



Arctic Climate Change, Variability, and Extremes

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Abstract

Global warming over the past half century has been amplified in the Arctic, especially in the cold season. Other Arctic indicators, especially those of the cryosphere, show signals consistent with the warming of the past half century. This Arctic amplification of the warming arises from a number of processes in the climate system, including the feedbacks associated with the loss of sea ice and snow, the increase of atmospheric moisture, and the vertical temperature structure of the Arctic atmosphere. Ocean heat fluxes into the Arctic from the North Atlantic and North Pacific also appear to have contributed to the Arctic warming through a reduction of sea ice. Internal variability, which played a major role in Arctic warming during the early twentieth century, appears to have been a minor contributor to the more recent warming, which has also been associated with unprecedented extremes of Arctic temperature and sea ice. There is evidence for increased moisture content of the Arctic atmosphere and corresponding impacts on episodes of extreme warmth. The recent variations of Arctic temperature and associated variables fit well with the simulations of Arctic climate by global and regional climate models. Projected changes include a continued warming of the Arctic even under moderate mitigation scenarios, and an increase of Arctic precipitation consistent with the higher temperatures and atmospheric humidities.

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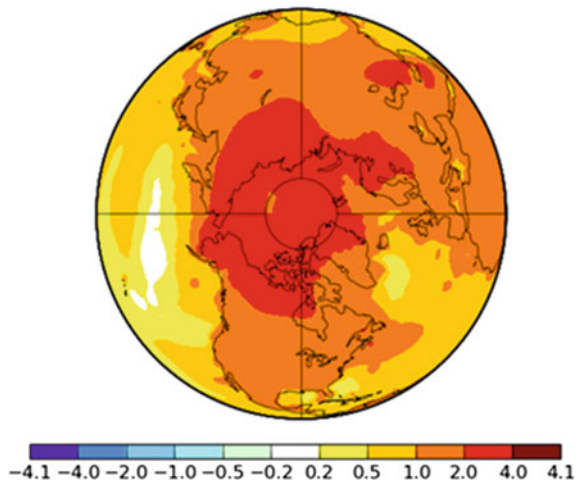
1.1 Introduction

While the subject of this volume is Arctic hydrology, temperature is a primary driver of many of the variations and trends in hydrology, especially in high latitudes where phase transitions between the solid and liquid phases of water are prominent and pervasive. Temperature's reach in the Arctic extends to changes in sea ice, snow cover, permafrost, glaciers and the Greenland Ice Sheet, with corresponding impacts on the ocean. Even the Arctic's dynamical connection to midlatitude climate and weather is related to temperature through the latitudinal dependence of warming and cooling, as discussed in Sect. 1.3.

Systematically compiled records of Arctic temperatures extend back only about 100 years, although the record lengths are shorter in some areas and extremely sparse over the high latitude oceans. Earlier expeditions and whaling activity provided occasional observations for specific marine locations, but these observations do not permit robust detection of changes. Inferences about Arctic temperatures over time periods longer than about 100 years are based on paleoclimatic reconstructions from proxy data (tree rings, sediments, diatoms, ice cores), some of which are heavily weighted toward the warm season. One such reconstruction by Kaufman et al. (2009) showed that the Arctic slowly cooled for much of the past 2000 years, consistent with earth-sun orbital changes, until a recent warming over the past 150 years or so. The warming is confirmed by instrumental data (e.g., Bekyraev et al. 2010) and is most striking in the past 50–60 years. As stated by the IPCC (2013), “Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia.” The Arctic has warmed at about twice the global rate over the past 50–60 years, a pattern known as Arctic amplification. This warming is apparent in Fig. 1.1, which

Fig. 1.1 Changes in Arctic temperatures over 1961–2017, based on linear trends of annual temperatures at each location. *Source* NASA GISTEMP (<http://data.giss.nasa.gov/gistemp/maps/>)

Change in annual mean temperature, 1961-2017



shows the spatial pattern of the change of the annual mean temperature since 1961. The warming is between 2 and 4 °C over most of the Arctic. In middle latitudes, the warming is generally greater over land, where it ranges from 1 to 2 °C than over the ocean. The subarctic land areas of Eurasia and North America have warmed by more than 2 °C since 1961.

The recent Arctic warming varies seasonally, with the strongest warming in autumn and winter and the weakest warming in summer (Fig. 1.2). The seasonal warming since 1960 exceeds 4 °C in some areas: Alaska and northwest Canada in winter, and the central Arctic Ocean in autumn and winter. It must be noted, however, that the lack of instrumental data from the Arctic Ocean in the 1960s and 1970s introduces a reliance on interpolation over the Arctic Ocean. Nevertheless, a pattern of Arctic amplification is apparent in all seasons in Fig. 1.2, with the

