

Chapter 11

Climate Change in the Arctic



Torben Koenigk, Jeff Key, and Timo Vihma

Abstract Observations over the last decades showed large changes in the Arctic regions with a strong warming of the Arctic, which is about twice that of the global mean warming. The largest warming rates with up to 10 K since 1980 are reached near the surface in the Chukchi Sea in autumn and in the Barents Sea in winter. Changes in Arctic climate are a result of complex interactions between the cryosphere, atmosphere, and ocean and different processes contribute to the amplified warming signal such as the ice albedo feedback, changes in clouds and water vapour, enhanced meridional energy transport in the atmosphere and in the ocean, vertical mixing in Arctic winter inversions and temperature feedbacks.

The observed warming is concurrent with a large reduction of the sea ice cover particularly in summer and autumn. The impact of Arctic amplification and sea ice retreat on the atmospheric circulation is still discussed. Positive winter sea level pressure trends along the Siberian Arctic coast have been linked to negative winter temperature trends over Central Asia.

Ocean heat and freshwater transports into and out of the Arctic undergo changes as well with potentially strong consequences for deep water formation in the North Atlantic Ocean and the entire large scale oceanic circulation.

Climate projections indicate that the Arctic will continue to warm faster than the rest of the world in the twenty-first century. Whether summer sea ice is going to melt completely depends on the future emission scenario.

T. Koenigk (✉)

Swedish Meteorological and Hydrological Institute, Norrköping, Sweden
e-mail: torben.koenigk@smhi.se

J. Key

National Oceanic and Atmospheric Administration, Madison, WI, USA
e-mail: jeff.key@noaa.gov

T. Vihma

Finnish Meteorological Institute, Helsinki, Finland
e-mail: timo.vihma@fmi.fi

This chapter will review the state of knowledge of mechanisms of the observed changes, the potential consequences of future Arctic warming for sea ice, ocean and atmosphere, and uncertainties due to emission scenarios, model shortcomings and natural variability.

Keywords Arctic temperature amplification · Arctic climate change · Natural variability · Future climate scenarios · Arctic observations · Climate modelling · Ocean- sea ice - atmosphere interactions · Arctic - lower latitude interactions · Climate processes

11.1 Introduction

The Arctic plays an important role in the global climate system. Snow and ice cover have a large influence on both the local and remote climate. Small changes in the sea ice cover may have a strong impact on the large-scale atmospheric circulation, which affects the local climate but could also affect remote regions. The Arctic Ocean is a large source of freshwater for the global oceans. The export of freshwater from the Arctic alters the deep water formation in the North Atlantic and affects thus the entire global ocean circulation system.

Observations over the last few decades showed an ongoing climate change in the Arctic regions with a strong warming of the Arctic, which is about twice of the global mean warming. The observed warming is concurrent with a large reduction of the sea ice cover, which has accelerated since 2000 with recent minima in September of 2007 and 2012.

Arctic warming and sea ice reduction have large impacts on the Arctic ecosystem and social-economic activities in the Arctic. Changes in Arctic ice cover affect ice algae and phytoplankton. Consequently, fish stocks move further to the north, affecting fishery and coastal communities. With the reduction of sea ice, new shipping routes through the Arctic open and the exploitation of nature resources such as oil and gas is becoming more economically feasible. This puts the Arctic environment at risk, and actions need be taken to prevent Arctic pollution. Further, increased shipping in the tough Arctic environment requires rescue plans for people and nature in case of accidents.

11.2 Observed Changes in Recent Decades

11.2.1 *Atmosphere*

Observations indicate that Arctic near-surface temperature trends have been about twice the rate of the global mean warming over the last few decades (ACIA 2005; Stocker et al. 2013; Richter-Menge and Jeffries 2011). The largest warming rates

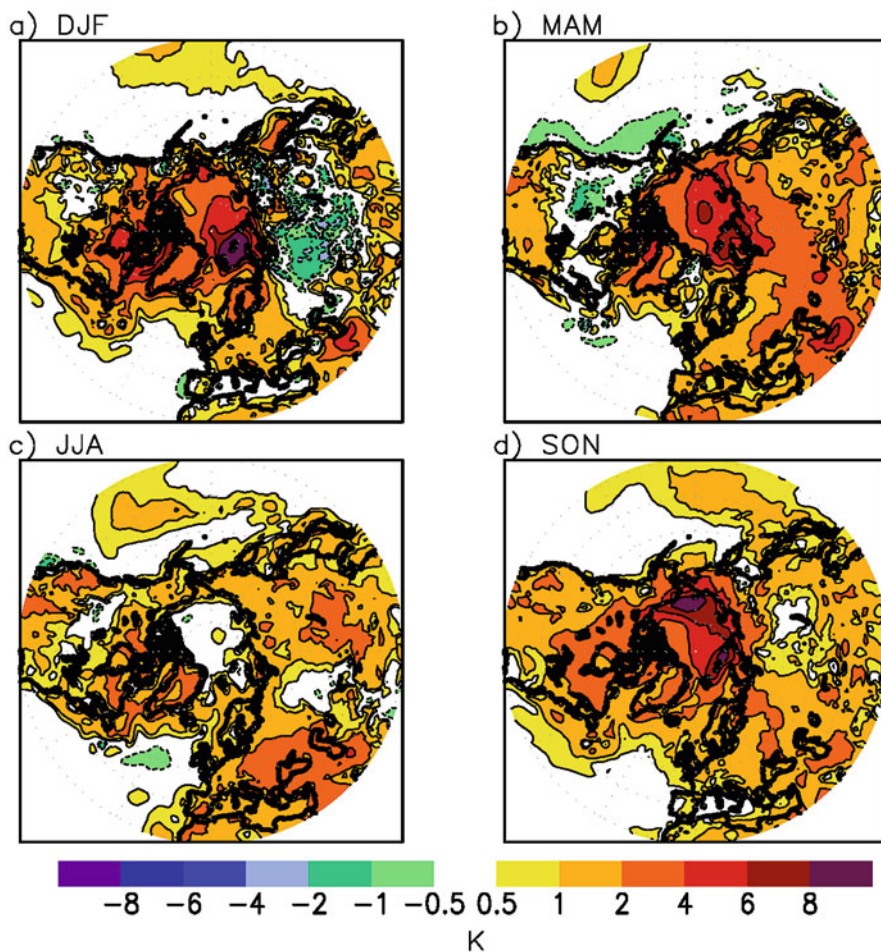


Fig. 11.1 Seasonal two meter air temperature trends calculated from ERA-Interim reanalysis data (Dee et al. 2011) between 1980 and 2017

with up to 10 K between 1980 and 2017 are reached in the Chukchi Sea in autumn and in the Barents Sea in winter (Fig. 11.1). In contrast, surface warming in summer is small and no amplification of surface temperature can be seen.

The warming, particularly in winter but to a lesser degree also in autumn and spring, is especially pronounced at the surface and is strongly reduced with height. However, even above the surface, the warming is amplified compared to lower latitudes (Cohen et al. 2014). In summer, the strongest warming occurs above the surface at 900–950 hPa height.

The winter Arctic is often dominated by a near surface temperature inversion. The warmest temperatures typically occur at about 850–900 hPa while the surface

is on average approximately 6 K colder than the air above (Medeiros et al. 2011; Koenigk et al. 2013).

The observed strong warming at the surface in winter leads to a reduction of the winter inversion weather situations in the Arctic. This has impacts on cloud and precipitation formation. A reduced winter inversion allows for more formation of clouds further up in the atmosphere replacing low level clouds. On the other hand, more open water regions lead to increased formation of low-level clouds. While there is rather large agreement that precipitation in the warming Arctic has increased, uncertainties in cloud trends are still large.

Different processes have been suggested to contribute to the amplified warming signal. The traditional explanation is the ice albedo feedback (Serreze et al. 2009; Screen and Simmonds 2010a, b; Letterly et al. 2018), where an initial global warming signal leads to reduced sea ice, which in turn leads to additional warming due to reduced reflectivity of solar radiation at the surface. However, other studies suggested that changes in clouds and water vapour (Graversen and Wang 2009; Liu et al. 2008, 2009; Liu et al. 2018), enhanced meridional energy transport in the atmosphere (Graversen et al. 2008) and in the ocean (Spielhagen et al. 2011; Koenigk and Brodeau 2014), vertical mixing in Arctic winter inversions (Bintanja et al. 2011), and temperature feedbacks (Pithan and Mauritsen 2014) might play a similarly large role as the sea ice albedo feedback.

The change patterns in the atmospheric circulation in recent decades vary strongly throughout the year (Fig. 11.2) and most trends in the period 1980–2017 are rather small compared to the natural variability. The trends are of similar amplitude in all seasons. The most robust pattern across seasons is a positive SLP trend over parts of the North Pacific. Also, the positive trend along the Siberian Arctic coast in winter raised attention, and there is an ongoing discussion if this trend can be linked to Arctic sea ice reduction. More details on the potential impact of the Arctic amplification on lower latitudes is provided in Sect. 11.3.

11.2.2 *Sea Ice*

The rapid Arctic warming is accompanied by a strong reduction of Arctic sea ice. Satellite data, which can reliably estimate the Arctic sea ice extent, provides a record starting in 1979 (Fig. 11.3). Since then, the sea ice extent has been decreased in all seasons (Stroeve et al. 2012; Devasthale et al. 2013; Meier et al. 2014). The trend is most negative in late summer (Fig. 11.3), and the average minimum ice extent in the last decade has been more than 30% below the average of the 1980s and 1990s. The lowest minimum sea ice extent was observed in September 2012 with an ice extent of about 3.6 million km², approximately 50% below the average of the 80s and 90s. Spatially, the summer sea ice reduction is most pronounced in the Beaufort and East Siberian Seas.

The maximum winter sea ice extent decreased from around 16.5 million km² in the 80s and 90s to around 14.5 million km² in the recent decade. A reduction of

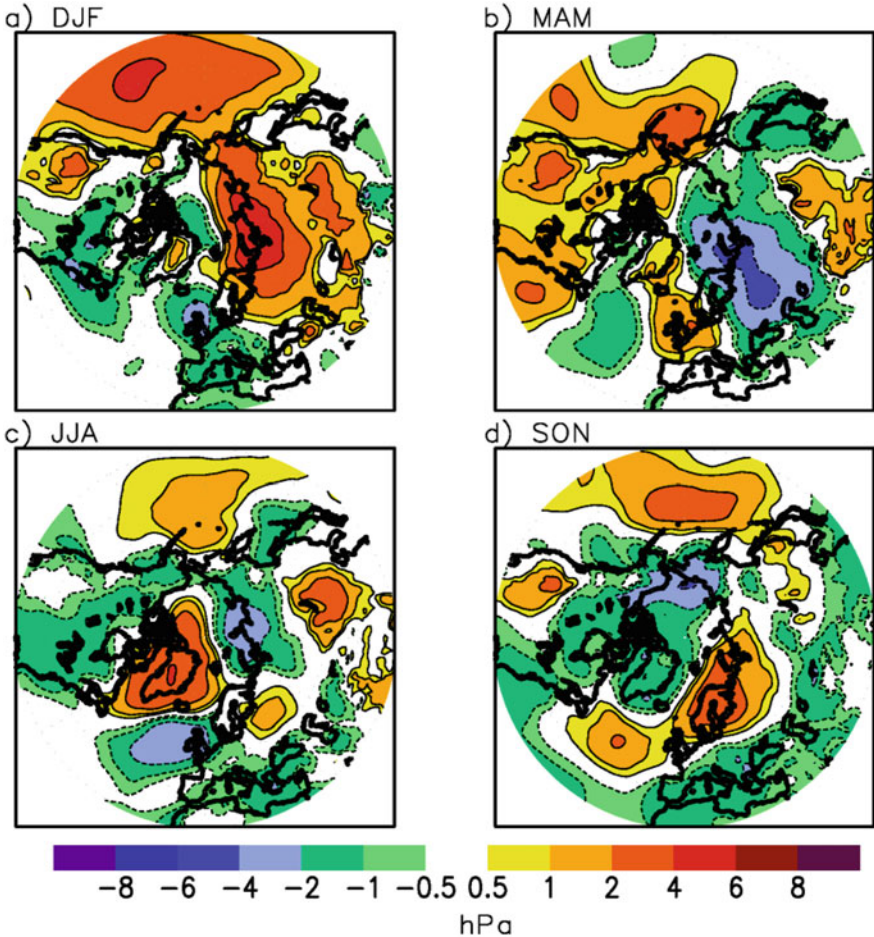


Fig. 11.2 As Fig. 11.1 but for SLP

sea ice has a direct impact on temperature changes in the Arctic. In the cold season, sea ice isolates the warm ocean (around freezing temperature) from the very cold atmosphere (on average around -30°C). Where sea ice disappears, a large amount of heat is released from the ocean to the atmosphere, leading to local warming rates of more than 20°C .

