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The urgency of Arctic change

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ABSTRACT

This article provides a synthesis of the latest observational trends and projections for the future of the Arctic. First, the Arctic is already changing rapidly as a result of climate change. Contemporary warm Arctic temperatures and large sea ice deficits (75% volume loss) demonstrate climate states outside of previous experience. Modeled changes of the Arctic cryosphere demonstrate that even limiting global temperature increases to near 2 °C will leave the Arctic a much different environment by mid-century with less snow and sea ice, melted permafrost, altered ecosystems, and a projected annual mean Arctic temperature increase of +4 °C. Second, even under ambitious emission reduction scenarios, high-latitude land ice melt, including Greenland, are foreseen to continue due to internal lags, leading to accelerating global sea level rise throughout the century. Third, future Arctic changes may in turn impact lower latitudes through tundra greenhouse gas release and shifts in ocean and atmospheric circulation. Arctic-specific radiative and heat storage feedbacks may become an obstacle to achieving a stabilized global climate. In light of these trends, the precautionary principle calls for early adaptation and mitigation actions.

1. Introduction

During September 2017 the icebreaker *Healy* headed north in the Chukchi Sea, north of the Bering Strait, with scientists in search of sea ice to study biological and chemical oceanographic changes in the "new Arctic". Where in previous years there had been sea ice, this time they found no ice in their target area. This anecdote is an example of a larger truth—the Arctic is currently changing at an unprecedented rate, driven by increasing temperatures due to increases in atmospheric greenhouse gas (GHG) concentrations.

This article provides a synthesis of the latest observed trends in the Arctic cryosphere, and their feedbacks to the global climate system, and builds on recent assessments by the Arctic Monitoring and Assessment Program (AMAP, 2017a,b,c,d). The impact of climate change on the Arctic will remain large even if much of the world adopts aggressive mitigation of GHG emissions. The stated goal of limiting global temperature rise to "well below" 2 °C by the end of the century (IPCC, 2018; UNFCCC, 2015; Boucher et al., 2016; Hulme, 2016; Sigmond et al., 2018) would result in an annual Arctic temperatures increase by ~4 °C by mid-century, with major consequences to local and global climate, ecosystems and societal systems.

These trends do come with uncertainty. For example, the rates of change for ongoing Arctic cryospheric feedbacks are substantially positive, but are incompletely understood and may strengthen over the next decades. Such feedbacks involve albedo and heat storage shifts from loss of glaciers, sea ice, and snow cover; increased carbon releases from permafrost; shifts in clouds and increases in water vapor; and atmospheric and ocean transport changes (Coumou et al., 2014; Pistone et al., 2014; Alraddawi et al., 2017). The magnitude of exactly how much changes in the Arctic will affect the larger global climate system is also open to question. Continued scientific research is required to better underpin both mitigation and adaptation planning.

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Fig. 1. Recent Arctic erosion and loss of permafrost along the Alaskan coast near Drew Point. Thawing land ice (white) is clearly visible. This is part of the current rapid changes happening in the Arctic. Photo from USGS (https://on.doi.gov/arctic-coasts).

2. Contemporary conditions

The collapsing ice-rich permafrost along the Arctic coast of Alaska shown in Fig. 1 demonstrates two features of the contemporary Arctic: *irreversible* changes from release of water, CO_2, and methane from thawing permafrost, and *accelerating interacting* changes caused by increased wave action driving erosion, given more sea-ice-free coastlines.

While observations in any one year are the combination of trends and internal climate variability, three recent examples of contemporary multi-year persistent states occur outside the envelope of past experience: large warm air temperature anomalies in winter, record low winter sea ice extent, and expanded land ice melt seasons. Arctic winters in 2016 (January through March) and in 2018 (January through February) saw extreme warm temperature anomalies; nearly double (+6 °C) those of previous record highs (Fig. 2A) (Overland and Wang, 2016). Further, sea ice extents in four successive winters 2015–2018 (January through March) were at record low levels (Fig. 2B). Since thin sea ice grows faster than thick sea ice for the same atmospheric conditions, sea ice in winter normally rapidly returned to previous values, for example after the record low minimum summer sea ice in 2012; however, this was not the case for winters 2015–2018. Because multi-year sea ice coverage, extent and thickness, is an integrator of climate over years to decades, its loss is a sensitive indicator of Arctic and global climate change. Major sea ice shifts have occurred; the lateral extent of multiyear old, thick sea ice extent is currently 60% below that of the 1980s (AMAP, 2017a; Kwok, 2018) and September Arctic sea ice volume has reduced by 75% since 1979 (Schweiger et al., 2011, updated A. Schweiger). In addition, the Greenland ice sheet exhibited surface melt significantly earlier and stronger in some recent years (Kintisch, 2017).

