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Our globally changing climate

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Abstract

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

2. The frequency and intensity of extreme heat and heavy precipitation events are increasing in most continental regions of the world (very high confidence). These trends are consistent with expected physical responses to a warming climate. Climate model studies are also consistent with these trends, although models tend to underestimate the observed trends, especially for the increase in extreme precipitation events (very high confidence for temperature, high confidence for extreme precipitation). The frequency and intensity of extreme temperature events are virtually certain to increase in the future as global temperature increases (high confidence). Extreme precipitation events will very likely continue to increase in frequency and intensity throughout most of the world (high confidence). Observed and projected trends for some other

types of extreme events, such as floods, droughts, and severe storms, have more variable regional characteristics.

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

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

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

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

1. Our Globally Changing Climate

KEY FINDINGS

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

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

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

4. Global climate is projected to continue to change over this century and beyond. The magnitude of climate change beyond the next few decades will depend primarily on the amount of greenhouse (heat-trapping) gases emitted globally and on the remaining uncertainty in the sensitivity of Earth's climate to those emissions (very *high confidence).* With significant reductions in the emissions of greenhouse gases, the global annually

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

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

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

1.1. Introduction

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

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

Many lines of evidence demonstrate that human activities, especially emissions of greenhouse gases, are primarily responsible for the observed climate changes in the industrial era, especially over the last six decades (see attribution analysis in Ch. 3: Detection and Attribution). Formal detection and attribution studies for the period 1951 to 2010 find that the observed global mean surface temperature warming lies in the middle of the range of likely human contributions to warming over that same period. The Intergovernmental Panel on Climate Change concluded that it is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century (IPCC 2013). Over the last century, there are no alternative explanations supported by the evidence that are either credible or that can contribute more than marginally to the observed patterns. We find no convincing evidence that natural variability can account for the amount of global warming observed over the industrial era. Solar flux variations over the last six decades have been too small to explain the observed changes in climate (Bindoff et al. 2013). There are no apparent natural cycles in the observational record that can explain the recent changes in climate (e.g., PAGES 2K Consortium 2013; Marcott et al. 2013). In addition, natural cycles within the Earth's climate system can only redistribute heat; they cannot be responsible for the observed increase in the overall heat content of the climate system (Church et al. 2011). Any explanations for the observed changes in climate must be grounded in understood physical mechanisms, appropriate in scale, and consistent in timing and direction with the long-term observed trends. Known human activities quite reasonably explain what has happened without the need for other factors. Internal variability and forcing factors other than human activities cannot explain what is happening and there are no suggested factors, even speculative ones, that can explain the timing or magnitude and that would somehow cancel out the role of human factors (Anderson et al. 2012). The science underlying this evidence, along with the observed and projected changes in climate, is discussed in later chapters, starting with the basis for a human influence on climate in Chapter 2: Physical Drivers of Climate Change.

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

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

1.2. Indicators of a Globally Changing Climate

Highly diverse types of direct measurements made on land, sea, and in the atmosphere over many decades have allowed scientists to conclude with high confidence that global mean temperature is increasing. Observational datasets for many other climate variables support the conclusion with high confidence that the global climate is changing (Blunden and Arndt 2016; Meehl et al. 2016a; also see EPA 2016). Figure 1.1 depicts several of the observational indicators that demonstrate trends consistent with a warming planet over the last century. Temperatures in the lower atmosphere and ocean have increased, as have near-surface humidity and sea level. Not only has ocean heat content increased dramatically (Figure 1.1), but more than 90% of the energy gained in the combined ocean–atmosphere system over recent decades has gone into the ocean (Rhein et al. 2013; Johnson et al. 2015).

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

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

[INSERT FIGURE 1.1 HERE]

1.3. Trends in Global Temperatures

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

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

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

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

[INSERT FIGURE 1.2 HERE]

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

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

[INSERT FIGURE 1.3 HERE]

Figure 1.4 shows the projected changes in globally averaged temperature for a range of future pathways that vary from assuming strong continued dependence on fossil fuels in energy and transportation systems over the 21st century (the high scenario is Representative Concentration Pathway 8.5, or RCP8.5) to assuming major emissions-reduction actions (the very low scenario, RCP2.6). Chapter 4: Projections describes the future scenarios and the models of Earth's climate system being used to quantify the impact of human choices and natural variability on future climate. These analyses also suggest that global surface temperature increases for the end of the 21st century are *very likely* to exceed 1.5°C (2.7°F) relative to the 1850–1900 average for all projections, with the exception of the lowest part of the uncertainty range for RCP2.6 (IPCC 2013).

[INSERT FIGURE 1.4 HERE]

----- START BOX 1.1 HERE -----

Box 1.1. Was there a "Hiatus" in Global Warming?

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

[INSERT FIGURE 1.5 HERE]

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

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

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

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

- In the Pacific Ocean, a number of interrelated features, including cooler than expected tropical ocean surface temperatures, stronger than normal trade winds, and a shift to the cool phase of the Pacific Decadal Oscillation (PDO) led to cooler than expected surface temperatures in the Eastern Tropical Pacific, a region that has been shown to have an influence on global-scale climate (Kosaka and Xie 2013).

- For most of the world's oceans, heat was transferred from the surface into the deeper ocean (Balmaseda et al. 2013; Chen and Tung 2014; Nieves et al. 2015), causing a reduction in surface warming worldwide.

- Other studies attributed part of the cause of the measurement/model discrepancy to natural fluctuations in radiative forcings, such as volcanic aerosols, stratospheric water vapor, or solar output (Solomon et al. 2010; Schmidt et al 2014; Huber and Knutti 2014; Ridley et al. 2014; Santer et al. 2014).

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

Although 2014 already set a new high in globally averaged temperature record up to that time, in 2015–2016, the situation changed dramatically. A switch of the PDO to the positive phase, combined with a strong El Niño event during the fall and winter of 2015–2016, led to months of record-breaking globally averaged temperatures in both the surface and satellite temperature records (see Figure 1.5; Trenberth 2015), bringing observed temperature trends into better agreement with model expectations (see Figure 1.6).

