

Linking Northern High-Latitude Cryospheric Changes to Large-Scale Atmospheric Circulation

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Dissertation for the degree of Philosophiae Doctor (PhD)

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March 2015

Dissertation date: March 20, 2015

Boredom didn't frighten me. There are worse pangs: the sorrow of not sharing with a loved one the beauty of lived moments. Solitude: what others miss out on by not being with the person who experiences it.

*Sylvain Tesson,
The Consolations of the Forest*

Acknowledgments

Numerous people have directly or indirectly helped me to get to the stage of writing my PhD dissertation. Firstly, my main advisor Prof. Tore Furevik should get recognition for balancing supervising me with travelling the world's research institutions as the leader of the Bjerknnes Centre for Climate Research (BCCR) and the Centre for Climate Dynamics (SKD). Secondly, my two other co-advisors, Dr. Yvan J. Orsolini at the Norwegian Institute for Air Research and Prof. Nils Gunnar Kvamstø at the Geophysical Institute (GFI), University of Bergen (UiB), also provided valuable contribution along the way. I would like to especially draw attention to the former's patience and constructive criticism as significant in finalizing my work.

Thirdly, this work was financially supported by the Research Council of Norway through the *BlueArc* project (no. 207650), and I wish to thank project leader Dr. Yongqi Gao for a great topic and inspiring meetings.

Fourthly, both Prof. David W.J. Thompson and Prof. John E. Walsh deserve special thanks. As hosts during my research stays at the Colorado State University (CSU), and the International Arctic Research Center (IARC)/University of Alaska Fairbanks (UAF), respectively, they both provided challenges and strengthened my ability to stand on my own legs. In particular, I found Walsh' ability to lead graduate students in finding good solutions and becoming independent researchers being second to none.

Fifthly, I am highly grateful to my colleagues and fellow students at GFI/UiB, SKD/BCCR, the Nansen Environmental and Remote Sensing Center, University of Oslo (during my shorter stays here), the Norwegian Research School in Climate Dynamics (over short courses and seminars), CSU (during my 11 months research stay here) and UAF (during my 2 months research stay here). In addition to coffee breaks and sports conversations, you have also had important contributions in sharing frustration and experiences — dampening the feeling of solitude a PhD degree might give. Starting from scratch socially in both Fort Collins and Fairbanks, friends while at CSU and IARC/UAF deserve extra thanks for making the transition from the Norwegian to the American culture as smooth as possible.

Finally, family, friends and sport club buddies should get the last recognition. As the blinders grew bigger and bigger towards the end of my PhD period, you gave me understanding and room to focus.

Erlend Moster Knudsen
Bergen, December 2014

Abstract

Warming twice as fast as the rest of the globe, the northern high-latitudes arguably show the clearest evidences of observed and projected climate changes. Two of these are the rapid loss of Arctic sea ice and the shrinking of the Greenland Ice Sheet. In this dissertation, three papers analyze the interaction between the cryospheric changes and the atmospheric circulation.

In the first paper, summers of observed anomalous Arctic sea ice melt are composited in order to distinguish large-scale atmospheric patterns associated with sea ice loss. While a positive cloud feedback characterizes warm high-latitude summers, storms track more zonally in midlatitudes, leaving summers stormier, wetter and cooler in northwestern Europe and around the Sea of Okhotsk. Farther south, a heating band from the Mediterranean Sea to East Asia indicates an increased probability of heat extremes in these areas in summers of high Arctic sea ice melt.

The second paper analyzes projected changes in Arctic sea ice and Northern Hemisphere storminess. Here, a general poleward-shift of the main storm tracks is revealed. Cyclone intensities generally follow cyclone frequencies, but with an elevated intensification over new open ocean areas. For most of the domain, precipitation increases significantly, with the highest enhancements along the poleward-shifted storm tracks and in the sea ice diminishing Arctic.

Finally, the influence of cyclonic and anticyclonic activities on the observed Greenland Ice Sheet (GrIS) surface mass balance (SMB) variability annually is analyzed in the third paper. The synoptic features correlate with the SMB changes through their impact on temperature and snow accumulation. Generally, enhanced cyclonic activity contributes to increased snow accumulation over the GrIS by transporting more heat and moisture from the south. A warming effect also results from enhanced anticyclonic activity in summer, where fewer clouds increase the incoming shortwave radiation and thus surface temperature. Overall, up to 60 % of the regional SMB variability can be explained by these synoptic activities.

All together, the three papers illustrate how the Arctic sea ice and the GrIS interconnect with local and remote changes in the atmospheric circulation. While various studies find the regional changes to significantly alter ecosystems, impact local communities and enhance industry potential, distant consequences might include sea level rise, elevated risks of extreme weather events, decline in agricultural production, economic disruption and hence political instabilities.

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1 Outline

The thesis consists of an introductory part and a collection of three journal paper manuscripts. A brief scientific background is given in section 2 before section 3 describes the study's objectives, tools and methods. The main results are given in section 4. Finally, section 5 sees the results in a wider perspective and offers an outlook for how future studies can build on the results presented here.

The manuscripts included in the thesis are listed below.

PAPER I

Observed anomalous atmospheric patterns in summers of unusual Arctic sea ice melt

Knudsen, E.M., Orsolini, Y.J., Furevik, T., Hodges, K.I.

Revised manuscript submitted to Journal of Geophysical Research

PAPER II

Northern Hemisphere storminess in the Norwegian Earth System Model (NorESM1-M)¹

Knudsen, E.M., Walsh, J.E.

Geoscientific Model Development Discussions, **7**, 8975–9015

PAPER III

The variability of surface mass balance over the Greenland Ice Sheet and associated cyclonic and anticyclonic activities

Chen, L., Knudsen, E.M., Fettweis, X., Johannessen, O.M.

Manuscript in preparation

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2 Background

The Arctic is home to arguably the most pronounced manifestation of climate change. It is warming twice as fast as the global mean (*Serreze et al.*, 2009; *Bekryaev et al.*, 2010; *Screen and Simmonds*, 2010). This is mainly due to strong radiative feedbacks such as tropospheric warming that deviates from the vertically uniform profile (lapse-rate feedback), vertically uniform warming of the surface and troposphere (Planck feedback), replacement of white ice- or snow-covered surfaces by darker water, vegetation or soil (albedo feedback), and to a lesser extent also dynamic feedbacks such as increased atmospheric and oceanic poleward transports of heat and moisture (*Perovich et al.*, 2007; *Screen and Simmonds*, 2010; *Riihelä et al.*, 2013; *Pistone et al.*, 2014; *Pithan and Mauritsen*, 2014; *Walsh*, 2014).

2.1 Sea ice cover

A consequence of — and also a reason for — the anomalous warming in the Arctic is the sea ice retreat (*Screen and Simmonds*, 2010; *Screen et al.*, 2012; *Cohen et al.*, 2014). Since the start of the modern satellite era in the late 1970s, the mean sea ice extent at the end of the melt season (September) has decreased substantially and at an accelerated pace since the entry to the 21st century (*Stroeve et al.*, 2012a). The present record low of $3.4 \cdot 10^6$ km² was set 13 September 2012, close to 50 % below the long-term mean (1979-2000) (*Liu et al.*, 2013; *Parkinson and Comiso*, 2013).