Looking forward over the next decade, expected rates of change are based on extrapolation and models. Attributing new record high temperatures or low values in sea ice extent to climate change can be challenging owing to the short record length of change (decades) relative to the natural variability. For example, based on large ensemble simulations using the Community Earth System Model, internal variability alone can lead to a prediction uncertainty of about two decades for the timing of an ice-free Arctic summer (Jahn et al., 2016). Recent reviews suggest that Arctic climate change may be occurring at a rate that is greater than that projected by global climate models (AMAP, 2017a; WMO, 2017). The range of results from climate model hindcasts and projections, and observational limitations, add quantitative uncertainty in prediction of future Arctic climate states (Hawkins and Sutton, 2012; Najafi et al., 2015; Niederdrenk and Notz, 2018). That said, contemporary extremes are consistent with a rapidly changing Arctic cryosphere.

3. What will happen to the Arctic in the future?

3.1. GHG concentration scenarios and global temperatures

In looking beyond a decade into the future, we utilize temperature projections under the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) scenarios from Coupled Model Intercomparison Project Phase 5 (CMIP5) of the World Climate Research Programme), referred to as RCPs (Representative Concentration Pathway). Of primary interest is RCP 4.5, which is an aggressive but not implausible mitigation scenario (IPCC, 2013, Table SPM.1) that leads to temperature rises somewhat above the global mitigation aim of +2 °C by the end of the 21st century (IPCC, 2018; UNFCCC, 2015). Simulations by global climate models under the RCP 4.5 emissions scenario show a global mean warming for 2046–2065 of 2.0 ± 0.3 °C compared to 1900–1950 levels with near-stabilized GHG concentrations near 540 ppm in the second half of the century and globally averaged air temperatures in 2100 of +2.4 ± 0.5 C (blue line, Fig. 3A). Thus, a +2 °C limit goal falls below the average for RCP 4.5 but within the range of uncertainty of RCP 4.5 projections (Fig. 3A).

IPCC AR5 (IPCC, 2013) also consider a low emission scenario, RCP 2.6, which requires both a halt of anthropogenic GHG emissions over the next few decades and assumes negative emissions in the second half of the 21st century. RCP 2.6 produces a global warming of ~1.6 °C for 2046–2065 and stabilizes more of the Arctic cryosphere than for RCP 4.5 conditions (Henley and King, 2017; Screen and Williamson, 2017; IPCC, 2018). RCP 2.6 is ambitious as discussed by many authors and reviewed by IPCC (Fuss et al., 2014; Knutti et al., 2016; Schellnhuber et al., 2016; Schleussner et al., 2016; Henley and King, 2017; Millar et al., 2017; Ricke et al., 2017; Rockström et al., 2017; IPCC, 2018). A high end, "business as usual" emission scenario is given by RCP 8.5, also shown in Fig. 3. We focus on Arctic impacts of RCP 4.5 as a representative baseline emission scenario leading to leveling-off of global temperatures slightly above +2 °C by the end of the century. This represents the best proxy for projecting future changes if the pledges of the Paris Climate Agreement are fulfilled.

