Certain aspects of high-latitude climate variability

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PREFACE

A collection of papers and their synthesis are presented in partial fulfillment of the requirement for the degree of philosophiae doctor at the University of Bergen, Norway.

The thesis is organized into six chapters. The first chapter is an introduction that highlights the principal motivation for the thesis. Chapter two presents the general scientific background of the primary questions addressed in the thesis. An overview of the climatic data used in the thesis is presented in chapter three. The fourth chapter gives the objectives and summarizes the studies that constrain the thesis. Concluding remarks and future perspectives are given in chapter five. Chapter six is composed of the original research as follows:

Paper I: Sorokina, S.A. and I.N. Esau, 2011: Meridional energy flux in the Arctic from data of the IGRA. Izvestiya, Atmospheric and Oceanic Physics, 47 (5), 572–583, doi:10.1134/S0001433811050112.

Paper II: Esau, I.N. and S.A. Sorokina, 2010: Climatology of the Arctic planetary boundary layer. Atmospheric turbulence, meteorological modeling and aerodynamics. Lang, P.R. and F.S. Lombargo (eds.), Nova Science Publishers, pp. 3–58.

Paper III: Alexeev, V.A., I.N. Esau, I.V Polyakov, S.J. Byam, and S.A. Sorokina, 2012: Vertical structure of recent Arctic warming from observed data and reanalysis products. Climatic Change, 111 (2), 215–239, doi:10.1007/s10584-011-0192-8.

Paper IV: Sorokina S.A, J.J. Wettstein, C. Li , and N.G. Kvamstø, 2014: Two-way coupling between the Barents Sea ice and anomalous Eurasian winters. Manuscript (in prep. for submission to J. Climate).

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Svetlana A. Sorokina,
Bergen, April 2014

CONTENTS

I. INTRODUCTION

Significant changes in the climate have occurred during the twentieth century worldwide, but the largest changes have been observed at northern high latitudes (ACIA 2005, Serreze and Francis 2006, IPCC 2007). An enhanced high-latitude near-surface warming (up to 2.5 °C decade^{-1}) called Arctic amplification has been particularly evident over the most recent decades (Serreze et al. 2009); this warming is possibly unprecedented over the last 2000 years (Kaufman et al. 2009). Figure 1 shows a map of surface air temperature (SAT) anomalies for 2000 to 2009 and time series of global annual-mean SAT from 1880 to 2009.

Arctic amplification manifests itself in a number of ways. A faster-than-linear decline (up to 13 % decade^{-1}) in Arctic sea ice extent (e.g., Screen and Simmonds 2010, Stroeve et al. 2012) and Greenland ice sheet melting (e.g., Tedesco et al. 2013) have been the most visible signals of the recent warming. In addition to the regional consequences of high-latitude warming, there are global effects, including a rise in the global sea level (IPCC 2007) and an increased probability of mid-latitude extreme weather events and natural hazards (e.g., IPCC 2007, Rahmstorf and Coumou 2011, Coumou and Rahmstorf 2012, Francis and Vavrus 2012, Rhines and Huybers 2013). The impact of these changes on different ecosystems, and human societies is large and projected to grow throughout this century and beyond.

a) b)

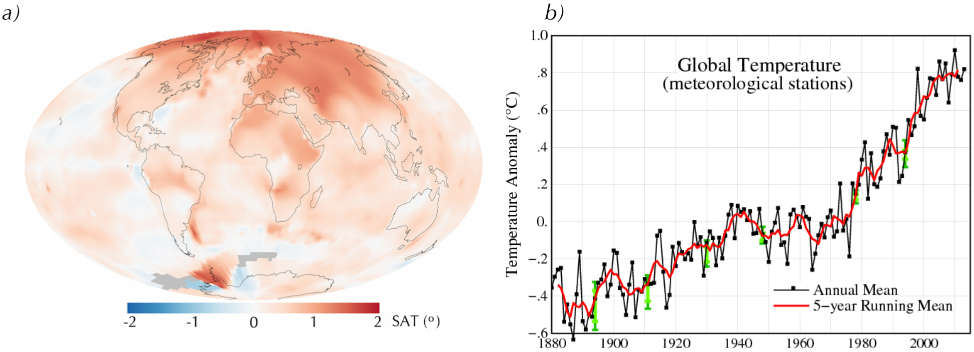

Figure 1. a) Annual SAT anomalies for 2000 to 2009 compared to the norm for that region from 1951 to 1980. Credit: NASA, image by R. Simmon, based on GISS surface temperature analysis data including ship and buoy data from the Hadley Centre, http://earthobservatory.nasa.gov. b) Global annual-mean SAT anomalies, relative to the base period 1951–1980, derived from the meteorological station network. Uncertainty bars (95 % confidence limits) are shown for both the annual and five-year means, account only for incomplete spatial sampling of data. Credit: NASA/Goddard Institute for Space Studies, http://data.giss.nasa.gov/gistemp.

The occurring changes represent not only new challenges, but also new opportunities (e.g., Ivanov 2000, AMAP 2007, Heininen 2013). The Arctic Ocean holds possibly the world's largest remaining untapped gas reserves and some of the largest undeveloped oil reserves. A potential decline in Arctic sea ice will open new opportunities for the energy sector and will attract more shipping and commercial exploitation.

To respond to these challenges and opportunities, an accurate prediction of future changes is required. However there is significant uncertainty about the magnitude and rate of the projected high-latitude climate changes (Holland and Bitz 2003, Stroeve et al. 2007, 2012). This uncertainty arises in part due to incomplete knowledge of the natural climate processes, including the processes that are intrinsic to the atmosphere, the ocean, and the coupled ocean-atmosphere system. To minimize the uncertainty, an understanding of these processes that are associated with the natural climate variability and determine the region's climate is required. The primary motivation of this thesis is to contribute to the understanding of these processes.

II. General background

The climate of high-latitude regions is determined by complex interactions between the atmosphere, ocean, sea ice, and land, and by the strong connection with low-latitudes. Radiative processes continuously act to warm the low latitudes, whereas the high latitudes experience a lack of incoming solar radiation and longwave cooling (Figure 2a); only the meridional energy transport compensates for this contrast.

1. Meridional energy transport

A number of studies have investigated global and hemispheric meridional energy transport (e.g., Savijärvi 1988, Michaud and Derome 1991, Trenberth and Solomon 1994, Trenberth and Caron 2001, Trenberth et al. 2001a, Trenberth and Stepaniak 2003a, Trenberth and Stepaniak 2003b, Trenberth and Fasullo 2009, Vallis and Farnetti 2009), whereas other studies have concentrated on the northern high-latitude region, estimating the meridional energy transport or the meridional energy flux (MEF) across a hypothetical atmospheric wall at 70 °N (Nakamura and Oort 1988, Overland et al. 1996, Serreze and Barry 2005, Semmler et al. 2005, Serreze et al. 2007). The average magnitude of the total meridional energy transport into the high latitudes at 70 °N is approximately 1.58 PW (Figure 2b, Trenberth and Caron 2001), which corresponds to ~105 W m^{-2} of MEF (watts per square meter of the horizontal area of the surface poleward of 70 °N). At 70 °N, the atmosphere transports approximately 95 % of the energy, whereas the ocean transports only 5 % of total energy amount. The transport in the atmosphere and the ocean may partially compensate each other particularly on multidecadal time scales (Bjerknes 1964, Shaffrey and Sutton 2006, Yang 2013). However, the atmospheric heat transport still plays a primary role in maintaining the climate of high latitudes.

