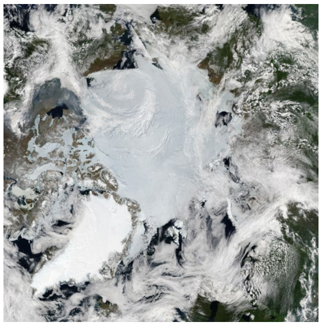

11

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 carbon dioxide 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 compromise the ability to limit global temperature increases.

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 *very likely* that human activities have contributed to observed arctic surface temperature warming, sea ice loss, glacier mass loss, and Northern Hemisphere snow extent decline (*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.

Recommended Citation for Chapter

Taylor, P.C., W. Maslowski, J. Perlwitz, and D.J. Wuebbles, 2017: Arctic changes and their effects on Alaska and the rest of the United States. In: *Climate Science Special Report: Fourth National Climate Assessment, Volume I* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 303-332, doi: 10.7930/J00863GK.

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,[1] 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[2] and will influence climate in the future.

As an arctic nation, United States' decisions regarding climate change adaptation and mitigation, resource development, trade, national security, transportation, etc., depend on projections of future Alaskan and arctic climate. Aside from uncertainties due to natural variability, scientific uncertainty, and human activities including greenhouse gas emissions (see Ch. 4: Projections), additional unique uncertainties in our understanding of arctic processes thwart projections, including mixed-phase cloud processes;[3] boundary layer processes;[4] sea ice mechanics;[4] and ocean currents, eddies, and tides that affect the advection of heat into and around the Arctic Ocean.[5, 6] 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.[7, 8] 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.[9, 10, 11] Interannual variations in Alaskan temperatures are strongly influenced by decadal variability like the Pacific Decadal Oscillation (Ch. 5: Circulation and Variability).[12, 13] 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.[14, 15, 16, 17, 18] 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.[19]

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.[20]

Enhanced arctic warming is a robust feature of the climate response to anthropogenic forcing.[21, 22] An anthropogenic contribution to arctic and Alaskan surface temperature warming over the past 50 years is *very likely*.[23, 24, 25, 26, 27] One study argues that the natural forcing has not contributed to the long-term arctic warming in a discernable way.[27] Also, other anthropogenic forcings (mostly aerosols) have *likely* offset up to 60% of the high-latitude greenhouse gas warming since 1913,[27] suggesting that arctic warming to date would have been larger without the offsetting influence of aerosols. Other studies argue for a more significant contribution of natural variability to observed arctic temperature trends[24, 28] and indicate that natural variability alone cannot explain observed warming. It is *very likely* that arctic surface temperatures will continue to increase faster than the global mean through the 21st century.[25, 26, 27, 29]

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.[7, 10, 30, 31, 32, 33, 34, 35, 36, 37] 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.[38, 39, 40, 41, 42, 43, 44]

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.[19, 20, 45, 46] Although sea ice loss is found in all months, satellite observations show the fastest loss in late summer and autumn.[45] Since 1979, the annual average arctic sea ice extent has *very likely* decreased at a rate of 3.5%–4.1% per decade.[19, 37] 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.[20] 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.[47] 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,[47] contributing to a new record low in winter ice-volume (see http://psc.apl.uw.edu/research/projects/arctic-sea-ice-volume-anomaly).[48]

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.[37, 45] 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).[37] The age distribution