While most climate models project the summer Arctic sea ice to disappear by the end of the current century (Figure 1) (*Boé et al.*, 2009; *Mahlstein and Knutti*, 2012; *Liu et al.*, 2013; *Stroeve et al.*, 2012b), some models reach this point already within two to three decades (*Wang and Overland*, 2012). This state, referred to as the Blue Arctic, has the Arctic Ocean covered by less than $1 \cdot 10^6$ km² by September, with most of this ice in the region north of Greenland and Ellesmere Island (*Rothrock and Zhang*, 2005; *Maslanik et al.*, 2007; *Haas et al.*, 2008). However, the model spread and scientific discussion on the timeline of a Blue Arctic is large (*Boé et al.*, 2010; *Liu et al.*, 2013). An ongoing debate is whether a tipping point is reached (*Smedsrud et al.*, 2008; *Eisenman and Wettlaufer*, 2009; *Maslanik et al.*, 2011; *Tietsche et al.*, 2011; *Wadhams*, 2012). This “point of no return” denotes a situation where sea ice formed in winter does not survive the summer melt (*Eisenman and Wettlaufer*, 2009), even if the atmospheric forcing should return to what was considered to be normal some decades ago.

None of the Coupled Model Intercomparison Project (CMIP) models are able to repro-

duce the observed trend in Arctic sea ice (Figure 2) (*Stroeve et al.*, 2007; *Wang and Overland*, 2009; *Stroeve et al.*, 2012b; *Wang and Overland*, 2012). Even though CMIP phase 5 (CMIP5) models are more consistent with observations than CMIP phase 3 (CMIP3) models, they still underestimate the rapid decline (*Stroeve et al.*, 2012b). Moreover, the spread within CMIP5 models do not appear to be significantly reduced compared to that of CMIP3 models (*Stroeve et al.*, 2012b).

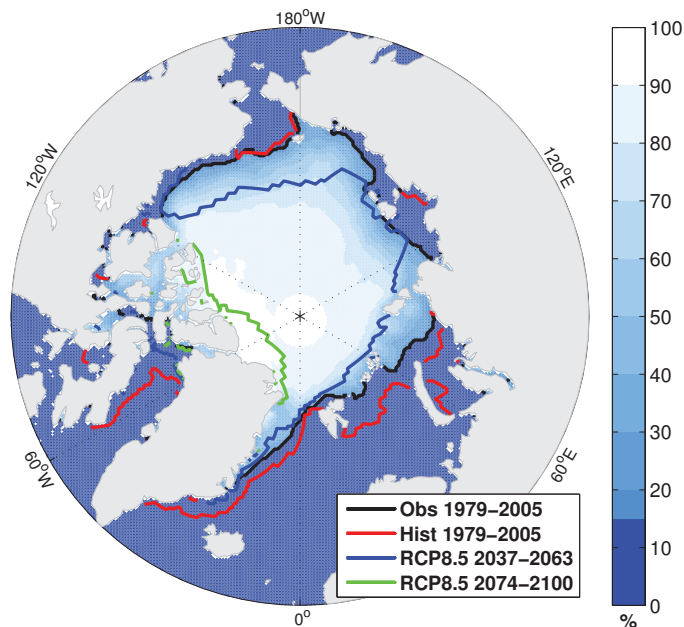


Figure 1: Map of observed and modeled Arctic sea ice concentration (in %) and boundaries in September for three 27-year time periods. Shades of blue to white mark observed sea ice concentration averaged over 1979–2005 from the National Snow and Ice Data Center (cf. section 3.2.1), with its boundaries in black. Red, blue and green lines show the corresponding modeled sea ice boundaries from the Norwegian Earth System Model (cf. section 3.2.4) over the historical 1979–2005 and future scenario (following the RCP8.5 scenario; cf. section 4.2) 2037–2063 and 2074–2100 time periods, respectively. Boundaries are calculated using a threshold of 15 % sea ice concentration.

2.2 Sea ice thickness and volume

The sea ice retreat is more dramatic than what the areal extent indicates. From 1991 to 2001, helicopter-borne electromagnetic-inductive measurements by *Haas* (2004) showed a

mean summer thinning of 23 % in the North Pole region, with an accelerated reduction of up to 44 % by 2007 (*Haas et al.*, 2008). This accentuates the rapid decline over the last decades when compared to the Arctic-wide 1.6 m or 53 % summer thinning from 1958–1976 (submarine data) to 2003–2008 (satellite data) found by *Kwok and Rothrock* (2009). Furthermore, using the Pan-Arctic Ice Ocean Modeling and Assimilation System (PIOMAS), *Overland and Wang* (2013) estimated the September 2012 sea ice volume to drop 72 % below the 1979–2012 mean.

This thinning and volume loss mainly follows from a regime shift from primarily multi- and second-year ice (MYI and SYI; ice surviving previous summer melt) to first-year ice (FYI; ice formed since last summer) (*Maslanik et al.*, 2007; *Haas et al.*, 2008; *Kwok et al.*, 2009; *Maslanik et al.*, 2011). Compared to MYI and SYI, FYI is thinner, and subsequently is more easily broken up and transported around — with a potential for more rapid changes in sea ice cover (*Maslanik et al.*, 2007; *Haas et al.*, 2008). The more mobile ice leaves converging or diverging transports with stronger impacts on air-sea fluxes of momentum, heat and gas including moisture and greenhouse gasses (*Thorndike and Colony*, 1982; *Ogi et al.*, 2010; *Spreen et al.*, 2011; *Weiss*, 2013). Hence, the thinning might have more severe climatic consequences than the areal loss more easily detected by satellites and ship traffic.

2.3 Seasonal variability of sea ice

Substantial intraannual and interannual variability characterize the Arctic sea ice. While the sea ice extent traditionally has been in the range of $15\text{--}16 \cdot 10^6$ km² of the polar and subpolar oceans in March, it has been only $4\text{--}7 \cdot 10^6$ km² in September (*Parkinson and Cavalieri*, 2008; *Cavalieri and Parkinson*, 2012). In other words, the annual sea ice minimum is less than half of its maximum extent. Nevertheless, the intraannual in the Arctic is small compared to the Antarctic, where only about 1/6 of winter sea ice remains by the end of summer (*National Snow and Ice Data Center*, 2014a).

From an average value of about $7 \cdot 10^6$ km² in the 1980's and 1990's, September Arctic sea ice extent has dropped by about 13 % per decade (relative to the 1981 to 2010 average) to about $5 \cdot 10^6$ km² over the last decade (Figure 2) (*Cavalieri and Parkinson*, 2012; *National Snow and Ice Data Center*, 2014b). Concurrently, March sea ice extent has retreated by 3 % per decade (relative to the 1981 to 2010 average) (*Vizcarra*, 2014). With the exception of the Bering Sea, the negative trend spans the whole Arctic, with the highest yearly retreats found around the Sea of Okhotsk, Gulf of St. Lawrence and the Kara and Barents seas (*Cavalieri and Parkinson*, 2012). Correspondingly, interannual

spread is larger in months with the largest negative trend over the satellite period (*Serreze et al.*, 2007a; *Cavalieri and Parkinson*, 2012; *Langehaug et al.*, 2013).

The fall is especially interesting from a climatological sense. At this time of year, the atmosphere cools off rapidly, increasing the temperature gradient between ocean and atmosphere due to the formers high thermal inertia. Because of the increasingly negative trend in September sea ice cover and greater amounts of heat absorbed by the ocean during the longer summer, it takes the sea ice on average more time each year to refreeze (*Francis et al.*, 2009a; *Markus et al.*, 2009; *Stroeve et al.*, 2014). Consequently, strong heat and moisture fluxes from the warm ocean to the colder atmosphere are allowed in area normally covered by sea ice, thus heating the lower troposphere and altering the static stability (*Francis et al.*, 2009a; *Serreze and Barry*, 2009; *Strey et al.*, 2010; *Cohen et al.*, 2014).