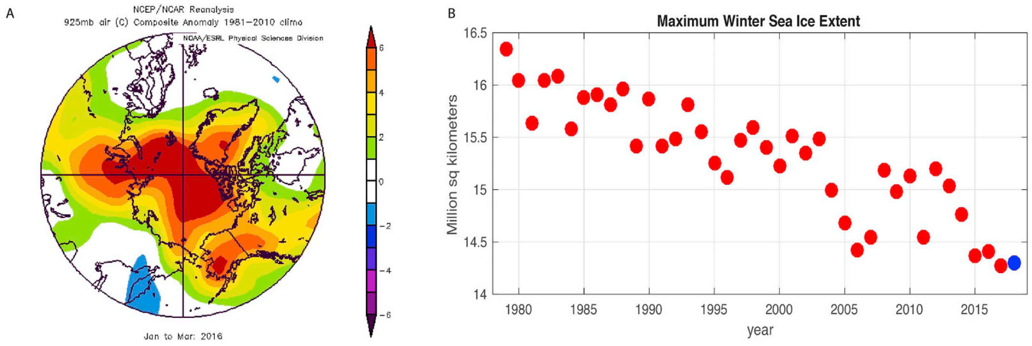

Fig. 2. Examples of recent Arctic changes paint a picture of a rapidly and irreversibly changing Arctic cryosphere: A) Extreme winter 2016 Arctic temperature anomalies of ~6 °C in the central Arctic. These anomalies were roughly double the maximum of previous years (Overland and Wang, 2016). Winter 2018 had similar extremes. Data from the NOAA/NCAR reanalysis using the NOAA/ESRL online plotting routines. B) Winter sea ice extents were below previous values during winter 2015–2018. Sea ice data were obtained from the National Snow and Ice Data Center. Blue dot denotes 2018. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

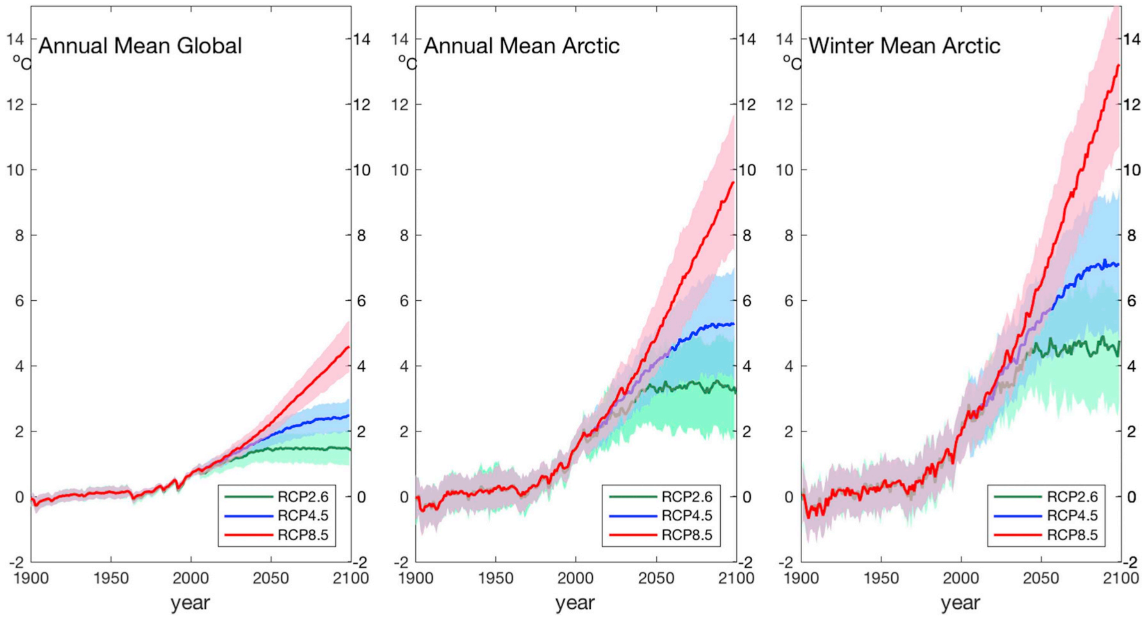

Fig. 3. Projections of annual mean surface air temperatures for A) the globe and B) the Arctic (60–90° N), averaged over available CMIP5 global climate models (36 models for RCP 4.5 and RCP 8.5, and 19 models for RCP 2.6) and expressed as departures from the mean of 1900–1950, near the pre-industrial level. The blue line is the ensemble mean for RCP 4.5, the green line is for RCP 2.6 and red for RCP 8.5. Shaded areas denote ± one standard deviation among the models from the ensemble mean. The right panel (C) shows the corresponding projections of Arctic winter (Dec–Feb) temperature anomalies. For the same future years, note that Arctic temperature increases, and especially winter, are considerably larger than the global mean temperature changes. The envelope about the central lines in Fig. 3 illustrate the range of uncertainty arising from both model differences and internal modeled climate system variability. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3.2. Arctic air temperatures

Observed and projected annual average Arctic warming (north of 60° N) is approximately twice the global mean (Fig. 3A and B). This ratio of 2:1 for annual Arctic to global surface mean air temperature change, one definition of Arctic Amplification, is a robust for the future in at least the last two generations of global climate models (Kattsov and Pavlova, 2015). Winter temperature (Fig. 3C) exhibits greater increases of 5.8 ± 1.5 °C by mid-century and more than 7.1 ± 2.3 °C by 2100 under RCP 4.5. Arctic projections highlight the difference between the near future (before mid-century) and the long term (beyond 2040) for Arctic warming. Past, present, and near-future emissions have locked in near-term temperature increases (Mahlstein and Knutti, 2012; Gillett et al., 2013). Only in the second half of the 21st century do projections from different RCPs significantly diverge due to different emissions scenarios (AMAP, 2017a). Changes in Arctic air temperatures are driving changes in the Arctic cryosphere as discussed in the next section.