Sea ice thickness measurements are still difficult and no reliable, long term Arctic-wide observations are available. However, in-situ measurements, estimates from satellites and model simulations indicate that sea ice has become much thinner in recent decades. The most commonly used comprehensive ice volume data set is the Pan-Arctic Ice Ocean Modeling and Assimilation System (PIOMAS) data set (Schweiger et al. 2011). It indicates that the total sea ice volume in September shrank by more than 50% since the 1980s and 1990s. In contrast to sea ice extent,

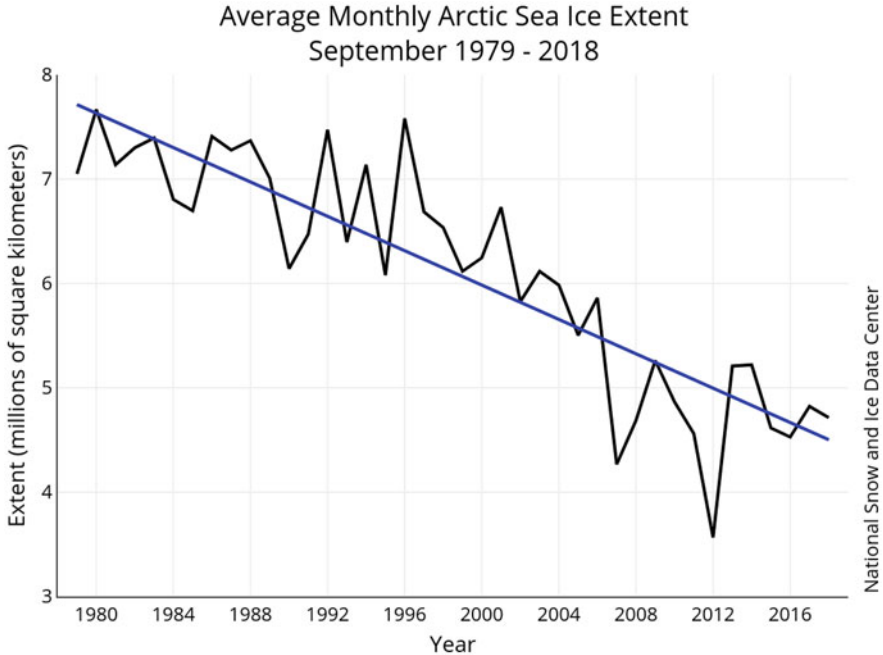


Fig. 11.3 Arctic sea ice extent in September between 1979 and 2018. (National Snow and Ice Data Center, NSIDC; Fetterer et al. 2017)

sea ice volume reduction is rather uniformly occurring throughout the entire year. Thus, the lesser ice extent decrease in winter compared to summer is misleading: the remaining winter sea ice is thinning at the same rate as the summer sea ice. This also has as a consequence that the amount of old, multi-year sea ice in the Arctic is reduced. Large parts of the Arctic Ocean are now covered by ice that is one year and younger.

11.2.3 Ocean

The ocean circulation in the Arctic in layers near the surface is characterized by a pronounced Beaufort Gyre, transpolar currents from the Siberian coast towards Fram Strait and southerly flows through Fram Strait as well as inflowing waters through the Barents Sea Opening and further along the Siberian coast.

The Arctic Ocean is a large source of freshwater and the Arctic freshwater export has an important impact on the formation of deep water in the North Atlantic Ocean and thus potentially the entire thermohaline circulation (Dickson et al. 1988; Häkkinen 1999; Haak et al. 2003; Koenigk et al. 2006).

Observations indicate an increase in the discharge in river runoff and precipitation in the second half of the twentieth century (Peterson et al. 2002; McClelland et al. 2006). Furthermore, sea ice is expected to melt at least partly. All this led to freshening of the Arctic Ocean. Although, observations are rare, it seems that most of the additional freshwater input into the Arctic in recent decades have been stored in the Arctic, particularly in the Canadian Arctic and Beaufort Gyre, and were not exported into the North Atlantic Ocean yet. As one main reason for this, a strengthening of the anticyclonic wind pattern has been discussed. Such a strengthening would cause a convergence of fresh surface water in the Beaufort Gyre. A release of this freshwater, which is now several times the freshwater amount that has been exported into the North Atlantic during the Great Salinity Anomaly (Dickson et al. 1988) could have large consequences for the global thermohaline circulation.

Observations also suggest an increase in the oceanic heat transport into the Arctic (Polyakov et al. 2005) and indicate a potential for accelerated sea ice melt. Hereby, the Barents Sea plays a key role for the heat transport since most of the heat coming from the south has to pass the rather small and shallow Barents Sea. Observations of the temperature of the inflowing Atlantic water show a positive trend over recent decades (Skagseth et al. 2008. Smedsrud et al. 2013). Schlichtholz (2016) showed, based on proxies, that the temperature of the Atlantic water reaching the Arctic has never been as high as today during the last 2000 years.

The additional heat that arrives in the Barents Sea is mainly passed to the atmosphere, thus contributing to Arctic warming and affecting atmospheric stability and circulation (Koenigk and Brodeau 2014). The rest of the additional heat is used to reduce the sea ice in the Barents Sea or is mixed into the Arctic waters below the cold, fresh surface layer, thus affecting the oceanic stratification of the Arctic Ocean.

11.2.4 Cloud-Ice Interactions, Forcings, and Feedbacks

Observational assessments have shown that trends in Arctic cloud and sea ice cover are linked. Liu et al. (2012) employed an equilibrium feedback assessment to quantify this relationship using satellite-derived sea ice concentration and cloud cover in the Arctic over the period 2000–2010. They found that a 1% decrease in sea ice concentration leads to an increase in cloud cover of approximately 0.4%, and that 22–34% of the cloud cover variance can be explained by the variability in sea ice extent. This suggests that a further decline in sea ice cover will result in an even cloudier Arctic.

Cloud feedbacks are the main factor behind the uncertainty in patterns of warming, primarily through their indirect influence on meridional transport between the tropics and the Arctic (Bonan et al. 2018). The radiative effects of Arctic clouds on the surface energy budget - cloud “forcing” - can also result in warming (or cooling) through their direct effect on sea ice growth and melt. Similarly, changes

in cloud cover influence the ice albedo and snow albedo feedbacks, which have large-scale impacts on warming through changes in the absorption of solar radiation at the surface.

For example, Liu and Key (2014) examined the record minimum Arctic sea ice extent in September 2012 and the “rebound” of the ice cover the following year. During the 2012–2013 winter the sea ice cover quickly returned, carrying through to the summer when the ice extent was 48% greater than the same time in 2012. Most of this rebound was in the Chukchi and Beaufort Seas, areas experiencing the greatest recent decline in sea ice. While factors such as ice dynamics, heat transport, and solar insolation may have contributed, it was demonstrated that below-average Arctic cloud cover in January–February 2013 resulted in a strongly negative surface radiation budget, which cooled the surface and allowed for greater ice growth. More thick ice was observed in March 2013 relative to March 2012 in the western Arctic Ocean, and the areas of ice growth estimated from the negative cloud cover anomaly that were advected from winter to summer corresponded well with the September ice concentration anomaly pattern. Therefore, decreased wintertime cloud cover appears to have played an important role in the return of the sea ice cover the following summer, providing a partial explanation for large year-to-year variations.

Letterly et al. (2016) extended this work to cover the period 1983–2013. Using satellite data and two climate reanalyses it was shown that cloud forcing anomalies in the East Siberian and Kara Seas precondition the ice pack and, as a result, explain 25% of the variance in late summer sea ice concentration. This suggests that winter cloud forcing anomalies in this area have predictive capabilities for summer sea ice anomalies across much of the central and Eurasian Arctic.

Changes in Arctic climate are a result of complex interactions between the cryosphere, atmosphere, and ocean. With regard to climate warming, more cryosphere feedbacks are positive and result in further warming than are negative, resulting in a reduced rate of warming or cooling (Callaghan et al. 2011). Both the ice albedo feedback over the ocean and the snow albedo feedback over land have played an important role in Arctic warming. Recent declines in sea ice and snow extent have led to an increase in the absorption of solar energy at the surface, which has resulted in additional surface heating and a further decline in snow and ice. These are the ice and snow albedo feedbacks. Letterly et al. (2018) used satellite data covering the period 1982–2015 to show that the positive trend in solar absorption over the Arctic Ocean is more than double the trend over Arctic land, and that the magnitude of the ice–albedo feedback is four times that of the snow–albedo feedback in summer. The timing of the high-to-low albedo transition is important for the future, as it has shifted closer to the summer solstice over ocean when solar insolation is highest, but further away from the summer solstice toward earlier in the year over land. The implication of this shift is that decreasing sea ice cover, not changes in terrestrial snow cover, has been the dominant radiative feedback mechanism in recent decades and will continue to play an important role in future Arctic climate change.

11.3 Effects of Arctic Changes on Mid-Latitude Weather and Climate

In Sect. 11.2, rapid changes in Arctic climate in the last decades were discussed. Sea ice has been substantially reduced in extent and thickness, particularly since the early 2000s. At the same time, several mid-latitude regions experienced a number of cold winters and parts of Eurasia and North America show negative winter temperature trends since the 1980s.

Effects of Arctic changes on mid-latitude weather and climate is a challenging study topic, which has recently received considerable attention (Cohen et al. 2014; Walsh 2014; Vihma 2014, 2017; Gao et al. 2015; Overland et al. 2015) and perspective papers (Overland et al. 2016; Francis 2017; Screen 2017). Studies based on both observational data and model simulations have indicated a connection between variations of late summer Arctic sea ice extent and winter mid-latitude conditions (Petoukhov and Semenov 2010; Francis et al. 2009; Francis and Vavrus 2012; Yang and Christensen 2012; Overland and Wang 2010; Hopsch et al. 2012; Garcia-Serrano and Frankignoul 2014; Mori et al. 2014). Most of these studies found that a reduction or negative anomaly in late summer sea ice extent leads to winter atmospheric circulation anomalies resembling the negative phase of the North Atlantic Oscillation (NAO) and thus to more frequent cold winters in mid-latitudes of Eurasia. On the contrary, there are also studies suggesting that Arctic warming or sea ice decline sometimes favors the positive phase of NAO (Orsolini et al. 2012; Screen et al. 2014). Contrasting results have also been obtained for the Arctic effects on the Polar front jet stream (Francis and Vavrus 2012; Barnes 2013).

Despite these controversies, advances been made in understanding the multifaceted effects of Arctic changes. We can presently recognize several dynamical mechanisms that transmit the effects of Arctic changes on mid-latitude weather and climate, six of them introduced below. Some of them have might have contributed to the recent cold winters in mid-latitudes.

11.3.1 Dynamical Mechanisms

First, due to Arctic Amplification, wintertime cold-air outbreaks originating from the Arctic have become warmer (Serreze et al. 2011; Screen 2014). This has opposed the recent occurrence of cold mid-latitude winters. However, contrary to general trend in mid-latitudes, in East Asia wintertime cold-air outbreaks have become colder (Kim et al. 2014).

Second, due to Arctic Amplification, the north-south geopotential height gradients have become weaker, in particular in mid- and upper-troposphere. This has decreased the westerly winds according to the thermal wind law (Francis and Vavrus 2012, 2015), and resulted in a wavier jet stream (Vavrus et al. 2017), which has slowed down the eastward motion of weather patterns, increasing

the likelihood of extremes related to persistent weather patterns (Overland et al. 2015; Coumou et al. 2015). However, the tropical amplification of climate warming in the upper troposphere tends to oppose these effects (McGraw and Barnes 2016). The net effect of Arctic and tropical amplifications is unclear and may depend on the season and region. This is seen, among others, in regionally different observed and predicted changes in blocking occurrence. According to Hoskins and Woollings (2015), a general decrease in blocking occurrence is expected under warming climate but, according to Masato et al. (2013) and Dunn-Sigouin and Son (2013), blocking may increase, e.g., in summer in western Russia when the European blocking shifts eastward. Further, Mori et al. (2014) show that Arctic sea ice decline has favored Eurasian blocking, and Hanna et al. (2016) associate recent strong events of Greenland Blocking to Arctic Amplification.

Third, several studies suggest that Arctic changes have triggered planetary wave trains responsible for remote effects in mid-latitudes. For example, spring sea ice anomalies in the Arctic have been associated with anomalies in summer precipitation in China (Zhao et al. 2004; Wu et al. 2009, 2013; Guo et al. 2014; Uotila et al. 2014) and Europe. In the case of Europe, the Sea of Okhotsk, Hudson Bay and Labrador Sea have been named as the most influential regions of sea ice decline (Mesquita et al. 2011; Wu et al. 2013). The summertime effects may be particularly strong, if the planetary waves resonate with quasi-stationary thermal and orographic forcing. According to Petoukhov et al. (2013) and Coumou et al. (2014, 2015), trapping of planetary waves typically with zonal wave numbers 6, 7, or 8 have contribution to heat waves in Europe (Summer 2003), Russia (2010), and the USA (2011), as well as the floods in Pakistan (2010).