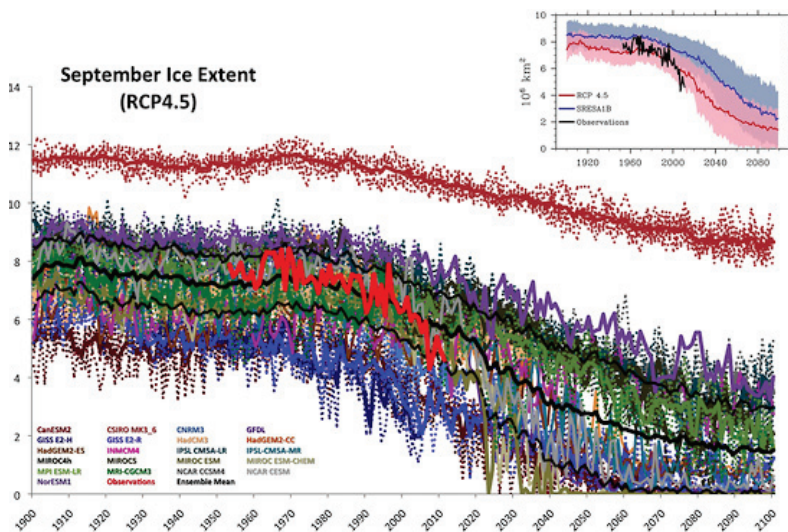


Figure 2: Time series of observed (solid red line) and modeled (colored lines) Arctic sea ice extent (in 10^6 km^2) in September over 1900–2100. Dotted colored lines mark all 56 individual ensemble members from 20 CMIP5 models, with individual model ensemble means in solid colored lines. Solid black line denote the multi-model mean based on 38 ensemble members from 17 CMIP5 models, with ± 1 standard deviation (STD) in dotted black lines. All model scenarios follow the low emission scenario RCP4.5 (c.f. section 4.2). Inset shows observations compared to multi-model means from CMIP3 and CMIP5 models, with ± 1 STD in shaded color. From *Stroeve et al.* (2012b).

2.4 Arctic cyclonic activity

A reduced static stability and increased contrasts between cold land and warm ocean provide favorable conditions for cyclonic activity (*Bengtsson et al.*, 2006). Cyclones are found to be highly related to the Arctic sea ice (*Sorteberg and Kvingedal*, 2006), and they have major impacts on precipitation, the radiation budget and cloudiness, in addition to poleward heat and moisture transport (*Bengtsson et al.*, 2006; *Sorteberg and Walsh*, 2008; *Budikova*, 2009; *Sepp and Jaagus*, 2011).

While storm are stronger in wintertime (*Bengtsson et al.*, 2009; *Long and Perrie*, 2012), summer is the most synoptically active period of the year over the central Arctic Ocean (*Serreze and Barrett*, 2008), making summer cyclones crucial for high-latitude climate in this time of the year (*Mesquita et al.*, 2008). This is exemplified by ‘The Great Arctic Cyclone of August 2012’, which likely further amplified the record-breaking sea ice minimum (*Simmonds and Rudeva*, 2012; *Parkinson and Comiso*, 2013; *Zhang et al.*, 2013). Earlier studies have shown that the cyclone tracks in summer are climatologically more tightly defined and poleward located compared to storm tracks in winter (*Mesquita et al.*, 2008). In summer, the heating contrast between the Eurasian continent and the Arctic Ocean helps to develop a strong cyclone activity over Northern Eurasia (*Wernli and Schwierz*, 2006). This underlies a distinct summertime Arctic Ocean Cyclone Maximum (AOCM) (*Serreze and Barrett*, 2008; *Orsolini and Sorteberg*, 2009) that appears in climatological storm track patterns. However, *Screen et al.* (2011) found this AOCM to be missing in summers preceding Septembers of anomalously low sea ice area, in part conflicting the previous results found by the same group (*Simmonds and Keay*, 2009).

Toward the end of the century, cyclones are generally expected to shift poleward (most marked in the Southern Hemisphere) (*Bengtsson et al.*, 2006, 2009; *Lang and Waugh*, 2011; *Mizuta*, 2012). No significant global changes in intensity are found, with the exception of a minor reduction in the number of weaker storms (*Bengtsson et al.*, 2006, 2009). On the other hand, *Bengtsson et al.* (2009) reported an 11 % raise in cumulative precipitation along the storm tracks, about twice the increase in the global average. The overall precipitation enhancement is consistent with an increase of temperature and the ability of warm air to contain more moisture (*Knutti and Sedláček*, 2013), resulting in an acceleration of the hydrologic cycle (*Held and Soden*, 2006).

Most studies of storm tracks under the changing climate have focused on midlatitudes. Of the ones including high-latitudes, *Bengtsson et al.* (2006) and *Orsolini and Sorteberg* (2009) examined the AOCM in future climates by applying Lagrangian cyclone tracking (cf. section 3.2.5) to the European Centre Hamburg Model (ECHAM) and Bergen

Climate Model (BCM; cf. section 3.2.4), respectively. *Bengtsson et al.* (2006) reported an intensification of summertime cyclones over the Arctic, but no significant changes in frequency. A summertime intensification of cyclones was also found by *Orsolini and Sorteberg* (2009), but along with a raise in the number of cyclones, particularly over the Siberian coast. They linked this feature to an enhanced meridional temperature gradient between the Arctic Ocean and the warming Eurasian continent.

2.5 Sea ice-atmosphere interaction

Cyclones and external forcings (e.g., global warming) can significantly alter the Arctic sea ice distribution (e.g., *Bhatt et al.*, 2008; *Deser and Teng*, 2008; *Francis et al.*, 2009b; *Balmaseda et al.*, 2010; *Ogi et al.*, 2010; *Long and Perrie*, 2012; *Overland et al.*, 2012; *Kapsch et al.*, 2013), but variability in the sea ice also feeds back into the other components of the climate system (e.g., *Francis et al.*, 2009b; *Higgins and Cassano*, 2009; *Seierstad and Bader*, 2009; *Kay et al.*, 2011; *Vavrus et al.*, 2011; *Liu et al.*, 2012b; *Orsolini et al.*, 2012; *Sedláček et al.*, 2012). Consequences for albedo and exchanges of heat, momentum and water vapor are apparent (*Budíkova*, 2009; *Vihma*, 2014, and references therein).

Changes in Arctic sea ice can be seen both locally and remotely. Local effects are primarily given as enhanced turbulent heat fluxes and outgoing longwave radiation (*Serreze et al.*, 2007b; *Screen et al.*, 2014). Remote impacts are much more complex to disentangle as they are often mixed with responses to many other local or remote factors that can affect the climate in a given region at various space and time scales (*Turner et al.*, 2007; *Strey et al.*, 2010; *Screen et al.*, 2014). Hence, it is difficult based on observations alone to isolate the effects of diminishing Arctic sea ice cover on midlatitude climate (*Screen and Simmonds*, 2013; *Cohen et al.*, 2014).

Nevertheless, *Screen* (2013) found anomalously low Arctic sea ice to be associated with wet summers over northern Europe following southward shift of the jet stream in the region. Moreover, *Francis and Vavrus* (2012) linked Arctic amplification to midlatitude extreme weather through changes in the jet stream. Due to the polar warming, they found a reduced poleward gradient in 1000–500 hPa thicknesses and an northward elongation of ridge peaks in 500 hPa waves, resulting in more prolonged weather conditions favoring stationary weather systems contributing to droughts or flooding, cold spells or heat waves. Although other studies have found supporting results for the hypothesis (*Tang et al.*, 2013a; *Coumou et al.*, 2014; *Francis and Vavrus*, 2014, in press), it is still heavily debated within the scientific community (*Barnes*, 2013; *Screen and Simmonds*, 2013; *Cohen et al.*, 2014; *Wallace et al.*, 2014; *Walsh*, 2014).