3.3. Projections for the Arctic cryosphere

Even if the world achieves maintaining global temperatures near 2 °C, the Arctic will have a distinctly different environment by mid-century. By continuing present trends and projections, the melt season will arrive earlier and last longer—leading to shorter snow and ice durations. Even under the RCP4.5 GHG reduction scenario, the resulting warming will stress Arctic ecosystems and societal systems (IPCC, 2013; AMAP, 2017a,b,c,d; IPCC, 2018) and have potential global impacts. Four cryospheric features of importance are: losses of sea ice, snow, permafrost, and land ice; all are projected to occur over the next half century, with strong dependencies after 2040 on which emission scenario is followed.

Sea Ice: Arctic sea ice has undergone and continues a regime shift from multiyear to seasonal sea ice with reduced extents and thickness. Averages of global climate models for RCP 4.5 approach a sea-ice-free Arctic Ocean in late summer near the end of the century (Fig. 4); however, some models suggest that, in accord with extrapolation of the recent trends, a seasonally ice-free Arctic Ocean may occur within the next few decades, (Massonnet et al., 2012; Stroeve et al., 2012; Overland and Wang, 2013; Rogers et al., 2015). Some summer sea ice remains in projections for the late 21st century under RCP 2.6 (Screen and Williamson, 2017; Jahn, 2018; Niederdrenk and Notz, 2018). The lack of model agreement for sea ice extent (Fig. 4), even for hindcasts, suggests residual inadequacies in model representation of not only sea ice extent but other Arctic processes (atmosphere, ocean and cryosphere) that affect sea ice. Some models may be more realistic than others, but metrics for model selection remain controversial (Overland and Wang, 2013; Notz et al., 2016; Massonnet et al., 2018).

Snow: Snow extent has decreased in recent decades especially during spring (Fig. 5). Projected changes in Arctic snow cover include a 10–20% duration decrease over most of the Arctic by mid-century, but with larger (> 30%) decreases over the European sector, western Alaska, and during late spring (AMAP, 2017a). This trend will continue as Arctic temperatures continue to rise, but model projections show that efforts to reduce GHG emissions could allow for a stabilization of Arctic snow cover loss by the end of the 21st century. Projections show future Arctic precipitation increases, and a larger fraction of the precipitation falls as rain rather than snow (AMAP, 2017a).

Permafrost: Societal impacts on infrastructure from permafrost warming will increase substantially between the current decade to mid-century (Fig. 6; AMAP, 2017a). Model projections show a 20% decrease in Northern Hemisphere near-surface permafrost area from roughly 15 M km^2 at present to 12 M km^2 by 2040, with little dependence on the RCP scenario (Arzhanov et al., 2013; Slater and Lawrence, 2013). For RCP 4.5, relative to present, there is a 50% loss of permafrost area by 2080. Under, RCP 2.6 and 4.5 near surface permafrost area stabilize at the end of the century.

Land Ice: With atmospheric and ocean warming over the century, even with a successful limitation of mean global warming near 2 °C, projected mass loss from land ice does not stabilize before the end of the