The most important components of the MEF at 70 °N are the sensible heat, potential energy, and latent heat fluxes, while the kinetic energy account for less than 1 % of the total energy flux (Nakamura and Oort 1988, Overland and Turet 1994, Overland et al. 1996, Trenberth and Stepaniak 2003, Semmler et al. 2005, Serreze et al. 2007). However the quantitative estimates of these components differ almost by 50 % in different data sources (e.g., Nakamura and Oort 1988, Overland et al. 1996, Semmler et al. 2005). For example, Overland and Turet (1994) have estimated the potential energy flux to be 48 W m^{-2}, whereas estimation by Semmler et al. (2005) was 25 W m^{-2}. The estimations of the sensible heat fluxes differ by 25 % in these two studies.

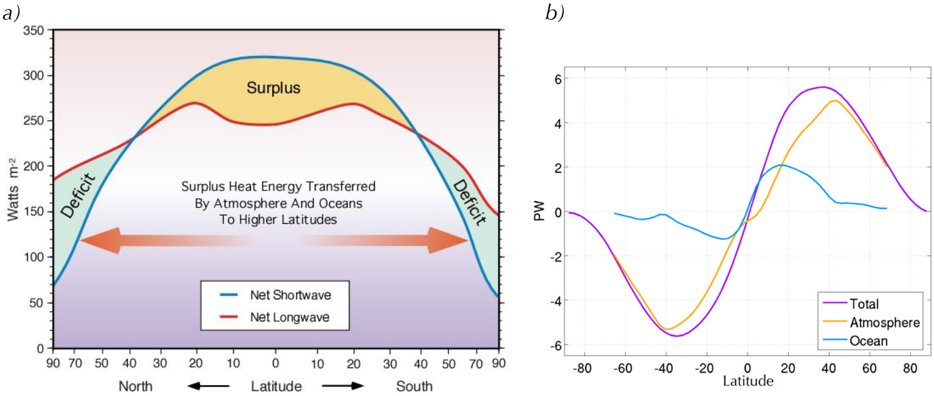

Figure 2. a) The annual values of the incoming net shortwave and ongoing net longwave radiation from the South Pole to the North Pole. Credit: http://www.physicalgeography.net. b) The northward energy transport (in PW [10^{15} W]) and its partition between the atmosphere and ocean plotted against latitude. Modified from Trenberth and Caron (2001).

The MEF exhibits considerable spatial and temporal variations, contributing substantially to climate variability across high latitudes. These variations in the MEF are associated with the position of stationary planetary waves and cyclonic activity at middle and high latitudes (Nakamura and Oort 1988, Overland et al. 1996, Serreze and Barry 2005), which are in turn controlled by a number of factors, including variability in incoming solar radiation, the earth's rotation, land mass distribution and zonal variability in the topography

A number of studies (e.g., Nakamura and Oort 1988, Overland et al. 1996, Serreze and Barry 2005) have attempted to quantify the spatial and temporal variability in the MEF at 70 °N. The MEF can be separated into the following four parts: (1) the stationary eddy energy flux, (2) the transient eddy energy flux, (3) the mean meridional circulation energy flux, and (4) the net mass flow. It has been shown (Nakamura and Oort 1988, Overland et al. 1996) that the stationary eddy flux accounts for 13–21 % of the total MEF. The stationary eddy flux has a strong annual cycle, and is stronger during winter than during summer. The transient eddy heat flux carries approximately 50 % of the total value (Nakamura and Oort 1988, Overland et al. 1996) and is the largest component of the MEF in both summer and winter. The seasonal cycle of the transient eddy heat flux is relatively small. The stationary eddy and the transient eddy fluxes largely control the zonal variability in the MEF, leading to an alternation of directions of the MEF across 70 °N.

The mean meridional circulation flux accounts for 24–32 % of the total MEF (Nakamura and Oort 1988, Overland et al. 1996). A signature of the mean meridional circulation flux clearly highlights a thermally direct circulation, namely, a Polar circulation cell. Circulation within the Polar cell is driven by the aforementioned equator-to-pole temperature gradient. Within the Polar circulation cell energy is transported into the Arctic in the upper atmosphere and out of the Arctic near the surface.

Overland and Turet (1994) have shown total mean spatial (longitudinal and vertical) structure of the MEF, for the winter season of earlier (1964–1989) decades. The authors have concluded that the major transport of heat into the Arctic occurs at 0° (Greenland Sea), 110 °W (north-central Canada) and 180 °W (Bering Strait) with a smaller center of poleward flux at 70 °E (Kara Sea). The only major energy transfer out of the Arctic is 130 °E (Siberia). The mean spatial structure of the MEF however was not updated since this study and may have experienced changes because of the recent warming of the high latitudes (ACIA 2005, Serreze and Francis 2006, IPCC 2007). In the current thesis we will highlight the mean spatial structure of the MEF over the recent years both for winter and summer seasons and estimate its linear trends. Quantification of the contribution from the stationary eddy, transient eddy, and mean meridional circulation fluxes is beyond the scope of our study.

On time scales of one month and longer, the net mass flux across the Arctic boundary is assumed to be zero according to the principle of mass conservation. However, calculations of the mass budget using real data reveal that the mass is not conserved by the analyses (Boer and Sargent 1985, Nakamura and Oort 1988, Alexander and Schubert 1990, Trenberth 1991, Trenberth et al. 1995, Overland et al. 1996), and this lack of conservation introduces significant errors into the estimations of the MEF. Different approximations have been made to account for this problem. For example, Oort (1983) has used values of the zonal mean meridional wind that were computed indirectly from the zonally averaged balance equation of angular momentum. Other studies (Nakamura and Oort 1988, Overland et al. 1996) have subtracted a value of the net mass flux from the vertical profiles of the original data. In addition, Overland and Turet (1994) have replaced the 50 hPa wind value with a climatological mean value because of the inexplicably large variability of fluxes compared to their contribution to the mean flux at this level. Trenberth (1991, 1997) has proposed a mass correction method for uniform gridded data (reanalysis or model data) that minimizes the mass budget residual and provides more accurate estimations of the MEF. However, the characteristics of models output that are important for the MEF estimations (e.g., air temperature or winds) are not always well simulated and quality of reanalysis data might be poor, especially over areas with sparse observations (Beesley et al. 2000, Bengtsson et al. 2004 a, Bengtsson et al. 2004 b, Simmons et al. 2004, Bromwich and Wang 2005, Rinke et al. 2006, Byrkjedal et al. 2008, Bitz and Fu 2008, Grant et al. 2008, Thorne 2008, Screen and Simmonds 2011). These factors might add different types of uncertainties to the MEF estimations.

In summary, the meridional energy transport plays a primary role in shaping the high-latitude climate and its variability over a range of spatial and temporal scales. The concept of the meridional energy transport is generally well understood. However, significant uncertainties remain in the quantitative estimations of meridional energy transport, including the primary components of the MEF and its spatial and temporal variations. The uncertainties primarily stem from discontinuities in the observational systems and the quality of the data.