Questions also arise regarding the so-called warm Arctic/cold continents climate pattern. First introduced by *Overland et al.* (2011), the signal links Arctic sea ice melt to continental snowfall and extreme winter weather. This pattern increases the frequency of cold Arctic air outbreaks at lower latitudes with extreme low temperatures and often snowstorms (*Honda et al.*, 2009; *Overland et al.*, 2011; *Liu et al.*, 2012a; *Outten and Esau*, 2012; *Song et al.*, 2012; *Tang et al.*, 2013b; *Guo et al.*, 2014). The weakening of the polar jet stream seems to be accompanied by a strengthening of the subtropical jet stream (*Cohen et al.*, 2013).

Various studies have indicated a relationship where anomalously low sea ice extent in late summer increases the availability of atmospheric moisture and snowfall potential (*Cohen et al.*, 2012; *Liu et al.*, 2012a). Building the Siberian snowpack in autumn would strengthen and expand the Siberian High, with potential influence on the wintertime circulation mediated by the stratosphere (*Wu et al.*, 2011). This results from the Eurasian Siberian snow influence on the planetary Rossby wave vertical propagation from the troposphere to the stratosphere, a high snow anomaly leading to enhanced wave activity, weakening of the polar vortex, and a lagged negative AO at the surface (e.g., *Cohen et al.*, 2013; *Orsolini and Kvamstø*, 2009). However, the complete link between sea ice retreat, autumn snowfall and wintertime circulation anomalies is not fully understood.

2.6 Gaps in our understanding

Despite an increased focus on the changing Arctic sea ice from the scientific community, media, politics and industry over the recent years, important questions remain unanswered. How much of the observed sea ice retreat can be explained by external forcing? What role does internal variability play in the forcing and feedbacks of sea ice variability? What causes the strong year-to-year fluctuations on top of the long-term negative trend? How is the sea ice retreat affecting the cyclonic activity in the region? Is there a link between the Arctic amplification and midlatitude extreme weather, and if so, what are the physical mechanisms behind this?

It is not possible to answer all these questions in one PhD dissertation alone. Nevertheless, the quest for these answers provides the background and motivation for the analyses carried out during the PhD period. While not providing final conclusions, this PhD dissertation aims to significantly contribute to the discussions on the role of the Arctic sea ice in the climate system.

3 This study

3.1 Motivation and objectives

The PhD dissertation is part of the research project *Impact of Blue Arctic on climate at high latitudes* (abbreviated *BlueArc*), funded by the Research Council of Norway. Its primary objective is to quantify the impact of the Blue Arctic on climate and climate variability at high-latitudes. This will be achieved by comparing simulations of a future blue Arctic Ocean high-latitude climate with the present-day situation to assess the impacts on the atmospheric and oceanic circulation, and to isolate and analyze anomalous low sea ice events in observational and modeling data.

For reasons discussed in section 5.2, it is difficult to isolate the effects of retreating Arctic sea ice on atmospheric circulation in the papers constituting this thesis. Nevertheless, the role of sea ice loss on climate variability is implicit in the results presented here, thus contributing to the overall *BlueArc* project. In this thesis, satellite data, observational-based reanalysis data and model data are used. The objectives of this thesis are:

- Isolate observed summers of anomalous Arctic sea ice extent to understand what atmospheric mechanisms have caused and resulted from these anomalies.
- Increase the understanding of the interaction between synoptic atmospheric systems and sea and land ice in the Arctic region.
- Evaluate changes in storm-related parameters in high-latitudes with projected climate changes.

The results of this study are expected to be of interest to a wide-ranging field. In addition to contribute to the currently strong scientific interest of these topics, changes in the cryosphere are of great importance to ecosystems, human infrastructure, industry and politics. The Arctic is getting hot, for more than climatic reasons.

3.2 Data sets and methods

The Arctic is a remote region with relatively scarce in situ observations. Hence, the analyses performed in this work heavily rely on data from satellites and model simulations.

3.2.1 Satellite data

Although ship-based records of sea ice extent in some regions extend several centuries back in time (e.g., *Vinje*, 2001), even modern Arctic ship and buoy data are not sufficiently comprehensive for measures of high-resolution as well as area-integrated variations of the different sea ice quantities. Only satellites can provide the necessary information (*Yang et al.*, 2013, and references therein), although a circular mask over the geographic North Pole is inevitable due to the orbit inclination and instrument swath (*Cavalieri et al.*, 2013).

Since 26 October 1978, satellites have provided information on nearly daily variations in the Arctic sea ice cover. Lately (October 2010), the CryoSat satellite from the European Space Agency (ESA) added sea ice thickness and hence volume to this picture.

In this dissertation, Arctic sea ice observations stem from the National Snow and Ice Data Center (NSIDC) (*Cavalieri et al.*, 2013). They are generated from brightness temperature data derived from five sensors. These are (in chronological order) the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR), the Defense Meteorological Satellite Program (DMSP) -F8, -F11 and -F13 Special Sensor Microwave/Imagers (SSM/Is), and the DMSP-F17 Special Sensor Microwave Imager/Sounder (SSMIS). They measure sea ice concentration (the fraction or percentage of ocean area covered by sea ice; SIC), of which sea ice area (SIA) and extent (SIE) can be estimated using different algorithms. While the SIA of a grid cell is the area multiplied by the SIC (threshold of 15 %, i.e., less ice is considered to be open water), the SIE calculation assumes each grid cell is either “ice-covered” ($SIC > 15\%$) or “not ice-covered” ($SIC \leq 15\%$). Hence, $SIA \leq SIE$.

The NSIDC data are provided in the polar stereographic projection at a grid cell size of 25 km x 25 km. While the SMMR sensor transmitted data every other day, the subsequent sensors have provided data with daily resolution. For daily data analysis in Paper I, missing data is therefore linearly interpolated from neighboring days. This method was also used for the data gaps in August 1982, August 1984, December 1987 and January 1988.

3.2.2 Reanalysis data

All reanalysis data in this study stem from the European Re-Analysis Interim (ERA-Interim) data set. The reason for this is the good and physically consistent representation of all the atmospheric fields when compared to the sparse observations in the regions

(*Jakobson et al.*, 2012; *Chung et al.*, 2013). Moreover, ERA-Interim is also found to be among the best data sets for storm tracking (*Hodges et al.*, 2011; *Zappa et al.*, 2013), although it captures fewer Arctic cyclones than the higher-resolution Arctic System Reanalysis (*Tilinina et al.*, 2014).

ERA-Interim is produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). The project was carried out in order to replace their previous atmospheric reanalysis, ERA-40, with improved methods to correct known problems of ERA-40. ERA-Interim also includes improvements in number of pressure levels (from 23 to 37) and added cloud parameters.

Described in more detail by *Dee et al.* (2011), ERA-Interim is a high-resolution reanalysis in space and time. Continuously updated in real time, it stretches from the start of the modern satellite period in 1979, with 6-hourly, daily and monthly data available. With T255 Gaussian grid (approximately $0.75^\circ \times 0.75^\circ$ or 80 km x 80 km), it spans from 0.000° to 359.250°E and from -89.425° to 89.425°N . Its 60 model levels stretch from the surface to 0.1 hPa. The analyses presented in this dissertation include data from the surface, 850, 500 and 300 hPa levels, all interpolated to a $0.50^\circ \times 0.50^\circ$ grid before downloading.

The data assimilation system used to produce ERA-Interim is based on a 2006 release of the Integrated Forecast System, cycle 31r2 (IFS-Cy31r2). This system includes a 4-dimensional variational analysis (4D-Var) with a 12-hour analysis window.

