Master of Science thesis in meteorology

DIMINISHING ARCTIC SEA ICE EXTENT AND ITS EFFECTS ON ATMOSPHERIC CIRCULATION IN THE NORTHERN HEMISPHERE IN DIFFERENT SEASONS

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Tiivistelmä – Referat – Abstract

The aim of this Master's thesis is to study the local and remote effects of the Arctic sea ice decline on atmospheric circulation in the Northern Hemisphere in the Eurasian continent.

The climate in the Arctic area has been getting warmer due to global warming and the Arctic Amplification enhancing its effect. This has caused a decline in the Arctic sea ice extent and thickness, and a lengthening of the melting season.

Local effects of the sea ice decline have been the rise in surface air temperature, increase in sensible and latent heat fluxes from the ocean, increase of moisture in the troposphere and therewith increase in cloudiness and precipitation. This has also caused more turbulence and smaller stratification in the lower troposphere, and an increased boundary layer thickness.

A warmer Arctic area and a consequent sea ice decline has decreased the meridional pressure field height gradient and thereby the westerly geostrophic wind in the upper troposphere. The jet stream trajectory has become more meridional and meandering, which resembles the negative phase of the NAO/AO index. This has advected in winter warm air to the Pole and cold air to the Eurasian continent. Blocking highs over the Atlantic and Siberia have further advected cold air to the continent with cold and snow-rich winters as a result. In China the effect has been a more stable lower troposphere with less cyclone activity in winter whereas in spring the sea ice decline has brought lower temperatures and a weakening of the East Asian Jet. In summer Europe has experienced higher precipitation and eastern Asia a strengthening of the Eastern Asia Summer Monsoon. Different studies have suggested different mechanisms for this. Effects in autumn have been mainly the same as in winter, with weather patterns similar to the negative phase of the NAO/AO index.

As a conclusion, it was found in the study that the decline in Arctic sea ice has had quite expected, better understood local effects. The results on remote effects are still partly controversial and not as well comprehended. A decrease in the meridional pressure gradient seems to have effects in several seasons and geographical regions through changes in tropospheric cold/warm advection and in jet stream strength and trajectories. Longer and more accurate data series and more studies with enhanced models are needed in the future in order to get a better understanding of the mechanisms and to separate them from other sources of atmospheric variability.

Avainsanat – Nyckelord – Keywords

Arctic sea, sea ice extent, atmospheric circulation, seasonal effects, climate change

Säilytyspaikka – Förvaringställe – Where deposited

Muita tietoja – Övriga uppgifter – Additional information

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1. Introduction

The on-going climate change and global atmospheric warming has had a profound impact on the Artic area with a rate of change in surface air temperatures much larger than the global average. It has been estimated that the warming in the Artic area has been at least twice as large as in other parts of the world with especially Artic winters getting much warmer than previously (Overland et al. 2018). This phenomenon where the Artic area is heating up in a ratio of approximately 2:1 to the global warming due to climate change is known as Artic amplification (Cheung 2017).

Arctic warming has already had a significant effect on different aspects of the Artic region, one of the most notable and well-discussed areas being the reduction in Artic sea ice extent (AIE) across the Arctic area with also major changes in Arctic ice structure (AIS). The summer AIE minimum has decreased substantially, the length of the ice-free period has been prolonged, the thickness of the Arctic ice has diminished and the composition of the ice has changed. The decline in Arctic sea ice extent has even accelerated during the last decades as temperatures in the area have risen (Gimeno-Sotello et al. 2018). Arctic warming has also affected snow coverage, precipitation patterns and local cloud formation, and accelerated perma-frost and land ice melting in and around the Arctic area (Overland et al. 2018). Dynamical effects of the decline in AIE have also induced a positive feedback loop to the ice cover in the Arctic sea through changes in atmospheric circulation via dynamical or thermodynamic factors, which in turn have promoted the sea ice retreat. Changes in surface winds and increasing turbulence in the lower atmosphere have affected the ice dynamics. Important thermodynamic factors include changes in heat and moisture fluxes in the Arctic, of which the latter has emerged as one of the most significant in terms of the climate change induced effects (Gimeno-Sotello et al. 2018).

The Arctic sea ice, its extent and variation have an important effect on global climate and atmospheric circulation especially in terms of heat transfer between the lower atmosphere and the oceans (Cheung 2018). Changes in sea ice extent affect both the atmospheric circulation over the Artic area itself and areas further away due to remote effects. They also have a dynamic impact on the ocean circulation as the melting and formation of sea ice can influence the surface water density through changes in salinity (Gao et al. 2015).

Changes in the ocean circulation can in turn influence both the Arctic sea ice extent through feedback mechanisms and the atmospheric circulation.

During the last few decades more and more studies have been conducted with the aim of trying to assess the impact of Arctic sea ice decline in atmospheric conditions and climate in Northern Hemisphere mid and high latitudes especially in the Eurasian continent (Cheung 2018). These areas, especially northern mid latitudes, have experiences several extremely cold and snow-rich winters like in years 2005-2006, 2009-2010 and 2010-2011 (Vihma 2014), and many studies have indicated that the decline in AIE could have had a potential connection to these kind of cold winters with anomalously high snowfall.

As Arctic warming and therewith also Arctic sea ice decline is predicted to continue in the coming decades even if greenhouse gas emissions would be radically reduced from present levels (Overland 2018), it is important to study what kind of effects this change will have both on the local climate and the atmospheric circulation in general. It has been estimated that the Artic sea would be totally ice free at the end of the melting season in September by 2050 if the present trend in ice extent decline will continue as with the same pace as until now (Overland et al. 2011).

The purpose of this Master’s thesis is to study the effects of the decline in the Arctic sea ice extent on general atmospheric circulation in the Northern Hemisphere, mainly in high and mid latitudes. Most of the studies that have been conducted until now have concentrated on these effects in autumn and winter and to some extent in summer. This thesis work will look into the changes in atmospheric circulation in all four seasons in order to cover the seasonal aspects of these phenomena. Changes in the atmospheric circulation include both remote effects and local-to-regional effects over the Arctic area. The local effects are of interest also for understanding the remote effects, as local atmospheric changes will transmit the effects of the sea ice decline to changes in the wider atmospheric circulation. As changes in Arctic sea ice extent (AIE) affect many aspects of atmospheric circulation and as there is quite a lot of uncertainty and ambiguity regarding the actual phenomena and the mechanisms how these effects are transmitted, and as some studies show conflicting results, only the main effects both locally and in a wider Northern Hemisphere context are described here. This Master’s thesis is based on a literature study mainly drawn on recent articles and other relevant material.

Changes in Arctic sea ice means in this Master’s thesis the inter-annual variation of the sea ice extent, both in terms of the area covered by the ice and the composition and thickness of the ice, of the length of the ice-free period, and the starting and ending point of the melting season, but not the intra-annual variation in these parameters. Atmospheric circulation covers both local effects in the Arctic area and non-local effects in the Northern Hemisphere, and seasonal effects cover all four seasons, winter, spring, summer, and autumn. The Arctic Ocean and the different regional seas within the Arctic area can be seen in Figure 1, which also illustrates the large difference in sea ice extent in an extremely negative anomaly (2012) against a longer term average (2003-2016).

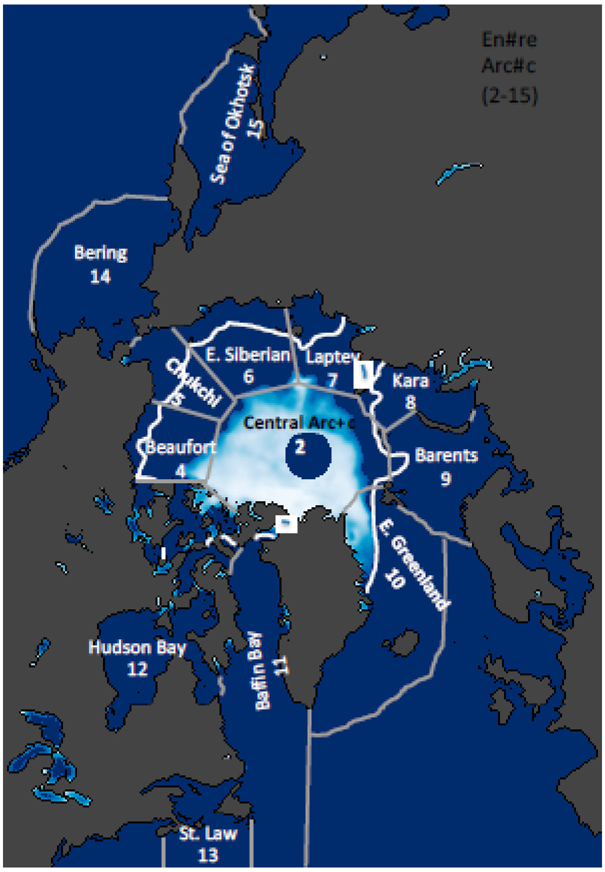


Figure 1. *The Arctic area with the Arctic Ocean and regional seas. An extreme minimum September 2012 monthly average sea ice extent is illustrated by sea ice concentration contours compared to the 2003–2016 average September sea ice extent (solid white line). (Taylor et al. 2018).*

This Master's thesis is organized in the following way. Chapter 2 describes the changes that have happened in the Arctic sea ice extent, ice thickness and ice structure during the last decades and century and Chapter 3 the dynamics of the ocean - sea ice - atmosphere interactions. Chapter 4 has a brief overview of the methods and models used in studying the effects of the changes in the Artic sea ice extent to atmospheric circulation, and Chapter 5 takes up some of the relevant phenomena in mid/high latitude Northern Hemisphere atmospheric circulation like the Arctic Oscillation (AO) and the North Atlantic Oscillation (NAO). Chapters 6 and 7 describe the effects of Arctic sea ice decline, Chapter 6 local effects in the Arctic sea area and Chapter 7 the effects on general atmospheric circulation in all four seasons. Chapter 8 draws some conclusions based on the previous chapters and presents a brief summary of the results.

2. Changes in Arctic sea ice extent

Artic sea ice and its variation have been of interest to researchers and scientists already for several centuries. Early observational data was based on ship observations, drifting sea ice stations, data from expeditions and similar campaigns. Both the temporal and the spatial coverage of the observations were of differing quality and in many cases uncomplete and inaccurate. Precise measurements on the extent and structure of the Arctic sea ice have been available only since 1979 when satellite observation data from the whole Arctic area based on passive microwave radiation became available (Vihma 2014). Efforts have been made to try and recompile older observational data and build a more consistent data set at least on coarser grid level and with less temporal coverage. For example, Walsh et al. at the National Snow & Ice Data Center (2015) have composed a reconstructed data set based on observations from historical sources (ship observations, compilations by naval oceanographers, analyses made by national ice services etc.) that extends back to year 1850. This data composition provides a long time series of monthly sea ice concentrations in the Arctic sea on a much more aggregate level (a grid size of 1/4 degree latitude by 1/4 degree longitude) than present day satellite-based observations. Even though most of the research and analysis on the impact of variations in Artic sea ice extent on atmospheric circulation are based on the more accurate satellite data, these kind of reconstituted historical, less reliable data sets could also be useful in assessing the theories based only on recent satellite observations.

The maximum extent of the Arctic sea ice is reached at the end of the Arctic winter in March and the minimum at the end of the summer melting season in September, when the ice starts to grow again with falling temperatures. The annual variation of the sea ice extent is illustrated in Figure 2. This chapter will look into changes in both the minimum and maximum extent, and into changes in the thickness of the ice. Also, variations in the structure and composition of the ice and the snow layer that covers the ice will be discussed. Relevant factors in assessing the impact of the Arctic sea ice decline to atmospheric phenomena are also changes in the start and end times of the melting season and its total length.

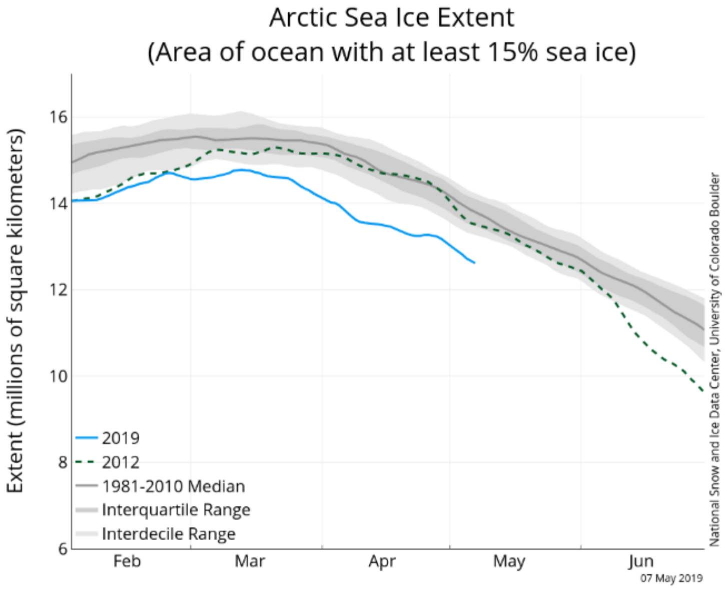


Figure 2. *Annual variation in the Arctic sea ice extent, with 1981-2010 median, 2012 (a year of extended decline), and with also incomplete data from 2019 until 7th May (graph courtesy of National Snow and Ice Data Center, University of Colorado, Boulder).*

2.1 Decline in the sea ice extent

In present day studies and calculations (as well as in this Master's thesis), the sea ice extent is defined as the sum of those satellite data pixels where the ice coverage is at least 15% of the pixel size (Cavalieri & Parkinson 2012). In an older definition by the World Meteorological Organization WMO this threshold value was set at 10% of the pixel size (Vihma 2014).