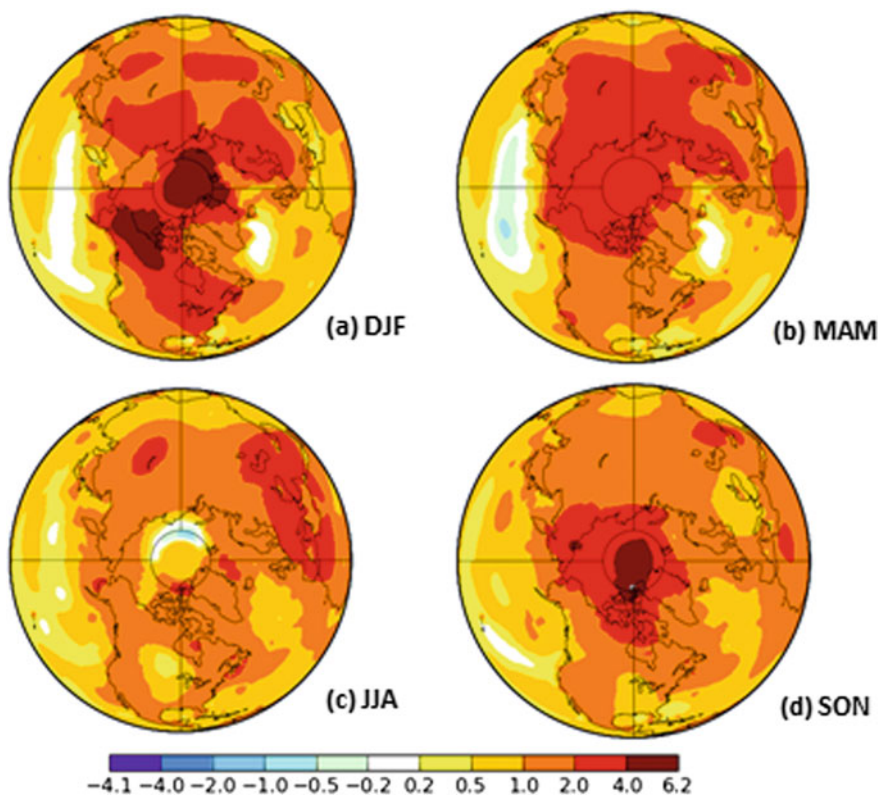


Fig. 1.2 Changes in Arctic temperatures by season over 1961–2017, based on linear trends of temperatures at each location. Seasons are **a** winter (Dec–Feb), **b** spring (Mar–May), **c** summer (Jun–Aug), and **d** autumn (Sep–Nov). *Source* NASA GISTEMP (<http://data.giss.nasa.gov/gistemp/maps/>)

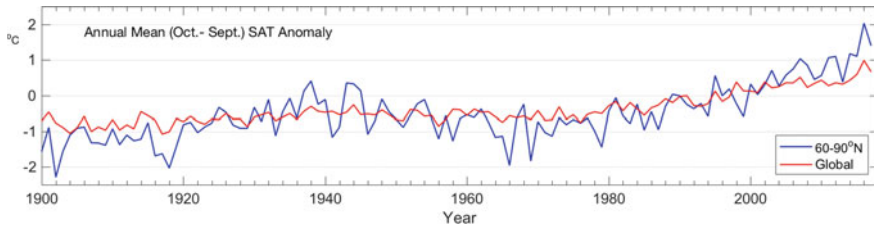


Fig. 1.3 Arctic (blue) and global (red) air temperatures, 1900–2017. *Source* NOAA Arctic Report Card (2017), <http://www.arctic.noaa.gov/Report-Card/Report-Card-2017>

exception of the immediate polar cap (70–90°N) during summer, when the thermal inertia of the Arctic Ocean and its sea ice limits the warming. It should also be noted that the summer warming over northern land areas corresponds to a rate of more than 2 °C per century, which is two orders of magnitude larger than the Arctic’s longer-term rate of summer cooling deduced by Kaufman et al. (2009).

While the Arctic has warmed more than the rest of the globe in recent decades, variability is also greater in the Arctic. Figure 1.3 shows that this greater variability characterizes temperature swings over interannual, multiyear, and multidecadal timescales. In particular, the Arctic also warmed at a greater rate than the global mean in the early twentieth century and it cooled at a greater rate in the middle twentieth century. This greater variability complicates the attribution of recent changes, as the importance of internal variability relative to external forcing is greater in the Arctic than in lower latitudes. For this reason, several recent evaluations of global climate model simulations under greenhouse forcing have found that the emergence of the anthropogenic warming signal occurs later in the Arctic (around the present decade) than in other parts of the world (Kattsov and Sporyshev 2006; Hawkins and Sutton 2009). Nevertheless, it is apparent from Fig. 1.3 that (1) the Arctic is warmer now than at any time since 1900, (2) the most recent years (2015–2017) are the warmest in the entire instrumental record, and (3) the 1998–2012 “hiatus” in global warming (red curve in Fig. 1.3) was not evident in the Arctic.

1.2 Temperature-Related Changes

The recent Arctic warming has been accompanied by a rapid loss of sea ice, especially during the warm season. September sea ice extent during the past 5–10 years was approximately 50% of the mean for the 1979–2000 period. (Consistent measurements by satellite passive microwave sensors began in 1979). The recent decline is unprecedented in the satellite record and in paleo reconstructions spanning more than 1400 years (Kinnard et al. 2011). The recent reduction of sea ice has been much less in winter and spring than in summer and autumn, resulting

in a sea ice cover that is largely seasonal. The increasingly seasonal ice cover contrasts with the Arctic Ocean's predominantly multiyear ice pack of the pre-2000 decades. The seasonality of Arctic sea ice loss is highlighted here because it has direct relevance to the interpretation of the drivers as well as the impacts of Arctic temperature change, as discussed in the following two sections.

When compared to the reductions in ice extent, the percentage reductions of ice volume and thickness are even greater. Ice thickness decreased by more than 50% from 1958–1976 to 2003–2008 (Kwok and Rothrock 2009), and the percentage of the March ice cover made up of thicker multiyear ice (ice that has survived a summer melt season) decreased from 75% in the mid-1980s to 45% in 2011 (Maslanik et al. 2001). Laxon et al. (2013) indicate an even greater decrease of 64% in autumn sea ice volume from 2003–08 to 2012.

Changes in other cryospheric variables, including terrestrial snow cover, permafrost, glaciers, and the Greenland Ice Sheet, are summarized in the most recent *Snow, Water, Ice and Permafrost in the Arctic*, a synthesis report published recently by the Arctic Monitoring and Assessment Programme (AMAP 2017). Figure 1.4 is a plot of time series of key Arctic variables from the AMAP report. The changes in these other variables are consistent with the warming Arctic in recent decades. Because the primary focus of the present paper is the Arctic warming, we refer the reader to the AMAP report for additional information on recent changes in other components of the Arctic's physical system.

1.3 Attribution

Recent attribution studies have attempted to explain why, prior to the recent warming, the Arctic warmed at a greater rate than the global mean in the early twentieth century and cooled at a greater rate in the mid-twentieth century. Fyfe et al. (2013) used a series of controlled model experiments to deduce the contributions of various forcings (including solar, volcanic, and anthropogenic) as well as internal variability. Fyfe et al. show the contribution of these various factors to Arctic temperature trends during three periods of the twentieth century. Natural variability made a positive contribution before 1939 but opposed the emerging Greenhouse Gas (GHG) contribution during the mid-twentieth century. In the last third of the century, GHG is the dominant contributor to warming. There were also small contributions to low-frequency Arctic temperature variations from the oceanic deep circulation in the Atlantic Ocean, the Atlantic Multidecadal Oscillation. Miles et al. (2014) and Kravtsov et al. (2014) provide further discussion of the role of multidecadal Atlantic variability and other manifestations of low-frequency variations.