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

[INSERT FIGURE 1.6 HERE]

----- END BOX 1.1 HERE -----

1.4. Trends in Global Precipitation

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

[INSERT FIGURE 1.7 HERE]

The hydrological cycle and the amount of global mean precipitation is primarily controlled by the atmosphere's energy budget and its interactions with clouds (Allen and Ingram 2002). The amount of global mean precipitation also changes as a result of a mix of fast and slow atmospheric responses to the changing climate (Collins et al. 2013). In the long term, increases in tropospheric radiative effects from increasing amounts of atmospheric CO_2 (i.e., increasing CO_2 leads to greater energy absorbed by the atmosphere and re-emitted to the surface, with the additional transport to the atmosphere coming by convection) must be balanced by increased latent heating, resulting in precipitation increases of approximately 0.55% to 0.72% per °F (1% to 3% per °C) (IPCC 2013; Held and Soden 2006). Global atmospheric water vapor should increase by about 6%–7% per °C of warming based on the Clausius–Clapeyron relationship (see

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

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

1.5. Trends in Global Extreme Weather Events

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

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

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

Extreme Heat and Cold

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

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

Extreme Precipitation

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

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

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

Tornadoes and Thunderstorms

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

Winter Storms

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

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

Tropical Cyclones

Detection and attribution of trends in past tropical cyclone (TC) activity is hampered by uncertainties in the data collected prior to the satellite era and by uncertainty in the relative contributions of natural variability and anthropogenic influences. Theoretical arguments and numerical modeling simulations support an expectation that radiative forcing by greenhouse gases and anthropogenic aerosols can affect tropical cyclone activity in a variety of ways, but robust formal detection and attribution for past observed changes has not yet been realized. Since the IPCC AR5 (2013), there is new evidence that the locations where tropical cyclones reach their peak intensity have migrated poleward in both the Northern and Southern Hemispheres, in concert with the independently measured expansion of the tropics (Kossin et al. 2014). In the western North Pacific, this migration has substantially changed the tropical cyclone hazard exposure patterns in the region and appears to have occurred outside of the historically measured modes of regional natural variability (Kossin et al. 2016).

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

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

1.6. Global Changes in Land Processes

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

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

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

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

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

Natural terrestrial ecosystems are gaining carbon through uptake of CO_2 by enhanced photosynthesis due to higher CO_2 levels, increased nitrogen deposition, and longer growing seasons in mid- and high latitudes. Anthropogenic atmospheric CO_2 absorbed by land ecosystems is stored as organic matter in live biomass (leaves, stems, and roots), dead biomass (litter and woody debris), and soil carbon.

Many studies have documented a lengthening growing season, primarily due to the changing climate (Myneni et al. 1997; Menzel et al. 2006; Schwartz et al. 2006; Kim et al. 2012), and elevated CO_2 is expected to further lengthen the growing season in places where the length is water limited (Reyes-Fox et al. 2014). In addition, a recent study has shown an overall increase in greening of the Earth in vegetated regions (Zhu et al. 2016), while another has demonstrated evidence that the greening of Northern Hemisphere extratropical vegetation is attributable to anthropogenic forcings, particularly rising atmospheric greenhouse gas levels (Mao et al. 2016). However, observations (Finzi et al. 2006; Palmroth et al. 2006; Norby et al. 2010) and models (Sokolov et al. 2008; Thornton et al. 2009; Zaehle and Friend 2010) indicate that nutrient limitations and land availability will constrain future land carbon sinks.

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

Snow and ice albedo feedbacks are positive, leading to increased temperatures with loss of snow and ice extent. While land ecosystems are expected to have a net positive feedback due to reduced natural sinks of CO_2 in a warmer world, anthropogenically increased nitrogen deposition may reduce the magnitude of the net feedback (Churkina et al. 2009; Zaehle et al. 2010; Thornton et al. 2009). Increased temperature and reduced precipitation increase wildfire risk and susceptibility of terrestrial ecosystems to pests and disease, with resulting feedbacks on carbon storage. Increased temperature and precipitation, particularly at high latitudes, drives up soil decomposition, which leads to increased CO_2 and CH_4 (methane) emissions (Page et al. 2002; Ciais et al. 2005; Chambers et al. 2007; Kurz et al. 2008; Clark et al. 2010; van der Werf et al. 2010; Lewis et al. 2011). While some of these feedbacks are well known, others are not so well quantified and yet others remain unknown; the potential for surprise is discussed further in Chapter 15: Potential Surprises.

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

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

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

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

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

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

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

In addition, permafrost temperatures and active layer thicknesses have increased across much of the Arctic (Shiklomanov et al. 2012; IPCC 2013; Romanovsky et al. 2015; also see Ch. 11: Arctic Changes). Rising permafrost temperatures causing permafrost to thaw and become more discontinuous raises concerns about potential emissions of carbon dioxide and methane (IPCC 2013). The potentially large contribution of carbon and methane emissions from permafrost and the continental shelf in the Arctic to overall warming is discussed further in Chapter 15: Potential Surprises).

1.8. Global Changes in Sea Level

Statistical analyses of tide gauge data indicate that global mean sea level has risen about 8–9 inches (20–23 cm) since 1880, with a rise rate of approximately 0.5–0.6 inches/decade from 1901 to1990 (about 12–15 mm/decade; Church and White 2011; Hay et al. 2015; also see Ch. 12: Sea Level Rise). However, since the early 1990s, both tide gauges and satellite altimeters have recorded a faster rate of sea level rise of about 1.2 inches/decade (approximately 3 cm/decade; Church and White 2011; Nerem et al. 2010; Hay et al. 2015), resulting in about 3 inches (about 8 cm) of the global rise since the early 1990s. Nearly two-thirds of the sea level rise measured since 2005 has resulted from increases in ocean mass, primarily from land-based ice melt; the remaining one-third of the rise is in response to changes in density from increasing ocean temperatures (Merrifield et al. 2015).