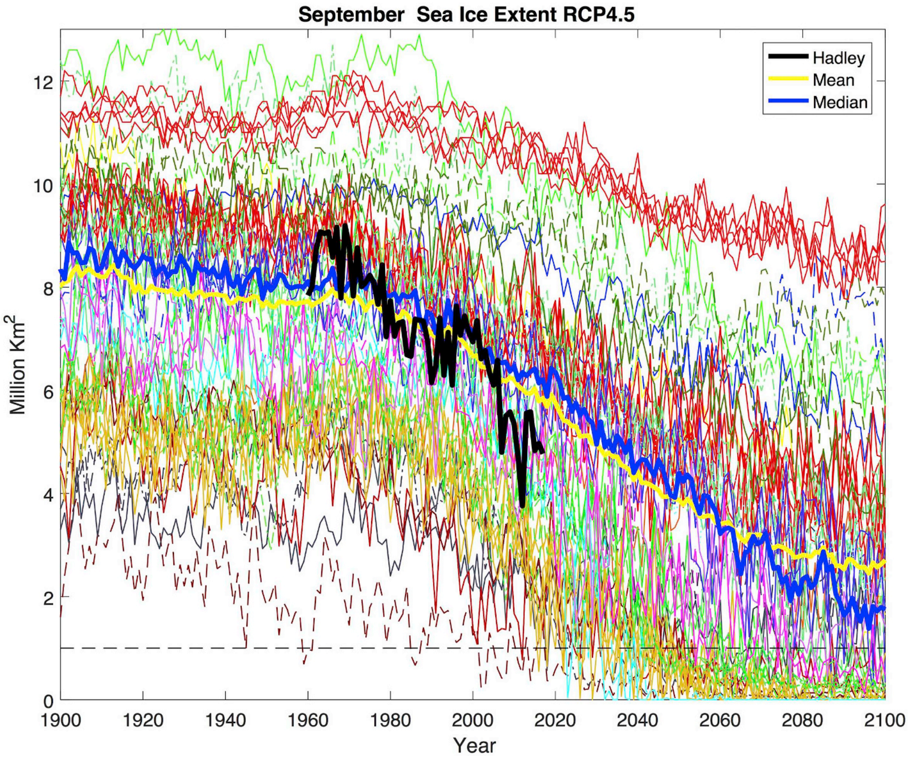

Fig. 4. September sea ice extent based on 82 ensemble members from 36 CMIP5 models under the RCP 4.5 scenario. Each thin colored line represents one member from a model. Up to five members per model are shown. The thick yellow line is the simple arithmetic mean of all ensemble members, and the blue line illustrates the median value. The thick black line represents observations based on the adjusted HadISST ice/sea ice analysis (https://www.metoffice.gov.uk/hadobs/hadisst/data/download.html). The horizontal black dashed line marks the 1.0 M km^2 value, which indicates a nearly sea ice-free summer Arctic (Wang and Overland, 2009). The median suggests a sea-ice-free Arctic Ocean in late summer near the end of the century under RCP 4.5. However, observations and some models suggest that the Arctic Ocean could be seasonally ice-free significantly sooner (10–30 years; Overland and Wang, 2013). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

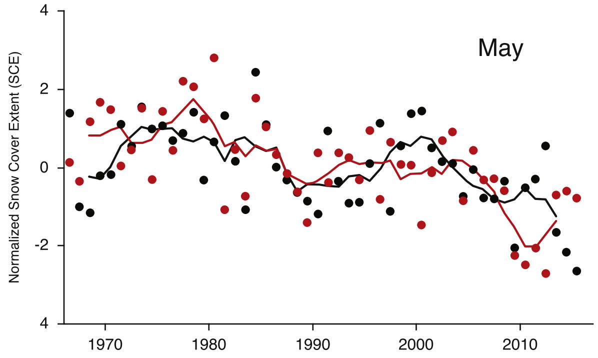

Fig. 5. May Arctic (land areas > 60°N) snow cover extent standardized (and thus unitless) anomaly time series for 1967–2016 (with respect to the 1981–2010 mean and standard deviation) from the NOAA CDR product (AMAP, 2017a; Estilow et al., 2015). Black dots are for North American Arctic and red dots are for Eurasian Arctic. Solid lines depict 5-year running means. Overall, snow extent in the Arctic has decreased in recent decades. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

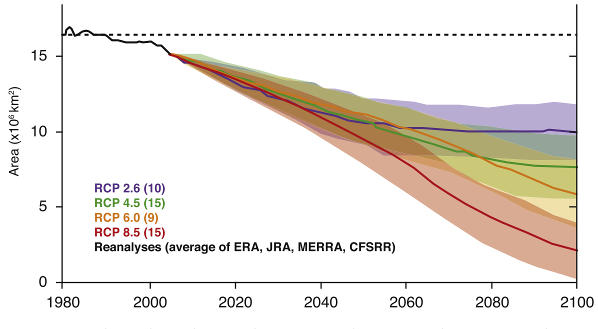

Fig. 6. Projected northern hemisphere permafrost area show a 20% decrease by 2040, leading to substantial impacts on Arctic infrastructure. Figure from Slater and Lawrence (2013).