2. TELECONNECTION PATTERNS

Atmospheric flow variability is often described using a set of Northern Hemisphere ''teleconnection patterns'', including the Arctic Oscillation (AO), North Atlantic Oscillation (NAO), eastern Atlantic (EA), Pacific–North America (PNA), western Atlantic (WA), western Pacific (WP), Eurasian (EU) and the North Pacific (NP) patterns (Walker and Bliss 1932, van Loon and Rogers 1978, Wallace and Gutzler 1981, Barnston and Livezey 1987, Hurrell 1995, Thompson and Wallace 1998, Thompson and Wallace 2000). These patterns display a strong co-variability between different climatic variables at widely separated points, which are associated with standing oscillations in the Northern Hemispheric planetary waves. The teleconnection patterns display variability over a range of time scales, and can be associated with changes in the strength and location of energy and moisture transport (Lorenz 1950, Kutzbach 1970, Thompson and Wallace 1998, Thompson and Wallace 2000, Thompson et al. 2000), temperature, wind and precipitation patterns (Walker and Bliss 1932, van Loon and Rogers 1978, Rogers and van Loon 1979), and the ocean surface condition, including ocean-to-atmosphere heat fluxes (Bjerknes 1964, Cayan 1991, Gulev et al. 2013) and sea ice (Rigor et al. 2002, Rigor and Wallace 2004, Belchansky et al. 2005, Ogi and Wallace 2007, Ogi et al. 2010, Stroeve et al. 2011, Ogi and Wallace 2012). The patterns emerge in all of the months, but appear to be strongest during the winter season. In the current thesis, the following patterns will be introduced: the AO, the NAO and the EA patterns. Discussion of other patterns is beyond the scope of this study.

a. The Arctic Oscillation and the North Atlantic Oscillation

The AO (Figure 3a) can be defined as the first mode of the winter Northern Hemisphere (20 °N–90 °N) sea level pressure (SLP) variability (Kutzbach 1970, Trenberth 1981, Wallace and Gutzler 1981). The AO is associated with 23 % of the variance and is characterized by a SLP dipole with one anomaly center over the Arctic and with opposite anomalies centered near 45 °N. In the North Atlantic the AO is clearly dominated by another teleconnection pattern, namely, the NAO (Figure 3b). The NAO (Hurrell 1995, Thompson et al. 2000) manifests itself as a meridional seesaw between the Icelandic Low and the Azores High and is associated with the intensity and position of these quasistationary circulation systems. The NAO can also be defined as the first mode of variability in the winter SLP anomalies over the North Atlantic (20 °N–80 °N, 90 °W–40 °E) and accounts for 30 % of the total SLP variability in this region. The AO and NAO patterns are highly correlated and often used synonymously. However, there are certain subtle differences between these patterns, such as larger amplitude anomalies over the North Pacific (Wallace 2000, Ambaum et al. 2001). A discussion of the differences between these patterns is beyond the scope of our study.

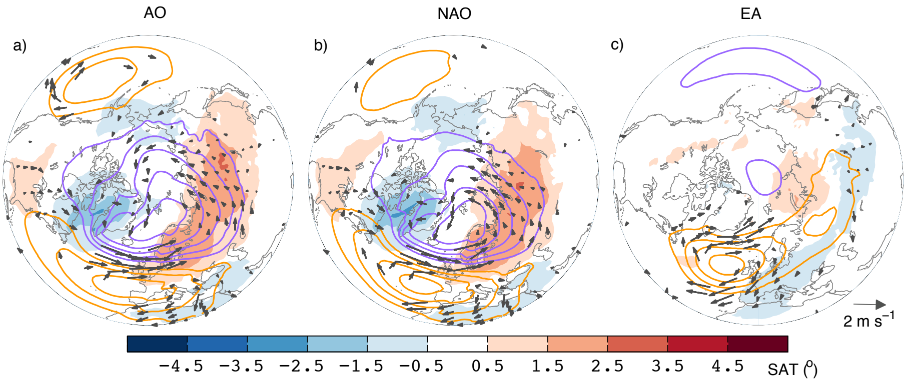

Figure 3. a) AO, b) NAO, and c) EA patterns, defined respectively as the EOF1 of winter (December–February) Northern Hemisphere (NH, 20 °N–90 °N), and the EOF1 and EOF2 of winter North Atlantic SLP anomalies (NA, 20 °N–80 °N, 90 °W–40 °E). Anomalies in SAT (color shading), SLP (contours: orange and violet denotes positive and negative values, interval 1 hPa), and near-surface 10 m winds (arrows) defined as regressions onto standardized indices of (a) SLP_{NH} PC1, (b) SLP_{NA} PC1, and (c) SLP_{NA} PC2. Only significant values are plotted for near-surface 10 m winds and SLP, which were defined using a two-sided t-test at the 0.05 significance level. The data are from ECMWF reanalysis product ERA-Interim, 1979–2012.

When pressure is low over the pole and high in the subpolar belt, we refer to a positive state of the AO / NAO (Figure 3a, 3b). The positive AO / NAO leads to abnormally strong westerlies at 45 °N and easterly anomalies centered at 35 °N. The strengthening occurs mostly in the Atlantic sector, but there is also a small Pacific contribution. An important aspect of AO / NAO variability is its relationship to the SAT. Figure 3 shows the SAT pattern for the AO / NAO from ERA-Interim reanalysis from 1979–2012. The positive AO / NAO state is accompanied by cold SAT anomalies over eastern Canada, Western Greenland and Southern Europe, whereas warm conditions prevail over Northern and Western Europe, Siberia and parts of the United States in the subpolar belt (Hurrell 1995). For a negative state of the AO / the NAO the westerlies are relatively weaker and more zonal and the temperature and precipitation patterns are reversed compared with the positive phase (Hurrell 1995).

The AO and the NAO also affect the Arctic sea ice. The positive phase of the AO and NAO is associated with enhanced ice export through the Fram Strait and thinner ice cover over the eastern Arctic (Kwok and Rothrock 1999, Rigor et al. 2002, Zhang et al. 2004, Kwok et al. 2004). Conversely, when the AO / NAO state is negative, there is a clockwise circulation pattern centered in the Beaufort Sea, which maintains sea ice in the cold central Arctic, leading to a yearly increase in the sea ice thickness. The NAO also influences the winter sea ice variability over the Labrador and Nordic Seas. The positive NAO leads to positive sea ice anomalies over the Labrador Sea and negative sea ice anomalies over the Greenland and Barents Seas (Deser et al. 2000, Vinje 2001).

b. The eastern Atlantic Pattern

The EA pattern (Wallace and Gutzler 1981, Barnston and Livezey 1987) manifests itself as the second dominant mode of variability in the winter SLP anomalies over the North Atlantic (20 °N–80 °N, 90 °W–40 °E). The EA pattern (Figure 3) consists of a well-defined monopole in the sea-level pressure field to the south of Iceland and west of the United Kingdom near 52 °N, 22 °W and is associated with a north-south migration of the NAO pattern (Woolings et al. 2010). The positive phase of the EA pattern is associated with above-average surface temperatures in Northern Europe and Norwegian, Barents and Kara Seas, and below-average temperatures over the Southern Europe and mid-latitude Eurasia. It is also associated with above-average precipitation over northern Europe and Scandinavia, and with below-average precipitation across southern Europe (Murphy and Washington 2001). The reciprocal argument can be made for the negative phase of the EA pattern.

3. THE ARCTIC SEA ICE AND ITS INTERACTION PROCESSES

Climate variations are communicated through fluxes of heat, moisture, and momentum. In the high latitudes sea ice plays a critical role in these communications. Sea ice influences the albedo, the surface turbulent heat flux (THF) and the surface wind drag and responds to local atmospheric features and large-scale atmospheric variability. The ocean–sea ice–atmosphere interaction processes are not limited by the high-latitude region, but extends to global scales (Holland et al. 2001, ACIA 2005, Liu and Alexander 2007).

Generally the extent of Arctic sea ice ranges from 14 to 16 million km^2 in March and from 5 to 7.5 million km^2 in September (Comiso 2006), responding to the seasonal cycle of the incoming solar radiation (Figure 4a). The area of major sea ice variability – a so-called marginal ice zone is located in the Labrador, Greenland and Barents Seas, as well as the Bering Sea and the Sea of Okhotsk (Deser et al. 2000). Ocean–sea ice–atmosphere interaction is particularly strong in the marginal ice zone of the Atlantic basin during the cold season because of relatively large vertical temperature gradients and the enhanced variability of the NAO and storm track. The Barents Sea has been shown to be one of the "hot spots" in these interactions (e.g., Smedsrud et al. 2013).