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

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

1.9. Recent Global Changes Relative to Paleoclimates

Paleoclimate records demonstrate long-term natural variability in the climate and overlap the records of the last two millennia, referred to here as the "Common Era". Before the emissions of greenhouse gases from fossil fuels and other human-related activities became a major factor over the last few centuries, the strongest drivers of climate during the last few thousand years had been volcanoes and land-use change (which has both albedo and greenhouse gas emissions effects) (Schmidt et al. 2011). Based on a number of proxies for temperature (for example, from tree rings, fossil pollen, corals, ocean and lake sediments, and ice cores), temperature records are available for the last 2,000 years on hemispherical and continental scales (Figures 1.8 and 1.9) (Mann et al. 2008; PAGES 2K Consortium 2013). High-resolution temperature records for North America extend back less than half of this period, with temperatures in the early parts of the Common Era inferred from analyses of pollen and other archives. For this era, there is a general cooling trend, with a relatively rapid increase in temperature over the last 150–200 years (Figure 1.9, PAGES 2k Consortium 2013). For context, global annual-averaged temperatures for 1986–2015 are likely much higher, and appear to have risen at a more rapid rate during the last 3 decades, than any similar period possibly over the past 2,000 years or longer (IPCC [2013] makes a similar statement, but for the last 1,400 years because of data quality issues before that time).

[INSERT FIGURES 1.8 AND 1.9 HERE]

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

Modeling studies suggest that the Eemian period warming can be explained in part by the hemispheric changes in solar insolation from orbital forcing as a result of cyclic changes in the shape of Earth's orbit around the sun (e.g., Kaspar et al. 2005), even though greenhouse gas concentrations were similar to preindustrial levels. Equilibrium climate with modern greenhouse gas concentrations (about 400 ppm CO_2) most recently occurred 3 million years ago during the Pliocene. During the warmest parts of this period, global temperatures were 5.4°F–7.2°F (3°C–4°C) higher than today, and sea levels were about 82 feet (25 meters) higher (Haywood et al. 2013).

----- START BOX 1.2 HERE -----

Box 1.2: Advances Since NCA3

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

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

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

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

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

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

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

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

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

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

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

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

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

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

----- END BOX 1.2 HERE -----

TRACEABLE ACCOUNTS

Key Finding 1

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

Description of evidence base

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

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

Major uncertainties

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

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

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

Summary sentence or paragraph that integrates the above information

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

Key Finding 2

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

Description of evidence base

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

Major uncertainties

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

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

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

Summary sentence or paragraph that integrates the above information

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

Key Finding 3

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

Description of evidence base

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

Major uncertainties

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

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

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

Summary sentence or paragraph that integrates the above information

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

Key Finding 4

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

Description of evidence base

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

Major uncertainties

Key remaining uncertainties relate to the precise magnitude and nature of changes at global, and particularly regional, scales, and especially for extreme events and our ability to simulate and attribute such changes using climate models. Of particular importance are remaining uncertainties in the understanding of feedbacks in the climate system, especially in ice-albedo and cloud cover feedbacks. Continued improvements in climate modeling to represent the physical processes affecting Earth's climate system are aimed at reducing uncertainties. Monitoring and observation programs also can help improve the understanding needed to reduce uncertainties.

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

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

Summary sentence or paragraph that integrates the above information

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

Key Finding 5

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

Description of evidence base

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

Major uncertainties

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

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

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

Summary sentence or paragraph that integrates the above information

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

Key Finding 6

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

Description of evidence base

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

Major uncertainties

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

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

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

Summary sentence or paragraph that integrates the above information

The Key Finding and supporting text summarizes extensive evidence documented in the climate science peer-reviewed literature. There has been an extensive increase in the understanding of past climates on our planet, including a number of new findings since NCA3.

