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Abstract

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

2. Rising Alaskan permafrost temperatures are causing permafrost to thaw and become more discontinuous; this process releases additional CO_2 and methane, resulting in an amplifying feedback and additional warming (*high confidence*). The overall magnitude of the permafrost–carbon feedback is uncertain; however, it is clear that these emissions have the potential to complicate the ability to meet policy goals for the reduction of greenhouse gas concentrations.

3. Arctic land and sea ice loss observed in the last three decades continues, in some cases accelerating (*very high confidence*). It is *virtually certain* that Alaska glaciers have lost mass over the last 50 years, with each year since 1984 showing an annual average ice mass less than the previous year. Based on gravitational data from satellites, average ice mass loss from Greenland was −269 Gt per year between April 2002 and April 2016, accelerating in recent years (*high confidence*). Since the early 1980s, annual average Arctic sea ice has decreased in extent between 3.5% and 4.1% per decade, become thinner by between 4.3 and 7.5 feet, and began melting at least 15 more days each year. September sea ice extent has decreased between 10.7% and 15.9% per decade (*very high confidence*). Arctic-wide ice loss is expected to continue through the 21st century, *very likely* resulting in nearly sea ice-free late summers by the 2040s (*very high confidence*).

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

5. Atmospheric circulation patterns connect the climates of the Arctic and the contiguous United States. Evidenced by recent record warm temperatures in the Arctic and emerging science, the midlatitude circulation has influenced observed Arctic temperatures and sea ice (*high confidence*). However, confidence is *low* regarding whether or by what mechanisms observed Arctic warming may have influenced the midlatitude circulation and weather patterns over the continental United States. The influence of Arctic changes on U.S. weather over the coming decades remains an open question with the potential for significant impact.

11. Arctic Changes and their Effects on Alaska and the Rest of the United States

KEY FINDINGS

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

2. Rising Alaskan permafrost temperatures are causing permafrost to thaw and become more discontinuous; this process releases additional CO_2 and methane resulting in an amplifying feedback and additional warming (*high confidence*). The overall magnitude of the permafrost–carbon feedback is uncertain; however, it is clear that these emissions have the potential to complicate the ability to meet policy goals for the reduction of greenhouse gas concentrations.

3. Arctic land and sea ice loss observed in the last three decades continues, in some cases accelerating (*very high confidence*). It is *virtually certain* that Alaska glaciers have lost mass over the last 50 years, with each year since 1984 showing an annual average ice mass less than the previous year. Based on gravitational data from satellites, average ice mass loss from Greenland was −269 Gt per year between April 2002 and April 2016, accelerating in recent years (*high confidence*). Since the early 1980s, annual average Arctic sea ice has decreased in extent between 3.5% and 4.1% per decade, become thinner by between 4.3 and 7.5 feet, and began melting at least 15 more days each year. September sea ice extent has decreased between 10.7% and 15.9% per decade (*very high confidence*). Arctic-wide ice loss is expected to continue through the 21st century, *very likely* resulting in nearly sea ice-free late summers by the 2040s (*very high confidence*).

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

5. Atmospheric circulation patterns connect the climates of the Arctic and the contiguous United States. Evidenced by recent record warm temperatures in the Arctic and emerging science, the midlatitude circulation has influenced observed Arctic temperatures and sea ice (*high confidence*). However, confidence is *low* regarding whether or by what mechanisms observed Arctic warming may have influenced the midlatitude circulation and weather patterns over the continental United States. The influence of Arctic changes on U.S. weather over the coming decades remains an open question with the potential for significant impact.

11.1. Introduction

Climate changes in Alaska and across the Arctic continue to outpace changes occurring across the globe. The Arctic, defined as the area north of the Arctic Circle, is a vulnerable and complex system integral to Earth's climate. The vulnerability stems in part from the extensive cover of ice and snow, where the freezing point marks a critical threshold that when crossed has the potential to transform the region. Because of its high sensitivity to radiative forcing and its role in amplifying warming (Manabe and Wetherald 1975), the Arctic cryosphere is a key indicator of the global climate state. Accelerated melting of multiyear sea ice, mass loss from the Greenland Ice Sheet (GrIS), reduction of terrestrial snow cover, and permafrost degradation are stark examples of the rapid Arctic-wide response to global warming. These local Arctic changes influence global sea level, ocean salinity, the carbon cycle, and potentially atmospheric and oceanic circulation patterns. Arctic climate change has altered the global climate in the past (Knies et al. 2014) and will influence climate in the future.

As an Arctic nation, United States' adaptation, mitigation, and policy decisions depend on projections of future Alaskan and Arctic climate. Aside from uncertainties due to natural variability, scientific uncertainty, and greenhouse gas emissions uncertainty (see Ch. 4: Projections), additional unique uncertainties in our understanding of Arctic processes thwart projections, including mixed-phase cloud processes (Wyser et al. 2008); boundary layer processes (Bourassa et al. 2013); sea ice mechanics (Bourassa et al. 2013); and ocean currents, eddies, and tides that affect the advection of heat into and around the Arctic Ocean (Maslowski et al. 2012, 2014). The inaccessibility of the Arctic has made it difficult to sustain the high-quality observations of the atmosphere, ocean, land, and ice required to improve physically-based models. Improved data quality and increased observational coverage would help address societally relevant Arctic science questions.

Despite these challenges, our scientific knowledge is sufficiently advanced to effectively inform policy. This chapter documents significant scientific progress and knowledge about how the Alaskan and Arctic climate has changed and will continue to change.

11.2. Arctic Changes

11.2.1. Alaska and Arctic Temperature

Surface temperature—an essential component of the Arctic climate system—drives and signifies change, fundamentally controlling the melting of ice and snow. Further, the vertical profile of boundary layer temperature modulates the exchange of mass, energy, and momentum between the surface and atmosphere, influencing other components such as clouds (Kay and Gettelman 2009; Taylor et al. 2015). Arctic temperatures exhibit spatial and interannual variability due to interactions and feedbacks between sea ice, snow cover, atmospheric heat transports, vegetation, clouds, water vapor, and the surface energy budget (Overland et al. 2015b; Johannessen et al.

2016; Overland and Wang 2016). Interannual variations in Alaskan temperatures are strongly influenced by decadal variability like the Pacific Decadal Oscillation (Hartmann and Wendler 2005; McAfee 2014; Ch. 5: Circulation and Variability). However, observed temperature trends exceed this variability.

Arctic surface and atmospheric temperatures have substantially increased in the observational record. Multiple observation sources, including land-based surface stations since at least 1950 and available meteorological reanalysis datasets, provide evidence that Arctic near-surface air temperatures have increased more than twice as fast as the global average (Serreze et al. 2009; Bekryaev et al. 2010; Screen and Simmonds 2010; Hartmann et al. 2013; Overland et al. 2014). Showing enhanced Arctic warming since 1981, satellite-observed Arctic average surface skin temperatures have increased by 1.08 ± 0.13°F (+0.60 ± 0.07°C) per decade (Comiso and Hall 2014). As analyzed in Chapter 6: Temperature Change (Figure 6.1), strong near-surface air temperature warming has occurred across Alaska exceeding 1.5°F (0.8°C) over the last 30 years. Especially strong warming has occurred over Alaska's North Slope during autumn. For example, Utqiagvik's (formally Barrow) warming since 1979 exceeds 7°F (3.8°C) in September, 12°F (6.6°C) in October, and 10°F (5.5°C) in November (Wendler et al. 2014).

Enhanced Arctic warming is a robust feature of the climate response to anthropogenic forcing (Collins et al. 2013; Taylor et al. 2013). An anthropogenic contribution to Arctic and Alaskan surface temperature warming over the past 50 years is *virtually certain* and *likely* amounting to more than 50% of observed warming (Gillett et al. 2008; Bindoff et al. 2013). One study argues that the natural forcing has not contributed to the long-term Arctic warming in a discernable way (Najafi et al. 2015). Also, other anthropogenic forcings (mostly aerosols) have *likely* offset up to 60% of the high-latitude greenhouse gas warming since 1913 (Najafi et al. 2015), suggesting that Arctic warming to date would have been larger without the offsetting aerosols influence. It is *virtually certain* that Arctic surface temperatures will continue to increase faster than the global mean through the 21st century (Christensen et al. 2013).

11.2.2. Arctic Sea Ice Change

Arctic sea ice strongly influences Alaskan, Arctic, and global climate by modulating exchanges of mass, energy, and momentum between the ocean and the atmosphere. Variations in Arctic sea ice cover also influence atmospheric temperature and humidity, wind patterns, clouds, ocean temperature, thermal stratification, and ecosystem productivity (Kay and Gettelman 2009; Kay et al. 2011a; Pavelsky et al. 2011; Taylor et al. 2011a; Boisvert et al. 2013; Vaughan et al. 2013; Solomon et al. 2014; Boisvert et al. 2015a,b; Johannessen et al. 2016). Arctic sea ice exhibits significant interannual, spatial, and seasonal variability driven by atmospheric wind patterns and cyclones, atmospheric temperature and humidity structure, clouds, radiation, sea ice dynamics, and the ocean (Ogi and Wallace 2007; Kwok and Untersteiner 2011; Taylor et al. 2011b; Stroeve et al. 2012a,b; Ogi and Rigor 2013; Carmack et al. 2015).

Overwhelming evidence indicates that the character of Arctic sea ice is rapidly changing. Observational evidence shows Arctic-wide sea ice decline since 1979, accelerating ice loss since 2000, and some of the fastest loss along the Alaskan coast (Stroeve et al. 2014a,b; Comiso and Hall 2014; Wendler et al. 2014). Although sea ice loss is found in all months, satellite observations show the fastest loss in late summer and autumn (Stroeve et al. 2014a). Since 1979, the annual average Arctic sea ice extent has *very likely* decreased at a rate of 3.5%–4.1% per decade (Vaughan et al. 2013; Comiso and Hall 2014). Regional sea ice melt along the Alaskan coasts exceeds the Arctic average rates with declines in the Beaufort and Chukchi Seas of −4.1% and −4.7% per decade, respectively (Wendler et al. 2014). The annual minimum and maximum sea ice extent have decreased over the last 35 years by −13.3 ± 2.6% and −2.7± 0.5% per decade, respectively (Perovich et al. 2016). The ten lowest September sea ice extents over the satellite period have all occurred in the last ten years, the lowest in 2012. The 2016 September sea ice minimum tied with 2007 for the second lowest on record, but rapid refreezing resulted in the 2016 September monthly average extent being the fifth lowest. Despite the rapid initial refreezing, sea ice extent was again in record low territory during fall–winter 2016/2017 due to anomalously warm temperatures in the marginal seas around Alaska (Perovich et al. 2016), contributing to a new record low in winter ice-volume (See: http://psc.apl.uw.edu/research/projects/arctic-sea-ice-volume-anomaly, Schweiger et al. 2011).

Other important characteristics of Arctic sea ice have also changed, including thickness, age, and volume. Sea ice thickness is monitored using an array of satellite, aircraft, and vessel measurements (Vaughan et al. 2013; Stroeve et al. 2014a). The mean thickness of the Arctic sea ice during winter between 1980 and 2008 has decreased between 4.3 and 7.5 feet (1.3 and 2.3 meters) (Vaughan et al. 2013). The age distribution of sea ice has become younger since 1988. In March 2016, first-year (multi-year) sea ice accounted for 78% (22%) of the total extent, whereas in the 1980s first-year (multi-year) sea ice accounted for 55% (45%) (Perovich et al. 2016). Moreover, ice older than four years accounted for 16% of the March 1985 icepack but accounted for only 1.2% of the icepack in March 2016, indicating significant changes in sea ice volume (Perovich et al. 2016). The top two panels in Figure 11.1 show the September sea ice extent and age in 1984 and 2016, illustrating significant reductions in sea ice age (Tschudi et al. 2016). While these panels show only two years (beginning point and ending point) of the complete time series, these two years are representative of the overall trends discussed and shown in the September sea ice extent time series in the bottom panel of Fig 11.1. Younger, thinner sea ice is more susceptible to melt, therefore reductions in age and thickness imply a larger interannual variability of extent.

[INSERT FIGURE 11.1 HERE]

Sea ice melt season—defined as the number of days between spring melt onset and fall freeze-up—has lengthened Arctic-wide by at least five days per decade since 1979, with larger regional changes (Stroeve et al. 2014b; Parkinson 2014). Some of the largest observed changes in sea ice

melt season (Figure 11.2) are found along Alaska's northern and western coasts, lengthening the melt season by 20–30 days per decade and increasing the annual number of ice-free days by more than 90 (Parkinson 2014). Summer sea ice retreat along coastal Alaska has led to longer open water seasons, making the Alaskan coastline more vulnerable to erosion (Chapin et al. 2014; Gibbs and Richmond 2015). Increased melt season length corresponds to increased absorption of solar radiation by the Arctic Ocean during summer and increases upper ocean temperature delaying fall freeze-up. Overall, this process significantly contributes to reductions in Arctic sea ice (Stroeve et al. 2012a; Stroeve et al. 2014b). Wind-driven sea ice export through the Fram Strait has not increased over the last 80 years (Vaughn et al. 2013), however one recent study suggests that it may have increased since 1979 (Smedsrud et. al. 2017).

[INSERT FIGURE 11.2 HERE]

It is *virtually certain* that there is an anthropogenic contribution to the observed Arctic sea ice decline since 1979. A range of modeling studies analyzing the September sea ice extent trends in simulations with and without anthropogenic forcing conclude that these declines cannot be explained by natural variability alone (Vinnikov et al. 1999; Stroeve et al. 2007; Min et al. 2008; Kay et al. 2011b; Day et al. 2012; Wang and Overland 2012). Further, observational-based analyses considering a range of anthropogenic and natural forcing mechanisms for September sea ice loss reach the same conclusion (Notz and Marotzke 2012). Considering the occurrence of individual September sea ice anomalies, internal climate variability alone *very likely* could not have caused recently observed record low Arctic sea ice extents, such as in September 2012 (Zhang and Knutson 2013; Kirchmeyer-Young et al. 2017). The potential contribution of natural variability to Arctic sea ice trends is significant (Kay et al. 2011b; Jahn et al. 2016; Swart et al. 2015). One recent study (Ding et al. 2017) indicates that internal variability dominates Arctic atmospheric circulation trends, accounting for 30%–50% of the sea ice reductions since 1979, and up to 60% in September. However, previous studies indicate that the contributions from internal variability are smaller than 50% (Kay et al. 2011b; Day et al. 2012). This apparent significant contribution of natural variability to sea ice decline is consistent with the statement that *likely* more than half of the observed sea ice loss since 1979 has an anthropogenic contribution.

Continued sea ice loss is expected across the Arctic, which is *very likely* to result in late summers becoming nearly ice-free (areal extent less than 10^6 km^2 or approximately 3.9×10^5 mi^2) by mid-century (Collins et al. 2013; Snape and Forster 2014). Natural variability (Wettstein and Deser 2014), future emissions, and model uncertainties (Gagné et al. 2015; Stroeve and Notz 2015; Swart et al. 2015) all influence sea ice projections. One study suggests that internal variability alone accounts for a 20-year prediction uncertainty in the timing of the first occurrence of an ice-free summer, whereas emissions scenario differences between RCP8.5 and RCP4.5 add only 5 years (Jahn et al. 2016). Projected September sea ice reductions by 2081–2100 range from 43% for RCP2.6 to 94% for RCP8.5 (Collins et al. 2013). However, September sea ice projections

over the next few decades are similar for the different anthropogenic forcing associated with these scenarios; scenario dependent sea ice loss only becomes apparent after 2050. Another study (Notz and Stroeve 2016) indicates that the total sea ice loss scales roughly linearly with CO_2 emissions, such that an additional 1,000 GtC from present day levels corresponds to ice-free conditions in September. A key message from the Third National Climate Assessment (NCA3; Melillo et al. 2014) was that Arctic sea ice is disappearing. The fundamental conclusion of this assessment is unchanged; additional research corroborates the NCA3 statement.

11.2.3. Arctic Ocean and Marginal Seas

SEA SURFACE TEMPERATURE

Arctic Ocean sea surface temperatures (SSTs) have increased since comprehensive records became available in 1982. Satellite-observed Arctic Ocean SSTs, poleward of 60°N, exhibit a trend of 0.16 ± 0.02°F (0.09 ± 0.01°C) per decade (Comiso and Hall 2014). Arctic Ocean SST is controlled by a combination of factors, including solar radiation and energy transport from ocean currents and atmospheric winds. Summertime Arctic Ocean SST trends and patterns strongly couple with sea ice extent; however, clouds, ocean color, upper-ocean thermal structure, and atmospheric circulation also play a role (Ogi and Rigor 2013; Rhein et al. 2013). Along coastal Alaska, SSTs in the Chukchi Sea exhibit a statistically significant (95% confidence) trend of 0.9 ± 0.5°F (0.5 ± 0.3°C) per decade (Timmermans and Proshutinksy 2015).

Arctic Ocean temperatures also increased at depth (Polyakov et al. 2012; Rhein et al. 2013). Since 1970, Arctic Ocean Intermediate Atlantic Water—located between 150 and 900 meters—has warmed by 0.86 ± 0.09°F (0.48 ± 0.05°C) per decade; the most recent decade being the warmest (Polyakov et al. 2012). The observed temperature level is unprecedented in the last 1,150 years for which proxy indicators provide records (Spielhagen et al. 2011; Jungclaus et al. 2014). The influence of Intermediate Atlantic Water warming on future Alaska and Arctic sea ice loss is unclear (Döscher et al. 2014; Carmack et al. 2015).