The minimum Arctic sea ice extent (SIE) at the end of the melting period in September has decreased since the start of the satellite observations in 1979. The fitted trendline of the decline in the annual minimum Arctic SIE has been as much as -12.7% per decade, whereas the decline in annual mean has been only-4% (Hegyi et al. 2018). Figure 3 depicts the extent of the Arctic sea ice as yearly September average values during 1979 – 2018. As can be seen in the figure, the rate of change of the decline has increased during the last few decades. Still at the beginning of the 2010's it was estimated that the whole Arctic sea would be ice-free at the end of the melting season in September first in the 2050's (Overland 2011). More recent studies have assessed that this milestone could be reached much earlier, even as soon as by the end of the 2030's (Mård et al. 2017).

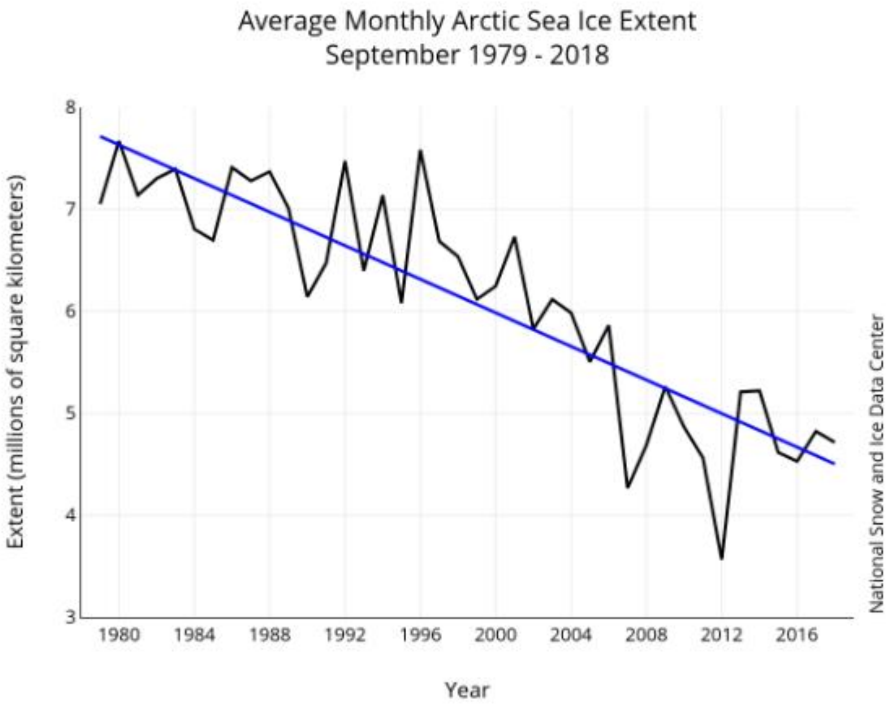


Figure 3. *Arctic sea ice extent, September average years 1979-2018, based on passive microwave measurement from satellite data. Blue line depicts the least-squares linear trend, which gives a decline of 12.8% per decade (graph courtesy of National Snow and Ice Data Center, University of Colorado, Boulder).*

Most media and research attention has been paid to changes in the minimum ice extent coverage during late summer/early autumn as the possibility of an ice-free Arctic sea would have profound climatological, ecological and economic consequences. An ice-free Arctic sea would for example enable a viable sea route from Asia to Europe via the North-East Passage shortening transport times significantly. On the other hand it would have a huge detrimental impact on the ecology and the flora and fauna of the area and imply major changes in the climatological features in the higher latitudes. Even though much interest has been put on the decline in the minimum extent of the sea ice at the end of summer, also maximum extent of the ice coverage during the wintertime (end of March) has decreased, even though to a lesser degree than in summer. Since 2005 the maximum sea ice coverage has been two standard deviations smaller in the winter than the average at the same period during 1979-2000 (Vihma 2014) The change in the maximum sea ice extent (March average) can be seen in Figure 4. Even here the trend has been declining with larger decreases during the recent years and with the lowest observed values obtained during the most recent years (in 2017 and 2018). For the whole period 1979-2019 the trend has been a decline of 2.7% per decade.

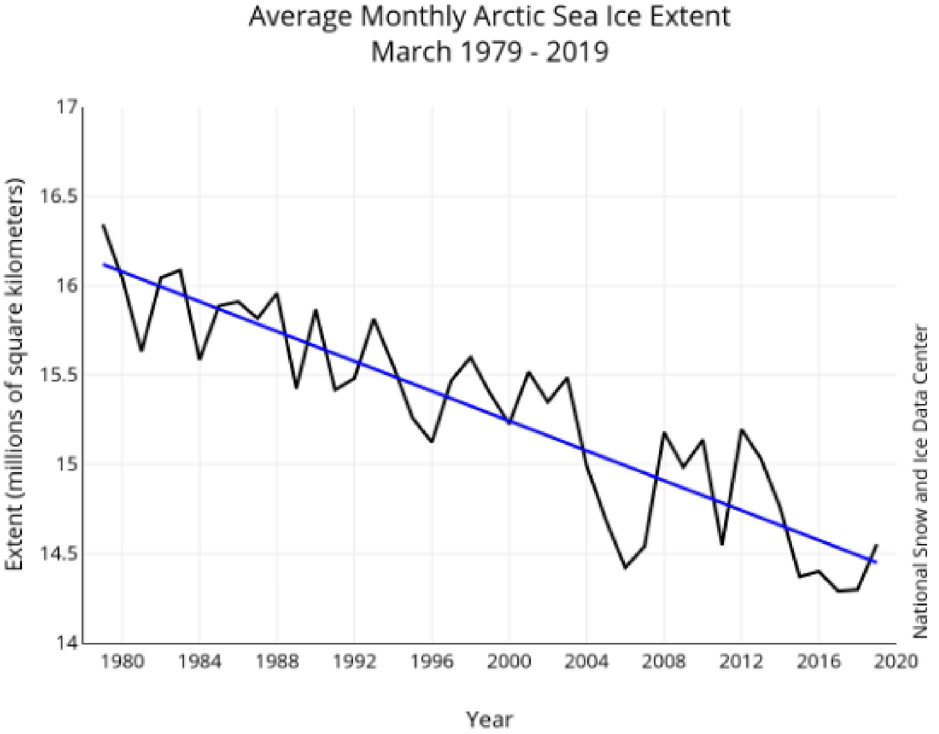


Figure 4. *Arctic sea ice extent, March average years 1979-2019, based on passive microwave measurement from satellite data. Blue line depicts the least-squares linear trend, which gives a decline of 2.7% per decade (graph courtesy of National Snow and Ice Data Center, University of Colorado, Boulder).*

The rate of change of the sea ice extent (SIE) has not been uniform throughout the whole Arctic area. In terms of changes in different geographical areas of the Arctic sea, the largest declines in the SIE have been in the summer and in the autumn in the Arctic Ocean (especially in the Chukchi, East Siberian, and Beaufort Seas), Kara and Barents Seas, and the Baffin Bay/Labrador Sea region (Vihma 2014), whereas the largest changes during wintertime have been observed in southern areas: the Greenland Sea, Kara and Barents Seas, Baffin Bay/Labrador Sea region, and the Sea of Okhotsk (Cavalieri and Parkinson 2012).

2.2 Changes in ice thickness

At the same time as the Arctic sea ice extent has declined, the thickness of the ice has also decreased significantly. Ron Kwok (2018) has compiled in his recent study data from submarine sonar measurements (1958-2000), satellite altimeters (2003-2018), and satellite scatterometer records (1999-2017). According to his analysis, the average ice thickness just after the end of the melting season in autumn (October-November) has decreased over these six decades by some 2/5 or over 1.0 meter (see Figure 5). The largest decline has occurred during the submarine measurement period (1958-2000), whereas the changes during the last two decades have been very moderate. Also, in wintertime (February-March) when the ice extent has been at its largest the ice thickness has stayed roughly on the same level during the last two decades, i.e. around 2 meters (see also figure 5).

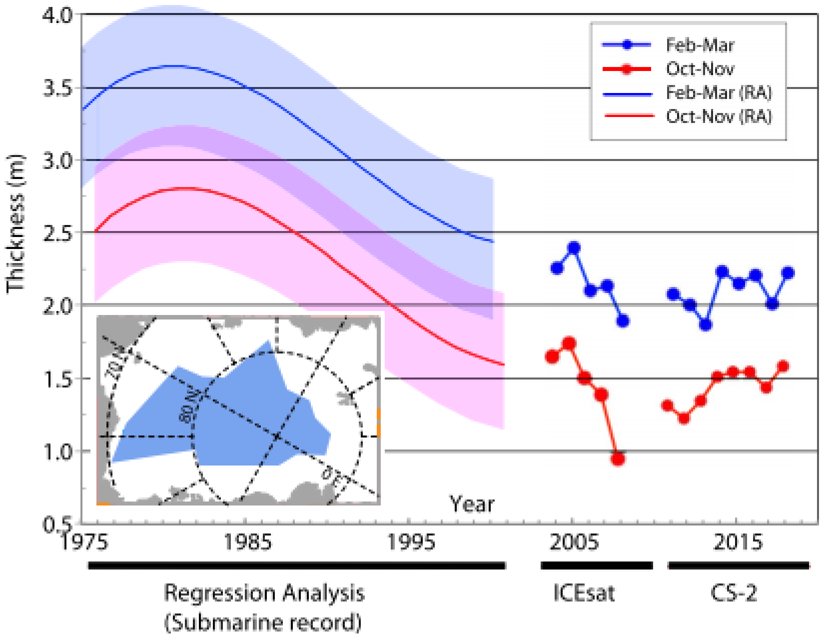


Figure 5. *Interannual changes in mean winter and autumn ice thickness within the depicted data release area (irregular blue polygon), from submarine sonar measurements (1958-2000), satellite altimeters (2003-2018), and satellite scatterometer records (1999-2017). The data release area covers around 38% of the Arctic Ocean, data from US Navy cruises. Shadings show expected residuals in the regression analysis (Kwok 2018).*

As the ice cover has been getting thinner, it has also changed character. Already in the beginning of the 1990's it could be observed that more and more of the ice extent consisted of thin, first year ice (Vihma 2014). Most of the ice coverage in the Arctic sea area seems already for a while have consisted of only first year ice that will melt during the summer melting period (Overland 2011). According to Kwok (2018) the Arctic area has lost around 50% or more 2 x 10^6 km^2 of multi-year ice since the peak multi-year ice coverage in 2002, and multi-year ice now covers only less than one-third of the Arctic Ocean (see also Figure 6 for changes in sea ice volume, autumn and winter figures). Multi-year ice is now concentrated mainly in a few areas of the Arctic, to the north of the coast of Greenland and in the Canadian Arctic Archipelago (Kwok 2018). Kwok (2018) estimates that the Arctic Ocean ice volume has declined by some 2870 km^3/decade during winter (February-March) and 5130 km^3/decade in autumn (October-November).

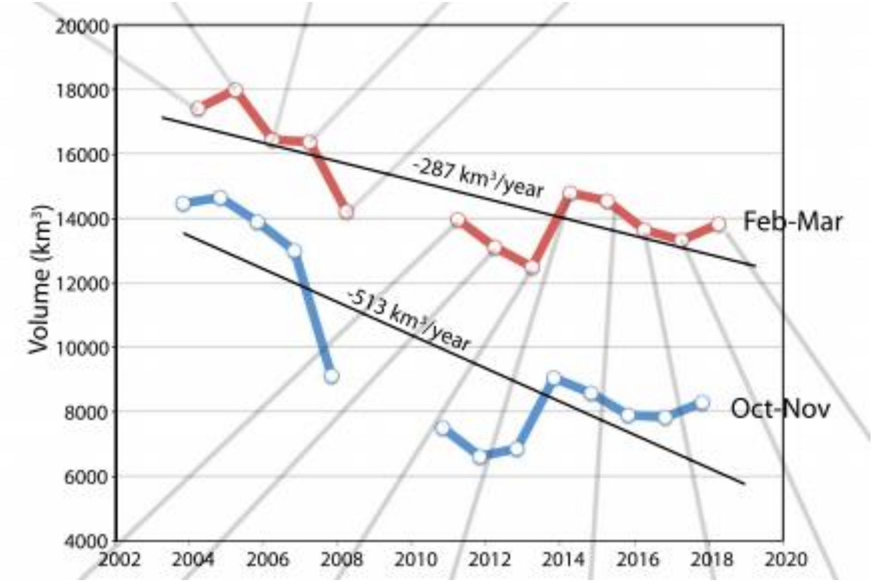


Figure 6. *Arctic sea ice volume calculated from data from satellite altimeters, ICESat (2003-2008) and CryoSat-2 (2011-2018) thickness fields. Volume is computed within the Arctic basin. (Kwok 2018).*

The thickness of the ice has also had an effect on the thickness of the snow coverage on the ice. Blanchard et al. (2015) have estimated that the thickness of the snow in winter on first year ice is only half of that on multi-year ice. This thinning of the snow cover has an impact on the ice as well as it changes the seasonal ice production and mass balance. A thinner snow cover doesn't isolate the underlying ice and ocean from the cold Arctic air as well as deeper snow resulting in faster growth of the ice and larger ice volume production during winter even though this ice sheet doesn't then grow thick enough to survive the summer melting period (Kwok 2018). In this way, paradoxically, less multi-year, thick sea ice during winter means more ice volume production but thinner ice in total. This has also an effect on the atmosphere/ocean heat balance over the Arctic sea area as described in Chapter 3.