21st century because of their slow response times of land ice masses, especially for the Greenland ice sheet (AMAP, 2017a). Just to be in equilibrium with current (1981–2010) temperatures, Arctic glaciers should lose an additional ~35% of their volume (Mernild et al., 2013; Shepherd and Nowicki, 2017). This delayed impact for land ice loss is illustrated in Fig. 7 with large differences in the amount of land ice loss between 2030 and 2080 (AMAP, 2017a; Rahmstorf, 2007).

The summer air temperature "viability threshold" that triggers irreversible wastage of the Greenland ice sheet was previously estimated to be for an annual global temperature increase of 2–5 °C (Gregory and Huybrechts, 2006; Huybrechts et al., 2011). An updated estimate based on a higher resolution simulation that explicitly incorporates albedo and elevation feedbacks suggests a lower loss threshold: 0.8–3.2 °C (95% confidence range) (Robinson et al., 2012) with 1.6 °C above pre-industrial conditions as a best estimate. It is likely that the Greenland ice sheet enters a phase of irreversible loss under the RCP 4.5 scenario.

4. How will changes in the Arctic affect the rest of the world?

The Arctic is linked to the global climate system through north-south heat and water exchanges, atmosphere and ocean circulation, river discharge, and the global carbon cycle (Brown and Caldeira, 2017; Ceppi and Gregory, 2017; Huang et al., 2017). There is growing evidence that the Arctic cryosphere has the potential to affect humans outside the Arctic through sea level rise and influence on atmospheric circulation. Other physical global impacts include potential increases of carbon dioxide and methane releases from previously frozen ground and effects on ocean thermohaline circulation.

4.1. *Patterns of atmospheric circulation*

Shifts in Arctic sea ice and snow cover and increased surface temperatures are warming the lower atmosphere in the Arctic, which decreases air density and north-south horizontal pressure gradients and thus influences wind patterns and the jet stream. There is evidence for regional Arctic/midlatitude weather connections from Barents-Kara sea ice loss and cold air outbreaks into eastern Asia (Wu et al., 2011; Kim

