen, M. Amann, Z. Klimont, S.C.
11 Anenberg, N. Muller, G. Janssens-Maenhout, F. Raes, J. Schwartz, G. Faluvegi, L.
12 Pozzoli, K. Kupiainen, L. Hoglund-Isaksson, L. Emberson, D. Streets, V. Ramanathan,
13 K. Hicks, N.T.K. Oanh, G. Milly, M. Williams, V. Demkine, and D. Fowler, 2012:
14 Simultaneously mitigating near-term climate change and improving human health and
15 food security. *Science*, **335**, 183-189. <http://dx.doi.org/10.1126/science.1210026>
- 16 Solomon, S., G.K. Plattner, R. Knutti, and P. Friedlingstein, 2009: Irreversible climate
17 change due to carbon dioxide emissions. *Proceedings of the National Academy of*
18 *Sciences of the United States of America*, **106**, 1704-1709.
19 <http://dx.doi.org/10.1073/pnas.0812721106>
- 20 Tebaldi, C. and P. Friedlingstein, 2013: Delayed detection of climate mitigation benefits due
21 to climate inertia and variability. *Proceedings of the National Academy of Sciences*, **110**,
22 17229-17234. <http://dx.doi.org/10.1073/pnas.1300005110>
- 23 Tebaldi, C. and M.F. Wehner, 2016: Benefits of mitigation for future heat extremes under
24 RCP4.5 compared to RCP8.5. *Climatic Change*, **First online**, 1-13.
25 <http://dx.doi.org/10.1007/s10584-016-1605-5>
- 26 Tilmes, S., B.M. Sanderson, and B.C. O'Neill, 2016: Climate impacts of geoengineering in a
27 delayed mitigation scenario. *Geophysical Research Letters*, **43**, 8222-8229.
28 <http://dx.doi.org/10.1002/2016GL070122>
- 29 UNFCCC, 2015: Paris Agreement. United Nations Framework Convention on Climate
30 Change, [Bonn, Germany]. 25 pp.
31 [http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agr](http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf)
32 [eement.pdf](http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf)
- 33 Zaelke, D. and N. Borgford-Parnell, 2015: The importance of phasing down
34 hydrofluorocarbons and other short-lived climate pollutants. *Journal of Environmental*
35 *Studies and Sciences*, **5**, 169-175. <http://dx.doi.org/10.1007/s13412-014-0215-7>

15. Potential Surprises: Compound Extremes and Tipping Elements

KEY FINDINGS

1. Positive feedbacks (self-reinforcing cycles) within the climate system have the potential to accelerate human-induced climate change and even shift the Earth's climate system, in part or in whole, into new states that are very different from those experienced in the recent past (for example, ones with greatly diminished ice sheets or different large-scale patterns of atmosphere or ocean circulation). Some feedbacks and potential state shifts can be modeled and quantified; others can be modeled or identified but not quantified; and some are probably still unknown. (*Very high confidence* in the potential for state shifts and in the incompleteness of knowledge about feedbacks and potential state shifts).
2. The physical and socioeconomic impacts of compound extreme events (such as simultaneous heat and drought, wildfires associated with hot and dry conditions, or flooding associated with high precipitation on top of snow or waterlogged ground) can be greater than the sum of the parts (*very high confidence*). Few analyses consider the spatial or temporal correlation between extreme events.
3. While climate models incorporate important climate processes that can be well quantified, they do not include all of the processes that can contribute to feedbacks, compound extreme events, and abrupt and/or irreversible changes. For this reason, future changes outside the range projected by climate models cannot be ruled out (*very high confidence*). Moreover, the systematic tendency of climate models to underestimate temperature change during warm paleoclimates suggests that climate models are more likely to underestimate than to overestimate the amount of long-term future change (*medium confidence*).

15.1 Introduction

The Earth system is made up of many components that interact in complex ways across a broad range of temporal and spatial scales. As a result of these interactions the behavior of the system cannot be predicted by looking at individual components in isolation. Negative feedbacks, or self-stabilizing cycles, within and between components of the Earth system can dampen changes (Ch. 2: Physical Drivers of Climate Change). However, their stabilizing effects render such feedbacks of less concern from a risk perspective than positive feedbacks, or self-reinforcing cycles. Positive feedbacks magnify both natural and anthropogenic changes. Some Earth system components, such as arctic sea ice and the polar ice sheets, may exhibit thresholds beyond which these self-reinforcing cycles can drive the component, or the entire system, into a radically different state. Although the probabilities of these state shifts may be difficult to assess, their consequences could be high, potentially exceeding anything anticipated by climate model projections for the coming century.

1 Humanity is conducting an unprecedented experiment with the Earth system through the large-
2 scale combustion of fossil fuels and widespread deforestation and the resulting release of carbon
3 dioxide (CO₂) into the atmosphere, as well as through emissions of other greenhouse gases and
4 radiatively active substances from human activities (Ch. 2: Physical Drivers of Climate Change).
5 These forcings are driving changes in temperature and other climate variables. Previous chapters
6 have covered a variety of observed and projected changes in such variables, including averages
7 and extremes of temperature, precipitation, sea level, and storm events (see Chapters 1, 4–13).

8 While the distribution of climate model projections provides insight into the range of possible
9 future changes, this range is limited by the fact that models do not include or fully represent all
10 of the known processes and components of the Earth system (e.g., ice sheets or arctic carbon
11 reservoirs) (Flato et al. 2013), nor do they include all of the interactions between these
12 components that contribute to the self-stabilizing and self-reinforcing cycles mentioned above
13 (e.g., the dynamics of the interactions between ice sheets, the ocean, and the atmosphere). They
14 also do not include currently unknown processes that may become increasingly relevant under
15 increasingly large climate forcings. This limitation is emphasized by the systematic tendency of
16 climate models to underestimate temperature change during warm paleoclimates (Section 15.5).
17 Therefore, there is significant potential for our planetary experiment to result in unanticipated
18 surprises and a broad consensus that the further and faster the Earth system is pushed towards
19 warming, the greater the risk of such surprises.

20 Scientists have been surprised by the Earth system many times in the past. The discovery of the
21 ozone hole is a clear example. Prior to groundbreaking work by Molina and Rowland (1974),
22 chlorofluorocarbons (CFCs) were viewed as chemically inert; the chemistry by which they
23 catalyzed stratospheric ozone depletion was unknown. Within eleven years of Molina and
24 Rowland's work, British Antarctic Survey scientists reported ground observations showing that
25 spring ozone concentrations in the Antarctic, driven by chlorine from human-emitted CFCs, had
26 fallen by about one-third since the late 1960s (Farman et al. 1985). The problem quickly moved
27 from being an “unknown unknown” to a “known known,” and by 1987, the Montreal Protocol
28 was adopted to phase out these ozone-depleting substances.

29 Another surprise has come from arctic sea ice. While the potential for powerful positive ice-
30 albedo feedbacks has been understood since the late 19th century, climate models have struggled
31 to capture the magnitude of these feedbacks and to include all the relevant dynamics that affect
32 sea ice extent. As of 2007, the observed decline in arctic sea ice from the start of the satellite era
33 in 1979 outpaced that projected by almost all the models used by the Intergovernmental Panel on
34 Climate Change's Fourth Assessment Report (AR4) (Stroeve et al. 2007), and it was not until
35 AR4 that the IPCC first raised the prospect of an ice-free summer Arctic during this century
36 (Meehl et al. 2007). More recent studies are more consistent with observations and have moved
37 the date of an ice-free summer Arctic up to approximately mid-century (Stroeve et al. 2012; see
38 Ch. 11: Arctic Changes). But continued rapid declines—2016 featured the lowest annually

1 averaged arctic sea ice extent on record, and the 2017 winter maximum was also the lowest on
2 record—suggest that climate models may still be underestimating or missing relevant feedback
3 processes. These processes could include, for example, effects of melt ponds, changes in
4 storminess and ocean wave impacts, and warming of near surface waters (Schröder et al. 2014;
5 Asplin et al. 2012; Perovich et al. 2008).

6 This chapter focuses primarily on two types of potential surprises. The first arises from changing
7 correlations in extreme events which may not be surprising on their own but together can
8 increase the likelihood of compound extremes, in which multiple events occur simultaneously or
9 in rapid sequence. Increasingly frequent compound extremes—either of multiple types of events
10 (such as paired extremes of droughts and intense rainfall) or over greater spatial or temporal
11 scales (such as a drought occurring in multiple major agricultural regions around the world or
12 lasting for multiple decades)—are often not captured by analyses that focus solely on one type of
13 extreme.

14 The second type of surprise arises from self-reinforcing cycles, which can give rise to “tipping
15 elements”—subcomponents of the Earth system that can be stable in multiple different states and
16 can be “tipped” between these states by small changes in forcing, amplified by positive
17 feedbacks. Examples of potential tipping elements include ice sheets, modes of atmosphere–
18 ocean circulation like the El Niño–Southern Oscillation, patterns of ocean circulation like the
19 Atlantic Meridional Overturning Circulation, and large-scale ecosystems like the Amazon
20 rainforest (Lenton et al. 2008; Kopp et al. 2016). While compound extremes and tipping
21 elements constitute at least partially “known unknowns,” the paleoclimate record also suggests
22 the possibility of “unknown unknowns.” These possibilities arise in part from the tendency of
23 current climate models to underestimate past responses to forcing, for reasons that may or may
24 not be explained by current hypotheses (e.g., hypotheses related to positive feedbacks that are
25 unrepresented or poorly represented in existing models).

26 **15.2 Risk Quantification and Its Limits**

27 Quantifying the risk of low-probability, high-impact events, based on models or observations,
28 usually involves examining the tails of a probability distribution function (PDF). Robust
29 detection, attribution, and projection of such events into the future is challenged by multiple
30 factors, including an observational record that often does not represent the full range of physical
31 possibilities in the climate system, as well as the limitations of the statistical tools, scientific
32 understanding, and models used to describe these processes (Zwiers et al. 2013).

33 The 2013 Boulder, Colorado floods and the Dust Bowl of the 1930s in the central United States
34 are two examples of extreme events whose magnitude and/or extent are unprecedented in the
35 observational record. Statistical approaches such as Extreme Value Theory can be used to model
36 and estimate the magnitude of rare events that may not have occurred in the observational record,
37 such as the “1,000-year flood event” (i.e., a flood event with a 0.1% chance of occurrence in any

1 given year) (e.g., Smith 1987). While useful for many applications, these are not physical
2 models: they are statistical models that are typically based on the assumption that observed
3 patterns of natural variability (that is, the sample from which the models derive their statistics)
4 are both valid and stationary beyond the observational period. Extremely rare events can also be
5 assessed based upon paleoclimate records and physical modeling. In the paleoclimatic record,
6 numerous abrupt changes have occurred since the last deglaciation, many larger than those
7 recorded in the instrumental record. For example, tree ring records of drought in the western
8 United States show abrupt, long-lasting megadroughts that were similar to but more intense and
9 longer-lasting than the 1930s Dust Bowl (Woodhouse and Overpeck 1998).

10 Since models are based on physics rather than observational data, they are not inherently
11 constrained to any given time period or set of physical conditions. They have been used to study
12 the Earth in the distant past and even the climate of other planets (e.g., Lunt et al. 2012; Navarro
13 et al. 2014). Looking to the future, thousands of years' worth of simulations can be generated
14 and explored to characterize small-probability, high-risk extreme events, as well as correlated
15 extremes (see Section 15.4). However, the likelihood that such model events represent real risks
16 is limited by well-known uncertainties in climate modeling related to parameterizations, model
17 resolution, and limits to scientific understanding (Ch. 4: Projections). For example, conventional
18 convective parameterizations in global climate models systematically underestimate extreme
19 precipitation (Kang et al. 2015). In addition, models often do not accurately capture or even
20 include the processes, such as permafrost feedbacks, by which abrupt, non-reversible change
21 may occur (see Section 15.4). An analysis focusing on physical climate predictions over the last
22 20 years found a tendency for scientific assessments such as those of the IPCC to under-predict
23 rather than over-predict changes that were subsequently observed (Brysse et al. 2013).

24 **15.3 Compound Extremes**

25 An important aspect of surprise is the potential for compound extreme events. These can be
26 events that occur at the same time or in sequence (such as consecutive floods in the same region)
27 and in the same geographic location or at multiple locations within a given country or around the
28 world (such as the 2009 Australian floods and wildfires). They may consist of multiple extreme
29 events or of events that by themselves may not be extreme but together produce a multi-event
30 occurrence (such as a heat wave accompanied by drought [Quarantelli 1986]). It is possible for
31 the net impact of these events to be less than the sum of the individual events if their effects
32 cancel each other out. For example, increasing CO₂ concentrations and acceleration of the
33 hydrological cycle may mitigate the future impact of extremes in gross primary productivity that
34 currently impact the carbon cycle (Zscheischler et al. 2014). However, from a risk perspective,
35 the primary concern relates to compound extremes with additive or even multiplicative effects.

36 Some areas are susceptible to multiple types of extreme events that can occur simultaneously.
37 For example, certain regions are susceptible to both flooding from coastal storms and riverine
38 flooding from snow melt, and a compound event would be the occurrence of both

1 simultaneously. Compound events can also result from shared forcing factors, including natural
2 cycles like the El Niño–Southern Oscillation (ENSO); large-scale circulation patterns, such as
3 the ridge observed during the current California drought (e.g., Swain et al. 2016; see also Ch. 8:
4 Droughts, Floods, and Wildfires); or relatively greater regional sensitivity to global change, as
5 may occur in “hot spots” such as the western United States (Diffenbaugh and Giorgi 2012).
6 Finally, compound events can result from mutually-reinforcing cycles between individual events,
7 such as the relationship between drought and heat, linked through soil moisture and evaporation,
8 in water-limited areas (IPCC 2012).

9 In a changing climate, the probability of compound events can be altered if there is an underlying
10 trend in conditions such as mean temperature, precipitation, or sea level that alters the baseline
11 conditions or vulnerability of a region. It can also be altered if there is a change in the frequency
12 or intensity of individual extreme events relative to the changing mean (for example, stronger
13 storm surges, more frequent heat waves, or heavier precipitation events).

14 The occurrence of warm/dry and warm/wet conditions is discussed extensively in the literature;
15 at the global scale, these conditions have increased since the 1950s (Hao et al. 2013), and
16 analysis of NOAA’s billion-dollar disasters illustrates the correlation between temperature and
17 precipitation extremes during the costliest climate and weather events since 1980 (Figure 15.1,
18 right). In the future, hot summers will become more frequent, and although it is not always clear
19 for every region whether drought frequency will change, droughts in already dry regions, such as
20 the southwestern United States, are likely to be more intense in a warmer world due to faster
21 evaporation and associated surface drying (Collins et al. 2013; Trenberth et al. 2014; Cook et al.
22 2015). For other regions, however, the picture is not as clear. Recent examples of heat/drought
23 events (in the southern Great Plains in 2011 or in California, 2012–2015) have highlighted the
24 inadequacy of traditional univariate risk assessment methods (AghaKouchak et al. 2014). Yet a
25 bivariate analysis for the contiguous United States of precipitation deficits and positive
26 temperature anomalies finds no significant trend in the last 30 years (Serinaldi 2016).

27 Another compound event frequently discussed in the literature is the increase in wildfire risk
28 resulting from the combined effects of high precipitation variability (wet seasons followed by
29 dry), elevated temperature, and low humidity. If followed by heavy rain, wildfires can in turn
30 increase the risk of landslides and erosion. They can also radically increase emissions of
31 greenhouse gases, as demonstrated by the amount of carbon dioxide produced by the Fort
32 McMurray fires of May 2016—more than 10% of Canada’s annual emissions.

33 A third example of a compound event involves flooding arising from wet conditions due to
34 precipitation or to snowmelt, which could be exacerbated by warm temperatures. These wet
35 conditions lead to high groundwater levels, saturated soils, and/or elevated river flows, which
36 can increase the risk of flooding associated with a given storm days or even months later (IPCC
37 2012).

1 Compound events may surprise in two ways. The first is if known types of compound events
2 recur, but are stronger, longer-lasting, and/or more widespread than those experienced in the
3 observational record or projected by model simulations for the future. One example would be
4 simultaneous drought events in different agricultural regions across the country, or even around
5 the world, that challenge the ability of human systems to provide adequate affordable food.
6 Regions that lack the ability to adapt would be most vulnerable to this risk (e.g., Fraser et al.
7 2013). Another example would be the concurrent and more severe heavy precipitation events that
8 have occurred in the U.S. Midwest in recent years. After record insurance payouts following the
9 events, in 2014 several insurance companies, led by Farmers Insurance, sued the city of Chicago
10 and surrounding counties for failing to adequately prepare for the impacts of a changing climate.
11 Although the suit was dropped later that same year, their point was made: in some regions of the
12 United States, the insurance industry is not able to cope with the increasing frequency and/or
13 concurrence of certain types of extreme events.

14 The second way in which compound events could surprise would be the emergence of new types
15 of compound events not observed in the historical record or predicted by model simulations, due
16 to model limitations (in terms of both their spatial resolution as well as their ability to explicitly
17 resolve the physical processes that would result in such compound events), an increase in the
18 frequency of such events from human-induced climate change, or both. An example is Hurricane
19 Sandy, where sea level rise, anomalously high ocean temperatures, and high tides combined to
20 strengthen both the storm and the magnitude of the associated storm surge (Reed et al. 2015). At
21 the same time, a blocking ridge over Greenland—a feature whose strength and frequency may be
22 related to both Greenland surface melt and reduced summer sea ice in the Arctic (Liu et al. 2016;
23 see also Ch. 11: Arctic Changes)—redirected the storm inland to what was, coincidentally, an
24 exceptionally high-exposure location.

25 **[INSERT FIGURE 15.1 HERE]**

26 **15.4 Climatic Tipping Elements**

27 Different parts of the Earth system exhibit *critical thresholds*, sometimes called “tipping points”
28 (e.g., Lenton et al. 2008; Collins et al. 2013; NRC 2013; Kopp et al. 2016). These parts, known
29 as *tipping elements*, have the potential to enter into self-amplifying cycles that commit them to
30 shifting from their current state into a new state: for example, from one in which the summer
31 Arctic Ocean is covered by ice, to one in which it is ice-free. In some potential tipping elements,
32 these state shifts occur abruptly; in others, the commitment to a state shift may occur rapidly, but
33 the state shift itself may take decades, centuries, or even millennia to play out. Often the forcing
34 that commits a tipping element to a shift in state is unknown. Sometimes, it is even unclear
35 whether a proposed tipping element actually exhibits tipping behavior. Through a combination of
36 physical modeling, paleoclimate observations, and expert elicitations, scientists have identified a
37 number of possible tipping elements in atmosphere–ocean circulation, the cryosphere, the carbon
38 cycle, and ecosystems (Figure 15.1, left; Table 15.1).

[INSERT TABLE 15.1 HERE]

One important tipping element is the Atlantic Meridional Overturning Circulation (AMOC), a major component of global ocean circulation. Driven by the sinking of cold, dense water in the North Atlantic near Greenland, its strength is projected to decrease with warming due to freshwater input from increased precipitation, glacial melt, and melt of the Greenland Ice Sheet (Rahmstorf et al. 2015; see also discussion in Ch. 11: Arctic Changes). A decrease in AMOC strength is probable and may already be culpable for the “warming hole” observed in the North Atlantic (Drijfhout et al. 2012; Rahmstorf et al. 2015), although it is still unclear whether this decrease represents a forced change or internal variability (Cheng et al. 2016). Given sufficient freshwater input, there is even the possibility of complete AMOC collapse. Most models do not predict such a collapse in the 21st century (NRC 2013), although one study that used observations to bias-correct climate model simulations found that CO₂ concentrations of 700 ppm led to a AMOC collapse within 300 years (Liu et al. 2017).