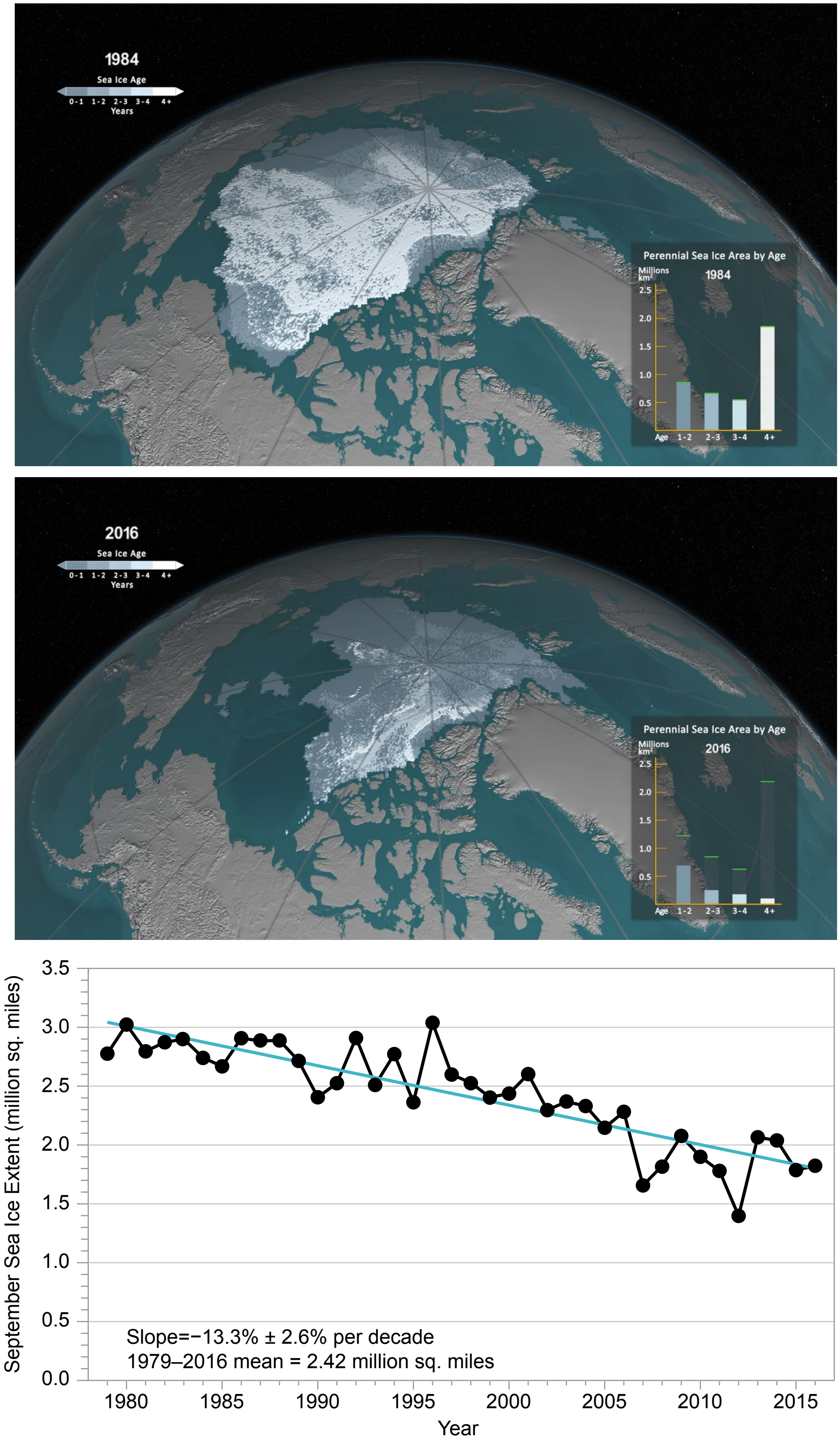

Figure 11.1: September sea ice extent and age shown for (a) 1984 and (b) 2016, illustrating significant reductions in sea ice extent and age (thickness). Bar graph in the lower right of each panel illustrates the sea ice area (unit: million km²) covered within each age category (>1 year), and the green 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 mi²). [Figure source: Panels (a),(b): NASA Science Visualization Studio; data: Tschudi et al. 2016;[49] Panel (c) data: Fetterer et al. 2016[209]].

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%).[47] 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.[47] 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.[49] 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.

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.[46, 50] 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.[50] Summer sea ice retreat along coastal Alaska has led to longer open water seasons, making the Alaskan coastline more vulnerable to erosion.[51, 52] 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.[42, 46] Wind-driven sea ice export through the Fram Strait has not increased over the last 80 years;[37] however, one recent study suggests that it may have increased since 1979.[53]

It is *very likely* 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.[54, 55, 56, 57, 58, 59] Further, observational-based analyses considering a range of anthropogenic and natural forcing mechanisms for September sea ice loss reach the same conclusion.[60] 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.[61, 62] The potential contribution of natural variability to arctic sea ice trends is significant.[55, 63, 64] One recent study[28] 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%.[54, 55] This apparent significant contribution of natural variability to sea ice decline indicates that natural variability alone cannot explain the observed sea ice decline and is consistent with the statement that it is *very likely* there is an anthropogenic contribution to the observed arctic sea ice decline since 1979.