In the recent decades, the Arctic sea ice has experienced significant changes during all of the seasons, including diminishing in extent, thickness, and shifting from multiyear to first year ice. The most significant decline in Arctic sea ice extent has been observed in late summer (up to 10 % decade^{-1}). Whereas the multiyear ice cover is decreasing more rapidly in winter (Comiso 2012). A significant interannual sea ice variability (Figure 4b) is superimposed on the observed sea ice trend, including extreme events such as the 2005 (5.32 million km^2, NSIDC), the 2007 (Figure 4a, 4.17 million km^2, NSIDC), and 2012 (Figure 4a, 3.41 million km^2, NSIDC) sea ice minima.

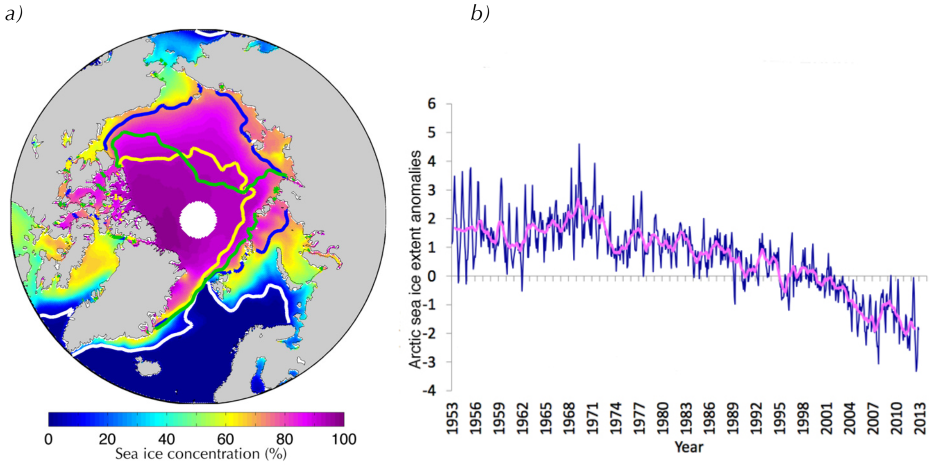

Figure 4. a) 1979–2012 climatological mean Arctic sea ice concentration (shadings, %) and sea ice extent (contours) indicated by different colors: white – climatological mean March sea ice extent, blue – climatological mean September sea ice extent, green – 2007 September sea ice extent, yellow – 2012 September sea ice extent. Sea ice extent is defined as the total area of Arctic grid cells with at least 15% sea ice concentration. The data are obtained from the NSIDC. b) Arctic sea ice extent standardized anomalies for January 1953 through December 1979, relatively to 1981–2010 mean. For January 1953 through December 2012, data have been obtained from the UK Hadley Centre and are based on operational ice charts and other sources. For January 1979 through December 2012, data are derived from passive microwave (SMMR / SSM/I). Credit: figure 4b is modified from an image by Meier W. and Stroeve J., NSIDC, http://nsidc.org/cryosphere/sotc/sea_ice.html.

Variability in the Arctic sea ice has been attributed to a number of processes including, regional (Vinje 2001, Tsukernik et al. 2010) and hemispheric-scale (Rigor et al. 2002, Rigor and Wallace 2004, Belchansky et al. 2005, Overland and Wang 2005, Wu et al. 2006, Ogi and Wallace 2007, L'Heureux et al. 2008, Wang et al. 2009, Overland and Wang 2010, Ogi et al. 2010, Screen et al. 2011, Stroeve et al. 2011, Smedsrud et al. 2011, Ogi and Wallace 2012) atmospheric circulation patterns, the thermodynamic energy exchange across the ice-ocean-atmosphere interface (Francis and Hunter 2007, Perovich et al. 2007), and anomalies in ocean heat transport (Vinje 2001, Kauker et al. 2003, Polyakov et al. 2005, Shimada et al. 2006, Francis and Hunter 2007, Schlichtholz 2011, Årtun et al. 2012).

Although the atmosphere forces sea ice, according to a zero-order approximation, sea ice changes can also have an effect on the atmosphere, primarily because of its insulating effect and high albedo values. A number of observational and model studies have been conducted to investigate the atmospheric anomalies associated with sea ice changes in various regions of the Arctic. The model studies have prescribed the sea ice conditions, ranging from realistic (e.g., Alexander et al. 2004, Singarayer et al. 2006, Liptak and Strong 2014a) to more idealized (Magnusdottir et al. 2004, Deser et al. 2004, Kvamstø et al. 2004) values, associated with present-day sea ice conditions (Magnusdottir et al. 2004, Deser et al. 2004, Alexander et al. 2004, Kvamstø et al. 2004, Honda et al. 2009, Petoukhov and

Semenov 2010, Blüthgen et al. 2012, Orsolini et al. 2012, Liptak and Strong 2014a) or projected future changes (Singarayer et al. 2006, Seierstad and Bader 2009, Deser et al. 2010, Screen et al. 2012). Observational studies (e.g., Deser et al. 2000, Francis et al. 2009, Overland and Wang 2010, Jaiser et al. 2012, Overland et al. 2011, Hori et al. 2011, Inoue et al. 2012, Outten and Esau 2012, Hopsch et al. 2012, Tang et al. 2013, Tang et al. 2014) have been performed to investigate the atmospheric anomalies associated with either sea ice variability (including extreme cases) or sea ice trends. In addition, some of the aforementioned model and observational studies have concentrated on a simultaneous changes associated with winter sea ice anomalies (e.g., Magnusdottir et al. 2004, Deser et al. 2004, Alexander et al. 2004, Kvamstø et al. 2004, Singarayer et al. 2006, Seierstad and Bader 2009, Petoukhov and Semenov 2010, Liptak and Strong 2014a, among others), whereas others, investigated delayed atmospheric anomalies in response to the diminishing autumn sea ice (e.g., Honda et al. 2009, Blüthgen et al. 2012, Orsolini et al. 2012). Furthermore, sea ice–atmosphere feedbacks were illuminated in a number of studies (e.g., Magnusdottir et al. 2004, Strong et al. 2009, Strong and Magnusdottir 2010, Liptak and Strong 2014b), but this will not be trended in our thesis.

The local simultaneous atmospheric anomalies associated with reduced sea ice in all of the aforementioned studies are largely consistent, exhibiting the enhanced ocean-to-atmosphere THF and the corresponding local surface warming. The strongest response of the surface THF was found during winter (Deser et al. 2010), over the Nordic Seas.

The large-scale atmospheric anomalies and effects associated with sea ice changes in the aforementioned studies, in turn, varies significantly, depending on the location and polarity of the sea ice changes, and the time of the year. For example, declining summer and autumn sea ice cover, primary in the Pacific sector has been associated with enhanced snowfall over Eurasia and the United States in the following winter (Ghatak et al. 2010, Liu et al. 2012), and extreme weather conditions over the northern continents, including summer heat waves (e.g., Tang et al. 2014) and cold air outbreaks in the following winter (e.g., Francis et al. 2009, Honda et al. 2009, Overland and Wang 2010, Blüthgen et al. 2012, Jaiser et al. 2012, Tang et al. 2013). The simultaneous response to reduced winter sea ice cover in the Barents, Norwegian and Greenland Seas has been associated with the negative NAO pattern (e.g., Magnusdottir et al. 2004, Deser et al. 2004, Deser et al. 2007, Strong and Magnusdottir 2010, Seierstad and Bader 2009, Liptak and Strong 2014a), decreased extratropical storm activity, particularly in March (Seierstad and Bader 2009) and extremely cold Eurasian winters (e.g., Petoukhov and Semenov 2010, Inoue et al. 2012, Outten and Esau 2012).

The associations between the mid-latitude extreme weather events and the reduced Arctic sea ice cover have received a significant amount of attention, particularly in the recent observational studies. However, whether and how enhanced Arctic warming, reduced sea ice and the extreme mid-latitude weather are related remains one of the most controversial questions in the scientific community (e.g., Barnes 2013, Screen and Simmonds 2013, Barnes et al. 2014, Wallace et al. 2014, Overland 2014).