2.3 Changes in ice structure

The thinning of the Arctic sea ice and the change to a situation where most of the ice coverage consists of first year ice (as described in the previous chapter) has also had an effect of the structure and composition of the ice. As the ice gets thinner it also breaks easier, fractures, and drifts further within the Arctic sea and to more southward areas. Larger scale fractures, leads and polynyas have an important impact on both the ice cover itself and on the near surface atmosphere above them. A lead is defined by the World Meteorological Organization (WMO) as an elongated crack in the ice that is more than 50 m wide and several to hundreds of kilometers long (Willmes and Heinemann 2016), whereas a polynya is a larger area (on mesoscale) of open water or thin ice that can be found at predictable, recurrent locations which are otherwise covered by sea ice (Stringer and Groves 1991).

The number of leads and polynyas has in some estimates increased at the same time as the Arctic sea ice extent has declined, although the results of different studies are not totally conclusive. The main areas where leads and polynyas can be found in the Arctic area are the Fram Straight and the Beaufort Sea (Willmes and Heinemann 2016). Eicken et al. (2016) have concluded in a recent study that lead frequency in the Beaufort Sea had increased in the period 2004-2010 compared to 1993-2004. The researchers attributed this phenomenon to the decrease in multi-year ice and the increase in divergence. On the other hand, Willmes and Heinemann (2016) didn’t discover a similar trend in their data from Chukchi and Beaufort Seas during 2003-2015. The findings in this study pointed to a large annual variation in lead formation but couldn’t discern a clear trend towards more frequent occurrence of leads or polynyas within the Arctic sea area.

2.4 Changes in the length of the melting period

Decline in the Arctic sea ice extent during the last few decades has also been accompanied with a lengthening of the ice-free period. Compared to the first few years of the satellite-based observations (1979-1980), the ice-free period in the beginning of the 2010's had lengthened by three months in those areas where the sea ice decline had been the largest (Vihma 2014). This lengthening was more pronounced in spring; the melting of the ice started two months earlier than previously, whereas the ice started to grow in the autumn a month later than previously. Both of these dates (start and end date of the melting period) showed a trend wise change. The start date of the melting season had gotten earlier by 9 days per decade and the end date of the melting season by 7-8 days per decade (Vihma 2014). The length of the melt season in the Arctic ranges normally between 5 and 7 months in the seasonal ice zone, in the central Arctic closest to the Pole the length of the melt season is only about 2.5 months (Stroeve at al. 2014).

3. Dynamics of the sea ice change and ocean-atmosphere interaction

Changes in sea ice extent, its composition, and thickness, and in the length of the ice-free melting period affect not only the atmosphere but also the dynamics of the ice itself, the ocean, and the ocean - atmosphere interaction. These changes have many positive feedback mechanisms to the observed Arctic warming caused by the climate change and the larger positive temperature anomaly in the Arctic region caused by the Arctic Amplification phenomenon (see Chapter 5.1 for a definition and further discussion). In this chapter the consequences of these observed changes to the Arctic Ocean and the ice cover in it will be examined and those mechanisms that affect the atmosphere described. This analysis is based on the different observed changes in the Arctic sea ice as discussed in Chapter 2. Understanding these sea ice – ocean - atmosphere dynamics will lay a ground for studying the effects of the Arctic sea ice decline to both local and general atmospheric circulation that are described in Chapters 6 and 7.

3.1 Sea ice extent

With declining sea ice extent, less and less of the Arctic Ocean is covered with ice during the summer months and early autumn which means that the ocean has the capacity to store more heat energy during the ice-free melting season. This stored heat capacity will then be released later during the autumn and to some extent even in the winter months. The albedo of water is much less (0.10) than that of ice (0.20-0.45) or of ice with snow cover (fresh snow up to 0.90) which means that the open water areas of the Artic sea absorb more incoming solar short-wave radiation than the ice-covered parts. The sea surface temperature in the summer in ice-free ocean areas is therefore higher and the heat capacity of the ocean larger compared to earlier years with more extensive sea ice coverage. This means that the beginning of the freezing period will occur later and that the ice that is formed is thinner as there is a net heat flux from the warmer near surface ocean layers to the ocean surface.

Even though there has been a significant decline in the sea ice in the winter as well, it hasn't had the same kind of effect on ocean and sea ice dynamics as the decline in the summer. With almost zero incoming short-wave radiation during Polar winter when the

Sun is below the horizon for several months, no more heat energy is stored in the open water than in ice covered areas and sea ice extent doesn't have a similar effect as during the summer when the Sun doesn't set again for many months. Even in the autumn and spring time the angle of the incoming solar radiation is so small that most of the short-wave radiation is reflected rather than absorbed and the amount of solar radiation is otherwise also much smaller. Also, the difference in heat absorption capacity between open sea and ice-covered sea is relatively small. On the other hand, the decline in sea ice extent in winter has had a large positive impact on the near surface air temperatures (SAT) above open water/ice covered ocean, and vice versa regarding the sea water temperatures near the ocean surface (Vihma 2014). Ice cover isolates the underlying ocean from the cold polar air above the ice surface which reduces heat fluxes (sensible and latent) from the ocean compared to areas with ice-free waters.

3.2 Sea ice thickness

According to the study by Kwok (2018) most of the winter ice in the Arctic area is nowadays seasonal ice, i.e. first year ice (over 70 % as a January mean). This change in the character and thickness of the ice has a dynamic effect also on the sea ice extent. Thinner first-year ice is more prone to melting and to be broken down by winds and storm activity resulting in a decline in the spatial reach of the ice cover (Vihma 2014). Thin ice that is deformed and broken to smaller units drifts more easily transported by winds and surface currents away from the Pole to lower latitudes where it is exposed to warmer temperatures both in the ocean and in the near surface atmosphere and therefore more likely to melt. Thinner sea ice is in general more susceptible to dynamic and thermodynamic disturbances, which again strengthen the interconnection between the ice coverage and the atmosphere (Hegyi et al. 2018). The thinning of the ice and the dominance of first-year ice over multi-year ice has also increased the ice drift over the Arctic ocean in recent decades. As the thinner ice doesn't stay as long in the colder Polar areas as earlier, its thickness doesn't grow in the same way either, and it stays both thinner and more fragile than earlier (Overland 2011). Thinning of the ice and the consequent increase in ice dynamics also further decrease the share of multi-year ice in the Arctic area. According to the study by Kwok (2108), the increased melting of multi-year ice occurs when it is advected into the southern Beaufort Sea from the still remaining source areas for multi-year ice (the north coast of Greenland and the Canadian Arctic

Archipelago), whereas with less ice drift in the earlier years the multi-year ice was more stable further north and protected from melting during the summer months.

The thinning of the ice and the prevalence of first year ice has impacted the snow cover on the ice. Changes in the snow cover thickness or its total disappearance have a feedback effect on the ice itself and on ice-atmosphere interaction. The albedo of snow is higher (fresh snow even up to 0.95) compared to sea ice (0.20-0.45) which means that ice with a snow cover absorbs less short-wave radiation than clear ice. Clear ice with no snow cover will absorb more heat energy in the spring and start to melt earlier resulting in a decline in the ice extent, an earlier start to the melting season, and thinner ice in general with again having a positive feedback loop to the decline in the Artic sea ice extent. Less snow on the ice means also that it melts earlier, and the meltwater from snow forms melt ponds on the ice in low-lying areas. With increasing temperatures these melt ponds grow in size and as the albedo of these areas (water) is greater than that of the surrounding surface (ice), the total absorption of short-wave radiation increases resulting in enhanced melting. This positive feedback mechanism is referred to as the snow/ice-albedo feedback (Wang et al. 2018).

The snow cover on the ice has also a large impact on the sensible heat flow through the ice from the ocean to the atmosphere. If there is a 30 cm thick snow cover on the ice, the sensible heat flux through the ice increases only by about 3 Wm^{-2} when the ice thickness decreases from 3 m to 1.5 m. If there is no snow on the ice the same decrease in ice thickness results in an over four times larger heat flux (13 Wm^{-2}) through the ice (Vihma 2014).

3.3 Changes in the structure of the ice

The fracturing of the ice increases the area of open water in the ice cover and thereby the absorption of solar radiation compared to a situation with no ice-free areas. Leads and polynyas can open and close very quickly, even large areas within 24 hours, especially in the middle of the winter (Stinger and Groves 1991) which also means that the radiation absorption in the area varies quite quickly. On the other hand, both sensible and latent heat fluxes from the ocean through the cracks, leads, and polynyas that are formed in the ice cover, are largely cooling the ocean water and having an opposite effect to the radiative warming. It has been estimated (Taylor et al. 2018) that turbulent fluxes from leads and polynyas can decrease the air–sea temperature gradients by over 20 °C. When they are formed, the warm ocean surface is exposed to the cold, dry overlying air creating instability in the boundary layer and large sensible and latent heat flux exchanges. According to Stinger and Groves (1991) the positive correlation between temperature and polynya extent becomes most noticeable in spring after the spring equinox when the solar heating starts to become a major factor in the high latitudes. More lead and polynyas in spring time would then increase ocean heat content and contribute with a positive feedback loop to the decline in sea ice extent.

3.4 Ice-free season and the length of the melting period

When the melting season starts earlier in the spring there are more ice-free areas during the time when the angle of the incoming solar radiation is large enough to enable absorption of the radiation into the ocean as the radiation per unit area is dependent on the sine of the elevation angle of the incoming radiation and as the absorption per unit area increases with an increase in the elevation angle. Of these the first one is more important as the absorption rate is also dependent on the characteristics of the sea surface (the straightforward dependency on the elevation angle being only valid for a calm surface, waves increase reflection and decrease absorption). The decline in the Arctic sea ice increases in this way both the absorption time and the absorption area and therefore increases the heat content in the upper layers of the ocean. Earlier snow melt and thinning of the snow cover as described in Chapter 3.2 decrease the albedo of the area in question and result in a positive feedback mechanism on the ice melt (Vihma 2014). The Arctic ocean stores more heat energy with a longer melting season which then delays the beginning of the freezing period. A later start with a thinner ice with even most of the total ice coverage being first-year ice makes the ice cover more susceptible to the deforming forces of autumn storms and winds. On the other hand, the ocean also loses more stored heat to the atmosphere through sensible and latent heat fluxes in late autumn if the sea is ice-free compared to a situation where the freezing season starts earlier (sea ice isolating the underlying ocean from the atmosphere and thereby reducing the heat fluxes).

4. Methods and models in studies on atmospheric effects

The aim of this chapter is to give a short overview of the methodologies used in different studies and research projects as a background to Chapters 6 and 7 where the results of the current understanding on effects of the decline in sea ice extent on atmospheric circulation are presented. Some representative examples are described in order to give a clearer picture of how these complex phenomena, where observational data is not always in abundance, have been studied.

As described in Chapter 2, more accurate and comprehensive observations on the Arctic sea ice extent are available only from 1979 onwards with the advent of satellite-based passive remote sensing measurements. These satellite observations can reasonably well provide data on the sea ice extent, whereas their ability to measure sea ice thickness and volume has been less exact. Sea ice model reanalyzes have been employed to provide estimates of thickness and volume, but their accuracy has been left lacking compared to observational data (Lindsay and Schweiger 2015). More accurate satellite-based thickness data has been available since 2003 from the ICESat (during 2003-2007) and CryoSat-2 (2011-2017) satellites (Kwok 2018). As the timeseries from these have been of shorter duration and not even continuous, the usability of thickness data in studies on the atmospheric effects has not been as good as with data on sea ice extent. Efforts have been made to combine thickness measurements from different sources (drill holes, sea ice station, underwater sonar measurements from submarines, aircraft-based radar and lidar instruments) to provide longer timeseries, for example The Unified Sea Ice Thickness Climate Data Record (Sea Ice CDR) available at National Snow and Ice Data Center with data from 1947 onwards (Lindsay and Schweiger 2015). Estimates for snow thickness for periods where no appropriate satellite measurements are available are made from reanalysis data using models for calculating the snow cover from precipitation and temperature data, though these tend to overestimate the snow thickness (Lindsay and Schweiger 2015).

For studying the effect of sea ice decline on atmospheric circulation different climate models are used, ranging from atmosphere-only to fully coupled atmosphere-ice-ocean models, with reanalysis from the period that is studied. Earlier studies may have used more simple models with sometimes an atmosphere-only model, which according to

Rinke at al. (2018) may explain some of the discrepancy in the results that have been obtained (e.g. the imprint of late summer sea ice anomalies on the following winter atmospheric circulation). Commonly used models are for example The Weather Research & Forecast (WRF) model as a regional coupled model and the Community Climate Model version 5 (CCM5) (or earlier versions 3 or 4). Many studies use the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis or NCEP/NCAR reanalysis dataset for the reanalysis data (Cai et al. 2018) and Hadley Centre's sea ice dataset or sea ice data from the National Snow and Ice Data Center (NSIDC). Quite often the timeframe for the model runs is the period from where satellite data on sea ice extent is available, as pre-satellite era data is less accurate and not so useful for trying to establish connecting mechanisms and correlations between the ice variables and the atmospheric circulation phenomena.