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 the 2040s.[21, 65] Natural variability,[66] future scenarios, and model uncertainties[64, 67, 68] all influence sea ice projections. One study suggests that internal variability alone accounts for a 20-year prediction uncertainty in

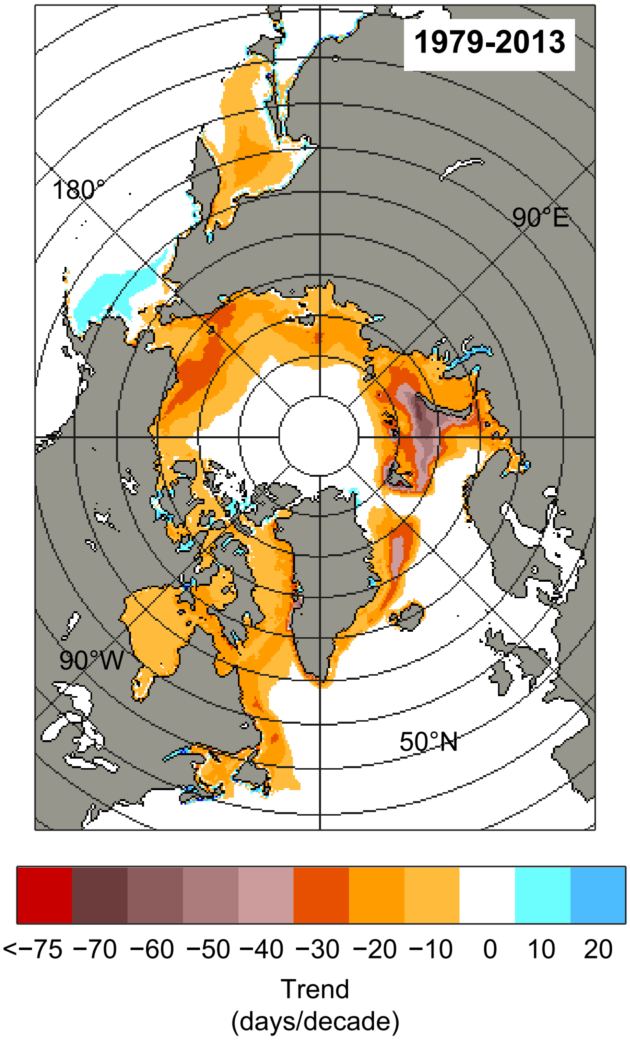

Figure 11.2: A 35-year trend in arctic sea ice melt season length, in days per decade, from passive microwave satellite observations, illustrating that the sea ice season has shortened by more than 60 days in coastal Alaska over the last 30 years. (Figure source: adapted from Parkinson 2014[50]).

the timing of the first occurrence of an ice-free summer, whereas differences between a higher scenario (RCP8.5) and a lower scenario (RCP4.5) add only 5 years.[63] Projected September sea ice reductions by 2081–2100 range from 43% for an even lower scenario (RCP2.6) to 94% for RCP8.5.[21] 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[69] 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)[70] 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.[19] 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.[40, 71] 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.[72]

Arctic Ocean temperatures also increased at depth.[71, 73] 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.[73] The observed temperature level is unprecedented in the last 1,150 years for which proxy indicators provide records.[74, 75] The influence of Intermediate Atlantic Water warming on future Alaska and arctic sea ice loss is unclear.[38, 76]

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 (Ch. 12: Sea Level Rise).[77] However, considerable uncertainty in relative sea level rise exists 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.[78] 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.[71] Increased river runoff, rapid melting of sea and land ice, and changes in freshwater transport have influenced observed Arctic Ocean salinity.[71, 79]

Ocean Acidification

Arctic Ocean acidification is occurring at a faster rate than the rest of the globe (see also Ch. 13: Ocean Changes).[80] 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.[80] 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.[81, 82, 83, 84, 85, 86] 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.[80]

11.2.4 Boreal Wildfires

Alaskan wildfire activity has increased in recent decades. This increase has occurred both in the boreal forest[87] and in the arctic tundra,[88] where fires historically were smaller and less frequent. A shortened snow cover season and higher temperatures over the last 50 years[89] make the Arctic more vulnerable to wildfire.[87, [88, 90] Total area burned and the number of large fires (those with area greater than 1,000 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.[91] The most recent decade has seen an unusually large number of years with anomalously large wildfires in Alaska.[92] Studies indicate that anthropogenic climate change has *likely* lengthened the wildfire season and increased the risk of severe fires.[93] Further, wildfire risks are expected to increase through the end of the century due to warmer, drier conditions.[90, 94] 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.[95] A transition into a regime of fire activity unprecedented in the last 10,000 years is possible.[96] 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.[97, 98, 99] Increased fire activity could deplete these stores, releasing them to the atmosphere to serve as an additional source of atmospheric CO_2.[97, 100] Increased fires may also enhance the degradation of Alaska's permafrost by blackening the ground, reducing surface albedo, and removing protective vegetation.[101, 102, 103, 104]