Given the prominence of Arctic amplification in the historical temperature records, a key question is: What are the relative contributions of various feedbacks to Arctic warming? While these feedbacks are notoriously difficult to untangle in observational data, the feedbacks have been evaluated using the more

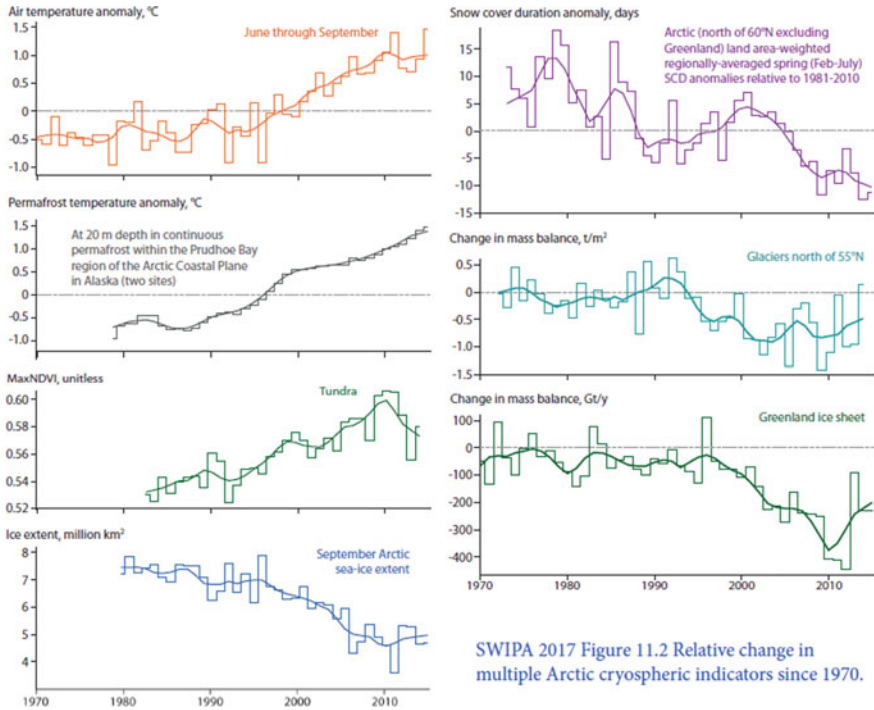


Fig. 1.4 Annual values of indicators of Arctic change from AMAP (2017). Left column (from top): Arctic summer air temperature (June–September), permafrost temperatures on the North Slope of Alaska; tundra vegetative greenness (maximum Normalized Difference Vegetation Index); September pan-Arctic sea ice extent. Right column (from top): February–July anomalies of snow cover duration on land north of 60°N; the mass balance of glaciers north of 55°N; the mass balance of the Greenland ice sheet. See Chap. 11 of AMAP (2017) for details

comprehensive information from global climate model simulations (Pithan and Mauritsen 2014). As shown in Fig. 1.5, the two largest feedbacks are the surface albedo (snow and ice) feedback and the lapse rate feedback, both of which are positive in the Arctic. The Planck effect and the water vapor feedback are also positive in the Arctic, ranking third and fourth, respectively, followed by the direct radiative effect of increased CO₂ concentrations. The largest (and only substantial) negative feedback in the Arctic is ocean heat transport, which decreases as the Arctic warms in the models. This negative feedback contrasts with the apparent positive contribution of ocean heat influxes to the recent Arctic warming. Figure 1.5 compares the various feedbacks and shows how the magnitude of each feedback varies among the major global climate models. In the following sections, we address several of the key processes underlying the stronger feedbacks.

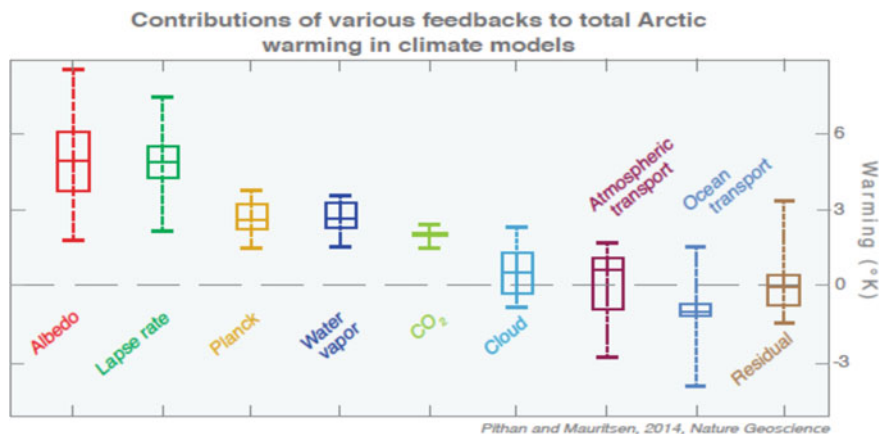


Fig. 1.5 Contributions of various feedbacks to total Arctic warming in CMIP5 global climate models. Source: Pithan and Mauritsen (2014, Nature Geosci. Fig. 1.3)

The feedbacks described above were evaluated from a general framework provided by global climate model simulations. A more tangible example is provided by the recent Arctic warming and associated sea ice loss, the explanation of which has become one of the grand challenges of Arctic research (Kattsov et al. 2010). Three temperature-related factors have been identified as contributors to the accelerated sea ice loss of the post-2000 period, so the post-2000 warming and sea ice loss can serve as an illustrative example of the key feedbacks in Fig. 1.5. The three factors are:

- the albedo-temperature feedback triggered by a loss of sea ice
- increased downwelling longwave radiation resulting from increases in atmospheric moisture
- an increase in poleward heat transports in the atmosphere and the ocean

Although these three factors can be interdependent (e.g., increased humidity and/or poleward heat transports can lead to warming that drives a loss of sea ice), they are discussed sequentially in the following sections in order to provide structure to the presentation.