The models can then be run with a different number of ensemble simulations or the same ice extent data can be used in different models to test the consistency and robustness of the results. Models can also be run with two different sets of ice extent data, one period with (extreme) positive anomaly and another with (extreme) negative anomaly. In this way it is more likely that possible effects on atmospheric circulation can be found and isolated from the normal variation that is due to other dynamic and thermodynamic processes present in the atmosphere. For example, Bian et al. (2016) used this kind of approach in their study (described in Chapter 6), where the years 2010 and 2014 (sea ice extent larger than normal) were compared to the year 2012 (extreme sea ice decline). Rinke et al. (2018) used in the simulations two sets of years and compared the atmospheric anomalies of different variables (e.g. SAT, SLP, and geopotential thickness of z500-z850) between those, one data set being years with high sea ice concentration and the other with low sea ice concentration.

5. Atmospheric circulation phenomena in mid/high latitudes

The purpose of this chapter is to briefly describe some of the main large-scale phenomena in atmospheric general circulation in mid to high latitudes in the Northern Hemisphere that affect the mechanisms connecting Arctic sea ice decline and changes in atmospheric circulation. These are the Artic Amplification (AA), the Arctic Oscillation (AO), the North Atlantic Oscillation (NAO), and the Arctic Dipole (AD). The first three of these will be described in more detail in the following Chapters 5.1, 5.2, and 5.3. Arctic Dipole is connected with changes in geopotential height in the Arctic area and the Eurasian continent. A positive AD index is defined as a situation when a negative geopotential height anomaly exists over the Eurasian continent with a positive anomaly over the Artic area. When the AD index is negative, these geopotential height anomalies are the other way round (Hegyi and Taylor 2017).

5.1 Arctic Amplification (AA)

Arctic amplification as a climatological concept can be defined as the more rapid change in the surface air temperature (SAT) in the Arctic region compared to the Northern Hemisphere mean (Davy et al. 2018). The rate of change in the Arctic mean temperature has been around the twice the global warming that has been caused by the continuous climate change (Cheung 2017). This phenomenon has large interannual variation and is especially strong in the winter when the SAT anomaly has in some cases been as much as +8 ^{o}C compared to a longer-term average, whereas the increases during the summer period have been smaller (Overland et al. 2018). The present excess warming of the Arctic is not a new phenomenon even during the last few centuries, a similar Arctic warming has been observed in the 1920s to 1940s (Davy et al. 2018). It has been partly attributed to the effects of the Arctic sea ice decline and the feedback effects induced by it (as described in more detail in Chapter 6) such as thermal forcing due to reduced surface albedo, changes in atmospheric water vapour content, increased cloud cover, and increased advection of warmer air lower latitudes, and partly due to local temperature feedback effects (Davy et al. 2018). In some areas of the Artic, like in the Canadian archipelago, the sea ice area has not decreased in winter although winter surface air temperatures have risen more than in mid-latitudes implying that other mechanisms than just the decrease in sea ice extent play a significant role in the Artic Amplification (Vihma 2014).

5.2 Arctic Oscillation (AO)

Arctic Oscillation (AO) can be characterized as variations in sea level pressure (SLP) on one hand side in the Arctic area (within 20° from the North Pole) and a zone more equatorward between 37º-45º from the Pole. From the pressure difference between these two areas an Arctic Oscillation index can be calculated (Thompson and Wallace 1998). A positive AO index is defined as a situation where an area of low (surface) pressure is formed above the Arctic (and a high pressure further out from the Pole). This pressure anomaly results in strong, more straight-lined westerly jet streams around the Pole which will then keep the colder Arctic air from advecting from the Pole towards mid-latitudes. A situation with a negative AO index is then characterized by high SLP over the Arctic with jet streams that meander more and enable the incursion of cold polar air to lower latitudes, as the winds have a more northerly character. The jet streams are in this case also located more poleward than during the positive AO index phase (Thompson and Wallace 1998) The difference between these two opposing phases of the AO can be seen in Figure 7.

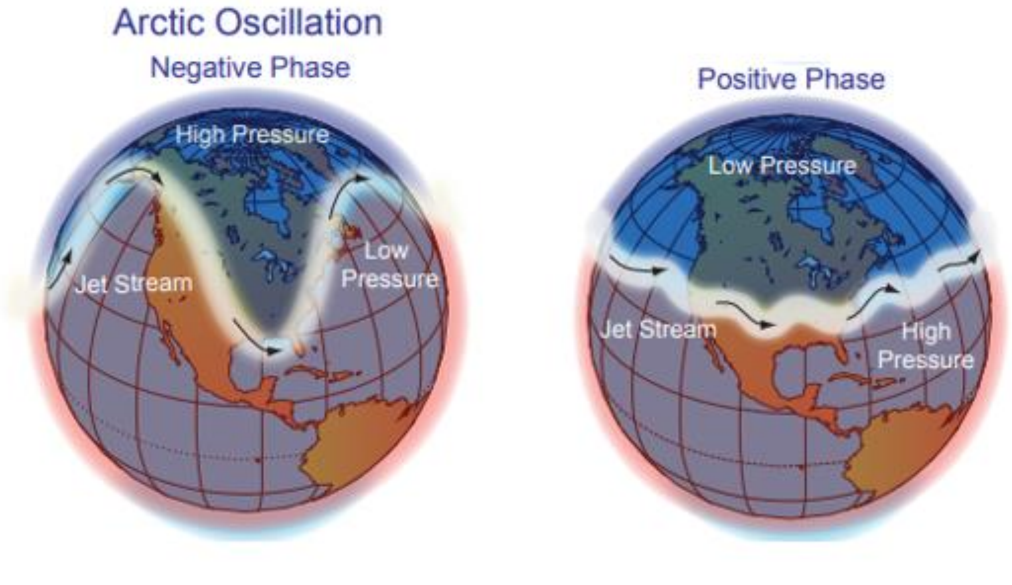


Figure 7. *Negative and positive phase of the Arctic Oscillation (AO) with differences in sea level pressures over the Arctic area and the mid-latitudes and jet stream location and form (NOAA 2012).*

5.3 North Atlantic Oscillation (NAO)

The general atmospheric circulation in the North Atlantic is characterized by trade winds between the intertropical convergence zone (ITCZ) and a region of high pressure around the Azores (Azores High), and on the other hand the predominantly westerly winds between the Azores High and the region of low pressure near Iceland (Iceland Low) (Polonskii 2004). The pressure gradient between on one hand the Azores High and on the other hand the Iceland Low specifies the intensity of westerly winds and the cyclone track at mid-latitudes affecting the climatology of the European continent. The pressures in these two areas oscillate in a quasi-synchronous manner and this oscillation is called the North Atlantic Oscillation (NAO). The North Atlantic Oscillation index then measures the pressure difference between the Azores High and the Icelandic Low (see Figure 8). When this pressure gradient is large, the index value is positive, and when it is small, the index is negative (Fogg and Thomas 2008). A positive NAO index is associated with strong, more poleward cyclone activity, and a negative NAO-index correspondingly with less intense storms and storm trajectories that are shifted to a more southerly position (Thompson and Wallace 1998).

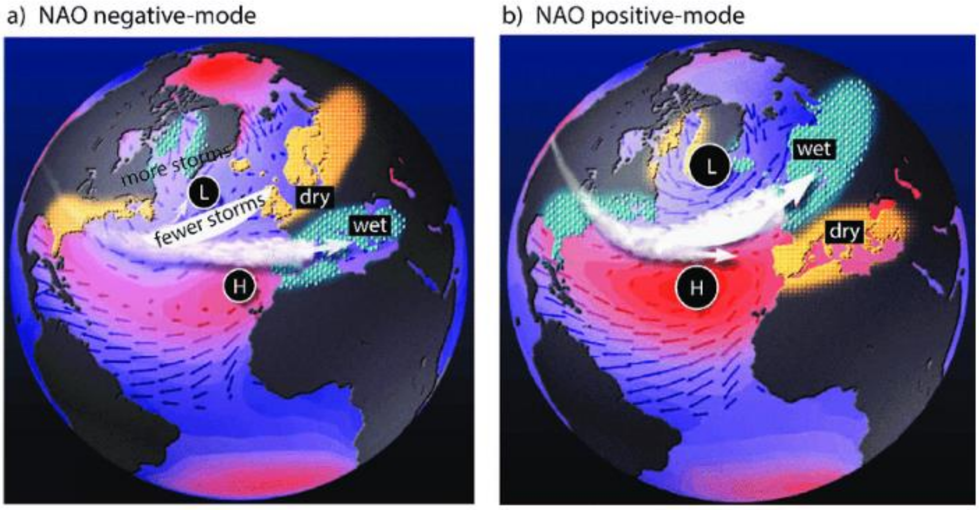


Figure 8. *A schematic picture of the North Atlantic Oscillation (NAO), negative and positive index mode, and their different effects on the European area in terms of precipitation and storm intensity (Moura et al. 2017).*

The time series of the North Atlantic Oscillation and Arctic Oscillation have also been found to be highly correlated as atmospheric phenomena with an observed correlation coefficient that has been as high as r = 0.92. This high correlation is mainly caused by the overlap of the NAO and the AO patterns in the Atlantic sector (Ambaum et al. 2001). The NAO can be seen as a more local mechanism in the Atlantic region, whereas the AO represents a more zonally symmetric mode around the globe. The NAO has therefore been called a sectoral paradigm and the AO an annular paradigm (Ambaum et al. 2001).

6. Local atmospheric effects of Arctic sea ice decline

This chapter describes the local atmospheric effects of the changes in the sea ice coverage in the Arctic Ocean area and in the marginal seas around it. Understanding the effects and mechanisms of the sea ice change in the local atmospheric context is also essential in discussing the effects on general atmospheric circulation in mid/high latitudes in the Northern Hemisphere in Chapter 7, as the local effects are the mechanism by which the impact of the sea ice decline is transmitted into the atmosphere in general. The discussion in this chapter is based on several studies and research projects on this subject. These utilize the methods (observational analysis, reanalysis, data models) described in Chapter 4. The following local atmospheric variables and changes in these are taken up: heat fluxes (sensible and latent), tropospheric humidity, cloudiness and precipitation, and air pressure. The discussion in this chapter is not organized by a seasonal division but the seasonal aspects are rather taken into account when applicable, and highlighted in the description of each of the local atmospheric effects mentioned above.

6.1 Air temperature

There has been a direct connection between the sea ice decline and the lengthening of the ice-free period to surface air temperature (2 m height, SAT) in the Arctic atmosphere. A larger area of open, ice-free water at the end of the melting season in September has created a positive temperature anomaly in these areas as the sensible heat flux from the well-mixed ocean surface layer has increased significantly. According to a study by Stroeven et al. (2012) the positive temperature anomaly was especially strong a month after the sea ice cover minimum in October when the freezing season had already started. Tezlaff et al. (2013) found out that 70-90% of the variation in SAT in winter and spring could be explained by the changes in sea ice extent. Sensible heat flux from the ocean surface to the atmosphere is much smaller through ice and especially through ice covered with snow than through ice-free open water. In the same manner the thinning of the sea ice and the prevalence of thin first year ice over multi-year ice increases the sensible heat flux from the ocean and warms up the atmosphere above it (Lang et al. 2017). The largest temperature anomalies (SAT) are found in those areas where the Arctic sea ice extent has declined the most and where the ocean stays longer ice-free, like the marginal coastal seas by the North American and Eurasian continents (Land et al. 2017) (see Figure 9).

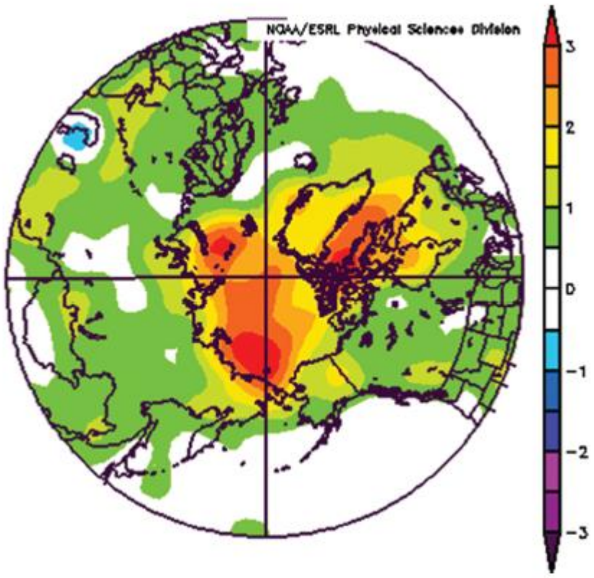


Figure 9. *Anomalies in annual mean surface air temperature in 2001-2010 compared to the annual mean in 1971-2000. The map is based on reanalysis data from the National Centers for Environmental Prediction and the National Center for Atmospheric Research (Overland 2011).*

The largest seasonal anomalies in the Arctic surface air temperatures can be encountered in winter. In the Polar night with no solar radiation to warm up the surface and in weather conditions with no cloud cover to retain some of the outgoing long-wave radiation, the air temperatures can reach very low levels (average winter minimum temperatures around -40 ^{o}C) whereas an open ice-free ocean will keep the SAT closer to the temperature of the ocean water (around -2 ^{o}C) (Vihma 2014). Local temperature anomalies can in these kinds of circumstances reach several tens of degrees Centigrade. During the summer, the temperature anomalies in SAT are much smaller as the melting ice keeps the temperature of the ocean surface layer and thereby also the air temperature immediately above the surface close to the freezing (melting) point of water, which is around -2 ^{o}C in sea water with normal oceanic salinity. The ice-free ocean surface absorbs also heat energy from solar radiation which is then further transferred deeper down in the mixed ocean surface layer by the impact of turbulence and wind drift. This heat transfer keeps the water temperature of the ocean surface layer more constant until the whole mixed layer starts to warm up. (Vihma 2014). In this way also the SAT above the ice-free water is more constant and the temperature anomalies between ice-free and ice-covered sea are much smaller than in winter. A difference this large between air temperature anomalies in the winter and the summer can also be seen in more specific local effects. A study by Cai et al. (2018) found that of the total atmospheric warming in the area they analyzed (the North Slope of Alaska), sea ice decline accounted for up to 45% of the effect in the winter but less than 10% in the summer, the rest being attributed to global warming and Arctic Amplification in general.