A slowing or collapse of the AMOC would have several consequences for the United States. A decrease in AMOC strength would accelerate sea level rise off the northeastern United States (Yin and Goddard 2013), while a full collapse could result in as much as approximately 1.6 feet (0.5 m) of regional sea level rise (Gregory and Lowe 2000; Levermann et al. 2005), as well as a cooling of approximately 0°F–4°F (0°C–2°C) over the country (Jackson et al. 2015; Liu et al. 2017). These changes would occur in addition to preexisting global and regional sea level and temperature change. A slowdown of the AMOC would also lead to a reduction of ocean carbon dioxide uptake, and thus an acceleration of global-scale warming (Pérez et al. 2013).

Another tipping element is the atmospheric–oceanic circulation of the equatorial Pacific that, through a set of feedbacks, drives the state shifts of the El Niño–Southern Oscillation. This is an example of a tipping element that already shifts on a sub-decadal, interannual timescale, primarily in response to internal noise. Climate model experiments suggest that warming will reduce the threshold needed to trigger extremely strong El Niño and La Niña events (Cai et al. 2014, 2015). As evident from recent El Niño and La Niña events, such a shift would negatively impact many regions and sectors across the United States (for more on ENSO impacts, see Ch. 5: Circulation and Variability).

A third potential tipping element is arctic sea ice, which may exhibit abrupt state shifts into summer ice-free or year-round ice-free states (Lindsay and Zhang 2005; Eisenman and Wetlaufer 2013). As discussed above, climate models have historically underestimated the rate of arctic sea ice loss. This is likely due to insufficient representation of critical positive feedbacks in models. Such feedbacks could include: greater high-latitude storminess and ocean wave penetration as sea ice declines; more northerly incursions of warm air and water; melting associated with increasing water vapor; loss of multiyear ice; and albedo decreases on the sea ice surface (e.g., Schroder et al. 2014; Asplin et al. 2012; Perovich et al. 2008). At the same time, however, the point at which the threshold for an abrupt shift would be crossed also depends on

1 the role of natural variability in a changing system; the relative importance of potential
2 stabilizing negative feedbacks, such as more efficient heat transfer from the ocean to the
3 atmosphere in fall and winter as sea declines; and how sea ice in other seasons, as well as the
4 climate system more generally, responds once the first “ice-free” summer occurs (e.g., Ding et
5 al. 2017). It is also possible that summer sea ice may not abruptly collapse, but instead respond
6 in a manner proportional to the increase in temperature (Armour et al. 2011; Ridley et al. 2012;
7 Li et al. 2013; Wagner and Eisenman 2015). Moreover, an abrupt decrease in winter sea ice may
8 result simply as the gradual warming of Arctic Ocean causes it to cross a critical temperature for
9 ice formation, rather than from self-reinforcing cycles (Bathiany et al. 2016).

10 Two possible tipping elements in the carbon cycle also lie in the Arctic. The first is buried in the
11 permafrost, which contains an estimated 1,300–1,600 Gt C (Schuur et al. 2015; see also Ch. 11:
12 Arctic Changes). As the Arctic warms, about 5–15% is estimated to be vulnerable to release in
13 this century (Schuur et al., 2015). Locally, the heat produced by the decomposition of organic
14 carbon could serve as a positive feedback, accelerating carbon release (Hollesen et al. 2015).
15 However, the release of permafrost carbon, as well as whether that carbon is initially released as
16 CO₂ or as the more potent greenhouse gas CH₄, is limited by many factors, including the freeze-
17 thaw cycle, the rate with which heat diffuses into the permafrost, the potential for organisms to
18 cycle permafrost carbon into new biomass, and oxygen availability. Though the release of
19 permafrost carbon would probably not be fast enough to trigger a runaway self-amplifying cycle
20 leading to a permafrost-free Arctic (Schuur et al. 2015), it still has the potential to significantly
21 amplify both local and global warming, reduce the budget of human-caused CO₂ emissions
22 consistent with global temperature targets, and drive continued warming even if human-caused
23 emissions stopped altogether (MacDougall et al. 2012, 2015).

24 The second possible arctic carbon cycle tipping element is the reservoir of methane hydrates
25 frozen into the sediments of continental shelves of the Arctic Ocean (see also Ch. 11: Arctic
26 Changes). There is an estimated 500 to 3,000 Gt C in methane hydrates (Archer 2007; Ruppel
27 2011; Piñero et al. 2013), with a most recent estimate of 1,800 Gt C (equivalently, 2,400 Gt CH₄)
28 (Ruppel and Kessler 2017). If released as methane rather than CO₂, this would be equivalent to
29 about 82,000 Gt CO₂ using a global warming potential of 34 (Myhre et al. 2013). While the
30 existence of this reservoir has been known and discussed for several decades (e.g., Kvenvolden
31 1988), only recently has it been hypothesized that warming bottom water temperatures may
32 destabilize the hydrates over timescales shorter than millennia, leading to their release into the
33 water column and eventually the atmosphere (e.g., Archer 2007; Kretschmer et al. 2015). Recent
34 measurements of the release of methane from these sediments in summer find that, while
35 methane hydrates on the continental shelf and upper slope are undergoing dissociation, the
36 resulting emissions are not reaching the ocean surface in sufficient quantity to affect the
37 atmospheric methane budget significantly, if at all (Myhre et al. 2016; Ruppel and Kessler 2017).
38 Estimates of plausible hydrate releases to the atmosphere over the next century are only a

1 fraction of present-day anthropogenic methane emissions (Kretschmer et al. 2015; Stranne et al.
2 2016; Ruppel and Kessler 2017).

3 These estimates of future emissions from permafrost and hydrates, however, neglect the
4 possibility that humans may insert themselves into the physical feedback systems. With an
5 estimated 53% of global fossil fuel reserves in the Arctic becoming increasingly accessible in a
6 warmer world (Lee and Holder 2001), the risks associated with this carbon being extracted and
7 burned, further exacerbating the influence of humans on global climate, are evident (Jakob and
8 Hilaire 2015; McGlade and Elkins 2015). Of less concern but still relevant, arctic ocean waters
9 themselves are a source of methane, which could increase as sea ice decreases (Kort et al. 2012).

10 The Antarctic and Greenland Ice Sheets are clear tipping elements. The Greenland Ice Sheet
11 exhibits multiple stable states as a result of feedbacks involving the elevation of the ice sheet,
12 atmosphere-ocean-sea ice dynamics, and albedo (Ridley et al. 2010; Robinson et al. 2012;
13 Levermann et al. 2013; Koenig et al. 2014). At least one study suggests that warming of 2.9°F
14 (1.6°C) above a preindustrial baseline could commit Greenland to an 85% reduction in ice
15 volume and a 20 ft (6 m) contribution to global mean sea level over millennia (Robinson et al.
16 2012). One 10,000-year modeling study (Clark et al. 2016) suggests that following the higher
17 RCP8.5 pathway (see Ch. 4: Projections) over the 21st century would lead to complete loss of
18 the Greenland Ice Sheet over 6,000 years.

19 In Antarctica, the amount of ice that sits on bedrock below sea level is enough to raise global
20 mean sea level by 75.5 feet (23 m) (Fretwell et al. 2013). This ice is vulnerable to collapse over
21 centuries to millennia due to a range of feedbacks involving ocean-ice sheet-bedrock interactions
22 (Schoof 2007; Gomez et al. 2010; Ritz et al. 2015; Mengel and Levermann et al. 2014; Pollard et
23 al. 2015; Clark et al. 2016). Observational evidence suggests that ice dynamics already in
24 progress have committed the planet to as much as 3.9 feet (1.2 m) worth of sea level rise from
25 the West Antarctic Ice Sheet alone, although that amount is projected to occur over the course of
26 many centuries (Joughin et al. 2014; Rignot et al. 2014). Plausible physical modeling indicates
27 that, under the higher RCP8.5 scenario, Antarctic ice could contribute 3.3 feet (1 m) or more to
28 global mean sea level over the remainder of this century (DeConto and Pollard 2016), with some
29 authors arguing that rates of change could be even faster (Hansen et al. 2016). Over 10,000
30 years, one modeling study suggests that 3.6°F (2°C) of sustained warming could lead to about 70
31 feet (25 m) of global mean sea level rise from Antarctica alone (Clark et al. 2016).

32 Finally, tipping elements also exist in large-scale ecosystems. For example, boreal forests such as
33 those in southern Alaska may expand northward in response to arctic warming. Because forests
34 are darker than the tundra they replace, their expansion amplifies regional warming, which in
35 turn accelerates their expansion (Jones et al. 2009). As another example, coral reef ecosystems,
36 such as those in Florida, are maintained by stabilizing ecological feedbacks among corals,
37 coralline red algae, and grazing fish and invertebrates. However, these stabilizing feedbacks can
38 be undermined by warming, increased risk of bleaching events, spread of disease, and ocean

1 acidification, leading to abrupt reef collapse (Hoegh-Guldberg et al. 2007). More generally,
2 many ecosystems can undergo rapid regime shifts in response to a range of stressors, including
3 climate change (e.g., Scheffer et al. 2001; Folke et al. 2004).

4 **15.5 Paleoclimatic Hints of Additional Potential Surprises**

5 The paleoclimatic record provides evidence for additional state shifts whose driving mechanisms
6 are as yet poorly understood. As mentioned, global climate models tend to underestimate both
7 the magnitude of global mean warming in response to higher CO₂ levels as well as its
8 amplification at high latitudes, compared to reconstructions of temperature and CO₂ from the
9 geological record. Three case studies—all periods well predating the first appearance of *Homo*
10 *sapiens* around 200,000 years ago (Tattersall 2009)—illustrate the limitations of current
11 scientific understanding in capturing the full range of self-reinforcing cycles that operate within
12 the Earth system, particularly over millennial time scales.

13 The first of these, the late Pliocene, occurred about 3.6 to 2.6 million years ago. Climate model
14 simulations for this period systematically underestimate warming north of 30°N (Salzmann et al.
15 2013). Similarly, during the middle Miocene (about 17–14.5 million years ago), models also fail
16 to simultaneously replicate global mean temperature—estimated from proxies to be
17 approximately 14°F ± 4°F (8°C ± 2°C) warmer than preindustrial—and the approximately 40%
18 reduction in the pole-to-equator temperature gradient relative to today (Goldner et al. 2014).
19 Although about one-third of the global mean temperature increase during the Miocene can be
20 attributed to changes in geography and vegetation, geological proxies indicate CO₂
21 concentrations of around 400 ppm (Goldner et al. 2014; Foster et al. 2012), similar to today. This
22 suggests the possibility of as yet unmodeled feedbacks, perhaps related to a significant change in
23 the vertical distribution of heat in the tropical ocean (LaRiviere et al. 2012).

24 The last of these case studies, the early Eocene, occurred about 56–48 million years ago. This
25 period is characterized by the absence of permanent land ice, CO₂ concentrations peaking around
26 1,400 ± 470 ppm (Anagnostu et al. 2016), and global temperatures about 25°F ± 5°F (14°C ±
27 3°C) warmer than the preindustrial (Caballero and Huber 2013). Like the late Pliocene and the
28 middle Miocene, this period also exhibits about half the pole-to-equator temperature gradient of
29 today (Huber and Caballero 2011; Lunt et al. 2012). About one-third of the temperature
30 difference is attributable to changes in geography, vegetation, and ice sheet coverage (Caballero
31 and Huber 2013). However, to reproduce both the elevated global mean temperature and the
32 reduced pole-to-equator temperature gradient, climate models would require CO₂ concentrations
33 that exceed those indicated by the proxy record by two to five times (Lunt et al. 2012) —
34 suggesting once again the presence of as yet poorly understood processes and feedbacks.

35 One possible explanation for this discrepancy is a planetary state shift that, above a particular
36 CO₂ threshold, leads to a significant increase in the sensitivity of the climate to CO₂. Paleo-data
37 for the last 800,000 years suggest a gradual increase in climate sensitivity with global mean

1 temperature over glacial-interglacial cycles (von der Heydt et al. 2014; Friedrich et al. 2016),
2 although these results are based on a time period with CO₂ concentrations lower than today. At
3 higher CO₂ levels, one modeling study (Caballero and Huber 2013) suggests that an abrupt
4 change in atmospheric circulation (the onset of equatorial atmospheric superrotation) between
5 1,120 and 2,240 ppm CO₂ that could lead to a reduction in cloudiness and an approximate
6 doubling of climate sensitivity. However, the critical threshold for such a transition is poorly
7 constrained. If it occurred in the past at a lower CO₂ level, it might explain the Eocene
8 discrepancy and potentially also the Miocene discrepancy: but in that case, it could also pose a
9 plausible threat within the 21st century under the higher RCP8.5 pathway.

10 Regardless of the particular mechanism, the systematic paleoclimatic model-data mismatch for
11 past warm climates suggests that climate models are omitting at least one, and probably more,
12 processes crucial to future warming, especially in polar regions. For this reason, future changes
13 outside the range projected by climate models cannot be ruled out, and climate models are more
14 likely to underestimate than to overestimate the amount of long-term future change.

15

FINAL DRAFT

1 TRACEABLE ACCOUNTS

2 Key Finding 1

3 Positive feedbacks (self-reinforcing cycles) within the climate system have the potential to
4 accelerate human-induced climate change and even shift the Earth's climate system, in part or in
5 whole, into new states that are very different from those experienced in the recent past (for
6 example, ones with greatly diminished ice sheets or different large-scale patterns of atmosphere
7 or ocean circulation). Some feedbacks and potential state shifts can be modeled and quantified;
8 others can be modeled or identified but not quantified; and some are probably still unknown.
9 (*Very high confidence* in the potential for state shifts and in the incompleteness of knowledge
10 about feedbacks and potential state shifts).

11 Description of evidence base

12 This key finding is based on a large body of scientific literature recently summarized by Lenton
13 et al. (2008), NRC (2013), and Kopp et al. (2016). As NRC (2013, page vii) states, "A study of
14 Earth's climate history suggests the inevitability of 'tipping points'—thresholds beyond which
15 major and rapid changes occur when crossed—that lead to abrupt changes in the climate system"
16 and (page xi), "Can all tipping points be foreseen? Probably not. Some will have no precursors,
17 or may be triggered by naturally occurring variability in the climate system. Some will be
18 difficult to detect, clearly visible only after they have been crossed and an abrupt change
19 becomes inevitable." As IPCC AR5 WG1 Chapter 12, section 12.5.5 (Collins et al. 2013) further
20 states, "A number of components or phenomena within the Earth system have been proposed as
21 potentially possessing critical thresholds (sometimes referred to as tipping points) beyond which
22 abrupt or nonlinear transitions to a different state ensues." Collins et al. (2013) further
23 summarizes critical thresholds that can be modeled and others that can only be identified.

24 Major uncertainties

25 The largest uncertainties are 1) whether proposed tipping elements actually undergo critical
26 transitions; 2) the magnitude and timing of forcing that will be required to initiate critical
27 transitions in tipping elements; 3) the speed of the transition once it has been triggered; 4) the
28 characteristics of the new state that results from such transition; and 5) the potential for new
29 tipping elements to exist that are yet unknown.

30 Assessment of confidence based on evidence and agreement, including short description of 31 nature of evidence and level of agreement

32 There is *very high confidence* in the likelihood of the existence of positive feedbacks and tipping
33 elements statement is based on a large body of literature published over the last 25 years that
34 draws from basic physics, observations, paleoclimate data, and modeling.

1 There is *very high confidence* that some feedbacks can be quantified, others are known but
2 cannot be quantified, and others may yet exist that are currently unknown.

3 **Summary sentence or paragraph that integrates the above information**

4 The key finding is based on NRC (2013) and IPCC AR4 WG1 Chapter 12 section 12.5.5 (IPCC
5 2007), which made a thorough assessment of the relevant literature.

6

7 **Key Finding 2**

8 The physical and socioeconomic impacts of compound extreme events (such as simultaneous
9 heat and drought, wildfires associated with hot and dry conditions, or flooding associated with
10 high precipitation on top of snow or waterlogged ground) can be greater than the sum of the parts
11 (*very high confidence*). Few analyses consider the spatial or temporal correlation between
12 extreme events.

13 **Description of evidence base**

14 This key finding is based on a large body of scientific literature summarized in the 2012 IPCC
15 Special Report on Extremes (IPCC 2012). The report's Summary for Policymakers (page 6)
16 states, "exposure and vulnerability are key determinants of disaster risk and of impacts when risk
17 is realized... extreme impacts on human, ecological, or physical systems can result from
18 individual extreme weather or climate events. Extreme impacts can also result from non-extreme
19 events where exposure and vulnerability are high or from a compounding of events or their
20 impacts. For example, drought, coupled with extreme heat and low humidity, can increase the
21 risk of wildfire."

22 **Major uncertainties**

23 The largest uncertainties are in the temporal congruence of the events and the compounding
24 nature of their impacts.

25 **Assessment of confidence based on evidence and agreement, including short description of
26 nature of evidence and level of agreement**

27 There is *very high confidence* that the impacts of multiple events could exceed the sum of the
28 impacts of events occurring individually.

29 **Summary sentence or paragraph that integrates the above information**

30 The key finding is based on the 2012 IPCC SREX report, particularly section 3.1.3 on compound
31 or multiple events, which presents a thorough assessment of the relevant literature.

32

1 Key Finding 3

2 While climate models incorporate important climate processes that can be well quantified, they
3 do not include all of the processes that can contribute to feedbacks, compound extreme events,
4 and abrupt and/or irreversible changes. For this reason, future changes outside the range
5 projected by climate models cannot be ruled out (*very high confidence*). Moreover, the
6 systematic tendency of climate models to underestimate temperature change during warm
7 paleoclimates suggests that climate models are more likely to underestimate than to overestimate
8 the amount of long-term future change (*medium confidence*).

9 Description of evidence base

10 This key finding is based on the conclusions of IPCC AR5 WG1 (IPCC 2013), specifically
11 Chapter 7 (Flato et al. 2013); the state of the art of global models is briefly summarized in
12 Chapter 4: Projections of this report. The second half of this key finding is based upon the
13 tendency of global climate models to underestimate, relative to geological reconstructions, the
14 magnitude of both long-term global mean warming and the amplification of warming at high
15 latitudes in past warm climates (e.g., Salzmann et al. 2013; Goldner et al. 2014; Caballeo and
16 Huber 2013; Lunt et al. 2012).

17 Major uncertainties

18 The largest uncertainties are structural: are the models including all the important components
19 and relationships necessary to model the feedbacks and if so, are these correctly represented in
20 the models?

**21 Assessment of confidence based on evidence and agreement, including short description of
22 nature of evidence and level of agreement**

23 There is *very high confidence* that the models are incomplete representations of the real world;
24 and there is *medium confidence* that their tendency is to under- rather than over-estimate the
25 amount of long-term future change.

26 Summary sentence or paragraph that integrates the above information

27 The key finding is based on the IPCC AR5 WG1 Chapter 9 (IPCC 2013), as well as systematic
28 paleoclimatic model/data comparisons.

29

1 **TABLE**2 **Table 15.1:** Potential tipping elements (adapted from Kopp et al. 2016).