ALASKAN SEA LEVEL RISE

The Alaskan coastline is vulnerable to sea level rise (SLR); however, strong regional variability exists in current trends and future projections. Some regions are experiencing relative sea level fall, whereas others are experiencing relative sea level rise, as measured by tide gauges that are part of NOAA's National Water Level Observation Network. These tide gauge data show sea levels rising fastest along the northern coast of Alaska but still slower than the global average, due to isostatic rebound (Church et al. 2013; Ch. 12: Sea Level Rise). However, considerable uncertainty in relative sea level rise exists to due to a lack of tide gauges; for example, no tide gauges are located between Bristol Bay and Norton Sound or between Cape Lisburne and Prudhoe Bay. Under almost all future scenarios, SLR along most of the Alaskan coastline is projected to be less than the global average (Ch. 12: Sea Level Rise).

SALINITY

Arctic Ocean salinity influences the freezing temperature of sea ice (less salty water freezes more readily) and the density profile representing the integrated effects of freshwater transport, river runoff, evaporation, and sea ice processes. Arctic Ocean salinity exhibits multidecadal variability, hampering the assessment of long-term trends (Rawlins et al. 2010). Emerging evidence suggests that the Arctic Ocean and marginal sea salinity has decreased in recent years despite short-lived regional salinity increases between 2000 and 2005 (Rhein et al. 2013). Increased river runoff, rapid melting of sea and land ice, and changes in freshwater transport have influenced observed Arctic Ocean salinity (Rhein et al. 2013; Köhl and Serra 2014).

OCEAN ACIDIFICATION

Arctic Ocean acidification is occurring at a faster rate than the rest of the globe (Mathis et al. 2015; see also Ch. 13: Ocean Changes). Coastal Alaska and its ecosystems are especially vulnerable to ocean acidification because of the high sensitivity of Arctic Ocean water chemistry to changes in sea ice, respiration of organic matter, upwelling, and increasing river runoff (Mathis et al. 2015). Sea ice loss and a longer melt season contribute to increased vulnerability of the Arctic Ocean to acidification by lowering total alkalinity, permitting greater upwelling, and influencing the primary production characteristics in coastal Alaska (Arrigo et al. 2008; Cai et al. 2010; Hunt et al. 2011; Stabeno et al. 2012; Mathis et al. 2012; Bates et al. 2014). Global-scale modeling studies suggest that the largest and most rapid changes in pH will continue along Alaska's coast, indicating that ocean acidification may increase enough by the 2030s to significantly influence coastal ecosystems (Mathis et al. 2015).

11.2.4. Boreal Wildfires

Alaskan wildfire activity has increased in recent decades. This increase has occurred both in the boreal forest (Flannigan et al. 2009) and in the Arctic tundra (Hu et al. 2015), where fires historically were smaller and less frequent. A shortened snow cover season and higher temperatures over the last 50 years (Derksen et al. 2015) make the Arctic more vulnerable to wildfire (Flannigan et al. 2009; Hu et al. 2015; Young et al. 2016). Total area burned and the number of large fires (those with area greater than 1000 km^2 or 386 mi^2) in Alaska exhibit significant interannual and decadal variability, from influences of atmospheric circulation patterns and controlled burns, but have *likely* increased since 1959 (Kasischke and Turetsky 2006). The most recent decade has seen an unusually large number of years with anomalously large wildfires in Alaska (Sanford et al. 2015). Studies indicate that anthropogenic climate change has *likely* lengthened the wildfire season and increased the risk of severe fires (Partain et al. 2016). Further, wildfire risks are expected to increase through the end of the century due to warmer, drier conditions (French et al. 2015; Young et al. 2017). Using climate simulations to force an ecosystem model over Alaska (Alaska Frame-Based Ecosystem Code, ALFRESCO), the total area burned is projected to increase between 25% and 53% by 2100 (Joly et al. 2012). A

transition into a regime of fire activity unprecedented in the last 10,000 years is possible (Kelly et al. 2013). We conclude that there is *medium confidence* for a human-caused climate change contribution to increased forest fire activity in Alaska in recent decades. See Chapter 8: Drought, Floods, and Wildfires for more details.

A significant amount of the total global soil carbon is found in the boreal forest and tundra ecosystems, including permafrost (McGuire et al. 2009; Mishra and Riley 2012; Mishra et al. 2013). Increased fire activity could deplete these stores, releasing them to the atmosphere to serve as an additional source of atmospheric CO_2 (McGuire et al. 2009; Kelly et al. 2016). Increased fires may also enhance the degradation of Alaska's permafrost by blackening the ground, reducing surface albedo, and removing protective vegetation (Swanson 1996; Yoshikawa et al. 2003; Myers-Smith et al. 2008; Brown et al. 2015).

11.2.5. Snow Cover

Snow cover extent has significantly decreased across the Northern Hemisphere and Alaska over the last decade (Derksen and Brown 2012; Kunkel et al. 2016; see also Ch. 7: Precipitation Change and Ch. 10: Land Cover). Northern Hemisphere June snow cover decreased by more than 65% between 1967 and 2012 (Brown and Robinson 2011; Vaughan et al. 2013), at a trend of −17.2% per decade since 1979 (Derksen et al. 2015). June snow cover dipped below 3 million square km (approximately 1.16 million square miles) for the fifth time in six years between 2010 and 2015, a threshold not crossed in the previous 43 years of record (Derksen et al. 2015). Early season snow cover in May, which affects the accumulation of solar insolation through the summer, has also declined at −7.3% per decade, due to reduced winter accumulation from warmer temperatures. Regional trends in snow cover duration vary, with some showing earlier onsets while others show later onsets (Derksen et al. 2015). In Alaska, the 2016 May statewide snow coverage of 595,000 square km (approximately 372,000 square miles) was the lowest on record dating back to 1967; the snow coverage of 2015 was the second lowest, and 2014 was the fourth lowest.

Human activities have contributed to observed snow cover declines over the last 50 years. Attribution studies indicate that observed trends in Northern Hemisphere snow cover cannot be explained by natural forcing alone, but instead require anthropogenic forcing (Rupp et al. 2013; Bindoff et al. 2013; Kunkel et al. 2016). Declining snow cover is expected to continue and will be affected by both the anthropogenic forcing and evolution of Arctic ecosystems. The observed tundra shrub expansion and greening (Myers-Smith et al. 2011; Mao et al. 2016) affects melt by influencing snow depth, melt dynamics, and the local surface energy budget. Nevertheless, model simulations show that future reductions in snow cover influence biogeochemical feedbacks and warming more strongly than changes in vegetation cover and fire in the North American Arctic (Euskirchen et al. 2016).

11.2.6. Continental Ice Sheets and Mountain Glaciers

Mass loss from ice sheets and glaciers influences sea level rise, the oceanic thermohaline circulation, and the global energy budget. Moreover, the relative contribution of GrIS to global sea level rise continues to increase, exceeding the contribution from thermal expansion (see Ch. 12: Sea Level Rise). Observational and modeling studies indicate that GrIS and glaciers in Alaska are out of mass balance with current climate conditions and are rapidly losing mass (Vaughan et al. 2013; Zemp et al. 2015). In recent years, mass loss has accelerated and is expected to continue (Zemp et al. 2015; Harig and Simons 2016).

Dramatic changes have occurred across GrIS, particularly at its margins. GrIS average annual mass loss from January 2003 to May 2013 was −244 ± 6 Gt per year (approximately 0.26 inches per decade sea level equivalent) (Harig and Simons 2016). One study indicates that ice mass loss from Greenland was −269 Gt per year between April 2002 and April 2016 (Perovich et al. 2016). Increased surface melt, runoff, and increased outlet glacier discharge from warmer air temperatures are primary contributing factors (Howat et al. 2008; van den Broeke et al. 2009; Rignot et al. 2010; Straneo et al. 2011; Khan et al. 2014). The effects of warmer air and ocean temperatures on GrIS can be amplified by ice dynamical feedbacks, such as faster sliding, greater calving, and increased submarine melting (Joughin et al. 2008; Holland et al. 2008; Rignot et al. 2010; Bartholomew et al. 2011). Shallow ocean warming and regional ocean and atmospheric circulation changes also contribute to mass loss (Dupont and Alley 2005; Lim et al. 2016; Tedesco et al. 2016). The underlying mechanisms of the recent discharge speed-up remain unclear (Straneo et al. 2010; Johannessen et al. 2011); however, warmer subsurface ocean and atmospheric temperatures (Velicogna 2009; van den Broeke et al. 2009; Andresen et al. 2012) and meltwater penetration to the glacier bed (Johannessen et al. 2011; Mernild et al. 2012) *very likely* contribute.

Annual average ice mass from Arctic-wide glaciers has decreased every year since 1984 (AMAP 2011; Pelto 2015; Zemp et al. 2015), with significant losses in Alaska, especially over the past two decades (Figure 11.3; Vaughan et al. 2013; Sharp et al. 2015). Figure 11.4 illustrates observed changes from U.S. Geological Survey repeat photography of Alaska's Muir Glacier, retreating more than 4 miles between 1941 and 2004, and its tributary the Riggs Glacier. Total glacial ice mass in the Gulf of Alaska region has declined steadily since 2003 (Harig and Simons 2016). NASA's Gravity Recovery and Climate Experiment (GRACE) indicates mass loss from the northern and southern parts of the Gulf of Alaska region of −36 ± 4 Gt per year and −4 ± 3 Gt per year, respectively (Harig and Simons 2016). Studies show imbalances in Alaskan glaciers, indicating that melt will continue through the 21st century (Zemp et al. 2015; Mengel et al. 2016). Multiple datasets indicate that it is *extremely likely* that Alaskan glaciers have lost mass over the last 50 years and will continue to do so (Larsen et al. 2015).

[INSERT FIGURES 11.3 AND 11.4 HERE]

11.3. Arctic Feedbacks on the Lower 48 and Globally

11.3.1. Linkages between Arctic Warming and Lower Latitudes

Midlatitude circulation influences Arctic climate and climate change (Rigor et al. 2002; Graversen 2006; Perlwitz et al. 2015; Francis et al. 2017; Screen et al. 2012; Park et al. 2015; Lee 2014; Lee et al. 2011; Ding et al. 2014; Screen and Francis 2016; Overland and Wang 2016). Record warm Arctic temperatures in winter 2016 resulted primarily from the transport of midlatitude air into the Arctic, demonstrating the significant midlatitude influence (Overland et al. 2016). Emerging science demonstrates that warm, moist air intrusions from midlatitudes results in increased downwelling longwave radiation, warming the Arctic surface and hindering wintertime sea ice growth (Liu and Key 2014; Lee 2014; Park et al. 2015; Woods and Caballero 2016).

The extent to which enhanced Arctic surface warming and sea ice loss influence the large-scale atmospheric circulation and midlatitude weather and climate extremes has become an active research area (Overland et al. 2016; Francis et al. 2017). Several pathways have been proposed (see reference in Cohen et al. 2014 and Barnes and Screen 2015): reduced meridional temperature gradient, a more sinuous jet-stream, trapped atmospheric waves, modified storm tracks, weakened stratospheric polar vortex. While modeling studies link a reduced meridional temperature gradient to fewer cold temperature extremes in the continental United States (Ayarzagüena and Screen 2016; Sun et al. 2016; Screen et al. 2015a,b), other studies hypothesize that a slower jet stream may amplify Rossby waves and increase the frequency of atmospheric blocking, causing more persistent and extreme weather in midlatitudes (Francis and Vavrus 2012).

Multiple observational studies suggest that the concurrent changes in the Arctic and Northern Hemisphere large-scale circulation since the 1990s did not occur by chance, but were caused by arctic amplification (Cohen et al. 2014; Vihma 2014; Barnes and Screen 2015). Reanalysis data suggest a relationship between arctic amplification and observed changes in persistent circulation phenomena like blocking and planetary wave amplitude (Francis and Skific 2015; Francis and Vavrus 2012, 2015). The recent multi-year California drought serves as an example of an event caused by persistent circulation phenomena (Swain et al. 2014; Seager et al. 2015; Teng and Branstator 2017; see Ch. 5: Circulation and Variability and Ch. 8: Drought, Floods, and Wildfires). Robust empirical evidence is lacking because the Arctic sea ice observational record is too short (Overland et al. 2015a) or because the atmospheric response to arctic amplification depends on the prior state of the atmospheric circulation, reducing detectability (Overland et al. 2016). Furthermore, it is not possible to draw conclusions regarding the direction of the relationship between Arctic warming and midlatitude circulation based on empirical correlation and covariance analyses alone. Observational analyses have been combined with modeling studies to test causality statements.

Studies with simple models and Atmospheric General Circulation Models (AGCMs) provide evidence that Arctic warming can affect midlatitude jet streams and location of storm tracks (Barnes and Screen 2015; Overland et al. 2016; Francis et al. 2017). In addition, analysis of CMIP5 models forced with increasing greenhouse gases suggests that the magnitude of arctic amplification affects the future midlatitude jet position, specifically during boreal winter (Barnes and Polvani 2015). However, the effect of arctic amplification on blocking is not clear (Hoskins and Woollings 2015; Ch. 5: Circulation and Variability).

Regarding attribution, AGCM simulations forced with observed changes in Arctic sea ice suggest that the sea ice loss effect on observed recent midlatitude circulation changes and winter climate in the continental United States is small compared to natural large-scale atmospheric variability (Screen et al. 2012; Perlwitz et al. 2015; Sigmond and Fyfe 2016; Sun et al. 2016). It is argued, however, that climate models do not properly reproduce the linkages between arctic amplification and lower latitude climate due to model errors, including incorrect sea ice–atmosphere coupling and poor representation of stratospheric processes (Cohen et al. 2013; Francis et al. 2017)

In summary, emerging science demonstrates a strong influence of the midlatitude circulation on the Arctic, affecting temperatures and sea ice (*high confidence*). The influence of Arctic changes on the midlatitude circulation and weather patterns are an area of active research. Currently, confidence is *low* regarding whether or by what mechanisms observed Arctic warming may have influenced midlatitude circulation and weather patterns over the continental United States. The nature and magnitude of arctic amplification's influence on U.S. weather over the coming decades remains an open question.

11.3.2. Freshwater Effects on Ocean Circulation

The addition of freshwater to the Arctic Ocean from melting sea ice and land ice can influence important Arctic climate system characteristics, including ocean salinity, altering ocean circulation, density stratification, and sea ice characteristics. Observations indicate that river runoff is increasing, driven by land ice melt, adding freshwater to the Arctic Ocean (Nummelin et al. 2016). Melting Arctic sea and land ice combined with time-varying atmospheric forcing (Giles et al. 2012; Köhl and Serra 2014) control Arctic Ocean freshwater export to the North Atlantic. Large-scale circulation variability in the central Arctic not only controls the redistribution and storage of freshwater in the Arctic (Köhl and Serra 2014) but also the export volume (Morison et al. 2012). Increased freshwater fluxes can weaken open ocean convection and deep water formation in the Labrador and Irminger seas, weakening the Atlantic meridional overturning circulation (AMOC; Rahmstorf et al. 2015; Yang et al. 2016). AMOC-associated poleward heat transport substantially contributes to North American and continental European climate; any AMOC slow-down could have implications for global climate change as well (Smeed et al. 2014; Liu et al. 2017; see Ch. 15: Potential Surprises). Connections to subarctic

ocean variations and the Atlantic Meridional Overturning Circulation have not been conclusively established and require further investigation (see Ch. 13: Ocean Changes).

11.3.3. Permafrost–Carbon Feedback

Alaska and Arctic permafrost characteristics have responded to increased temperatures and reduced snow cover in most regions since the 1980s (AMAP 2011). The permafrost warming rate varies regionally; however, colder permafrost is warming faster than warmer permafrost (Vaughan et al. 2013; Romanovsky et al. 2015). This feature is most evident across Alaska, where permafrost on the North Slope is warming more rapidly than in the interior. Permafrost temperatures across the North Slope at various depths ranging from 39 to 65 feet (12 to 20 meters) have warmed between 0.3° and 1.3°F (0.2° and 0.7°C) per decade over the observational period (Figure 11.5; Romanovsky et al. 2016). Permafrost active layer thickness increased across much of the Arctic while showing strong regional variations (AMAP 2011; Shiklomanov et al. 2012; Vaughan et al. 2013). Further, recent geologic survey data indicate significant permafrost thaw slumping in northwestern Canada and across the circumpolar Arctic that indicate significant ongoing permafrost thaw, potentially priming the region for more rapid thaw in the future (Kokelj et al. 2017). Continued degradation of permafrost and a transition from continuous to discontinuous permafrost is expected over the 21st century (Vaughan et al. 2013; Schuur et al. 2015; Grosse et al. 2016).

[INSERT FIGURE 11.5 HERE]

Permafrost contains large stores of carbon. Though the total contribution of these carbon stores to global methane emission is uncertain, Alaska's permafrost contains rich and vulnerable organic carbon soils (Tarnocai et al. 2009; Mishra and Riley 2012; Schuur et al. 2015). Thus, warming Alaska permafrost is a concern for the global carbon cycle as it provides a possibility for a significant and potentially uncontrollable release of carbon, complicating the ability to meet global policy goals. Current methane emissions from Alaskan Arctic tundra and boreal forests contribute a small fraction of the global methane (CH_4) budget (Chang et al. 2014). However, gas flux measurements have directly measured the release of CO_2 and CH_4 from Arctic permafrost (Schuur et al. 2009). Recent measurement indicate that cold season methane emissions (after snowfall) are greater than summer emissions in Alaska, and methane emissions in upland tundra are greater than in wetland tundra (Zona et al. 2016).