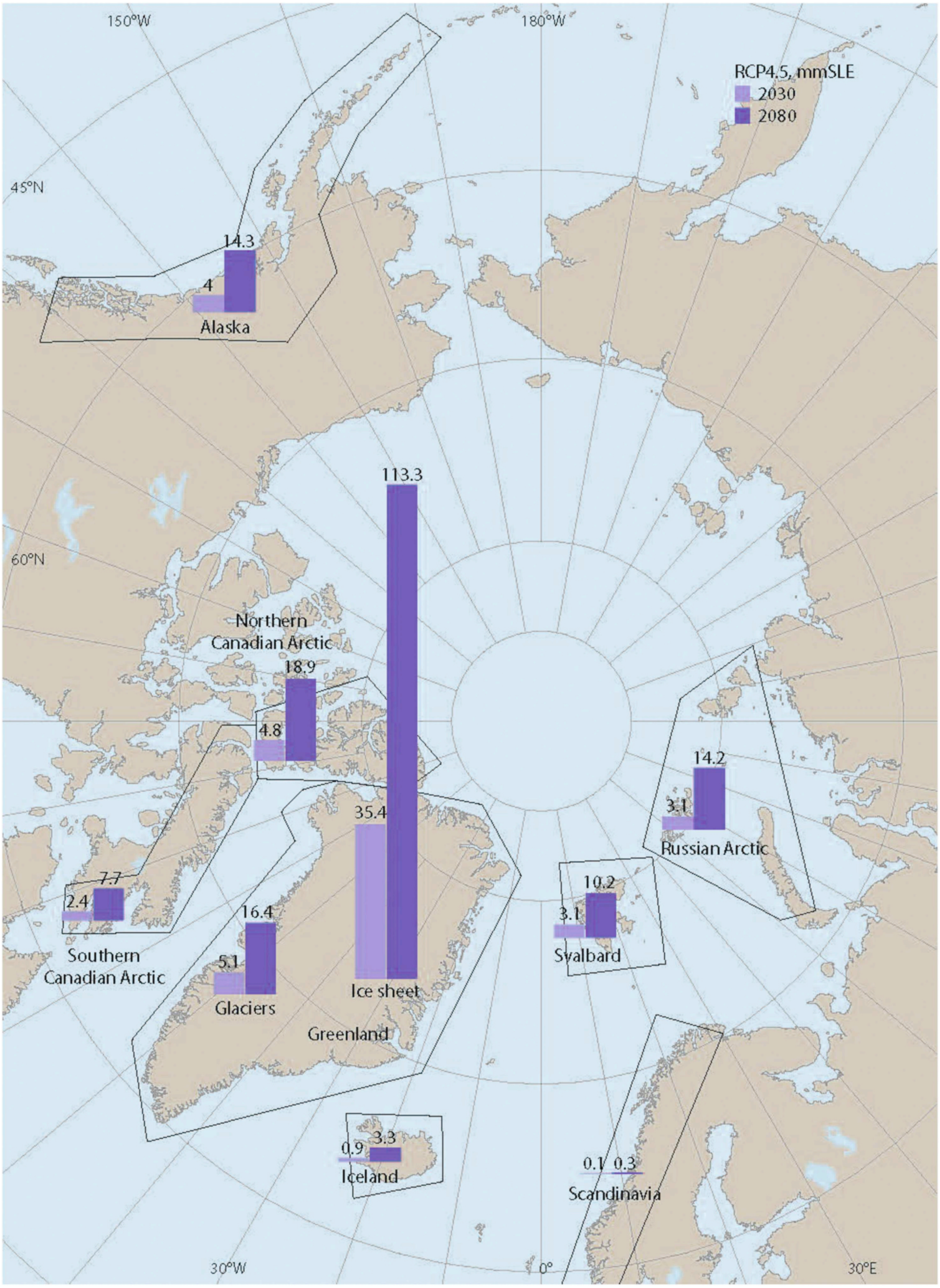

Fig. 7. Projected mass loss from local glaciers, ice caps and Greenland ice sheets for 2030 and 2080 (expressed in millimeters sea level equivalence) based on four studies (AMAP, 2017a). Note the much larger loss in the second half of the 21st century. Modified from AMAP (2017a).

et al., 2014; Kretschmer et al., 2016). Although there have been extensive new sea-ice-free areas in all years of the past decade, latitude and longitudinal phasing of the tropospheric jet stream pattern have not been conducive for North American midlatitude weather linkages in most years (Kug et al., 2015; Ayarzagüena and Screen, 2016; Ballinger et al., 2017; Chen and Luo, 2017; Cvijanovic et al., 2017; Overland and Wang, 2018), indicating the importance of internal variability and other forcings such as midlatitude and equatorial sea surface temperatures. Despite a growing literature (Cohen et al., 2018; Vavrus, 2018), there is little consensus on the topic in the scientific community (Wallace et al., 2014; Barnes and Screen, 2015; McCusker et al., 2016). At present what we can say is that global forcing from the Arctic (sea ice loss, increased temperatures, and moisture) will continue to increase. There is case study evidence that multiple linkage mechanisms are regional, episodic, and based on amplification of existing jet stream wave patterns (Overland et al., 2014; Cohen et al., 2018).

4.2. Atlantic Ocean circulation

There is a hypothesis for future impact of Arctic change on ocean circulation in the North Atlantic due to the accumulation of freshwater in the Arctic (Prowse et al., 2015; Carmack et al., 2016; Marnela et al., 2016; Rudels, 2016; Yang et al., 2016). There is paleoclimate data that show large changes to Atlantic Ocean circulation patterns. This topic is controversial as some current literature suggests weakening of Atlantic meridional overturning circulation (AMOC) related to Arctic warming (Sévellec et al., 2017), while other work shows that the Arctic component of AMOC did not weaken during the last two decades of Arctic change (Jochumsen et al., 2017).

4.3. Greenhouse gas release

Estimates of the amount of global organic carbon in Arctic soils have been revised upward, amounting to ∼50% of the world's global soil carbon (Hugelius et al., 2014). The storage rate is declining or reversing (Schuur et al., 2013, 2015; Commane et al., 2017; Jeong et al., 2018). Studies show (5–15%) permafrost soil carbon losses under the RCP 4.5 scenario (Koven et al., 2015; Schuur et al., 2015; Jeong et al., 2018). Any substantial warming results in a committed, long-term carbon release from thawing permafrost with 60% of emissions occurring after 2100 (Schaefer et al., 2014; Schuur et al., 2015; Christensen et al., 2017; Parmentier et al., 2017).