In summary, the Arctic sea ice is an integral player both in the high-latitude and the global climate systems because of its ability to influence the exchange of radiation, heat, and momentum between the atmosphere and the ocean. Over the last decades, the sea ice has experienced significant changes, responding to and affecting the local atmospheric features and large-scale variability. Although numerous studies have addressed the relationship across the ice-ocean-atmosphere interface, many questions remain unanswered, because of the complex nature of the ocean–sea ice–atmosphere interactions.

4. THE ARCTIC PLANETARY BOUNDARY LAYER

The strongest vertical heat, moisture and momentum exchange between Earth's surface and the atmosphere occurs in the planetary boundary layer (PBL). Generally, the PBL responds to surface changes within an hour or less, and the flow within the PBL is dominated by turbulence. In the mid-latitudes, the PBL is typically deep, because of the relatively large amount of incoming solar radiation, whereas in the high latitudes, it is shallow (typically a few hundred meters or less) and stably stratified. A lack of incoming solar radiation, longwave cooling, and the vertical structure of the meridional heat transport in the high latitudes are responsible for the unique shallow and stably stratified PBL, which is also often dynamically isolated from the free atmosphere. The shallowness and dynamical isolation of the Arctic PBL have been suggested as particularly important factors for the increased Arctic near-surface warming (ACIA 2005). The PBL processes have received a relatively significant amount of attention in theoretical studies (e.g., Steeneveld et al. 2006, Mauritsen et al. 2005, Zilitinkevich and Esau 2005, Esau 2007, Mauritsen et al. 2007), however, these processes have only been marginally highlighted in observational studies, particularly in the high latitudes.

Pan-Arctic estimations of the PBL have been assembled in certain studies (Treshnikov 1985, Khrol 1992); however, they were based on fragmentary observations in the pre-satellite era, and are relatively inconsistent with more recent findings. Other observational studies (e.g., Holzworth 1964, Holzworth 1967, Uttal et al. 2002, Tjernström 2005, Tjernström and Mauritsen 2009) also attempted to understand the Arctic PBL. These studies highlighted the PBL structure and stratification, temperature inversions, diurnal cycle, the PBL clouds and mesoscale circulation within the PBL. However, the majority of the published studies have evaluated the Arctic PBL in a limited spatial area and over a very short time interval (occasionally, just a few days). There are a number of complete climatologies of the PBL over areas in the continental United States and Europe (Seidel et al. 2010, Seidel et al. 2012, Jacobson and Medeiros 2012) that highlight various features of the PBL, including the PBL depth, patterns of diurnal and seasonal cycle, surface-based inversion frequency, as well as compare different methods of the PBL depth estimation. However, the Arctic high-latitude PBL features have not been highlighted in these studies. Only a few stations from Alaska belong to the Arctic region in these studies.

One major issue in this context is the lack of observational datasets that are able to resolve the PBL processes and that are suitable to study the PBL. The atmospheric PBL has been difficult to observe from space, impeding a detailed understanding of its properties at large spatial scales. This fact also explains the relatively poor representation of the PBL processes in climate models, among which many schemes have yet to be evaluated.

III. CLIMATE DATA IN THE HIGH LATITUDES

A thorough investigation of the high-latitude climate critically depends on systematic and high-quality, long-term observations. There are a variety of data sources available for the Arctic region. However, a certain amount of the climate data is incomplete, inconsistent and even contradictory and has different levels of quality and uncertainty. This fact complicates investigations of climate processes in the high latitudes. The datasets used in this study along with a short description and references are presented in Table 1. A more detailed description of the datasets can be found in the original research, presented in the chapter six.

One of the primary data sources used in this study is the Integrated Global Radiosonde Archive (IGRA). The IGRA contains observations from radiosondes and pilot balloons at more than 1 500 stations distributed worldwide (Table 1). In this study, the IGRA data have been sampled for the Arctic region at latitudes poleward of 60 °N. There are 113 radiosonde stations in the selected region. The meridional energy transport at 70 ºN (Paper I), the Arctic PBL climatology (Paper II), and certain details of the vertical structure of the Arctic temperature trends (Paper III) have been explored using the IGRA dataset. To ensure that the observations were representative, we performed a statistical analysis of the IGRA dataset, examining the length and quality of the time series, and estimating the vertical resolution (see Paper II for more details). We found two major problems in using the IGRA data to reconstruct Arctic climate processes. First, the observation period varies significantly from station to station (Table 3 in Paper II). Therefore, it is difficult to study a particular climate phenomenon using only the radiosonde data. For example, in Paper III, the area of the largest disagreement between the temperature trends in different reanalysis datasets could potentially be tested at several high-latitude stations, but there was only one station with a sufficiently long radiosonde record located in the area of interest. Second, the vertical and horizontal resolution of the observation is coarse, which can result in significant errors (up to 30 %) in estimations and shorten the time series (Paper I and Paper II). For example, because the Arctic PBL is expected to be shallow, processes at the 925 hPa level are of particular importance. Therefore, the reconstructions of the MEF (Paper I) and the Arctic PBL (Paper II) from the IGRA data were performed only since 1992 due to the absence of the 925 hPa level prior to 1992. Moreover, many records of the IGRA do not include a complete set of the required variables, e.g., pressure, temperature, humidity, geopotential height, and wind speed, or may not include these variables on standard levels (Table 3 in Paper II). For example, station Murmansk (WMO ID 22113) launched 47 540 radiosondes from 1946 to 2008. Only 11 % of the radiosonde profiles were complete. Stations that did not include variables required for the calculations were excluded from the analysis. Consequently, 52 of the 113 stations (46 %) were used for the analysis of the climate processes in the Arctic region.

The second important source of data in this thesis is the satellite products. The satellite products are advantageous for reconstruction of climate processes due to their global spatial data coverage. The disadvantages of satellite products are the presence of relatively large data gaps and a substantial inaccuracy in certain meteorological characteristics because they are retrieved using proxy radiometer data and a set of analytical bulk algorithms (e.g., Xiong et al. 2002, Chen et al. 2002).

The third important source of data in this thesis is the atmospheric reanalysis products (Table 1). The reanalysis products combine the available observations with a numerical model using data assimilation techniques (http://reanalysis.org/). The reanalysis products include a set of global data, which describes the state of the atmospheric, land and oceanic conditions. The reanalysis products typically extend over several decades, covering often the entire globe. In the data-sparse regions such as high northern latitudes, the reanalysis is largely dependent on numerical model, assumptions and assimilation procedures, leading into large disagreements in output characteristics (e.g., Covey et al. 2002, Bromwich and Wang 2005).

Significant discrepancies among the reanalysis products are discussed in the current thesis (Paper III). However, the reanalysis products are, by construction, one of the most suitable data sources for studying spatial and temporal variability of the large-scale atmospheric processes (Paper I, IV) and certain PBL processes (Paper II, Paper IV), because of their high temporal and spatial resolution, global coverage and absence of observational gaps.

Table 1. Datasets used in this study.