Positive air temperature anomalies especially in winter are not restricted to the lowest layers of the atmosphere in the Arctic area but the effect can be seen even higher up in the troposphere up to the 850 hPa level (Overland 2011). Vertical advection of heat energy from the ice-free open ocean is heightened by the increase in storm and wind activity. According to Overland (2011), one of the most important indicators of changes in the Arctic atmosphere is the increased storm activity above areas that have earlier been ice-free. A study based on data from 2007 made by Kumar et al. (2010) showed that the strong negative anomaly in the Arctic sea ice during that year could almost entirely explain the simultaneous positive temperature anomaly in the lowest 1000 m of the troposphere. This signal was at its strongest in autumn (September-December) when exceptionally large areas of the Arctic sea were ice-free.

Bian et al. (2016) have studied the effects of the sea ice decline to temperature anomalies in the troposphere based not only on reanalysis data but also based on three sounding campaigns in August-September 2010, 2012, and 2014. Of these three years, the sea ice decline was most pronounced in 2012 (ice coverage of only 70% of that of the other two years). The results of the study show that there was hardly any thermal inversion near the ocean surface in 2012 (a year with extreme sea ice decline) due to the mixing effects of the ice-free water and strong airflows at the surface layer, whereas in years with less sea ice decline (2010 and 2014) a more stable inversion layer closer to the surface was found. An analysis by Bian et al. (2016) also found a negative correlation coefficient between the sea ice coverage and the temperature at 1000 hPa (-0.83) and at 850 hPa (-0.74). The results of this analysis can be found in Figure 10.

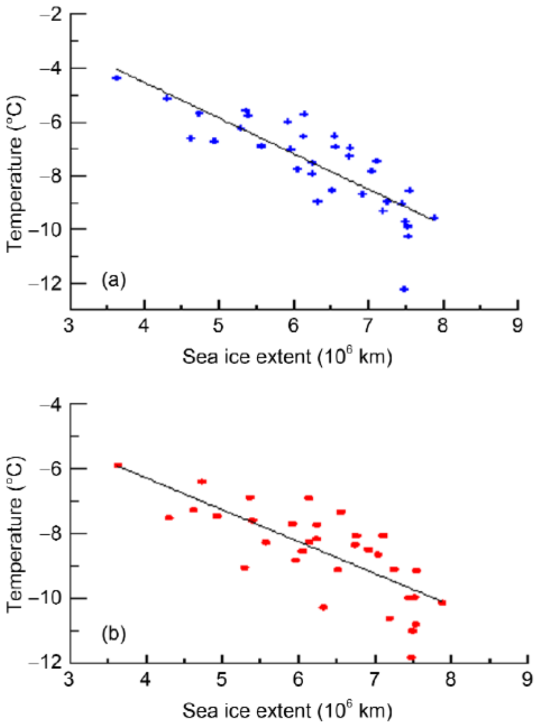


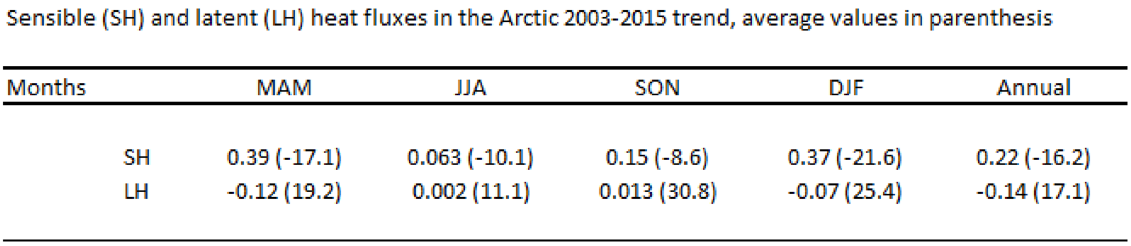
Figure 10. *Correlation between Arctic sea ice extent with air temperature at 1000 hPa (a) and 850 hPa (b) in September, years 1979-2014, in the middle of the Arctic Ocean (80°–90°N) (Bian et al 2016).*

6.2 Heat fluxes, precipitation and cloudiness

An ice-free sea area increases the heat transfer from the ocean surface layer directly to the atmosphere not only by sensible heat fluxes but also by large latent heat fluxes that transport both heat and humidity to the otherwise quite dry lower troposphere above the ocean. Rinke at al. (2018) have estimated in a recent simulation-based study that anomalies in these two fluxes reach up to 140 W/m^{-2} in wintertime when the temperature difference between the cold atmosphere and the warm ocean is at its largest. Locally this can lead to a surface air warming of up to +8 °C. These large latent heat fluxes bringing humidity to the lower troposphere increase low-level cloud formation and precipitation in the Arctic area (Alexander et al. 2004). The corresponding increase in heat fluxes is much smaller in the autumn, when a larger part of the Arctic ocean has already earlier been ice-free. Rinke et al. (2018) have estimated in a recent study that the total turbulent heat flux anomalies are in the autumn in the order of 10-20 W/m^{-2}, in some areas up to 40 W/m^{-2}.

Vihma (2014) has reviewed several studies based on reanalysis data on this subject. The results of most of these indicate that the decline in Arctic sea ice extent imply an increase in humidity, cloudiness, and precipitation. The results from these reanalysis and simulations seem to correspond quite well to data from different types of observations. Screen et al. (2013) saw in a study the largest increases in precipitation during the autumn and winter, whereas Porter et al. (2012) found the largest positive precipitation anomalies only in October-November. Increasing sensible and latent heat fluxes and humidity affect also the stability of the lower troposphere with decreasing stratification and a deeper atmospheric boundary layer (see Table 1 for the average fluxes and the trend in these). In summertime, the sea ice decline is seen to inhibit low-level cloud formation as a result of destabilization of the boundary layer (Cai et al. 2018).

Table 1. *Trends in sensible heat (SH) and latent heat (LH) fluxes in the Arctic area with 2003–2015 average values in parentheses (both in Wm^{-2}yr^{-1}) (Taylor et al 2018).*



Sensible (SH) and latent (LH) heat fluxes in the Arctic 2003-2015 trend, average values in parenthesis

Months	MAM	JJA	SON	DJF	Annual
SH	0.39 (-17.1)	0.063 (-10.1)	0.15 (-8.6)	0.37 (-21.6)	0.22 (-16.2)
LH	-0.12 (19.2)	0.002 (11.1)	0.013 (30.8)	-0.07 (25.4)	-0.14 (17.1)

Leads and polynyas are also an important contributor to lower troposphere humidity and to increased sensible and latent heat fluxes above the ocean surface. On a local and a regional scale they both warm the boundary layer above and downwind from the area, and modify mesoscale atmospheric motions and cloudiness further downstream (Taylor et al. 2018).

On an all-season level, another atmospheric circulation phenomenon on top of the increased latent heat fluxes and overall rising humidity in the low troposphere is the effect of ice-free open water to cloud formation through particle formation. New particle formation and growth to a size where the particles can act as cloud condensation nuclei are an important contributor to cloud formation in the boundary layer and the free troposphere (Kerminen et al. 2018). Dall'Osto et al. (2018) used observational data from five years of continuous measurements of air particles over a specific area in the Arctic and compared this with the sea ice extent. The researchers found a very strong negative correlation between sea ice extent and particle formation in the study area suggesting a possible further strengthening of cloud formation in the Arctic area in the future.

6.3 Air pressure

The studies referred to in the article by Vihma (2014) mentioned in the previous chapter show partly contradictory results in what comes to a possible connection between decreasing sea ice extent and sea level air pressure (SLP). In any case, most of the studies show at least some level of correlation between declining sea ice and changes in the SLP both in the autumn and the winter. Alexander et al. (2004) found that negative anomalies of the sea ice extent were associated with lower sea level pressure (thermal low), and according to their analysis many observational studies supported these findings both in what comes to simultaneous and delayed effects of the sea ice extent to lower SLP. A negative sea ice extent anomaly correlated with lower surface level pressure during the following winter.

7. Effects of Arctic sea ice decline on general atmospheric circulation

This chapter looks into the remote effects of the decline in the Arctic sea ice on general atmospheric circulation in mid/high latitudes in the Northern Hemisphere. It is divided into four parts, one per each season, in order to get a categorical picture of the different phenomena and the mechanisms by which these changes are transmitted from and influenced by the changes in the sea ice extent. Further, a general part is included to describe how the local warming of the troposphere affects wider atmospheric circulation through changes in meridional pressure gradient and geostrophic winds. For some of the phenomena this categorization can seem to be somewhat artificial, and some of the phenomena can also easily extend over more than one season. A seasonal division may give a more balanced picture of the effects as most of the studies have concentrated on impacts in atmospheric circulation in winter, partly because the remote effects have been clearer and have had a larger impact in the atmosphere further away from the Pole. When a weather phenomenon encompasses several seasons, it is described in the season where the effect of the sea ice decline is at its largest with a reference to the other relevant season(s) as well. At the end of this chapter there is a overview of the different studies described in this chapter with the main remote effects and their geographical reach.

Central parameters in this discussion are changes in the temperature and geopotential gradient in the atmosphere between the Polar region and lower latitudes with corresponding changes in jet stream locations, jet stream trajectory and strength, in storm track activity, and in atmospheric circulation in midlatitudes. Some of the phenomena can even have a wide spatial reach where the circulation changes span around the globe. An interesting example of this (although outside the scope of this thesis and therefore more of a curiosity) is the new link found in a recent study by Cvijanovic et al. (2017) between Arctic sea ice decline and extreme drought in California in 2012-2016. In a two-step teleconnection, a reorganization of tropical convection in the Pacific caused by the decline in the Arctic sea ice triggered an anticyclonic response over the North Pacific which then resulted in significant drying over California. The effects of the decline in Arctic sea ice on the large-scale weather phenomena (Arctic Amplification, Arctic Oscillation, and North Atlantic Oscillation) are also discussed. The uncertainty surrounding the effects in atmospheric circulation is taken into account as many studies have shown partly contradictory results or results which are not so well backed up by observational data. Also, in some cases the interdecadal variation or the internal stochastic atmospheric variability could play an important role in the observed changes in midlatitude circulation as suggested by Xu et al. (2019). The observed correlations between the Arctic sea ice decline and changes in the midlatitude atmospheric circulation could also to a varying degree be caused by midlatitude circulation affecting Arctic warming which then contributes to the decline in the sea ice extent, creating also a positive feedback loop between Arctic sea ice and midlatitude atmospheric circulation.

7.1 Decrease in meridional temperature and pressure gradient

As temperature in the lower troposphere in the Arctic increases more than in midlatitudes due to the Arctic amplification described in Chapter 5, the temperature gradient between these areas decreases. This will also diminish the north-south pressure gradient as the relative thickness between different pressure levels will decrease (thickness in high latitudes increases relatively more than in midlatitudes). According to the thermal wind law, the zonal westerly geostrophic wind increases upwards as the meridional south to north pressure gradient increases with height (see Figure 11). When the difference in the thickness of different pressure layers decreases due to Arctic amplification (temperature gradient diminishes), the velocity of the westerly geostrophic wind that normally blows in the upper troposphere also decreases (Sui et al 2017). Several studies have been able to model these kinds of large-scale changes in pressure fields and the corresponding weakening of the geostrophic wind (Vihma 2014). Observational data in these studies has also confirmed the findings in the model. For example, Francis and Vavrus (2012) studied changes in pressure field thickness (1000-500 hPa) and geostrophic wind (at 500 hPa) using reanalysis data from North America and North Atlantic and could show a decreasing trend in both of these, especially during the winter half-year. The results of this study can be seen in Figure 12.