The permafrost–carbon feedback represents the additional release of CO_2 and CH_4 from thawing permafrost soils providing additional radiative forcing, a source of a potential surprise (Treat et al. 2015; Ch. 15: Potential Surprises). Thawing permafrost makes previously frozen organic matter available for microbial decomposition, producing CO_2 and CH_4. The specific condition under which microbial decomposition occurs, aerobic or anaerobic, determines the proportion of CO_2 and CH_4 released. This distinction has potentially significant implications, as CH_4 has a 100-year global warming potential 35 times that of CO_2 (Myhre et al. 2013). Emerging science

indicates that 3.4 times more carbon is released under aerobic conditions than anaerobic conditions, and 2.3 times more carbon after accounting for the stronger greenhouse effect of CH_4 (Schädel et al. 2016). Additionally, CO_2 and CH_4 production strongly depends on vegetation and soil properties (Treat et al. 2015).

Combined data and modeling studies indicate a positive permafrost–carbon feedback with a global sensitivity between −14 and −19 GtC per °C (approximately −25 to −34 GtC per °F) soil carbon loss (Koven et al. 2015a,b) resulting in a total 120 ± 85 GtC release from permafrost by 2100 and an additional global temperature increase of 0.52 ± 0.38°F (0.29 ± 0.21°C) by the permafrost–carbon feedback (Schaefer et al. 2014). More recently, Chadburn et al. (2017) infer a −4 million km^2 per °C (or approximately 858,000 mi^2 per °F) reduction in permafrost area to globally averaged warming at stabilization by constraining climate models with the observed spatial distribution of permafrost; this sensitivity is 20% higher than previous studies. In the coming decades, enhanced high-latitude plant growth and its associated CO_2 sink should partially offset the increased emissions from permafrost thaw (Friedlingstein et al. 2006; Schaefer et al. 2014; Schuur et al. 2015); thereafter, decomposition is expected to dominate uptake. Permafrost thaw is occurring faster than models predict due to poorly understood deep soil, ice wedge, and thermokarst processes (Fisher et al. 2014; Koven et al. 2015a; Liljedahl et al. 2016). Additional, uncertainty stems from the surprising uptake of methane from mineral soils (Oh et al. 2016). There is *high confidence* in the positive sign of the permafrost–carbon feedback, but *low confidence* in the feedback magnitude.

11.3.4. Methane Hydrate Instability

Significant stores of CH_4, in the form of methane hydrates (also called clathrates), lie below permafrost and under the global ocean. The estimated total global inventory of methane hydrates ranges from 500 to 3,000 GtC (Archer 2007; Ruppel 2011; Piñero et al. 2013) with a central estimate of 1800 GtC (Ruppel and Kessler 2017). Methane hydrates are solid compounds formed at high pressures and cold temperatures trapping methane gas within the crystalline structure of water. In the Arctic Ocean and along the shallow coastal Alaskan seas, methane hydrates form on shallow but cold continental shelves and may be vulnerable to small increases in ocean temperature (Bollman et al. 2010; Ruppel 2011; Ruppel and Kessler 2017).

Rising sea levels and warming oceans have a competing influence on methane hydrate stability (Bollman et al. 2010; Hunter et al. 2013). Studies indicate that the temperature effect dominates and that the overall influence is *likely* a destabilizing effect. Projected warming rates for the 21st century Arctic Ocean are not expected to lead to sudden or catastrophic destabilization of sea floor methane hydrates (Kretschmer et al. 2015). Recent observations indicate increased CH_4 emission from the Arctic sea floor near Svalbard; however, these emissions are not reaching the atmosphere (Graves et al. 2015; Ruppel and Kessler 2017). It is likely that most of the methane hydrate deposits will remain stable for the foreseeable future (the next few thousand years).

However, deposits off of coastal Alaska are among the most vulnerable and are expected to continue to release CH_4 during the 21st century (Archer 2007; Kretschmer et al. 2015).

TRACEABLE ACCOUNTS

Key Finding 1

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

Description of evidence base

The Key Finding is supported by observational evidence from ground-based observing stations, satellites, and data-model temperature analyses from multiple sources and independent analysis techniques (Serreze et al. 2009; Bekryaev et al. 2010; Screen and Simmonds 2010; Hartmann et al. 2013; Overland et al. 2014; Comiso and Hall 2014; Wendler et al. 2014). For more than 40 years, climate models have predicted enhanced Arctic warming, indicating a solid grasp on the underlying physics and positive feedbacks driving the accelerated Arctic warming (Manabe and Wetherald 1975; Collins et al. 2013; Taylor et al. 2013). Lastly, similar statements have been made in NCA3 (Melillo et al. 2014), IPCC AR5 (Hartmann et al. 2013), and in other Arctic-specific assessments such as the Arctic Climate Impacts Assessment (ACIA 2005) and Snow, Water, Ice and Permafrost in the Arctic (AMAP 2011).

Major Uncertainties

The lack of high quality and restricted spatial resolution of surface and ground temperature data over many Arctic land regions and essentially no measurements over the Central Arctic Ocean hampers the ability to better refine the rate of Arctic warming and completely restricts our ability to quantify and detect regional trends, especially over the sea ice. Climate models generally produce an Arctic warming between two to three times the global mean warming. A key uncertainty is our quantitative knowledge of the contributions from individual feedback processes in driving the accelerated Arctic warming. Reducing this uncertainty will help constrain projections of future Arctic warming.

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

V*ery high confidence* that the Arctic surface and air temperatures have warmed across Alaska and the Arctic at a much faster rate than the global average is provided by the multiple datasets analyzed by multiple independent groups indicating the same conclusion. Additionally, climate models capture the enhanced warming in the Arctic indicating a solid understanding of the underlying physical mechanisms.

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

It is *very likely* that the accelerated rate of Arctic warming will have a significant consequence for the United States due to accelerated land and sea ice melt driving changes in the ocean including sea level rise threatening our coastal communities and freshening of sea water that is influencing marine ecology.

Summary sentence or paragraph that integrates the above information

Annual average near-surface air temperatures across Alaska and the Arctic have increased over the last 50 years at a rate more than twice the global average. Observational studies using ground-based observing stations and satellites analyzed by multiple independent groups support this finding. The enhanced sensitivity of the Arctic climate system to anthropogenic forcing is also supported by climate modeling evidence, indicating a solid grasp on the underlying physics. These multiple lines of evidence provide *very high confidence* of enhanced Arctic warming with potentially significant impacts on coastal communities and marine ecosystems.

Key Finding 2

Rising Alaskan permafrost temperatures are causing permafrost to thaw and become more discontinuous; this process releases additional CO_2 and methane resulting in an amplifying feedback and additional warming (*high confidence*). The overall magnitude of the permafrost–carbon feedback is uncertain; however, it is clear that these emissions have the potential to complicate the ability to meet policy goals for the reduction of greenhouse gas concentrations.

Description of evidence base

The Key Finding is supported by observational evidence of warming permafrost temperatures and a deepening active layer, in situ gas measurements and laboratory incubation experiments of CO_2 and CH_4 release, and model studies (Vaughan et al. 2013; Fisher et al. 2014; Schuur et al. 2015; Koven et al. 2015a,b; Schädel et al. 2016; Liljedahl et al. 2016). Alaska and Arctic permafrost characteristics have responded to increased temperatures and reduced snow cover in most regions since the 1980s, with colder permafrost warming faster than warmer permafrost (AMAP 2011; Vaughan et al. 2013; Romanovsky et al. 2016). Large carbon soil pools (more than 50% of the global below-ground organic carbon pool) are locked up in the permafrost soils (Tarnocai et al. 2009), with the potential to be released. Thawing permafrost makes previously frozen organic matter available for microbial decomposition. In situ gas flux measurements have directly measured the release of CO_2 and CH_4 from Arctic permafrost (Schuur et al. 2009; Zona et al. 2016). The specific conditions of microbial decomposition, aerobic or anaerobic, determines the relative production of CO_2 and CH_4. This distinction is significant as CH_4 is a

much more powerful greenhouse gas than CO_2 (Myhre et al. 2013). However, incubation studies indicate that 3.4 times more carbon is released under aerobic conditions than anaerobic conditions, leading to a 2.3 times the stronger radiative forcing under aerobic conditions (Schädel et al. 2016). Combined data and modeling studies suggest a global sensitivity of the permafrost–carbon feedback warming global temperatures in 2100 by 0.52 ± 0.38°F (0.29 ± 0.21°C) alone (Schaefer et al. 2014). Chadburn et al. (2017) infer the sensitivity of permafrost area to globally averaged warming to be 4 million km^2 by constraining a group of climate models with the observed spatial distribution of permafrost; this sensitivity is 20% higher than previous studies. Permafrost thaw is occurring faster than models predict due to poorly understood deep soil, ice wedge, and thermokarst processes (Fisher et al. 2014; Koven et al. 2015a; Hollesen et al. 2015; Liljedahl et al. 2016). Additional uncertainty stems from the surprising uptake of methane from mineral soils (Oh et al. 2016) and dependence of emissions on vegetation and soil properties (Treat et al. 2015). The observational and modeling evidence supports the Key Finding that the permafrost–carbon cycle is positive.

Major uncertainties

A major limiting factor is the sparse observations of permafrost in Alaska and remote areas across the Arctic. Major uncertainties are related to deep soil, ice wedging, and thermokarst processes and the dependence of CO_2 and CH_4 uptake and production on vegetation and soil properties. Uncertainties also exist in relevant soil processes during and after permafrost thaw, especially those that control unfrozen soil carbon storage and plant carbon uptake and net ecosystem exchange. Many processes with the potential to drive rapid permafrost thaw (such as thermokarst) are not included in current earth system models.

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

There is *high confidence* that permafrost is thawing, becoming discontinuous, and releasing CO_2 and CH_4. Physically-based arguments and observed of increases in CO_2 and CH_4 emissions as permafrost thaws indicate that the feedback is positive. This confidence level is justified based on observations of rapidly changing permafrost characteristics.

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

Thawing permafrost *very likely* has significant impacts to the global carbon cycle and serves as a source of CO_2 and CH_4 emission that complicates the ability to meet policy goals

Summary sentence or paragraph that integrates the above information

Permafrost is thawing, becoming more discontinuous, and releasing CO_2 and CH_4. Observational and modeling evidence indicates that permafrost has thawed and released additional CO_2 and

CH_4 indicating that the permafrost–carbon cycle feedback is positive accounting for additional warming of approximately 0.08ºC to 0.50ºC on top of climate model projections. Although the magnitude of the permafrost–carbon feedback is uncertain due to a range of poorly understood processes (deep soil and ice wedge processes, plant carbon uptake, dependence of uptake and emissions on vegetation and soil type, and the role of rapid permafrost thaw processes, such as thermokarst), emerging science and the newest estimates continue to indicate that this feedback is more likely on the larger side of the range. Impacts of permafrost thaw and the permafrost carbon feedback complicates our ability to meet policy goals by adding a currently unconstrained radiative forcing to the climate system.

Key Finding 3

Arctic land and sea ice loss observed in the last three decades continues, in some cases accelerating (*very high confidence*). It is *virtually certain* that Alaska glaciers have lost mass over the last 50 years, with each year since 1984 showing an annual average ice mass less than the previous year. Based on gravitational data from satellites, average ice mass loss from Greenland was −269 Gt per year between April 2002 and April 2016, accelerating in recent years (*high confidence*). Since the early 1980s, annual average Arctic sea ice has decreased in extent between 3.5% and 4.1% per decade, become thinner by between 4.3 and 7.5 feet, and began melting at least 15 more days each year. September sea ice extent has decreased between 10.7% and 15.9% per decade (*very high confidence*). Arctic-wide ice loss is expected to continue through the 21st century, *very likely* resulting in nearly sea ice-free late summers by the 2040s (*very high confidence*).

Description of evidence base

The Key Finding is supported by observational evidence from multiple ground-based and satellite-based observational techniques (including passive microwave, laser and radar altimetry, and gravimetry) analyzed by independent groups using different techniques reaching similar conclusions (Vaughan et al. 2013; Comiso and Hall 2014; Stroeve et al. 2014a; Larsen et al. 2015; Zemp et al. 2015; Larsen et al. 2015; Harig and Simons 2016; Mengel et al. 2016; Perovich et al. 2016). Additionally, the U.S. Geological Survey repeat photography database shows the glacier retreat for many Alaskan glaciers (Figure 11.4: Muir Glacier). Several independent model analysis studies using a wide array of climate models and different analysis techniques indicate that sea ice loss will continue across the Arctic, *very likely* resulting in late summers becoming nearly ice-free by mid-century (Wang and Overland 2012; Collins et al. 2013; Snape and Forster 2014).

Major uncertainties

Key uncertainties remain in the quantification and modeling of key physical processes that contribute to the acceleration of land and sea ice melting. Climate models are unable to capture the rapid pace of observed sea and land ice melt over the last 15 years; a major factor is our inability to quantify and accurately model the physical processes driving the accelerated melting. The interactions between atmospheric circulation, ice dynamics and thermodynamics, clouds, and specifically the influence on the surface energy budget are key uncertainties. Mechanisms controlling marine-terminating glacier dynamics—specifically the roles of atmospheric warming, seawater intrusions under floating ice shelves, and the penetration of surface meltwater to the glacier bed—are key uncertainties in projecting Greenland Ice Sheet melt.

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 Arctic sea and land ice melt is accelerating and mountain glacier ice mass is declining given the multiple observational sources and analysis technique documented in the peer reviewed climate science literature.

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

It is *very likely* that accelerating Arctic land and sea ice melt impacts the United States. Accelerating Arctic Ocean sea ice melt increases coastal erosion in Alaska and makes Alaskan fisheries more susceptible to ocean acidification by changing Arctic Ocean chemistry. Greenland Ice Sheet and Alaska mountain glacier melt drives sea level rise threatening coastal communities in the United State and worldwide, influencing marine ecology, and potentially altering the thermohaline circulation.

Summary sentence or paragraph that integrates the above information

Arctic land and sea ice loss observed in the last three decades continues, in some cases accelerating. A diverse range of observational evidence from multiple data sources and independent analysis techniques provide consistent evidence of substantial declines in Arctic sea ice extent, thickness, and volume since at least 1979, mountain glacier melt over the last 50 years, and accelerating mass loss from Greenland. An array of different models and independent analyses indicate that future declines in ice across the Arctic are expected resulting in late summers in the Arctic becoming ice free by midcentury.

Key Finding 4

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

Description of evidence base

The Key Finding is supported by many attribution studies including a wide array of climate models documenting the anthropogenic influence on Arctic temperature, sea ice, mountain glaciers and snow extent (Vinnikov et al. 1999; Stroeve et al. 2007; Gillett et al. 2008; Min et al. 2008; Kay et al. 2011b; Day et al. 2012; Wang and Overland 2012; Bindoff et al. 2013; Christensen et al. 2013; Najafi et al. 2015). Observation-based analyses also support an anthropogenic influence (Notz and Marotzke 2012; Notz and Stroeve 2015). Emerging science indicates it is *very likely* that natural variability alone could not have caused the recently observed record low Arctic sea ice extents, such as in September 2012 (Zhang and Knutson 2013; Kirchmeyer-Young et al. 2017). Natural variability in the Arctic is significant (Swart et al. 2015; Jahn et al. 2016), however the majority of studies indicate that the contribution from internal variability to observed trends in Arctic temperature and sea ice are less than 50% (Kay et al. 2011b; Day et al. 2012; Ding et al. 2017), therefore human activities have *likely* contributed to more than half of the observed sea ice loss since 1979. Multiple lines evidence, independent analysis techniques, models, and studies support the Key Finding.

Major uncertainties

A major limiting factor in our ability to attribute Arctic sea ice and glacier melt to human activities is the significant natural climate variability in the Arctic. Longer data records and a better understanding of the physical mechanisms that drive natural climate variability in the Arctic are required to reduce this uncertainty. Another major uncertainty is the ability of climate models to capture the relevant physical processes and climate changes at a fine spatial scale, especially those at the land and ocean surface in the Arctic.

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 human activities have contributed to Arctic surface temperature warming, sea ice loss since 1979, glacier mass loss, and northern hemisphere snow extent given multiple independent analysis techniques from independent groups using many different climate models indicate the same conclusion.

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

Arctic sea ice and glacier mass loss impacts the United States by affecting coastal erosion in Alaska and key Alaskan fisheries through an increased vulnerability to ocean acidification. Glacier mass loss is a significant driver of sea level rise threatening coastal communities in the United States and worldwide, influencing marine ecology, and potentially altering the Atlantic Meridional Overturning Circulation (Liu et al. 2017).

Summary sentence or paragraph that integrates the above information

Evidenced by the multiple independent studies, analysis techniques, and the array of different climate models used over the last 20 years, it is *virtually certain* that human activities have contributed to Arctic surface temperature warming, sea ice loss since 1979, glacier mass loss, and Northern Hemisphere snow extent decline observed across the Arctic. Key uncertainties remain in the understanding and modeling of Arctic climate variability; however, the majority of studies indicate that contribution from internal variability to observed trends in Arctic temperature and sea ice are less than 50%. This suggests that it is also *likely* that human activities have contributed to more than half of the observed September sea ice decline since 1979.

Key Finding 5

Atmospheric circulation patterns connect the climates of the Arctic and the contiguous United States. Evidenced by recent record warm temperatures in the Arctic and emerging science, the midlatitude circulation has influenced observed Arctic temperatures and sea ice (*high confidence*). However, confidence is *low* regarding whether or by what mechanisms observed Arctic warming may have influenced the midlatitude circulation and weather patterns over the continental United States. The influence of Arctic changes on U.S. weather over the coming decades remains an open question with the potential for significant impact.