11.2.5 Snow Cover

Snow cover extent has significantly decreased across the Northern Hemisphere and Alaska over the last decade (see also Ch. 7: Precipitation Change and Ch. 10: Land Cover).[105, 106] Northern Hemisphere June snow cover decreased by more than 65% between 1967 and 2012,[37, 107] at a trend of −17.2% per decade since 1979.[89] 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.[89] 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.[89] 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 *very likely* 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.[24, 106, 108] 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[109, 110] 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.[111]

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.[37, 112] In recent years, mass loss has accelerated and is expected to continue.[112, 113]

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).[113] One study indicates that ice mass loss from Greenland was −269 Gt per year between April 2002 and April 2016.[47] Increased surface melt, runoff, and increased outlet glacier discharge from warmer air temperatures are primary contributing factors.[114, 115, 116, 117, 118] 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.[116, 119, 120, 121] Shallow ocean warming and regional ocean and atmospheric circulation changes also contribute to mass loss.[122, 123, 124] The underlying mechanisms of the recent discharge speed-up remain unclear;[125, 126] however, warmer subsurface ocean and atmospheric temperatures[118, 127, 128] and meltwater penetration to the glacier bed[125, 129] *very likely* contribute.

Annual average ice mass from Arctic-wide glaciers has decreased every year since 1984,[112, 130, 131] with significant losses in Alaska, especially over the past two decades (Figure 11.3).[37, 132] 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.[113] 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.[113] Studies suggest an anthropogenic imprint on imbalances in Alaskan glaciers, indicating that melt will continue through the 21st century.[112, 133, 134] Multiple datasets indicate that it is *virtually certain* that Alaskan glaciers have lost mass over the last 50 years and will continue to do so.[135]

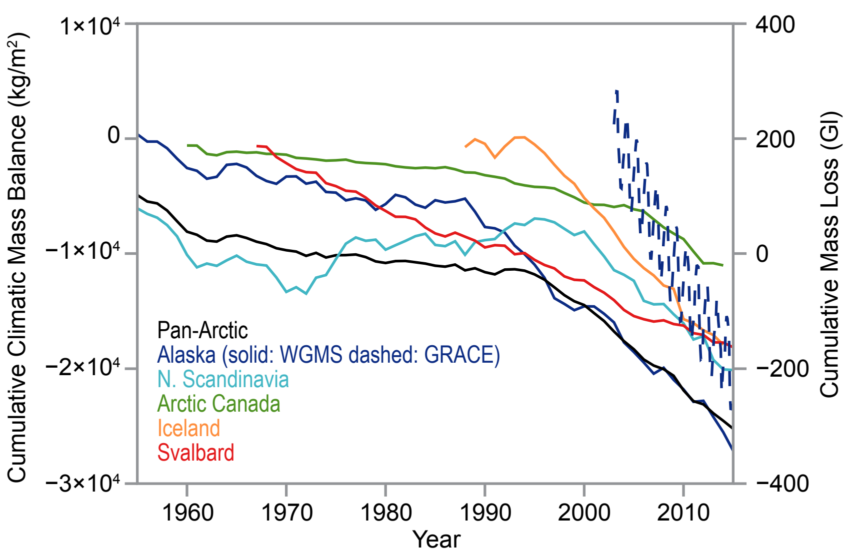

Figure 11.3: Time series of the cumulative climatic mass balance (units: kg/m^2) in five arctic regions and for the Pan-Arctic from the World Glacier Monitoring Service (WGMS;[210] Wolken et al.;[211] solid lines, left y-axis), plus Alaskan glacial mass loss observed from NASA GRACE[113] (dashed blue line, right y-axis). (Figure source: Harig and Simons 2016[113] and Wolken et al. 2016;[211] © American Meteorological Society, used with permission.)