Fourth, the Arctic sea ice decline and changes in Eurasian snow cover in autumn have probably contributed to Eurasian winter weather via stratosphere-troposphere interactions (e.g. Cohen et al. 2012; Jaiser et al. 2013; Garcia-Serrano and Frankignoul 2014). They argue that reduced autumn sea ice and thus more humid air affects precipitation patterns which lead to enhanced autumn snow cover over Siberia. Cohen (2007) showed that this can affect the Siberian High and changes planetary wave fluxes into the stratosphere. Also, a more direct link between sea ice and stratospheric circulation through generating anomalous Rossby waves (Honda et al. 2009; Peings and Magnusdottir 2014) or by preconditioning static stability and baroclinicity (Rinke et al. 2013) has been suggested. All these suggested processes might slow down the Polar Vortex, which in turn feeds back to the troposphere leading to a negative NAO/AO signal. Inoue et al. (2012) and Koenigk et al. (2016) suggested that the meridional temperature gradient due to ice variations in the Barents Sea is the main reason for the observed SLP anomalies and the connected “warm Arctic – cold continent” temperature patterns in recent years. Earlier studies (Magnusdottir et al. 2004; Deser et al. 2004; Alexander et al. 2004; Koenigk et al. 2006) also supported a link via the meridional temperature gradient caused

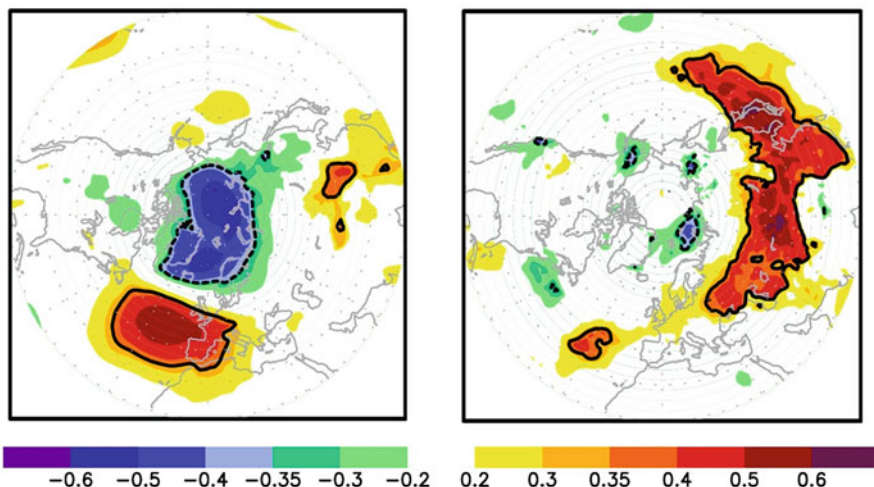


Fig. 11.4 Correlation between Barents-Kara Seas ice area in November and next winters SLP (hPa, left) and T2 m (K, right) in the period 1980–2013 in ERA-interim atmosphere data and OSISAF sea ice data

by sea ice anomalies leading to a baroclinic adjustment to the introduced mass gradient anomaly.

Fifth, combined effects of the Arctic and Pacific have been identified, so that the atmospheric sensitivity to sea ice loss depends on SST anomalies related to the Pacific Decadal Oscillation (PDO). For the same pattern and amount of sea-ice loss, warming is larger during the negative PDO phase (Screen and Francis 2016). Sixth, sea ice in the Barents Sea has been identified as the region with the strongest impact on NAO and Eurasian winters (Inoue et al. 2012; Koenigk et al. 2016). Figure 11.4 shows that November sea ice anomalies in the Barents-Kara Seas are significantly correlated to a NAO-like SLP pattern and widespread surface air temperature anomalies over Eurasia in the following winter. Negative sea ice anomalies would be followed by a negative NAO and a cooling over large parts of Eurasia. It is an unsolved question whether this atmospheric response to sea ice anomalies is linear. Liptak and Strong (2014) showed, performing sensitivity experiments with the atmosphere model CAM, a similar response of the NAO to both negative and positive sea ice anomalies in the Barents Sea. Koenigk et al. (2016) performed a composite analysis for observed low and high ice cases in autumn Barents-Kara Seas ice area and found a very strong NAO-like response after low ice conditions while the response after high ice conditions was not significant. Also, an earlier study by Petoukhov and Semenov (2010) showed a dependency of the response on the size of the ice anomaly, thus indicating a non-linear response of the atmosphere to ice anomalies.

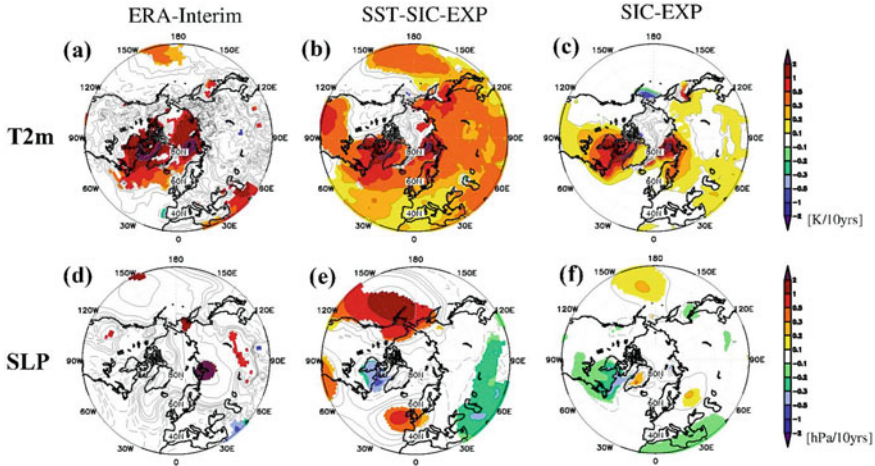


Fig. 11.5 (a–c) Mean observed 2 m temperature trends in DJF from 1982 to 2014. (a) is for ERA-Interim, (b–c) are for the simulated multi-model ensemble mean trends in SST-SIC-EXP and SIC-EXP, respectively. (d–f) as in (a–c), but for the SLP. Shading is applied for the statistical significance by a Student’s t-test with 95% confidence level. (From Ogawa et al. 2018, Fig. 1)

11.3.2 Recent Model Experiments

The largest existing multi-model ensemble study to analyse the potential impact of sea ice on lower-latitudes has been performed in the GREENICE project (<https://greenice.w.uib.no/>). Six different Atmosphere General Circulation Models (AGCM) have been used to perform two sets of ensemble experiments. In the first, observed daily varying sea ice concentration and sea surface temperature (SST) between 1982 and 2014 have been prescribed. In the second experiment, the varying SST has been replaced by the climatological annual cycle over 1982–2014. The results indicate that the impact of sea ice trend and variations on mid-latitudes is low (Ogawa et al. 2018). Figure 11.5 shows that the observed negative trends over Eurasia are almost nowhere significant and neither the simulations with full SST and sea ice forcing nor the runs with only varying sea ice forcing show any mid-latitude cooling. Further, Ogawa et al. (2018) showed that the Siberian temperature trends are extremely strongly varying among ensemble members and that the observed trends are well captured by these variations.

Also results from long coupled climate model simulations by Koenigk and Brodeau (2017), highlighted the large natural variability on timescales of up to 30 years. For selected 30-year periods, both strong cooling trends and strong warming trends of similar size of the observed one have been found. Similarly, correlation patterns between autumn Barents-Kara Seas ice area and winter SLP are heavily varying depending on the period. 30-year periods are found where low sea ice in the Barents/Kara Seas is followed by negative NAO-like SLP patterns and other 30-year periods with the opposite correlation between ice NAO (Fig. 11.6).

SLP correlation

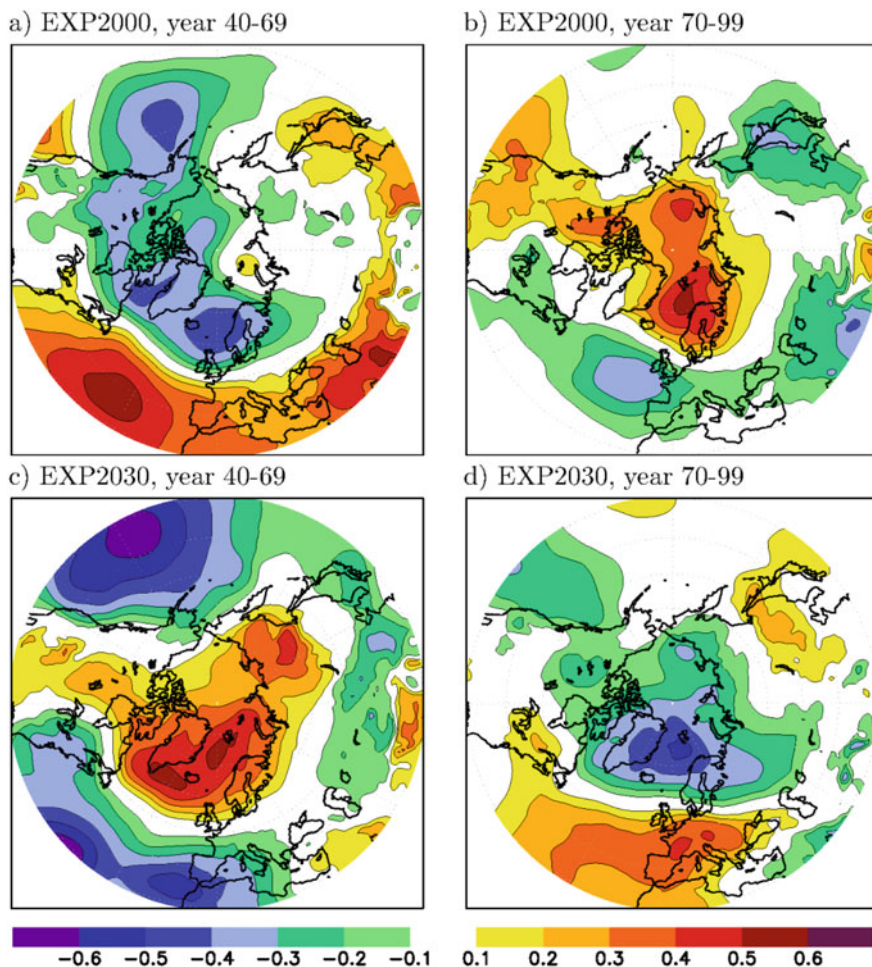


Fig. 11.6 Correlation between sea ice area in the Barents-Kara Seas (70°N–82°N, 15°E–100°E) in November and SLP in the following winter (DJF) in EXP2000 (a, b) and EXP2030 (c, d). Correlations are shown for two selected 30-year time periods: years 40–69 (a, c) and years 70–99 (b, d). (From Koenigk and Brodeau 2017, Fig. 13)

An update of the observational time series until winter 2017 indicates a substantial reduction of the negative winter trends over Siberia due to mainly warm winters in the winters 2014–2017 (Fig. 11.7). This is caused by a return of the NAO-index towards normal or above normal values – the trend in the winter NAO-index from 1980–2017 is zero – and a return of the Pacific Decadal Oscillation (PDO) index to normal values. The sea ice extent in the Barents-Kara Seas stays low even after

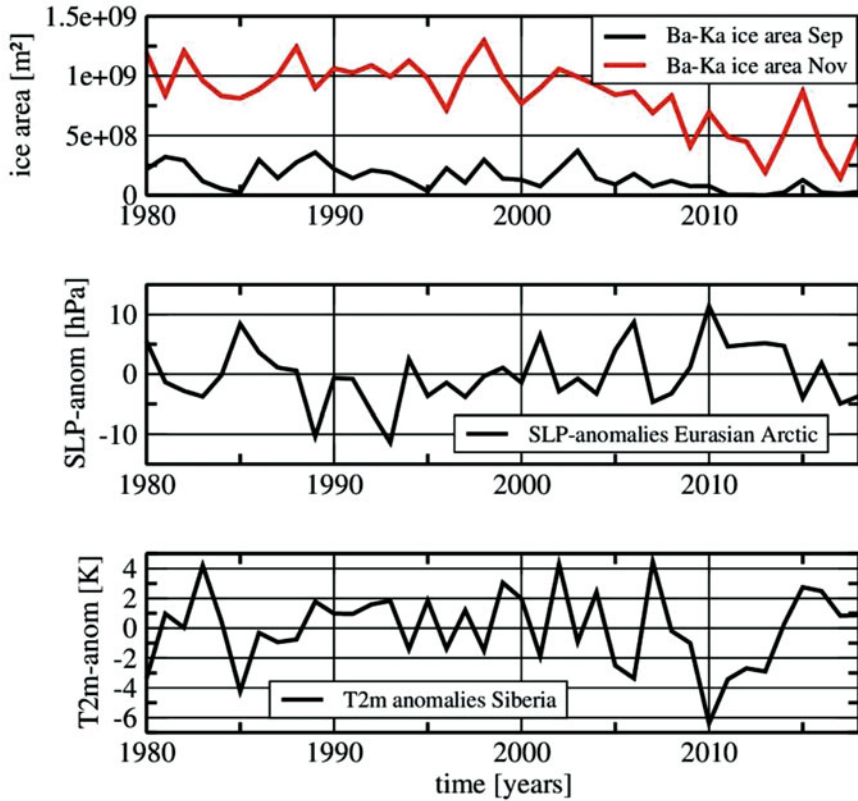


Fig. 11.7 First row: November and September Sea ice area in the Barents and Kara Seas, averaged over 70°N–82°N, 15°E–100°E. Second row: DJF SLP-anomalies, averaged over a box along the Eurasian Arctic coast with the strongest trend in 1980–2013 (65°N–80°N, 30°E–120°E). Third row: DJF T2 m-anomalies, averaged over a box in Central Eurasia with the strongest negative trend 1980–2013 (50°N–60°N, 60°E–100°E)

2013, which indicates that the linkage to the NAO and to Siberian cooling might be lower than anticipated by many studies a few years ago.