Name	Type	Coverage	Period	Resolution	Reference
IGRA	Radiosonde	Globe	Varies	Varies	Gaffen (1996), http://ncdc.noaa.gov/oa/climate /igra/index.php
SHEBA	Radiosonde	Central Arctic	11.1997–10.1998	Varies	Uttal et al. (2002), http://eol.ucar.edu/projects/sheba/
ERA-40	Reanalysis	Globe	1957–2002	2.5°×2.5° 23 pressure levels	Uppala et al. (2005), http://data-portal.ecmwf.int/data/d/era40_moda
ERA-Interim	Reanalysis	Globe	1979–present	1.5°×1.5° 37 pressure levels	Dee et al. (2011), http://data.ecmwf.int/data/index.html
NCEP-1	Reanalysis	Globe	1948–present	2.5°×2.5° 17 pressure levels	Kalnay et al. (1996), http://esrl.noaa.gov/psd/
NCEP-2	Reanalysis	Globe	1979–2009	2.5°×2.5° 17 pressure levels	Kanamitsu et al. (2002), http://esrl.noaa.gov/psd/
JRA-25	Reanalysis	Globe	1979–2004	2.5°×2.5° 23 pressure levels	http://jra.kishou.go.jp/JRA-25/
OAFlux	Objective analysis	Globe	1958–2006	2.5°×2.5°	Yu et al. (2008), http://oaflux.whoi.edu/
IABP/POLES	Objective analysis	Arctic Ocean	1979–2004	1.0°×1.0°	Rigor et al. (2000), Chen et al. (2002), http://iabp.apl.washington.edu
NSIDC	Satellite	Globe	1979–2012	25×25 km	Cavalieri et al. (1996), Meier et al. (2006), http://nsidc.org/
HOAPS-3	Satellite	World Ocean	1987–2005	1.0°×1.0°	Andersson et al. (2007), http://www.hoaps.zmaw.de/
GCC (HIRHAM4)	Regional climate model	Greenland	1961–1990	25×25 km	Christensen et al. (1996), Stendel et al. (2007), http://klimagroenland.dmi.dk/datauk.html

IV. OBJECTIVES AND SUMMARY OF THE ORIGINAL RESEARCH

The thesis aims to gain a more detailed knowledge on certain processes that are associated with the natural climate variability and determine the high-latitude region's climate. In addition we address uncertainty issues related to data quality.

- The first paper investigates the meridional energy transport between the middle and high latitudes, which is one of the most important factors for Arctic climate formation.
- The second paper is dedicated to the Arctic PBL, which properties have been suggested as particularly important factors for the increased Arctic surface warming (ACIA 2005), however were relatively little highlighted in the climatological studies.
- The third paper investigates the robustness of the temperature trends throughout the Arctic atmosphere, which has been a controversial topic. We also suggest possible mechanisms responsible for those trends.
- The fourth paper is focused on the understanding of the observed Arctic/mid-latitude linkages, which has been one of the most debatable questions in the scientific community. Namely, we investigate simultaneous co-variability between winter Barents Sea THF and sea ice anomalies and anomalies in Eurasian SAT.

PAPER I: MERIDIONAL ENERGY FLUX IN THE ARCTIC FROM DATA OF THE IGRA

This study presents an evaluation of the climatological mean meridional energy flux (MEF) at 70 °N from 1992 to 2007. We highlight MEF annual mean and seasonal spatial structures, which received relatively less attention in the earlier studies and might undergo significant changes during the recent decades. We use radiosonde observations from the IGRA and compare the estimates with those from the NCEP-1 reanalysis (Kalnay et al. 1996). One of the original objectives of this study was to estimate the MEF from "clean" observational data and to highlight potential errors and uncertainties that may stem from the model or reanalysis data, in which the quality was questioned in a number of studies (Beesley et al. 2000, Bengtsson et al. 2004 a, Bengtsson et al. 2004 b, Simmons et al. 2004, Bromwich and Wang 2005, Rinke et al. 2006, Byrkjedal et al. 2008, Bitz and Fu 2008, Grant et al. 2008, Thorne 2008, Screen and Simmonds 2011). However, we found that errors and uncertainties in the MEF estimations from the radiosonde data are significantly larger compared with those in the reanalysis data. Therefore, in the current thesis, we highlight the applicability of the radiosonde and reanalysis data for the MEF estimations and compare our results with earlier studies.

The results of this study can be summarized into the following key findings.

- The integrated climatological annual MEF based on the radiosonde data is 70.6 W m^{-2}, which is smaller than the NCEP-1 value (103 W m^{-2} [current thesis, see also Serreze et al. 2007]) and values from other data sources (98±6 W m^{-2}, e.g., Semmler et al. 2005). We suggest that this inconsistency is likely attributed to the lack of conservation of the mass budget and the inhomogeneity and low spatial resolution of the radiosonde data.

- The annual and seasonal mean spatial structures (longitudinal and vertical distribution) agree fairly well in the radiosonde and reanalysis data, although there are certain subtle differences particularly in the areas between 0–30 °E and 120–210 °E. The spatial structure of the MEF shows that the main poleward energy transport occurs in the mid-troposphere–lower stratosphere layer, whereas the energy is mainly transported out of the Arctic in the lower troposphere. The key regions of a poleward MEF are located near 160 °E (the northeastern part of Eurasia, Pacific sector) and 50 °W (Greenland sector). The regions of a negative (directed out of the Arctic) MEF are located near 120 °W (Canadian Arctic Archipelago) and from 20 °E to 90 °E (the northwestern part of Eurasia). The regions of positive and negative MEFs remain for the winter and summer seasons; however, during the winter, the MEF is stronger and shows larger regional contrasts.
- During the period from 1992 to 2007, we found the overall tendency toward weakening of the MEF (–0.26 W m^{-2} yr^{-1}) based on the radiosonde data. The estimations are in agreement with those based on the reanalysis data (Smedsrud et al. 2008). Considering the spatial structures of MEF liner trends one can note the following: the MEF displays a tendency toward weakening in the middle and upper troposphere and in the stratosphere. Simultaneously, there is a tendency toward strengthening in the lower troposphere. The MEF increased in the region of the Canadian Arctic Archipelago and over the North Atlantic. Large negative trends were observed over northeastern Eurasia, Greenland, and near Novaya Zemlya Island. The spatial distribution of the linear MEF trends is consistent in both datasets, except for the region between 40 °E and 120 °E (the Barents and Kara Seas). In this region, the trends based on the radiosonde data display positive values, whereas the estimations from the reanalysis data are negative.
- Determination of the mechanisms behind the MEF trends is beyond the scope of this study. However, the overall negative MEF trend might be attributed to changes in large-scale atmospheric patterns, including the AO and NAO (Hurrell 1995, Thompson and Wallace 1998, Thompson and Wallace 2000). The negative MEF trend is also in agreement with atmospheric adjustments associated with the enhanced high-latitude warming (Hwang et al. 2011, Yoshimori et al. 2014).

As a general note on the usability of the reanalysis and radiosonde data in the estimations of the MEF, although reanalysis data might be poor, especially over areas with sparse observations (Bengtsson et al. 2004 a, Bengtsson et al. 2004 b, Simmons et al. 2004, Bromwich and Wang 2005, Bitz and Fu 2008, Grant et al. 2008, Thorne 2008, Screen and Simmonds 2011, Alexeev et al. 2012 [Paper III in the current thesis]), they appear to be more suitable for the investigation of large-scale processes, such as the meridional energy exchange between high and low latitudes. Radiosonde data might be useful for the validation of processes over a specific narrow region in which the reanalysis data diverge or fail to provide accurate information.

PAPER II: CLIMATOLOGY OF THE ARCTIC PLANETARY BOUNDARY LAYER

The shallowness and dynamical isolation of the Arctic planetary boundary layer (PBL) have been suggested as particularly important factors for the increased Arctic surface warming (ACIA 2005). The PBL processes have received a relatively large amount of attention in theoretical studies; however the observed climatology of the high-latitude PBL has received relatively little attention, partly because of a lack of the observations. The second paper is dedicated to the observed climatology of the Arctic PBL, aiming to provide summary of our current understanding of the high-latitude PBL climatology. We summarize already published efforts as well as perform new estimations. We aim to highlight different aspects of the Arctic PBL, including the PBL depth and its associations with various atmospheric and surface parameters. We also show the PBL depth spatial and temporal variability, and the most recent PBL trends. Because different types of observations may reveal different aspects of the PBL structure, we attempt to characterize the Arctic PBL from radiosonde (1992–2007), reanalysis, and satellite products, as well as from episodic turbulence field campaigns (different time periods). An additional purpose of the current study is to combine climate data that might be used in the characterization of the Arctic PBL and to discuss their accessibility, strengths, limitations and applicability.