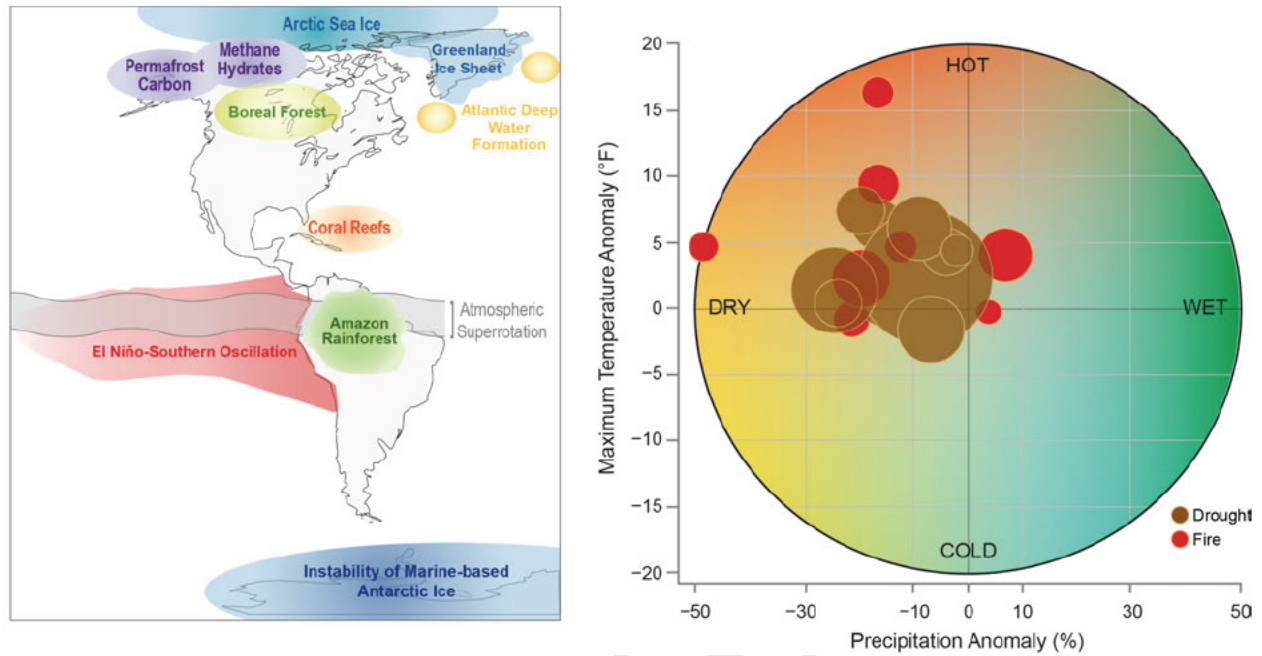
Candidate Climatic Tipping Element	State Shift	Main impact pathways
<i>Atmosphere–ocean circulation</i>		
Atlantic meridional overturning circulation	Major reduction in strength	regional temperature and precipitation; global mean temperature; regional sea level
El Niño–Southern Oscillation	Increase in amplitude	regional temperature and precipitation
Equatorial atmospheric superrotation	Initiation	cloud cover; climate sensitivity
Regional North Atlantic Ocean convection	Major reduction in strength	regional temperature and precipitation
<i>Cryosphere</i>		
Antarctic Ice Sheet	Major decrease in ice volume	sea level; albedo; freshwater forcing on ocean circulation
Arctic sea ice	Major decrease in summertime and/or perennial area	regional temperature and precipitation; albedo
Greenland Ice Sheet	Major decrease in ice volume	sea level; albedo; freshwater forcing on ocean circulation
<i>Carbon cycle</i>		

Methane hydrates	Massive release of carbon	greenhouse gas emissions
Permafrost carbon	Massive release of carbon	greenhouse gas emissions
<i>Ecosystem</i>		
Amazon rainforest	Dieback, transition to grasslands	greenhouse gas emissions; biodiversity
Boreal forest	Dieback, transition to grasslands	greenhouse gas emissions; albedo; biodiversity
Coral reefs	Die-off	biodiversity

1

1 **FIGURE**

2



3

4 **Figure 15.1:** (left) Potential climatic tipping elements affecting the Americas (Figure source:
 5 adapted from Lenton et al. 2008). (right) Wildfire and drought events from the NOAA Billion
 6 Dollar Weather Events list (1980–2016), and associated temperature and precipitation anomalies.
 7 Dot size scales with the magnitude of impact, as reflected by the cost of the event. These high-
 8 impact events occur preferentially under hot, dry conditions.

9

1 **REFERENCES**

- 2 AghaKouchak, A., L. Cheng, O. Mazdiyasi, and A. Farahmand, 2014: Global warming and
3 changes in risk of concurrent climate extremes: Insights from the 2014 California drought.
4 *Geophysical Research Letters*, **41**, 8847-8852. <http://dx.doi.org/10.1002/2014GL062308>
- 5 Anagnostou, E., E.H. John, K.M. Edgar, G.L. Foster, A. Ridgwell, G.N. Inglis, R.D. Pancost,
6 D.J. Lunt, and P.N. Pearson, 2016: Changing atmospheric CO₂ concentration was the
7 primary driver of early Cenozoic climate. *Nature*, **533**, 380-384.
8 <http://dx.doi.org/10.1038/nature17423>
- 9 Archer, D., 2007: Methane hydrate stability and anthropogenic climate change. *Biogeosciences*,
10 **4**, 521-544. <http://dx.doi.org/10.5194/bg-4-521-2007>
- 11 Armour, K.C., I. Eisenman, E. Blanchard-Wrigglesworth, K.E. McCusker, and C.M. Bitz, 2011:
12 The reversibility of sea ice loss in a state-of-the-art climate model. *Geophysical Research*
13 *Letters*, **38**, L16705. <http://dx.doi.org/10.1029/2011GL048739>
- 14 Asplin, M.G., R. Galley, D.G. Barber, and S. Prinsenberg, 2012: Fracture of summer perennial
15 sea ice by ocean swell as a result of Arctic storms. *Journal of Geophysical Research:*
16 *Oceans*, **117**, C06025. <http://dx.doi.org/10.1029/2011JC007221>
- 17 Bathiany, S., D. Notz, T. Mauritsen, G. Raedel, and V. Brovkin, 2016: On the potential for
18 abrupt Arctic winter sea ice loss. *Journal of Climate*, **29**, 2703-2719.
19 <http://dx.doi.org/10.1175/JCLI-D-15-0466.1>
- 20 Brysse, K., N. Oreskes, J. O'Reilly, and M. Oppenheimer, 2013: Climate change prediction:
21 Erring on the side of least drama? *Global Environmental Change*, **23**, 327-337.
22 <http://dx.doi.org/10.1016/j.gloenvcha.2012.10.008>
- 23 Caballero, R. and M. Huber, 2013: State-dependent climate sensitivity in past warm climates and
24 its implications for future climate projections. *Proceedings of the National Academy of*
25 *Sciences*, **110**, 14162-14167. <http://dx.doi.org/10.1073/pnas.1303365110>
- 26 Cai, W., S. Borlace, M. Lengaigne, P. van Rensch, M. Collins, G. Vecchi, A. Timmermann, A.
27 Santoso, M.J. McPhaden, L. Wu, M.H. England, G. Wang, E. Guilyardi, and F.-F. Jin, 2014:
28 Increasing frequency of extreme El Niño events due to greenhouse warming. *Nature Climate*
29 *Change*, **4**, 111-116. <http://dx.doi.org/10.1038/nclimate2100>
- 30 Cai, W., G. Wang, A. Santoso, M.J. McPhaden, L. Wu, F.-F. Jin, A. Timmermann, M. Collins,
31 G. Vecchi, M. Lengaigne, M.H. England, D. Dommenges, K. Takahashi, and E. Guilyardi,
32 2015: Increased frequency of extreme La Niña events under greenhouse warming. *Nature*
33 *Climate Change*, **5**, 132-137. <http://dx.doi.org/10.1038/nclimate2492>

- 1 Cheng, J., Z. Liu, S. Zhang, W. Liu, L. Dong, P. Liu, and H. Li, 2016: Reduced interdecadal
2 variability of Atlantic Meridional Overturning Circulation under global warming.
3 *Proceedings of the National Academy of Sciences*, **113**, 3175-3178.
4 <http://dx.doi.org/10.1073/pnas.1519827113>
- 5 Clark, P.U., J.D. Shakun, S.A. Marcott, A.C. Mix, M. Eby, S. Kulp, A. Levermann, G.A. Milne,
6 P.L. Pfister, B.D. Santer, D.P. Schrag, S. Solomon, T.F. Stocker, B.H. Strauss, A.J. Weaver,
7 R. Winkelmann, D. Archer, E. Bard, A. Goldner, K. Lambeck, R.T. Pierrehumbert, and G.-
8 K. Plattner, 2016: Consequences of twenty-first-century policy for multi-millennial climate
9 and sea-level change. *Nature Climate Change*, **6**, 360-369.
10 <http://dx.doi.org/10.1038/nclimate2923>
- 11 Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J.
12 Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver, and M. Wehner,
13 2013: Long-term climate change: Projections, commitments and irreversibility. *Climate*
14 *Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth*
15 *Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D.
16 Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and
17 P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New
18 York, NY, USA, 1029–1136. <http://www.climatechange2013.org/report/full-report/>
- 19 Cook, B.I., T.R. Ault, and J.E. Smerdon, 2015: Unprecedented 21st century drought risk in the
20 American Southwest and Central Plains. *Science Advances*, **1**.
21 <http://dx.doi.org/10.1126/sciadv.1400082>
- 22 DeConto, R.M. and D. Pollard, 2016: Contribution of Antarctica to past and future sea-level rise.
23 *Nature*, **531**, 591-597. <http://dx.doi.org/10.1038/nature17145>
- 24 Diffenbaugh, N.S. and F. Giorgi, 2012: Climate change hotspots in the CMIP5 global climate
25 model ensemble. *Climatic Change*, **114**, 813-822. [http://dx.doi.org/10.1007/s10584-012-](http://dx.doi.org/10.1007/s10584-012-0570-x)
26 [0570-x](http://dx.doi.org/10.1007/s10584-012-0570-x)
- 27 Ding, Q., A. Schweiger, M. Lheureux, D.S. Battisti, S. Po-Chedley, N.C. Johnson, E. Blanchard-
28 Wrigglesworth, K. Harnos, Q. Zhang, R. Eastman, and E.J. Steig, 2017: Influence of high-
29 latitude atmospheric circulation changes on summertime Arctic sea ice. *Nature Climate*
30 *Change*, **7**, 289-295. <http://dx.doi.org/10.1038/nclimate3241>
- 31 Drijfhout, S., G.J.v. Oldenborgh, and A. Cimadoribus, 2012: Is a decline of AMOC causing the
32 warming hole above the North Atlantic in observed and modeled warming patterns? *Journal*
33 *of Climate*, **25**, 8373-8379. <http://dx.doi.org/10.1175/jcli-d-12-00490.1>

- 1 Eisenman, I. and J.S. Wettlaufer, 2009: Nonlinear threshold behavior during the loss of Arctic
2 sea ice. *Proceedings of the National Academy of Sciences*, **106**, 28-32.
3 <http://dx.doi.org/10.1073/pnas.0806887106>
- 4 Farman, J.C., B.G. Gardiner, and J.D. Shanklin, 1985: Large losses of total ozone in Antarctica
5 reveal seasonal ClO_x/NO_x interaction. *Nature*, **315**, 207-210.
6 <http://dx.doi.org/10.1038/315207a0>
- 7 Flato, G., J. Marotzke, B. Abiodun, P. Braconnot, S.C. Chou, W. Collins, P. Cox, F. Driouech, S.
8 Emori, V. Eyring, C. Forest, P. Gleckler, E. Guilyardi, C. Jakob, V. Kattsov, C. Reason, and
9 M. Rummukainen, 2013: Evaluation of climate models. *Climate Change 2013: The Physical
10 Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the
11 Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M.
12 Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds.
13 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 741–
14 866. <http://www.climatechange2013.org/report/full-report/>
- 15 Folke, C., Carpenter, S., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L., & Holling, C. S.
16 (2004). Regime shifts, resilience, and biodiversity in ecosystem management. *Annu. Rev.
17 Ecol. Evol. Syst.*, **35**, 557-581.
- 18 Foster, G.L., C.H. Lear, and J.W.B. Rae, 2012: The evolution of pCO₂, ice volume and climate
19 during the middle Miocene. *Earth and Planetary Science Letters*, **341–344**, 243-254.
20 <http://dx.doi.org/10.1016/j.epsl.2012.06.007>
- 21 Fraser, E.D.G., E. Simelton, M. Termansen, S.N. Gosling, and A. South, 2013: “Vulnerability
22 hotspots”: Integrating socio-economic and hydrological models to identify where cereal
23 production may decline in the future due to climate change induced drought. *Agricultural
24 and Forest Meteorology*, **170**, 195-205. <http://dx.doi.org/10.1016/j.agrformet.2012.04.008>
- 25 Fretwell, P., H.D. Pritchard, D.G. Vaughan, J.L. Bamber, N.E. Barrand, R. Bell, C. Bianchi,
26 R.G. Bingham, D.D. Blankenship, G. Casassa, G. Catania, D. Callens, H. Conway, A.J.
27 Cook, H.F.J. Corr, D. Damaske, V. Damm, F. Ferraccioli, R. Forsberg, S. Fujita, Y. Gim, P.
28 Gogineni, J.A. Griggs, R.C.A. Hindmarsh, P. Holmlund, J.W. Holt, R.W. Jacobel, A.
29 Jenkins, W. Jokat, T. Jordan, E.C. King, J. Kohler, W. Krabill, M. Riger-Kusk, K.A.
30 Langley, G. Leitchenkov, C. Leuschen, B.P. Luyendyk, K. Matsuoka, J. Mouginot, F.O.
31 Nitsche, Y. Nogi, O.A. Nost, S.V. Popov, E. Rignot, D.M. Rippin, A. Rivera, J. Roberts, N.
32 Ross, M.J. Siegert, A.M. Smith, D. Steinhage, M. Studinger, B. Sun, B.K. Tinto, B.C. Welch,
33 D. Wilson, D.A. Young, C. Xiangbin, and A. Zirizzotti, 2013: Bedmap2: Improved ice bed,
34 surface and thickness datasets for Antarctica. *The Cryosphere*, **7**, 375-393.
35 <http://dx.doi.org/10.5194/tc-7-375-2013>

- 1 Friedrich, T., A. Timmermann, M. Tigchelaar, O. Elison Timm, and A. Ganopolski, 2016:
2 Nonlinear climate sensitivity and its implications for future greenhouse warming. *Science*
3 *Advances*, **2**. <http://dx.doi.org/10.1126/sciadv.1501923>
- 4 Goldner, A., N. Herold, and M. Huber, 2014: The challenge of simulating the warmth of the
5 mid-Miocene climatic optimum in CESM1. *Climate of the Past*, **10**, 523-536.
6 <http://dx.doi.org/10.5194/cp-10-523-2014>
- 7 Gomez, N., J.X. Mitrovica, P. Huybers, and P.U. Clark, 2010: Sea level as a stabilizing factor for
8 marine-ice-sheet grounding lines. *Nature Geoscience*, **3**, 850-853.
9 <http://dx.doi.org/10.1038/ngeo1012>
- 10 Gregory, J.M. and J.A. Lowe, 2000: Predictions of global and regional sea-level rise using
11 AOGCMs with and without flux adjustment. *Geophysical Research Letters*, **27**, 3069-3072.
12 <http://dx.doi.org/10.1029/1999GL011228>
- 13 Hansen, J., M. Sato, P. Hearty, R. Ruedy, M. Kelley, V. Masson-Delmotte, G. Russell, G.
14 Tselioudis, J. Cao, E. Rignot, I. Velicogna, B. Tormey, B. Donovan, E. Kandiano, K.
15 von Schuckmann, P. Kharecha, A.N. Legrande, M. Bauer, and K.W. Lo, 2016: Ice melt, sea
16 level rise and superstorms: Evidence from paleoclimate data, climate modeling, and modern
17 observations that 2°C global warming could be dangerous. *Atmospheric Chemistry and*
18 *Physics*, **16**, 3761-3812. <http://dx.doi.org/10.5194/acp-16-3761-2016>
- 19 Hao, Z., A. AghaKouchak, and T.J. Phillips, 2013: Changes in concurrent monthly precipitation
20 and temperature extremes. *Environmental Research Letters*, **8**, 034014.
21 <http://dx.doi.org/10.1088/1748-9326/8/3/034014>
- 22 Hollesen, J., H. Matthiesen, A.B. Møller, and B. Elberling, 2015: Permafrost thawing in organic
23 Arctic soils accelerated by ground heat production. *Nature Climate Change*, **5**, 574-578.
24 <http://dx.doi.org/10.1038/nclimate2590>
- 25 Hoegh-Guldberg, O., P.J. Mumby, A.J. Hooten, R.S. Steneck, P. Greenfield, E. Gomez, C.D.
26 Harvell, P.F. Sale, A.J. Edwards, K. Caldeira, N. Knowlton, C.M. Eakin, R. Iglesias-Prieto,
27 N. Muthiga, R.H. Bradbury, A. Dubi, and M.E. Hatzioios, 2007: Coral reefs under rapid
28 climate change and ocean acidification. *Science*, **318**, 1737-1742.
29 <http://dx.doi.org/10.1126/science.1152509>
- 30 Huber, M. and R. Caballero, 2011: The early Eocene equable climate problem revisited. *Climate*
31 *of the Past*, **7**, 603-633. <http://dx.doi.org/10.5194/cp-7-603-2011>
- 32 IPCC, 2007: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group*
33 *I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.*
34 Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L.
35 Miller, Eds. Cambridge University Press, Cambridge. U.K, New York, NY, USA, 996 pp.