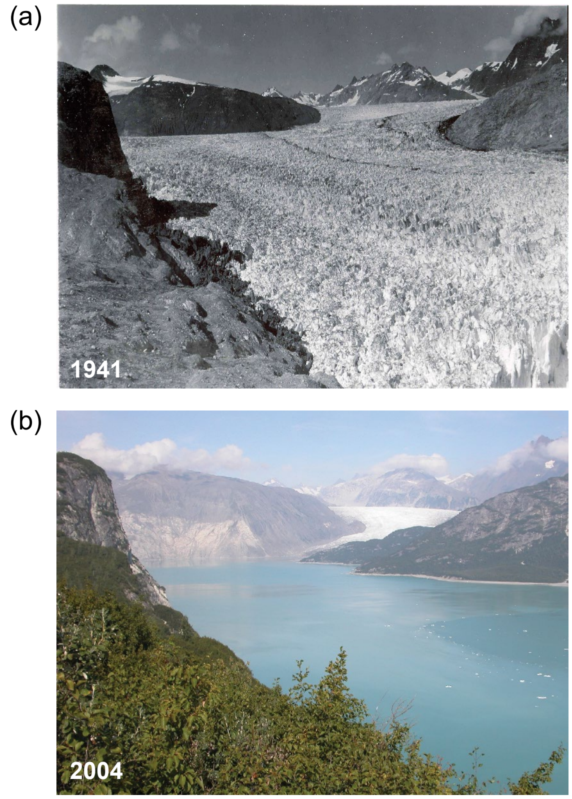

Figure 11.4: Two northeast-looking photographs of the Muir Glacier located in southeastern Alaska taken from a Glacier Bay Photo station in (a) 1941 and (b) 2004. U.S. Geological Survey repeat photography allows the tracking of glacier changes, illustrating that between 1941 and 2004 the Muir Glacier 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[212]).

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.[11, 136, 137, 138, 139, 140, 141, 142, 143, 144, 145] Record warm arctic temperatures in winter 2016 resulted primarily from the transport of midlatitude air into the Arctic, demonstrating the significant midlatitude influence.[146] 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.[139, 141, 147, 148]

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.[137, 146] Several pathways have been proposed (see references in Cohen et al.[149] and Barnes and Screen[150]): 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,[151, 152, 153, 154] 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.[155]

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.[149, 150, 156] Reanalysis data suggest a relationship between arctic amplification and observed changes in persistent circulation phenomena like blocking and planetary wave amplitude.[155, 157, 158] The recent multi-year California drought serves as an example of an event caused by persistent circulation phenomena (see Ch. 5: Circulation and Variability and Ch. 8: Drought, Floods, and Wildfires).[159, 160, 161] Robust empirical evidence is lacking because the arctic sea ice observational record is too short[162] or because the atmospheric response to arctic amplification depends on the prior state of the atmospheric circulation, reducing detectability.[146] 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.[137, 146, 150] 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.[163] However, the effect of arctic amplification on blocking is not clear (Ch. 5: Circulation and Variability).[164]

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.[142, 144, 154, 165] 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.[137, 166]

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.[167] Melting arctic sea and land ice combined with time-varying atmospheric forcing[79, 168] 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[79] but also the export volume.[169] 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).[170, 171] AMOC-associated poleward heat transport substantially contributes to North American and continental European climate; any AMOC slowdown could have implications for global climate change as well (see Ch. 15: Potential Surprises).[172, 173] 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.[130] The permafrost warming rate varies regionally; however, colder permafrost is warming faster than warmer permafrost.[37, 174] 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).[175] Permafrost active layer thickness increased across much of the Arctic while showing strong regional variations.[37, 130, 176] 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.[177] Continued degradation of permafrost and a transition from continuous to discontinuous permafrost is expected over the 21st century.[37, 178, 179]

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.[99, 179, 180] 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 limit global temperature increases. Current methane emissions from Alaskan arctic tundra and boreal forests contribute a small fraction of the global methane (CH_4) budget.[181] Howev-