1.3.1 The Albedo-Temperature Feedback

Figure 1.5 shows the change of Arctic temperature over 1961–2017 as a function of latitude and calendar month. The warming is strongest over the latitudes of the Arctic Ocean and during the autumn and winter. On the other hand, the loss of sea ice reduces the warming during spring and summer by enabling greater

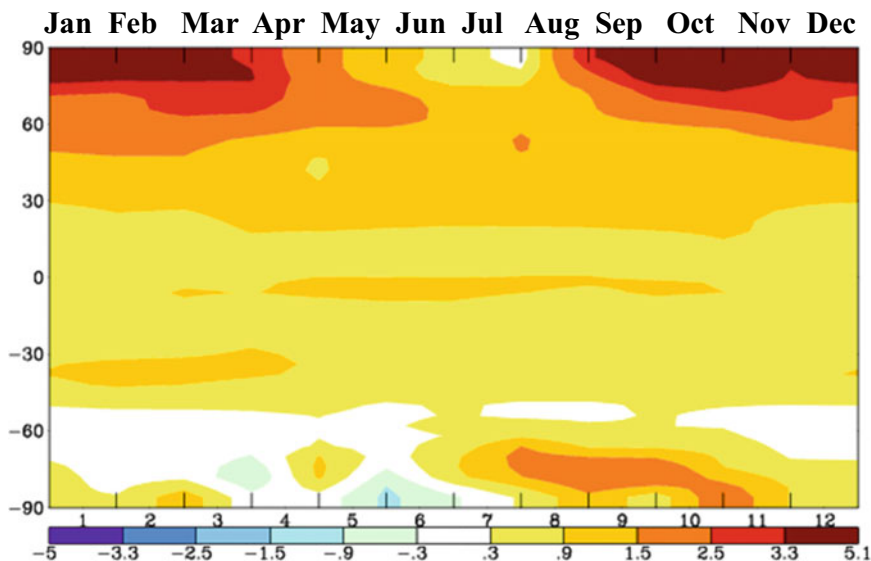


Fig. 1.6 Changes of zonal mean air temperature (°C) over the period 1961–2017. Changes are differences between starting and ending values of linear trend lines. *Source* NASA Goddard Institute for Space Studies, https://data.giss.nasa.gov/gistemp/seas_cycle/

oceanic absorption of the incoming solar radiation during these seasons. The additional heat absorbed by the ocean is released back to the atmosphere during autumn and early winter (Perovich and Richter-Menge 2009), contributing to the warming in those seasons. Figure 1.6 shows a clear signal of this seasonality of changes in the surface heat fluxes.

1.3.2 Increased Atmospheric Humidity and Associated Downwelling Radiation

The air’s water vapor-holding capacity increases exponentially with temperature. If the atmosphere’s relative humidity does not change substantially, the actual humidity will increase with climate warming. This increase in humidity has important thermodynamic implications because water vapor is a strong greenhouse gas, which will further increase the downward longwave radiation to the surface. A loss of sea ice will result in increased surface moisture fluxes to the atmosphere and hence increased atmospheric humidity, which then increases the downwelling radiation and warming of the surface (Francis and Hunter 2006). This “water vapor feedback” can be expected to amplify the surface warming in the Arctic. The model experiments by Pithan and Mauritsen (2014) support this expectation, as shown in Fig. 1.5, as do the reanalysis- and model-derived results of Bintanja and van der Linden (2013)

Observational data analyses confirm that humidity in the Arctic has increased in recent years (Screen and Simmonds 2010; Serreze et al. 2012). Consistent with the seasonality of sea ice loss, the increase of humidity has been found to be largest in the autumn months (Cohen et al. 2013). More recently, associations between regional increases in humidity and atmospheric warming have been identified (Cullather et al. 2016; Alexeev et al. 2017). Ghatak and Miller (2013) also show that increased water vapor has made a much greater contribution to the increased downwelling longwave flux and Arctic warming in winter than in summer, consistent with the seasonality of the Arctic warming in Fig. 1.6.

1.3.3 Increased Poleward Transports by the Ocean and Atmosphere

Poleward heat and moisture transports, which are key processes in the Arctic's energy budget (Serreze and Barry 2014), are achieved by the atmospheric circulation (winds). Ocean currents also account for a substantial portion of the heat transport into the Arctic. The greatest inflow of oceanic heat occurs in the North Atlantic. Interannual, decadal, and multidecadal variations of North Atlantic Ocean heat inflow to the Arctic Ocean are superimposed on a warming trend (Polyakov et al. 2010, 2011). This combination of trend and variability has been manifest as a series of increasingly warm inflow pulses. One such pulse occurred in 2005–2006, preceding the 2007 sea ice loss event, which may have been responsible for an acceleration of the albedo-temperature feedback in the Arctic (Perovich and Richter-Menge 2009).

Pacific Ocean water enters the Arctic through Bering Strait. The heat content of this water has also increased over the past decade (Woodgate et al. 2012). Serreze et al. (2016) show that this increased heating has reduced the coverage and thickness of sea ice in the Chukchi, East Siberian, and Beaufort Seas. The thinning has made the ice more responsive to the winds that drive the Beaufort gyre, increasing the transport of the warmer Pacific water to the deeper Arctic Ocean from the continental shelves (Shimada et al. 2006). The additional melt of sea ice then enhances the albedo-temperature feedback. The greatest recent loss of sea ice has been in the Pacific sector, pointing to the importance of Pacific Water inflow for the Arctic energy budget.

As the atmosphere in lower latitudes becomes warmer and moister, poleward transports of atmospheric heat as well as moisture should increase if there are no major changes in the atmospheric circulation. A time series of the poleward transports computed using an atmospheric reanalysis displays a peak in the 2005–2006 time period, after which the summers showed increases in retreat of Arctic sea ice (Alexeev et al. 2017). The recent increase in the moisture content of the Arctic atmosphere (Sect. 1.3.2) is likely attributable to a combination of increased poleward transports and local evaporation. The relative contributions of these two changes to the increased temperature of the Arctic remain to be determined.