3.2.3 Regional model data

In Paper III, the observationally constrained regional climate model Modèle Atmosphérique Régional (MAR) is used for simulations of the Greenland Ice Sheet (GrIS) climate and surface mass balance. Described in *Gallée and Schayes* (1994), the model is forced 6-hourly by ERA-Interim at the lateral boundaries. MAR has a horizontal resolution of 25 km x 25 km, with the output interpolated to a 5 km x 5 km grid in our study. This is done to be able to resolve the various parameters needed at the GrIS margins, with its steep slope and complex topography.

Previous studies have found MAR to realistically simulate the surface mass balance (SMB) and other meteorological parameters of the GrIS (*Lefebvre et al.*, 2003, 2005; *Fettweis*, 2007; *Fettweis et al.*, 2011; *Vernon et al.*, 2013). Due to its ability to separate the components of the GrIS SMB, it is an ideal tool for examining the relationship between the changes in SMB subcomponents and the cyclone and anticyclone activity in the region, as analyzed in Paper III.

3.2.4 Global model data

Two coupled global climate models are used for the analysis in Paper II. These are two CMIP5 models, the Norwegian Earth System Model version 1 with intermediate resolution (NorESM1-M) and Community Climate System Model version 4 (CCSM4).

NorESM1-M is a joint modeling effort of eight Norwegian research institutions, building on and replacing BCM (*Furevik et al.*, 2003) as the Norwegian CMIP model in the Intergovernmental Panel on Climate Change (IPCC) assessment reports. It is described in more detail in *Bentsen et al.* (2013), *Iversen et al.* (2013) and others in the same special issue of the *Geoscientific Model Development*.

NorESM1-M is based on CCSM4 and the Community Earth System Model (CESM) projects operated at the National Center for Atmospheric Research (NCAR) on behalf of University Corporation for Atmospheric Research (UCAR) (*Gent et al.*, 2011), but differs from CCSM4 in the following components: an advanced scheme for chemistry-aerosol-cloud-radiation interactions in the atmospheric module (CAM4-Oslo; *Kirkevåg et al.*, 2013); an isopycnic coordinate ocean general circulation model modified from the Miami Isopycnic Coordinate Ocean Model (MICOM; *Bleck et al.*, 1992; *Drange et al.*, 2005; *Bentsen et al.*, 2013); and a biogeochemical ocean module from the HAMBURG Ocean Carbon Cycle (HAMOCC) model developed at the Max Planck Institute for Meteorology (MPI) in Hamburg (*Maier-Reimer*, 1993; *Maier-Reimer et al.*, 2005) that has been adapted to the isopycnic ocean model framework (*Tjiputra et al.*, 2010).

The intermediate resolution version of NorESM has a horizontal resolution of approximately 2° for atmosphere and land components and 1° for ocean and ice components. Its vertical resolution consists of 26 levels of hybrid sigma-pressure coordinates with a model top of 2.9 hPa.

CCSM4 has twice the horizontal resolution of NorESM1-M, with $1.25^\circ \times 0.9^\circ$ horizontal resolution and 26 vertical layers. A more complete description of CCSM4 is presented by *Gent et al.* (2011), *de Boer et al.* (2012) and others in the same special issue of the *Journal of Climate*.

These two models are chosen for the similarity of their model components. Thus, differences between the models highlight the roles of the ocean and atmospheric chemistry in particular, although with contributions also from the differences among realizations. Since both models undergo strengthened polar-amplified warming and rapid loss of their sea ice cover by the end of the century, the impacts of the Arctic Amplification (AA) and the Blue Arctic on atmospheric components like storm activity are distinct in our results.

3.2.5 Storm tracking algorithm

All papers include storm track analysis based on the TRACK algorithm (*Hodges, 1994, 1995, 1999*). It uses 6-hourly 850-hPa relative vorticity (ζ) to identify and track cyclones (maxima) and anticyclones (minima; Paper III only), here calculated from the horizontal wind fields. Rather than sea level pressure (SLP), ζ is used for tracking due to being less dependent on extrapolation, smaller influence from the large-scale background pressure field, and focus on the small-scale end of the synoptic range (*Hoskins and Hodges, 2002*). This results in many more systems being identified. Moreover, ζ is more focused on the wind field while SLP is linked to the mass field, representing the low frequency scale better (*Hodges et al., 2003*). Overall, *Neu et al. (2013)* found the methods based on vorticity to be somewhat in the middle of the range among storm tracking algorithms.

The ζ field at moderate to high resolution can nevertheless be very noisy. Hence, to allow the same spatial synoptic scales to be identified across various data sets, the analysis is performed at a spectral resolution of T42 on a Gaussian grid. Additionally, to focus on synoptic variability, planetary scales with wave numbers below 5 and above 42 are removed. Finally, the synoptic systems must fulfill criteria regarding their displacement distance (minimum 1000 km) and lifetime (minimum 2 days).

The three papers in this dissertation involve the analysis of five Eulerian statistical fields: the track density (a measure of how many systems passing through a region), the mean intensity (a measure of the strength of the systems), the genesis density (a measure of how many systems forming in a region), the lysis density (a measure of how many cyclones dying out in a region) and the mean lifetime (a measure of the lifetime of the systems). Spherical kernel estimators are used to calculate the five quantities as described in *Hodges (1996)*. While the mean intensity unit corresponds to relative vorticity (10^{-5} s^{-1}), the density fields are given in units of number density per month per unit area where the unit area is equivalent to a 5° spherical cap ($\sim 10^6 \text{ km}^2$). The unit for mean lifetime is days (d).

4 Summary of papers

4.1 Paper I: Observed anomalous atmospheric patterns in summers of unusual Arctic sea ice melt

Paper I investigates the anomalous atmospheric circulation, precipitation, radiation and temperature in summer months of observed high and low Arctic sea ice melt. Hence, the method differs from other studies in that here we put emphasis on causes and consequences of strong or weak sea ice *melt rates* and not the case of high or low sea ice *cover*. Naturally, occurrences of months with high melt rate (*HMR*) typically correspond to months with low SIE, but might also be the result of a larger than normal SIE at the start of the month. The reverse holds for low melt rate (*LMR*) months and high SIE.

By standardizing the sea ice melts over the 140 May, June, July and August (MJJA) months from 1979 to 2013, we end up with composites of 23 *HMR* and 17 *LMR* months defined as having melt rates exceeding +1 STD and -1 STD respectively. Differentiating the two groups we gain insight into the role of anomalous Arctic sea ice on the overlying atmosphere and vice versa, with a tool for studying the possible feedbacks. The latter connections are established based on known, physical mechanisms even though the simultaneous covariance makes it hard to determine causality.

Compared to *LMR* months, *HMR* months are characterized by anomalous high SLP in the Arctic (up to 7 hPa), with a corresponding tendency of storms to track on a more zonal path. As a result, the Arctic receives less precipitation overall and 39 % less snowfall. This lowers the albedo of the region and reduces the negative feedback the snowfall provides for the sea ice. With the relative anticyclone, 12 W/m^2 more incoming shortwave radiation reaches the surface in the start of the season and warms the surface (0.3°C over the Arctic Ocean, up to 2.7°C over Greenland). The melting sea ice in turn promotes cloud development in the marginal ice zones and enhances downwelling longwave radiation at the surface toward the end of the season (9 W/m^2). A positive cloud feedback emerges.

In midlatitudes, the more zonally tracking cyclones give stormier, cloudier, wetter and cooler summers in most of northern Europe and around the Sea of Okhotsk. Farther south, the region from the Mediterranean Sea to East Asia experiences significant surface warming (up to 2.4°C), possibly linked to changes in the jet stream.