The results of this study can be summarized into the following key findings:

- The Arctic PBL is stably stratified and shallow, usually below 200 m. We suggested that both radiation and dynamical processes support the atmospheric stable stratification of the Arctic PBL. The lack of incoming solar radiation and longwave cooling create the required condition for the stable atmospheric stratification. Simultaneously, a thermal-loop-like circulation within the polar cell (previously mentioned in the thesis) reinforces this stratification.
- Variations in the PBL depth and stratification are closely related to the strength and direction of the surface turbulent heat fluxes (THF), which are in turn strongly dependent on the presence of sea ice. We distinguished 10 regions by the similarities of the PBL physical processes as follows: (i) European Sub-Arctic, (ii) Siberian Sub-Arctic, (iii) Siberian, (iv) Canadian, (v) Greenland, (vi) Alaska Sub-Arctic, (vii) Sub-Atlantic, (viii) Atlantic, (ix) Pacific and (x) Baffin Bay regions. These 10 regions may be combined into continental (i-vi) and maritime groups (vii–x).
- The Arctic PBL climate has experienced significant changes over recent years. Generally, the PBL has become deeper in the maritime Arctic and shallower in the continental sub-Arctic. The trends in the PBL depth in the continental Arctic are in agreement with a reduction in the sensible heat flux and the near-surface wind speed. However the trends in the maritime Arctic cannot be as easily explained. Perhaps the deepening of the PBL in this region might be attributed to an increase in precipitation or more intensive cyclonic activity.
- The out-of-phase signature of the PBL trends between the continental (e.g., north of Eurasia) and maritime (the North Atlantic) regions is in agreement with the aforementioned linear trends in the MEF (Paper I) and might be also related to changes in large-scale atmospheric patterns, including the AO / NAO (Hurrell 1995, Thompson and Wallace 1998, Thompson and Wallace 2000) or perhaps to sea ice and SAT changes and associated circulation adjustments (e.g., Overland et al. 2011, Inoue et al. 2012, Outten and Esau 2012). However, further investigation is required for quantification of possible reasons responsible for the PBL trends.

A thorough investigation of the Arctic PBL critically depends on systematic and high-quality observations. However, the climate data, which can be used for estimations of the PBL processes, were found to be often incomplete, inconsistent and even contradictory. Much of the existing climate data poorly resolve the PBL processes. The available data sources for estimations of the Arctic PBL can be found in the associated section of the Paper II. We suggest that the Pan-Arctic datasets, such as reanalysis, satellite products and regular radiosonde observations, are best suited for characterizing the general properties of the Arctic PBL climate. Satellite products are advantageous for the reconstruction of THFs within the Arctic PBL. Whereas field turbulent campaigns provide high-quality and high-resolution data, allowing a more detailed investigation of various small-scale processes of the Arctic PBL. Data accessibility and quality increase rapidly each year, allowing the investigation of a topic in far more detail. A comprehensive overview of the climate data at the current time can be found at https://climatedataguide.ucar.edu.

PAPER III: VERTICAL STRUCTURE OF RECENT ARCTIC WARMING FROM OBSERVED DATA AND REANALYSIS PRODUCTS

The recent surface temperature trend in the Arctic is approximately twice as large as the Northern Hemisphere trend (IPCC 2007). However, the relative rates of the temperature trends throughout the Arctic atmosphere and the possible mechanisms responsible for those trends are controversial topics. A number of studies have suggested that the surface warming in the Arctic should be preceded by a warming in the troposphere above the PBL induced by meridional heat transport (Flannery 1984, Schneider et al. 1997, Alexeev 2003, Rodgers et al. 2003, Alexeev et al. 2005, Langen and Alexeev 2005, 2007). Graversen et al. (2008) have found this type of elevated warming trend. However, subsequently, it has been shown that those trends are dataset-dependent and might be caused by the inhomogeneous origin of the data (Bitz and Fu 2008, Grant et al. 2008, Thorne 2008, Screen and Simmonds 2011).

The primary goal of this study is to highlight the vertical structure of the recent Arctic temperature trends and to suggest possible explanations of the observed changes. We address the uncertainty issues related to the data quality. Similar to the previous studies (Bitz and Fu 2008, Grant et al. 2008, Thorne 2008, Screen and Simmonds 2011), we contrast the spatiotemporal patterns of the recent Arctic air temperature trends, but we do so in a larger number of datasets, including different reanalysis products (ERA-40, NCEP-1, NCEP-2, and JRA-25 [1979–2002]), the IABP/POLES dataset [1979–2004] and radiosonde data from the IGRA [various periods]. The choice of different periods is explained by the availability of the datasets.

The results of this study can be summarized in the following key findings:

- The reanalysis datasets show a substantial discrepancy in the spatial patterns of the Arctic temperature trends. The disagreement is the largest after 1997 and the area of largest disagreement is located poleward of 80 °N.
- We found that near the surface, NCEP-1, NCEP-2, ERA-40 and JRA-25 disagree substantially over the magnitude and even sign of the temperature trend. In the troposphere, ERA-40 shows a more rapid warming trend in the central Arctic, which is not found in other reanalysis products (NCEP-1, NCEP-2, and JRA-25) and the radiosonde data.
- In the lower stratosphere (200 hPa to 70 hPa), both the radiosonde and reanalysis data show that the winter temperature trends experience a change of sign from negative to

positive in the late 1980s, particularly over the Canadian Arctic. The changes are robust in the reanalysis data and throughout the array of the available radiosonde stations.

- The uncertainty in the temperature trends in the troposphere is too significant to make any conclusive statements about the elevated warming in the Arctic, and about possible physical mechanisms responsible for these elevated trends. Our conclusions are in agreement with previous investigations (Thorne 2008, Grant et al. 2008, Bitz and Fu 2008, Screen and Simmonds 2011). One possible explanation of the lower stratosphere temperature trends is changes in the position and strength of the AO.

PAPER IV: TWO-WAY COUPLING BETWEEN THE BARENTS SEA ICE AND ANOMALOUS EURASIAN WINTERS

Mid-latitude extremes including the heat waves in 2010 and 2012, and the cold air outbreaks in 2009–2010 and 2010–2011 across different parts of Eurasia and North America, have received an abundant amount of attention both in the scientific community and in the popular media. Skeptics have pointed to the cold weather extremes "as evidence that the globe is not warming". In the scientific community, viewpoints vary concerning whether to attribute the mid-latitude extremes to the global changes (e.g., Francis et al. 2009, Honda et al. 2009, Francis and Vavrus 2012, Jaiser et al. 2012, Inoue et al. 2012, Outten and Esau 2012, Tang et al. 2013, Tang et al. 2014, among others) or the superimposition of those extremes on a warming climate resulting from the natural climate variability (Cattiaux et al. 2010, Wallace et al. 2014, Gerber et al. 2014). Debate on this matter continues (Wallace et al. 2014, Overland 2014). One of the aforementioned associations is called a "warm-Arctic cold-Siberia" (WACS, Inoue et al. 2012) pattern, which links the Barents Sea ice conditions and anomalous Eurasian SATs. A common premise is that the Barents Sea ice conditions are communicated to the atmosphere by THF and that anomalously cold Eurasian winters result from the large-scale atmospheric response associated with changes in the meridional SAT gradient, storm tracks, Rossby waves and the Siberian High (Honda et al. 2009, Petoukhov and Semenov 2010, Inoue et al. 2012, Outten and Esau 2012).