FIGURES

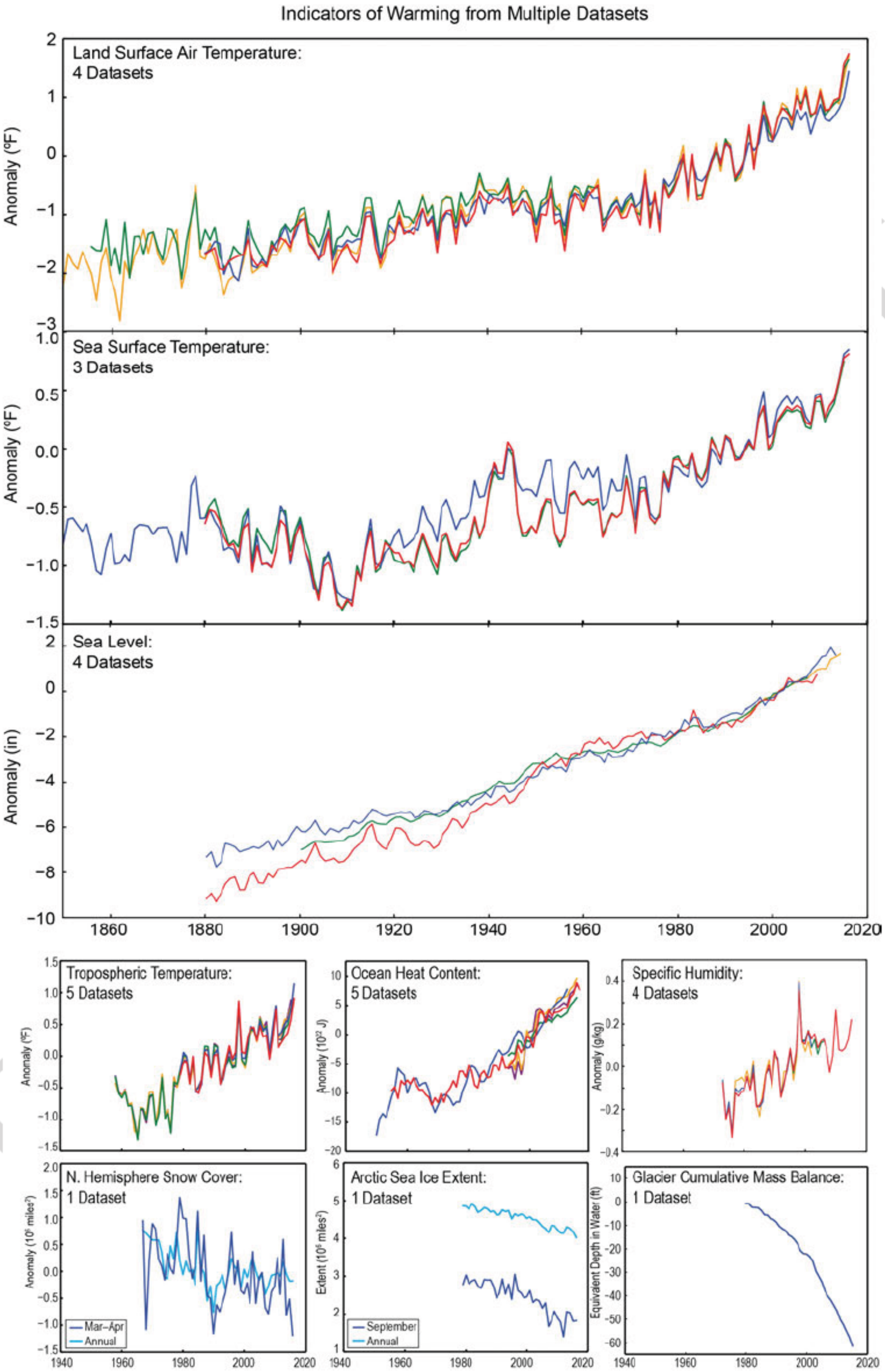
Indicators of Warming from Multiple Datasets
Land Surface Air Temperature:
4 Datasets
Anomaly (°F)
2
1
0
−1
−2
−3
Sea Surface Temperature:
3 Datasets
Anomaly (°F)
1.0
0.5
0.0
−0.5
−1.0
−1.5
Sea Level:
4 Datasets
Anomaly (in)
2
0
−2
−4
−6
−8
−10
1860
1880
1900
1920
1940
1960
1980
2000
2020
Tropospheric Temperature:
5 Datasets
Anomaly (°F)
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
Ocean Heat Content:
5 Datasets
Anomaly (10²² J)
10
5
0
-5
-10
-15
-20
Specific Humidity:
4 Datasets
Anomaly (g/kg)
0.4
0.2
0.0
-0.2
-0.4
N. Hemisphere Snow Cover:
1 Dataset
Anomaly (10⁶ miles²)
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
Mar–Apr
Annual
Arctic Sea Ice Extent:
1 Dataset
Extent (10⁶ miles²)
6
5
4
3
2
1
September
Annual
Glacier Cumulative Mass Balance:
1 Dataset
Equivalent Depth in Water (ft)
10
0
-10
-20
-30
-40
-50
-60
1940
1960
1980
2000
2020

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

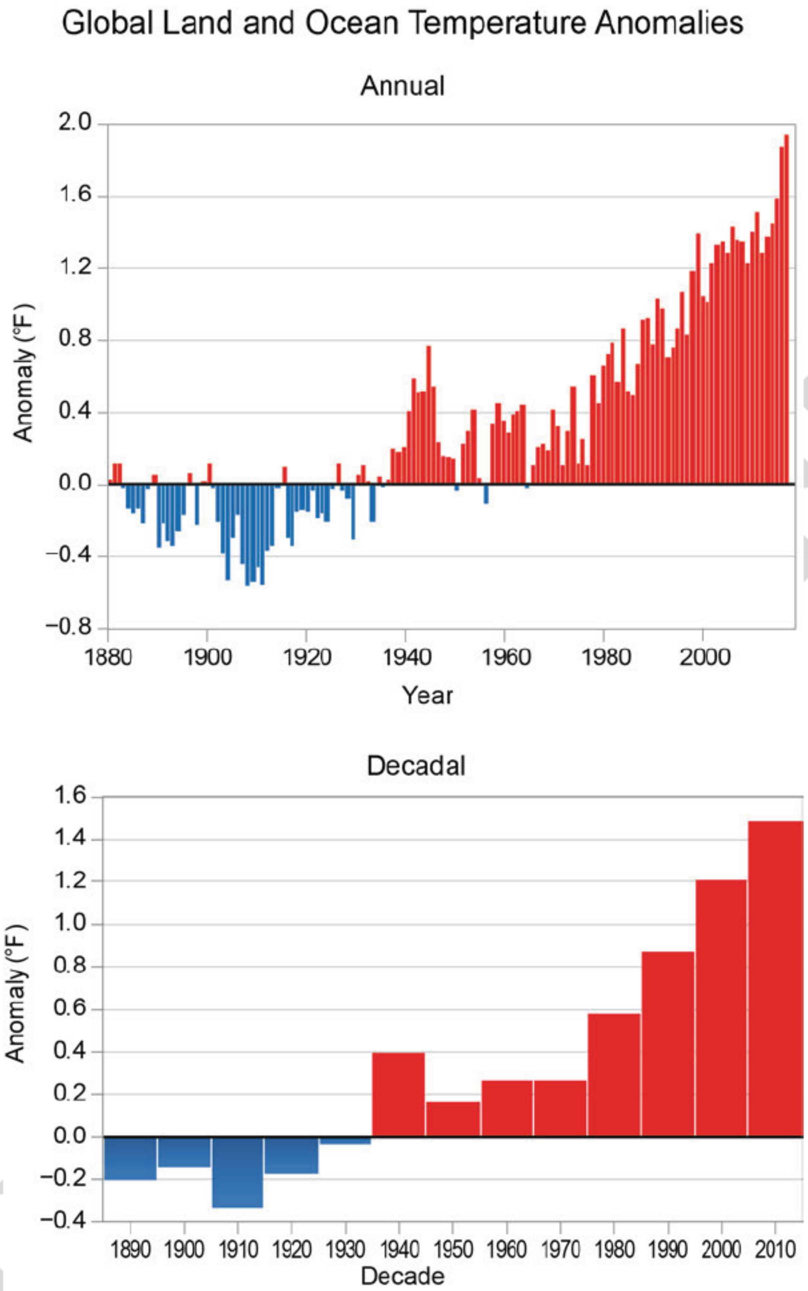

Figure 1.2. Top: Global annual average temperatures (as measured over both land and oceans) for 1880–2016 relative to the reference period of 1901–1960; red bars indicate temperatures above the average over 1901–1960, and blue bars indicate temperatures below the average. Global annual average temperature 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:

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

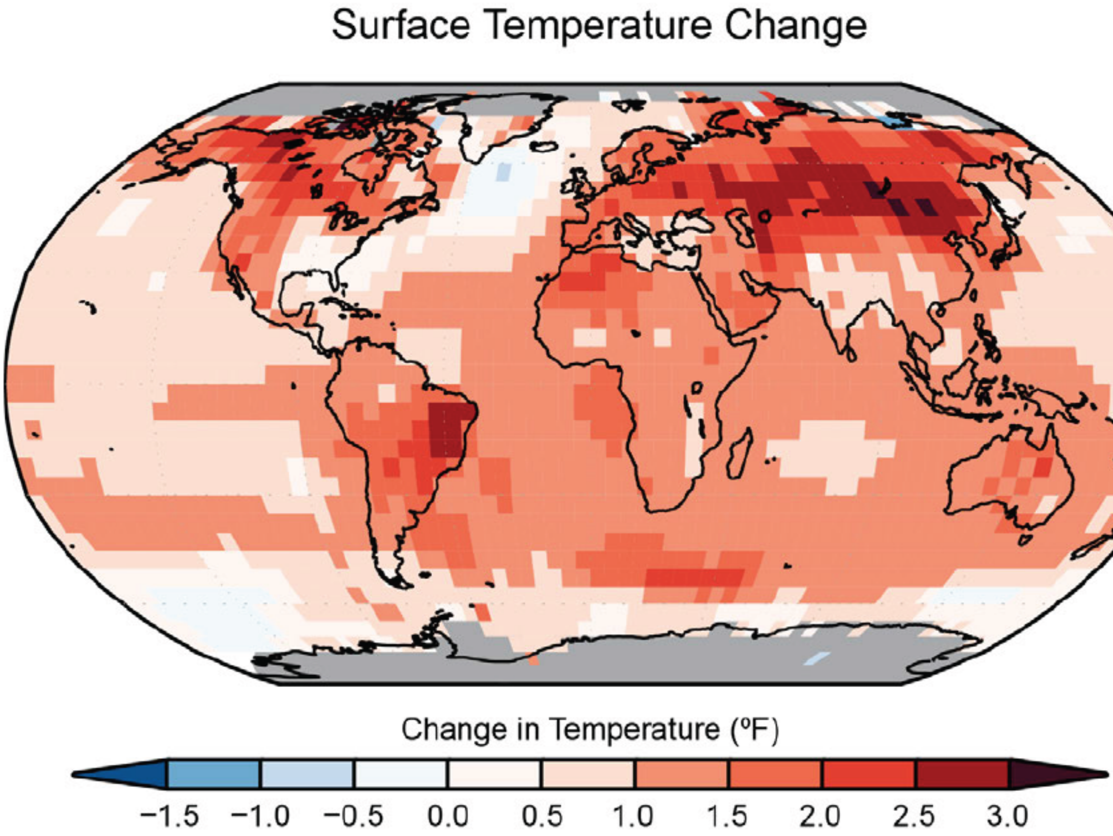

Figure 1.3. Surface temperature change (in °F) for the period 1986–2015 relative to 1901–1960 from the NOAA National Centers for Environmental Information's (NCEI) surface temperature product. For visual clarity, statistical significance is not depicted on this map. Changes are generally significant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