Description of evidence base

The midlatitude circulation influences the Arctic through the transport of warm, moist air, altering the Arctic surface energy budget (Rigor et al. 2002; Graverson et al. 2006; Screen et al. 2012; Perlwitz et al. 2015). The intrusion of warm, moist air from midlatitudes increases downwelling longwave radiation, warming the Arctic surface and hindering wintertime sea ice growth (Lee 2014; Liu and Key 2014). Emerging research provides a new understanding of the importance of synoptic time scales and the episodic nature of midlatitude air intrusions (Lee 2014; Park et al. 2015; Woods and Caballero 2016). The combination of recent observational and model-based evidence as well as the physical understanding of the mechanisms of midlatitude circulation effects on Arctic climate supports this Key Finding.

In addition, research on the impact of Arctic climate on midlatitude circulation is rapidly evolving, including observational analysis and modeling studies. Multiple observational studies provide evidence for concurrent changes in the Arctic and Northern Hemisphere large-scale circulation changes (Cohen et al. 2014; Vihma 2014; Barnes and Screen 2015). Further, modeling studies demonstrate that Arctic warming can influence the midlatitude jet stream and storm track (Barnes and Screen 2015; Barnes and Polvani 2015; Overland et al. 2016; Francis et al. 2017). However, attribution studies indicate that the observed midlatitude circulation changes over the continental United States are smaller than natural variability and are therefore not detectable in the observational record (Screen et al. 2012; Perlwitz et al. 2015; Sigmond and Fyfe 2016; Sun et al. 2016). This disagreement between independent studies using different analysis techniques and the lack of understanding of the physical mechanism(s) support this Key Finding.

Major uncertainties

A major limiting factor is our understanding and modeling of natural climate variability in the Arctic. Longer data records and a better understanding of the physical mechanisms that drive natural climate variability in the Arctic are required to reduce this uncertainty. The inability of climate models to accurately capture interactions between sea ice and the atmospheric circulation and polar stratospheric processes limits our current understanding.

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

High confidence in the impact of midlatitude circulation on Arctic changes from the consistency between observations and models as well as a solid physical understanding.

Low confidence on the detection of an impact of Arctic warming on midlatitude climate is based on short observational data record, model uncertainty, and lack of physical understanding.

Summary sentence or paragraph that integrates the above information

The midlatitude circulation has influenced observed Arctic temperatures, supported by recent observational and model-based evidence as well as the physical understanding from emerging science. In turn, confidence is low regarding the mechanisms by which observed Arctic warming has influenced the midlatitude circulation and weather patterns over the continental United States, due to the disagreement between numerous studies and a lack of understanding of the physical mechanism(s). Resolving the remaining questions requires longer data records and improved understanding and modeling of physics in the Arctic. The influence of Arctic changes on U.S. weather over the coming decades remains an open question with the potential for significant impact.

FIGURES

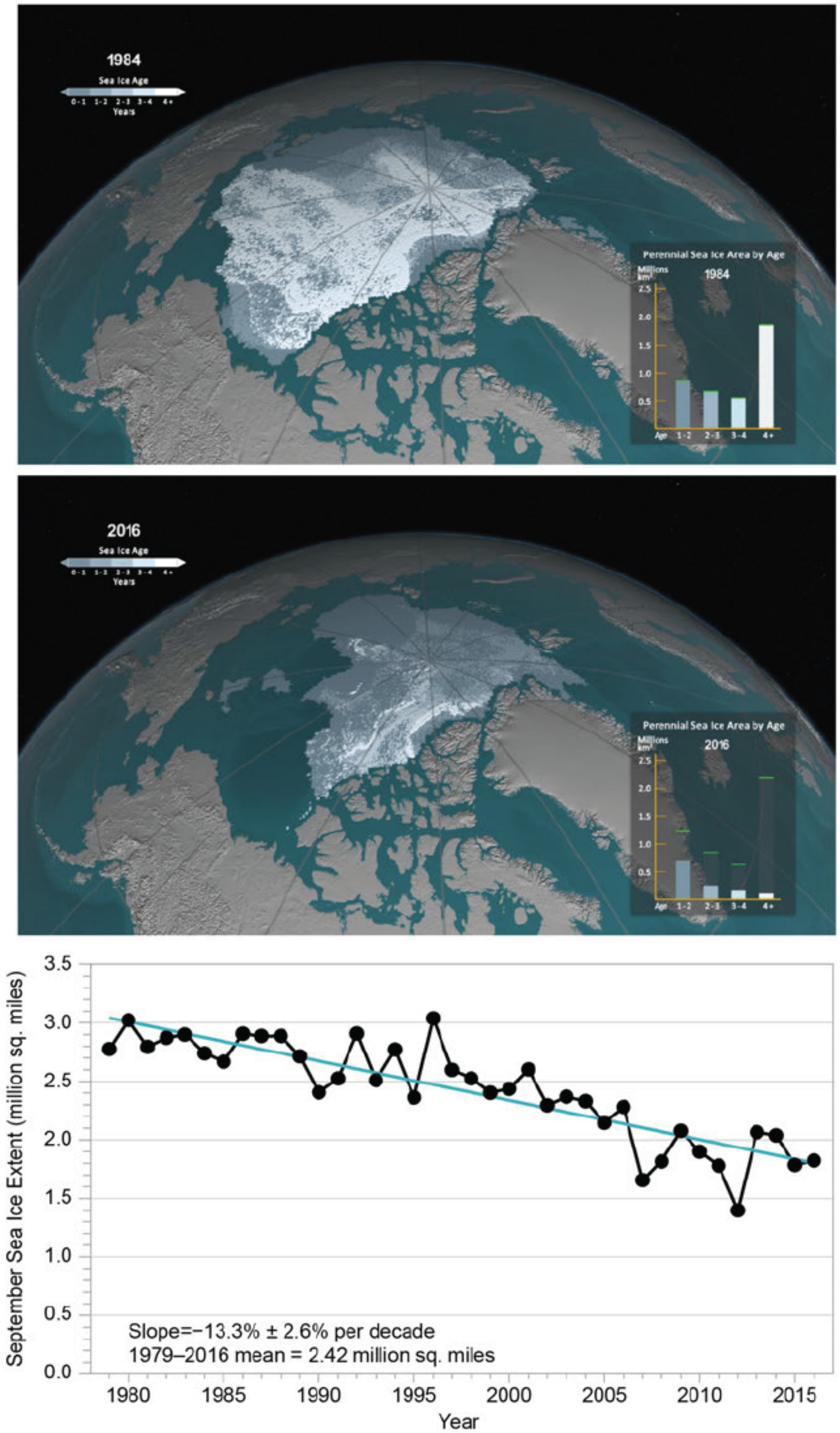

Figure 11.1: September sea ice extent and age shown for (a) 1984 and (b) 2016, illustrating significant reductions in sea ice extent and age (thickness). Bar graph in the lower right of each panel illustrates the sea ice area (unit: million km^2) covered within each age category (> 1 year),

and the green bars represent the maximum value for each age range during the record. The year 1984 is representative of September sea ice characteristics during the 1980s. The years 1984 and 2016 are selected as endpoints in the time series; a movie of the complete time series is available at http://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=4489. (c) Shows the satellite-era Arctic sea ice areal extent trend from 1979 to 2016 for September (unit: million mi^2). (Figure source: Panel (a,b): NASA Science Visualization Studio; data: Tschudi et al. 2016; Panel (c) data: Fetterer et al. 2016).

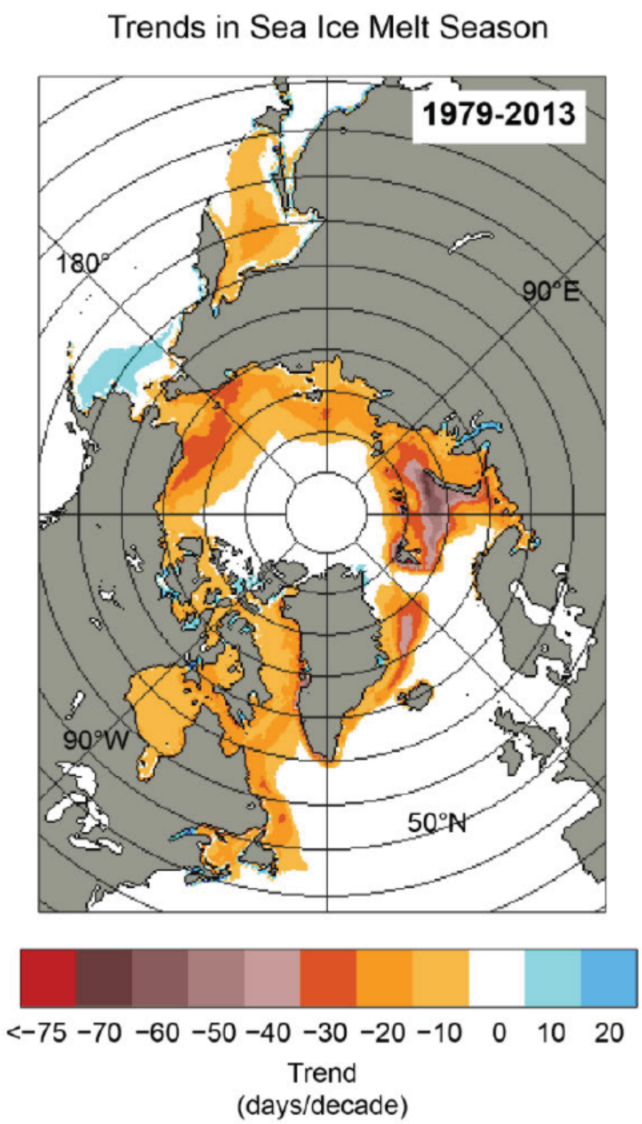

Figure 11.2: 35-year trend in Arctic sea ice melt season length, in days per decade, from passive microwave satellite observations, illustrating that the sea ice season has shortened by more than 60 days in coastal Alaska over the last 30 years. (Figure source: adapted from Parkinson 2014).

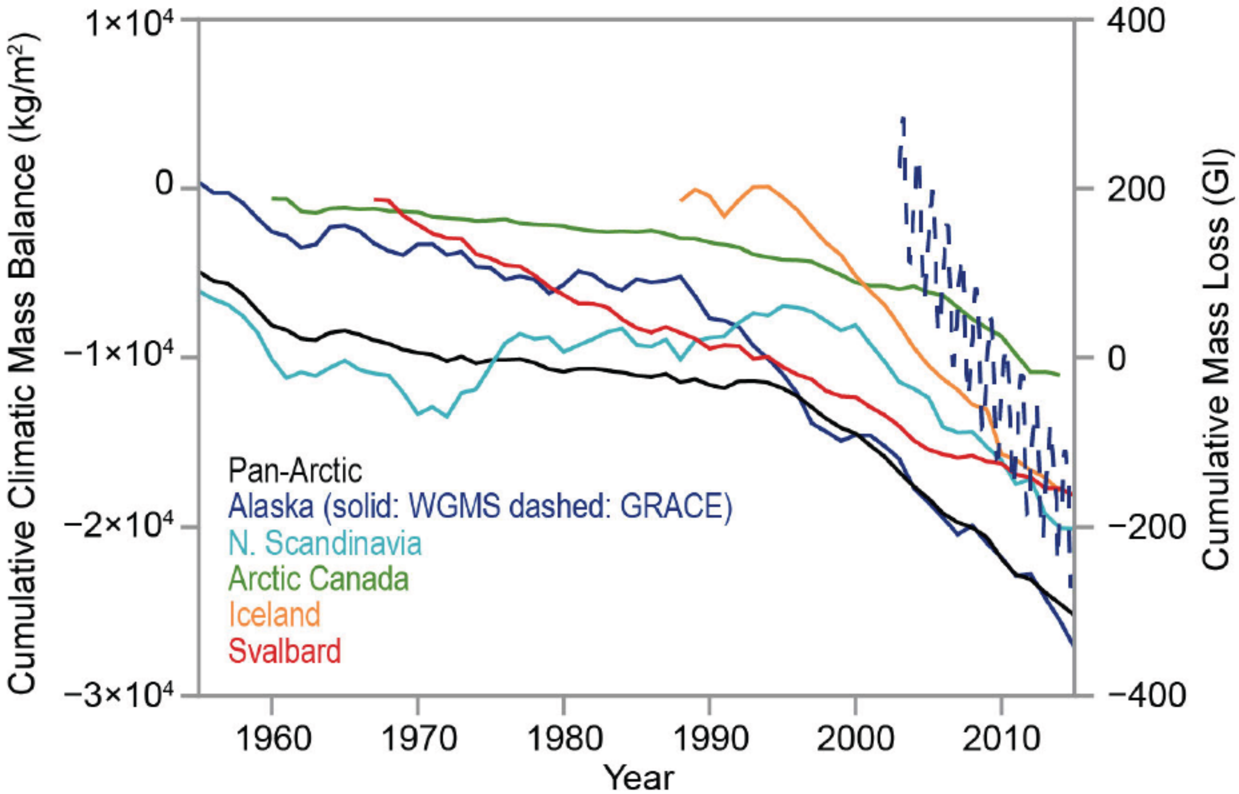

Figure 11.3: Time series of the cumulative climatic mass balance (units: kg/m^2) in five Arctic regions and for the Pan-Arctic from the World Glacier Monitoring Service (WGMS 2016; Wolken et al. 2016; solid lines, left y-axis), plus Alaskan glacial mass loss observed from NASA GRACE (Harig and Simons 2016; dashed blue line, right y-axis). (Figure source: Harig and Simons 2016 and Wolken et al. 2016; © American Meteorological Society, used with permission).

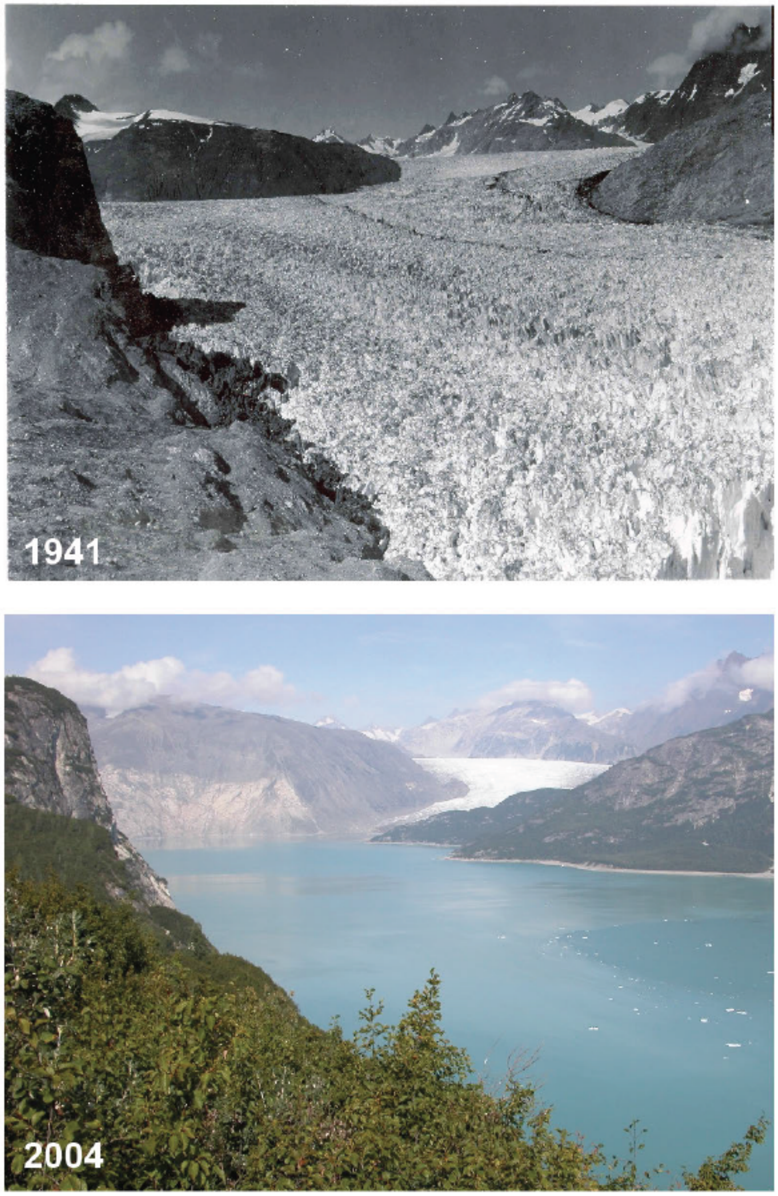

Figure 11.4: Two northeast-looking photographs of the Muir Glacier located in southeastern Alaska are shown taken from a Glacier Bay Photo station in (a) 1941 and (b) 2004. U.S. Geological Survey repeat photography allows the tracking of glacier changes, illustrating that between 1941 and 2004 the Muir Glacier has retreated more than 4 miles to the northwest and out of view. Riggs Glacier (in view) is a tributary to Muir Glacier and has retreated by as much as 0.37 miles and thinned by more than 0.16 miles. The photographs also illustrate a significant change in the surface type between 1941 and 2004 as bare rock in the foreground has been replaced by dense vegetation (Figure source: USGS 2004).