- 1 www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1_repor
2 t_the_physical_science_basis.htm
- 3 IPCC, 2012: Managing the Risks of Extreme Events and Disasters to Advance Climate Change
4 Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on
5 Climate Change. Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D.
6 Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (Eds.).
7 Cambridge University Press, Cambridge, UK and New York, NY. 582 pp. [http://ipcc-
wg2.gov/SREX/images/uploads/SREX-All_FINAL.pdf](http://ipcc-
8 wg2.gov/SREX/images/uploads/SREX-All_FINAL.pdf)
- 9 IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group
10 I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.*
11 Cambridge University Press, Cambridge, UK and New York, NY, 1535 pp.
12 <http://www.climatechange2013.org/report/>
- 13 Jackson, L.C., R. Kahana, T. Graham, M.A. Ringer, T. Woollings, J.V. Mecking, and R.A.
14 Wood, 2015: Global and European climate impacts of a slowdown of the AMOC in a high
15 resolution GCM. *Climate Dynamics*, **45**, 3299-3316. [http://dx.doi.org/10.1007/s00382-015-
2540-2](http://dx.doi.org/10.1007/s00382-015-
16 2540-2)
- 17 Jakob, M. and J. Hilaire, 2015: Climate science: Unburnable fossil-fuel reserves. *Nature*, **517**,
18 150-152. <http://dx.doi.org/10.1038/517150a>
- 19 Jones, C., J. Lowe, S. Liddicoat, and R. Betts, 2009: Committed terrestrial ecosystem changes
20 due to climate change. *Nature Geoscience*, **2**, 484-487. <http://dx.doi.org/10.1038/ngeo555>
- 21 Joughin, I., B.E. Smith, and B. Medley, 2014: Marine ice sheet collapse potentially under way
22 for the Thwaites Glacier Basin, West Antarctica. *Science*, **344**, 735-738.
23 <http://dx.doi.org/10.1126/science.1249055>
- 24 Kang, I.-S., Y.-M. Yang, and W.-K. Tao, 2015: GCMs with implicit and explicit representation
25 of cloud microphysics for simulation of extreme precipitation frequency. *Climate Dynamics*,
26 **45**, 325-335. <http://dx.doi.org/10.1007/s00382-014-2376-1>
- 27 Koenig, S.J., R.M. DeConto, and D. Pollard, 2014: Impact of reduced Arctic sea ice on
28 Greenland ice sheet variability in a warmer than present climate. *Geophysical Research
29 Letters*, **41**, 3933-3942. <http://dx.doi.org/10.1002/2014GL059770>
- 30 Kopp, R.E., R.L. Shwom, G. Wagner, and J. Yuan, 2016: Tipping elements and climate–
31 economic shocks: Pathways toward integrated assessment. *Earth's Future*, **4**, 346-372.
32 <http://dx.doi.org/10.1002/2016EF000362>
- 33 Kort, E.A., S.C. Wofsy, B.C. Daube, M. Diao, J.W. Elkins, R.S. Gao, E.J. Hints, D.F. Hurst, R.
34 Jimenez, F.L. Moore, J.R. Spackman, and M.A. Zondlo, 2012: Atmospheric observations of

- 1 Arctic Ocean methane emissions up to 82° north. *Nature Geoscience*, **5**, 318-321.
2 <http://dx.doi.org/10.1038/ngeo1452>
- 3 Kretschmer, K., A. Biastoch, L. Rüpke, and E. Burwicz, 2015: Modeling the fate of methane
4 hydrates under global warming. *Global Biogeochemical Cycles*, **29**, 610-625.
5 <http://dx.doi.org/10.1002/2014GB005011>
- 6 Kvenvolden, K.A., 1988: Methane hydrate — A major reservoir of carbon in the shallow
7 geosphere? *Chemical Geology*, **71**, 41-51. [http://dx.doi.org/10.1016/0009-2541\(88\)90104-0](http://dx.doi.org/10.1016/0009-2541(88)90104-0)
- 8 LaRiviere, J.P., A.C. Ravelo, A. Crimmins, P.S. Dekens, H.L. Ford, M. Lyle, and M.W. Wara,
9 2012: Late Miocene decoupling of oceanic warmth and atmospheric carbon dioxide forcing.
10 *Nature*, **486**, 97-100. <http://dx.doi.org/10.1038/nature11200>
- 11 Lee, S.-Y. and G.D. Holder, 2001: Methane hydrates potential as a future energy source. *Fuel*
12 *Processing Technology*, **71**, 181-186. [http://dx.doi.org/10.1016/S0378-3820\(01\)00145-X](http://dx.doi.org/10.1016/S0378-3820(01)00145-X)
- 13 Lenton, T.M., H. Held, E. Kriegler, J.W. Hall, W. Lucht, S. Rahmstorf, and H.J. Schellnhuber,
14 2008: Tipping elements in the Earth's climate system. *Proceedings of the National Academy*
15 *of Sciences*, **105**, 1786-1793. <http://dx.doi.org/10.1073/pnas.0705414105>
- 16 Levermann, A., A. Griesel, M. Hofmann, M. Montoya, and S. Rahmstorf, 2005: Dynamic sea
17 level changes following changes in the thermohaline circulation. *Climate Dynamics*, **24**, 347-
18 354. <http://dx.doi.org/10.1007/s00382-004-0505-y>
- 19 Levermann, A., P.U. Clark, B. Marzeion, G.A. Milne, D. Pollard, V. Radic, and A. Robinson,
20 2013: The multimillennial sea-level commitment of global warming. *Proceedings of the*
21 *National Academy of Sciences*, **110**, 13745-13750.
22 <http://dx.doi.org/10.1073/pnas.1219414110>
- 23 Li, C., D. Notz, S. Tietsche, and J. Marotzke, 2013: The transient versus the equilibrium
24 response of sea ice to global warming. *Journal of Climate*, **26**, 5624-5636.
25 <http://dx.doi.org/10.1175/JCLI-D-12-00492.1>
- 26 Lindsay, R.W. and J. Zhang, 2005: The thinning of Arctic sea ice, 1988–2003: Have we passed a
27 tipping point? *Journal of Climate*, **18**, 4879-4894. <http://dx.doi.org/10.1175/jcli3587.1>
- 28 Liu, J., Z. Chen, J. Francis, M. Song, T. Mote, and Y. Hu, 2016: Has Arctic sea ice loss
29 contributed to increased surface melting of the Greenland Ice Sheet? *Journal of Climate*, **29**,
30 3373-3386. <http://dx.doi.org/10.1175/JCLI-D-15-0391.1>
- 31 Liu, W., S.-P. Xie, Z. Liu, and J. Zhu, 2017: Overlooked possibility of a collapsed Atlantic
32 Meridional Overturning Circulation in warming climate. *Science Advances*, **3**.
33 <http://dx.doi.org/10.1126/sciadv.1601666>

- 1 Lunt, D.J., T. Dunkley Jones, M. Heinemann, M. Huber, A. LeGrande, A. Winguth, C. Loptson,
2 J. Marotzke, C.D. Roberts, J. Tindall, P. Valdes, and C. Winguth, 2012: A model–data
3 comparison for a multi-model ensemble of early Eocene atmosphere–ocean simulations:
4 EoMIP. *Climate of the Past*, **8**, 1717-1736. <http://dx.doi.org/10.5194/cp-8-1717-2012>
- 5 MacDougall, A.H., C.A. Avis, and A.J. Weaver, 2012: Significant contribution to climate
6 warming from the permafrost carbon feedback. *Nature Geoscience*, **5**, 719-721.
7 <http://dx.doi.org/10.1038/ngeo1573>
- 8 MacDougall, A.H., K. Zickfeld, R. Knutti, and H.D. Matthews, 2015: Sensitivity of carbon
9 budgets to permafrost carbon feedbacks and non-CO₂ forcings. *Environmental Research*
10 *Letters*, **10**, 125003. <http://dx.doi.org/10.1088/1748-9326/10/12/125003>
- 11 McGlade, C. and P. Ekins, 2015: The geographical distribution of fossil fuels unused when
12 limiting global warming to 2°C. *Nature*, **517**, 187-190. <http://dx.doi.org/10.1038/nature14016>
- 13 Meehl, G.A., T.F. Stocker, W.D. Collins, P. Friedlingstein, A.T. Gaye, J.M. Gregory, A. Kitoh,
14 R. Knutti, J.M. Murphy, A. Noda, S.C.B. Raper, I.G. Watterson, A.J. Weaver, and Z.-C.
15 Zhao, 2007: Global Climate Projections. *Climate Change 2007: The Physical Science Basis.*
16 *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental*
17 *Panel on Climate Change*. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B.
18 Averyt, M. Tignor, and H.L. Miller, Eds. Cambridge University Press, Cambridge, United
19 Kingdom and New York, NY, USA, 747-845.
- 20 Mengel, M. and A. Levermann, 2014: Ice plug prevents irreversible discharge from East
21 Antarctica. *Nature Climate Change*, **4**, 451-455. <http://dx.doi.org/10.1038/nclimate2226>
- 22 Molina, M.J. and F.S. Rowland, 1974: Stratospheric sink for chlorofluoromethanes: Chlorine
23 atom-catalysed destruction of ozone. *Nature*, **249**, 810-812.
24 <http://dx.doi.org/10.1038/249810a0>
- 25 Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestedt, J. Huang, D. Koch, J.-F.
26 Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura, and H.
27 Zhang, 2013: Anthropogenic and natural radiative forcing. *Climate Change 2013: The*
28 *Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of*
29 *the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M.
30 Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds.
31 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 659–
32 740. <http://www.climatechange2013.org/report/full-report/>
- 33 Myhre, C.L., B. Ferré, S.M. Platt, A. Silyakova, O. Hermansen, G. Allen, I. Pizzo, N.
34 Schmidbauer, A. Stohl, J. Pitt, P. Jansson, J. Greinert, C. Percival, A.M. Fjaeraa, S.J. O'Shea,
35 M. Gallagher, M. Le Breton, K.N. Bower, S.J.B. Bauguitte, S. Dalsøren, S.

- 1 Vadakkepuliambatta, R.E. Fisher, E.G. Nisbet, D. Lowry, G. Myhre, J.A. Pyle, M. Cain,
2 and J. Mienert, 2016: Extensive release of methane from Arctic seabed west of Svalbard
3 during summer 2014 does not influence the atmosphere. *Geophysical Research Letters*, **43**,
4 4624-4631. <http://dx.doi.org/10.1002/2016GL068999>
- 5 Navarro, T., J.B. Madeleine, F. Forget, A. Spiga, E. Millour, F. Montmessin, and A. Määttänen,
6 2014: Global climate modeling of the Martian water cycle with improved microphysics and
7 radiatively active water ice clouds. *Journal of Geophysical Research: Planets*, **119**, 1479-
8 1495. <http://dx.doi.org/10.1002/2013JE004550>
- 9 NRC, 2013: *Abrupt Impacts of Climate Change: Anticipating Surprises*. The National
10 Academies Press, Washington, DC, 222 pp. <http://dx.doi.org/10.17226/18373>
- 11 Pérez, F.F., H. Mercier, M. Vazquez-Rodriguez, P. Lherminier, A. Velo, P.C. Pardo, G. Roson,
12 and A.F. Rios, 2013: Atlantic Ocean CO₂ uptake reduced by weakening of the meridional
13 overturning circulation. *Nature Geoscience*, **6**, 146-152. <http://dx.doi.org/10.1038/ngeo1680>
- 14 Perovich, D.K., J.A. Richter-Menge, K.F. Jones, and B. Light, 2008: Sunlight, water, and ice:
15 Extreme Arctic sea ice melt during the summer of 2007. *Geophysical Research Letters*, **35**,
16 L11501. <http://dx.doi.org/10.1029/2008GL034007>
- 17 Piñero, E., M. Marquardt, C. Hensen, M. Haeckel, and K. Wallmann, 2013: Estimation of the
18 global inventory of methane hydrates in marine sediments using transfer functions.
19 *Biogeosciences*, **10**, 959-975. <http://dx.doi.org/10.5194/bg-10-959-2013>
- 20 Pollard, D., R.M. DeConto, and R.B. Alley, 2015: Potential Antarctic Ice Sheet retreat driven by
21 hydrofracturing and ice cliff failure. *Earth and Planetary Science Letters*, **412**, 112-121.
22 <http://dx.doi.org/10.1016/j.epsl.2014.12.035>
- 23 Quarantelli, E.L., 1986: *Disaster Crisis Management*. 113. University of Delaware, Newark, DE.
24 10 pp. <http://udspace.udel.edu/handle/19716/487>
- 25 Rahmstorf, S., J.E. Box, G. Feulner, M.E. Mann, A. Robinson, S. Rutherford, and E.J.
26 Schaffernicht, 2015: Exceptional twentieth-century slowdown in Atlantic Ocean overturning
27 circulation. *Nature Climate Change*, **5**, 475-480. <http://dx.doi.org/10.1038/nclimate2554>
- 28 Reed, A.J., M.E. Mann, K.A. Emanuel, N. Lin, B.P. Horton, A.C. Kemp, and J.P. Donnelly,
29 2015: Increased threat of tropical cyclones and coastal flooding to New York City during the
30 anthropogenic era. *Proceedings of the National Academy of Sciences*, **112**, 12610-12615.
31 <http://dx.doi.org/10.1073/pnas.1513127112>
- 32 Ridley, J., J.M. Gregory, P. Huybrechts, and J. Lowe, 2010: Thresholds for irreversible decline
33 of the Greenland ice sheet. *Climate Dynamics*, **35**, 1049-1057.
34 <http://dx.doi.org/10.1007/s00382-009-0646-0>

- 1 Ridley, J.K., J.A. Lowe, and H.T. Hewitt, 2012: How reversible is sea ice loss? *The Cryosphere*,
2 **6**, 193-198. <http://dx.doi.org/10.5194/tc-6-193-2012>
- 3 Rignot, E., J. Mouginot, M. Morlighem, H. Seroussi, and B. Scheuchl, 2014: Widespread, rapid
4 grounding line retreat of Pine Island, Thwaites, Smith, and Kohler Glaciers, West Antarctica,
5 from 1992 to 2011. *Geophysical Research Letters*, **41**, 3502-3509.
6 <http://dx.doi.org/10.1002/2014GL060140>
- 7 Ritz, C., T.L. Edwards, G. Durand, A.J. Payne, V. Peyaud, and R.C.A. Hindmarsh, 2015:
8 Potential sea-level rise from Antarctic ice-sheet instability constrained by observations.
9 *Nature*, **528**, 115-118. <http://dx.doi.org/10.1038/nature16147>
- 10 Robinson, A., R. Calov, and A. Ganopolski, 2012: Multistability and critical thresholds of the
11 Greenland ice sheet. *Nature Climate Change*, **2**, 429-432.
12 <http://dx.doi.org/10.1038/nclimate1449>
- 13 Ruppel, C.D. *Methane hydrates and contemporary climate change*. Nature Education
14 Knowledge, 2011. **3**.
- 15 Ruppel, C.D. and J.D. Kessler, 2017: The interaction of climate change and methane hydrates.
16 *Reviews of Geophysics*, **55**, 126-168. <http://dx.doi.org/10.1002/2016RG000534>
- 17 Salzmann, U., A.M. Dolan, A.M. Haywood, W.-L. Chan, J. Voss, D.J. Hill, A. Abe-Ouchi, B.
18 Otto-Bliesner, F.J. Bragg, M.A. Chandler, C. Contoux, H.J. Dowsett, A. Jost, Y. Kamae, G.
19 Lohmann, D.J. Lunt, S.J. Pickering, M.J. Pound, G. Ramstein, N.A. Rosenbloom, L. Sohl, C.
20 Stepanek, H. Ueda, and Z. Zhang, 2013: Challenges in quantifying Pliocene terrestrial
21 warming revealed by data-model discord. *Nature Climate Change*, **3**, 969-974.
22 <http://dx.doi.org/10.1038/nclimate2008>
- 23 Scheffer, M., Carpenter, S., Foley, J. A., Folke, C., & Walker, B. (2001). Catastrophic shifts in
24 ecosystems. *Nature*, **413**(6856), 591-596.
- 25 Schoof, C., 2007: Ice sheet grounding line dynamics: Steady states, stability, and hysteresis.
26 *Journal of Geophysical Research*, **112**, F03S28. <http://dx.doi.org/10.1029/2006JF000664>
- 27 Schröder, D., D.L. Feltham, D. Flocco, and M. Tsamados, 2014: September Arctic sea-ice
28 minimum predicted by spring melt-pond fraction. *Nature Climate Change*, **4**, 353-357.
29 <http://dx.doi.org/10.1038/nclimate2203>
- 30 Schuur, E.A.G., A.D. McGuire, C. Schadel, G. Grosse, J.W. Harden, D.J. Hayes, G. Hugelius,
31 C.D. Koven, P. Kuhry, D.M. Lawrence, S.M. Natali, D. Olefeldt, V.E. Romanovsky, K.
32 Schaefer, M.R. Turetsky, C.C. Treat, and J.E. Vonk, 2015: Climate change and the
33 permafrost carbon feedback. *Nature*, **520**, 171-179. <http://dx.doi.org/10.1038/nature14338>

- 1 Serinaldi, F., 2016: Can we tell more than we can know? The limits of bivariate drought analyses
2 in the United States. *Stochastic Environmental Research and Risk Assessment*, **30**, 1691-
3 1704. <http://dx.doi.org/10.1007/s00477-015-1124-3>
- 4 Smith, J.A., 1987: Estimating the upper tail of flood frequency distributions. *Water Resources*
5 *Research*, **23**, 1657-1666. <http://dx.doi.org/10.1029/WR023i008p01657>
- 6 Stranne, C., M. O'Regan, G.R. Dickens, P. Crill, C. Miller, P. Preto, and M. Jakobsson, 2016:
7 Dynamic simulations of potential methane release from East Siberian continental slope
8 sediments. *Geochemistry, Geophysics, Geosystems*, **17**, 872-886.
9 <http://dx.doi.org/10.1002/2015GC006119>
- 10 Stroeve, J., M.M. Holland, W. Meier, T. Scambos, and M. Serreze, 2007: Arctic sea ice decline:
11 Faster than forecast. *Geophysical Research Letters*, **34**, L09501.
12 <http://dx.doi.org/10.1029/2007GL029703>
- 13 Stroeve, J.C., V. Kattsov, A. Barrett, M. Serreze, T. Pavlova, M. Holland, and W.N. Meier,
14 2012: Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations. *Geophysical*
15 *Research Letters*, **39**, L16502. <http://dx.doi.org/10.1029/2012GL052676>
- 16 Swain, D.L., D.E. Horton, D. Singh, and N.S. Diffenbaugh, 2016: Trends in atmospheric patterns
17 conducive to seasonal precipitation and temperature extremes in California. *Science*
18 *Advances*, **2**. <http://dx.doi.org/10.1126/sciadv.1501344>
- 19 Tattersall, I., 2009: Human origins: Out of Africa. *Proceedings of the National Academy of*
20 *Sciences*, **106**, 16018-16021. <http://dx.doi.org/10.1073/pnas.0903207106>
- 21 Trenberth, K.E., A. Dai, G. van der Schrier, P.D. Jones, J. Barichivich, K.R. Briffa, and J.
22 Sheffield, 2014: Global warming and changes in drought. *Nature Climate Change*, **4**, 17-22.
23 <http://dx.doi.org/10.1038/nclimate2067>
- 24 von der Heydt, A.S., P. Köhler, R.S.W. van de Wal, and H.A. Dijkstra, 2014: On the state
25 dependency of fast feedback processes in (paleo) climate sensitivity. *Geophysical Research*
26 *Letters*, **41**, 6484-6492. <http://dx.doi.org/10.1002/2014GL061121>
- 27 Wagner, T.J.W. and I. Eisenman, 2015: How climate model complexity influences sea ice
28 stability. *Journal of Climate*, **28**, 3998-4014. <http://dx.doi.org/10.1175/JCLI-D-14-00654.1>
- 29 Woodhouse, C.A. and J.T. Overpeck, 1998: 2000 years of drought variability in the central
30 United States. *Bulletin of the American Meteorological Society*, **79**, 2693-2714.
31 [http://dx.doi.org/10.1175/1520-0477\(1998\)079<2693:YODVIT>2.0.CO;2](http://dx.doi.org/10.1175/1520-0477(1998)079<2693:YODVIT>2.0.CO;2)

- 1 Yin, J. and P.B. Goddard, 2013: Oceanic control of sea level rise patterns along the East Coast of
2 the United States. *Geophysical Research Letters*, **40**, 5514-5520.
3 <http://dx.doi.org/10.1002/2013GL057992>
- 4 Zscheischler, J., M. Reichstein, J. von Buttlar, M. Mu, J.T. Randerson, and M.D. Mahecha, 2014:
5 Carbon cycle extremes during the 21st century in CMIP5 models: Future evolution and
6 attribution to climatic drivers. *Geophysical Research Letters*, **41**, 8853-8861.
7 <http://dx.doi.org/10.1002/2014GL062409>
- 8 Zwiers, F.W., L.V. Alexander, G.C. Hegerl, T.R. Knutson, J.P. Kossin, P. Naveau, N. Nicholls,
9 C. Schär, S.I. Seneviratne, and X. Zhang, 2013: Climate extremes: Challenges in estimating
10 and understanding recent changes in the frequency and intensity of extreme climate and
11 weather events. *Climate Science for Serving Society: Research, Modeling and Prediction*
12 *Priorities*. Asrar, G.R. and J.W. Hurrell, Eds. Springer Netherlands, Dordrecht, 339-389.
13 http://dx.doi.org/10.1007/978-94-007-6692-1_13

1 **Appendix A. Observational Datasets Used in Climate Studies**

2 **Climate Datasets**

3 Observations, including those from satellites, mobile platforms, field campaigns and ground-
4 based networks, provide the basis of knowledge on many temporal and spatial scales for
5 understanding the changes occurring in Earth's climate system. These observations also inform
6 the development, calibration, and evaluation of numerical models of the physics, chemistry, and
7 biology being used in analyzing the past changes in climate and for making future projections.
8 As all observational data collected by support from Federal agencies are required to be made
9 available free of charge with machine readable metadata, everyone can access these products for
10 their personal analysis and research and for informing decisions. Many of these datasets are
11 accessible through web services.