1.4 Arctic Warming's Impacts on Middle Latitudes

The extent to which Arctic warming impacts the large-scale atmospheric circulation and middle latitudes is an active research topic. Several mechanisms have been proposed for linkages between the Arctic and the midlatitude circulation. The first is an Arctic-warming induced effect on geopotential height and the jet stream. To the extent that an amplified Arctic warming alters the pole-to-equator temperature gradient, an impact of Arctic warming on the jet stream is indeed plausible. Blocking patterns in the jet stream have been invoked in this linkage, and the role of the stratosphere in the linkage is gaining increasing traction in the atmospheric dynamics community (Overland et al. 2020). A second mechanistic linkage involves Eurasian snow cover, which also impacts the temperatures of the lower troposphere and the pressure gradients aloft (Cohen et al. 2007). We summarize these mechanistic linkages in the following two subsections.

1.4.1 Impacts on Geopotential Heights and Blocking Events

In order to illustrate the scale of Arctic thermal anomalies that may impact upper-level pressures, Fig. 1.7 extends the analysis of Overland and Wang (2010) by showing the longitudinally averaged temperature anomalies for October–November 2012–2017 as a function of altitude (pressure) poleward of 50°N. Figure 1.8 shows that the strongest warming during this six-year period was surface-based. The location of this surface-based warming in the Arctic implicates sea ice loss in the warming. The zonally averaged warming poleward of about 75°N in Fig. 1.7 exceeds 3.5 °C close to the surface and 1.5 °C when averaged over the lowest 200 hPa (about 2 km). By contrast, the warming in the middle troposphere of the Arctic is typically 0.5–1.5 °C.

Heating of the lower atmosphere results in thermal expansion, which increases the thickness (depth) of the air column between two pressures and increases the pressures aloft (i.e., thermal expansion “lifts” the pressure surfaces). Figure 1.8 shows that pressures have indeed increased aloft above the latitudes of warming in the Arctic during the autumns of 2012–2017. The changes in the north–south gradients of the pressure in the upper atmosphere result in changes in the zonal (west-to-east) winds, for which the speed at any altitude is proportional to the equatorward pressure gradient at that altitude. Because the changes in Fig. 1.8 reduce the normal equatorward gradient of pressure, the zonal winds weaken.

The jet stream's meanders, consisting of troughs (southward dips) and ridges (northward bulges), become stronger as the west-to-east component of the wind speed decreases. The troughs in the jet stream represent southward intrusions of cold polar air masses into middle latitudes, while ridges represent poleward excursions of warmer air. Jet stream waves with longer wavelengths and larger amplitudes tend to propagate more slowly. Accordingly, an amplified pattern is generally associated with persistent anomalies, often associated with extreme

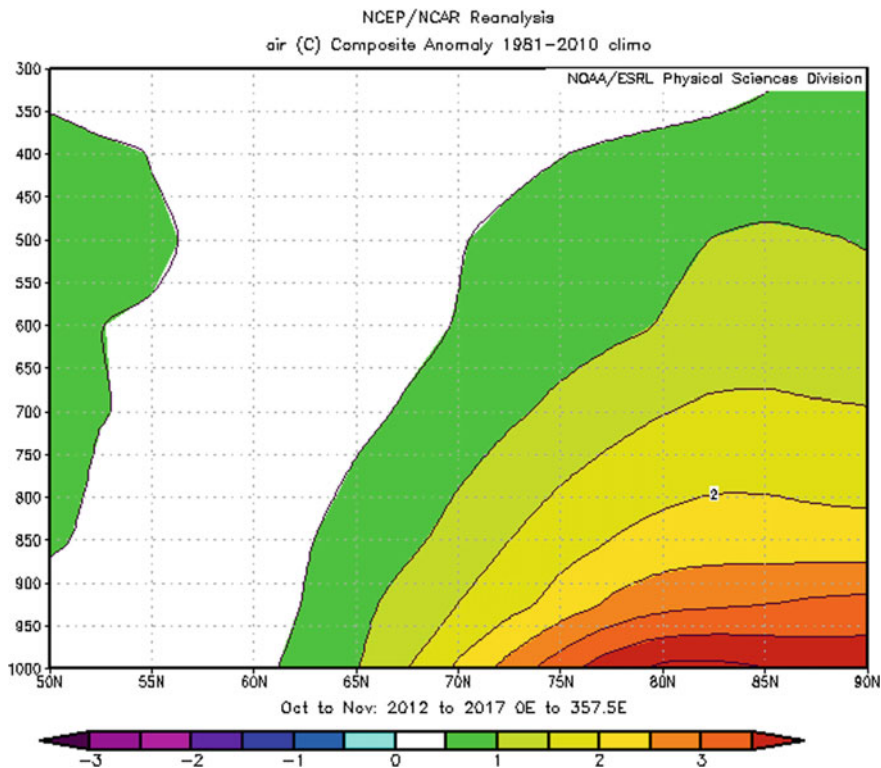


Fig. 1.7 Latitude-height cross-section of the departures from mean (1981–2010) of the zonally averaged air temperatures (°C) during October–November of 2012–2017. *Source* NOAA Earth System Research Laboratory, <https://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl>

weather, in middle latitudes. Francis and Vavrus (2012) found evidence of decreased zonal wind speeds and increased wave amplitudes in winter and autumn of the post-1979 period. The changes are especially apparent in the Atlantic hemisphere. They are consistent with Arctic-amplified warming that favors poleward extensions of ridges and with extended periods of anomalous weather in middle latitudes. Such periods are termed “blocking” episodes, as the highly amplified waves (often with embedded closed pressure centers) tend to block the normal eastward propagation of the upper-atmospheric waves that control the evolution of surface weather systems. However, subsequent work has shown that conclusions about recent changes in wave activity are sensitive to the metric of waviness and the choice of the geographical region (e.g., Screen and Simmons 2013; Barnes 2013; Barnes and Screen 2015; Overland et al. 2016; Screen et al. 2018). Screen et al. (2015) also showed that the warming of the cold Arctic air masses that move equatorward during cold air outbreaks will outweigh the effects of changes in the frequency of cold air outbreaks through the twenty-first century.