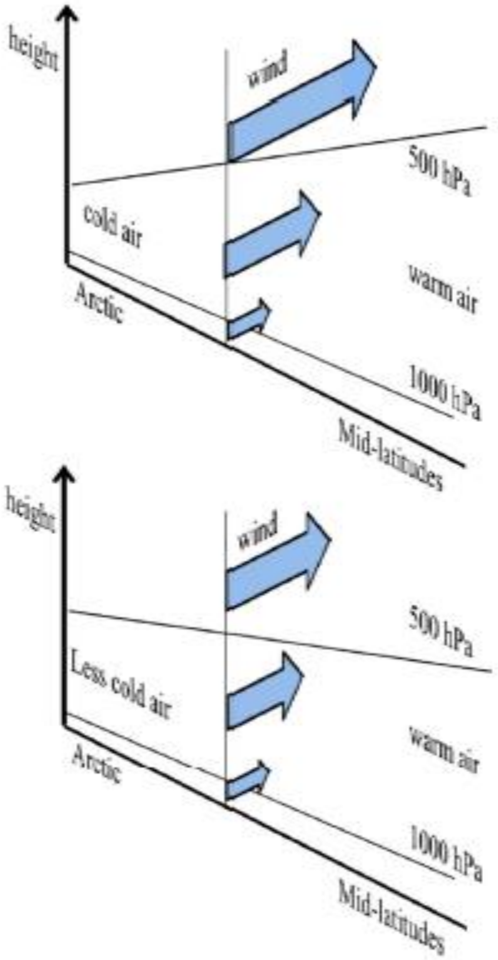


Figure 11. *A simplified description on the effect of high latitude low and mid troposphere warming due to Arctic amplification to zonal wind on different levels of the troposphere. When the thickness of the 1,000 – 500 hPa layer increases in the Arctic area, the geostrophic wind in the upper troposphere decreases according to the thermal wind law. (Vihma 2014).*

These large-scale changes in pressure fields and the consequent weakening of the geostrophic wind have also been found in many different studies using models based on observational data and the physical mechanism can be derived from the baroclinic effect as depicted in Figure 11 (Sui et al. 2017). According to Vihma (2014), this baroclinic component can in many cases be difficult to observe, as anomalies in geopotential height are often dominated by barotropic features. Also, it is difficult to assess whether the changes in pressure and wind fields in the winter are caused by anomalies in sea ice extent during the previous summer and autumn, i.e. a delayed reaction in the atmospheric circulation to sea ice forcing, or whether they are rather a simultaneous, quick reaction to winter ice decline. The former interpretation would be supported by delayed effects through mechanisms that are described in detail in Chapter 7.2 (phenomena resembling the negative NAO/AO index phase). The decline in Arctic sea ice extent being at its largest at the end of summer/early autumn would also lend support to this interpretation, whereas the fact that the positive anomalies in surface air temperature are largest in winter would favour the latter theory of an instantaneous effect. As the atmospheric circulation affects the sea ice extent through heat and moisture advection from lower latitudes and through sea ice fracturing and ice drift induced by increased surface winds, the correlation between sea ice extent and changes in atmospheric circulation could be caused by a simultaneous effect of atmospheric circulation to the sea ice extent or a two-way feedback mechanism between the two. A correlational relationship does not necessarily in this case mean a causal relationship.

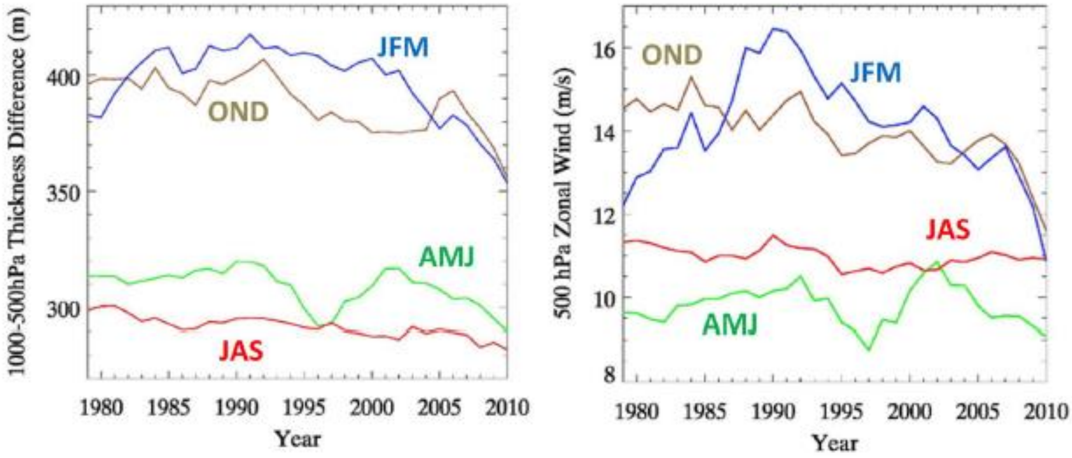


Figure 12. *(left) Time series of seasonal differences in 1000–500 hPa thickness between 80–60 °N and 50–30 °N over the study region of 140 °W to 0 °W. (right) Seasonal zonal mean winds at 500 hPa between 60–40 °N over the study region. Seasons are labeled with months. Data obtained from the NCEP/NCAR reanalysis, http://www.esrl.noaa.gov/psd. (Francis and Vavrus 2012).*

The Arctic Amplification is also seen to shift the routes of the mid-latitude jet streams more towards north even though the regional variation in these changes can be large (Zappa et al. 2018). According to Overland et al. (2011) (based on modelling studies), the increase in the geopotential height has an impact on the Polar vortex through the decrease in the westerly geostrophic wind. This in turn strengthens the meridional air mass flow around the Arctic area. In this manner, both the weakening of the jet streams and the change in their trajectories more poleward and more to a meandering structure affect the meridional air flows as well and contribute to cold air advection from the Polar area and the warm air advection towards the Pole. At the same time the warm air advection to the Arctic area is weakened as the south-north temperature gradient is getting smaller through the Arctic warming (and Arctic Amplification).

7.2 Effects in winter

Changes in atmospheric circulation in the Northern Hemisphere in the winter have in most cases been connected to variability in the Arctic sea ice extent during the previous autumn or during the same winter period. This chapter describes these effects mainly in two areas, the northern Eurasian continent in general (including Europe) and the eastern parts of the continent, around the area of China.

7.2.1 Eurasian continent

One of the phenomena in general atmospheric circulation in the Northern Hemisphere during wintertime that has gained a lot of attention in recent studies is the winter warm-Arctic–cold-midlatitude temperature pattern that has been observed. This has inspired researchers to study how the changes in the Arctic area sea ice and surface temperature are connected to anomalous weather events further away from the Pole (Cheung et al. 2018). Many studies during the last decade have looked into the mechanisms that would convey the local atmospheric effects of the Arctic sea ice decline to changes in the general atmospheric circulation in winter in the Eurasian continent, especially to snow conditions and winter temperatures in the northern parts of the continent.

Peings and Magnusdottir (2013) simulated the atmospheric circulation in the Northern Hemisphere in winter using observational data on sea ice extent from 2007-2012. The two researchers found that the decline in the Arctic sea ice in autumn correlated with lower surface air temperatures in mid-latitudes the following winter. Liu et al. (2012) used data from observations from 1979-2010 and compared the sea ice extent and the mid-latitude surface air temperatures and snow cover in the winter (December-February).

According to these studies, there was a clear connection between the anomalies in temperature and snow thickness and the variation in sea ice extent in the Arctic Ocean. A decrease of the sea ice extent by 1 million km^2 in the autumn was associated with 2-3 ^{o}C lower than normal surface air temperatures in a zone extending from Western Europe to central China and with a larger snow cover (3-12%) the following winter in large parts of northwestern and central Europe and China.

Petoukhov and Semenov (2010) studied the atmospheric response to declines in wintertime sea ice extent (SIE) in the Barents and Kara Seas and showed that the response was non-linear in its character. A small decrease in SIE (from 100% to 80%) resulted in an anomalously cyclonic circulation over the Arctic Ocean and a larger decrease (from 80% to 40%) an anomalously anticyclonic circulation. If the decrease was almost total (down to 1%) the circulation turned to cyclonic again. In the case when the SIE decreases were large, Petoukhov and Semenov (2010) could find in their general circulation model anomalous easterly winds over the Eurasian continent that resulted in a winter cooling of about -1.5 ^{o}C over large parts of the continent and in an almost threefold increase in the probability of cold winter extremes. The atmospheric response in the case when the ice cover had almost totally disappeared, was that the anomalously cyclonic circulation generated in the Eurasian continent warmer winters than normal. These results by Petoukhov and Semenov (2010) supported a conceptual model developed by them in which the non-linear atmospheric response was mainly due to an interaction of convection over the open sea and the baroclinic effect that was the result of the modified temperature gradients near the ice-free sea areas. This study demonstrates the possible non-linearity in the connection between declining SIE and the remote atmospheric responses and could be one of the reasons why different studies have yielded different results on the same phenomenon.

Overland et al. (2011) investigated snow rich winters in the Northern Hemisphere during the years 2008, 2009, and 2010. The researchers could show in the study that the strong negative Arctic sea ice extent anomaly during the previous autumn had a clear correlation with the negative surface air temperature (SAT) anomalies in mid-latitudes the following winter and on the other hand with the positive SAT anomalies in the Polar area (during the following winter as well), confirming the winter warm-Arctic-cold-midlatitude weather pattern.

This weather pattern in the Northern Hemisphere resembles the negative phase of the NAO/AO index what comes to large scale air pressure patterns and jet stream trajectories. Many studies have shown that the decline in the Arctic sea ice extent favours formation of this kind of a phenomenon (Vihma 2014). The weakening of the westerly geostrophic jet stream due to the diminishing south-north pressure gradient as described in Chapter 7.1 increases the meridional component of the flow and on the other hand changes the form of the jet stream track to more meandering with ridges in the flow moving more to the north and throughs more to the south (Liu et al. 2012). At the same time blocking highs are formed over the North Atlantic in a pattern resembling the negative phase of the NAO index. These highs in turn advect warm air masses from the North Atlantic to the Polar area warming it further (warm-Arctic part) and on the other hand causing cold air incursions from the Polar areas to the northern part of the Eurasian continent (cold-midlatitudes part). For example, Overland et al. (2011) estimated that the winter in 2009/2010 when there was a positive anomaly in the geopotential height over the Arctic area and a corresponding negative anomaly over the continent and when the northern parts of Eurasia experienced a very cold and snow-rich weather, had the most negative NAO index since the beginning of the index measurements in 1865.

The weakening of the westerly jet streams favours also the turning of the flow in the northern part of the Eurasian continent to a more easterly flow, which then advects cold air from the eastern parts of the Eurasian continent (Siberia) to the western parts of the continent. The weakening of the westerly jet stream weakens also the Polar vortex around the Pole area leading to the discharge of cold artic air from the Arctic area further south to the Eurasian continent. Also the positive anomaly in the Rossby waves can cause these waves to penetrate the stratosphere and then further weaken the Polar vortex (Vihma 2014).

According to a review by Vihma (2014), there was clear evidence that the thickness of the snow cover in many parts of Russia had increased (and decreased in the Polar area). He suggested that this increase in snow coverage could favour the formation of high pressure anomalies over northern Russia which would then increase easterly winds from the continent during the winter and thereby induce lower winter temperatures in Europe. In this way the increased snow cover and snowfall would have a positive feedback effect on the negative temperature anomaly in Europe resembling the negative phase of the NAO/AO index as described in Chapter 5.1.

7.2.2 Eastern parts of the Eurasian continent and southern China

Wang et al. (2015) have studied the connection between the decreasing Arctic sea ice and the increasing number of winter haze days in eastern China during winter, haze days meaning in this context days with elevated levels of air pollution (particulate matter) in the low, near surface atmosphere. The number of haze days during the winter has risen due to on one hand more air pollution from industry, transportation etc. but on the other hand changes in atmospheric circulation that favour less cyclone activity and a more stable atmosphere trapping more air pollution in the low troposphere. Wang et al. (2015) analyzed Arctic sea ice extent (SIE) data from 1979-2012 and compared it to air pollution measurements around eastern China. They found a clear negative correlation ($r = –0.67$, above 99% confidence level) between autumn (September-November) sea ice extent and winter (December-February) haze days. According to them, around 45% - 67% of the interannual variability in winter haze day frequency could be explained by the variability in SIE. In order to control that this variability was not caused by any other large-scale atmospheric variability, they also calculated the correlation between winter haze days and winter AO, but found almost no correlation between those two. This finding may lend support to the suggestions in many other studies that it is in many cases difficult to separate the effects of the variation in sea ice extent from the general variation and complex processes in atmospheric circulation.

In their study, Wang et al. (2015) suggest a mechanism how the signal from declining sea ice extent in the autumn is transmitted to those kind of weather patterns in eastern China that promote more haze days, i.e. a more stable atmosphere and less cyclone activity. According to them, the reduction in sea ice leads to positive sea-level pressure anomalies in the mid-latitude Eurasian continent extending from northern Europe and the Arctic Ocean to eastern and central-north China. These pressure anomalies along with a dipole pattern over Europe and North Atlantic change circulation patterns so that the typical westerly-northwesterly winds blowing in eastern China are weakened and the wind patterns shift to a more meridional wind pattern which favours incursions of cold air from the Arctic area. Colder surface air conditions in the winter would then enhance the atmospheric temperature inversion trapping the air pollutants near the surface. They also found an association between diminishing SIE and a reduced water vapor content in the low-level atmosphere (850 hPa) over East Asia, which in turn would further worsen air conditions close to the surface. Decreased water vapour content is seen as one of the most important characteristics for haze weather (Wang et al. 2015). Other features favouring a more stable atmosphere and less ventilation of pollutants that were found in their study were a northward shift in cyclone track activity in China and a weaker Rossby wave activity in eastern China (south of 40^{o}N) during winter.