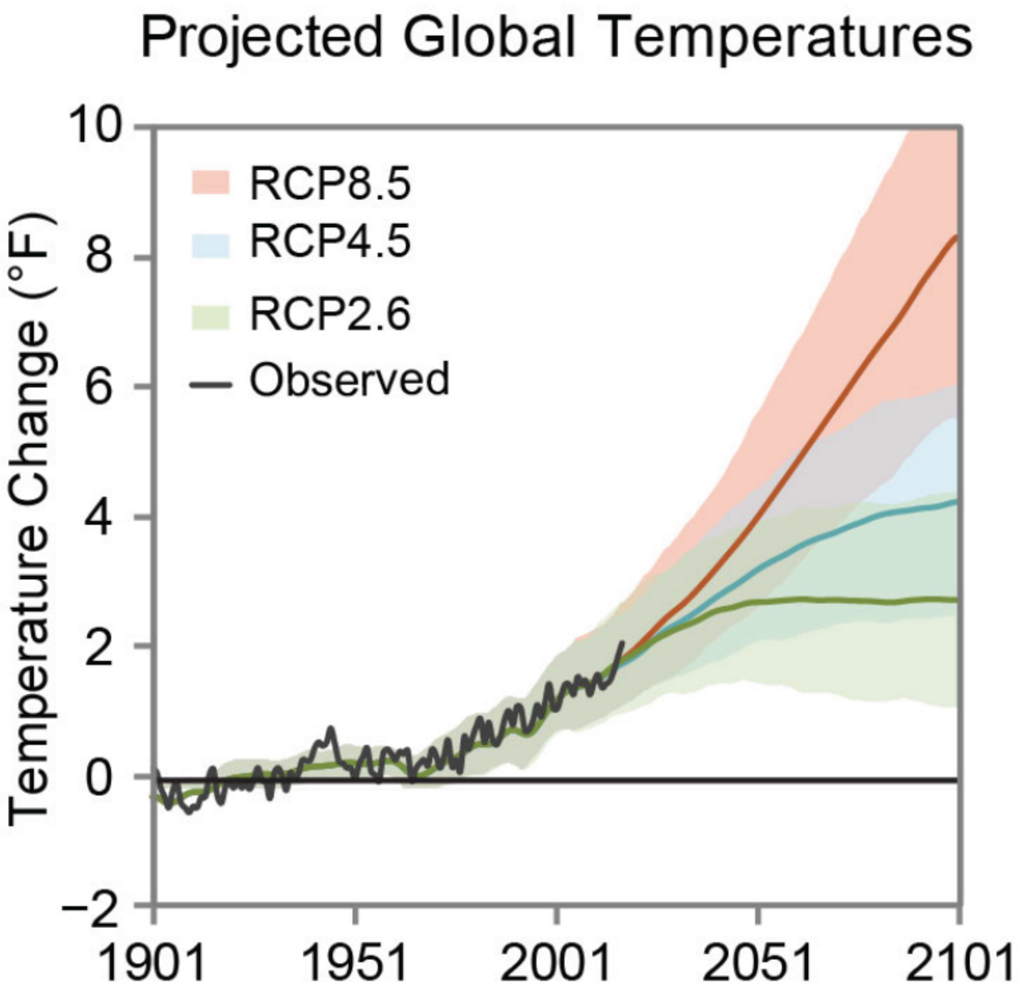

Figure 1.4. Multimodel simulated time series from 1900 to 2100 for the change in global annual mean surface temperature relative to 1901–1960 for a range of the Representative Concentration Pathways (RCPs; see Ch. 4: Projections for more information). These scenarios account for the uncertainty in future 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).

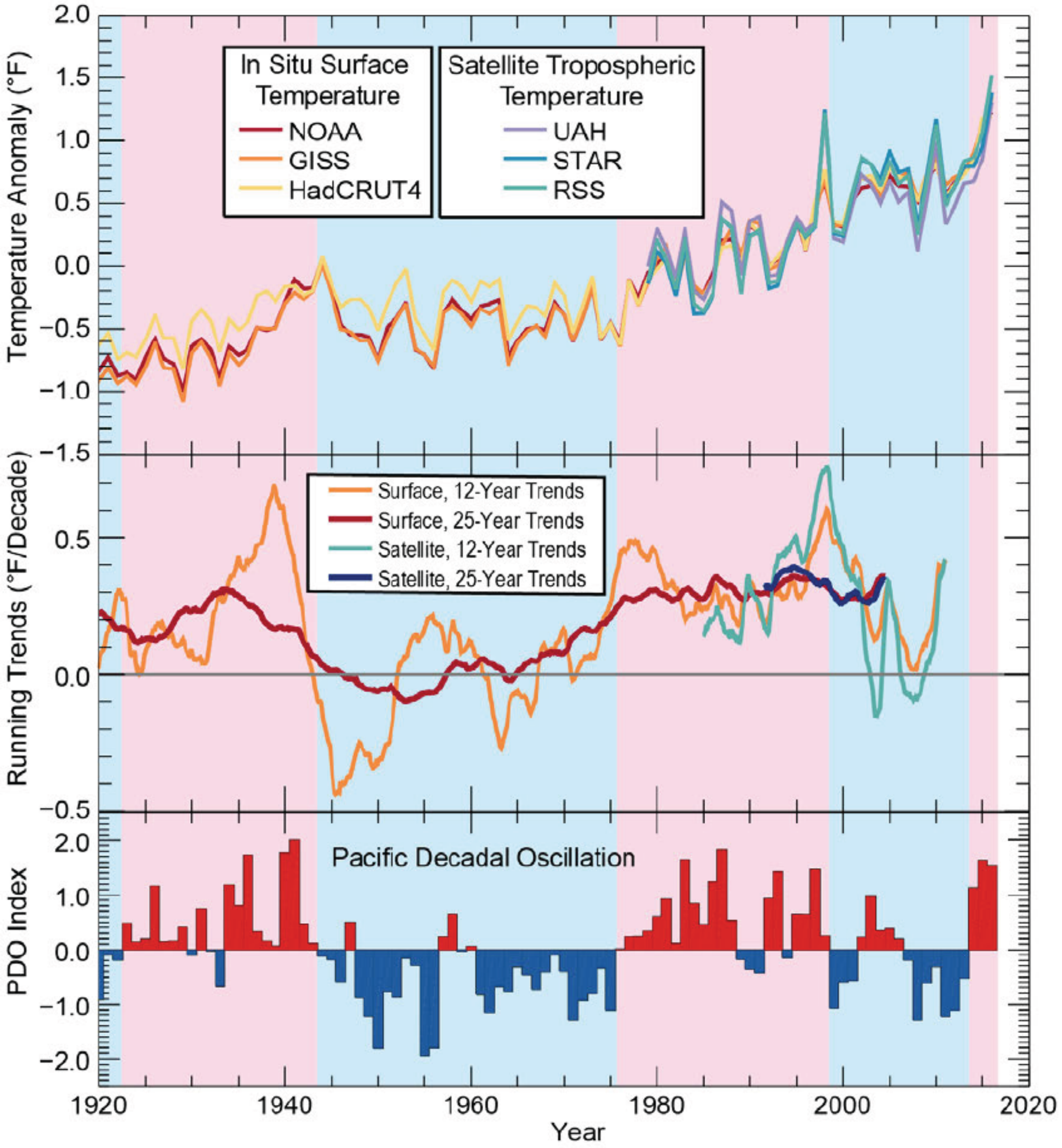

Figure 1.5. Panel A shows the annual mean temperature anomalies relative to a 1901–1960 baseline for global mean surface temperature and global mean tropospheric temperature. Short-term variability is superposed on a long-term warming signal, particularly since the 1960s. Panel B shows the linear trend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