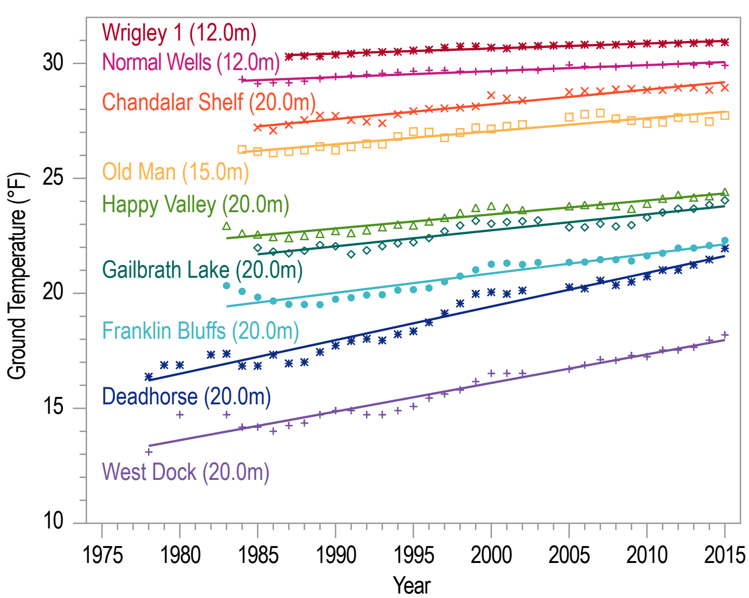

Figure 11.5: Time series of annual mean permafrost temperatures (units: °F) at various depths from 39 to 65 feet (12 to 20 meters) from 1977 through 2015 at several sites across Alaska, including the North Slope continuous permafrost region (purple/blue/green shades), and the discontinuous permafrost (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;[175] © American Meteorological Society, used with permission.)

er, gas flux measurements have directly measured the release of CO_2 and CH_4 from arctic permafrost.[182] Recent measurements 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.[183]

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 (Ch. 15: Potential Surprises).[184] 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.[185] 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.[186] Additionally, CO_2 and CH_4 production strongly depends on vegetation and soil properties.[184]

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[187, 188] 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.[189] More recently, Chadburn et al.[190] 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;[179, 189, 191] 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.[188, 192, 193] Additionally, uncertainty stems from the surprising uptake of methane from mineral soils.[194] 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 within and below permafrost and under the global ocean on continental margins. The estimated total global inventory of methane hydrates ranges from 500 to 3,000 GtC[195, 196, 197] with a central estimate of 1,800 GtC.[198] Methane hydrates are solid compounds formed at high pressures and cold temperatures, trapping methane gas within the crystalline structure of water. Methane hydrates within upper continental slopes of the Pacific, Atlantic, and Gulf of Mexico margins and beneath the Alaskan arctic continental shelf may be vulnerable to small increases in ocean temperature.[197, 198, 199, 200, 201, 202, 203]

Rising sea levels and warming oceans have a competing influence on methane hydrate stability.[199, 204] Studies indicate that the temperature effect dominates and that the overall influence is *very likely* a destabilizing effect.[198] Projected warming rates for the 21st century Arctic Ocean are not expected to lead to sudden or catastrophic destabilization of seafloor methane hydrates.[205] Recent observations indicate increased CH_4 emission from the arctic seafloor near Svalbard; however, these emissions are not reaching the atmosphere.[198, 206]

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.[14, 15, 16, 17, 18, 19, 20] 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.[1, 21, 22] Lastly, similar statements have been made in NCA3,[70] IPCC AR5,[17] and in other arctic-specific assessments such as the Arctic Climate Impacts Assessment[207] and Snow, Water, Ice and Permafrost in the Arctic.[130]

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 hamper the ability to better refine the rate of arctic warming and completely restrict 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

Very 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 carbon dioxide 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 compromise the ability to limit global temperature increases.

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.[37, 179, 186, 187, 188, 192, 193] 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.[37, 130, 175] Large carbon soil pools (more than 50% of the global below-ground organic carbon pool) are locked up in the permafrost soils,[180] 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.[182, 183] 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.[185] 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.[186] 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.[189] Chadburn et al.[190] 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.[188, 192, 193, 208] Additional uncertainty stems from the surprising uptake of methane from mineral soils[194] and dependence of emissions on vegetation and soil properties.[184] 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 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 limit global temperature increases.

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 0.08° to 0.50°C 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 limit global temperature increases 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.[19, 37, 45, 47, 112, 113, 134, 135] 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 the 2040s.[21, 59, 65]

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 techniques 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 States 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 the 2040s.

Key Finding 4

It is *very likely* that human activities have contributed to observed arctic surface temperature warming, sea ice loss, glacier mass loss, and Northern Hemisphere snow extent decline (*high confidence*).