The fact that extending the time series by a few years leads to strong changes in the trends, shows clearly the high natural variability, and that time series are still too short to make final statements on the linkage between Arctic sea ice and mid-latitude climate and weather.

Even if the linkage between low sea ice and mean winter temperature is less pronounced, it is still possible that reduced sea ice could affect the occurrence of weather extremes. While much focus in recent years was on cold episodes in winter, also a number of very warm winter periods occurred in many northern hemispheric mid-latitude areas. These have been generally linked to global warming while it is

possible that even these warm extremes are particularly extreme due to a reduced meridional temperature gradient caused by Arctic warming and related wavier and slower moving Rossby waves as discussed by Francis and Vavrus (2012). Warm and cold periods might cancel out each other in the seasonal means.

11.3.3 Discussion

On the basis of numerous studies, it is evident that the effects of a certain Arctic forcing depend on the region, season, and the state of the atmosphere and ocean. Accordingly, Arctic forcing may reinforce or weaken existing weather patterns. Small signal-to-noise ratios and multiple forcing factors acting simultaneously in a chaotic dynamical system makes the Arctic effects on mid-latitudes inconsistent, episodic, non-linear and hard to distinguish from other effects (Overland et al. 2016). This is one of the reasons why different studies have yielded different and controversial results. The other reasons include (a) different study periods and regions, (b) application of different (sometimes ill-suited) metrics to quantify the linkages, and (c) errors and uncertainties in reanalyses and climate models. Further, some studies have focused on the effects of Arctic Amplification, whereas some have only focused on the effects of Arctic sea ice decline.

As Shepherd (2016) formulated: “The question is not whether Arctic changes are affecting mid-latitudes but rather how and by how much.” We need to better understand the role of the Arctic forcing compared to other forcings and natural variability. The Arctic forcing always acts in concert with other forcings on mid-latitude weather and climate. These include SST variations in the tropical and northern Atlantic (Davini et al. 2015; Hall et al. 2015; Yeager and Robson 2017) and Pacific (Screen and Francis 2016), which may be partly responsible for the recent cooling over the northern continents (Kosaka and Xie 2013; Peings and Magnusdottir 2014). As the recent Arctic Amplification only started in late 1990s, the observed time series are still short, which makes it challenging to distinguished between forced effects and natural variability (Barnes 2013; Screen et al. 2014; Sun et al. 2016; Koenigk and Brodeau 2017; McCusker et al. 2016; Ogawa et al. 2018). Further, dynamical mechanisms originating from the Arctic Amplification partly compensate for each other. The most direct effect - warmer cold-air outbreaks originating from the Arctic - favours mid-latitude warming, enhancing the effects of greenhouse forcing (Screen et al. 2015), whereas many of the other effects described above often tend to generate mid-latitude cooling, opposing (but not dominating) the global warming. In addition to the temperature trends, an important aspect is that the Arctic Amplification probably favors more persistent weather patterns in mid-latitudes, increasing the risk of floods, droughts, as well as long-lasting heat waves and cold spells.

11.4 Projected Changes until the End of the Twenty-First Century

Climate projections indicate that the Arctic will continue to warm faster than the rest of the world in the twenty-first century. The projected changes in atmosphere, ocean and sea ice are closely linked, and it is often difficult to distinguish between causes and effects. In this section, we will focus on the simulated mean changes of Arctic key variables in global and regional future projections.

11.4.1 Projected Changes in Sea Ice

The sea ice conditions strongly govern the exchanges of heat, freshwater and momentum between ocean and atmosphere. Thus, sea ice changes can have a huge impact on the atmosphere above. At the same time, the sea ice is itself very sensitive to changes in atmosphere conditions.

Satellite-based retrievals of sea ice extent are now available since 1979, covering a period of 40 years (Meier et al. 2014). The northern hemispheric ice extent showed a strong negative trend during this period, particularly during late summer. Future climate model projections indicate a continuation of this negative sea ice trend in the twenty-first century (Stocker et al. 2013). However, whether or not sea ice will completely melt in late summer in the twenty-first century depends on the emission scenario and on the model. While most global CMIP5 models indicate a total summer sea ice loss under the strong RCP8.5 emission scenario, around 1/3 of all CMIP5 models indicate an almost total loss of late summer sea ice loss using the RCP4.5 emission scenario (Stroeve et al. 2012). Under the low emission scenario RCP2.6, almost all models show a survival of Arctic summer sea ice.

Sea ice reduction does not only vary between different emission scenarios but also between different models (using the same emission scenario) and due to natural variations. For the RCP8.5, September sea ice disappears between year 2020 and later than year 2100 dependent on the model. Massonnet et al. (2012) selected those models, which agree best with observed historical ice concentrations and trends and found that the most likely date of first Arctic sea ice loss under RCP8.5 would be between year 2040 and 2060. However, there is no guarantee that models with high agreement of historical sea ice conditions to observations are most reliable for the future.

Generally, many models show a smaller sea ice reduction in recent decades than the observations. Thus, a few studies made the attempt to correct the models for this potential underestimation, e.g., Wang and Overland (2012) estimated that sea ice loss is likely to happen in the 2030s taking into account the potential underestimation of the observed sea ice trends in the models.

Despite the underestimation of the CMIP5-model mean trend, the observed trend is still inside the range of sea ice trends of the CMIP5 models. Thus, it cannot be

ruled out that natural variations caused the apparent difference between simulated and observed summer sea ice trend. Ding et al. (2017) concluded that 30–50% of the observed summer sea ice decline since 1979 could be due to natural variations.

The natural variation of sea ice trends is commonly estimated by comparing the results from different simulations with the same model. The CESM large ensemble (Deser et al. 2010) consists of 40 ensemble members and shows large spread across different ensemble members. The year when an ice-free September is reached for the first time varies between 2032 and 2053 in this ensemble for the RCP8.5 emission scenario (Jahn et al. 2016).

Spatially, summer sea ice disappears first in the Beaufort Sea and along the Siberian shelf seas; sea ice disappears last along the north coast of Greenland and the north of the Canadian Archipelago. In winter, sea ice extent will be reduced but at a somewhat slower rate as in summer. In contrast to summer, sea ice melt is largest along the North Atlantic Arctic ice edges, particularly in the Barents Sea. The Barents Sea will thus be the first Arctic region where sea ice disappears year around. Koenigk and Brodeau (2014), using the EC-Earth climate model, estimated that the Barents Sea will be ice free year-around at around year 2030.

The year to year variations of Arctic sea ice extent might increase in future when sea ice becomes thinner and thus more vulnerable to atmospheric circulation anomalies. Dynamical regional downscalings of global climate model simulations with the regional coupled atmosphere-ocean-sea ice model RCAO show a number of 2007-like rapid sea ice reduction events throughout the first half of the twenty-first century with partial recovery thereafter (Koenigk et al. 2011). Anomalously warm temperatures in the winter before the summer event and anomalous summer circulation situations that advect warm air into the Arctic have been identified as the main causes for rapid reduction events (Döscher and Koenigk 2013; Paquin et al. 2013). The warm winter conditions reduce sea ice formation, and thus sea ice thickness is thinner than normal in the beginning of the melting seasons and can more easily be melted during summer. The summer atmospheric circulation anomalies, which lead to sea ice reduction events can vary, but they have in common that they favour enhanced meridional flow and thus advection of warm air into the Arctic during the summer.

11.4.2 Projected Changes in the Atmosphere

Climate model simulations of the future indicate an accelerated climate change in the Arctic in the twenty-first century but the spread between different models is large (e.g. Holland and Bitz 2003). At the decadal time scale, this spread is mainly due to a large inherent variability in the Arctic system, while at longer time scales different model physics may be the cause of this large uncertainty (Sorteberg et al. 2005).

11.4.2.1 Turbulent Heat Fluxes

Changes in the sea ice cover have strong consequences for sensible and latent heat fluxes at the surface in the Arctic. The most extreme local changes in the sensible heat fluxes occur in the North Atlantic Arctic section and can reach up to 35 W m^{-2} under the RCP4.5 emission scenario (Koenigk et al. 2013). The primary reason for the changes is related to the retreating sea-ice edge in the northern North Atlantic and is dominated by winter conditions. In the RCP8.5 emission scenario, there is also a widespread but smaller increase in the sensible heat flux over the entire sea-ice area of about $5\text{--}15 \text{ W m}^{-2}$, also dominated by winter conditions. This is likely the result of thinner winter ice and thus more heat being conducted to the surface from the underlying ocean.

The changes in the latent heat flux across the different emission scenarios exhibit a small change maximum east of Iceland and a large area of increased fluxes centered in the Barents Sea, extending into the Kara Sea. Maximum changes reach about $35\text{--}40 \text{ W m}^{-2}$, but do not increase in magnitude with emission scenario; instead the area of the maxima increases. Over the Greenland Sea, between these two maxima, there is a slight decrease in the upward flux, which remains unchanged with emission scenario. Thus, the pattern of change is less markedly tied to the retreating ice edge in latent than in sensible heat flux. Like for the sensible heat flux, the latent heat flux also exhibit a widespread increase in the annual average upward flux over the central Arctic Ocean; however, unlike for the sensible heat flux, the latent heat flux in summer shows a widespread decrease of about $5\text{--}10 \text{ W m}^{-2}$ over the central Arctic Ocean sea ice.

11.4.2.2 Temperature

The warming until 2081–2100 compared to the period 1986–2005 varies from $2.2 \text{ }^\circ\text{C}$ in RCP2.6 until $8.3 \text{ }^\circ\text{C}$ in RCP8.5 averaged across all CMIP5-models. As comparison, same values for the global mean warming are $1.0 \text{ }^\circ\text{C}$ and $3.7 \text{ }^\circ\text{C}$. However, the spread across models is large and 5 and 95% confidence interval ranges from $-0.5 \text{ }^\circ\text{C}$ to $5.0 \text{ }^\circ\text{C}$ in RCP2.6 and $5.2 \text{ }^\circ\text{C}$ to $11.4 \text{ }^\circ\text{C}$ in RCP8.5.

The strongest warming in the Arctic occurs in autumn and winter and is linked to the decline of sea ice, which allows for large vertical surface heat fluxes from the relatively warm ocean (around freezing level) to the cold atmosphere above. While the warming in autumn is relatively uniformly distributed over the entire Arctic Ocean, the winter warming is most pronounced in the Barents Sea region since here winter sea ice declines strongest (Chapman and Walsh 2007; Koenigk et al. 2013). Figure 11.8 shows the results for the EC-Earth model. The warming is by far the smallest in summer and does not exceed one Kelvin over most of the Arctic Ocean. This is caused by the fact that the surface stays near $0 \text{ }^\circ\text{C}$ in summer until almost all sea ice has been melted. Only in RCP8.5, some Arctic Ocean regions warm up due to the earlier onset of the sea ice melt period.

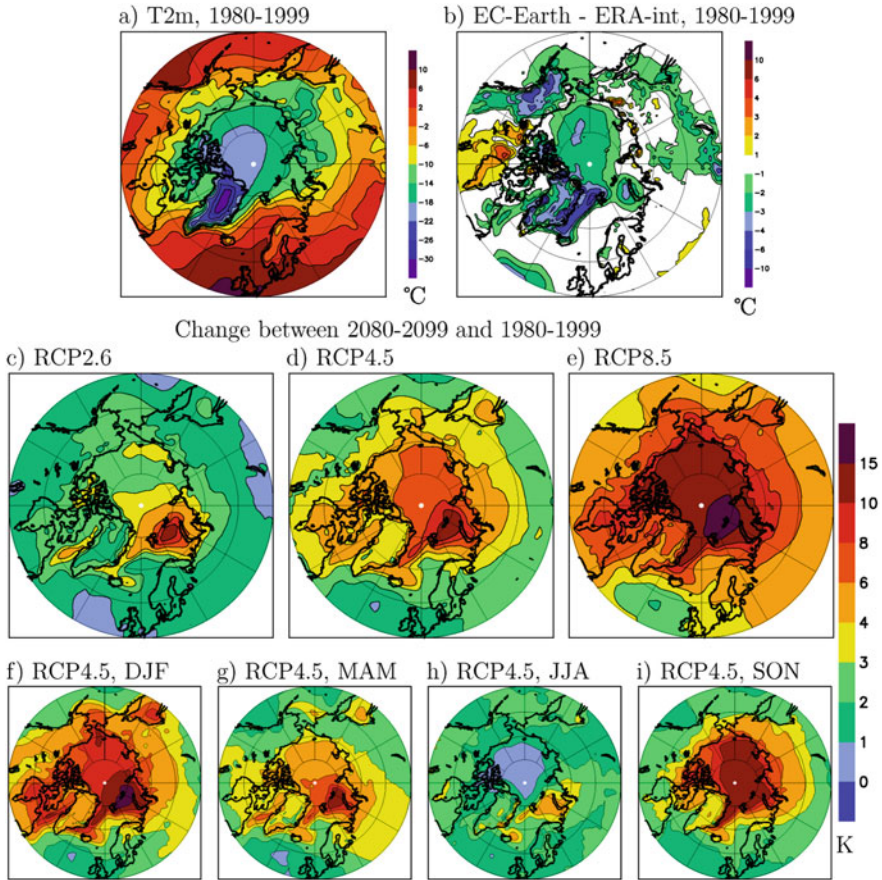


Fig. 11.8 (a) Annual mean two meter air temperature in °C in EC-Earth, averaged over 1980–1999 and (b) difference to ERA-Interim reanalysis. (c–e) Change in annual mean two meter air temperature between 2080–2099 and 1980–1999 in RCP2.6 (c), RCP4.5 (d) and RCP8.5 (e). (f–i) Seasonal mean two meter air temperature changes between 2080–2099 and 1980–1999 in RCP4.5. Shown are ensemble means. Note that there is only one RCP2.6 simulation. (From Koenigk et al. 2013, Fig. 7)

The zonal mean, vertical winter temperature distribution in the Arctic in the twentieth century is dominated by a strong surface near inversion with warmest average temperatures at about 850 to 900 hPa (Fig. 11.9). At the surface, the temperature is up to 6 K colder than the air aloft, primarily due to the effect of the negative net radiation at the surface. Thus, the lower atmosphere is sometimes very stable stratified. In summer, temperature inversion is much weaker and often not existent; the temperature decrease with height is, however, relatively small compared to the lower latitudes.