4.2 Paper II: Northern Hemisphere storminess in the Norwegian Earth System Model (NorESM1-M)

Projected alterations in storm-related parameters with climate changes are outlined in Paper II. Here, two state-of-the-art global climate models, NorESM1-M and CCSM4, are compared to the reanalysis ERA-Interim for the historical time period 1979–2005. Only NorESM1-M is named in the title as this paper is submitted to the special issue for this model (cf. section 3.2.4). In Paper II, the focus is on the fall and early winter (SOND), the period when the ongoing and projected Arctic sea ice retreat is greatest.

Both models reproduce the observed seasonality of the sea ice loss and the general patterns of SLP and cyclone metrics well, although the storm characteristics are somewhat less sharp relative to ERA-Interim because of the models' coarser resolution.

Through the 21st century, expected changes in storm intensity (as well as SIC, SLP and precipitation) appear to scale generally linearly with time and the Representative Concentration Pathway (RCP) forcing value. Hence, we highlight the results for the end of the century time period (2074–2100) and the highest emission scenario (RCP8.5; business-as-usual scenario).

Cyclones are generally projected to become stronger and more numerous at high-latitudes and weaker and less numerous at midlatitudes. This is partly a result of poleward-shifted storm tracks in the start of the season, especially over the North Atlantic and North Pacific oceans. With more (less) cyclones in a region, there is an increased likelihood of more (less) strong cyclones tracking in.

The poleward shift of storm tracks takes place on a background of global warming, with resulting Arctic sea ice decline. While Paper II does not separate the effects from the sea ice, it is likely that the diminishing Arctic sea ice enhances the heat fluxes from the ocean to the atmosphere, destabilizes the air column and reduces the SLP. Hence, the 2–3 hPa SLP decrease found over the polar cap in the two models toward the end of the century is due to the transition toward the Blue Arctic as well as the increased frequency of cyclones. With more cyclones, a particular grid point in their storm track is likely to experience lower SLP for more time steps. However, compared to cyclone frequency, we find smaller reductions in cyclone intensity in midlatitudes and higher enhancements in high-latitudes, indicating that changes in cyclone strength do not correlate proportionally to cyclone frequency.

Projected changes in precipitation depend on changes in cyclonic activity as well as temperature. More or less cyclones alter the frontal precipitation one way or the other,

while global warming raises the ability to contain water in warm air, accelerating the hydrologic cycle (*Held and Soden, 2006*). The resulting pattern generally correlates well with the wet-gets-wetter, dry-gets-drier pattern reported elsewhere (e.g., *Held and Soden, 2006; Stocker et al., 2013*). Although the pattern differs from the start to the end of the SOND season, both models predict significantly less precipitation in the Mediterranean region and significantly more precipitation in high-latitudes.

Both wind and precipitation changes are likely to have costly impacts on human society, especially on top of sea level rise and loss of sea ice. This adds to the importance of reducing the uncertainties in future changes of Arctic cyclone activity and related variables that will impact northern coasts, communities and offshore activities.

4.3 Paper III: The variability of surface mass balance over the Greenland Ice Sheet and associated cyclonic and anticyclonic activities

Paper III evaluates the influence of synoptic scale systems on the SMB variability of the GrIS. This is done through correlation analysis between the SMB variability and two indices: Cyclone Activity Index (CAI) and Anticyclone Activity Index (ACAI).

The indices are defined as the sum of the standardized track density and mean intensity (cf. Section 3.2.5) for cyclones and anticyclones, respectively. They efficiently represent the comprehensive effects of synoptic activity. Here, a positive (negative) anomaly of the CAI or ACAI corresponds to stronger (weaker) than normal cyclonic or anticyclonic activity, respectively.

The CAI analysis indicates an increased snow accumulation over most of GrIS with enhanced cyclonic activity in the Davis Strait and Baffin Bay regions. Moreover, strong cyclonic activity from Baffin Bay toward northern Greenland transports more heat to the GrIS, particularly in its western part. The ACAI analysis reveals how strong (weak) anticyclonic activity along the west (east) coast of Greenland favors warming over the GrIS, especially along its west coast.

Overall, cyclonic and anticyclonic activities can explain up to 70 % of the GrIS SMB variability over west Greenland in winter and along its west coast in summer. These results suggest that the synoptic activity is important for the weather conditions over Greenland and thus has a significant impact on the GrIS SMB variability.

5 Perspectives and outlook

5.1 Questions answered in this thesis

The importance of the Arctic sea ice in the climate system is established throughout this thesis. Its reciprocal influence on atmospheric circulation, temperature and radiation on high- and midlatitudes is analyzed in Paper I, with discussion of connections based on known, physical parameters. Significant disparities between summers of high (HMR months) and low (LMR months) sea ice melt are found. Compared to *LMR* months, *HMR* months are characterized by an anomalous anticyclone over the Arctic associated with lower cloud cover and thus higher incoming shortwave radiation. This initiates a strong sea ice melt at the start of the season (May) and subsequent surface evaporation enhancement. Consequently, cloud formation soars into the season, which increases the size of the re-emitted longwave radiation on behalf of the dwindling shortwave radiation in July and August. A positive cloud feedback is inferred.

The anticyclonic anomaly also reduces the albedo feedback that snowfall provides for the sea ice. Fewer cyclones track into the Arctic, leaving the region drier with lower albedo. Instead, the cyclones track more zonally across the North Atlantic and North Pacific oceans. Consequently, summers of anomalous high Arctic sea ice melt are characterized as stormier, wetter and cooler over northwestern Europe and around the Sea of Okhotsk. From the Mediterranean Sea to East Asia and over most of North America and Greenland are HMR months associated with drying and warming. These exacerbate the recent tendencies of droughts and heat waves (two former regions) and surface melting (latter region).

Paper II indicates a shift of the Northern Hemisphere (NH) storminess in the coming decades. The two global climate models used show signs of poleward-shifted storm tracks, although this signal is clearer for cyclone intensity than frequency. The discrepancy with Paper I suggests that the reduced meridional temperature gradient and raised water availability in warmer air following current emission trends might prevail over the observed variability in sea ice. However, significant storm intensification is found in regions of new sea ice-free regions in Paper III, emphasizing the role sea ice plays as a lid between the cold atmosphere and warmer ocean in fall. In addition to enhanced baroclinicity, evaporation increases with significantly more rainfall as a consequence.

The observed SMB variability of the GrIS is further studied in Paper III. Here, a regional climate model is used to determine changes in the GrIS SMB with variations in cyclonic and anticyclonic activities. Strong snow accumulation and elevated temperatures

are generally associated with cyclonic activity from the south. For most of the GrIS, the net effect throughout the year is accumulation due to its high altitude and elevation. The influence of anticyclonic activity is mainly confined to changes in surface temperature over the GrIS, with warming in its western half with more (less) anticyclones in the Labrador Sea and Baffin Bay (Greenland Sea). Overall, the inclusion of synoptic patterns as precursors for surface temperature and snowfall improved our understanding of the GrIS SMB variability over the recent decades.

Overall, the three papers provide insights to the role of natural variability (Papers I and III) as well as external forcing (Paper II) in the Arctic climate system. The interaction between cyclonic activity (and anticyclonic activity in Paper III) and the cryosphere in high-latitudes are thoroughly analyzed in all three papers. Although the simultaneous covariance limits causality determination, Paper I nevertheless discusses interaction between anomalous Arctic sea ice and midlatitude weather patterns, including extreme weather, based on known physical mechanisms.