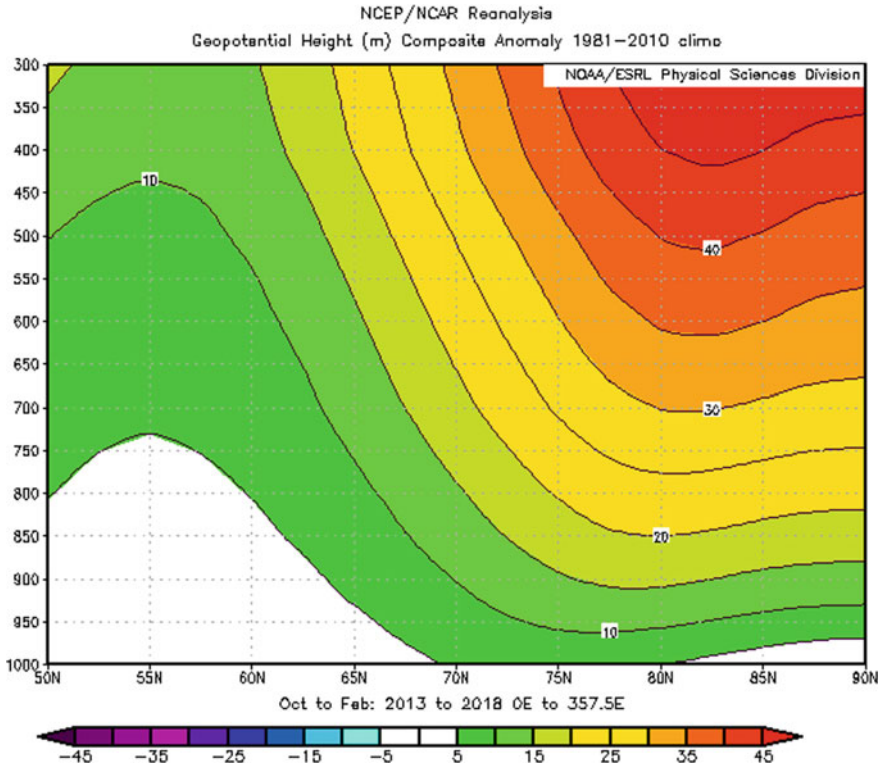


Fig. 1.8 Latitude-height cross-section of the departures from mean (1981–2010) of the zonally averaged geopotential height (m) during October–November of 2012–2017. A northward increase of the change of geopotential height implies a decrease of the west-to-east wind speed. *Source* NOAA Earth System Research Laboratory, <https://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl>

This warming of the cold air masses has been shown to already be underway by Kanno et al. (2016) in a study based on historical (reanalysis) data. Moreover, even when frequent cold air outbreaks occur during a midlatitude winter, the Arctic outbreaks may be manifestations of internal variability that is associated with forcing from other regions, e.g., the tropics (Hartmann 2015; Abdillah et al. 2018).

1.4.2 The Arctic-Midlatitude Connection via Terrestrial Snow Cover

On the basis of both observational data analyses and model simulations, reduced Arctic sea ice during autumn favors an increase of snow cover over Eurasia (Liu et al. 2012; Cohen et al. 2013). This type of association is physically plausible

because an increase of open water during autumn enhances the supply of moisture to the atmosphere. Autumn sea ice/snow cover are indeed correlated with wintertime snow cover, atmospheric circulation and air temperature. For example, observational data analysis shows that a reduction of *autumn* sea ice coverage by 1 million km² corresponds to an increase of 3–12% in *winter* snow cover over eastern Asia, parts of Europe, eastern Asia, and the northern United States (Liu et al. 2012). A climate model's sea ice sensitivity experiments (Honda et al. 2009) showed a pattern of temperature anomalies consistent with these observational results. The associated atmospheric circulation anomaly pattern corresponds to the negative phase of the Arctic Oscillation, in which the Arctic is warmer than normal and middle-latitude land areas are colder than normal. These anomalies are associated with an increased frequency of blocking, in agreement with the results described in Sect. 1.4.1.

Cohen et al. (2013) presented an analysis of observational data, showing statistically significant trends in Jul–Sep Arctic mean air temperature, September fractional sea ice coverage, autumn Arctic tropospheric moisture, October Eurasian snow cover, and the Dec–Feb Arctic Oscillation index. The relationship between these significant trends forms the basis of Cohen et al.'s proposed linkage between the Arctic, its autumn sea ice, and midlatitude wintertime anomalies. The linkage across seasons (autumn ice/snow vs. winter Arctic Oscillation) is arguably the most tenuous link in the causal chain. Dynamical linkages involving stratosphere-troposphere are now emerging to explain the across-season correlation between the high-latitude surface state during autumn and the wintertime circulation of the atmosphere (e.g., Kim et al. 2014; Overland et al. 2020). However, in view of our limited understanding of the underlying mechanisms, Arctic-midlatitude linkages remain an active research topic (Francis 2017).

1.5 Changes in Extremes

Changes in extremes often have greater impacts on ecosystems, infrastructure, and humans than changes in climatic means (CCSP 2008; IPCC 2012). Historical data from Alaska show recent trends toward less frequent cold extremes and more frequent warm extremes (Fig. 1.9). By contrast, there is no systematic trend in extremes of heavy precipitation at the same Alaskan stations (Fig. 1.9c). As discussed elsewhere in this volume, however, precipitation measurements at weather observing stations are subject to heterogeneities to a greater extent than are measurements of temperature.

On the pan-Arctic scale, Matthes et al. (2015) showed widespread decreases in extreme cold spells, although there are small areas of increases in cold spells in Siberia. Changes in extreme warm spells were found to be generally small throughout the Arctic except in Scandinavia, where increases of up to 2.5 days per decade have occurred. Long cold spells (cold events lasting more than 15 days) have almost completely disappeared since 2000.