Description of evidence base

The Key Finding is supported by many attribution studies using a wide array of climate models documenting the anthropogenic influence on arctic temperature, sea ice, mountain glaciers, and snow extent.[23, 24, 25, 26, 27, 29, 54, 55, 56, 57, 58, 59, 61, 62, 106, 108, 133] Observation-based analyses also support an anthropogenic influence.[60, 69] Najafi et al.[27] show that the greenhouse warming signal in the Arctic could be even stronger, as a significant portion of greenhouse gas induced warming (approximately 60%) has been offset by anthropogenic aerosol emissions. The emerging science of extreme event attribution indicates that natural variability alone could not have caused the recently observed record low arctic sea ice extents, such as in September 2012.[61, 62] Natural variability in the Arctic is significant,[63, 64] however the majority of studies indicate that the contribution from individual sources of internal variability to observed trends in arctic temperature and sea ice are less than 50%[28, 54, 55] and alone cannot explain the observed trends over the satellite era. This Key Finding marks an increased confidence relative to the IPCC AR5[24] moving from *likely* to *very likely*. In our assessment, the new understanding of the anthropogenic forcing,[27] its relationship to arctic climate change,[69] arctic climate variability,[28, 63, 64] and especially extreme event attribution studies[61, 62] reaffirms previous studies and warrants the increased likelihood of an anthropogenic influence on arctic climate change. 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 *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.[172]

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 *very likely* 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, many independent studies indicate that internal variability alone cannot explain the trends or extreme events observed in arctic temperature and sea ice over the satellite era.

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.[138, 142, 143, 144] The intrusion of warm, moist air from midlatitudes increases downwelling longwave radiation, warming the arctic surface and hindering wintertime sea ice growth.[139, 147] Emerging research provides a new understanding of the importance of synoptic time scales and the episodic nature of midlatitude air intrusions.[139, 141, 148] 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.[149, 150, 156] Further, modeling studies demonstrate that arctic warming can influence the midlatitude jet stream and storm track.[137, 146, 150, 163] 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.[142, 144, 154, 165] This disagreement between independent studies using different analysis techniques and the lack of understanding of the physical mechanism(s) supports 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.

REFERENCES

1. Manabe, S. and R.T. Wetherald, 1975: The effects of doubling the CO2 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

2. 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

3. 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

4. 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

5. 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

6. 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

7. 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

8. 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

9. 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

10. 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**, 28234. http://dx.doi.org/10.3402/tellusa.v68.28234

11. 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

12. 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

13. 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

14. 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

15. 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

16. 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

17. 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/

18. 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

19. 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

20. 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

21. 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/

22. 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

23. 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

24. 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/

25. Fyfe, J.C., K. von Salzen, N.P. Gillett, V.K. Arora, G.M. Flato, and J.R. McConnell, 2013: One hundred years of Arctic surface temperature variation due to anthropogenic influence. *Scientific Reports*, **3**, 2645. http://dx.doi.org/10.1038/srep02645

26. Chylek, P., N. Hengartner, G. Lesins, J.D. Klett, O. Humlum, M. Wyatt, and M.K. Dubey, 2014: Isolating the anthropogenic component of Arctic warming. *Geophysical Research Letters*, **41**, 3569-3576. http://dx.doi.org/10.1002/2014GL060184

27. 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

28. 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

29. 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/

30. 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

31. 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

32. 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

33. Kay, J.E., K. Raeder, A. Gettelman, and J. Anderson, 2011: 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

34. 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

35. 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

36. 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

37. 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/

38. 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

39. 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

40. 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

41. 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

42. 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

43. 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

44. 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

45. 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

46. 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

47. 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

48. Schweiger, A., R. Lindsay, J. Zhang, M. Steele, H. Stern, and R. Kwok, 2011: Uncertainty in modeled Arctic sea ice volume. *Journal of Geophysical Research*, **116**, C00D06. http://dx.doi.org/10.1029/2011JC007084

49. 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.

50. 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

51. 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

52. 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, 96 pp. http://dx.doi.org/10.3133/ofr20151048

53. 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

54. 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

55. Kay, J.E., M.M. Holland, and A. Jahn, 2011: 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

56. 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

57. 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

58. 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

59. 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

60. 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

61. 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

62. 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

63. 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

64. 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

65. 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

66. 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

67. 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

68. 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

69. 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

70. 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., 841 pp. http://dx.doi.org/10.7930/J0Z31WJ2

71. 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/

72. 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

73. 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

74. 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

75. 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

76. 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

77. 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/

78. 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

79. 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

80. 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

81. 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

82. 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

83. 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

84. 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

85. 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

86. 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

87. 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

88. 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

89. 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

90. Young, A.M., P.E. Higuera, P.A. Duffy, and F.S. Hu, 2017: Climatic thresholds shape northern high-latitude fire regimes and imply vulnerability to future climate change. *Ecography*, **40**, 606-617. http://dx.doi.org/10.1111/ecog.02205