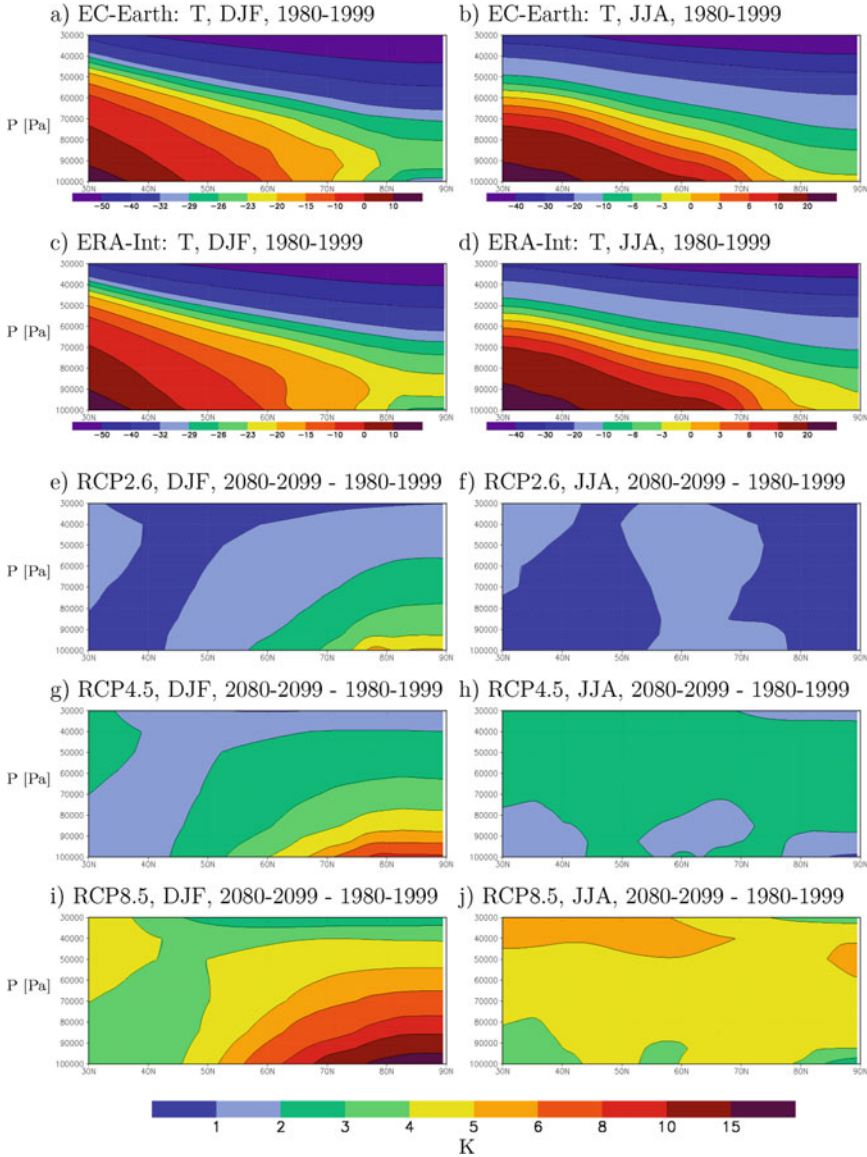


Fig. 11.9 Vertical temperature distribution (in °C) as a function of latitude in winter (DJF, **a**) and summer (JJA, **b**) averaged over 1980–1999 in the twentieth century simulations with EC-Earth and ERA-Interim reanalysis (**c**, **d**). (**e**) and (**f**) Changes in winter and summer in RCP2.6 between 2080–2099 and 1980–1999. (**g**) and (**h**) Same as (**e**) and (**f**) but for RCP4.5. (**i**) and (**j**) Same as (**e**) and (**f**) but for RCP8.5. Shown are ensemble means except for RCP2.6. (From Koenigk et al. 2013, Fig. 9)

The simulated future changes differ distinctively between summer and winter. In summer, the atmosphere is relatively uniformly warmed by about 0–2 K in RCP2.6, 1–3 K in RCP4.5 and 3–6 K in RCP8.5. The warming near the surface is slightly reduced north of 80°N because of the melting sea ice and the cold ocean.

In winter, the warming near the surface is strongly amplified in high northern latitudes compared to lower latitudes. The temperature amplification decreases with increasing height, and above 600 hPa, no amplification can be found anymore. Thus, the Arctic atmosphere becomes less stable during winter and the winter temperature inversion totally disappears at the end of the twenty-first century in RCP8.5.

Regional downscalings of four different global model future projections in the CORDEX (Co-Ordinated Regional Downscaling Experiment)-context reveal the results from the global models (Koenigk et al. 2015).

The diurnal temperature rate shows a decreasing trend in reanalysis data since 1980 and according to both global and regional future model projections, this negative trend will continue in the future (Koenigk et al. 2013; Rinke and Dethloff 2008). Again, the change is most pronounced over future ice-free oceans in winter.

11.4.2.3 Sea Level Pressure and Atmospheric Circulation

Most CMIP5 models indicate a reduction of sea level pressure (SLP) in the Arctic in winter and summer (Stocker et al. 2013) until the end of the twenty-first century. This SLP reduction increases and is becoming more robust in the higher emission scenarios. From the North Atlantic towards Southern Europe, models tend to show an increase of SLP but the response is not robust across models. Regional model future projections reproduce most of the results from the driving global models (Koenigk et al. 2015). Figure 11.10 shows the SLP response to greenhouse gas warming in the EC-Earth model. The SLP change pattern indicates a slightly northward shift of the storm track over the North Atlantic and an extension of the storm track into the Arctic. The zonal mean winds at the surface are somewhat increased at around 60°N. In the upper troposphere, a stronger increase of zonal winds and a slight poleward and upward shift of the tropospheric jets are simulated by the models. The dynamical mechanisms behind these shifts are not yet fully understood but might be linked to increasing upper tropospheric temperature gradients.

11.4.2.4 Cloudiness and Precipitation

Observations of clouds and precipitation are very uncertain in the Arctic. Cloud cover is one of the largest uncertainties in model predictions of Arctic climate. Cloud amounts in global climate models and atmospheric reanalyses vary widely and may have large biases. Liu and Key (2016) examined the performance of five atmospheric reanalysis products in depicting monthly mean Arctic cloud amount anomalies (the National Aeronautics and Space Administration (NASA) Modern-Era Retrospective

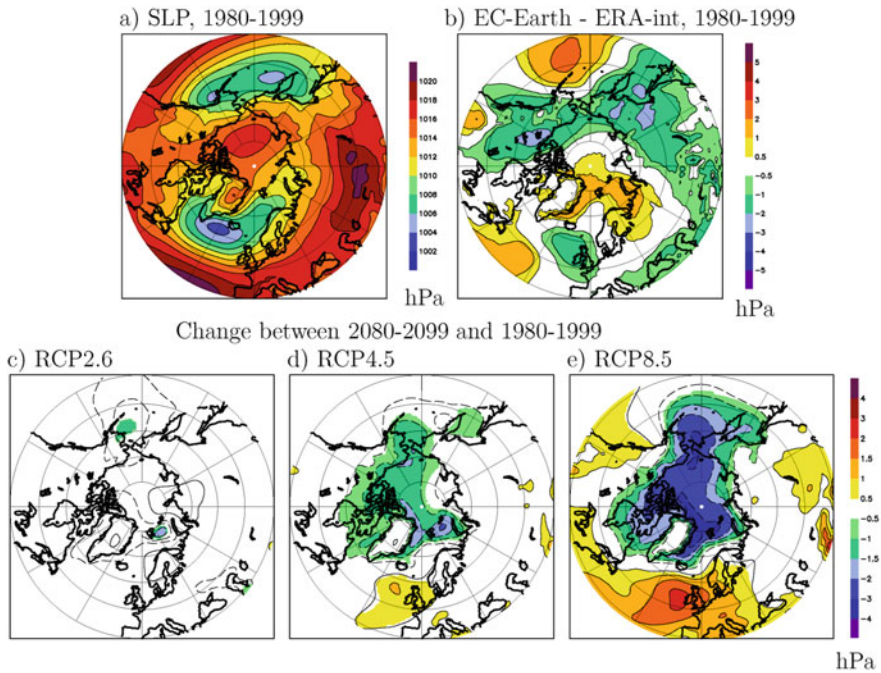


Fig. 11.10 (a) Annual mean SLP in hPa in EC-Earth, averaged over 1980–1999 and (b) difference to ERA-Interim reanalysis. c–e) Change in annual mean SLP between 2080–2099 and 1980–1999 in RCP2.6 (c), RCP4.5 (d) and RCP8.5 (e). Shown are ensemble means. Note that there is only one RCP2.6 simulation. The ensemble mean SLP-change is significant at the 95% significance level in all colored areas. (From Koenigk et al. 2013, Fig. 10)

Analysis for Research and Applications (MERRA and MERRA-2), the European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis, and the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) Reanalysis-1, NCEP/U.S. Department of Energy (DOE) Reanalysis-2). Reanalysis cloud anomalies were compared to satellite products from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite observations and the Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO). It was shown that all five reanalysis products exhibit biases in the mean cloud amount, especially in winter, but that the reanalyses do exhibit some capability for depicting the monthly mean cloud amount anomalies. There were no significant differences in the overall performance of reanalysis products. They all perform best in July, August, and September and worst in November, December, and January. All reanalysis datasets perform better over land than over ocean.

The CMIP5 multi-model mean indicates an increase of both total cloudiness and precipitation in the Arctic in the future. The increase of total cloud cover is rather small, on the order of a few percent in simulations based on the RCP2.6 and the

RCP4.5 emission scenarios, but up to 10% under the RCP8.5 emission scenario. Inter-model spread is large, and the response depends on the region, season, and the cloud type. While the total amount of clouds increases in large parts of the year, the amount of low clouds is reduced in regions where the winter temperature inversion disappears.

Models agree largely on an increase of precipitation in the entire Arctic and in all seasons in the future. The increase reaches more than 50% until the end of the twenty-first century (Stocker et al. 2013). In absolute values, the increase is largest in areas where sea ice disappears, which highlights the importance of increased vertical sensible and latent heat fluxes from the ocean to the atmosphere in these regions for the precipitation. Generally, the precipitation change in the Arctic increases linearly with the Arctic temperature change (Koenigk et al. 2015).

Regional downscaling of a number of global model scenarios with the regional atmosphere model RCA (Koenigk et al. 2015) indicated a stronger precipitation increase in summer compared to the global models. It remains unclear if this is caused by higher resolution or caused by different physical parameterizations in the regional RCA-model.

11.4.3 Projected Changes in the Arctic Ocean

The warming of the Arctic, increased river runoff and precipitation and the enhanced exposure to winds due to sea ice decline have strong effects on the Arctic Ocean. Despite the potentially large impact, literature on future Arctic Ocean changes is still limited. Here, we will mainly focus on results from CMIP5 simulations with the EC-Earth model (Koenigk et al. 2013; Koenigk and Brodeau 2014).

11.4.3.1 Ocean Circulation

In the future, the reduction of sea ice leads to an increased wind stress on the ocean and to a strengthening of the surface flow. In RCP2.6 and RCP4.5, the ocean currents are generally strengthened compared to the twentieth century but the patterns stay similar. The inflow through the Barents Sea Opening into the Arctic is strengthened, particularly in RCP8.5 due to increased south-westerly winds over the Nordic Seas. Also, the circulation pattern in the Arctic Basin changes substantially in RCP8.5. The size of the Beaufort Gyre is reduced and is displaced towards Chukchi Sea. This leads to strongly reduced velocities in the transpolar drift.