Honda et al. (2009) studied also the effects of autumn Arctic sea ice decline to winter climatological conditions in the eastern part of the Eurasian continent using observational data, the results of which were then supported by numerical experiments using an atmospheric general circulation model. More ice-free sea in the Arctic in autumn created larger turbulent heat fluxes over the open sea which then generated a stationary Rossby wave that induced the amplification of a high pressure over Siberia. This was then found to cause significant cold temperature anomalies over the Far East in the following early winter (December). In late winter (February) this anomaly induced cold anomalies in Far East and also in a zone all the way to Europe. Also Liu et al. (2012) found a similar pattern with cold anomalies in Europe, Siberia, and Far East combining observational data analyses and numerical experiments. The mechanism they suggested for this effect started with a sea ice decline induced positive surface level pressure (SLP) anomalies over high latitudes and negative SLP anomalies over mid-latitudes in winter. These then induce cooling in the Eurasian continent and a corresponding warming in the Arctic Ocean and over Greenland, being another example of the warm-Arctic-cold-mid-latitudes pattern.

Wu et al. (1999) analyzed observational data and used some numerical simulations and also found that the Arctic sea ice decline induced surface warming over the Polar region, caused by a change in the south-north temperature gradient, which then led to the westward penetration of the East Asian jet stream. This in turn strengthened the negative AO pattern already associated with sea ice decline and led to the enhancement of the East Asian Winter Monsoon. This link between the autumn Arctic sea ice area and winter AO index was also found in another study by Li and Wu (2012), where a correlation coefficient as high as 0.47 (99% confidence level) could be established. In a later study based on sea ice extent data (SIE) from 1978-2007 Wu et al. (2013) found also that a decline in SIE induced a negative surface level temperature anomaly over Central and East Asia, which in turn could bring with it more frequent and /or intense winter extreme weather conditions in the region.

7.3 Effects in spring

Even though most of the studies until now have looked into the remote effects of the Arctic sea ice decline to atmospheric circulation during the autumn and winter, there are also some studies that have found some possible connections between variation in sea ice extent and springtime anomalies in atmospheric variables. The results of some of these studies are discussed in this chapter.

Li and Wang (2013) analyzed temperature data from years 1998-2012 and found a cooling trend in surface air temperature (SAT) along the East Asian coast in springtime (March-May). Similarly, they found a corresponding cooling trend in sea surface temperatures (SST) in the northwestern Pacific Ocean and a weakening of the 300 hPa East Asian Jet (EAJ) during the same time period (spring). They showed then that this spring cooling, which was contrary to the global warming trend in general, could be related to the decline in the Arctic sea ice extent during the previous autumn. A diminishing sea ice cover during the autumn provided an enhanced moisture source to the atmosphere, a signal that continued over the winter, and consequently supported an increase in the snow cover in Siberia the following spring. This in turn would favour the southward invasion of cold air masses via strong radiative cooling and large-scale descending motion and induce negative temperature anomalies in East Asia. Their study could show a close association between loss of sea ice cover in the autumn and the northerly wind anomalies in Siberia and Mongolia in the spring. The weakening of the East Asian Jet would be supported by this advection of colder air from the Artic and on the other hand by the general warming of the Arctic and the decreasing pressure gradient between the Arctic area and mid-latitudes as described in Chapter 7.1., and in that sense be consistent with the general decrease in meridional temperature gradient.

In many cases the atmospheric circulation phenomenon of snow-rich and colder winters in the Eurasian continent as described in Chapter 7.2 can be seen extending to early spring months as well and would resemble the weather patterns normally associated with a negative NAO/AO index. According to Zuo et al. (2016), the decline in Arctic sea ice extent has been linked to the increase in spring snowfall and lower surface level temperatures over the Eurasian continent. On the other hand, Kapsch et al. (2018) found that in springtime years with low sea ice extent in the autumn could be related with circulation patterns in the spring that would be more consistent with the positive phase of the Arctic Oscillation, although they found that the evidence on this was inconclusive. On a local scale, Arctic autumnal sea ice decline favoured enhanced long wave radiative and turbulent fluxes the following spring with an earlier ice melt onset and with more thin, first year ice that could be more easily broken and fractured by the wind forces and ocean currents.

7.4 Effects in summer

There are several remote effects of the Arctic sea ice decline on the atmospheric circulation in the summer. Quite often these effects are transmitted with a time lag, most often they originate in sea ice conditions in the previous spring or winter/spring. This chapter describes some of the atmospheric circulation phenomena that are well researched and that are backed up by observational data and several studies that yield similar results.

7.4.1 Eurasian continent and Europe

According to Vihma (2014), the remote effects of the Artic sea ice decline can be observed in the Eurasian continent also in the summer. Screen (2013) analyzed observational data from 1979-2012 and analyzed data from those years where the summer precipitation in Europe was significantly higher than the average during the previous 30 years. He found that during those summers when there was a positive precipitation anomaly, the jet stream on the 300 hPa pressure level had moved to a more southerly route. In those kinds of conditions central and northern Europe (barring the northernmost part of Scandinavia) experienced higher than normal rainfall during the summer. According to Screen, approximately a third of the observed increase in precipitation could be explained by the decline in the Arctic sea ice during the previous spring. Similar results were obtained in another study that used a different simulation and reanalysis model (U.K. Meteorological Office Unified Model) (Vihma 2014). Also Wu et al. (2013) showed in their study based on data reanalysis that winter-spring sea ice extent anomalies off the western coast of Greenland had a statistically significant negative correlation with precipitation over the Eurasian continent during the following summer. A decline in the Arctic sea ice cover implied an increased rainfall in northwestern Europe the following summer.

Screen (2013) proposed an atmospheric mechanism through which the sea ice extent anomaly was transmitted to changes in precipitation in Europe. A local decline in sea ice in the Sea of Okhotsk during winter/spring increases storm activity over that sea which then strengthens storm tracks in the northern Pacific. A lasting low pressure system over North Pacific Ocean together with a decline in sea ice extent in Hudson Bay and Labrador Sea induce a stationary wave train over North America which then produces a prevailing low pressure over the northeastern Atlantic and the British Isles. Here a local change in the sea ice extent in a marginal sea can have a significant remote effect on the other side of the globe through a chain of different dynamic and thermodynamic mechanisms (see Figure 13 for a schematic view of the process).

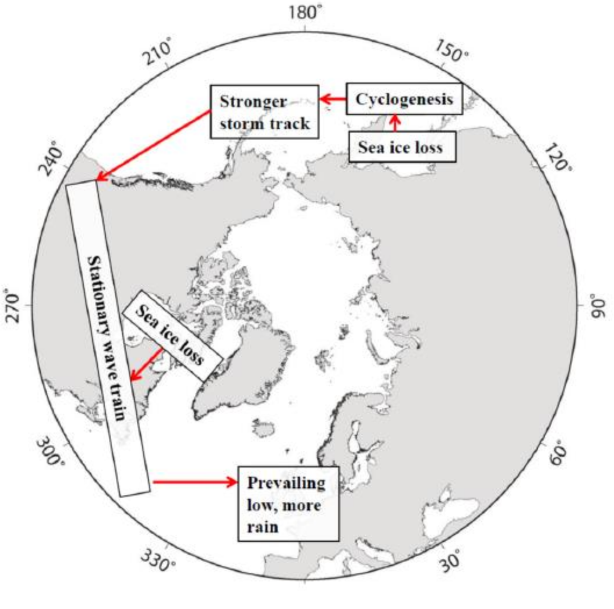


Figure 13. *A local decrease in sea ice extent in the Sea of Okhotsk, Hudson Bay, and the Labrador Sea increases summer precipitation in Europe. Mechanisms through which the remote effects are transmitted (Vihma 2014).*

7.4.2 Eurasian continent and summer monsoon in southern China

Sea ice decline also affects the climatological conditions in the eastern part of the Eurasian continent during the summer. Several studies have looked into shifts in the summer monsoon in southern China. The results of these have been, based on analysis of observational data and model experiments, that early spring sea ice decline in the Arctic area enhances summer monsoon rainfall in southeastern China (Vihma 2014). Guo et al. (2013) analyzed observational data on sea ice extent and changes in summer monsoon precipitation as represented by the Eastern Asia Summer Monsoon index (EASM). They found a negative correlation between February-March-April sea ice extent and EASM index in June-July-August with a correlation coefficient of $r = -0.42$ (significant at the 95 % confidence level). Based on their observationally based analysis and model experiments Guo et al. (2013) suggested a possible mechanism for the observed correlation.

According to Guo et el. (2013), the spring sea ice anomalies in the Arctic cause cyclonic circulation anomalies in the western North Pacific, which then affect the sea surface temperature (SST) in that area. These SST anomalies can then persist into summer and impact the summer monsoon circulation and precipitation over East Asia through several mechanisms. Higher than normal SST causes anomalous cyclone activity in the area and weakens the subtropical high in south China. Also, the East Asian summer westerly jet at 200 hPa moves northward. These three mechanisms together then lead to enhanced summer monsoon activity over southeastern China. The proposed mechanism between Arctic sea ice decline and higher precipitation in China is explained schematically in Figure 14.

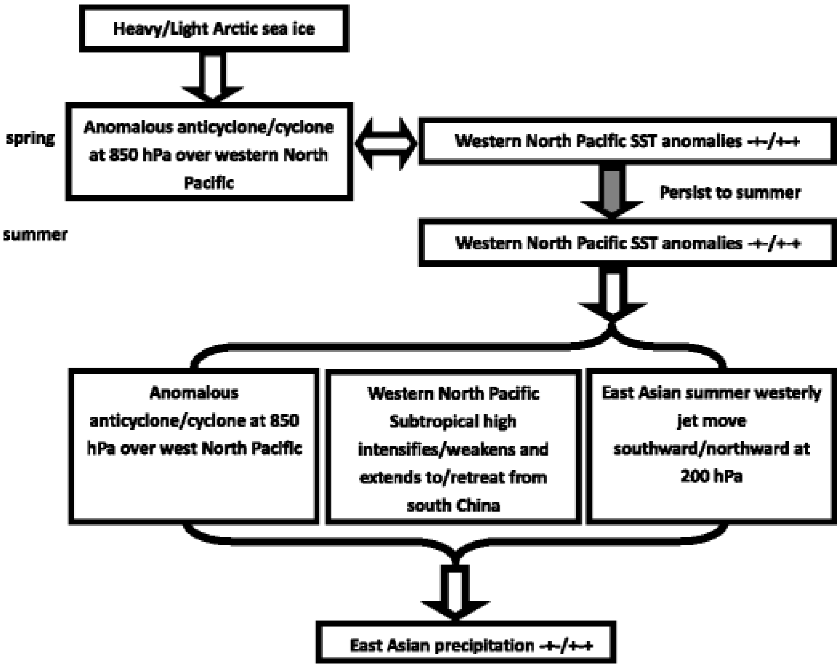


Figure 14. *A schematic summary of a proposed mechanism between spring Arctic sea ice decline and enhanced summer monsoon activity in southeastern China (Guo et al. 2013).*

Zao et al. (2004) had already much earlier observed the same phenomenon but suggested a partly different mechanism for the remote effect of the sea ice decline on eastern China precipitation. Based on an analysis of observed data and modeling experiments the researchers found the same pattern as Guo et al., i.e. that the western North Pacific cyclone activity led to a higher than normal sea surface temperature which then transmitted the sea ice decline effect to the summer monsoon, but they suggested another component in the equation as well. Negative anomalies in Arctic sea ice extent in spring can generate in the following summer high sea-level pressure, reduced soil moisture, and higher surface temperatures over Europe. These create an anomalous high at 500 hPa over southeastern Asian which then together with a sea ice decline induced wave train structure at the same pressure level effect the summer monsoon and precipitation in southeastern China.

7.5 Effects in autumn

Many effects of the decline in Arctic sea ice extent (SIE) on atmospheric circulation in the winter seen in Chapter 7.2, especially those involving enhanced snowfall and anomalously cold surface air temperatures (SAT) in the Eurasian continent, start already in the autumn and continue with more intensity during the winter. This may be part of the reason why there haven’t been so many studies that would be concentrating only on autumn. As seen with most of the wider range atmospheric effects described in this Chapter 7, there is a lag between the changes in the Arctic SIE and the remote effects of these on the Northern Hemisphere circulation patterns as the remote effects are often transmitted through several steps sometimes involving a stratospheric connection (whereas effects conveyed only by changes in Rossby waves would be more simultaneous in timescales of only weeks). Therefore it could be suggested that most of the remote effects are less felt in the autumn due to smaller SIE changes in the previous season(s), whereas the local effects are more simultaneous (as described in Chapter 6) and influenced heavily by the more dramatic decrease in the Arctic SIE in the beginning of the autumn. Although there are not so many studies available that are specifically addressing the autumn, some of the observed phenomena are described here in this chapter.

Stroeve et al. (2011) investigated observational reanalysis data from 1979-2008 to detect changes in cyclone activity and contrasted this to changes in the Arctic sea ice along with a reanalysis of several relevant atmospheric variables (i.a. fields of sea level pressure, precipitation, water vapour content, and surface fluxes). The findings of the study showed that years with small SIE were associated with reduced atmospheric stability and an increase in tropospheric moisture with a corresponding increase in the frequency and intensity of autumn cyclone activity in the Atlantic sector of the Arctic, which then could be observed over large parts of the Eurasian continent (Stroeve et al. 2011). It was difficult to establish a pattern in this, for although there was a correlation between SIE decline and cyclone activity, it was not as easy to find a causal relation. Increased cyclone activity in the Arctic could have also influenced the sea ice decline making it problematic to link the increased cyclone activity in Eurasia directly to the decline in the SIE.