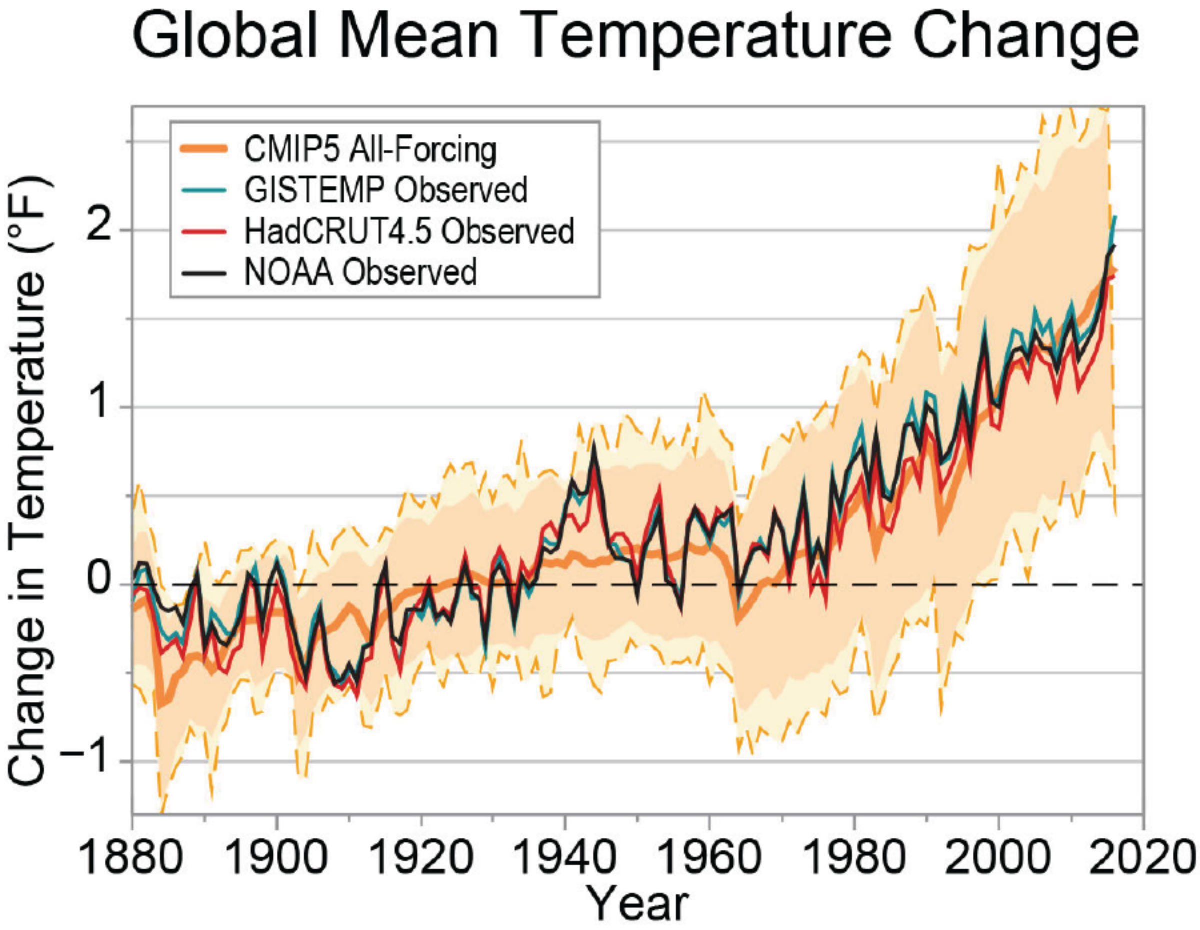

Figure 1.6. Comparison of global mean temperature anomalies (°F) from observations (through 2016) and the CMIP5 multimodel ensemble (through 2016), using the reference period 1901-1960. The CMIP5 multimodel ensemble (black) is constructed from blended surface temperature (ocean regions) and surface air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

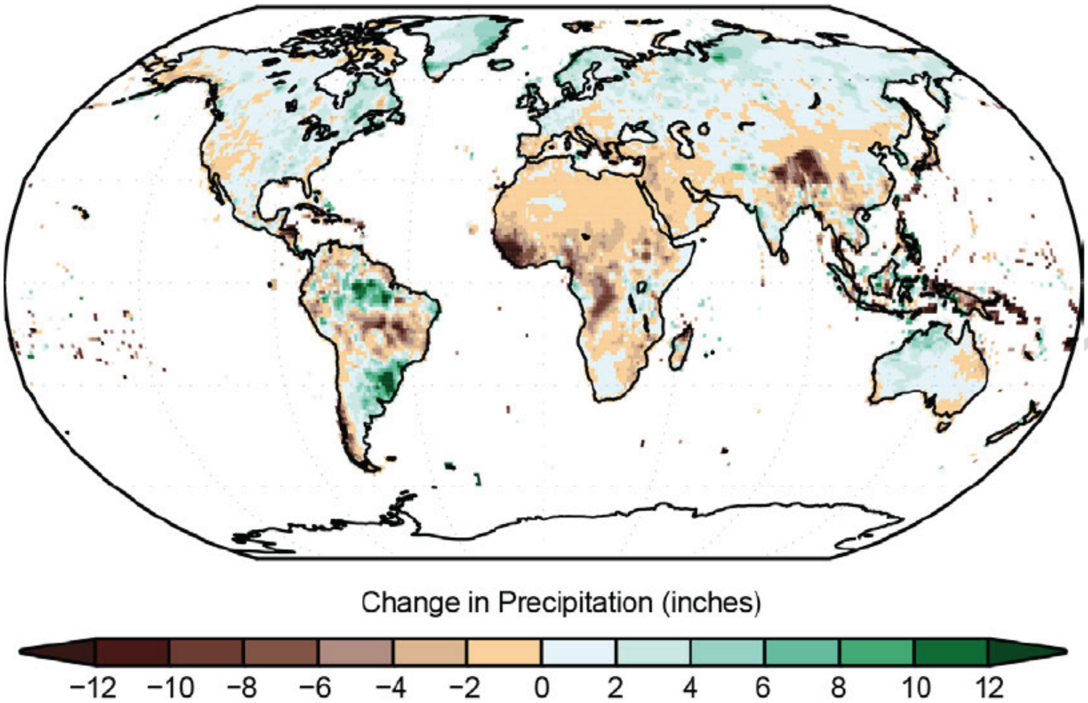

Figure 1.7. Surface annually averaged precipitation change (in inches) for the period 1986–2015 relative to 1901–1960. The data is from long-term stations, so precipitation changes over the ocean and Antarctica cannot be evaluated. The trends are not considered to be statistically significant because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