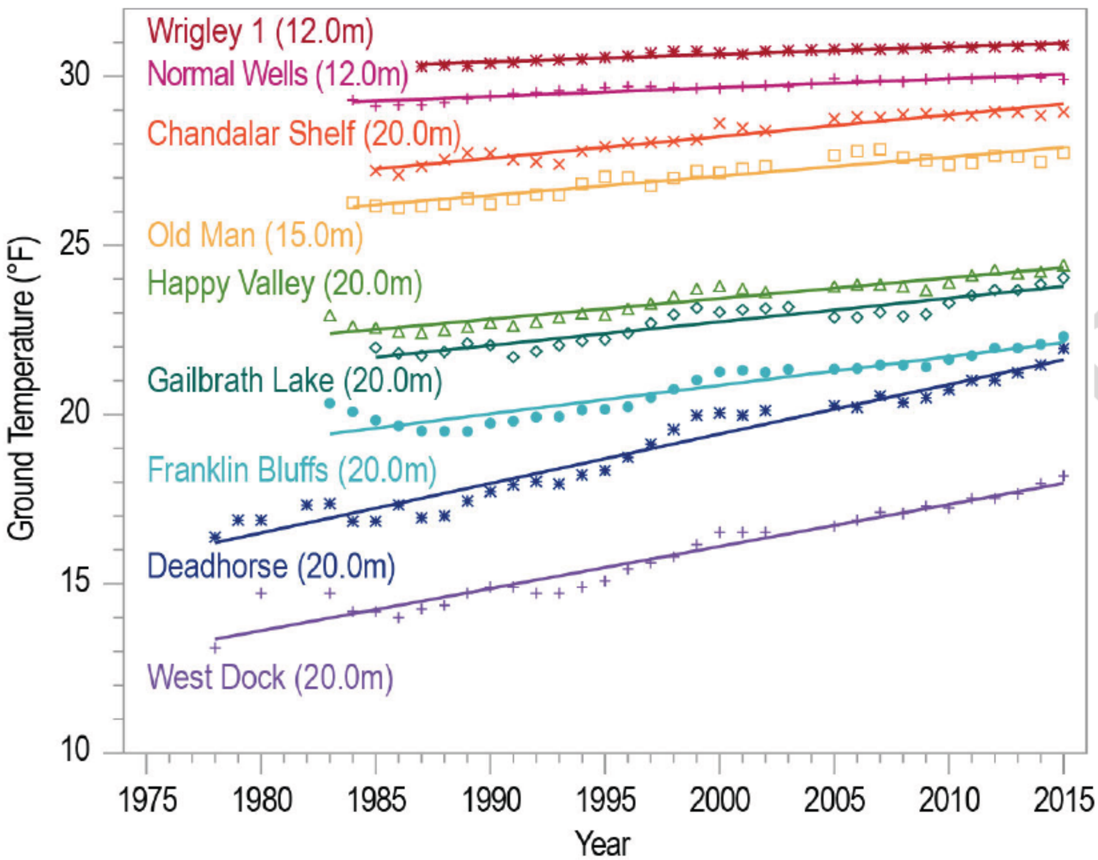

Figure 11.5: Time series of annual mean permafrost temperatures (units: °F) at various depths from 39 to 65 feet (12 to 20 meters) from 1977 through 2015 at several sites across Alaska, including the North Slope continuous permafrost region (purple/blue/green shades), and the discontinuous permafrost (orange/pink/red shades) in Alaska and northwestern Canada. Solid lines represent the linear trends drawn to highlight that permafrost temperatures are warming faster in the colder, coastal permafrost regions than the warmer interior regions. (Figure Source: adapted from Romanovsky et al. 2016; © American Meteorological Society, used with permission).

REFERENCES

ACIA, 2005: Arctic Climate Impact Assessment. ACIA Secretariat and Cooperative Institute for Arctic Research, 1042 pp. http://www.acia.uaf.edu/pages/scientific.html

AMAP, 2011: Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere. Oslo, Norway. 538 pp. http://www.amap.no/documents/download/1448

Andresen, C.S., F. Straneo, M.H. Ribergaard, A.A. Bjork, T.J. Andersen, A. Kuijpers, N. Norgaard-Pedersen, K.H. Kjaer, F. Schjoth, K. Weckstrom, and A.P. Ahlstrom, 2012: Rapid response of Helheim Glacier in Greenland to climate variability over the past century. *Nature Geoscience,* **5,** 37-41. http://dx.doi.org/10.1038/ngeo1349

Archer, D., 2007: Methane hydrate stability and anthropogenic climate change. *Biogeosciences,* **4,** 521-544. http://dx.doi.org/10.5194/bg-4-521-2007

Arrigo, K.R., G. van Dijken, and S. Pabi, 2008: Impact of a shrinking Arctic ice cover on marine primary production. *Geophysical Research Letters,* **35,** L19603. http://dx.doi.org/10.1029/2008GL035028

Ayarzagüena, B. and J.A. Screen, 2016: Future Arctic sea ice loss reduces severity of cold air outbreaks in midlatitudes. *Geophysical Research Letters,* **43,** 2801-2809. http://dx.doi.org/10.1002/2016GL068092

Barnes, E.A. and L.M. Polvani, 2015: CMIP5 projections of arctic amplification, of the North American/North Atlantic circulation, and of their relationship. *Journal of Climate,* **28,** 5254-5271. http://dx.doi.org/10.1175/JCLI-D-14-00589.1

Barnes, E.A. and J.A. Screen, 2015: The impact of Arctic warming on the midlatitude jet-stream: Can it? Has it? Will it? *Wiley Interdisciplinary Reviews: Climate Change,* **6,** 277-286. http://dx.doi.org/10.1002/wcc.337

Bartholomew, I.D., P. Nienow, A. Sole, D. Mair, T. Cowton, M.A. King, and S. Palmer, 2011: Seasonal variations in Greenland Ice Sheet motion: Inland extent and behaviour at higher elevations. *Earth and Planetary Science Letters,* **307,** 271-278. http://dx.doi.org/10.1016/j.epsl.2011.04.014

Bates, N.R., R. Garley, K.E. Frey, K.L. Shake, and J.T. Mathis, 2014: Sea-ice melt CO_2–carbonate chemistry in the western Arctic Ocean: Meltwater contributions to air–sea CO_2 gas exchange, mixed-layer properties and rates of net community production under sea ice. *Biogeosciences,* **11,** 6769-6789. http://dx.doi.org/10.5194/bg-11-6769-2014

Bekryaev, R.V., I.V. Polyakov, and V.A. Alexeev, 2010: Role of polar amplification in long-term surface air temperature variations and modern Arctic warming. *Journal of Climate,* **23,** 3888-3906. http://dx.doi.org/10.1175/2010jcli3297.1

Bindoff, N.L., P.A. Stott, K.M. AchutaRao, M.R. Allen, N. Gillett, D. Gutzler, K. Hansingo, G. Hegerl, Y. Hu, S. Jain, I.I. Mokhov, J. Overland, J. Perlwitz, R. Sebbari, and X. Zhang, 2013: Detection and attribution of climate change: From global to regional. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 867–952. http://www.climatechange2013.org/report/full-report/

Boisvert, L.N., T. Markus, and T. Vihma, 2013: Moisture flux changes and trends for the entire Arctic in 2003–2011 derived from EOS Aqua data. *Journal of Geophysical Research: Oceans,* **118,** 5829-5843. http://dx.doi.org/10.1002/jgrc.20414

Boisvert, L.N., D.L. Wu, and C.L. Shie, 2015: Increasing evaporation amounts seen in the Arctic between 2003 and 2013 from AIRS data. *Journal of Geophysical Research: Atmospheres,* **120,** 6865-6881. http://dx.doi.org/10.1002/2015JD023258

Boisvert, L.N., D.L. Wu, T. Vihma, and J. Susskind, 2015: Verification of air/surface humidity differences from AIRS and ERA-Interim in support of turbulent flux estimation in the Arctic. *Journal of Geophysical Research: Atmospheres,* **120,** 945-963. http://dx.doi.org/10.1002/2014JD021666

Bollmann, M., T. Bosch, F. Colijn, R. Ebinghaus, R. Froese, K. Güssow, S. Khalilian, S. Krastel, A. Körtzinger, M. Langenbuch, M. Latif, B. Matthiessen, F. Melzner, A. Oschlies, S. Petersen, A. Proelß, M. Quaas, J. Reichenbach, T. Requate, T. Reusch, P. Rosenstiel, J.O. Schmidt, K. Schrottke, H. Sichelschmidt, U. Siebert, R. Soltwedel, U. Sommer, K. Stattegger, H. Sterr, R. Sturm, T. Treude, A. Vafeidis, C.v. Bernem, J.v. Beusekom, R. Voss, M. Visbeck, M. Wahl, K. Wallmann, and F. Weinberger, 2010: *World Ocean Review: Living With the Oceans*. maribus gGmbH, 232 pp. http://worldoceanreview.com/wp-content/downloads/wor1/WOR1_english.pdf

Bourassa, M.A., S.T. Gille, C. Bitz, D. Carlson, I. Cerovecki, C.A. Clayson, M.F. Cronin, W.M. Drennan, C.W. Fairall, R.N. Hoffman, G. Magnusdottir, R.T. Pinker, I.A. Renfrew, M. Serreze, K. Speer, L.D. Talley, and G.A. Wick, 2013: High-latitude ocean and sea ice surface fluxes: Challenges for climate research. *Bulletin of the American Meteorological Society,* **94,** 403-423. http://dx.doi.org/10.1175/BAMS-D-11-00244.1

Brown, R.D. and D.A. Robinson, 2011: Northern Hemisphere spring snow cover variability and change over 1922–2010 including an assessment of uncertainty. *The Cryosphere,* **5,** 219-229. http://dx.doi.org/10.5194/tc-5-219-2011

Brown, D. R. N., M. T. Jorgenson, T. A. Douglas, V. E. Romanovsky, K. Kielland, C. Hiemstra, E. S. Euskirchen, and R. W. Ruess, 2015: Interactive effects of wildfire and climate on permafrost degradation in Alaskan lowland forests. *J. Geophys. Res. Biogeosci.*, **120**, 1619–1637. http://dx.doi.org/10.1002/2015JG003033

Cai, W.-J., L. Chen, B. Chen, Z. Gao, S.H. Lee, J. Chen, D. Pierrot, K. Sullivan, Y. Wang, X. Hu, W.-J. Huang, Y. Zhang, S. Xu, A. Murata, J.M. Grebmeier, E.P. Jones, and H. Zhang, 2010: Decrease in the CO_2 uptake capacity in an ice-free Arctic Ocean basin. *Science,* **329,** 556-559. http://dx.doi.org/10.1126/science.1189338

Carmack, E., I. Polyakov, L. Padman, I. Fer, E. Hunke, J. Hutchings, J. Jackson, D. Kelley, R. Kwok, C. Layton, H. Melling, D. Perovich, O. Persson, B. Ruddick, M.-L. Timmermans, J. Toole, T. Ross, S. Vavrus, and P. Winsor, 2015: Toward quantifying the increasing role of oceanic heat in sea ice loss in the new Arctic. *Bulletin of the American Meteorological Society,* **96 (12),** 2079-2105. http://dx.doi.org/10.1175/BAMS-D-13-00177.1

Chadburn, S.E., E.J. Burke, P.M. Cox, P. Friedlingstein, G. Hugelius, and S. Westermann, 2017: An observation-based constraint on permafrost loss as a function of global warming. *Nature Climate Change,* **7**, 340-344. http://dx.doi.org/10.1038/nclimate3262

Chang, R.Y.-W., C.E. Miller, S.J. Dinardo, A. Karion, C. Sweeney, B.C. Daube, J.M. Henderson, M.E. Mountain, J. Eluszkiewicz, J.B. Miller, L.M.P. Bruhwiler, and S.C. Wofsy, 2014: Methane emissions from Alaska in 2012 from CARVE airborne observations. *Proceedings of the National Academy of Sciences,* **111,** 16694-16699. http://dx.doi.org/10.1073/pnas.1412953111

Chapin III, F.S., S.F. Trainor, P. Cochran, H. Huntington, C. Markon, M. McCammon, A.D. McGuire, and M. Serreze, 2014: Ch. 22: Alaska. *Climate Change Impacts in the United States: The Third National Climate Assessment*. Melillo, J.M., Terese (T.C.) Richmond, and G.W. Yohe, Eds. U.S. Global Change Research Program, Washington, DC, 514-536. http://dx.doi.org/10.7930/J00Z7150

Christensen, J.H., K. Krishna Kumar, E. Aldrian, S.-I. An, I.F.A. Cavalcanti, M. de Castro, W. Dong, P. Goswami, A. Hall, J.K. Kanyanga, A. Kitoh, J. Kossin, N.-C. Lau, J. Renwick, D.B. Stephenson, S.-P. Xie, and T. Zhou, 2013: Climate phenomena and their relevance for future regional climate change. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A.

Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1217–1308. http://www.climatechange2013.org/report/full-report/

Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A. Merrifield, G.A. Milne, R.S. Nerem, P.D. Nunn, A.J. Payne, W.T. Pfeffer, D. Stammer, and A.S. Unnikrishnan, 2013: Sea level change. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1137–1216. http://www.climatechange2013.org/report/full-report/

Cohen, J., J. Jones, J.C. Furtado, and E. Tzipermam, 2013: Warm Arctic, cold continents: A common pattern related to Arctic sea ice melt, snow advance, and extreme winter weather. *Oceanography,* **26,** 150-160. http://dx.doi.org/10.5670/oceanog.2013.70

Cohen, J., J.A. Screen, J.C. Furtado, M. Barlow, D. Whittleston, D. Coumou, J. Francis, K. Dethloff, D. Entekhabi, J. Overland, and J. Jones, 2014: Recent Arctic amplification and extreme mid-latitude weather. *Nature Geoscience,* **7,** 627-637. http://dx.doi.org/10.1038/ngeo2234

Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver, and M. Wehner, 2013: Long-term climate change: Projections, commitments and irreversibility. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1029–1136. http://www.climatechange2013.org/report/full-report/

Comiso, J.C. and D.K. Hall, 2014: Climate trends in the Arctic as observed from space. *Wiley Interdisciplinary Reviews: Climate Change,* **5,** 389-409. http://dx.doi.org/10.1002/wcc.277

Day, J.J., J.C. Hargreaves, J.D. Annan, and A. Abe-Ouchi, 2012: Sources of multi-decadal variability in Arctic sea ice extent. *Environmental Research Letters,* **7,** 034011. http://dx.doi.org/10.1088/1748-9326/7/3/034011

Derksen, C. and R. Brown, 2012: Snow [in Arctic Report Card 2012]. ftp://ftp.oar.noaa.gov/arctic/documents/ArcticReportCard_full_report2012.pdf

Derksen, C., R. Brown, L. Mudryk, and K. Luojus, 2015: Terrestrial snow cover [in Arctic Report Card 2015]. ftp://ftp.oar.noaa.gov/arctic/documents/ArcticReportCard_full_report2015.pdf

Ding, Q., A. Schweiger, M. Lheureux, D.S. Battisti, S. Po-Chedley, N.C. Johnson, E. Blanchard-Wrigglesworth, K. Harnos, Q. Zhang, R. Eastman, and E.J. Steig, 2017: Influence of high-latitude atmospheric circulation changes on summertime Arctic sea ice. *Nature Climate Change,* **7,** 289-295. http://dx.doi.org/10.1038/nclimate3241

Ding, Q., J.M. Wallace, D.S. Battisti, E.J. Steig, A.J.E. Gallant, H.-J. Kim, and L. Geng, 2014: Tropical forcing of the recent rapid Arctic warming in northeastern Canada and Greenland. *Nature,* **509,** 209-212. http://dx.doi.org/10.1038/nature13260

Döscher, R., T. Vihma, and E. Maksimovich, 2014: Recent advances in understanding the Arctic climate system state and change from a sea ice perspective: A review. *Atmospheric Chemistry and Physics,* **14,** 13571-13600. http://dx.doi.org/10.5194/acp-14-13571-2014

Dupont, T.K. and R.B. Alley, 2005: Assessment of the importance of ice-shelf buttressing to ice-sheet flow. *Geophysical Research Letters,* **32,** n/a-n/a. http://dx.doi.org/10.1029/2004GL022024

Euskirchen, E.S., A.P. Bennett, A.L. Breen, H. Genet, M.A. Lindgren, T.A. Kurkowski, A.D. McGuire, and T.S. Rupp, 2016: Consequences of changes in vegetation and snow cover for climate feedbacks in Alaska and northwest Canada. *Environmental Research Letters,* **11,** 105003. http://dx.doi.org/10.1088/1748-9326/11/10/105003

Fetterer, F., K. Knowles, W. Meier, and M. Savoie, 2016, updated daily: Sea Ice Index, Version 2. National Snow and Ice Data Center, Boulder, CO.