11.4.3.2 Freshwater and Heat in the Arctic Ocean

The twentieth century Arctic Ocean is characterized by a cold and fresh upper layer and warmer and saltier water masses in deeper layers according to the World Ocean

Atlas 2009 (Antonov et al. 2010; Locarnini et al. 2010). The northward flowing warm and salty Atlantic water masses are cooled when they reach the Arctic, are getting denser and sink down near the ice edge to a depth of around 500 m and spread around the Arctic Ocean in this depth and form a warm and salty layer. Within the twenty-first century, enhanced oceanic heat inflow into the Arctic from the Atlantic strengthens this warm layer.

In the low emission scenario RCP2.6, the cold surface layer persists during the entire twenty-first century while in the high emission scenario RCP8.5, the surface layer is warmed by up to 3 K at the end of the twenty-first century and is getting much warmer than the deep ocean. The reduced sea ice area allows stronger wind mixing and a penetration of the warm surface waters almost down to the warm intermediate layer.

In the twenty-first century, river runoff into the Arctic will likely increase due to more precipitation in the catchment areas of the large Arctic rivers (Koenigk et al. 2007, 2013, Fig. 11.11). Precipitation over the Arctic Ocean basin itself will also grow faster than the evaporation. Both, the increase in river runoff and the growing positive difference between precipitation and evaporation lead to more freshwater input into the Arctic. Consequently, the Arctic Ocean is getting fresher. The largest reduction of salinity in the twenty-first century occurs near the surface - by up to 1.5 psu in the upper 100 m. The salinity differences between different RCPs are not as pronounced as for temperature but we see a clear tendency to more freshening in the higher emission scenarios.

More input of freshwater into the Arctic could be compensated by increased outflow of freshwater out of the Arctic. However, model results indicate that the change in the total Arctic freshwater export is relatively small and first increasing in the second half of the twenty-first century (Fig. 11.11). Investigating the individual straits, a strong increase of the total freshwater export (solid + liquid freshwater) through the Canadian Archipelago is evident, while the total exports through the Fram Strait and the Barents Sea are slightly reduced. The transport through Bering Strait shows a slight increase.

The freshwater transports are dominated by the liquid freshwater transport except for Fram Strait. In Fram Strait, the ice export dominates the total export and its variability. In the twenty-first century, the decrease in sea ice leads to strongly decreased Fram Strait ice exports, which is compensated by an increase in the liquid export. As the increase in freshwater input into the Arctic exceeds the increase in the

Fig. 11.11 (continued) and the sum of all (black) in RCP4.5 (solid) and RCP8.5 (dashed) in EC-Earth. Ensemble means are shown. **(b)** Annual mean P-E (blue) and river runoff (red) in m^3/s in RCP4.5 (solid) and RCP8.5 (dashed). Ensemble means are shown. **(c)** Annual mean liquid (solid) and solid (dashed) fresh water transports in m^3/s through Fram Strait in ensemble means of twentieth century simulations (black), RCP4.5 (blue) and RCP8.5 (red). **(d)** Annual mean Arctic freshwater content in m^3 (same area as in Fig. 16) in ensemble means of twentieth century simulations (black), RCP4.5 (blue) and RCP8.5 (red). As reference salinity 34.9 psu has been used. (From Koenigk et al. 2013, Fig. 17)

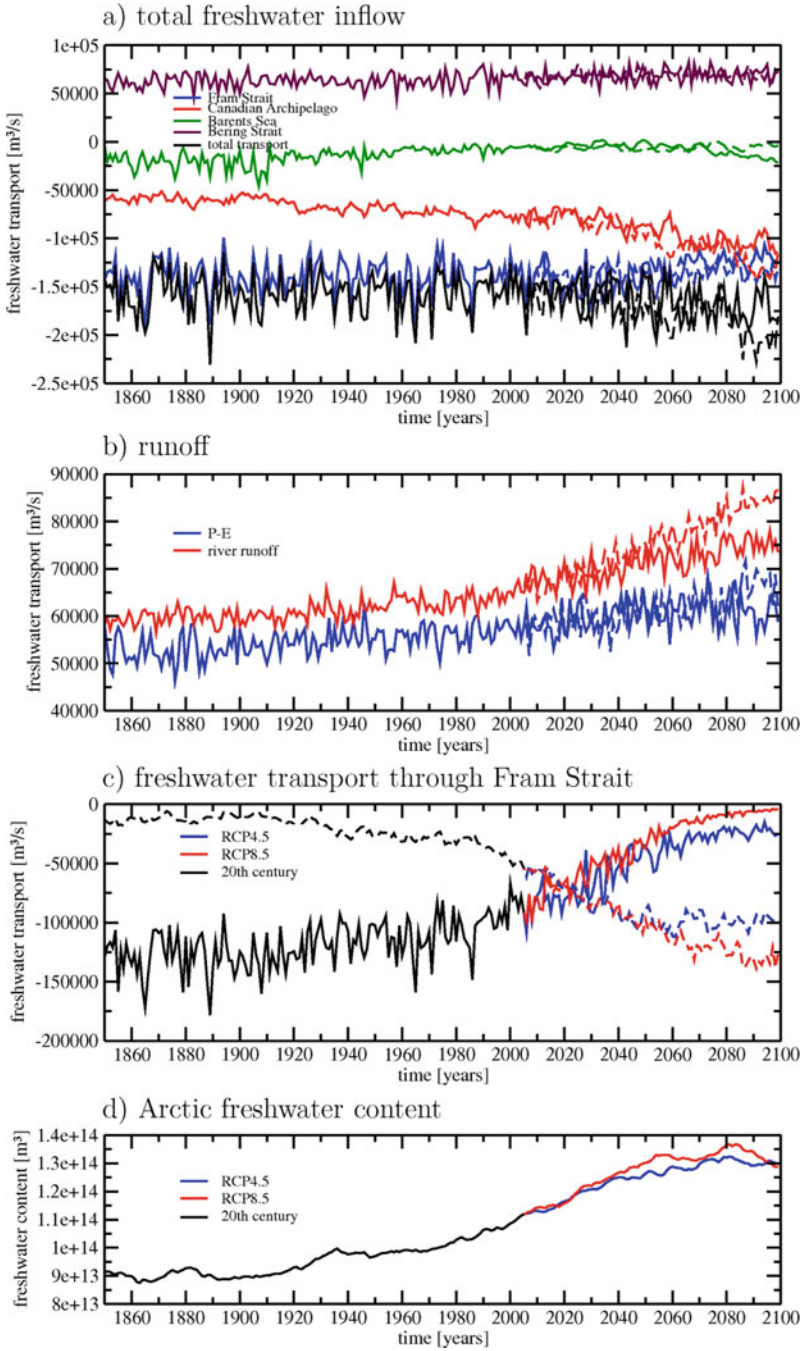


Fig. 11.11 (a) Annual mean total (liquid + solid) freshwater inputs into the Arctic in m^3/s through Fram Strait (blue), Canadian Archipelago (red), Barents Sea (green) and Bering Strait (maroon)

exports in the twenty-first century simulations, the fresh water content in the Arctic is increased and the Arctic Ocean is getting fresher.

Observations show an increasing ocean heat transport into the Arctic, particularly through the Barents Sea Opening (Skagseth et al. 2008; Smedsrud et al. 2013) in recent decades. This increase of ocean heat transport is projected to continue in the twenty-first century (Koenigk and Brodeau 2014), particularly through the Barents Sea Opening. The strong increase of heat transport in the Barents Sea is due both to the temperature increase of the transported water masses and increased northward volume transport.

The changes in ocean heat transport strongly contribute to the reduced sea ice cover in the Barents and Kara Sea region and govern sea ice variations at decadal scale time periods. However, most of the additional heat is passed to the atmosphere and contributes thus to the warming of the Arctic atmosphere and the Arctic amplification.

11.5 Conclusions

The Arctic climate is in rapid transition. There are few places in the world where the ongoing climate change is as obvious as in the Arctic:

- Sea ice area and volume have been reduced by more than 30% and 50%, respectively, in the last 30 years.
- Temperature, particularly at the surface, increases much faster than the global mean. Locally, temperature increased by almost 10 °C since 1980.
- Atmospheric stratification has changed, affecting cloud formation and precipitation.
- Increased precipitation, more river runoff into the Arctic, and melting land and sea ice led to a freshening of the Arctic Ocean.
- Arctic warming, the reduction of sea ice and related changes in the temperature difference between high and low latitudes might affect circulation and occurrence of extremes in lower latitudes. However, many uncertainties remain on the governing processes and the amplitude of this connection.
- Changes in sea ice and cloud cover are linked such that 22–34% of the cloud cover variance can be explained by the variability in sea ice extent. A further decline in sea ice cover will result in an even cloudier Arctic.
- The magnitude of the Arctic ice–albedo feedback (ocean) is four times that of the snow–albedo feedback (land) in summer. Decreasing sea ice cover, not changes in terrestrial snow cover, has been the dominant radiative feedback mechanism in recent decades and will continue to play an important role in future Arctic climate change.

Future climate scenarios show a continuous warming of the Arctic with the risk of total loss of late summer Arctic sea ice. This would lead to a completely different

Arctic climate, a “blue Arctic”, where ocean and atmosphere would interact much more directly compared to the past.

Acknowledgements Torben Koenigk has been supported by the NordForsk-funded Nordic Centre of Excellence project (award 76654) Arctic Climate Predictions: Pathways to Resilient, Sustainable Societies (ARCPATH) together with the JPI-CLimate-Belmont Forum project 407, InterDec. The research on cloud-ice interactions and snow- and ice-albedo feedbacks described herein was supported by the US National Oceanic and Atmospheric Administration (NOAA) Climate Data Records program. Thanks are due to Aaron Letterly, Yinghui Liu, Xuanji Wang, and Richard Dworak for their contributions to those projects. The views, opinions, and findings contained in this report are those of the author(s) and should not be construed as an official National Oceanic and Atmospheric Administration or US Government position, policy, or decision.

Timo Vihma has been supported by the Academy of Finland (contract 317999).

References

- ACIA. (2005). *Arctic climate impact assessment* (p. 1042). Cambridge, UK: Cambridge University Press.
- Alexander, M., Bhatt, U., Walsh, J., Timlin, M., Miller, J., & Scott, J. (2004). The atmospheric response to realistic Arctic Sea ice anomalies in an AGCM during winter. *Journal of Climate*, *17*, 890–905.
- Antonov, J. I., Seidov, D., Boyer, T. P., Locarnini, R. A., Mishonov, A. V., Garcia, H. E., Baranova, O. K., Zweng, M. M., Johnson, D. R. (2010). World Ocean Atlas 2009, Volume 2: Salinity. S. Levitus, Ed., NOAA Atlas NESDIS 69, U.S. Government Printing Office, Washington, DC, 184 pp.
- Barnes, E. A. (2013). Revisiting the evidence linking Arctic amplification to extreme weather in midlatitudes. *Geophysical Research Letters*, *40*, 4734–4739.
- Bintanja, R., Graverson, R. G., & Hazeleger, W. (2011). Arctic winter warming amplified by the thermal inversion and consequent low infrared cooling to space. *Nature Geoscience Letters*. <https://doi.org/10.1038/NGEO1285>.
- Bonan, D. B., Armour, K. C., Roe, G. H., Siler, N., & Feldl, N. (2018). Sources of uncertainty in the Meridional pattern of climate change. *Geophysical Research Letters*, *45*(17), 9131–9140. <https://doi.org/10.1029/2018GL079429>.
- Callaghan, T., Johansson, M., Key, J., Prowse, T., Ananicheva, M., & Klepikov, A. (2011). Feedbacks and interactions: From the Arctic cryosphere to the climate system. *Ambio*, *40*, 75–86. <https://doi.org/10.1007/s13280-011-0215-8>.
- Chapman, W. L., & Walsh, J. E. (2007). Simulations of Arctic temperature and pressure by global coupled models. *Journal of Climate*, *20*, 609–632. <https://doi.org/10.1175/JCLI4026.1>.
- Cohen, J., Barlow, M., Kushner, P. J., & Saito, K. (2007). Stratosphere-troposphere coupling and links with Eurasian land surface variability. *Journal of Climate*, *20*, 5335–5343.
- Cohen, J. L., Furtado, J. C., Barlow, M. A., Alexeev, V. A., & Cherry, J. E. (2012). Arctic warming, increasing snow cover and widespread boreal winter cooling. *Environmental Research Letters*, *7*. <https://doi.org/10.1088/1748-9326/7/1/014007>.
- Cohen, J., Screen, J. A., Furtado, J. C., Barlow, M., Whittleston, D., Coumou, D., et al. (2014). Recent Arctic amplification and extreme mid-latitude weather. *Nature Geoscience*, *7*, 627–637. <https://doi.org/10.1038/NGEO2234>.
- Coumou, D., Petoukhov, V., Rahmstorf, S., Petri, S., & Schellnguber, H. J. (2014). Quasi-resonant circulation regimes and hemispheric synchronization of extreme weather in boreal summer. *Proceedings of the National Academy of Sciences of the United States of America*, 12331–12336.