12 Many long-running observations worldwide have provided us with long-term records necessary
13 for investigating climate change and its impacts. These include important climate variables such
14 as surface temperature, sea ice extent, sea level rise, and streamflow. Perhaps one of the most
15 iconic climatic datasets, that of atmospheric carbon dioxide measured at Mauna Loa, HI, has
16 been recorded since the 1950s. The U.S. and Global Historical Climatology Networks have been
17 used as authoritative sources of recorded surface temperature increases, with some stations
18 having continuous records going back many decades. Satellite radar altimetry data (for example,
19 TOPEX/JASON1, 2 satellite data) have informed the development of the University of
20 Colorado's 20+ year record of global sea level changes. In the United States, the USGS (U.S.
21 Geological Survey) National Water Information System contains, in some instances, decades of
22 daily streamflow records which inform not only climate but land-use studies as well. The U.S.
23 Bureau of Reclamation and U.S. Army Corp of Engineers have maintained data about reservoir
24 levels for decades where applicable. Of course, datasets based on shorter-term observations are
25 used in conjunction with longer-term records for climate study, and the U.S. programs are aimed
26 at providing continuous data records. Methods have been developed and applied to process these
27 data so as to account for biases, collection method, earth surface geometry, the urban heat island
28 effect, station relocations, and uncertainty (e.g., see Vose et al. 2012; Rennie et al. 2014; Karl et
29 al. 2015).

30 Even observations not designed for climate have informed climate research. These include ship
31 logs containing descriptions of ice extent, readings of temperature and precipitation provided in
32 newspapers, and harvest records. Today, observations recorded both manually and in automated
33 fashions inform research and are used in climate studies.

34 The U.S Global Change Research Program (USGCRP) has established the Global Change
35 Information System (GCIS) to better coordinate and integrate the use of federal information
36 products on changes in the global environment and the implications of those changes for society.
37 The GCIS is an open-source, web-based resource for traceable global change data, information,

1 and products. Designed for use by scientists, decision makers, and the public, the GCIS provides
2 coordinated links to a select group of information products produced, maintained, and
3 disseminated by government agencies and organizations. Currently the GCIS is aimed at the
4 datasets used in Third National Climate Assessment (NCA3) and the USGCRP Climate and
5 Health Assessment. It is to be updated for the datasets used in this report (The Climate Science
6 Special Report, CSSR).

7 **Satellite Temperature Datasets**

8 A special look is given to the satellite temperature datasets because of controversies associated
9 with these datasets. Satellite-borne microwave sounders such as the Microwave Sounding Unit
10 (MSU) and Advanced Microwave Sounding Unit (AMSU) instruments operating on NOAA
11 polar-orbiting platforms make measurements of the temperature of thick layers of the atmosphere
12 with near global coverage. Because the long-term data record requires the piecing together of
13 measurements made by 16 different satellites, accurate instrument intercalibration is of critical
14 importance. Over the mission lifetime of most satellites, the instruments drift in both calibration
15 and local measurement time. Adjustments to counter the effects of these drifts need to be
16 developed and applied before a long-term record can be assembled. For tropospheric
17 measurements, the most challenging of these adjustments is the adjustment for drifting
18 measurement time, which requires knowledge of the diurnal cycle in both atmospheric and
19 surface temperature. Current versions of the sounder-based datasets account for the diurnal cycle
20 by either using diurnal cycles deduced from model output (Mears and Wentz 2009; Zou et al.
21 2009) or by attempting to derive the diurnal cycle from the satellite measurements themselves
22 (an approach plagued by sampling issues and possible calibration drifts) (Christy et al. 2003; Po-
23 Chedley et al. 2015). Recently a hybrid approach has been developed, RSS Version 4.0 (Mears
24 and Wentz 2016), that results in an increased warming signal relative to the other approaches,
25 particularly since 2000. Each of these methods has strengths and weaknesses, but neither has
26 sufficient accuracy to construct an unassailable long-term record of atmospheric temperature
27 change. The resulting datasets show a greater spread in decadal-scale trends than do the surface
28 temperature datasets for the same period, suggesting that they may be less reliable. In Figure A.1
29 shows annual time series for the global mean tropospheric temperature for some recent versions
30 of the satellite datasets. These data have been adjusted to remove the influence of stratospheric
31 cooling (Fu and Johanson 2005). Linear trend values are shown in Table A.1.

32 **[INSERT FIGURE A.1 AND TABLE A.1 HERE]**

33

1 **TABLE**

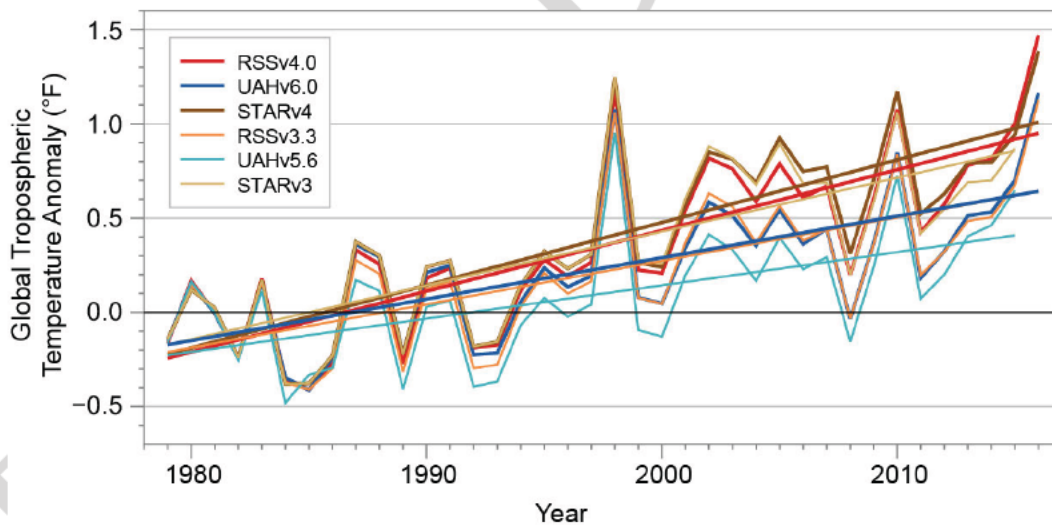
2 **Table A.1.** Global Trends in Temperature Total Troposphere (TTT) since 1979 and 2000 (in °F
 3 per decade).

Dataset	Trend (1979–2015) (°F/Decade)	Trend (2000–2015) (°F/Decade)
RSS V4.0	0.301	0.198
UAH V6Beta5	0.196	0.141
STAR V4.0	0.316	0.157
RSS V3.3	0.208	0.105
UAH V5.6	0.176	0.211
STAR V3.0	0.286	0.061

4

5 **FIGURE**

6



7

8

9 **Figure A.1.** Annual global (80°S–80°N) mean time series of tropospheric temperature for five
 10 recent datasets (see below). Each time series is adjusted so the mean value for the first three
 11 years is zero. This accentuates the differences in the long-term changes between the datasets.
 12 (Figure source: Remote Sensing Systems).

13

1 DATA SOURCES:

2 All Satellite Data are "Temperature Total Troposphere" time series calculated from TMT and TLS

3 (1.1*TMT) - (0.1*TLS). This combination reduces the effect of the lower stratosphere on the tropospheric
4 temperature. (Fu, Qiang et al. "Contribution of stratospheric cooling to satellite-inferred tropospheric
5 temperature trends." *Nature* 429.6987 (2004): 55-58.)

6 UAH. UAH Version 6.0Beta5. Yearly (yyyy) text files of TMT and TLS are available from

7 http://vortex.nsstc.uah.edu/data/msu/v6.0beta/tmt/tmtmonamg.yyyy_6.0beta5

8 http://vortex.nsstc.uah.edu/data/msu/v6.0beta/tls/tlsmoanmg.yyyy_6.0beta5

9 Downloaded 5/15/2016.

10 UAH. UAH Version 5.6. Yearly (yyyy) text files of TMT and TLS are available from

11 <http://vortex.nsstc.uah.edu/data/msu/t2/>

12 <http://vortex.nsstc.uah.edu/data/msu/t4/>

13 Downloaded 5/15/2016.

14 RSS. RSS Version 4.0. ftp://ftp.remss.com/msu/data/netcdf/RSS_Tb_Anom_Maps_ch_TTT_V4_0.nc

15 Downloaded 5/15/2016

16 RSS. RSS Version 3.3. ftp://ftp.remss.com/msu/data/netcdf/RSS_Tb_Anom_Maps_ch_TTT_V3.3.nc

17 Downloaded 5/15/2016

18 NOAA STAR. Star Version 3.0.

19 ftp://ftp.star.nesdis.noaa.gov/pub/smcd/emb/mscat/data/MSU_AMSU_v3.0/Monthly_Atmospheric_Layer_Mean_Temperature/Merged_Deep-Layer_Temperature/NESDIS-STAR_TCDR_MSU-AMSUA_V03R00_TMT_S197811_E201604_C20160513.nc

22 ftp://ftp.star.nesdis.noaa.gov/pub/smcd/emb/mscat/data/MSU_AMSU_v3.0/Monthly_Atmospheric_Layer_Mean_Temperature/Merged_Deep-Layer_Temperature/NESDIS-STAR_TCDR_MSU-AMSUA_V03R00_TLS_S197811_E201604_C20160513.nc

25 Downloaded 5/18/2016.

26

1 **REFERENCES**

- 2 Christy, J.R., R.W. Spencer, W.B. Norris, W.D. Braswell, and D.E. Parker, 2003: Error estimates
3 of version 5.0 of MSU–AMSU bulk atmospheric temperatures. *Journal of Atmospheric and*
4 *Oceanic Technology*, **20**, 613-629. [http://dx.doi.org/10.1175/1520-](http://dx.doi.org/10.1175/1520-0426(2003)20<613:EEOVOM>2.0.CO;2)
5 [0426\(2003\)20<613:EEOVOM>2.0.CO;2](http://dx.doi.org/10.1175/1520-0426(2003)20<613:EEOVOM>2.0.CO;2)
- 6 Fu, Q. and C.M. Johanson, 2005: Satellite-derived vertical dependence of tropical tropospheric
7 temperature trends. *Geophysical Research Letters*, **32**.
8 <http://dx.doi.org/10.1029/2004GL022266>
- 9 Karl, T.R., A. Arguez, B. Huang, J.H. Lawrimore, J.R. McMahon, M.J. Menne, T.C. Peterson,
10 R.S. Vose, and H.-M. Zhang, 2015: Possible artifacts of data biases in the recent global
11 surface warming hiatus. *Science*, **348**, 1469-1472. <http://dx.doi.org/10.1126/science.aaa5632>
- 12 Mears, C.A. and F.J. Wentz, 2009: Construction of the Remote Sensing Systems V3.2
13 atmospheric temperature records from the MSU and AMSU microwave sounders. *Journal of*
14 *Atmospheric and Oceanic Technology*, **26**, 1040-1056.
15 <http://dx.doi.org/10.1175/2008JTECHA1176.1>
- 16 Mears, C.A. and F.J. Wentz, 2016: Sensitivity of satellite-derived tropospheric temperature
17 trends to the diurnal cycle adjustment. *Journal of Climate*, **29**, 3629-3646.
18 <http://dx.doi.org/10.1175/JCLI-D-15-0744.1>
- 19 Po-Chedley, S., T.J. Thorsen, and Q. Fu, 2015: Removing diurnal cycle contamination in
20 satellite-derived tropospheric temperatures: Understanding tropical tropospheric trend
21 discrepancies. *Journal of Climate*, **28**, 2274-2290. [http://dx.doi.org/10.1175/JCLI-D-13-](http://dx.doi.org/10.1175/JCLI-D-13-00767.1)
22 [00767.1](http://dx.doi.org/10.1175/JCLI-D-13-00767.1)
- 23 Rennie, J.J., J.H. Lawrimore, B.E. Gleason, P.W. Thorne, C.P. Morice, M.J. Menne, C.N.
24 Williams, W.G. de Almeida, J.R. Christy, M. Flannery, M. Ishihara, K. Kamiguchi, A.M.G.
25 Klein-Tank, A. Mhanda, D.H. Lister, V. Razuvaev, M. Renom, M. Rusticucci, J. Tandy, S.J.
26 Worley, V. Venema, W. Angel, M. Brunet, B. Dattore, H. Diamond, M.A. Lazzara, F. Le
27 Blancq, J. Luterbacher, H. Mächel, J. Revadekar, R.S. Vose, and X. Yin, 2014: The
28 international surface temperature initiative global land surface databank: monthly
29 temperature data release description and methods. *Geoscience Data Journal*, **1**, 75-102.
30 <http://dx.doi.org/10.1002/gdj3.8> <http://dx.doi.org/10.1002/gdj3.8>
- 31 Vose, R.S., D. Arndt, V.F. Banzon, D.R. Easterling, B. Gleason, B. Huang, E. Kearns, J.H.
32 Lawrimore, M.J. Menne, T.C. Peterson, R.W. Reynolds, T.M. Smith, C.N. Williams, and
33 D.L. Wuertz, 2012: NOAA's Merged Land-Ocean Surface Temperature Analysis. *Bulletin of*
34 *the American Meteorological Society*, **93**, 1677-1685. [http://dx.doi.org/10.1175/BAMS-D-](http://dx.doi.org/10.1175/BAMS-D-11-00241.1)
35 [11-00241.1](http://dx.doi.org/10.1175/BAMS-D-11-00241.1)

- 1 Zou, C.-Z., M. Gao, and M.D. Goldberg, 2009: Error structure and atmospheric temperature
- 2 trends in observations from the microwave sounding unit. *Journal of Climate*, **22**, 1661-1681.
- 3 <http://dx.doi.org/10.1175/2008JCLI2233.1>

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1 **Appendix B. Weighting Strategy**

2 **for the Fourth National Climate Assessment**

3 **Introduction**

4 This document briefly describes a weighting strategy for use with the Climate Model
5 Intercomparison Project, Phase 5 (CMIP5) multimodel archive in the 4th National
6 Climate Assessment. This approach considers both skill in the climatological
7 performance of models over North America and the interdependency of models arising
8 from common parameterizations or tuning practices. The method exploits information
9 relating to the climatological mean state of a number of projection-relevant variables as
10 well as long-term metrics representing long-term statistics of weather extremes. The
11 weights, once computed, can be used to simply compute weighted mean and significance
12 information from an ensemble containing multiple initial condition members from co-
13 dependent models of varying skill.

14 Our methodology is based on the concepts outlined in Sanderson et al. (2015), and the
15 specific application to the Fourth National Climate Assessment (NCA4) is also described
16 in that paper. The approach produces a single set of model weights that can be used to
17 combine projections into a weighted mean result, with significance estimates which also
18 treat the weighting appropriately.

19 The method, ideally, would seek to have two fundamental characteristics:

- 20 • If a duplicate of one ensemble member is added to the archive, the resulting mean
21 and significance estimate for future change computed from the ensemble should
22 not change.
- 23 • If a demonstrably unphysical model is added to the archive, the resulting mean
24 and significance estimates should also not change.

25 **Method**

26 The analysis requires an assessment of both model skill and an estimate of intermodel
27 relationships— for which intermodel root mean square difference is taken as a proxy. The
28 model and observational data used here is for the contiguous United States (CONUS),
29 and most of Canada, using high-resolution data where available. Intermodel distances are
30 computed as simple root mean square differences. Data is derived from a number of
31 mean state fields and a number of fields that represent extreme behavior—these are listed
32 in Table B.1. All fields are masked to only include information from CONUS/Canada.

1 The root mean square error (RMSE) between observations and each model can be used to
2 produce an overall ranking for model simulations of the North American climate. Figure
3 B.1 shows how this metric is influenced by different component variables.

4 **[INSERT FIGURES B.1 AND B.2 HERE]**

5 Models are downweighted for poor skill if their multivariate combined error is
6 significantly greater than a “skill radius” term, which is a free parameter of the approach.
7 The calibration of this parameter is determined through a perfect model study (Sanderson
8 et al. 2016b). A pairwise distance matrix is computed to assess intermodel RMSE values
9 for each model pair in the archive, and a model is downweighted for dependency if there
10 exists another model with a pairwise distance to the original model significantly smaller
11 than a “similarity radius.” This is the second parameter of the approach, which is
12 calibrated by considering known relationships within the archive. The resulting skill and
13 independence weights are multiplied to give an overall “combined” weight—illustrated in
14 Figure B.2 for the CMIP5 ensemble and listed in Table B.2.

15 The weights are used in the Climate Science Special Report (CSSR) to produce weighted
16 mean and significance maps of future change, where the following protocol is used:

- 17 • Stippling—large changes, where the weighted multimodel average change is
18 greater than double the standard deviation of the 20-year mean from control
19 simulations runs, and 90% of the weight corresponds to changes of the same sign.
- 20 • Hatching—No significant change, where the weighted multimodel average
21 change is less than the standard deviation of the 20-year means from control
22 simulations runs.
- 23 • Whited out—Inconclusive, where the weighted multimodel average change is
24 greater than double the standard deviation of the 20-year mean from control runs
25 and less than 90% of the weight corresponds to changes of the same sign.

26 We illustrate the application of this method to future projections of precipitation change
27 under RCP8.5 in Figure B.3. The weights used in the report are chosen to be
28 conservative, minimizing the risk of overconfidence and maximizing out-of-sample
29 predictive skill for future projections. This results (as in Figure B.3) in only modest
30 differences in the weighted and unweighted maps. It is shown in Sanderson et al. (2016b)
31 that a more aggressive weighting strategy, or one focused on a particular variable, tends
32 to exhibit a stronger constraint on future change relative to the unweighted case. It is also
33 notable that tradeoffs exist between skill and replication in the archive (evident in Figure
34 B.2), such that the weighting for both skill and uniqueness has a compensating effect. As
35 such, mean projections using the CMIP5 ensemble are not strongly influenced by the
36 weighting. However, the establishment of the weighting strategy used in the CSSR

1 provides some insurance against a potential case in future assessments where there is a
2 highly replicated, but poorly performing model.