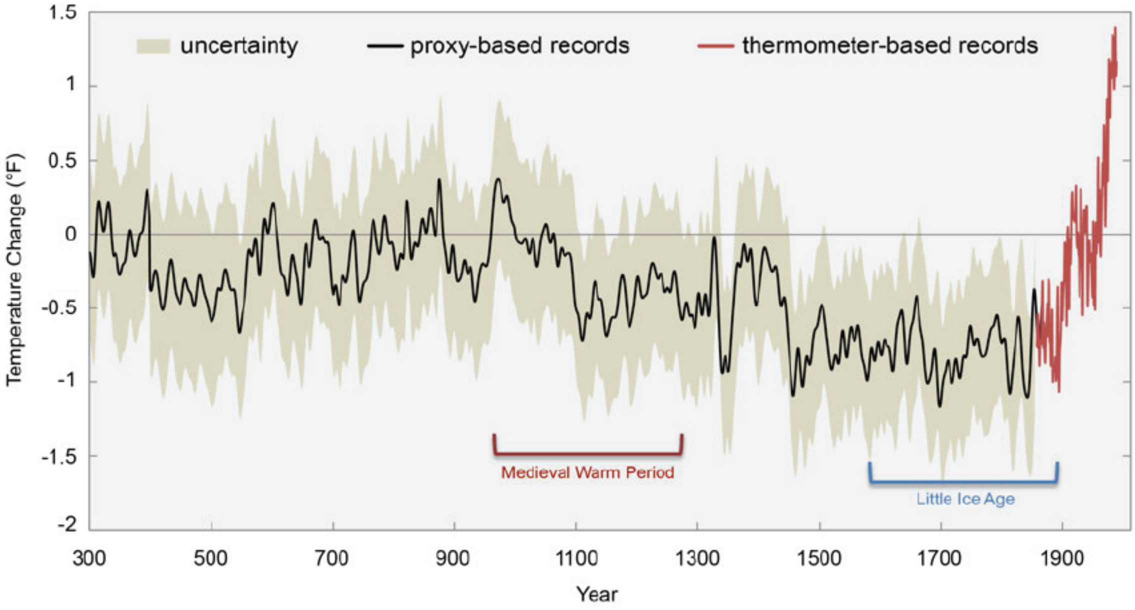

Figure 1.8. Changes in the temperature of the northern hemisphere from surface observations (in red) and from proxies (in black; uncertainty range represented by shading) relative to 1961–1990 average temperature. If this graph were plotted relative to 1901–1960 instead of 1961–1990, the temperature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

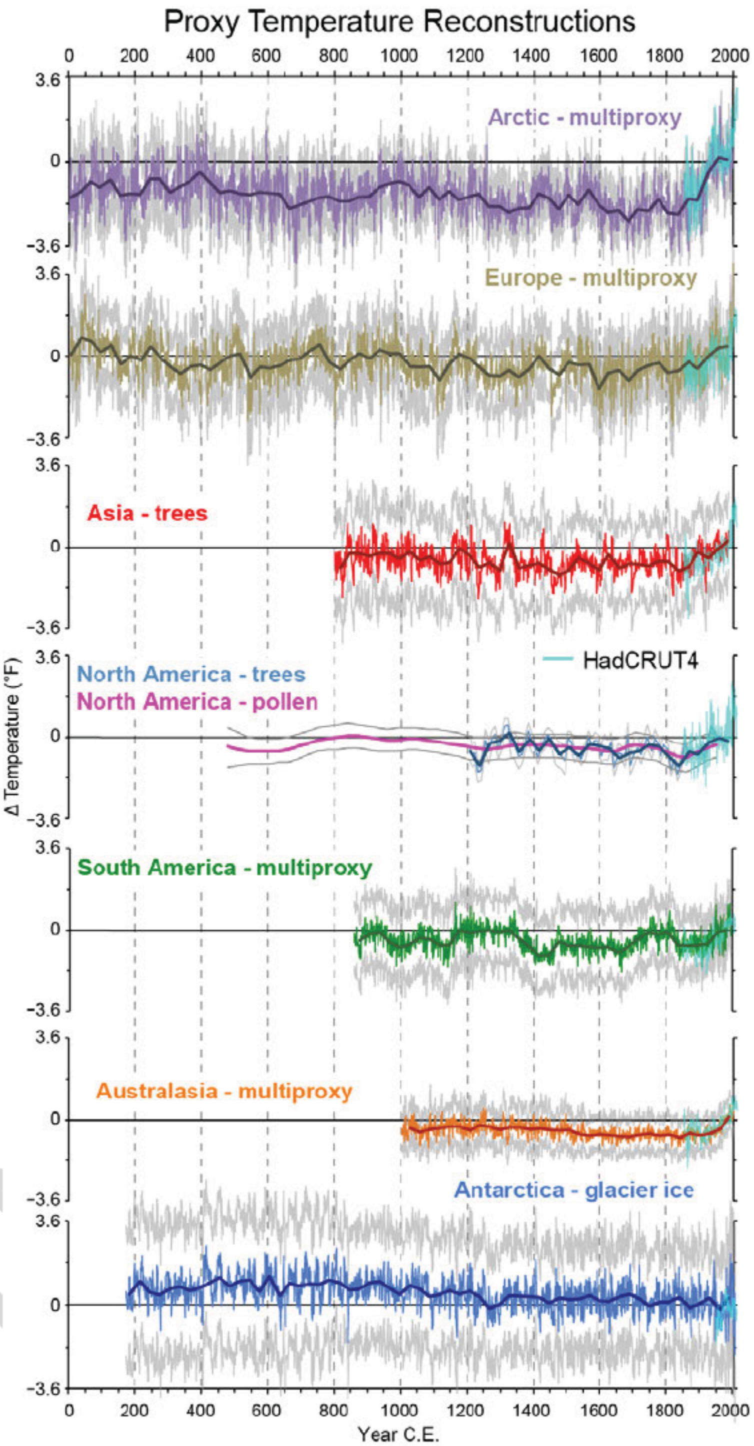

Figure 1.9. Proxy temperatures reconstructions for the seven regions of the PAGES 2K Network. Temperature anomalies are relative to the 1961–1990 reference period. If this graph were plotted relative to 1901–1960 instead of 1961–1990, the temperature changes would 0.47°F (0.26°C) higher. Grey lines around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

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

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