5.2 Questions remaining unanswered

All three papers address the atmospheric simultaneous covariability with the sea ice variations, but it is hard to distinguish the effects of the sea ice on the atmosphere from the atmosphere on the sea ice. To remedy this, a fourth paper is underway (*Knudsen et al.*, 2014, in prep.). This will be submitted in a separate paper but too late to be included in this thesis. Here, we perform a regression analysis of sea ice (from NSIDC) and atmospheric circulation (from ERA-Interim) patterns on anomalous Arctic SIE. The results reveal that July and August sea ice conditions largely determine the conditions in the two following months, while the rapid sea ice melt period May-June and growth period November-January leave low memory in these months (Figure 3). This forward memory provides a mechanism whereby summer sea ice can force fall and early winter weather, thereby justifying the focus on September SIE on September to December (SOND) atmospheric patterns.

Figure 4 shows the regression of September through December SIC and surface temperature (T_s) lagging on September SIE. It reveals how the effects of the anomalous SIE mainly are short-lived in the Arctic (September and October; two first rows in Figure 4). In these two months, the leading September SIE anomaly corresponds to significant reductions in SIC over most of the Arctic Ocean (Figure 4a), with increases in heat fluxes from the relative warm ocean to the cooling atmosphere (Figure 4b). The regional warming is typically in the range 0.5–3.5°C per 10^6 km² SIE anomaly, while the Gulf of Alaska,

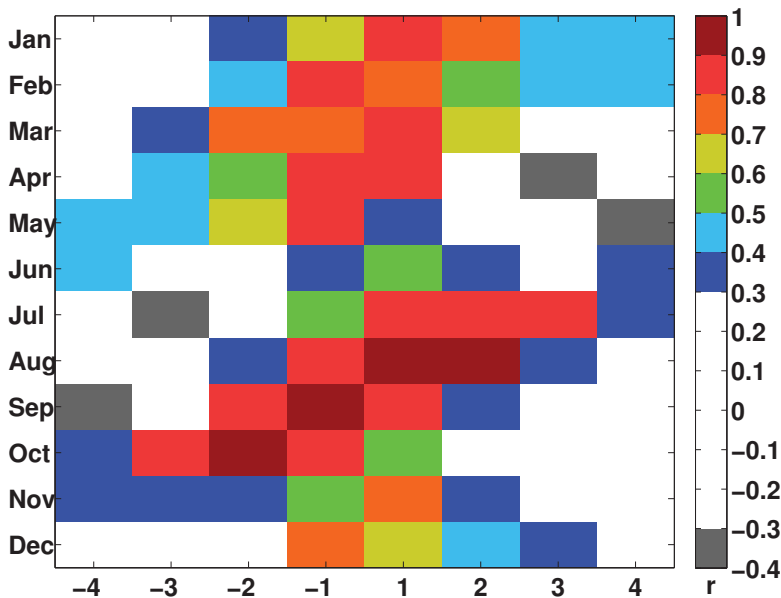


Figure 3: Monthly lead-lag linear autocorrelation coefficients (r) of Arctic sea ice extent. For each month along the y-axis, negative (positive) values along the x-axis represent memory from a previous (the current) month to the current (a coming) month. Only significant autocorrelations on a 95 % confidence level are colored. From Knudsen *et al.* (2014).

American east coast and parts of Russia warm up to 1.0°C per 10^6 km^2 anomaly.

By November and December (two last rows in Figure 4), the cold atmosphere causes rapid sea ice growth, with low memory of the anomalous September condition (cf. Figure 3). Consequently, significant alterations in SICs are only evident in the Barents and Kara seas (Figure 4a). However, this region is found to have a key role in the NH climate (Smedsrud *et al.*, 2013, and references therein). A warm Arctic-cold continents pattern (Overland *et al.*, 2011) develops toward the end of the season (Figure 4b), with a cooling over Mid-Asia, similar to the findings by Honda *et al.* (2009).

Our preliminary results suggest an observational-based evidence for a positive feedback where sea ice changes modulate the atmospheric circulation and local climate at high- and midlatitudes. However, more analysis is needed on the physical mechanisms behind this feedback. We thus plan to perform a similar investigation on perturbed model runs of the BCM. Here, the model is run with climatological Arctic SIE for the control run, separated from the sensitivity run by a stepwise removal of SIE in September and October of the latter. This analysis will be compared to our observational-based findings to

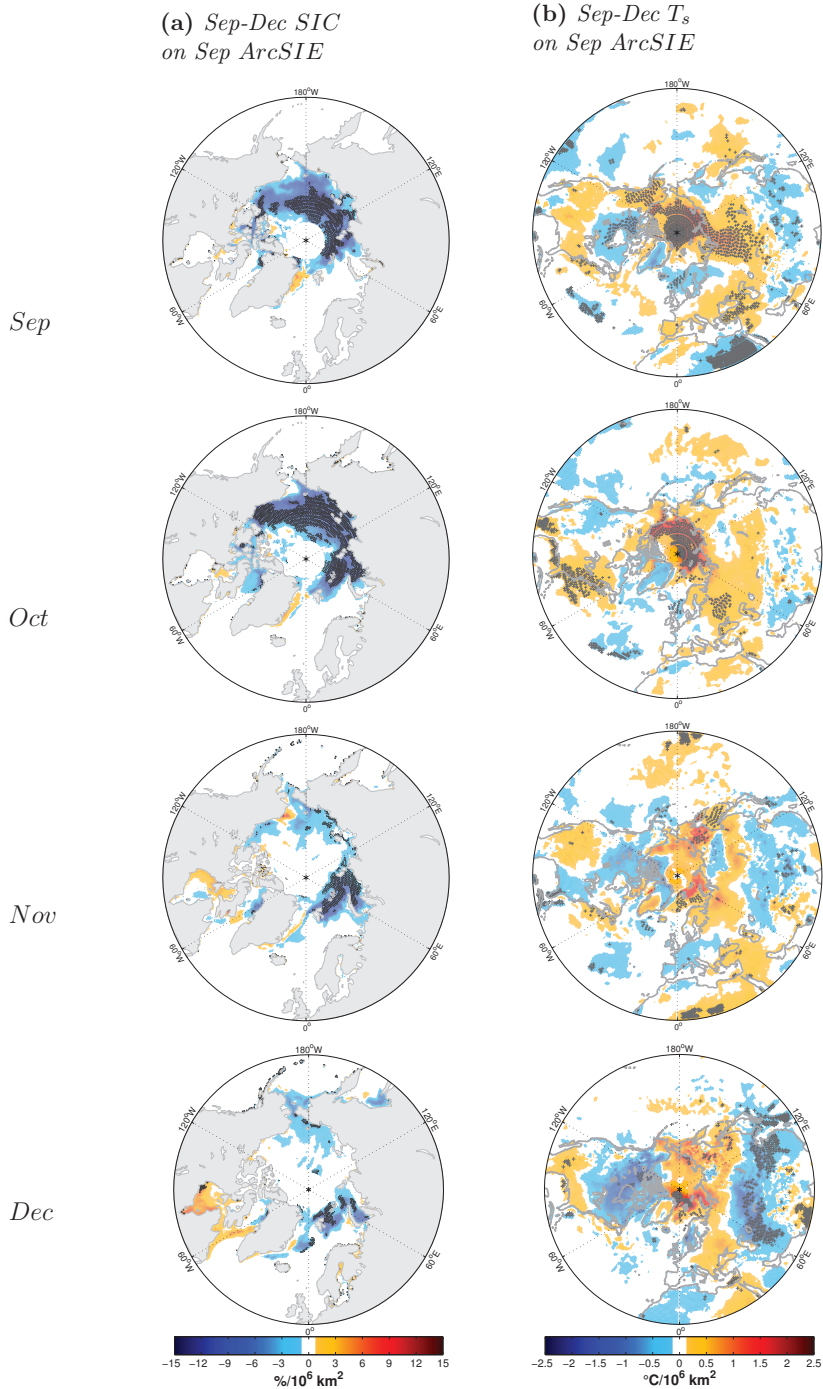


Figure 4: Monthly lag linear regression of Sep [1st row], Oct [2nd row], Nov [3rd row] and Dec [4th row] sea ice concentration (SIC) [1st column] and surface temperature (T_s) [2nd column] on Sep sea ice extent (ArcSIE). Grey crosses mark regions of significant correlation on a 95 % confidence level. From Knudsen et al. (2014).

further understand the dynamical effects of the diminishing Arctic sea ice on atmospheric components.