Fisher, J.B., M. Sikka, W.C. Oechel, D.N. Huntzinger, J.R. Melton, C.D. Koven, A. Ahlström, M.A. Arain, I. Baker, J.M. Chen, P. Ciais, C. Davidson, M. Dietze, B. El-Masri, D. Hayes, C. Huntingford, A.K. Jain, P.E. Levy, M.R. Lomas, B. Poulter, D. Price, A.K. Sahoo, K. Schaefer, H. Tian, E. Tomelleri, H. Verbeeck, N. Viovy, R. Wania, N. Zeng, and C.E. Miller, 2014: Carbon cycle uncertainty in the Alaskan Arctic. *Biogeosciences,* **11,** 4271-4288. http://dx.doi.org/10.5194/bg-11-4271-2014

Flannigan, M., B. Stocks, M. Turetsky, and M. Wotton, 2009: Impacts of climate change on fire activity and fire management in the circumboreal forest. *Global Change Biology,* **15,** 549-560. http://dx.doi.org/10.1111/j.1365-2486.2008.01660.x

Francis, J. and N. Skific, 2015: Evidence linking rapid Arctic warming to mid-latitude weather patterns. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences,* **373**. http://dx.doi.org/10.1098/rsta.2014.0170

Francis, J.A. and S.J. Vavrus, 2012: Evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geophysical Research Letters,* **39,** L06801. http://dx.doi.org/10.1029/2012GL051000

Francis, J.A. and S.J. Vavrus, 2015: Evidence for a wavier jet stream in response to rapid Arctic warming. *Environmental Research Letters,* **10,** 014005. http://dx.doi.org/10.1088/1748-9326/10/1/014005

Francis, J.A, S.J. Vavrus, and J. Cohen, 2017: Amplified Arctic warming and mid-latitude weather: New perspectives on emerging connections. WIREs Climate Change, e474. http://dx.doi.org/10.1002/wcc.474

French, N.H.F., L.K. Jenkins, T.V. Loboda, M. Flannigan, R. Jandt, L.L. Bourgeau-Chavez, and M. Whitley, 2015: Fire in arctic tundra of Alaska: Past fire activity, future fire potential, and significance for land management and ecology. *International Journal of Wildland Fire,* **24,** 1045-1061. http://dx.doi.org/10.1071/WF14167

Friedlingstein, P., P. Cox, R. Betts, L. Bopp, W.v. Bloh, V. Brovkin, P. Cadule, S. Doney, M. Eby, I. Fung, G. Bala, J. John, C. Jones, F. Joos, T. Kato, M. Kawamiya, W. Knorr, K. Lindsay, H.D. Matthews, T. Raddatz, P. Rayner, C. Reick, E. Roeckner, K.-G. Schnitzler, R. Schnur, K. Strassmann, A.J. Weaver, C. Yoshikawa, and N. Zeng, 2006: Climate–carbon cycle feedback analysis: Results from the C^4MIP model intercomparison. *Journal of Climate,* **19,** 3337-3353. http://dx.doi.org/10.1175/JCLI3800.1

Gagné, M.È., N.P. Gillett, and J.C. Fyfe, 2015: Impact of aerosol emission controls on future Arctic sea ice cover. *Geophysical Research Letters,* **42,** 8481-8488. http://dx.doi.org/10.1002/2015GL065504

Gibbs, A.E. and B.M. Richmond, 2015: National Assessment of Shoreline Change: Historical Shoreline Change Along the North Coast of Alaska, U.S.–Canadian Border to Icy Cape. U.S. Geological Survey Open-File Report 2015–1048. U.S. Geological Survey, 96 pp. http://dx.doi.org/10.3133/ofr20151048

Giles, K.A., S.W. Laxon, A.L. Ridout, D.J. Wingham, and S. Bacon, 2012: Western Arctic Ocean freshwater storage increased by wind-driven spin-up of the Beaufort Gyre. *Nature Geoscience,* **5,** 194-197. http://dx.doi.org/10.1038/ngeo1379

Gillett, N.P., D.A. Stone, P.A. Stott, T. Nozawa, A.Y. Karpechko, G.C. Hegerl, M.F. Wehner, and P.D. Jones, 2008: Attribution of polar warming to human influence. *Nature Geoscience,* **1,** 750-754. http://dx.doi.org/10.1038/ngeo338

Graversen, R.G., 2006: Do changes in the midlatitude circulation have any impact on the Arctic surface air temperature trend? *Journal of Climate,* **19,** 5422-5438. http://dx.doi.org/10.1175/JCLI3906.1

Graves, C.A., L. Steinle, G. Rehder, H. Niemann, D.P. Connelly, D. Lowry, R.E. Fisher, A.W. Stott, H. Sahling, and R.H. James, 2015: Fluxes and fate of dissolved methane released at the seafloor at the landward limit of the gas hydrate stability zone offshore western Svalbard. *Journal of Geophysical Research: Oceans,* **120,** 6185-6201. http://dx.doi.org/10.1002/2015JC011084

Grosse, G., S. Goetz, A.D. McGuire, V.E. Romanovsky, and E.A.G. Schuur, 2016: Changing permafrost in a warming world and feedbacks to the Earth system. *Environmental Research Letters,* **11,** 040201. http://dx.doi.org/10.1088/1748-9326/11/4/040201

Harig, C. and F.J. Simons, 2016: Ice mass loss in Greenland, the Gulf of Alaska, and the Canadian Archipelago: Seasonal cycles and decadal trends. *Geophysical Research Letters,* **43,** 3150-3159. http://dx.doi.org/10.1002/2016GL067759

Hartmann, B. and G. Wendler, 2005: The significance of the 1976 Pacific climate shift in the climatology of Alaska. *Journal of Climate,* **18,** 4824-4839. http://dx.doi.org/10.1175/JCLI3532.1

Hartmann, D.L., A.M.G. Klein Tank, M. Rusticucci, L.V. Alexander, S. Brönnimann, Y. Charabi, F.J. Dentener, E.J. Dlugokencky, D.R. Easterling, A. Kaplan, B.J. Soden, P.W. Thorne, M. Wild, and P.M. Zhai, 2013: Observations: Atmosphere and surface. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 159–254. http://www.climatechange2013.org/report/full-report/

Holland, D.M., R.H. Thomas, B. de Young, M.H. Ribergaard, and B. Lyberth, 2008: Acceleration of Jakobshavn Isbrae triggered by warm subsurface ocean waters. *Nature Geoscience,* **1,** 659-664. http://dx.doi.org/10.1038/ngeo316

Hollesen, J., H. Matthiesen, A.B. Møller, and B. Elberling, 2015: Permafrost thawing in organic Arctic soils accelerated by ground heat production. *Nature Climate Change,* **5,** 574-578. http://dx.doi.org/10.1038/nclimate2590

Hoskins, B. and T. Woollings, 2015: Persistent extratropical regimes and climate extremes. *Current Climate Change Reports,* **1,** 115-124. http://dx.doi.org/10.1007/s40641-015-0020-8

Howat, I.M., I. Joughin, M. Fahnestock, B.E. Smith, and T.A. Scambos, 2008: Synchronous retreat and acceleration of southeast Greenland outlet glaciers 2000–06: Ice dynamics and coupling to climate. *Journal of Glaciology,* **54,** 646-660. http://dx.doi.org/10.3189/002214308786570908

Hu, F.S., P.E. Higuera, P. Duffy, M.L. Chipman, A.V. Rocha, A.M. Young, R. Kelly, and M.C. Dietze, 2015: Arctic tundra fires: Natural variability and responses to climate change. *Frontiers in Ecology and the Environment,* **13,** 369-377. http://dx.doi.org/10.1890/150063

Hunt, G.L., Jr., K.O. Coyle, L.B. Eisner, E.V. Farley, R.A. Heintz, F. Mueter, J.M. Napp, J.E. Overland, P.H. Ressler, S. Salo, and P.J. Stabeno, 2011: Climate impacts on eastern Bering Sea foodwebs: A synthesis of new data and an assessment of the Oscillating Control Hypothesis. *ICES Journal of Marine Science,* **68,** 1230-1243. http://dx.doi.org/10.1093/icesjms/fsr036

Hunter, S.J., D.S. Goldobin, A.M. Haywood, A. Ridgwell, and J.G. Rees, 2013: Sensitivity of the global submarine hydrate inventory to scenarios of future climate change. *Earth and Planetary Science Letters,* **367,** 105-115. http://dx.doi.org/10.1016/j.epsl.2013.02.017

Jahn, A., J.E. Kay, M.M. Holland, and D.M. Hall, 2016: How predictable is the timing of a summer ice-free Arctic? *Geophysical Research Letters,* **43,** 9113-9120. http://dx.doi.org/10.1002/2016GL070067

Johannessen, O.M., A. Korablev, V. Miles, M.W. Miles, and K.E. Solberg, 2011: Interaction between the warm subsurface Atlantic water in the Sermilik Fjord and Helheim Glacier in southeast Greenland. *Surveys in Geophysics,* **32,** 387-396. http://dx.doi.org/10.1007/s10712-011-9130-6

Johannessen, O.M., S.I. Kuzmina, L.P. Bobylev, and M.W. Miles, 2016: Surface air temperature variability and trends in the Arctic: New amplification assessment and regionalisation. *Tellus A,* **68**. http://dx.doi.org/10.3402/tellusa.v68.28234

Joly, K., P.A. Duffy, and T.S. Rupp, 2012: Simulating the effects of climate change on fire regimes in Arctic biomes: Implications for caribou and moose habitat. *Ecosphere,* **3,** 1-18. http://dx.doi.org/10.1890/ES12-00012.1

Joughin, I., S.B. Das, M.A. King, B.E. Smith, I.M. Howat, and T. Moon, 2008: Seasonal speedup along the western flank of the Greenland Ice Sheet. *Science,* **320,** 781-783. http://dx.doi.org/10.1126/science.1153288

Jungclaus, J.H., K. Lohmann, and D. Zanchettin, 2014: Enhanced 20th-century heat transfer to the Arctic simulated in the context of climate variations over the last millennium. *Climate of the Past,* **10,** 2201-2213. http://dx.doi.org/10.5194/cp-10-2201-2014

Kasischke, E.S. and M.R. Turetsky, 2006: Recent changes in the fire regime across the North American boreal region—Spatial and temporal patterns of burning across Canada and Alaska. *Geophysical Research Letters,* **33,** n/a-n/a. http://dx.doi.org/10.1029/2006GL025677

Kay, J.E. and A. Gettelman, 2009: Cloud influence on and response to seasonal Arctic sea ice loss. *Journal of Geophysical Research,* **114,** D18204. http://dx.doi.org/10.1029/2009JD011773

Kay, J.E., K. Raeder, A. Gettelman, and J. Anderson, 2011a: The boundary layer response to recent Arctic sea ice loss and implications for high-latitude climate feedbacks. *Journal of Climate,* **24,** 428-447. http://dx.doi.org/10.1175/2010JCLI3651.1

Kay, J.E., M.M. Holland, and A. Jahn, 2011b: Inter-annual to multi-decadal Arctic sea ice extent trends in a warming world. *Geophysical Research Letters,* **38,** L15708. http://dx.doi.org/10.1029/2011GL048008

Kelly, R., M.L. Chipman, P.E. Higuera, I. Stefanova, L.B. Brubaker, and F.S. Hu, 2013: Recent burning of boreal forests exceeds fire regime limits of the past 10,000 years. *Proceedings of the National Academy of Sciences,* **110,** 13055-13060. http://dx.doi.org/10.1073/pnas.1305069110

Kelly, R., H. Genet, A.D. McGuire, and F.S. Hu, 2016: Palaeodata-informed modelling of large carbon losses from recent burning of boreal forests. *Nature Climate Change,* **6,** 79-82. http://dx.doi.org/10.1038/nclimate2832

Khan, S.A., K.H. Kjaer, M. Bevis, J.L. Bamber, J. Wahr, K.K. Kjeldsen, A.A. Bjork, N.J. Korsgaard, L.A. Stearns, M.R. van den Broeke, L. Liu, N.K. Larsen, and I.S. Muresan, 2014: Sustained mass loss of the northeast Greenland ice sheet triggered by regional warming. *Nature Climate Change,* **4,** 292-299. http://dx.doi.org/10.1038/nclimate2161

Kirchmeier-Young, M.C., F.W. Zwiers, and N.P. Gillett, 2017: Attribution of extreme events in Arctic sea ice extent. *Journal of Climate,* **30,** 553-571. http://dx.doi.org/10.1175/jcli-d-16-0412.1

Knies, J., P. Cabedo-Sanz, S.T. Belt, S. Baranwal, S. Fietz, and A. Rosell-Melé, 2014: The emergence of modern sea ice cover in the Arctic Ocean. *Nature Communications,* **5,** 5608. http://dx.doi.org/10.1038/ncomms6608

Köhl, A. and N. Serra, 2014: Causes of decadal changes of the freshwater content in the Arctic Ocean. *Journal of Climate,* **27,** 3461-3475. http://dx.doi.org/10.1175/JCLI-D-13-00389.1

Kokelj, S.V., T.C. Lantz, J. Tunnicliffe, R. Segal, and D. Lacelle, 2017: Climate-driven thaw of permafrost preserved glacial landscapes, northwestern Canada. *Geology,* **45,** 371-374. http://dx.doi.org/10.1130/g38626.1

Koven, C.D., D.M. Lawrence, and W.J. Riley, 2015: Permafrost carbon−climate feedback is sensitive to deep soil carbon decomposability but not deep soil nitrogen dynamics.

Proceedings of the National Academy of Sciences, **112,** 3752-3757. http://dx.doi.org/10.1073/pnas.1415123112

Koven, C.D., E.A.G. Schuur, C. Schädel, T.J. Bohn, E.J. Burke, G. Chen, X. Chen, P. Ciais, G. Grosse, J.W. Harden, D.J. Hayes, G. Hugelius, E.E. Jafarov, G. Krinner, P. Kuhry, D.M. Lawrence, A.H. MacDougall, S.S. Marchenko, A.D. McGuire, S.M. Natali, D.J. Nicolsky, D. Olefeldt, S. Peng, V.E. Romanovsky, K.M. Schaefer, J. Strauss, C.C. Treat, and M. Turetsky, 2015: A simplified, data-constrained approach to estimate the permafrost carbon–climate feedback. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences,* **373**. http://dx.doi.org/10.1098/rsta.2014.0423

Kretschmer, K., A. Biastoch, L. Rüpke, and E. Burwicz, 2015: Modeling the fate of methane hydrates under global warming. *Global Biogeochemical Cycles,* **29,** 610-625. http://dx.doi.org/10.1002/2014GB005011

Kunkel, K.E., D.A. Robinson, S. Champion, X. Yin, T. Estilow, and R.M. Frankson, 2016: Trends and extremes in Northern Hemisphere snow characteristics. *Current Climate Change Reports,* **2,** 65-73. http://dx.doi.org/10.1007/s40641-016-0036-8

Kwok, R. and N. Untersteiner, 2011: The thinning of Arctic sea ice. *Physics Today,* **64,** 36-41. http://dx.doi.org/10.1063/1.3580491

Larsen, C.F., E. Burgess, A.A. Arendt, S. O'Neel, A.J. Johnson, and C. Kienholz, 2015: Surface melt dominates Alaska glacier mass balance. *Geophysical Research Letters,* **42,** 5902-5908. http://dx.doi.org/10.1002/2015GL064349

Lee, S., 2014: A theory for polar amplification from a general circulation perspective. *Asia-Pacific Journal of Atmospheric Sciences,* **50,** 31-43. http://dx.doi.org/10.1007/s13143-014-0024-7

Lee, S., T. Gong, N. Johnson, S.B. Feldstein, and D. Pollard, 2011: On the possible link between tropical convection and the Northern Hemisphere Arctic surface air temperature change between 1958 and 2001. *Journal of Climate,* **24,** 4350-4367. http://dx.doi.org/10.1175/2011JCLI4003.1

Liljedahl, A.K., J. Boike, R.P. Daanen, A.N. Fedorov, G.V. Frost, G. Grosse, L.D. Hinzman, Y. Iijma, J.C. Jorgenson, N. Matveyeva, M. Necsoiu, M.K. Raynolds, V.E. Romanovsky, J. Schulla, K.D. Tape, D.A. Walker, C.J. Wilson, H. Yabuki, and D. Zona, 2016: Pan-Arctic ice-wedge degradation in warming permafrost and its influence on tundra hydrology. *Nature Geoscience,* **9,** 312-318. http://dx.doi.org/10.1038/ngeo2674

Lim, Y.-K., D.S. Siegfried, M.J.N. Sophie, N.L. Jae, M.M. Andrea, I.C. Richard, Z. Bin, and V. Isabella, 2016: Atmospheric summer teleconnections and Greenland Ice Sheet surface mass

variations: Insights from MERRA-2. *Environmental Research Letters,* **11,** 024002. http://dx.doi.org/10.1088/1748-9326/11/2/024002

Liu, W., S.-P. Xie, Z. Liu, and J. Zhu, 2017: Overlooked possibility of a collapsed Atlantic Meridional Overturning Circulation in warming climate. *Science Advances,* **3,** e1601666. http://dx.doi.org/10.1126/sciadv.1601666

Liu, Y. and J.R. Key, 2014: Less winter cloud aids summer 2013 Arctic sea ice return from 2012 minimum. *Environmental Research Letters,* **9,** 044002. http://dx.doi.org/10.1088/1748-9326/9/4/044002

Manabe, S. and R.T. Wetherald, 1975: The effects of doubling the CO_2 concentration on the climate of a General Circulation Model. *Journal of the Atmospheric Sciences,* **32,** 3-15. http://dx.doi.org/10.1175/1520-0469(1975)032<0003:teodtc>2.0.co;2

Mao, J., A. Ribes, B. Yan, X. Shi, P.E. Thornton, R. Seferian, P. Ciais, R.B. Myneni, H. Douville, S. Piao, Z. Zhu, R.E. Dickinson, Y. Dai, D.M. Ricciuto, M. Jin, F.M. Hoffman, B. Wang, M. Huang, and X. Lian, 2016: Human-induced greening of the northern extratropical land surface. *Nature Climate Change,* **6,** 959-963. http://dx.doi.org/10.1038/nclimate3056

Maslowski, W., J. Clement Kinney, M. Higgins, and A. Roberts, 2012: The future of Arctic sea ice. *Annual Review of Earth and Planetary Sciences,* **40,** 625-654. http://dx.doi.org/10.1146/annurev-earth-042711-105345

Maslowski, W., J. Clement Kinney, S.R. Okkonen, R. Osinski, A.F. Roberts, and W.J. Williams, 2014: The large scale ocean circulation and physical processes controlling Pacific-Arctic interactions. *The Pacific Arctic Region: Ecosystem Status and Trends in a Rapidly Changing Environment*. Grebmeier, M.J. and W. Maslowski, Eds. Springer Netherlands, Dordrecht, 101-132. http://dx.doi.org/10.1007/978-94-017-8863-2_5

Mathis, J.T., J.N. Cross, W. Evans, and S.C. Doney, 2015: Ocean acidification in the surface waters of the Pacific–Arctic boundary regions. *Oceanography,* **28,** 122-135. http://dx.doi.org/10.5670/oceanog.2015.36