4.4. Sea level rise

An estimate summing of land ice mass loss, ocean thermal expansion, and terrestrial storage yields a total historical sea level rise (SLR) of 0.2 ± 0.2 m for 1850–2000 (Kopp et al., 2017; Box and Colgan, 2017). Arctic land ice was responsible for 48% of this total (Box and Colgan, 2017). The expected contribution from Greenland ice loss to SLR is projected to accelerate through the century, while that from many smaller land ice bodies will start to decelerate because their increases in meltwater runoff become offset by decreased glacier volume (IPCC, 2013). Greenland's accelerating loss involves multiple known processes driven by atmospheric warming, e.g., biological albedo decrease (Stibal et al., 2017), increasing rainfall (Doyle et al., 2015), and bare ice area (Box et al., 2012), with an overall dominance of amplifying feedbacks over damping feedbacks.

While Arctic and Antarctic land ice losses occur in low-population areas, the resulting Earth gravitational readjustment focuses SLR in the high-population tropics (Jevrejeva et al., 2016). Regarding global SLR, two estimates range from 0.3 m to 1.2 m by 2100 relative to 2000 (Wuebbles et al., 2017) and a SLR during this century (2006–2100) of at least 0.5 ± 0.2 m to 0.7 ± 0.3 m (Box and Colgan, 2017). As illustrated in Fig. 7, the largest SLR contributions of Arctic land ice loss will occur during the second half of the 21st century (Rahmstorf, 2007; AMAP, 2017a; Box and Colgan, 2017).

These global SLR projections may represent underestimates due to known yet not well-simulated processes in the IPCC AR5 Report (DeConto and Pollard, 2016; Kopp et al., 2017) that include ongoing losses from marine-based sectors of West Antarctica (Bamber and Aspinall, 2013; Rohling et al., 2013; Rignot et al., 2014; Kopp et al., 2016). Under such additional Antarctic frameworks, high-end estimates of SLR by 2100 include: ∼1.8 m (5% probability of occurrence) (Rohling et al., 2013; Jevrejeva et al., 2014; Grinsted et al., 2015) and ∼2.2 m (1% probability) (Jackson and Jevrejeva, 2016). Global SLR value of 0.5 m or larger will affect tens to hundreds of millions of people living along coastlines in lower latitudes http://www.worldwatch.org/node/5056.

5. Policy relevant Arctic change

In assessing what a goal of limiting global temperature increases to near +2 °C would mean for the Arctic cryosphere, and its related impacts outside the Arctic, we draw three conclusions. First, the Arctic is changing in ways and at a pace not previously seen in recorded data. Contemporary shifts have occurred in Arctic cryospheric components and further new extremes are expected. No matter which emissions scenario is followed over the next few decades, the Arctic will be a substantially different environment at mid-century than at present (less snow and sea ice, melted permafrost, different ecosystems), and will be perhaps unrecognizable by the end of the 21st century.

Second, the committed mass loss from the Greenland ice sheet, glaciers, and ice caps loss lags atmospheric temperature increases. Melt of Arctic glaciers, ice sheets, and ice caps will continue even under ambitious emission reduction scenarios. Projected Arctic summer air temperature increases essentially sets the Greenland ice into a state of irreversible loss. The outstanding question becomes, how fast will Greenland ice be lost? GHG emission reductions will delay higher Greenland land ice loss rates, making adaptation to sea level rise more tractable. The fate of Antarctic ice is less certain (Rignot et al., 2014).

Third, the Arctic is part of the global climate system and acts in a regulatory role as a primary cold reservoir for global climate. Arctic-specific feedback processes may become an obstacle to achieving a stabilized global climate in this century even if the global 2 °C target emission goal is met. These include radiative and heat storage positive feedbacks in land ice, sea ice, snow, clouds, and frozen ground (Coumou et al., 2014; Pistone et al., 2014; Alraddawi et al., 2017). Radiative feedback is based on moisture increasing downward long-wave radiation that traps heat and increases evaporation. Heat storage feedback is due to increased ground and sea temperatures due to loss of snow and sea ice. There is no uncertainty about the sign of future Arctic change. There is uncertainty regarding the pace of change in the second half of the century, as well as its impacts on local and remote regions.

Global temperature limitation near 2 °C could slow, but not halt further changes in the Arctic for future decades. The precautionary principle calls for early adaptation and mitigation actions (Overland et al., 2014). These include not only measures where adaptation efforts already are happening—for example, relocation of coastal villages threatened by increased coastal erosion (Jones et al., 2018) and changes in traditional means of hunting and fishing—but also global adaptation efforts, such as flooding and inundation protection and extreme weather event forecasting (Schlosser et al., 2016). Further scientific research is required on the pace and causes of change in the Arctic cryosphere that underpin both mitigation and adaptation planning (AMAP, 2017b,c,d).

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Appendix A. Supplementary data

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