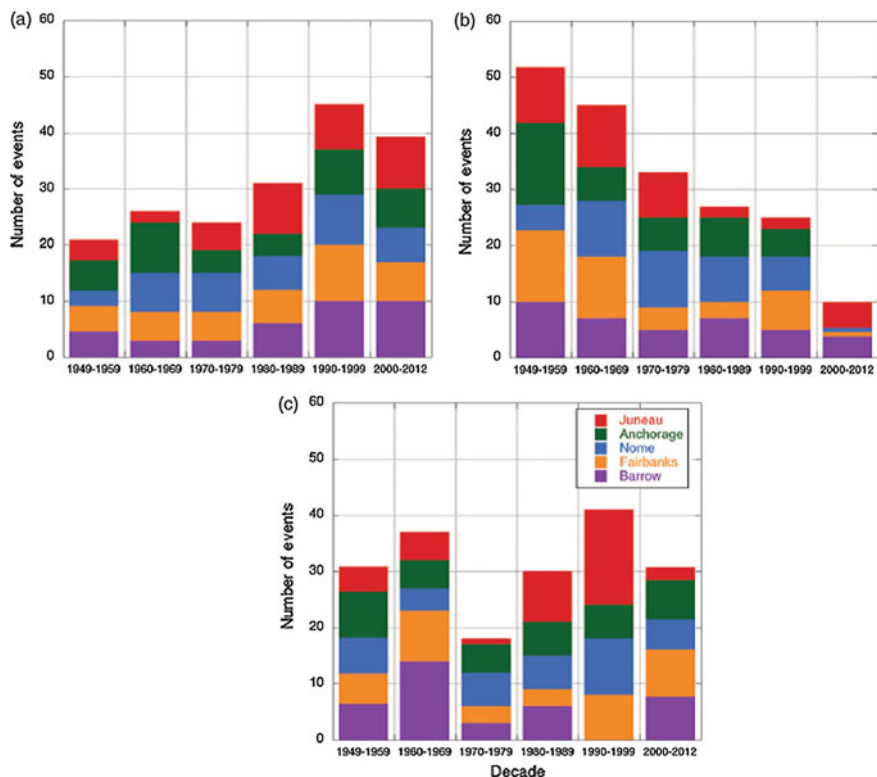


Fig. 1.9 Decadal distributions of **a** extreme high daily maximum temperatures **b** extreme low daily minimum temperatures, and **c** extreme 3-day precipitation amount for the period 1949–2012 at five first-order weather stations in Alaska. Each station is assigned a color (legend in Panel **c**). The bars for 2000–2012 have been adjusted to represent the number of events over 10 years (Bieniek and Walsh 2017)

A type of extreme event with major impact in the Arctic is freezing rain, or rain-on-snow events, which are dependent on temperature in the sense that they are favored by air temperatures close to 0°C in the lowest kilometer. As larger areas of the Arctic experience more frequent wintertime temperatures approaching (or exceeding) 0°C , these events can be expected to become more frequent. Hansen et al. (2014) examined the recent occurrence of such events in Svalbard and concluded that the likely increase of the frequency of rain-on-snow events has implications for wildlife, infrastructure, transportation, and other human activities. Studies of freezing rain events in other parts of the Arctic are needed for a pan-Arctic assessment of ongoing changes in icing events.

Cyclones in the Arctic represent another temperature-sensitive type of extreme event, as cyclones form and track in the zones of greatest baroclinicity (horizontal temperature gradient). While individual cyclones have been investigated, (e.g.,

Simmonds and Rudeva 2012; Parkinson and Comiso 2013), comprehensive data-based studies of storms over the pan-Arctic domain and evaluations of historical trends in subarctic storminess have not provided compelling evidence of trends (USGCRP 2014). There are some indications from models of a northward shift in the storm tracks over the North Atlantic Ocean, but the Northern Hemisphere shows a less spatially coherent poleward shift in storm tracks (Collins et al. 2013, their Fig. 12.20).

1.6 Future Projections

According to state-of-the-art global climate models, the recent Arctic warming is projected to continue. Warming depends on the global emission scenario, as shown in Fig. 1.10. Under RCP 8.5, which is the RCP emission scenario being tracked most closely by present emissions, the increase of the annual mean temperature over 60–90°N is approximately 10 °C by the end of the twenty-first century. For the RCP 2.6 scenario, which requires substantial negative global emissions (i.e., carbon uptake) by 2100, the warming averaged over 60–90°N is between 3 and 4 °C. The substantial difference between the business-as-usual and the mitigation scenarios emerges primarily after mid-century, indicating that several decades of future Arctic warming are already “locked into” the system (Overland et al. 2014). The projected warming resembles the observed warming (Figs. 1.1 and 1.2) in two notable respects: (1) the spatial pattern of the warming shows a strong polar amplification, and (2) the projected warming is largest in winter and autumn, and smallest in summer. Moreover, the rate of pan-Arctic warming of the past 50–60 years, 2–4 °C per half century (Fig. 1.1), is generally consistent with the model simulations.

While the consistency between the recent and projected Arctic warming lends credibility to the model simulations, uncertainty must be kept in mind. As summarized by Hodson et al. (2013), three sources of uncertainty apply to changes such as those mapped in Fig. 1.10: (1) internal variability, (2) across-model differences, and (3) the dependence on emission scenario. While (3) is acknowledged by the presentation of different panels for different scenarios and (2) by the use of stippling to indicate model agreement (or lack thereof), internal variability confounds the expected temperatures for any particular year or even decade. Excursions from the mean have characterized the historical Arctic temperature record, as shown in Fig. 1.3 and discussed in Sect. 1.1, and will almost certainly continue to do so in the future. Nevertheless, the aggregate of the model simulations suggests that these excursions will be relative to higher mean temperatures in the future.

Figure 1.11 shows the corresponding projections of future (2081–2100) precipitation, expressed as percentage changes from the averages for the 1986–2005 period. In both the low- and high-emission scenarios, Arctic precipitation increases. The percentage increases under RCP 8.5 are quite high, exceeding 20% over the subarctic land areas and exceeding 40% over the Arctic Ocean. Only the equatorial Pacific Ocean has a comparable percentage increase. The actual increases (e.g., mm