Mathis, J.T., R.S. Pickart, R.H. Byrne, C.L. McNeil, G.W.K. Moore, L.W. Juranek, X. Liu, J. Ma, R.A. Easley, M.M. Elliot, J.N. Cross, S.C. Reisdorph, F. Bahr, J. Morison, T. Lichendorf, and R.A. Feely, 2012: Storm-induced upwelling of high pCO2 waters onto the continental shelf of the western Arctic Ocean and implications for carbonate mineral saturation states. *Geophysical Research Letters,* **39,** L16703. http://dx.doi.org/10.1029/2012GL051574

McAfee, S.A., 2014: Consistency and the lack thereof in Pacific decadal oscillation impacts on North American winter climate. *Journal of Climate,* **27,** 7410-7431. http://dx.doi.org/10.1175/JCLI-D-14-00143.1

McGuire, A.D., L.G. Anderson, T.R. Christensen, S. Dallimore, L. Guo, D.J. Hayes, M. Heimann, T.D. Lorenson, R.W. MacDonald, and N. Roulet, 2009: Sensitivity of the carbon cycle in the Arctic to climate change. *Ecological Monographs,* **79,** 523-555. http://dx.doi.org/10.1890/08-2025.1

Melillo, J.M., T.C. Richmond, and G.W. Yohe, eds., 2014: *Climate Change Impacts in the United States: The Third National Climate Assessment*. U.S. Global Change Research Program: Washington, D.C., 842 pp. http://dx.doi.org/10.7930/J0Z31WJ2

Melillo, J.M., T.C. Richmond, and G.W. Yohe, eds., 2014: *Highlights of Climate Change Impacts in the United States: The Third National Climate Assessment*. U.S. Global Change Research Program: Washington, DC, 148 pp. http://dx.doi.org/10.7930/J0H41PB6

Mengel, M., A. Levermann, K. Frieler, A. Robinson, B. Marzeion, and R. Winkelmann, 2016: Future sea level rise constrained by observations and long-term commitment. *Proceedings of the National Academy of Sciences,* **113,** 2597-2602. http://dx.doi.org/10.1073/pnas.1500515113

Mernild, S.H., J.K. Malmros, J.C. Yde, and N.T. Knudsen, 2012: Multi-decadal marine- and land-terminating glacier recession in the Ammassalik region, southeast Greenland. *The Cryosphere,* **6,** 625-639. http://dx.doi.org/10.5194/tc-6-625-2012

Min, S.-K., X. Zhang, F.W. Zwiers, and T. Agnew, 2008: Human influence on Arctic sea ice detectable from early 1990s onwards. *Geophysical Research Letters,* **35,** L21701. http://dx.doi.org/10.1029/2008GL035725

Mishra, U., J.D. Jastrow, R. Matamala, G. Hugelius, C.D. Koven, J.W. Harden, C.L. Ping, G.J. Michaelson, Z. Fan, R.M. Miller, A.D. McGuire, C. Tarnocai, P. Kuhry, W.J. Riley, K. Schaefer, E.A.G. Schuur, M.T. Jorgenson, and L.D. Hinzman, 2013: Empirical estimates to reduce modeling uncertainties of soil organic carbon in permafrost regions: A review of recent progress and remaining challenges. *Environmental Research Letters,* **8,** 035020. http://dx.doi.org/10.1088/1748-9326/8/3/035020

Mishra, U. and W.J. Riley, 2012: Alaskan soil carbon stocks: Spatial variability and dependence on environmental factors. *Biogeosciences,* **9,** 3637-3645. http://dx.doi.org/10.5194/bg-9-3637-2012

Morison, J., R. Kwok, C. Peralta-Ferriz, M. Alkire, I. Rigor, R. Andersen, and M. Steele, 2012: Changing Arctic Ocean freshwater pathways. *Nature,* **481,** 66-70. http://dx.doi.org/10.1038/nature10705

Myers-Smith, I. H, J. W. Harden, M. Wilmking, C. C. Fuller, A. D. McGuire, and F. S. Chapin III, 2008. Wetland succession in a permafrost collapse: Interactions between fire and thermokarst. *Biogeosciences* **5**, 1273–1286. http://dx.doi.org/10.5194/bg-5-1273-2008

Myers-Smith, I.H., B.C. Forbes, M. Wilmking, M. Hallinger, T. Lantz, D. Blok, K.D. Tape, M. Macias-Fauria, U. Sass-Klaassen, E. Lévesque, S. Boudreau, P. Ropars, L. Hermanutz, A. Trant, L.S. Collier, S. Weijers, J. Rozema, S.A. Rayback, N.M. Schmidt, G. Schaepman-Strub, S. Wipf, C. Rixen, C.B. Ménard, S. Venn, S. Goetz, L. Andreu-Hayles, S. Elmendorf, V. Ravolainen, J. Welker, P. Grogan, H.E. Epstein, and D.S. Hik, 2011: Shrub expansion in tundra ecosystems: Dynamics, impacts and research priorities. *Environmental Research Letters,* **6,** 045509. http://dx.doi.org/10.1088/1748-9326/6/4/045509

Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura, and H. Zhang, 2013: Anthropogenic and natural radiative forcing. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 659–740. http://www.climatechange2013.org/report/full-report/

Najafi, M.R., F.W. Zwiers, and N.P. Gillett, 2015: Attribution of Arctic temperature change to greenhouse-gas and aerosol influences. *Nature Climate Change,* **5,** 246-249. http://dx.doi.org/10.1038/nclimate2524

Notz, D. and J. Marotzke, 2012: Observations reveal external driver for Arctic sea-ice retreat. *Geophysical Research Letters,* **39,** L08502. http://dx.doi.org/10.1029/2012GL051094

Notz, D. and J. Stroeve, 2016: Observed Arctic sea-ice loss directly follows anthropogenic CO_2 emission. *Science*, 354, 747-750. http://dx.doi.org 10.1126/science.aag2345

Nummelin, A., M. Ilicak, C. Li, and L.H. Smedsrud, 2016: Consequences of future increased Arctic runoff on Arctic Ocean stratification, circulation, and sea ice cover. *Journal of Geophysical Research: Oceans,* **121,** 617-637. http://dx.doi.org/10.1002/2015JC011156

Ogi, M. and I.G. Rigor, 2013: Trends in Arctic sea ice and the role of atmospheric circulation. *Atmospheric Science Letters,* **14,** 97-101. http://dx.doi.org/10.1002/asl2.423

Ogi, M. and J.M. Wallace, 2007: Summer minimum Arctic sea ice extent and the associated summer atmospheric circulation. *Geophysical Research Letters,* **34,** L12705. http://dx.doi.org/10.1029/2007GL029897

Oh, Y., B. Stackhouse, M.C.Y. Lau, X. Xu, A.T. Trugman, J. Moch, T.C. Onstott, C.J. Jørgensen, L. D'Imperio, B. Elberling, C.A. Emmerton, V.L. St. Louis, and D. Medvigy, 2016: A scalable model for methane consumption in Arctic mineral soils. *Geophysical Research Letters,* **43,** 5143-5150. http://dx.doi.org/10.1002/2016GL069049

Overland, J., J.A. Francis, R. Hall, E. Hanna, S.-J. Kim, and T. Vihma, 2015: The melting Arctic and midlatitude weather patterns: Are they connected? *Journal of Climate,* **28,** 7917-7932. http://dx.doi.org/10.1175/JCLI-D-14-00822.1

Overland, J., E. Hanna, I. Hanssen-Bauer, S.-J. Kim, J. Walsh, M. Wang, and U. Bhatt, 2014: Air temperature [in Arctic Report Card 2014]. ftp://ftp.oar.noaa.gov/arctic/documents/ArcticReportCard_full_report2014.pdf

Overland, J., E. Hanna, I. Hanssen-Bauer, S.-J. Kim, J. Walsh, M. Wang, U. Bhatt, and R.L. Thoman, 2016: Surface air temperature [in Arctic Report Card 2016]. http://arctic.noaa.gov/Report-Card/Report-Card-2016/ArtMID/5022/ArticleID/271/Surface-Air-Temperature

Overland, J., E. Hanna, I. Hanssen-Bauer, S.-J. Kim, J. Wlash, M. Wang, and U.S. Bhatt, 2015: [The Arctic] Arctic air temperature [in "State of the Climate in 2014"]. *Bulletin of the American Meteorological Society,* **96 (12),** S128-S129. http://dx.doi.org/10.1175/2015BAMSStateoftheClimate.1

Overland, J.E. and M. Wang, 2016: Recent extreme Arctic temperatures are due to a split polar vortex. *Journal of Climate,* **29,** 5609-5616. http://dx.doi.org/10.1175/JCLI-D-16-0320.1

Park, H.-S., S. Lee, S.-W. Son, S.B. Feldstein, and Y. Kosaka, 2015: The impact of poleward moisture and sensible heat flux on Arctic winter sea ice variability. *Journal of Climate,* **28,** 5030-5040. http://dx.doi.org/10.1175/JCLI-D-15-0074.1

Parkinson, C.L., 2014: Spatially mapped reductions in the length of the Arctic sea ice season. *Geophysical Research Letters,* **41,** 4316-4322. http://dx.doi.org/10.1002/2014GL060434

Partain, J.L., Jr., S. Alden, U.S. Bhatt, P.A. Bieniek, B.R. Brettschneider, R. Lader, P.Q. Olsson, T.S. Rupp, H. Strader, R.L.T. Jr., J.E. Walsh, A.D. York, and R.H. Zieh, 2016: An assessment of the role of anthropogenic climate change in the Alaska fire season of 2015 [in "Explaining Extreme Events of 2015 from a Climate Perspective"]. *Bulletin of the American Meteorological Society,* **97 (12),** S14-S18. http://dx.doi.org/10.1175/BAMS-D-16-0149.1

Pavelsky, T.M., J. Boé, A. Hall, and E.J. Fetzer, 2011: Atmospheric inversion strength over polar oceans in winter regulated by sea ice. *Climate Dynamics,* **36,** 945-955. http://dx.doi.org/10.1007/s00382-010-0756-8

Pelto, M.S., 2015: [Global Climate] Alpine glaciers [in "State of the Climate in 2014"]. *Bulletin of the American Meteorological Society,* **96 (12),** S19-S20. http://dx.doi.org/10.1175/2015BAMSStateoftheClimate.1

Perlwitz, J., M. Hoerling, and R. Dole, 2015: Arctic tropospheric warming: Causes and linkages to lower latitudes. *Journal of Climate,* **28,** 2154-2167. http://dx.doi.org/10.1175/JCLI-D-14-00095.1

Perovich, D., W. Meier, M. Tschudi, S. Farrell, S. Gerland, S. Hendricks, T. Krumpen, and C. Hass, 2016: Sea ice [in Arctic Report Cart 2016]. http://www.arctic.noaa.gov/Report-Card/Report-Card-2016/ArtMID/5022/ArticleID/286/Sea-Ice

Piñero, E., M. Marquardt, C. Hensen, M. Haeckel, and K. Wallmann, 2013: Estimation of the global inventory of methane hydrates in marine sediments using transfer functions. *Biogeosciences,* **10,** 959-975. http://dx.doi.org/10.5194/bg-10-959-2013

Polyakov, I.V., A.V. Pnyushkov, and L.A. Timokhov, 2012: Warming of the intermediate Atlantic water of the Arctic Ocean in the 2000s. *Journal of Climate,* **25,** 8362-8370. http://dx.doi.org/10.1175/JCLI-D-12-00266.1

Rahmstorf, S., J.E. Box, G. Feulner, M.E. Mann, A. Robinson, S. Rutherford, and E.J. Schaffernicht, 2015: Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. *Nature Climate Change,* **5,** 475-480. http://dx.doi.org/10.1038/nclimate2554

Rawlins, M.A., M. Steele, M.M. Holland, J.C. Adam, J.E. Cherry, J.A. Francis, P.Y. Groisman, L.D. Hinzman, T.G. Huntington, D.L. Kane, J.S. Kimball, R. Kwok, R.B. Lammers, C.M. Lee, D.P. Lettenmaier, K.C. McDonald, E. Podest, J.W. Pundsack, B. Rudels, M.C. Serreze, A. Shiklomanov, Ø. Skagseth, T.J. Troy, C.J. Vörösmarty, M. Wensnahan, E.F. Wood, R. Woodgate, D. Yang, K. Zhang, and T. Zhang, 2010: Analysis of the Arctic system for freshwater cycle intensification: Observations and expectations. *Journal of Climate,* **23,** 5715-5737. http://dx.doi.org/10.1175/2010JCLI3421.1

Rhein, M., S.R. Rintoul, S. Aoki, E. Campos, D. Chambers, R.A. Feely, S. Gulev, G.C. Johnson, S.A. Josey, A. Kostianoy, C. Mauritzen, D. Roemmich, L.D. Talley, and F. Wang, 2013: Observations: Ocean. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 255–316. http://www.climatechange2013.org/report/full-report/

Rignot, E., M. Koppes, and I. Velicogna, 2010: Rapid submarine melting of the calving faces of West Greenland glaciers. *Nature Geoscience,* **3,** 187-191. http://dx.doi.org/10.1038/ngeo765

Rigor, I.G., J.M. Wallace, and R.L. Colony, 2002: Response of sea ice to the Arctic oscillation. *Journal of Climate,* **15,** 2648-2663. http://dx.doi.org/10.1175/1520-0442(2002)015<2648:ROSITT>2.0.CO;2

Romanovsky, V.E., S.L. Smith, H.H. Christiansen, N.I. Shiklomanov, D.A. Streletskiy, D.S. Drozdov, G.V. Malkova, N.G. Oberman, A.L. Kholodov, and S.S. Marchenko, 2015: [The Arctic] Terrestrial permafrost [in "State of the Climate in 2014"]. *Bulletin of the American Meteorological Society,* **96 (12),** S139-S141. http://dx.doi.org/10.1175/2015BAMSStateoftheClimate.1

Romanovsky, V.E., S.L. Smith, K. Isaksen, N.I. Shiklomanov, D.A. Streletskiy, A.L. Kholodov, H.H. Christiansen, D.S. Drozdov, G.V. Malkova, and S.S. Marchenko, 2016: [The Arctic] Terrestrial permafrost [in "State of the Climate in 2015"]. *Bulletin of the American Meteorological Society,* **97,** S149-S152. http://dx.doi.org/10.1175/2016BAMSStateoftheClimate.1

Rupp, D.E., P.W. Mote, N.L. Bindoff, P.A. Stott, and D.A. Robinson, 2013: Detection and attribution of observed changes in Northern Hemisphere spring snow cover. *Journal of Climate,* **26,** 6904-6914. http://dx.doi.org/10.1175/JCLI-D-12-00563.1

Ruppel, C.D. *Methane hydrates and contemporary climate change*. Nature Education Knowledge, 2011. **3**.

Ruppel, C.D. and J.D. Kessler, 2017: The interaction of climate change and methane hydrates. *Reviews of Geophysics,* **55,** 126-168. http://dx.doi.org/10.1002/2016RG000534

Sanford, T., R. Wang, and A. Kenwa, 2015: *The Age of Alaskan Wildfires*. Climate Central, Princeton, NJ, 32 pp. http://assets.climatecentral.org/pdfs/AgeofAlaskanWildfires.pdf

Schädel, C., M.K.F. Bader, E.A.G. Schuur, C. Biasi, R. Bracho, P. Capek, S. De Baets, K. Diakova, J. Ernakovich, C. Estop-Aragones, D.E. Graham, I.P. Hartley, C.M. Iversen, E. Kane, C. Knoblauch, M. Lupascu, P.J. Martikainen, S.M. Natali, R.J. Norby, J.A. O'Donnell, T.R. Chowdhury, H. Santruckova, G. Shaver, V.L. Sloan, C.C. Treat, M.R. Turetsky, M.P. Waldrop, and K.P. Wickland, 2016: Potential carbon emissions dominated by carbon dioxide from thawed permafrost soils. *Nature Climate Change,* **6,** 950-953. http://dx.doi.org/10.1038/nclimate3054

Schaefer, K., H. Lantuit, E.R. Vladimir, E.A.G. Schuur, and R. Witt, 2014: The impact of the permafrost carbon feedback on global climate. *Environmental Research Letters,* **9,** 085003. http://dx.doi.org/10.1088/1748-9326/9/8/085003

Schuur, E.A.G., A.D. McGuire, C. Schadel, G. Grosse, J.W. Harden, D.J. Hayes, G. Hugelius, C.D. Koven, P. Kuhry, D.M. Lawrence, S.M. Natali, D. Olefeldt, V.E. Romanovsky, K. Schaefer, M.R. Turetsky, C.C. Treat, and J.E. Vonk, 2015: Climate change and the permafrost carbon feedback. *Nature,* **520,** 171-179. http://dx.doi.org/10.1038/nature14338

Schuur, E.A.G., J.G. Vogel, K.G. Crummer, H. Lee, J.O. Sickman, and T.E. Osterkamp, 2009: The effect of permafrost thaw on old carbon release and net carbon exchange from tundra. *Nature,* **459,** 556-559. http://dx.doi.org/10.1038/nature08031

Schweiger, A., R. Lindsay, J. Zhang, M. Steele, H. Stern, 2011: Uncertainty in modeled arctic sea ice volume. J. Geophys. Res. 116, C00D06, http://dx.doi.org/10.1029/2011JC007084

Screen, J.A., C. Deser, and I. Simmonds, 2012: Local and remote controls on observed Arctic warming. *Geophysical Research Letters,* **39,** L10709. http://dx.doi.org/10.1029/2012GL051598

Screen, J.A., C. Deser, and L. Sun, 2015: Reduced risk of North American cold extremes due to continued Arctic sea ice loss. *Bulletin of the American Meteorological Society,* **96 (12),** 1489-1503. http://dx.doi.org/10.1175/BAMS-D-14-00185.1