Francis et al. (2009) used observational data on the Arctic sea ice extent with in situ atmospheric observations. In the study variations in sea ice conditions in the summer could be associated with anomalies in atmospheric large-scale circulation in the following autumn and winter. Statistically significant anomalies were found in air temperature, sea-level pressure, and precipitation in several regions in the Northern Hemisphere, and the study could conclude that these anomalies seemed to be caused by changes in sea level pressure (SLP) in the Arctic area and mid-latitudes. A negative anomaly in sea ice cover during summer corresponded with higher SLP in the Artic and a lower SLP in mid-latitudes. Francis et al. (2009) found also that a small sea ice extent during summer would induce an atmospheric behaviour during the subsequent autumn that resembled the negative phase of the NAO index, similar to the same kind of a phenomenon in the winter as discussed in Chapter 7.2

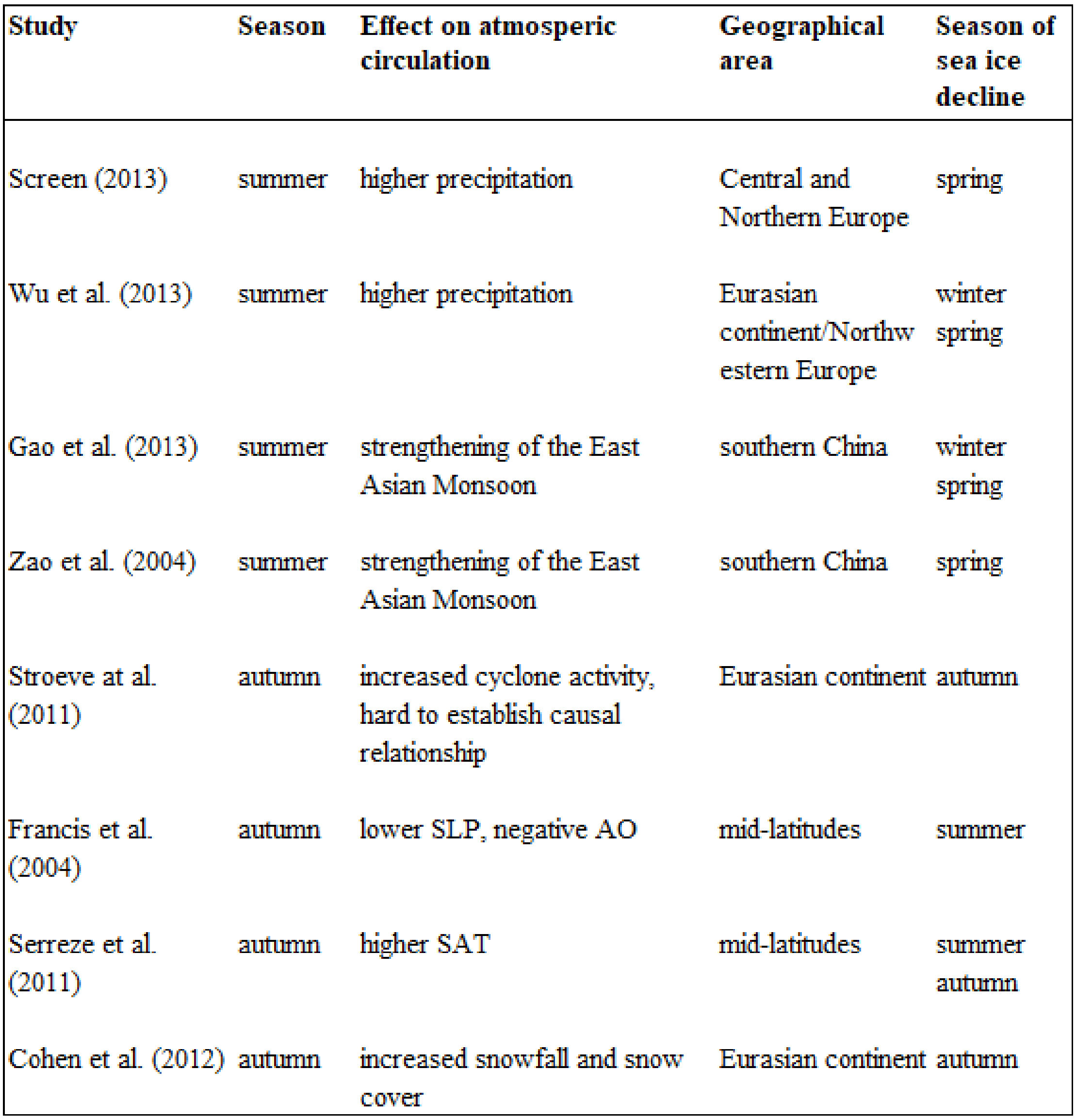
Based on a reanalysis of observational data, Serreze et al. (2009) compared surface air temperatures (SAT) in northern mid-latitudes (60-70^{o}N) during years with smaller sea ice extent (2000-2009) and a longer reference period (1979-2009) with on average larger sea ice cover. The study showed that during northerly winds the temperature in mid-latitudes was higher during the period 2000–2009 (negative sea ice extent anomaly) compared to the reference period, with the warming being largest, 0.5–2 ^{o}C in the autumn and the winter.

Contrary to the previous two studies where the changes in autumnal atmospheric circulation were caused by a lagged effect from variation in sea ice extent the previous summer, Cohen et al. (2012) found out a simultaneous mechanism in the autumn. The study used satellite measurements for ice cover data and measurements from sounding campaigns for assessing the moisture content in the Arctic troposphere. A combination of a general increase in atmospheric moisture content due to a warming climate and enhanced evaporation in autumn from a more ice-free Arctic Ocean contributed to an increase in snow fall and snow cover in the Eurasian continent during the same season. This change in autumnal snow cover would then dynamically force negative AO index weather condition the following winter. This is somewhat similar to the results discussed earlier in the study by Francis et al. (2009) and ties up with the discussion in Chapter 7.2 about the effects in winter with a negative NAO/AO anomaly.

7.6 Summary of the remote effects

This chapter gives a short overview of the different remote effects in different seasons discussed in the previous chapters in form of a simplified table (Table 2). As can be seen from the table, most of the effects in the Eurasian continent are related to changes in surface air temperature and precipitation and in the eastern part of the continent (mainly above and around China) to changes in the East Asian Monsoon (summer and winter). Also changes in the Arctic Oscillation pattern play a significant part.

Study	**Season**	**Effect on atmosperic circulation**	**Geographical area**	**Season of sea ice decline**
Peings and Magnusdottir (2013)	winter	lower SLP	mid-latitudes	autumn
Liu et al. (2012)	winter	larger snow cover lower SAT	mid-latitudes Western Europe to China	autumn
Petukhov and Semenov (2010)	winter	non-linear response large SIE decline: anomalously easterly winds, lower SAT total SIE decline: warmer SAT	Eurasian continent	winter
Overland et al. (2011)	winter	lower SAT	mid-latitudes	autumn
Wang et al. (2015)	winter	less cyclone activity, more stable atmosphere	eastern China	autumn
Honda et al. (2009)	winter	cold temperature anomalies	Far East	autumn
Wu et al. (1999)	winter	stronger East Asian Monsoon, negative AO pattern	Central and East Asia	autumn
Li and Wu (2012)	winter	negative AO pattern	Eurasian continent	autumn
Li and Wang (2013)	spring	lower SAT, weakening of the East Asian jet	Central and East Asia	autumn
Zao et al (2016)	spring	lower SAT, increased snowfall	East Asian coast	spring
Kapsch et al. (2018)	spring	positive phase of AO	northern Eurasian continent	autumn



Study	**Season**	**Effect on atmosperic circulation**	**Geographical area**	**Season of sea ice decline**
Screen (2013)	summer	higher precipitation	Central and Northern Europe	spring
Wu et al. (2013)	summer	higher precipitation	Eurasian continent/Northwestern Europe	winter spring
Gao et al. (2013)	summer	strengthening of the East Asian Monsoon	southern China	winter spring
Zao et al. (2004)	summer	strengthening of the East Asian Monsoon	southern China	spring
Stroeve at al. (2011)	autumn	increased cyclone activity, hard to establish causal relationship	Eurasian continent	autumn
Francis et al. (2004)	autumn	lower SLP, negative AO	mid-latitudes	summer
Serreze et al. (2011)	autumn	higher SAT	mid-latitudes	summer autumn
Cohen et al. (2012)	autumn	increased snowfall and snow cover	Eurasian continent	autumn

Table 2. A summary of the studies on the remote effects on atmospheric circulation of the Arctic sea ice decline discussed in Chapter 7.

8. Conclusions and discussion

The local and regional changes in atmospheric circulation over the Arctic area caused by the diminishing Arctic sea ice extent are fairly well described and studied. The mechanisms behind these phenomena are physically more straightforward and clearer and better understood as most of these are to do with the change in surface albedo and the isolation capacity of the surface. A significantly larger part of the incoming solar shortwave radiation is absorbed by ice-free open water than would be the case if the surface was covered by clear ice or ice with a thick snow cover on it. Without ice there is much less isolation between the ocean and the atmosphere which increases sensible and latent heat fluxes from the ocean. This is especially true in winter when the temperature gradient between the ice-free sea water and the extremely cold polar atmosphere is very large. The moisture mass flow from the ocean surface increases the humidity, cloudiness, and precipitation in the lower troposphere, and together with larger heat fluxes decreases stratification in the lower troposphere and increases turbulence. These in turn increase the height of the atmospheric boundary layer and make it more mixed.

These local atmospheric effects intensify the Arctic Amplification forming a positive feedback to the Arctic sea ice decline. More heat in the Arctic atmosphere mean less sea ice and less sea ice means again more heat in the atmosphere. This combined with global warming makes the assessment described in Chapter 2 by Mård et al. (2017) of a totally ice-free Artic Ocean (at the end of the melting season in September) already by 2030's a more probable scenario.

The remote effects and mechanisms of the Arctic sea ice decline to a wider atmospheric circulation in the Northern Hemisphere are not as clear as the local effects although a consensus has started to emerge regarding some of the main findings of recent studies. Lack of long-term reliable and encompassing data on the sea ice extent has been one of the challenges in many modelling studies that rely on reanalysis of observational and computed data, even though some efforts have been made to consolidate data even before the era of satellite-based measurements.

The decreasing north-south gradient of the pressure field thickness and the subsequent decrease in the westerly geostrophic wind (jet stream) is in its physical mechanisms well understood and is supported by observational data and can be reproduced in modelling studies. Many of the remote effects are based on or have their beginning in this phenomenon also through the subsequent increase in the meridional component of the jet streams and the changes in their trajectories. The mechanisms through which these changes effect wider atmospheric circulation in the mid and high latitude areas in the Northern Hemisphere resemble according to many studies the negative phase of the NAO/AO index. In the western and middle parts of the northern Eurasian continent this induces cold and snow-rich winters as the weather pattern comprises cold air incursion from the Artic area, an easterly wind anomaly caused by a Siberian high pressure, and a weakening of the Arctic Polar vortex. The cold air incursions are to some extent then dampened by the Arctic Amplification that keeps the polar air masses warmer than earlier.

In eastern parts of the Eurasian continent the Arctic sea ice decline strengthens the summer monsoon and increases precipitation especially over and around China. Several studies have come to the same conclusion, although the mechanisms proposed have varied. In winter the effect of diminishing sea ice extent has been to decrease cyclone activity and increase the stability of the atmosphere which has led to larger challenges with air pollution in China. Some of the winter effects tend to extend to the spring as well, but also a separate pattern with cooler surface air temperatures has been found.

Although this Master’s thesis is structured around the seasonal effects, in many cases the effects from one season extend to the previous or the following season (e.g. cold surface air temperatures in northern parts of the Eurasian continent). Most of the studies have looked into atmospheric circulation effects in winter, partly because of the effects of large negative sea ice extent anomalies in the autumn or large heat flux and temperature anomalies in the winter but partly also because of the recent occurrence of several anomalously cold winters with a lot of snowfall in the Eurasian continent. In the same manner the more extreme weather events in China (strengthening of the summer monsoon, increasing air pollution in the winter) have evoked research attention.

Even though there have been more and more studies on the effects of the Arctic sea ice decline on atmospheric circulation in the Northern Hemisphere and even though the local effects are better understood, there are still many gaps in the models used in what comes to for example a better simulation of variation in ice retreat and growth, the interactions between the troposphere and the stratosphere and the stratospheric feedback, and the ocean-(ice)-atmosphere interaction (Vihma 2014). Long-term reliable data are also needed to better utilize the models and consolidate the results with observations. Many other factors influence the atmospheric circulation and more studies are needed to what is the impact of the sea ice decline and what part is due to other dynamical and thermodynamical factors. The results that have been obtained may in some cases be caused by either the innate variation in the atmosphere or be influenced by some other, multi-decal variation that the still quite short data series (especially on sea ice extent) cannot yet capture. More studies are also needed to cover all the different seasons and to encapsulate possible inter-seasonal dependencies.

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