- Coumou, D., Lehmann, J., & Beckmann, J. (2015). The weakening summer circulation in the northern hemisphere midlatitudes. *Science*, *348*, 324–327. <https://doi.org/10.1126/science.1261768>.
- Davini, P., von Hardenberg, J., & Corti, S. (2015). Tropical origin for the impacts of the Atlantic multidecadal variability on the euro-Atlantic climate. *Environmental Research Letters*, *10*, 094010. <https://doi.org/10.1088/1748-9326/10/9/094010>.
- Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., et al. (2011). The ERA-interim reanalysis: Configuration and performance of the data assimilation system. *The Quarterly Journal of the Royal Meteorological Society*, *137*, 553–597. <https://doi.org/10.1002/qj.828>.
- Deser, C., Magnusdottir, G., Saravanan, R., & Philips, A. (2004). The effects of North Atlantic SST and sea ice anomalies on the winter circulation in CCM3. Part II: Direct and indirect components of the response. *Journal of Climate*, *17*, 2160–2176.
- Deser, C., Tomas, R., Alexander, M., & Lawrence, D. (2010). The seasonal atmospheric response to projected Arctic Sea ice loss in the late twenty-first century. *Journal of Climate*, *23*, 333–351. <https://doi.org/10.1175/2009JCLI3053.1>.
- Devasthale, A., Sedlar, J., Koenigk, T., & Fetzer, E. J. (2013). The thermodynamic state of the Arctic atmosphere observed by AIRS: Comparisons during the record minimum sea ice extent of 2007 and 2012. *Atmospheric Chemistry and Physics*, *13*, 7441–7450. <https://doi.org/10.5194/acp-13-7441-2013>.
- Dickson, R., Meincke, J., & Malmberg, S. A. (1988). The “great salinity anomaly” in the northern North Atlantic, 1968–1982. *Progress in Oceanography*, *20*, 103–151.
- Ding, Q., Schweiger, A., L’Heureux, M., Battisti, D. S., Po-Chedley, S., Johnson, N. C., Blanchard-Wrigglesworth, E., Harnos, K., Zhang, Q., Eastman, R., & Steig, E. J. (2017). Influence of high-latitude atmospheric circulation changes on summertime Arctic Sea ice. *Nature Climate Change*. <https://doi.org/10.1038/NCLIMATE3241>.
- Döscher, R., & Koenigk, T. (2013). Arctic rapid sea ice loss events in regional coupled climate scenario experiments. *Ocean Science*, *os-2012-65*. <https://doi.org/10.5194/os-9-217-2013>.
- Dunn-Sigouin, E., & Son, S. W. (2013). Northern hemisphere blocking frequency and duration in the CMIP5 models. *Journal of Geophysical Research – Atmospheres*, *118*, 1179–1188. <https://doi.org/10.1002/jgrd.50143>.
- Fetterer, F., Knowles, K., Meier, W., Savoie, M., Windnagel, A. K. (2017). updated daily. Sea Ice Index, Version 3.0. Boulder, Colorado USA. NSIDC: National Snow and Ice Data Center. doi: <https://doi.org/10.7265/N5K072F8>. Accessed September 2018.
- Francis, J. A. (2017). Why are Arctic linkages to extreme weather still up in the air? *The Bulletin of the American Meteorological Society*, *98*, 2551–2557.
- Francis, J. A., & Vavrus, S. J. (2012). Evidence linking Arctic amplification to extreme weather in midlatitudes. *Geophysical Research Letters*, *39*, L06801.
- Francis, J. A., & Vavrus, S. J. (2015). Evidence for a wavier jet stream in response to rapid Arctic warming. *Environmental Research Letters*, *10*. <https://doi.org/10.1088/1748-9326/10/1/014005>.
- Francis, J. A., Chan, W., Leathers, D. J., Miller, J. R., & Veron, D. E. (2009). Winter northern hemisphere weather patterns remember summer Arctic Sea-ice extent. *Geophysical Research Letters*, *36*(L07503). <https://doi.org/10.1029/2009GL037274>.
- Gao, Y., Sun, Y., Li, F., He, S., Sandven, S., Yan, Q., Zhang, Z., Lohmann, K., Keenlyside, N., Furevik, T., & Suo, L. (2015). Arctic Sea ice and Eurasian climate: A review. *Advances in Atmospheric Sciences*, *32*, 92–114.
- Garcia-Serrano, J., & Frankignoul, C. (2014). High predictability of the winter euro-Atlantic climate from cryospheric variability. *Nature Geoscience*. <https://doi.org/10.1038/NNGEO2118>.
- Graversen, R. G., & Wang, M. (2009). Polar amplification in a coupled climate model with locked albedo. *Climate Dynamics*, *33*, 629–643. <https://doi.org/10.1007/s00382-009-0535-6>.
- Graversen, R. G., Mauritsen, T., Tjernström, T., Källén, E., & Svensson, G. (2008). Vertical structure of recent Arctic warming. *Nature*, *541*. <https://doi.org/10.1038/nature06502>.

- Guo, D., Gao, Y., Bethke, I., Gong, D., Johannessen, O. M., & Wang, H. (2014). Mechanism on how the spring Arctic Sea ice impacts the east Asian summer monsoon. *Theoretical and Applied Climatology*, *115*, 107–119. <https://doi.org/10.1007/s00704-013-0872-6>.
- Haak, H., Jungclauss, J., Mikolajewicz, U., & Latif, M. (2003). Formation and propagation of great salinity anomalies. *Geophysical Research Letters*, *30*(9), 26/1–26/4.
- Häkkinen, S. (1999). A simulation of thermohaline effects of a great salinity anomaly. *Journal of Climate*, *6*(6), 1781–1795.
- Hall, R., Erdélyi, R., Hanna, E., Jones, J. M., & Scaife, A. A. (2015). Drivers of North Atlantic polar front jet stream variability. *International Journal of Climatology*, *35*, 1697–1720. <https://doi.org/10.1002/joc.4121>.
- Hanna, E., Cropper, T. E., Hall, R. J., & Cappelen, J. (2016). Greenland blocking index 1851–2015: A regional climate change signal. *International Journal of Climatology*, *36*, 4847–4861.
- Holland, M. M., & Bitz, C. M. (2003). Polar amplification of climate change in coupled models. *Climate Dynamics*, *21*, 221–232.
- Honda, M., Inoue, J., & Yamane, S. (2009). Influence of low Arctic Sea-ice minima on anomalously cold Eurasian winters. *Geophysical Research Letters*, *36*(L08707). <https://doi.org/10.1029/2008GL037079>.
- Hopsch, S., Cohen, J., & Dethloff, K. (2012). Analysis of a link between fall Arctic Sea ice concentration and atmospheric patterns in the following winter. *Tellus A*, *64*(18624). <https://doi.org/10.3402/tellusa.v64i0.18264>.
- Hoskins, B., & Woollings, T. (2015). Persistent extratropical regimes and climate extremes. *Current Climate Change Reports*. <https://doi.org/10.1007/s40641-015-0020-8>.
- Inoue, J., Masatake, H. E., & Koutarou, T. (2012). The role of Barents Sea ice in the wintertime cyclone track and emergence of a warm-Arctic cold-Siberian anomaly. *Journal of Climate*, *25*(7), 2561–2568.
- Jahn, A., Kay, J. E., Holland, M. M., & Hall, D. M. (2016). How predictable is the timing of a summer ice-free Arctic? *Geophysical Research Letters*, *43*(17). <https://doi.org/10.1002/2016GL070067>.
- Jaiser, R., Dethloff, K., & Handorf, D. (2013). Stratospheric response to Arctic Sea ice retreat and associated planetary wave propagation changes. *Tellus A*, *65*, 19375. <https://doi.org/10.3402/tellusa.v65i0.19375>.
- Kim, B. M., Son, S. W., Min, S. K., Jeong, J. H., Kim, S. J., Zhang, X., Shim, T., & Yoon, Y. H. (2014). Weakening of the stratospheric polar vortex by Arctic Sea-ice loss. *Nature Communications*, *5*, 4646. <https://doi.org/10.1038/ncomms5646>.
- Koenigk, T., & Brodeau, L. (2014). Ocean heat transport into the Arctic in the twentieth and twenty-first century in EC-earth. *Climate Dynamics*, *42*, 3101–3120. <https://doi.org/10.1007/s00382-013-1821-x>.
- Koenigk, T., & Brodeau, L. (2017). Arctic climate and its interaction with lower latitudes under different levels of anthropogenic warming in a global coupled climate model. *Climate Dynamics*, *49*, 471–492. <https://doi.org/10.1007/s00382-016-3354-6>.
- Koenigk, T., Mikolajewicz, U., Haak, H., & Jungclauss, J. (2006). Variability of Fram Strait sea ice export: Causes, impacts and feedbacks in a coupled climate model. *Climate Dynamics*, *26*, 17–34. <https://doi.org/10.1007/s00382-005-0060-1>.
- Koenigk, T., Mikolajewicz, U., Haak, H., & Jungclauss, J. (2007). Arctic freshwater export in the 20th and 21st century. *Journal of Geophysical Research*, *112*. <https://doi.org/10.1029/2006JG000274>.
- Koenigk, T., Döscher, R., & Nikulin, G. (2011). Arctic future scenario experiments with a coupled regional climate model. *Tellus*, *63A*(1), 69–86. <https://doi.org/10.1111/j.1600-0870.2010.00474.x>.
- Koenigk, T., Brodeau, L., Graverson, R. G., Karlsson, J., Svensson, G., Tjernström, M., Willen, U., & Wyser, K. (2013). Arctic climate change in 21st century CMIP5 simulations with EC-earth. *Climate Dynamics*, *40*, 2720–2742. <https://doi.org/10.1007/s00382-012-1505-y>.
- Koenigk, T., Berg, P., & Döscher, R. (2015). Arctic climate change in an ensemble of regional CORDEX simulations. *Polar Research*, *34*, 24603. <https://doi.org/10.3402/polar.v34.24603>.

- Koenigk, T., Caian, M., Nikulin, G., & Schimanke, S. (2016). Regional Arctic Sea ice variations as predictor for winter climate conditions. *Climate Dynamics*, *46*, 317–337. <https://doi.org/10.1007/s00382-015-2586-1>.
- Kosaka, Y., & Xie. (2013). Recent global-warming hiatus tied to equatorial Pacific surface cooling. *Nature*, *501*, 403–407. <https://doi.org/10.1038/nature12534>.
- Letterly, A., Key, J., & Liu, Y. (2016). The influence of winter cloud on summer sea ice in the Arctic, 1983–2013. *Journal of Geophysical Research – Atmospheres*, *121*. <https://doi.org/10.1002/2015JD024316>.
- Letterly, A., Key, J., & Liu, Y. (2018). Arctic climate: Changes in sea ice extent outweigh changes in snow cover. *The Cryosphere*, *12*, 3373–3382. <https://doi.org/10.5194/tc-12-3373-2018>.
- Liptak, J., & Strong, C. (2014). The winter atmospheric response to sea ice anomalies in the Barents Sea. *Journal of Climate*, *27*, 914–924. <https://doi.org/10.1175/JCLI-D-13-00186.1>.
- Liu, Y., & Key, J. (2014). Less winter cloud aids summer 2013 Arctic Sea ice return from 2012 minimum. *Environmental Research Letters*, *9*, 044002. <https://doi.org/10.1088/1748-9326/9/4/044002>.
- Liu, Y., & Key, J. (2016). Assessment of Arctic cloud cover anomalies in atmospheric reanalysis products using satellite data. *Journal of Climate*, *29*, 6065–6083. <https://doi.org/10.1175/JCLI-D-15-0861.1>.
- Liu, Y., Key, J. R., & Wang, X. (2008). The influence of changes in cloud cover on recent surface temperature trends in the Arctic. *Journal of Climate*, *21*, 705–715.
- Liu, Y., Key, J., & Wang, X. (2009). Influence of changes in sea ice concentration and cloud cover on recent Arctic surface temperature trends. *Geophysical Research Letters*, *36*, L20710. <https://doi.org/10.1029/2009GL040708>.
- Liu, Y., Key, J. R., Liu, Z., Wang, X., & Vavrus, S. J. (2012). A cloudier Arctic expected with diminishing sea ice. *Geophysical Research Letters*, *39*, L05705. <https://doi.org/10.1029/2012GL051251>.
- Liu, Y., Key, J., Vavrus, S., & Woods, C. (2018). Time evolution of cloud response to moisture intrusions into the Arctic during winter. *Journal of Climate*, *31*(22), 9389–9405. <https://doi.org/10.1175/JCLI-D-17-0896.1>.
- Locarnini, R. A., Mishonov, A. V., Antonov, J. I., Boyer, T. P., Garcia, H. E., Baranova, O. K., Zweng, M. M., Johnson, D. R. (2010). World Ocean Atlas 2009, Volume 1: Temperature. S. Levitus, Ed., NOAA Atlas NESDIS 69, U.S. Government Printing Office, Washington, DC, 184 pp.
- Magnusdottir, G., Deser, C., & Saravanan, R. (2004). The effects of North Atlantic SST and sea ice anomalies on the winter circulation in CCM3. Part I: Main features and storm track characteristics of the response. *Journal of Climate*, *17*(5), 857–876.
- Masato, G., Hoskins, B. J., & Woollings, T. (2013). Winter and summer northern hemisphere blocking in CMIP5 models. *Journal of Climate*, *26*, 7044–7059.
- Massonnet, F., Fichefet, T., Goosse, H., Bitz, C. M., Philippon-Berthier, G., Holland, M. M., & Barriat, P. Y. (2012). Constraining projections of summer Arctic Sea ice. *The Cryosphere*, *6*, 1383–1394. <https://doi.org/10.5194/tcd-6-1383-2012>.
- McClelland, J., Dery, S., Peterson, B., & Holmes, R. M. (2006). A pan-Arctic evaluation of changes in river discharge during the latter half of the 20th century. *Geophysical Research Letters*, *33*, L06715. <https://doi.org/10.1029/2006GL025753>.
- McCusker, K. E., Fyfe, K. C., & Sigmond, M. (2016). Twenty-five winters of unexpected Eurasian cooling unlikely due to Arctic Sea-ice loss. *Nature Geoscience*, *9*, 838–842. <https://doi.org/10.1038/NGEO2820>.
- McGraw, M., & Barnes, E. A. (2016). Seasonal sensitivity of the Eddy-driven jet to tropospheric heating in an idealized AGCM. *Journal of Climate*, *29*. <https://doi.org/10.1175/JCLI-D-15-0723.1>.
- Medeiros, D. C., Tomas, R. A., & Kay, J. E. (2011). Arctic inversion strength in climate models. *Journal of Climate*, *24*, 4733–4740.
- Meier, W., Hovelsrud, G., van Ort, B., Key, J., Kovacs, K., Michel, C., Haas, C., Granskog, M., Gerland, S., Perovich, D., Makshtas, A., & Reist, J. (2014). Arctic Sea ice in transformation:

- A review of recent observed changes and impacts on biology and human activity. *Reviews of Geophysics*, 51. <https://doi.org/10.1002/2013RG000431>.
- Mesquita, M. D. S., Hodges, K. L., Atkinson, D. A., & Bader, J. (2011). Sea-ice anomalies in the Sea of Okhotsk and the relationship with storm tracks in the northern hemisphere during winter. *Tellus A*, 63, 312–323.
- Mori, M., Watanabe, M., Shiogama, H., Inoue, J., & Kimoto, M. (2014). Robust Arctic Sea-ice influence on the frequent Eurasian cold winters in past decades. *Nature Geoscience*, 7, 869–873. <https://doi.org/10.1038/NGEO2277>.
- Ogawa, F., Keenlyside, N., Gao, Y., Koenigk, T., Yang, S., Suo, L., et al. (2018). Evaluating impacts of recent Arctic Sea ice loss on the northern hemisphere winter climate change. *Geophysical Research Letters*, 45. <https://doi.org/10.1002/2017GL076502>.
- Orsolini, Y. J., Senan, R., Benestad, R. E., & Melsom, A. (2012). Autumn atmospheric response to the 2007 low Arctic Sea ice extent in coupled ocean–atmosphere hindcasts. *Climate Dynamics*, 38, 2437–2448.
- Overland, J. E., & Wang, M. (2010). Large-scale atmospheric circulation changes are associated with the recent loss of Arctic Sea ice. *Tellus*, 62. <https://doi.org/10.1111/j.1600-0870.2009.00421.x>.
- Overland, J., Francis, J., Hall, R., Hanna, E., Kim, S. J., & Vihma, T. (2015). The melting Arctic and Midlatitude weather patterns: Are they connected? *Journal of Climate*, 28, 7917–7932. <https://doi.org/10.1175/JCLI-D-14-00822.1>.
- Overland, J. E., Dethloff, K., Francis, J. A., Hall, R. J., Hanna, E., Kim, S. J., Screen, J. A., Shepherd, T. G., & Vihma, T. (2016). The melting Arctic and Midlatitude weather patterns: Forced Chaos and a way forward. *Nature Climate Change*. <https://doi.org/10.1038/NCLIMATE3121>.
- Paquin, J. P., Döscher, R., Sushama, L., & Koenigk, T. (2013). Causes and consequences of mid-21st century rapid ice loss events simulated by the Rossby Centre regional Atmosphere-Ocean model. *Tellus A*, 2013(65), 19110. <https://doi.org/10.3402/tellusa.v65i0.19110>.
- Peings, Y., & Magnusdottir. (2014). Response of the wintertime Northern Hemisphere atmospheric circulation to current and projected Arctic sea ice decline: a numerical study with CAM5. *Journal of Climate*. <https://doi.org/10.1175/JCLI-D-13-00272.1>.
- Peterson, B., Holmes, R., McClelland, J., Vorosmarty, C., Lammers, R., Shiklmanov, A., Shiklomanov, I., & Rahmstorf, S. (2002). Increasing river discharge to the Arctic Ocean. *Science*, 298, 2171–2173.
- Petoukhov, V., & Semenov, V. A. (2010). A link between reduced Barents-Kara Sea ice and cold winter extremes over northern continents. *Journal of Geophysical Research*, 115(D21111). <https://doi.org/10.1029/2009JD013568>.
- Petoukhov, V., Rahmstorf, S., Petri, S., & Schellnhuber, H. J. (2013). Quasiresonant amplification of planetary waves and recent northern hemisphere weather extremes. *Proceedings of the National Academy of Sciences*, 110, 5336–5341.
- Pithan, F., & Mauritsen, T. (2014). Arctic amplification dominated by temperature feedbacks in contemporary climate models. *Nature Geoscience*, 7. <https://doi.org/10.1038/NGEO2071>.
- Polyakov, I. V., Beszczynska, A., Carmack, E. C., Dmitrenko, I. A., Fahrbach, E., Frolov, E. A., et al. (2005). One more step toward a warmer Arctic. *Geophysical Research Letters*, 32, L17605. <https://doi.org/10.1029/2005GL023740>.
- Richter-Menge, J., & Jeffries, M. (2011). The Arctic, in “State of the climate in 2010”. *Bulletin of the American Meteorological Society*, 92(6), S143–S160.
- Rinke, A., & Dethloff, K. (2008). Simulated circum-Arctic climate changes by the end of the 21st century. *Global and Planetary Change*, 62(2008), 173–186.
- Rinke, A., Dethloff, K., Dorn, W., Handorf, D., & Moore, J. C. (2013). Simulated Arctic atmospheric feedbacks associated with late summer sea ice anomalies. *Journal of Geophysical Research: Atmospheres*, 118, 7698–7714. <https://doi.org/10.1002/jgrd.50584>.
- Schlichtholz, P. (2016). Empirical relationships between summertime oceanic heat anomalies in the Nordic seas and large-scale atmospheric circulation in the following winter. *Climate Dynamics*, 47, 1735. <https://doi.org/10.1007/s00382-015-2930-5>.

- Schweiger, A., Lindsay, R., Zhang, J., Steele, M., & Stern, H. (2011). Uncertainty in modeled arctic sea ice volume. *Journal of Geophysical Research*. <https://doi.org/10.1029/2011JC007084>.
- Screen, J. A. (2014). Arctic amplification decreases temperature variance in northern mid- to high-latitudes. *Nature Climate Change*, 4, 577–582.
- Screen, J. A. (2017). Climate science: Far-flung effects of Arctic warming. *Nature Geoscience*, 10, 253–254.
- Screen, J. A., & Francis, J. A. (2016). Contribution of sea-ice loss to Arctic amplification is regulated by Pacific Ocean decadal variability. *Nature Climate Change*. <https://doi.org/10.1038/NCLIMATE3011>.
- Screen, J. A., & Simmonds, I. (2010a). Increasing fall-winter energy loss from the Arctic Ocean and its role in Arctic temperature amplification. *Geophysical Research Letters*, 37(L16707). <https://doi.org/10.1029/2010GL044136>.
- Screen, J. A., & Simmonds, I. (2010b). The central role of diminishing sea ice in recent Arctic temperature amplification. *Nature*, 464. <https://doi.org/10.1038/nature09051>.
- Screen, J. A., Deser, C., Simmonds, I., & Tomas, R. (2014). Atmospheric impacts of Arctic Sea-ice loss, 1979–2009: Separating forced change from atmospheric internal variability. *Climate Dynamics*. <https://doi.org/10.1007/s00382-013-1830-9>.
- Screen, J. A., Deser, C., & Sun, L. (2015). Reduced risk of North American cold extremes due to continued Arctic Sea ice loss. *Bulletin of the American Meteorological Society*, 1489–1503. <https://doi.org/10.1175/BAMS-D-14-00185.1>.
- Serreze, M. C., Barrett, A. P., Stroeve, J. C., Kindig, D. N., & Holland, M. M. (2009). The emergence of surface-based Arctic amplification. *The Cryosphere*, 3, 11–19.
- Serreze, M. C., Barrett, A. P., & Cassano, J. J. (2011). Circulation and surface controls on the lower tropospheric temperature field of the Arctic. *Journal of Geophysical Research*, 116, D07104.
- Shepherd, T. G. (2016). Effects of a warming Arctic. *Science*, 353, 989–990.
- Skagseth, Ø., Furevik, T., Ingvaldsen, R., Loeng, H., Mork, K. A., Orvik, K. A., & Ozhigin, V. (2008). Chapter 2: Volume and heat transports to the Arctic Ocean via the Norwegian and Barents seas. In B. Dickson, J. Meincke, & P. Rhines (Eds.), *Arctic-Subarctic Ocean fluxes: Defining the role of Nordic seas in climate*. Berlin: Springer.
- Smedsrud, L. H., Esau, I., Ingvaldsen, R. B., Eldevik, T., Haugan, P. M., Li, C., et al. (2013). The role of the Barents Sea in the Arctic climate system. *Reviews of Geophysics*, 51, 415–449. <https://doi.org/10.1002/rog.20017>.
- Sorteberg, A., Furevik, T., Drange, H., & Kvamstø, N. G. (2005). Effects of simulated natural variability on Arctic temperature projections. *Geophysical Research Letters*, 32(L18708). <https://doi.org/10.1029/2005GL023404>.
- Spielhagen, R. F., Werner, K., Aagaard Sørensen, S., Zamelczyk, K., Kandiano, E., Budeus, G., Marchitto, T. M., & Hald, M. (2011). Enhanced modern heat transfer to the Arctic by warm Atlantic water. *Science*, 331, 450–454. <https://doi.org/10.1126/science.1197397>.
- Stocker, T., et al. (2013). Climate change 2013: The physical science basis. In *Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change*. Cambridge, UK/New York: Cambridge University Press.
- Stroeve, J. C., Kattsov, V., Barrett, A., Serreze, M., Pavlova, T., Holland, M., & Meier, W. M. (2012). Trends in Arctic Sea ice extent from CMIP5, CMIP3 and observations. *Geophysical Research Letters*, 39(16). <https://doi.org/10.1029/2012GL052676>.
- Sun, L., Perlwitz, J., & Hoerling, M. (2016). What caused the recent “warm Arctic, cold continents” trend pattern in winter temperatures? *Geophysical Research Letters*, 43, 5345–5352. <https://doi.org/10.1002/2016GL069024>.
- Uotila, P., Karpechko, A., & Vihma, T. (2014). Links between Arctic sea ice and extreme summer precipitation in China: An alternative view. *Advances in Polar Science*, 25, 222–233. <https://doi.org/10.13679/j.advps.2014.4.00222>.
- Vavrus, S. J., Wang, F., Martin, J. E., Francis, J. A., Peings, Y., & Cattiaux, J. (2017). Changes in north American atmospheric circulation and extreme weather: Influence of Arctic amplification and northern hemisphere snow cover. *Journal of Climate*, 30, 4317–4333.

- Vihma, T. (2014). Effects of Arctic Sea ice decline on weather and climate: A review. *Surveys in Geophysics*, 35, 1175–1214. <https://doi.org/10.1007/s10712-014-9284-0>.
- Vihma, T. (2017). Weather extremes linked to interaction of the Arctic and mid-latitudes. In S.-Y. Wang et al. (Eds.), *Climate extremes: Mechanisms and potential prediction* (Geophysical monograph series, 226) (pp. 39–49). American Geophysical Union.
- Walsh, J. E. (2014). Intensified warming of the Arctic: Causes and impacts on middle latitudes. *Global and Planetary Change*, 117, 52–63. <https://doi.org/10.1016/j.gloplacha.2014.03.003>.
- Wang, M., & Overland, J. (2012). A sea ice free summer Arctic within 30 years: An update from CMIP5 models. *Geophysical Research Letters*, 39, L18501. <https://doi.org/10.1029/2012GL052868>.
- Wu, B., Zhang, R., Wang, B., & D'Arrigo, R. (2009). On the association between spring Arctic Sea ice concentration and Chinese summer rainfall. *Geophysical Research Letters*, 36, L09501.
- Wu, B., Zhang, R., D'Arrigo, R., & Su, J. (2013). On the relationship between winter sea ice and summer atmospheric circulation over Eurasia. *Journal of Climate*, 26, 5523–5536.
- Yang, S., & Christensen, J. H. (2012). Arctic Sea ice reduction and European cold winters in CMIP5 climate change experiments. *Geophysical Research Letters*, 39(L20707). <https://doi.org/10.1029/2012GL053333>.
- Yeager, S. G., & Robson, J. I. (2017). Recent progress in understanding and predicting Atlantic decadal climate variability. *Current Climate Change Reports*, 3, 112–127.
- Zhao, P., Zhang, X., Zhou, X., Ikeda, M., & Yin, Y. (2004). The sea ice extent anomaly in the North Pacific and its impact on the east Asian summer monsoon rainfall. *Journal of Climate*, 17, 3434–3447.