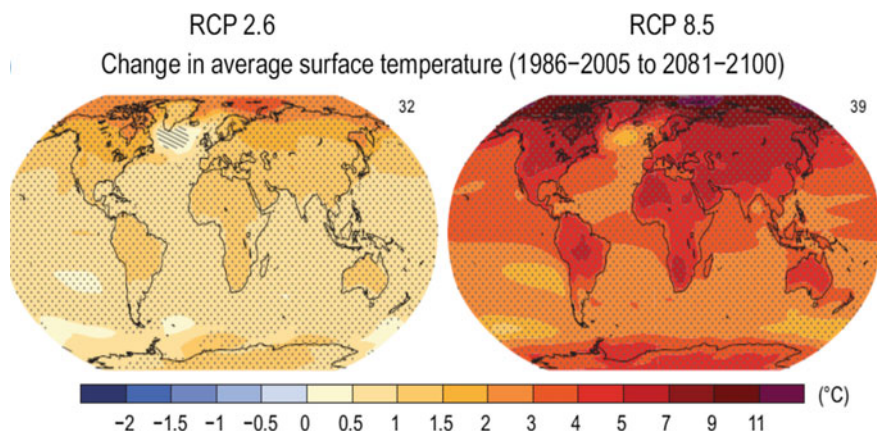


Fig. 1.10 Changes of surface air temperature ($^{\circ}\text{C}$) projected by the CMIP5 climate models for the period 2081–2100 relative to 1986–2005. Left and right panels are for RCP 2.6 (extreme mitigation) and RCP 8.5 (business-as-usual) emission scenarios. Stippling indicates regions where the multi-model mean change exceeds two standard deviations of internal variability and where at least 90% of the models agree on the sign of the change. The number of models is indicated above and to eight of each map. *Source* IPCC (2013, Fig. SPM.8)

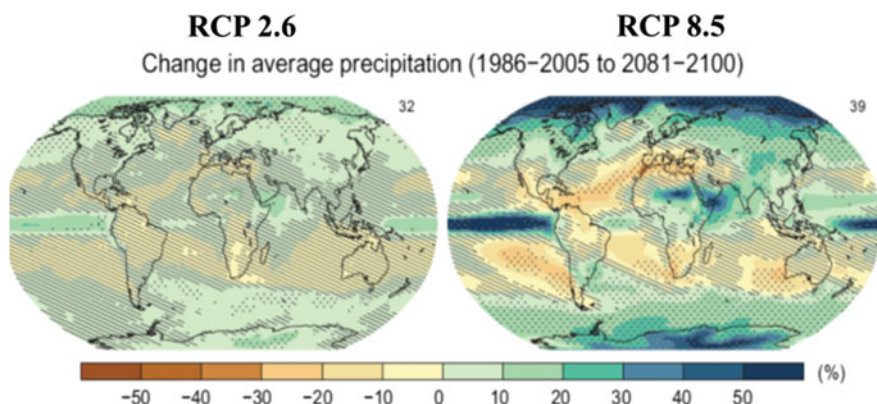


Fig. 1.11 Percentage change in annual mean precipitation projected by the CMIP5 climate models for the period 2081–2100 relative to 1986–2005. Left and right panels are for RCP 2.6 (extreme mitigation) and RCP 8.5 (business-as-usual) emission scenarios. Stippling indicates regions where the multi-model mean change exceeds two standard deviations of internal variability and where at least 90% of the models agree on the sign of the change. The number of models is indicated above and to eight of each map. *Source* IPCC (2013, Fig. SPM.8)

per year) are smaller in the Arctic than areas such as the tropical Pacific because the base-level (1986–2010) amounts are much smaller in the Arctic. Nevertheless, the projected increase of Arctic precipitation is one of the more robust signals in the

global model projections of climate change. The extent to which these increases of precipitation will be offset by other hydrologic changes in high latitudes is one of the central issues of Arctic change and will be addressed in later chapters of this volume.

1.7 Conclusion

Several conclusions about Arctic temperatures emerge from the survey provided here. First, the Arctic warming of recent decades is unambiguous. The warming is further supported by corresponding changes in other components of the Arctic system. Second, there is no longer much “debate” about the emergence of Arctic amplification (Serreze and Francis 2006; Serreze et al. 2009), which is now unmistakable in the pattern of recent air temperature change. Furthermore, there have been recent advances in establishing the relative importance of the processes and feedbacks contributing to Arctic amplification. For example, the albedo-temperature feedback is detectable and is almost certainly a contributor to the recent loss of sea ice. Other notable factors in the recent Arctic-amplified warming and loss of sea ice are the increases in atmospheric water vapor and the poleward heat transports, especially in the ocean.

While the evidence for Arctic warming is unambiguous, there are remaining diagnostic challenges. These challenges pertain to the following fundamental questions:

- Are Arctic warming and sea ice loss irreversible in a climate system in which multiyear multidecadal variability is known to have been prominent in the past? The fact that the recent Arctic warming and loss of sea ice are, according to some reconstructions, unprecedented in the past 1400–2000 years suggests at least the possibility that a threshold may have indeed been crossed.
- What is the role of cloudiness in ongoing and future changes of the Arctic system? Despite its important effect on air temperatures, cloudiness has received relatively little attention in diagnostic evaluations of historical (observed) and future (model-based) Arctic change. Given the role of the Arctic surface as a moisture source for the atmosphere and its clouds, hydrology will need to be a key consideration in addressing this question.
- What are the key dynamical mechanisms underlying the atmospheric “blocking” response to Arctic warming? The answer to this question has implications for the seasonal-to-decadal predictability of severe winters in middle latitudes.
- How robust are the associations between variations of sea ice, Eurasian snow cover and the atmospheric circulation? What are the hydrological implications of these associations?
- How will the atmospheric circulation change in response to Arctic-amplified global warming? These changes will have first-order impacts on the poleward transports of heat and moisture. While future changes in these transports are not presently known, they are highly relevant to Arctic hydrology.

Climate models are unanimous in predicting that the Arctic will warm and that its precipitation will increase by the end of the present century. However, on shorter timescales of years to decades, the Arctic is notorious for its internal or natural variability, so much so that the signal of greenhouse warming emerges above the “noise” of climate variability more slowly than in the tropics, as discussed in Sect. 1.1. Moreover, climate model experiments show that even under external forcing scenarios consistent with ongoing increases of greenhouse gases, the likelihood of an increase of Arctic sea ice over any particular 10-year period is about 30% (Kay et al. 2011). If models are capturing the key Arctic feedback processes and their timescales, it would therefore not be surprising if there is a pause or a reprieve from the Arctic warming and sea ice loss over several years or a decade. Such a pause would undoubtedly have hydrologic implications as well, so the trajectory of the Arctic hydrologic budget must be viewed in a framework of uncertainty that depends strongly on the timescale.

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