91. 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**, L09703. http://dx.doi.org/10.1029/2006GL025677

92. 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

93. 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

94. 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

95. 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

96. 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

97. 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

98. 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

99. 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

100. 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

101. 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. *Journal of Geophysical Research Biogeosciences*, **120**, 1619-1637. http://dx.doi.org/10.1002/2015JG003033

102. 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

103. Swanson, D.K., 1996: Susceptibility of permafrost soils to deep thaw after forest fires in interior Alaska, U.S.A., and some ecologic implications. *Arctic and Alpine Research*, **28**, 217-227. http://dx.doi.org/10.2307/1551763

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

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

106. 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

107. 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

108. 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

109. 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

110. 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

111. 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

112. 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

113. 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

114. 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

115. 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

116. 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

117. 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

118. 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

119. 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

120. 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

121. 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

122. Dupont, T.K. and R.B. Alley, 2005: Assessment of the importance of ice-shelf buttressing to ice-sheet flow. *Geophysical Research Letters*, **32**, L04503. http://dx.doi.org/10.1029/2004GL022024

123. 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

124. 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

125. 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

126. 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

127. 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

128. 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

129. 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

130. 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

131. 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

132. 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

133. Marzeion, B., J.G. Cogley, K. Richter, and D. Parkes, 2014: Attribution of global glacier mass loss to anthropogenic and natural causes. *Science*, **345**, 919-921. http://dx.doi.org/10.1126/science.1254702

134. 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

135. 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

136. 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

137. Francis, J.A., S.J. Vavrus, and J. Cohen, 2017: Amplified Arctic warming and mid-latitude weather: Emerging connections. *Wiley Interdesciplinary Review: Climate Change*, **8**, e474. http://dx.doi.org/10.1002/wcc.474

138. 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

139. 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

140. 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

141. 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

142. 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

143. 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

144. 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

145. 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

146. 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

147. 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

148. 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

149. 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

150. 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

151. 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

152. 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

153. 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

154. 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

155. 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

156. 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

157. 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**, 20140170. http://dx.doi.org/10.1098/rsta.2014.0170

158. 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

159. 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

160. 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

161. 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

162. 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

163. 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

164. 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

165. 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

166. 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

167. 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

168. 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

169. 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

170. 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

171. 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

172. 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

173. 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

174. 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

175. 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

176. 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

177. 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

178. 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

179. 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

180. 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

181. 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

182. 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

183. 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

184. 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

185. 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/

186. 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

187. 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

188. 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**, 20140423. http://dx.doi.org/10.1098/rsta.2014.0423

189. 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

190. 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

191. 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

192. 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

193. 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

194. 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

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

196. 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

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

198. 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

199. 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

200. Brothers, L.L., B.M. Herman, P.E. Hart, and C.D. Ruppel, 2016: Subsea ice-bearing permafrost on the U.S. Beaufort Margin: 1. Minimum seaward extent defined from multichannel seismic reflection data. *Geochemistry, Geophysics, Geosystems*, **17**, 4354-4365. http://dx.doi.org/10.1002/2016GC006584

201. Johnson, H.P., U.K. Miller, M.S. Salmi, and E.A. Solomon, 2015: Analysis of bubble plume distributions to evaluate methane hydrate decomposition on the continental slope. *Geochemistry, Geophysics, Geosystems*, **16**, 3825-3839. http://dx.doi.org/10.1002/2015GC005955

202. Ruppel, C.D., B.M. Herman, L.L. Brothers, and P.E. Hart, 2016: Subsea ice-bearing permafrost on the U.S. Beaufort Margin: 2. Borehole constraints. *Geochemistry, Geophysics, Geosystems*, **17**, 4333-4353. http://dx.doi.org/10.1002/2016GC006582

203. Skarke, A., C. Ruppel, M. Kodis, D. Brothers, and E. Lobecker, 2014: Widespread methane leakage from the sea floor on the northern US Atlantic margin. *Nature Geoscience*, **7**, 657-661. http://dx.doi.org/10.1038/ngeo2232

204. 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

205. 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

206. 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

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

208. 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

209. 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.

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

211. 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

212. USGS, 2004: Repeat Photography of Alaskan Glaciers: Muir Glacier (USGS Photograph by Bruce F. Molnia). Department of the Interior, U.S. Geological Survey. https://www2.usgs.gov/climate_landuse/glaciers/repeat_photography.asp