Screen, J.A., C. Deser, and L. Sun, 2015: Projected changes in regional climate extremes arising from Arctic sea ice loss. *Environmental Research Letters,* **10,** 084006. http://dx.doi.org/10.1088/1748-9326/10/8/084006

Screen, J.A. and J.A. Francis, 2016: Contribution of sea-ice loss to Arctic amplification is regulated by Pacific Ocean decadal variability. *Nature Climate Change,* **6,** 856-860. http://dx.doi.org/10.1038/nclimate3011

Screen, J.A. and I. Simmonds, 2010: The central role of diminishing sea ice in recent Arctic temperature amplification. *Nature,* **464,** 1334-1337. http://dx.doi.org/10.1038/nature09051

Seager, R., M. Hoerling, S. Schubert, H. Wang, B. Lyon, A. Kumar, J. Nakamura, and N. Henderson, 2015: Causes of the 2011–14 California drought. *Journal of Climate,* **28,** 6997-7024. http://dx.doi.org/10.1175/JCLI-D-14-00860.1

Serreze, M.C., A.P. Barrett, J.C. Stroeve, D.N. Kindig, and M.M. Holland, 2009: The emergence of surface-based Arctic amplification. *The Cryosphere,* **3,** 11-19. http://dx.doi.org/10.5194/tc-3-11-2009

Sharp, M., G. Wolken, D. Burgess, J.G. Cogley, L. Copland, L. Thomson, A. Arendt, B. Wouters, J. Kohler, L.M. Andreassen, S. O'Neel, and M. Pelto, 2015: [Global Climate] Glaciers and ice caps outside Greenland [in "State of the Climate in 2014"]. *Bulletin of the American Meteorological Society,* **96 (12),** S135-S137. http://dx.doi.org/10.1175/2015BAMSStateoftheClimate.1

Shiklomanov, N.E., D.A. Streletskiy, and F.E. Nelson, 2012: Northern Hemisphere component of the global Circumpolar Active Layer Monitory (CALM) program. In *Proceedings of the 10th International Conference on Permafrost,* Salekhard, Russia. Kane, D.L. and K.M. Hinkel, Eds., 377-382. http://research.iarc.uaf.edu/NICOP/proceedings/10th/TICOP_vol1.pdf

Sigmond, M. and J.C. Fyfe, 2016: Tropical Pacific impacts on cooling North American winters. *Nature Climate Change,* **6,** 970-974. http://dx.doi.org/10.1038/nclimate3069

Smedsrud, L.H., M.H. Halvorsen, J.C. Stroeve, R. Zhang, and K. Kloster, 2017: Fram Strait sea ice export variability and September Arctic sea ice extent over the last 80 years. *The Cryosphere,* **11,** 65-79. http://dx.doi.org/10.5194/tc-11-65-2017

Smeed, D.A., G.D. McCarthy, S.A. Cunningham, E. Frajka-Williams, D. Rayner, W.E. Johns, C.S. Meinen, M.O. Baringer, B.I. Moat, A. Duchez, and H.L. Bryden, 2014: Observed decline of the Atlantic meridional overturning circulation 2004–2012. *Ocean Science,* **10,** 29-38. http://dx.doi.org/10.5194/os-10-29-2014

Snape, T.J. and P.M. Forster, 2014: Decline of Arctic sea ice: Evaluation and weighting of CMIP5 projections. *Journal of Geophysical Research: Atmospheres,* **119,** 546-554. http://dx.doi.org/10.1002/2013JD020593

Solomon, A., M.D. Shupe, O. Persson, H. Morrison, T. Yamaguchi, P.M. Caldwell, and G.d. Boer, 2014: The sensitivity of springtime Arctic mixed-phase stratocumulus clouds to surface-layer and cloud-top inversion-layer moisture sources. *Journal of the Atmospheric Sciences,* **71,** 574-595. http://dx.doi.org/10.1175/JAS-D-13-0179.1

Spielhagen, R.F., K. Werner, S.A. Sørensen, K. Zamelczyk, E. Kandiano, G. Budeus, K. Husum, T.M. Marchitto, and M. Hald, 2011: Enhanced modern heat transfer to the Arctic by warm Atlantic water. *Science,* **331,** 450-453. http://dx.doi.org/10.1126/science.1197397

Stabeno, P.J., E.V. Farley, Jr., N.B. Kachel, S. Moore, C.W. Mordy, J.M. Napp, J.E. Overland, A.I. Pinchuk, and M.F. Sigler, 2012: A comparison of the physics of the northern and southern shelves of the eastern Bering Sea and some implications for the ecosystem. *Deep Sea Research Part II: Topical Studies in Oceanography,* **65-70,** 14-30. http://dx.doi.org/10.1016/j.dsr2.2012.02.019

Straneo, F., R.G. Curry, D.A. Sutherland, G.S. Hamilton, C. Cenedese, K. Vage, and L.A. Stearns, 2011: Impact of fjord dynamics and glacial runoff on the circulation near Helheim Glacier. *Nature Geoscience,* **4,** 322-327. http://dx.doi.org/10.1038/ngeo1109

Straneo, F., G.S. Hamilton, D.A. Sutherland, L.A. Stearns, F. Davidson, M.O. Hammill, G.B. Stenson, and A. Rosing-Asvid, 2010: Rapid circulation of warm subtropical waters in a major glacial fjord in East Greenland. *Nature Geoscience,* **3,** 182-186. http://dx.doi.org/10.1038/ngeo764

Stroeve, J., A. Barrett, M. Serreze, and A. Schweiger, 2014: Using records from submarine, aircraft and satellites to evaluate climate model simulations of Arctic sea ice thickness. *The Cryosphere,* **8,** 1839-1854. http://dx.doi.org/10.5194/tc-8-1839-2014

Stroeve, J., M.M. Holland, W. Meier, T. Scambos, and M. Serreze, 2007: Arctic sea ice decline: Faster than forecast. *Geophysical Research Letters,* **34,** L09501. http://dx.doi.org/10.1029/2007GL029703

Stroeve, J. and D. Notz, 2015: Insights on past and future sea-ice evolution from combining observations and models. *Global and Planetary Change,* **135,** 119-132. http://dx.doi.org/10.1016/j.gloplacha.2015.10.011

Stroeve, J.C., V. Kattsov, A. Barrett, M. Serreze, T. Pavlova, M. Holland, and W.N. Meier, 2012: Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations. *Geophysical Research Letters,* **39,** L16502. http://dx.doi.org/10.1029/2012GL052676

Stroeve, J.C., T. Markus, L. Boisvert, J. Miller, and A. Barrett, 2014: Changes in Arctic melt season and implications for sea ice loss. *Geophysical Research Letters,* **41,** 1216-1225. http://dx.doi.org/10.1002/2013GL058951

Stroeve, J.C., M.C. Serreze, M.M. Holland, J.E. Kay, J. Malanik, and A.P. Barrett, 2012: The Arctic's rapidly shrinking sea ice cover: A research synthesis. *Climatic Change,* **110,** 1005-1027. http://dx.doi.org/10.1007/s10584-011-0101-1

Sun, L., J. Perlwitz, and M. Hoerling, 2016: What caused the recent "Warm Arctic, Cold Continents" trend pattern in winter temperatures? *Geophysical Research Letters,* **43,** 5345-5352. http://dx.doi.org/10.1002/2016GL069024

Swain, D., M. Tsiang, M. Haughen, D. Singh, A. Charland, B. Rajarthan, and N.S. Diffenbaugh, 2014: The extraordinary California drought of 2013/14: Character, context and the role of climate change [in "Explaining Extreme Events of 2013 from a Climate Perspective"]. *Bulletin of the American Meteorological Society,* **95 (9),** S3-S6. http://dx.doi.org/10.1175/1520-0477-95.9.S1.1

Swanson, D. K, 1996: Susceptibility of permafrost soils to deep thaw after forest fires in Interior Alaska, USA, and some ecological implications. *Arct Antarct Alp Res*., **28**, 217–227. http://dx.doc.org/10.2307/1551763.

Swart, N.C., J.C. Fyfe, E. Hawkins, J.E. Kay, and A. Jahn, 2015: Influence of internal variability on Arctic sea-ice trends. *Nature Climate Change,* **5,** 86-89. http://dx.doi.org/10.1038/nclimate2483

Tarnocai, C., J.G. Canadell, E.A.G. Schuur, P. Kuhry, G. Mazhitova, and S. Zimov, 2009: Soil organic carbon pools in the northern circumpolar permafrost region. *Global Biogeochemical Cycles,* **23,** GB2023. http://dx.doi.org/10.1029/2008GB003327

Taylor, P.C., M. Cai, A. Hu, J. Meehl, W. Washington, and G.J. Zhang, 2013: A decomposition of feedback contributions to polar warming amplification. *Journal of Climate,* **26,** 7023-7043. http://dx.doi.org/10.1175/JCLI-D-12-00696.1

Taylor, P.C., R.G. Ellingson, and M. Cai, 2011: Geographical distribution of climate feedbacks in the NCAR CCSM3.0. *Journal of Climate,* **24,** 2737-2753. http://dx.doi.org/10.1175/2010JCLI3788.1

Taylor, P.C., R.G. Ellingson, and M. Cai, 2011: Seasonal variations of climate feedbacks in the NCAR CCSM3. *Journal of Climate,* **24,** 3433-3444. http://dx.doi.org/10.1175/2011jcli3862.1

Taylor, P.C., S. Kato, K.-M. Xu, and M. Cai, 2015: Covariance between Arctic sea ice and clouds within atmospheric state regimes at the satellite footprint level. *Journal of Geophysical Research: Atmospheres,* **120,** 12656-12678. http://dx.doi.org/10.1002/2015JD023520

Tedesco, M., T. Mote, X. Fettweis, E. Hanna, J. Jeyaratnam, J.F. Booth, R. Datta, and K. Briggs, 2016: Arctic cut-off high drives the poleward shift of a new Greenland melting record. *Nature Communications,* **7,** 11723. http://dx.doi.org/10.1038/ncomms11723

Teng, H. and G. Branstator, 2017: Causes of extreme ridges that induce California droughts. *Journal of Climate,* **30,** 1477-1492. http://dx.doi.org/10.1175/jcli-d-16-0524.1

Timmermans, M.-L. and A. Proshutinsky, 2015: [The Arctic] Sea surface temperature [in "State of the Climate in 2014"]. *Bulletin of the American Meteorological Society,* **96 (12),** S147-S148. http://dx.doi.org/10.1175/2015BAMSStateoftheClimate.1

Treat, C.C., S.M. Natali, J. Ernakovich, C.M. Iversen, M. Lupascu, A.D. McGuire, R.J. Norby, T. Roy Chowdhury, A. Richter, H. Šantrůčková, C. Schädel, E.A.G. Schuur, V.L. Sloan, M.R. Turetsky, and M.P. Waldrop, 2015: A pan-Arctic synthesis of CH_4 and CO_2 production from anoxic soil incubations. *Global Change Biology,* **21,** 2787-2803. http://dx.doi.org/10.1111/gcb.12875

Tschudi, M., C. Fowler, J. Maslanik, J.S. Stewart, and W. Meier, 2016: EASE-Grid Sea Ice Age, Version 3. In: NASA (ed.). National Snow and Ice Data Center Distributed Active Archive Center, Boulder, CO.

USGS 2004, Department of the Interior, U.S. Geological Survey, photo by Bruce F. Molnia. https://www2.usgs.gov/climate_landuse/glaciers/repeat_photography.asp)

van den Broeke, M., J. Bamber, J. Ettema, E. Rignot, E. Schrama, W.J. van de Berg, E. van Meijgaard, I. Velicogna, and B. Wouters, 2009: Partitioning recent Greenland mass loss. *Science,* **326,** 984-986. http://dx.doi.org/10.1126/science.1178176

Vaughan, D.G., J.C. Comiso, I. Allison, J. Carrasco, G. Kaser, R. Kwok, P. Mote, T. Murray, F. Paul, J. Ren, E. Rignot, O. Solomina, K. Steffen, and T. Zhang, 2013: Observations: Cryosphere. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 317–382. http://www.climatechange2013.org/report/full-report/

Velicogna, I., 2009: Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE. *Geophysical Research Letters,* **36,** L19503. http://dx.doi.org/10.1029/2009GL040222

Vihma, T., 2014: Effects of Arctic sea ice decline on weather and climate: A review. *Surveys in Geophysics,* **35,** 1175-1214. http://dx.doi.org/10.1007/s10712-014-9284-0

Vinnikov, K.Y., A. Robock, R.J. Stouffer, J.E. Walsh, C.L. Parkinson, D.J. Cavalieri, J.F.B. Mitchell, D. Garrett, and V.F. Zakharov, 1999: Global warming and Northern Hemisphere sea ice extent. *Science,* **286,** 1934-1937. http://dx.doi.org/10.1126/science.286.5446.1934

Wang, M. and J.E. Overland, 2012: A sea ice free summer Arctic within 30 years: An update from CMIP5 models. *Geophysical Research Letters,* **39,** L18501. http://dx.doi.org/10.1029/2012GL052868

Wendler, G., B. Moore, and K. Galloway, 2014: Strong temperature increase and shrinking sea ice in Arctic Alaska. *The Open Atmospheric Science Journal,* **8,** 7-15. http://dx.doi.org/10.2174/1874282301408010007

Wettstein, J.J. and C. Deser, 2014: Internal variability in projections of twenty-first-century Arctic sea ice loss: Role of the large-scale atmospheric circulation. *Journal of Climate,* **27,** 527-550. http://dx.doi.org/10.1175/JCLI-D-12-00839.1

WGMS, 2016: Fluctuations of Glaciers Database. World Glacier Monitoring Service, Zurich, Switzerland.

Wolken, G., M. Sharp, L.M. Andreassen, A. Arendt, D. Burgess, J.G. Cogley, L. Copland, J. Kohler, S. O'Neel, M. Pelto, L. Thomson, and B. Wouters, 2016: [The Arctic] Glaciers and ice caps outside Greenland [in "State of the Climate in 2015"]. *Bulletin of the American Meteorological Society,* **97,** S142-S145. http://dx.doi.org/10.1175/2016BAMSStateoftheClimate.1

Woods, C. and R. Caballero, 2016: The role of moist intrusions in winter Arctic warming and sea ice decline. *Journal of Climate,* **29,** 4473-4485. http://dx.doi.org/10.1175/jcli-d-15-0773.1

Wyser, K., C.G. Jones, P. Du, E. Girard, U. Willén, J. Cassano, J.H. Christensen, J.A. Curry, K. Dethloff, J.-E. Haugen, D. Jacob, M. Køltzow, R. Laprise, A. Lynch, S. Pfeifer, A. Rinke, M. Serreze, M.J. Shaw, M. Tjernström, and M. Zagar, 2008: An evaluation of Arctic cloud and radiation processes during the SHEBA year: Simulation results from eight Arctic regional climate models. *Climate Dynamics,* **30,** 203-223. http://dx.doi.org/10.1007/s00382-007-0286-1

Yang, Q., T.H. Dixon, P.G. Myers, J. Bonin, D. Chambers, and M.R. van den Broeke, 2016: Recent increases in Arctic freshwater flux affects Labrador Sea convection and Atlantic overturning circulation. *Nature Communications,* **7,** 10525. http://dx.doi.org/10.1038/ncomms10525

Yoshikawa, K., W. R. Bolton, V. E. Romanovsky, M. Fukuda, and L. D. Hinzman, 2003: Impacts of wildfire on the permafrost in the boreal forests of Interior Alaska. *J. Geophys. Res.*, **107**, 8148. http://dx.doi.org/10.1029/2001JD000438 2002.

Young, A.M., P.E. Higuera, P.A. Duffy, and F.S. Hu, 2016: Climatic thresholds shape northern high-latitude fire regimes and imply vulnerability to future climate change. *Ecography,* **Early view**. http://dx.doi.org/10.1111/ecog.02205

Zemp, M., H. Frey, I. Gärtner-Roer, S.U. Nussbaumer, M. Hoelzle, F. Paul, W. Haeberli, F. Denzinger, A.P. Ahlstrøm, B. Anderson, S. Bajracharya, C. Baroni, L.N. Braun, B.E. Cáceres, G. Casassa, G. Cobos, L.R. Dávila, H. Delgado Granados, M.N. Demuth, L. Espizua, A. Fischer, K. Fujita, B. Gadek, A. Ghazanfar, J.O. Hagen, P. Holmlund, N. Karimi, Z. Li, M. Pelto, P. Pitte, V.V. Popovnin, C.A. Portocarrero, R. Prinz, C.V. Sangewar, I. Severskiy, O. Sigurðsson, A. Soruco, R. Usubaliev, and C. Vincent, 2015: Historically unprecedented global glacier decline in the early 21st century. *Journal of Glaciology,* **61,** 745-762. http://dx.doi.org/10.3189/2015JoG15J017

Zhang, R. and T.R. Knutson, 2013: The role of global climate change in the extreme low summer Arctic sea ice extent in 2012 [in "Explaining Extreme Events of 2012 from a Climate Perspective"]. *Bulletin of the American Meteorological Society,* **94 (9),** S23-S26. http://dx.doi.org/10.1175/BAMS-D-13-00085.1

Zona, D., B. Gioli, R. Commane, J. Lindaas, S.C. Wofsy, C.E. Miller, S.J. Dinardo, S. Dengel, C. Sweeney, A. Karion, R.Y.-W. Chang, J.M. Henderson, P.C. Murphy, J.P. Goodrich, V. Moreaux, A. Liljedahl, J.D. Watts, J.S. Kimball, D.A. Lipson, and W.C. Oechel, 2016: Cold season emissions dominate the Arctic tundra methane budget. *Proceedings of the National Academy of Sciences,* **113,** 40-45. http://dx.doi.org/10.1073/pnas.1516017113