3 **[INSERT FIGURE B.3 HERE]**

4

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1 **TABLES**2 **Table B.1: Observational Datasets Used as Observations.**

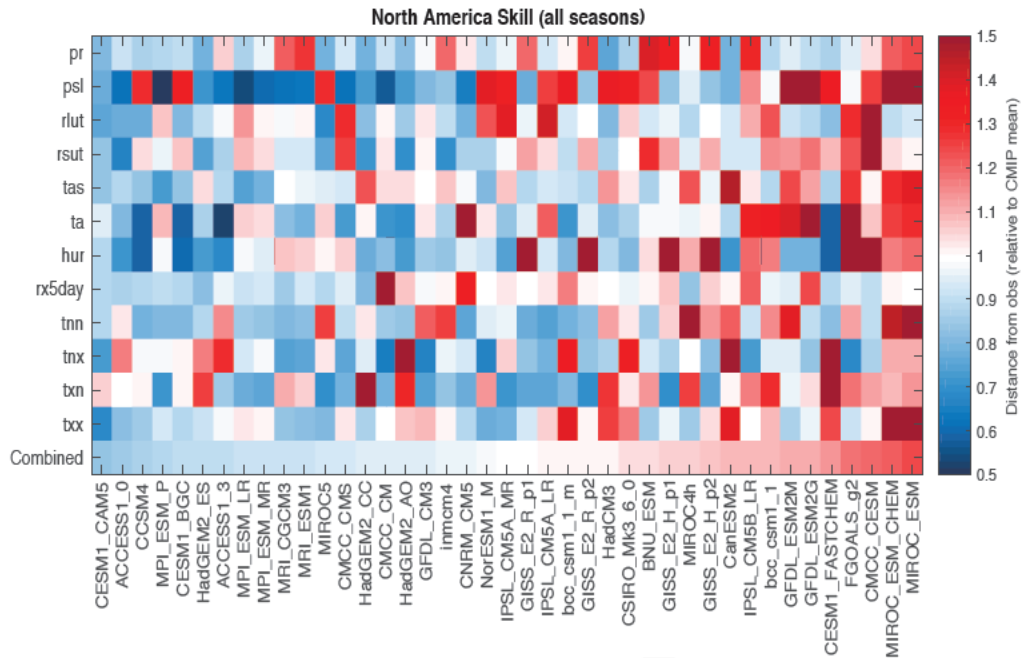
Field	Description	Source	Reference	Years
TS	Surface Temperature (seasonal)	Livneh,Hutchinson	(Hopkinson et al. 2012; Hutchinson et al. 2009; Livneh et al. 2013)	1950-2011
PR	Mean Precipitation (seasonal)	Livneh,Hutchinson	(Hopkinson et al. 2012; Hutchinson et al. 2009; Livneh et al. 2013)	1950-2011
RSUT	TOA Shortwave Flux (seasonal)	CERES-EBAF	(NASA 2011)	2000-2005
RLUT	TOA Longwave Flux (seasonal)	CERES-EBAF	(NASA 2011)	2000-2005
T	Vertical Temperature Profile (seasonal)	AIRS*	(Aumann et al. 2003)	2002-2010
RH	Vertical Humidity Profile (seasonal)	AIRS	(Aumann et al. 2003)	2002-2010
PSL	Surface Pressure (seasonal)	ERA-40	(Uppala et al. 2005)	1970-2000
Tnn	Coldest Night	Livneh,Hutchinson	(Hopkinson et al. 2012; Hutchinson et al. 2009; Livneh et al. 2013)	1950-2011
Txn	Coldest Day	Livneh,Hutchinson	(Hopkinson et al. 2012; Hutchinson et al. 2009; Livneh et al. 2013)	1950-2011
Tnx	Warmest Night	Livneh,Hutchinson	(Hopkinson et al. 2012; Hutchinson et al. 2009; Livneh et al. 2013)	1950-2011
Txx	Warmest day	Livneh,Hutchinson	(Hopkinson et al. 2012; Hutchinson et al. 2009; Livneh et al. 2013)	1950-2011
rx5day	seasonal max. 5-day total precip.	Livneh,Hutchinson	(Hopkinson et al. 2012; Hutchinson et al. 2009; Livneh et al. 2013)	1950-2011

1 **Table B.2:** Uniqueness, Skill and Combined weights for CMIP5

	Uniqueness weight	Skill Weight	Combined
ACCESS1-0	0.60	1.69	1.02
ACCESS1-3	0.78	1.40	1.09
BNU-ESM	0.88	0.77	0.68
CCSM4	0.43	1.57	0.68
CESM1-BGC	0.44	1.46	0.64
CESM1-CAM5	0.72	1.80	1.30
CESM1-FASTCHEM	0.76	0.50	0.38
CMCC-CESM	0.98	0.36	0.35
CMCC-CM	0.89	1.21	1.07
CMCC-CMS	0.59	1.23	0.73
CNRM-CM5	0.94	1.08	1.01
CSIRO-Mk3-6-0	0.95	0.77	0.74
CanESM2	0.97	0.65	0.63
FGOALS-g2	0.97	0.39	0.38
GFDL-CM3	0.81	1.18	0.95
GFDL-ESM2G	0.74	0.59	0.44
GFDL-ESM2M	0.72	0.60	0.43
GISS-E2-H-p1	0.38	0.74	0.28
GISS-E2-H-p2	0.38	0.69	0.26
GISS-E2-R-p1	0.38	0.97	0.37
GISS-E2-R-p2	0.37	0.89	0.33
HadCM3	0.98	0.89	0.87
HadGEM2-AO	0.52	1.19	0.62
HadGEM2-CC	0.50	1.21	0.60
HadGEM2-ES	0.43	1.40	0.61
IPSL-CM5A-LR	0.79	0.92	0.72
IPSL-CM5A-MR	0.83	0.99	0.82
IPSL-CM5B-LR	0.92	0.63	0.58
MIROC-ESM	0.54	0.28	0.15
MIROC-ESM-CHEM	0.54	0.32	0.17
MIROC4h	0.97	0.73	0.71
MIROC5	0.89	1.24	1.11
MPI-ESM-LR	0.35	1.38	0.49
MPI-ESM-MR	0.38	1.37	0.52
MPI-ESM-P	0.36	1.54	0.56
MRI-CGCM3	0.51	1.35	0.68
MRI-ESM1	0.51	1.31	0.67
NorESM1-M	0.83	1.06	0.88
bcc-csm1-1	0.88	0.62	0.55
bcc-csm1-1-m	0.90	0.89	0.80
inmcm4	0.95	1.13	1.08

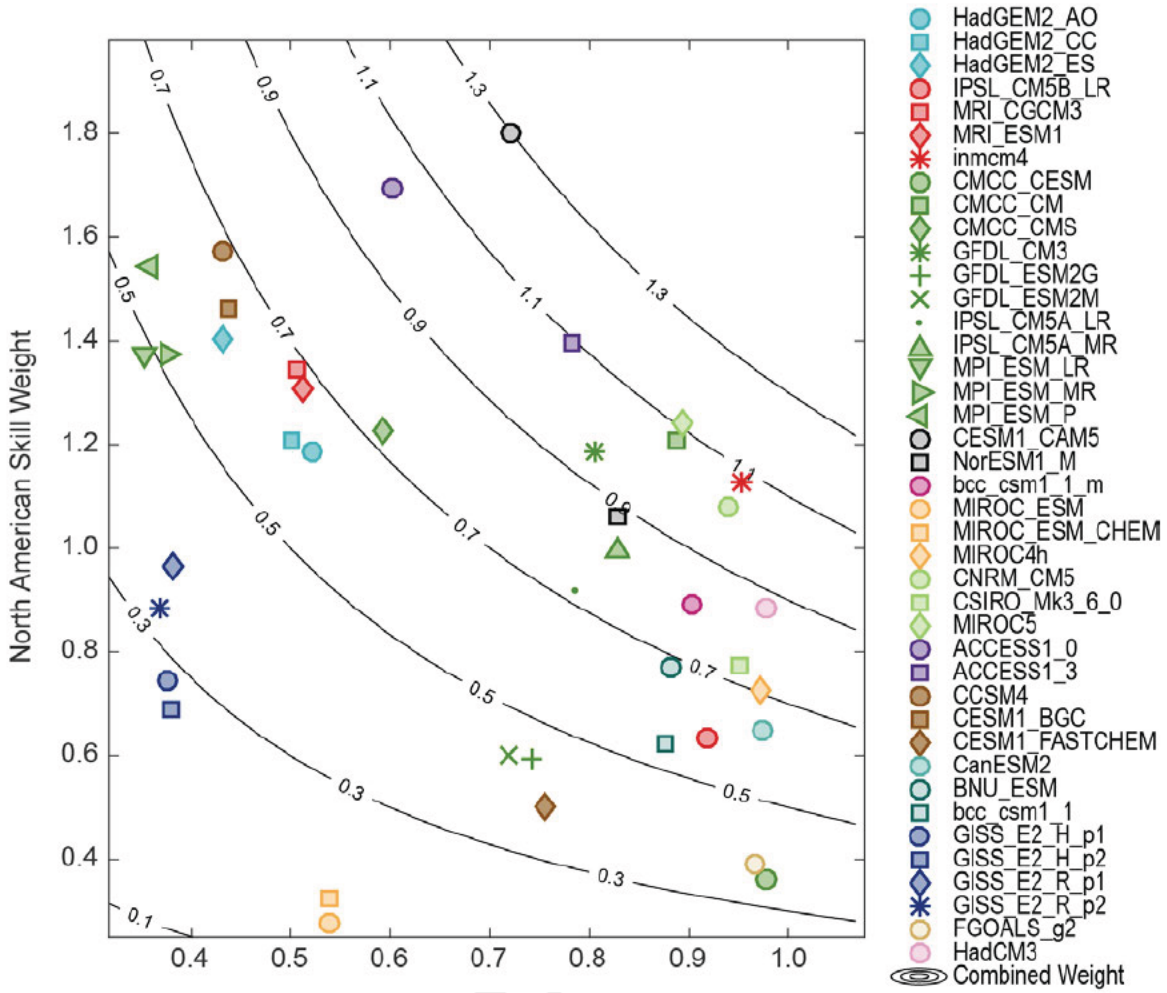
2

1 **FIGURES**



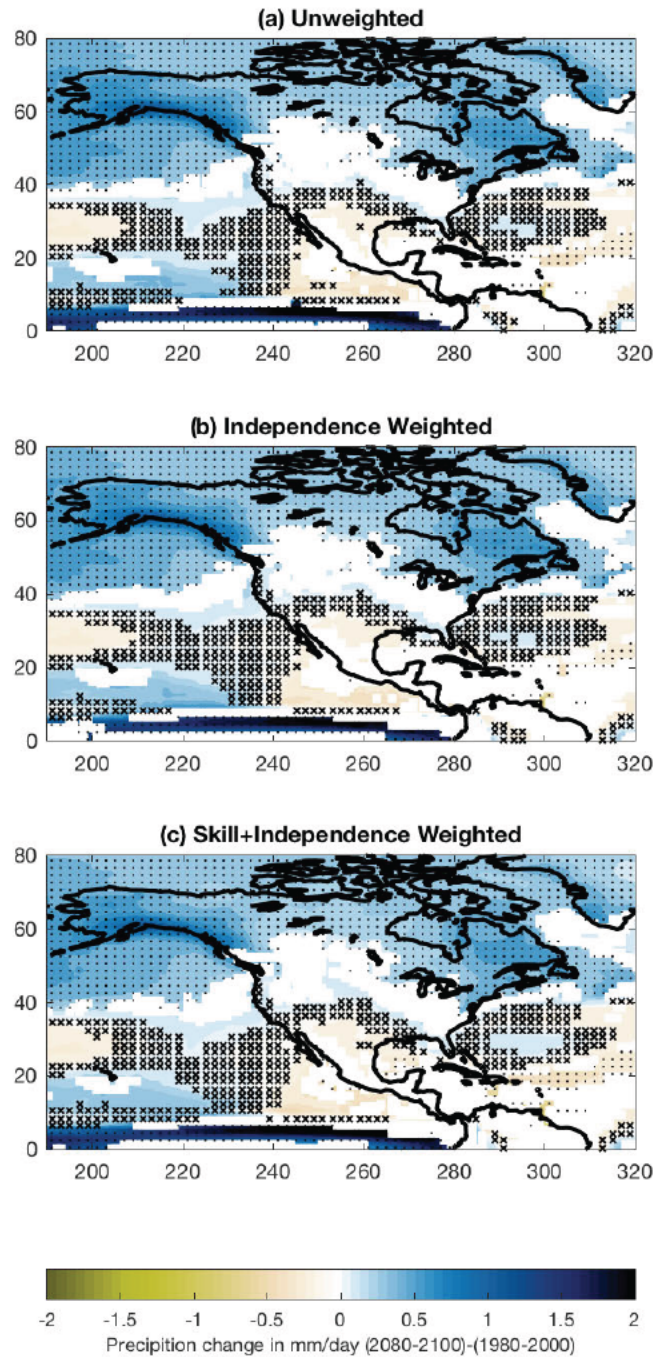
2

3 **Figure B.1:** A graphical representation of the intermodel distance matrix for CMIP5 and
 4 a set of observed values. Each row and column represents a single climate model (or
 5 observation). All scores are aggregated over seasons (individual seasons are not shown).
 6 Each box represents a pairwise distance, where warm (red) colors indicate a greater
 7 distance. Distances are measured as a fraction of the mean intermodel distance in the
 8 CMIP5 ensemble. (Figure source: Sanderson et al. 2016b).



1

2 **Figure B.2:** Model skill and independence weights for the CMIP5 archive evaluated over
 3 the North American domain. Contours show the overall weighting, which is the product
 4 of the two individual weights. (Figure source: Sanderson et al. 2016b).



1

2 **Figure B.3:** Projections of precipitation change over North America in 2080–2100,
 3 relative to 1980–2000 under RCP8.5. (a) shows the simple unweighted CMIP5 multi-
 4 model average, using the significance methodology from (IPCC 2013), (b) Shows the
 5 weighted results as outlined in Section 3 for models weighted by uniqueness only, and (c)
 6 shows weighted results for models weighted by both uniqueness and skill. (Figure source:
 7 Sanderson et al. 2016b).

1 **REFERENCES**

- 2 Aumann, H.H., M.T. Chahine, C. Gautier, M.D. Goldberg, E. Kalnay, L.M. McMillin, H.
3 Revercomb, P.W. Rosenkranz, W.L. Smith, D.H. Staelin, L.L. Strow, and J.
4 Susskind, 2003: AIRS/AMSU/HSB on the Aqua mission: Design, science objectives,
5 data products, and processing systems. *IEEE Transactions on Geoscience and Remote*
6 *Sensing*, **41**, 253-264. <http://dx.doi.org/10.1109/TGRS.2002.808356>
- 7 Hopkinson, R.F., M.F. Hutchinson, D.W. McKenney, E.J. Milewska, and P. Papadopol,
8 2012: Optimizing Input Data for Gridding Climate Normals for Canada. *Journal of*
9 *Applied Meteorology and Climatology*, **51**, 1508-1518.
10 <http://dx.doi.org/10.1175/JAMC-D-12-018.1>
- 11 Hutchinson, M.F., D.W. McKenney, K. Lawrence, J.H. Pedlar, R.F. Hopkinson, E.
12 Milewska, and P. Papadopol, 2009: Development and Testing of Canada-Wide
13 Interpolated Spatial Models of Daily Minimum–Maximum Temperature and
14 Precipitation for 1961–2003. *Journal of Applied Meteorology and Climatology*, **48**,
15 725-741. <http://dx.doi.org/10.1175/2008JAMC1979.1>
- 16 IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working*
17 *Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate*
18 *Change*. Cambridge University Press, Cambridge, UK and New York, NY, 1535 pp.
19 <http://dx.doi.org/10.1017/CBO9781107415324> www.climatechange2013.org
- 20 Livneh, B., E.A. Rosenberg, C. Lin, B. Nijssen, V. Mishra, K.M. Andreadis, E.P. Maurer,
21 and D.P. Lettenmaier, 2013: A Long-Term Hydrologically Based Dataset of Land
22 Surface Fluxes and States for the Conterminous United States: Update and
23 Extensions. *Journal of Climate*, **26**, 9384-9392. [http://dx.doi.org/10.1175/JCLI-D-](http://dx.doi.org/10.1175/JCLI-D-12-00508.1)
24 [12-00508.1](http://dx.doi.org/10.1175/JCLI-D-12-00508.1)
- 25 NASA, 2011: CERES EBAF Data Sets.
26 <https://ceres.larc.nasa.gov/products.php?product=EBAF-TOA>
- 27 Sanderson, B.M., R. Knutti, and P. Caldwell, 2015: A Representative Democracy to
28 Reduce Interdependency in a Multimodel Ensemble. *Journal of Climate*, **28**, 5171-
29 5194. <http://dx.doi.org/10.1175/JCLI-D-14-00362.1>
- 30 Sanderson, B.M., M. Wehner, and R. Knutti, 2016b: Skill and Independence weighting
31 for multi-model Assessment. *Geoscientific Model Development*.
32 <https://doi.org/10.5194/gmd-10-2379-2017>
- 33 Uppala, S.M., P.W. Kållberg, A.J. Simmons, U. Andrae, V.D.C. Bechtold, M. Fiorino,
34 J.K. Gibson, J. Haseler, A. Hernandez, G.A. Kelly, X. Li, K. Onogi, S. Saarinen, N.
35 Sokka, R.P. Allan, E. Andersson, K. Arpe, M.A. Balmaseda, A.C.M. Beljaars, L.V.D.

- 1 Berg, J. Bidlot, N. Bormann, S. Caires, F. Chevallier, A. Dethof, M. Dragosavac, M.
- 2 Fisher, M. Fuentes, S. Hagemann, E. Hólm, B.J. Hoskins, L. Isaksen, P.A.E.M.
- 3 Janssen, R. Jenne, A.P. McNally, J.F. Mahfouf, J.J. Morcrette, N.A. Rayner, R.W.
- 4 Saunders, P. Simon, A. Sterl, K.E. Trenberth, A. Untch, D. Vasiljevic, P. Viterbo, and
- 5 J. Woollen, 2005: The ERA-40 re-analysis. *Quarterly Journal of the Royal*
- 6 *Meteorological Society*, **131**, 2961-3012. <http://dx.doi.org/10.1256/qj.04.176>

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1 **Appendix C. Detection and Attribution Methodologies Overview**

2 **C.1 Introduction and Conceptual Framework**

3 In this appendix, we present a brief overview of the methodologies and methodological issues for
4 detection and attribution of climate change. Attributing an observed change or an event partly to
5 a causal factor (such as anthropogenic climate forcing) normally requires that the change first be
6 detectable (Hegerl et al. 2010). A *detectable* observed change is one which is determined to be
7 highly unlikely to occur (less than about a 10% chance) due to internal variability alone, without
8 necessarily being ascribed to a causal factor. An *attributable* change refers to a change in which
9 the relative contribution of causal factors has been evaluated along with an assignment of
10 statistical confidence (e.g., Bindoff et al. 2013; Hegerl et al. 2010).

11 As outlined in Bindoff et al. (2013), the conceptual framework for most detection and attribution
12 studies consists of four elements: 1) relevant observations; 2) the estimated time history of
13 relevant climate forcings (such as greenhouse gas concentrations or volcanic activity); 3) a
14 modeled estimate of the impact of the climate forcings on the climate variables of interest; and 4)
15 an estimate of the internal (unforced) variability of the climate variables of interest—that is, the
16 changes that can occur due to natural unforced variations of the ocean, atmosphere, land,
17 cryosphere, and other elements of the climate system in the absence of external forcings. The
18 four elements above can be used together with a detection and attribution framework to assess
19 possible causes of observed changes.