5.3 The wider perspective

The results of this PhD dissertation have far reaching importance, beyond the scientific community. Examples include the role of the diminishing Arctic sea ice for incidents of midlatitude extreme weather, degradation of lifestyle for local communities, disruption of regional ecosystems, as well as enhanced opportunities for petroleum and shipping industries.

Although we find little evidence for a slower moving and more meandering jet stream as proposed by *Francis and Vavrus* (2012), the anomalous summer heating over North America and from the Mediterranean Sea to East Asia found in Paper I bear resemblance to the results by *Tang et al.* (2013a). As in their case, we find this pattern to be associated with Arctic sea ice reductions. *Tang et al.* (2013a) further link this signal to an increased probability of extreme heat events, thus extending the implications from meteorology (T_s) to the society (heat waves).

In winter, the more stationary weather patterns might increase the occurrence of cold spells. *Tang et al.* (2013b) found reduced Arctic SIE in fall and winter to be associated with higher blocking tendencies over North America and Central Asia, favoring conditions for cold waves. Moreover, *Honda et al.* (2009) linked observed cold anomalies from Europe to the Far East in winter to reductions in Arctic sea ice cover in the preceding summer-to-fall seasons — a result also indicated by Figure 4b (lowermost panel) here.

More cold spells might give heavier snowfall locally (*Wallace et al.*, 2014), while the effects of decreased Arctic sea ice on snow cover over its neighboring continents vary regionally (*Olsen et al.*, 2011; *Cohen et al.*, 2014; *Vihma*, 2014; *Walsh*, 2014, and references therein). More open water in the Arctic Ocean will increase heat fluxes and evaporation into the air (*Francis et al.*, 2009b), leaving the dry and cold winter Arctic air more humid, and possibly enhancing snowfall over parts of Eurasia (*Olsen et al.*, 2011; *Walsh*, 2014, and references therein).

Another debated cryospheric link is the relation between the Arctic sea ice and the GrIS. Melting sea ice around the Greenland coast represents a removal of the mechanism that curbs the glacial ice discharge into the ocean (e.g., *Olsen et al.*, 2011). In Paper I, we find *HMR* months to be associated with significant warming over Greenland and thus reduced GrIS SMB. This is in accordance with *Rennermalm et al.* (2009), thus strengthening the suggested positive correlation between the two ice masses in the region.

While no changes in sea level result from sea ice melt, glacial melt from Greenland and other Arctic glaciers constituted over 40 % of the observed total 3.1 mm global sea level rise each year over 2003–2008 (*AMAP*, 2011).

The GrIS SMB melting found in Papers I and III are linked to changes in the North Atlantic storm track. Moreover, the projected increase in cyclonic activity over the Labrador Sea and Baffin Bay in September is accompanied by significant precipitation increments along the west coast of Greenland in Paper II. Alterations in cyclone numbers and intensities can have significant consequences in continental regions at the landfall of the North Atlantic and North Pacific storm tracks (*AMAP*, 2011). Nevertheless, these regions are generally accustomed to stormy weather, leaving the largest impacts related to changes in cyclone statistics likely to result from storm track displacements (*Stocker et al.*, 2013, and references therein). As shown in Paper II, there is a tendency of poleward-shifted and intensified storm tracks. Although the high-latitudes are home to fewer people than the midlatitudes, the consequences might cause more harm to the lifestyle in the former region (*AMAP*, 2011, and references therein).

In high-latitudes, the traditions of hunting and fishing are important components of the society (*AMAP*, 2011, and references therein). While storms directly hamper these activities, the diminishing Arctic sea ice is also expected to alter the local way of life (Figure 5) (e.g., *Stirling and Parkinson*, 2006; *Olsen et al.*, 2011, and references therein). This represents the removal of a strong wave dampening mechanism, hence enhancing coastal erosion on top of the projected sea level rise (e.g., *Serreze et al.*, 2007a). Moreover, human and animal mobility over ice will be reduced, affecting other parts of the ecosystem as well as traditional transportation modes (e.g., *Stirling and Parkinson*, 2006; *AMAP*, 2011, and references therein).

As the sea ice melts, more heat is stored in the ocean and the season for ice-free operations expands (e.g., *Shimada et al.*, 2006; *Olsen et al.*, 2011). This leaves opportunities for the oil and gas industry (Figure 5), with, respectively, 13 and 30 % of the undiscovered oil and gas reserves estimated to be located north of the Arctic Circle (*USGS*, 2008; *Jang and Lee*, 2013). While sailing the Northern Sea Route without icebreaker assistance was unthinkable less than a decade ago, the shipping traffic through this Europe to East Asia “shortcut” now increases rapidly for each year (*AMAP*, 2011, and references therein).

This disruption of the economic system will likely be felt throughout the society. Although some nations and industries might see an economic potential of a Blue Arctic, *Whiteman et al.* (2013) estimated that the total costs of a melting Arctic would far outweigh the profits. They found the cost of the methane release from thawing permafrost

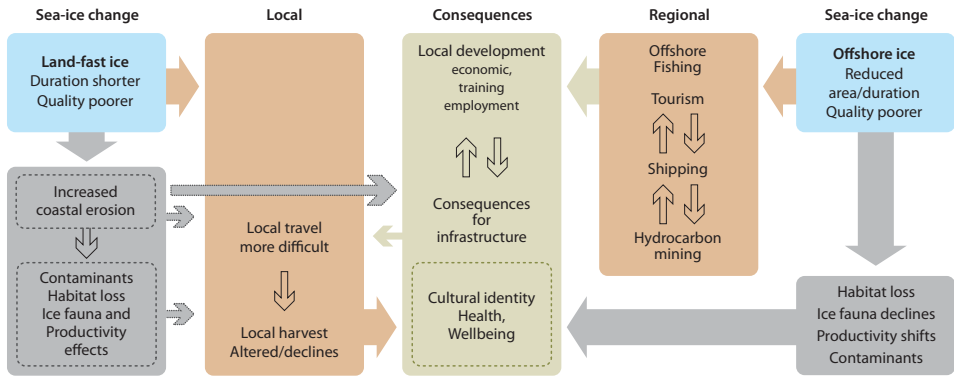


Figure 5: Scheme showing the direct and indirect effects of sea ice changes on humans. Large arrows indicate effects from/on the whole block with the arrow color. Small arrows and dashed blocks indicate effects between components of blocks. From AMAP (2011).

beneath the East Siberian Sea alone to 60 trillion USD in absence of mitigation action (for reference, the size of the world economy in 2012 was about 70 trillion USD). Of the much higher total cost of Arctic change, about 80 % will be borne by poorer economies in Africa, Asia and South America (Whiteman *et al.*, 2013).

Although current and projected changes in Arctic climate give reason for much pessimism, there is still potential of improvement. If current emission trends are sufficiently reduced to decrease the radiative forcing from greenhouse gas concentrations, the Arctic sea ice might start recovering (Hezel *et al.*, 2014). However, this forcing reduction must be large enough to dominate the delayed warming due to heat already accumulated in the ocean (Held *et al.*, 2010). Moreover, this possibility depends on the assumption that human-induced climate changes not already have reached the point of irreversibility (Solomon *et al.*, 2009).

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