20 **C.2 Fingerprint-Based Methods**

21 A key methodological approach for detection and attribution is the regression-based
22 “fingerprint” method (e.g., Hasselmann 1997; Allen and Stott 2003; Hegerl et al. 2007; Hegerl
23 and Zwiers 2011; Bindoff et al. 2013), where observed changes are regressed onto a model-
24 generated response pattern to a particular forcing (or set of forcings), and regression scaling
25 factors are obtained. When a scaling factor for a forcing pattern is determined to be significantly
26 different from zero, a detectable change has been identified. If the uncertainty bars on the scaling
27 factor encompass unity, the observed change is consistent with the modeled response, and the
28 observed change can be attributed, at least in part, to the associated forcing agent, according to this
29 methodology. Zwiers et al. (2011) showed how detection and attribution methods could be
30 applied to the problem of changes in daily temperature extremes at the regional scale by using a
31 generalized extreme value (GEV) approach. In their approach, a time-evolving pattern of GEV
32 location parameters (i.e., “fingerprint”) from models is fit to the observed extremes as a means of
33 detecting and attributing changes in the extremes to certain forcing sets (for example,
34 anthropogenic forcings).

35 A recent development in detection/attribution methodology (Ribes et al. 2017) uses hypothesis
36 testing and an additive decomposition approach rather than linear regression of patterns. The new

1 approach makes use of the magnitudes of responses from the models rather than using the model
2 patterns and deriving the scaling factors (magnitudes of responses) from regression. The new
3 method, in a first application, gives very similar attributable anthropogenic warming estimates to
4 the earlier methods as reported in Bindoff et al. (2013) and shown in Figure 3.2. Some further
5 methodological developments for performing optimal fingerprint detection and attribution
6 studies are proposed in Hannart (2016), who, for example, focuses on the possible use of raw
7 data in analyses without the use of dimensional reductions, such as projecting the data onto a
8 limited number of basis functions, such as spherical harmonics, before analysis.

9 **C.3 Non-Fingerprint Based Methods**

10 A simpler detection/attribution/consistency calculation, which does not involve regression and
11 pattern scaling, compares observed and simulated time series to assess whether observations are
12 consistent with natural variability simulations or with simulations forced by both natural and
13 anthropogenic forcing agents (Knutson et al. 2013; van Oldenborgh et al. 2013). Cases where
14 observations are inconsistent with model simulations using natural forcing only (a detectable
15 change), while also being consistent with models that incorporate both anthropogenic and natural
16 forcings, are interpreted as having an attributable anthropogenic contribution, subject to caveats
17 regarding uncertainties in observations, climate forcings, modeled responses, and simulated
18 internal climate variability. This simpler method is useful for assessing trends over smaller
19 regions such as sub-regions of the United States (see the example given in Figure 6.5 for regional
20 surface temperature trends).

21 Delsole et al. (2011) introduced a method of identifying internal (unforced) variability in climate
22 data by decomposing variables by timescale, using a measure of their predictability. They found
23 that while such internal variability could contribute to surface temperature trends of 30-years'
24 duration or less, and could be responsible for the accelerated global warming during 1977–2008
25 compared to earlier decades, the strong (approximately 0.8°C, or 1.4°F) warming trend seen in
26 observations over the past century was not explainable by such internal variability. Constructed
27 circulation analogs (van den Dool et al. 2003; Deser et al. 2016) is a method used to identify the
28 part of observed surface temperature changes that is due to atmospheric circulation changes
29 alone.

30 The timescale by which climate change signals will become detectable in various regions is a
31 question of interest in detection and attribution studies, and methods of estimating this have been
32 developed and applied (e.g., Mahlstein et al. 2011; Deser et al. 2012b). These studies illustrate
33 how natural variability can obscure forced climate signals for decades, particularly for smaller
34 (less than continental) space scales.

35 Other examples of detection and attribution methods include the use of multiple linear regression
36 with energy balance models (e.g., Canty et al. 2013) and Granger causality tests (e.g., Stern and
37 Kaufmann 2014). These are typically attempting to relate forcing time series, such as the

1 historical record of atmospheric CO₂ since 1860, to a climate response measure, such as global
2 mean temperature or ocean heat content, but without using a full coupled climate model to
3 explicitly estimate the response of the climate system to forcing (or the spatial pattern of the
4 response to forcing). Granger causality, for example, explores the lead–lag relationships between
5 different variables to infer causal relationships between them, and attempts to control for any
6 influence of a third variable that may be linked to the other two variables in question.

7 **C.4. Multistep Attribution and Attribution without Detection**

8 A growing number of climate change and extreme event attribution studies use a *multistep*
9 *attribution* approach (Hegerl et al. 2010), based on attribution of a change in climate conditions
10 that are closely related to the variable or event of interest. In the multistep approach, an observed
11 change in the variable of interest is attributed to a change in climate or other environmental
12 conditions, and then the changes in the climate or environmental conditions are separately
13 attributed to an external forcing, such as anthropogenic emissions of greenhouse gases. As an
14 example, some attribution statements for phenomena such as droughts or hurricane activity—
15 where there are not necessarily detectable trends in occurrence of the phenomenon itself—are
16 based on models and on detected changes in related variables such as surface temperature, as
17 well as an understanding of the relevant physical processes linking surface temperatures to
18 hurricanes or drought. For example, some studies of the recent California drought (e.g., Mao et
19 al. 2015; Williams et al. 2015) attribute a fraction of the event to anthropogenic warming or to
20 long-term warming based on modeling or statistical analysis, although without claiming that
21 there was a detectable change in the drought frequency or magnitude.

22 The multistep approach and model simulations are both methods that, in principle, can allow for
23 attribution of a climate change or a change in the likelihood of occurrence of an event to a causal
24 factor without necessarily detecting a significant change in the occurrence rate of the
25 phenomenon or event itself (though in some cases, there may also be a detectable change in the
26 variable of interest). For example, Murakami et al. (2015) used model simulations to conclude
27 that the very active hurricane season observed near Hawai‘i in 2014 was at least partially
28 attributable to anthropogenic influence; they also show that there is no clear long-term detectable
29 trend in historical hurricane occurrence near Hawai‘i in available observations. If an attribution
30 statement is made where there is not a detectable change in the phenomenon itself (for example,
31 hurricane frequency or drought frequency) then this statement is an example of *attribution*
32 *without detection*. Such an attribution without detection can be distinguished from a conventional
33 single-step attribution (for example, global mean surface temperature) where in the latter case
34 there is a detectable change in the variable of interest (or the scaling factor for a forcing pattern is
35 significantly different from zero in observations) and attribution of the changes in that variable to
36 specific external forcing agents. Regardless of whether a single-step or multistep attribution
37 approach is used, or whether there is a detectable change in the variable of interest, attribution

1 statements with relatively higher levels of confidence are underpinned by a thorough
2 understanding of the physical processes involved.

3 There are reasons why attribution without detection statements can be appropriate, despite the
4 lower confidence typically associated with such statements as compared to attribution statements
5 that are supported by detection of a change in the phenomenon itself. For example, an event of
6 interest may be so rare that a trend analysis for similar events is not practical. Including
7 attribution without detection events in the analysis of climate change impacts reduces the
8 chances of a false negative, that is, incorrectly concluding that climate change had no influence
9 on a given extreme events (Anderegg et al. 2014) in a case where it did have an influence.
10 However, avoiding this type of error through attribution without detection comes at the risk of
11 increasing the rate of false positives, where one incorrectly concludes that anthropogenic climate
12 change had a certain type of influence on an extreme event when in fact it did not have such an
13 influence (see Box 3.1).

14 **C.5 Extreme Event Attribution Methodologies**

15 Since the release of the Intergovernmental Panel on Climate Change's Fifth Assessment Report
16 (IPCC AR5) and the Third National Climate Assessment (NCA3; Melillo et al. 2014), there have
17 been further advances in the science of detection and attribution of climate change. An emerging
18 area in the science of detection and attribution is the attribution of extreme weather and climate
19 events (NAS 2016; Stott 2016; Easterling et al. 2016). According to Hulme (2014), there are four
20 general types of attribution methods that are applied in practice: physical reasoning, statistical
21 analysis of time series, fraction of attributable risk (FAR) estimation, and the philosophical
22 argument that there are no longer any purely natural weather events. As discussed in a recent
23 National Academy of Sciences report (NAS 2016), possible anthropogenic influence on an
24 extreme event can be assessed using a risk-based approach, which examines whether the odds of
25 occurrence of a type of extreme event have changed, or through an ingredients-based or
26 conditional attribution approach.

27 In the risk-based approach (Stott et al. 2004; Hulme 2014; NAS 2016), one typically uses a
28 model to estimate the probability (p) of occurrence of a weather or climate event within two
29 climate states: one state with anthropogenic influence (where the probability is p_1) and the other
30 state without anthropogenic influence (where the probability is p_0). Then the ratio (p_1/p_0)
31 describes how much more or less likely the event is in the modeled climate with anthropogenic
32 influence compared to a modeled hypothetical climate without anthropogenic influences.
33 Another common metric used with this approach is the fraction of attributable risk (FAR),
34 defined as $FAR = 1 - (p_0/p_1)$. Further refinements on such an approach using causal theory are
35 discussed in Hannart et al. (2016b).

36 In the conditional or ingredients-based approach (Trenberth et al. 2015; Shepherd 2016; Horton
37 et al. 2016; NAS 2016), an investigator may look for changes in occurrence of atmospheric

1 circulation and weather patterns relevant to the extreme event, or at the impact of certain
2 environmental changes (for example, greater atmospheric moisture) on the character of an
3 extreme event. Conditional or ingredients-based attribution can be applied to extreme events or
4 to climate changes in general. An example of the ingredients-based approach and more
5 discussion of this type of attribution method is given in Box C.2.

6 Hannart et al. (2016b) have discussed how causal theory can also be applied to attribution studies
7 in order to distinguish between necessary and sufficient causation. Hannart et al. (2016a) further
8 propose methodologies to use data assimilation systems, which are now used operationally to
9 update short-term numerical weather prediction models, for detection and attribution. They
10 envision how such systems could be used in the future to implement near-real time systematic
11 causal attribution of weather and climate-related events.

12 ----- **START BOX C.1 HERE** -----

13 **Box C.1. On the Use of Significance Levels and Significance Tests in Attribution Studies**

14 In detection/attribution studies, a detectable observed change is one which is determined to be
15 highly unlikely to occur (less than about a 10% chance) due to internal variability alone. Some
16 frequently asked questions concern the use of such a high statistical threshold (significance level)
17 in attribution studies. In this box, we respond to several such questions received in the public
18 review period.

- 19 - Why is such a high degree of confidence (for example, statistical significance at p level
20 of 0.05) typically required before concluding that an attributable anthropogenic
21 component to a climate change or event has been detected? For example, could
22 attribution studies be reframed to ask whether there is a 5% or more chance that
23 anthropogenic climate change contributed to the event?

24 This question is partly related to the issue of risk avoidance. For example, if there is a particular
25 climate change outcome that we wish to avoid (for example, global warming of 3°C, or 10°C, or
26 a runaway greenhouse) then one can use the upper ranges of confidence intervals of climate
27 model projections as guidance, based on available science, for avoiding such outcomes.
28 Detection/attribution studies typically deal with smaller changes than climate projections over
29 the next century or more. For detection/attribution studies, researchers are confronting models
30 with historical data to explore whether or not observed climate change signals are emerging from
31 the background of natural variability. Typically the emergent signal is just a small fraction of
32 what is predicted by the models for the coming century under continued strong greenhouse gas
33 emission scenarios. Detecting that a change has emerged from natural variability is not the same
34 as approaching a threshold to be avoided, unless the goal is to ensure no detectable
35 anthropogenic influence on climate. Consequently, use of a relative strong confidence level (or
36 p -value of 0.05) for determining climate change detection seems justified for the particular case
37 of climate change detection, since one can also separately use risk-avoidance strategies or

1 probability criteria to avoid reaching certain defined thresholds (for example, a 2°C global
2 warming threshold).

3 A related question concerns ascribing blame for causing an extreme event. For example, if a
4 damaging hurricane or typhoon strikes an area and causes much damage, affected residents may
5 ask whether human-caused climate change was at least partially to blame for the event. In this
6 case, climate scientists sometimes use the “Fraction of Attributable Risk” framework, where they
7 examine whether the odds of some threshold event occurring have been increased due to
8 anthropogenic climate change. This is typically a model-based calculation, where the probability
9 distribution related to the event in question is modeled under preindustrial and present-day
10 climate conditions, and the occurrence rates are compared for the two modeled distributions.
11 Note that such an analysis can be done with or without the detection of a climate change signal
12 for the occurrence of the event in question. In general, cases where there has been a detection
13 and attribution of changes in the event in question to human causes, then the attribution of
14 increased risk to anthropogenic forcing will be relatively more confident.

15 The question of whether it is more appropriate to use approaches that incorporate a high burden
16 of statistical evidence before concluding that anthropogenic forcings contributed significantly (as
17 in traditional detection/attribution studies) versus using models to estimate anthropogenic
18 contributions when there may not even be a detectable signal present in the observations (as in
19 some Fraction of Attributable Risk studies) may depend on what type of error or scenario one
20 most wants to avoid. In the former case, one is attempting to avoid the error of concluding that
21 anthropogenic forcing has contributed to some observed climate change, when in fact, it later
22 turns out that anthropogenic forcing has not contributed to the change. In the second case, one is
23 attempting to avoid the “error” of concluding that anthropogenic forcing has not contributed
24 significantly to an observed climate change or event when (as it later comes to be known)
25 anthropogenic forcing had evidently contributed to the change, just not at a level that was
26 detectable at the time compared to natural variability.

27 - What is the tradeoff between false positives and false negatives in attribution statistical
28 testing, and how is it decided which type of error one should focus on avoiding?

29 As discussed above, there are different types of errors or scenarios that we would ideally like to
30 avoid. However, the decision of what type of analysis to do may involve a tradeoff where one
31 decides that it is more important to avoid either falsely concluding that anthropogenic forcing
32 *has* contributed, or to avoid falsely concluding that anthropogenic forcing had *not* made a
33 detectable contribution to the event. Since there is no correct answer that can apply in all cases, it
34 would be helpful if, in requesting scientific assessments, policymakers provide some guidance
35 about which type of error or scenario they would most desire be avoided in the analyses and
36 assessments in question.

- 1 - Since substantial anthropogenic climate change (increased surface temperatures,
2 increased atmospheric water vapor, etc.) has already occurred, aren't all extreme events
3 affected to some degree by anthropogenic climate change?

4 Climate scientists are aware from modeling experiments that very tiny changes to initial
5 conditions in model simulations lead to very different realizations of internal climate variability
6 “noise” in the model simulations. Comparing large samples of this random background noise
7 from models against observed changes is one way to test whether the observed changes are
8 statistically distinguishable from internal climate variability. In any case, this experience also
9 teaches us that any anthropogenic influence on climate, no matter how tiny, has some effect on
10 the future trajectory of climate variability, and thus could affect the timing and occurrence of
11 extreme events. More meaningful questions are: 1) Has anthropogenic forcing produced a
12 statistically significant change in the probability of occurrence of some class of extreme event?
13 2) Can we determine with confidence the net sign of influence of anthropogenic climate change
14 on the frequency, intensity, etc., of a type of extreme event? 3) Can climate scientists quantify
15 (with credible confidence intervals) the effect of climate change on the occurrence frequency, the
16 intensity, or some other aspect of an observed extreme event?

17 ----- **END BOX C.1 HERE** -----

18 ----- **START BOX C.2 HERE** -----

19 **Box C.2 Illustration of Ingredients-based Event Attribution: The Case of Hurricane Sandy**

20 To illustrate some aspects of the conditional or ingredients-based attribution approach, the case
21 of Hurricane Sandy can be considered. If one considers Hurricane Sandy's surge event, there is
22 strong evidence that sea level rise, at least partly anthropogenic in origin (see Ch. 12: Sea Level
23 Rise), made Sandy's surge event worse, all other factors being equal (Reed et al. 2015). The
24 related question of whether anthropogenic climate change increased the risk of an event like
25 Sandy involves not just the sea level ingredient to surge risk but also whether the frequency
26 and/or intensity of Sandy-like storms has increased or decreased as a result of anthropogenic
27 climate change. This latter question is more difficult and is briefly reviewed here.

28 A conditional or ingredients-based attribution approach, as applied to a hurricane event such as
29 Sandy, may assume that the weather patterns in which the storm was embedded—and the storm
30 itself—could have occurred in a preindustrial climate, and the event is re-simulated while
31 changing only some aspects of the large-scale environment (for example, sea surface
32 temperatures, atmospheric temperatures, and moisture) by an estimated anthropogenic climate
33 change signal. Such an approach thus explores whether anthropogenic climate change to date has
34 altered the odds of occurrence or intensity of a Hurricane Sandy-like event. Modeling studies
35 show, as expected, that the anomalously warm sea surface temperatures off the U.S. East Coast
36 during Sandy led to a substantially more intense simulated storm than under present-day
37 climatological conditions (Magnusson et al. 2014). However, these anomalous sea surface

1 temperatures and other environmental changes are a mixture of anthropogenic and natural
2 influences, and so it is not generally possible to infer the anthropogenic component from such
3 experiments. Another study (Lackmann 2015) modeled the influence of just the anthropogenic
4 changes to the thermodynamic environment (including sea surface temperatures, atmospheric
5 temperatures, and moisture perturbations) and concluded that anthropogenic climate change to
6 date had caused Hurricane Sandy to be about 5 hPa more intense, but that this modeled change
7 was not statistically significant at the 95% confidence level. A third study used a statistical–
8 dynamical model to compare simulated New York City-area tropical cyclones in pre–
9 anthropogenic and anthropogenic time periods (Reed et al. 2015). It concluded that there have
10 been anthropogenically induced increases in the types of tropical cyclones that cause extreme
11 surge events in the region, apart from the effects of sea level rise, such as increased radius of
12 maximum winds in the anthropogenic era. However, the statistical–dynamical model used in the
13 study simulates an unusually large increase in global tropical cyclone activity in 21st century
14 projections (Emanuel 2013) compared to other tropical cyclone modeling studies using
15 dynamical models—a number of which simulate future decreases in late 21st century tropical
16 storm frequency in the Atlantic basin (e.g., Christensen et al. 2013). This range of uncertainty
17 among various model simulations of Atlantic tropical cyclone activity changes under climate
18 change imply that there is low confidence in determining the net impact to date of anthropogenic
19 climate change on the risk of Sandy-like events, though anthropogenic sea level rise, all other
20 things equal, has increased the surge risk.

21 In summary, while there is agreement that sea level rise alone has caused greater storm surge risk
22 in the New York City area, there is low confidence on whether a number of other important
23 determinants of storm surge climate risk, such as the frequency, size, or intensity of Sandy-like
24 storms in the New York region, have increased or decreased due to anthropogenic warming to
25 date.

26 ----- **END BOX C.2 HERE** -----

27

1 **REFERENCES**

- 2 Allen, M.R. and P.A. Stott, 2003: Estimating signal amplitudes in optimal fingerprinting, Part I:
3 Theory. *Climate Dynamics*, **21**, 477-491. <http://dx.doi.org/10.1007/s00382-003-0313-9>
- 4 Anderegg, W.R.L., E.S. Callaway, M.T. Boykoff, G. Yohe, and T.y.L. Root, 2014: Awareness of
5 both type 1 and 2 errors in climate science and assessment. *Bulletin of the American*
6 *Meteorological Society*, **95**, 1445-1451. <http://dx.doi.org/10.1175/BAMS-D-13-00115.1>
- 7 Bindoff, N.L., P.A. Stott, K.M. AchutaRao, M.R. Allen, N. Gillett, D. Gutzler, K. Hansingo, G.
8 Hegerl, Y. Hu, S. Jain, I.I. Mokhov, J. Overland, J. Perlwitz, R. Sebbari, and X. Zhang, 2013:
9 Detection and attribution of climate change: From global to regional. *Climate Change 2013:*
10 *The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report*
11 *of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M.
12 Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds.
13 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 867–
14 952. <http://www.climatechange2013.org/report/full-report/>
- 15 Canty, T., N.R. Mascioli, M.D. Smarte, and R.J. Salawitch, 2013: An empirical model of global
16 climate – Part 1: A critical evaluation of volcanic cooling. *Atmospheric Chemistry and*
17 *Physics*, **13**, 3997-4031. <http://dx.doi.org/10.5194/acp-13-3997-2013>
- 18 Christensen, J.H., K. Krishna Kumar, E. Aldrian, S.-I. An, I.F.A. Cavalcanti, M. de Castro, W.
19 Dong, P. Goswami, A. Hall, J.K. Kanyanga, A. Kitoh, J. Kossin, N.-C. Lau, J. Renwick, D.B.
20 Stephenson, S.-P. Xie, and T. Zhou, 2013: Climate phenomena and their relevance for future
21 regional climate change. *Climate Change 2013: The Physical Science Basis. Contribution of*
22 *Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate*
23 *Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A.
24 Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge,
25 United Kingdom and New York, NY, USA, 1217–1308.
26 <http://www.climatechange2013.org/report/full-report/>
- 27 DelSole, T., M.K. Tippett, and J. Shukla, 2011: A significant component of unforced
28 multidecadal variability in the recent acceleration of global warming. *Journal of Climate*, **24**,
29 909-926. <http://dx.doi.org/10.1175/2010jcli3659.1>
- 30 Deser, C., R. Knutti, S. Solomon, and A.S. Phillips, 2012: Communication of the role of natural
31 variability in future North American climate. *Nature Climate Change*, **2**, 775-779.
32 <http://dx.doi.org/10.1038/nclimate1562>
- 33 Deser, C., L. Terray, and A.S. Phillips, 2016: Forced and internal components of winter air
34 temperature trends over North America during the past 50 years: Mechanisms and

- 1 implications. *Journal of Climate*, **29**, 2237-2258. <http://dx.doi.org/10.1175/JCLI-D-15->
2 0304.1
- 3 Easterling, D.R., K.E. Kunkel, M.F. Wehner, and L. Sun, 2016: Detection and attribution of
4 climate extremes in the observed record. *Weather and Climate Extremes*, **11**, 17-27.
5 <http://dx.doi.org/10.1016/j.wace.2016.01.001>
- 6 Emanuel, K.A., 2013: Downscaling CMIP5 climate models shows increased tropical cyclone
7 activity over the 21st century. *Proceedings of the National Academy of Sciences*, **110**, 12219-
8 12224. <http://dx.doi.org/10.1073/pnas.1301293110>
- 9 Hannart, A., 2016: Integrated optimal fingerprinting: Method description and illustration.
10 *Journal of Climate*, **29**, 1977-1998. <http://dx.doi.org/10.1175/jcli-d-14-00124.1>
- 11 Hannart, A., A. Carrassi, M. Bocquet, M. Ghil, P. Naveau, M. Pulido, J. Ruiz, and P. Tandeo,
12 2016a: DADA: Data assimilation for the detection and attribution of weather and climate-
13 related events. *Climatic Change*, **136**, 155-174. <http://dx.doi.org/10.1007/s10584-016-1595-3>
- 14 Hannart, A., J. Pearl, F.E.L. Otto, P. Naveau, and M. Ghil, 2016b: Causal counterfactual theory
15 for the attribution of weather and climate-related events. *Bulletin of the American*
16 *Meteorological Society*, **97**, 99-110. <http://dx.doi.org/10.1175/bams-d-14-00034.1>
- 17 Hasselmann, K., 1997: Multi-pattern fingerprint method for detection and attribution of climate
18 change. *Climate Dynamics*, **13**, 601-611. <http://dx.doi.org/10.1007/s003820050185>
- 19 Hegerl, G. and F. Zwiers, 2011: Use of models in detection and attribution of climate change.
20 *Wiley Interdisciplinary Reviews: Climate Change*, **2**, 570-591.
21 <http://dx.doi.org/10.1002/wcc.121>
- 22 Hegerl, G.C., F.W. Zwiers, P. Braconnot, N.P. Gillett, Y. Luo, J.A.M. Orsini, N. Nicholls, J.E.
23 Penner, and P.A. Stott, 2007: Understanding and attributing climate change. *Climate Change*
24 *2007: The Physical Science Basis. Contribution of Working Group I to the Fourth*
25 *Assessment Report of the Intergovernmental Panel on Climate Change*. Solomon, S., D. Qin,
26 M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, Eds.
27 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 663-
28 745. http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch9.html
- 29 Hegerl, G.C., O. Hoegh-Guldberg, G. Casassa, M.P. Hoerling, R.S. Kovats, C. Parmesan, D.W.
30 Pierce, and P.A. Stott, 2010: Good practice guidance paper on detection and attribution
31 related to anthropogenic climate change. *Meeting Report of the Intergovernmental Panel on*
32 *Climate Change Expert Meeting on Detection and Attribution of Anthropogenic Climate*
33 *Change*. Stocker, T.F., C.B. Field, D. Qin, V. Barros, G.-K. Plattner, M. Tignor, P.M.
34 Midgley, and K.L. Ebi, Eds. IPCC Working Group I Technical Support Unit, University of

- 1 Bern, Bern, Switzerland, 1-8. [http://www.ipcc.ch/pdf/supporting-](http://www.ipcc.ch/pdf/supporting-material/ipcc_good_practice_guidance_paper_anthropogenic.pdf)
2 [material/ipcc_good_practice_guidance_paper_anthropogenic.pdf](http://www.ipcc.ch/pdf/supporting-material/ipcc_good_practice_guidance_paper_anthropogenic.pdf)
- 3 Horton, R.M., J.S. Mankin, C. Lesk, E. Coffel, and C. Raymond, 2016: A review of recent
4 advances in research on extreme heat events. *Current Climate Change Reports*, **2**, 242-259.
5 <http://dx.doi.org/10.1007/s40641-016-0042-x>
- 6 Hulme, M., 2014: Attributing weather extremes to 'climate change'. *Progress in Physical*
7 *Geography*, **38**, 499-511. <http://dx.doi.org/10.1177/0309133314538644>
- 8 Knutson, T.R., F. Zeng, and A.T. Wittenberg, 2013: Multimodel assessment of regional surface
9 temperature trends: CMIP3 and CMIP5 twentieth-century simulations. *Journal of Climate*,
10 **26**, 8709-8743. <http://dx.doi.org/10.1175/JCLI-D-12-00567.1>
- 11 Lackmann, G.M., 2015: Hurricane Sandy before 1900 and after 2100. *Bulletin of the American*
12 *Meteorological Society*, **96 (12)**, 547-560. <http://dx.doi.org/10.1175/BAMS-D-14-00123.1>
- 13 Magnusson, L., J.-R. Bidlot, S.T.K. Lang, A. Thorpe, N. Wedi, and M. Yamaguchi, 2014:
14 Evaluation of medium-range forecasts for Hurricane Sandy. *Monthly Weather Review*, **142**,
15 1962-1981. <http://dx.doi.org/10.1175/mwr-d-13-00228.1>
- 16 Mahlstein, I., R. Knutti, S. Solomon, and R.W. Portmann, 2011: Early onset of significant local
17 warming in low latitude countries. *Environmental Research Letters*, **6**, 034009.
18 <http://dx.doi.org/10.1088/1748-9326/6/3/034009>
- 19 Mao, Y., B. Nijssen, and D.P. Lettenmaier, 2015: Is climate change implicated in the 2013–2014
20 California drought? A hydrologic perspective. *Geophysical Research Letters*, **42**, 2805-2813.
21 <http://dx.doi.org/10.1002/2015GL063456>
- 22 Melillo, J.M., T.C. Richmond, and G.W. Yohe, eds., 2014: *Climate Change Impacts in the*
23 *United States: The Third National Climate Assessment*. U.S. Global Change Research
24 Program: Washington, D.C., 842 pp. <http://dx.doi.org/10.7930/J0Z31WJ2>
- 25 Murakami, H., G.A. Vecchi, T.L. Delworth, K. Paffendorf, L. Jia, R. Gudgel, and F. Zeng, 2015:
26 Investigating the influence of anthropogenic forcing and natural variability on the 2014
27 Hawaiian hurricane season [in "Explaining Extreme Events of 2014 from a Climate
28 Perspective"]. *Bulletin of the American Meteorological Society*, **96 (12)**, S115-S119.
29 <http://dx.doi.org/10.1175/BAMS-D-15-00119.1>
- 30 NAS, 2016: *Attribution of Extreme Weather Events in the Context of Climate Change*. The
31 National Academies Press, Washington, DC, 186 pp. <http://dx.doi.org/10.17226/21852>
- 32 Reed, A.J., M.E. Mann, K.A. Emanuel, N. Lin, B.P. Horton, A.C. Kemp, and J.P. Donnelly,
33 2015: Increased threat of tropical cyclones and coastal flooding to New York City during the

- 1 anthropogenic era. *Proceedings of the National Academy of Sciences*, **112**, 12610-12615.
2 <http://dx.doi.org/10.1073/pnas.1513127112>
- 3 Ribes, A., F.W. Zwiers, J.-M. Azais, and P. Naveau, 2017: A new statistical approach to climate
4 change detection and attribution. *Climate Dynamics*, **48**, 367-386.
5 <http://dx.doi.org/10.1007/s00382-016-3079-6>
- 6 Shepherd, T.G., 2016: A common framework for approaches to extreme event attribution.
7 *Current Climate Change Reports*, **2**, 28-38. <http://dx.doi.org/10.1007/s40641-016-0033-y>
- 8 Stern, D.I. and R.K. Kaufmann, 2014: Anthropogenic and natural causes of climate change.
9 *Climatic Change*, **122**, 257-269. <http://dx.doi.org/10.1007/s10584-013-1007-x>
- 10 Stott, P., 2016: How climate change affects extreme weather events. *Science*, **352**, 1517-1518.
11 <http://dx.doi.org/10.1126/science.aaf7271>
- 12 Stott, P.A., D.A. Stone, and M.R. Allen, 2004: Human contribution to the European heatwave of
13 2003. *Nature*, **432**, 610-614. <http://dx.doi.org/10.1038/nature03089>
- 14 Trenberth, K.E., J.T. Fasullo, and T.G. Shepherd, 2015: Attribution of climate extreme events.
15 *Nature Climate Change*, **5**, 725-730. <http://dx.doi.org/10.1038/nclimate2657>
- 16 van den Dool, H., J. Huang, and Y. Fan, 2003: Performance and analysis of the constructed
17 analogue method applied to U.S. soil moisture over 1981–2001. *Journal of Geophysical*
18 *Research*, **108**, 8617. <http://dx.doi.org/10.1029/2002JD003114>
- 19 van Oldenborgh, G.J., F.J. Doblas Reyes, S.S. Drijfhout, and E. Hawkins, 2013: Reliability of
20 regional climate model trends. *Environmental Research Letters*, **8**, 014055.
21 <http://dx.doi.org/10.1088/1748-9326/8/1/014055>
- 22 Williams, A.P., R. Seager, J.T. Abatzoglou, B.I. Cook, J.E. Smerdon, and E.R. Cook, 2015:
23 Contribution of anthropogenic warming to California drought during 2012–2014.
24 *Geophysical Research Letters*, **42**, 6819-6828. <http://dx.doi.org/10.1002/2015GL064924>
- 25 Zwiers, F.W., X.B. Zhang, and Y. Feng, 2011: Anthropogenic influence on long return period
26 daily temperature extremes at regional scales. *Journal of Climate*, **24**, 881-892.
27 <http://dx.doi.org/10.1175/2010jcli3908.1>

Appendix D. Acronyms and Units

AGCM	Atmospheric General Circulation Model
AIS	Antarctic Ice Sheet
AMO	Atlantic Multidecadal Oscillation
AMOC	Atlantic meridional overturning circulation
AMSU	Advanced Microwave Sounding Unit
AO	Arctic Oscillation
AOD	aerosol optical depth
AR	atmospheric river
AW	Atlantic Water
BAMS	Bulletin of the American Meteorological Society
BC	black carbon
BCE	Before Common Era
CAM5	Community Atmospheric Model, Version 5
CAPE	convective available potential energy
CCN	cloud condensation nuclei
CCSM3	Community Climate System Model, Version 3
CDR	carbon dioxide removal
CE	Common Era
CENRS	Committee on Environment, Natural Resources, and Sustainability (National Science and Technology Council, White House)
CESM-LE	Community Earth System Model Large Ensemble Project
CFCs	chlorofluorocarbons
CI	climate intervention
CMIP5	Coupled Model Intercomparison Project, Fifth Phase (also CMIP3 and CMIP6)
CONUS	contiguous United States
CP	Central Pacific
CSSR	Climate Science Special Report
DIC	dissolved inorganic carbon
DJF	December-January-February
DoD SERDP	U.S. Department of Defense, Strategic Environmental Research and Development Program
DOE	U.S. Department of Energy
EAIS	East Antarctic Ice Sheet
ECS	equilibrium climate sensitivity
ENSO	El Niño-Southern Oscillation
EOF analysis	empirical orthogonal function analysis
EP	Eastern Pacific

ERF	effective radiative forcing
ESD	empirical statistical downscaling
ESDM	empirical statistical downscaling model
ESM	Earth System Model
ESS	Earth system sensitivity
ETC	extratropical cyclone
ETCCDI	Expert Team on Climate Change Detection Indices
GBI	Greenland Blocking Index
GCIS	Global Change Information System
GCM	global climate model
GeoMIP	Geoengineering Model Intercomparison Project
GFDL HiRAM	Geophysical Fluid Dynamics Laboratory, global High Resolution Atmospheric Model (NOAA)
GHCN	Global Historical Climatology Network (National Centers for Environmental Information, NOAA)
GHG	greenhouse gas
GMSL	global mean sea level
GMT	global mean temperature
GPS	global positioning system
GRACE	Gravity Recovery and Climate Experiment
GrIS	Greenland Ice Sheet
GWP	global warming potential
HadCM3	Hadley Centre Coupled Model, Version 3
HadCRUT4	Hadley Centre Climatic Research Unit Gridded Surface Temperature Data Set 4
HCFCs	hydrochlorofluorocarbons
HFCs	hydrofluorocarbons
HOT	Hawai'i Ocean Time-series
HOT-DOGS	Hawai'i Ocean Time-series Data Organization & Graphical System
HURDAT2	revised Atlantic Hurricane Database (National Hurricane Center, NOAA)
IAM	integrated assessment model
IAV	impacts, adaptation, and vulnerability
INMCM	Institute for Numerical Mathematics Climate Model
IPCC	Intergovernmental Panel on Climate Change
IPCC AR5	Fifth Assessment Report of the IPCC; also SPM – Summary for Policymakers, and WG1, WG2, WG3 – Working Groups 1-3
IPO	Interdecadal Pacific Oscillation
IVT	integrated vapor transport
JGOFS	U.S. Joint Global Ocean Flux Study

JJA	June-July-August
JTWC	Joint Typhoon Warning Center
LCC	land-cover changes
LULCC	land-use and land-cover change
MAM	March-April-May
MSU	Microwave Sounding Unit
NAM	Northern Annular Mode
NAO	North Atlantic Oscillation
NARCCAP	North American Regional Climate Change Assessment Program (World Meteorological Organization)
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NCA	National Climate Assessment
NCA3	Third National Climate Assessment
NCA4	Fourth National Climate Assessment
NCEI	National Centers for Environmental Information (NOAA)
NDC	nationally determined contribution
NOAA	National Oceanic and Atmospheric Administration
NPI	North Pacific Index
NPO	North Pacific oscillation
NPP	net primary production
OMZs	oxygen minimum zones
OSTP	Office of Science and Technology Policy (White House)
PCA	principle component analysis
PDO	Pacific Decadal Oscillation
PDSI	Palmer Drought Severity Index
PETM	Paleo-Eocene Thermal Maximum
PFCs	perfluorocarbons
PGW	pseudo-global warming
PNA	Pacific North American Pattern
RCM	regional climate models
RCP	Representative Concentration Pathway
RF	radiative forcing
RFaci	aerosol–cloud interaction (effect on RF)
RFari	aerosol–radiation interaction (effect on RF)
RMSE	root mean square error
RSL	relative sea level
RSS	remote sensing systems
S06	surface-to-6 km layer
SCE	snow cover extent

SGCR	Subcommittee on Global Change Research (National Science and Technology Council, White House)
SLCF	short-lived climate forcer
SLCP	short-lived climate pollutant
SLR	sea level rise
SOC	soil organic carbon
SRES	IPCC Special Report on Emissions Scenarios
SREX	IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation
SRM	solar radiation management
SSC	Science Steering Committee
SSI	solar spectral irradiance
SSP	Shared Socioeconomic Pathway
SST	sea surface temperature
STAR	Center for Satellite Applications and Research (NOAA)
SWCRE	shortwave cloud radiative effect (on radiative fluxes)
LWCRE	longwave cloud radiative effect (on radiative fluxes)
TA	total alkalinity
TC	tropical cyclone
TCR	transient climate response
TCRE	transient climate response to cumulative carbon emissions
TOPEX/JASON1,2	Topography Experiment/Joint Altimetry Satellite Oceanography Network satellites (NASA)
TSI	total solar irradiance
TTT	temperature total troposphere
UAH	University of Alabama, Huntsville
UHI	urban heat island (effect)
UNFCCC	United Nations Framework Convention on Climate Change
USGCRP	U.S. Global Change Research Program
USGS	U.S. Geological Survey
UV	ultraviolet
VOCs	volatile organic compounds
WAIS	West Antarctic Ice Sheet
WCRP	World Climate Research Programme
WMGHG	well-mixed greenhouse gas
WOCE	World Ocean Circulation Experiment (JGOFS)

Abbreviations and Units

C	carbon
CO	carbon monoxide
CH ₄	methane
cm	centimeters
CO ₂	carbon dioxide
°C	degrees Celsius
°F	degrees Fahrenheit
GtC	gigatonnes of carbon
hPA	hectopascal
H ₂ S	hydrogen sulfide
H ₂ SO ₄	sulfuric acid
km	kilometers
m	meters
mm	millimeters
Mt	megaton
µatm	microatmosphere
N	nitrogen
N ₂ O	nitrous oxide
NO _x	nitrogen oxides
O ₂	molecular oxygen
O ₃	ozone
OH	hydroxyl radical
PgC	petagrams of carbon
ppb	parts per billion
ppm	parts per million
SF ₆	sulfur hexafluoride
SO ₂	sulfur dioxide
TgC	teragrams of carbon
W/m ²	Watts per meter squared

1
2

GLOSSARY TERMS

[relevant definitions to be linked from <globalchange.gov/glossary>]

FINAL DRAFT