This study seeks to characterize the interannual variability in the winter Barents Sea ice cover, the THF, and its association with the large-scale atmospheric flow, focusing on the WACS pattern. We apply an empirical orthogonal function (EOF) and a composite analysis to the reanalysis (ERA-Interim, 1979–2012) and satellite products (NSIDC). Whereas previous observational studies have suggested that the WACS pattern is a result of negative Barents Sea ice anomalies (Hori et al. 2011, Inoue et al. 2012) or Barents Sea ice trends (Outten and Esau 2012). We evaluate whether the WACS pattern can be also attributed in part to atmospheric variability. Specifically, we concentrate on the co-variability of the winter Barents Sea THF and the large-scale atmospheric flow, comparing evidence to determine whether the THF anomalies are altered by changes in sea ice or atmosphere.

Our findings include the following:

- The EOF analysis of the THF anomalies in the Barents Sea (THF_{Bar} EOFs) yields physically meaningful patterns in which the spatial structures imply different governing processes. We conclude that the first leading mode of the winter Barents Sea THF variability (THF_{Bar} EOF1) is associated with the variability in the large-scale atmospheric circulation. Only the second mode (THF_{Bar} EOF2) reflects a more direct local atmospheric response to the Barents Sea ice variability. The THF_{Bar} EOF2 consistently presents in all of the winter months. However its hemispheric-scale associations are not robust for the individual winter months and are inconsistent with a linear atmospheric response to an enhanced local heating.

- A WACS-like pattern appears independently of THF_{Bar} EOF2 or the Barents Sea ice composites and emerges as the second mode of the SAT variability over a Eurasian sector (SAT_{Eur} EOF2). The THF anomalies in the Barents Sea associated with the WACS-like pattern are negative. The relationship is inconsistent with the idea of sea ice reduction driving ocean-to-atmosphere THF and forcing the large-scale atmospheric anomalies.
- The collective results of our study, including lead-lag analysis between the WACS-like pattern and a variety of causal Barents Sea indicators, show that atmospheric variability contributes substantially to the observed anomalies in the Barents Sea THF, sea ice cover and the WACS pattern.
- The results highlight the complex, two-way coupling between the surface and the atmosphere and suggest that the WACS pattern is likely more complicated than a pure atmospheric response to the negative anomalies in the Barents Sea ice. The role of the Barents Sea ice variability in forcing the WACS pattern appears to be minor in the detrended analysis we performed. The conclusions of the current study hold true when tested against satellite (OAFlux and HOAPS) and reanalysis (NCEP1) THF products. The interpretation and comparison of the results with existing studies might be different if the recent trend in certain fields was included. Loss of the Barents Sea ice could potentially trigger anomalies that could reinforce the preexisting atmospheric circulation, which causes the WACS pattern

Our results are contradictory to certain previous observational studies (Hori et al. 2011, Inoue et al. 2012, Outten and Esau 2012), but they are more consistent with other studies, suggesting that anomalous cold winters in different parts of Eurasia are a consequence of the atmospheric circulation phenomena such as wave propagation, winter atmospheric blocking (e.g., Takaya and Nakamura 2005, Croci-Maspoli and Davies 2009, Park et al. 2011, Cheung et al. 2012), a weak polar vortex (e.g., Kolstad et al. 2010), and large-scale modes of internal atmospheric variability, including the NAO, AO, and EA patterns (e.g., Wallace and Gutzler 1981, Barnston and Livezey 1987, Hurrell 1995, Jeong and Ho 2005, Cattiaux et al. 2010) or combination of those patterns (Moore and Renfrew 2011).

A detailed comparison of our results with those from modeling studies (Honda et al. 2009, Petoukhov and Semenov 2010, Liptak and Strong 2014a, Liptak and Strong 2014b, Gerber et al. 2014; see also Magnusdottir et al. 2004, Deser et al. 2004) is not straightforward and is beyond the scope of our study. However our conclusions are in agreement with certain recent modeling studies (Liptak and Strong 2014a, Gerber et al. 2014) and relatively contradictory to other studies (Honda et al. 2009, Petoukhov and Semenov 2010).

Because the analysis is based on observations, a more rigorous diagnosis of causality between the WACS pattern and reduced sea ice cover in the Barents Sea requires further investigations, possibly in the form of a carefully designed coupled modeling experiment.

However this study makes a first step towards a better understanding of a two-way coupling between the observed sea ice changes and extreme weather conditions in the mid-latitudes, demonstrating that the proposed direct causal link between the variability in the Barents Sea ice and the WACS pattern is, at best, an incomplete characterization of nature.

V. CONCLUDING REMARKS AND FUTURE PERSPECTIVES

High northern latitudes are particularly sensitive to the ongoing climate changes; however understanding of the processes that are intrinsic to the atmosphere and the coupled ocean-atmosphere system is relatively poor in this region. Improving our knowledge of high-latitude climate require close collaboration among climatologists, oceanographers, and ice physicists, as well as combination of observational and model studies. New sets of high-quality climate data are also necessary.

This thesis investigates certain physical processes that shape the high-latitude climate based on available observational data. Additionally we address questions related to uncertainty issues related to data quality.

- The first paper improves our understanding of the spatial structure of the meridional energy transfer at 70 ºN, including its recent changes. We compare estimations of the MEF from "clean" observational data and reanalysis product and conclude that reanalysis data, by construction, are more suitable for the MEF estimation.
- In the second paper we synthesize knowledge about climatological aspects of the Arctic PBL. We illuminate variability and recent changes of the PBL depth over the high-latitudes and its relationship to different surface and atmospheric parameters. In addition we give an overview of existing datasets that are suitable for assessment of the PBL properties.
- In the third paper we test vertical structure of the recent high-latitude warming in a number of observational datasets and reanalysis products. We show substantial disagreement in the near-surface and tropospheric temperature trends. We conclude that the uncertainty is too great to make any assumption on physical mechanism that might be responsible for the positive tropospheric temperature trends, found in the ERA-40. In the stratosphere however, we found robust changes, which are likely associated with changes in the AO.
- In the fourth paper we examine nature of the recent apparently cold Eurasian winters, which have been commonly presumed to be a resultant response to the enhanced heating in the Barents Sea, associated with reduced sea ice. We highlight the two-way coupling between the winter Barents Sea ice, heat fluxes and the large-scale atmospheric circulation. We suggest that the WACS pattern has a complex nature and includes significant contribution from the natural atmospheric circulation variability. The study contributes to understanding of the Arctic/mid-latitude linkages, which are currently one of the most debatable issues in the scientific community.

There are many potential issues that may be addressed in a future study, but one of the most interesting questions, in my opinion, is how interactions between the changing Arctic sea ice cover and the atmosphere contribute to the climate variability. In the future we plan to investigate the potential influence of Arctic warming, associated with sea ice retreat on wintertime stationary wave activity, using an idealized approach. We will evaluate the atmospheric response of the mid-latitude stationary waves to the heating in a region, matching the observed thermal anomaly maxima during the record sea-ice minimum event of 2012, and identify the driving mechanisms.

REFERENCES

ACIA, 2005. Arctic Climate Impact Assessment. Cambridge University Press, 1042 pp.

Alexander, M.A. and S.D. Schubert, 1990: Regional earth-atmosphere energy balance estimates based on assimilations with a GCM. J. Climate, 3, 15–31, doi:10.1175/1520-0442(1990)003<0015:REAEBE>2.0.CO;2.

Alexander, M.A., U.S. Bhatt, J.E. Walsh, M.S. Timlin, J.S. Miller, and J.D. Scott, 2004: The atmospheric response to realistic arctic sea ice anomalies in an AGCM during winter. J. Climate, 17, 890–905, doi:10.1175/1520-0442(2004)017<0890:TARTRA>2.0.CO;2.

Alexeev, V.A., 2003: Sensitivity to CO2 doubling of an atmospheric GCM coupled to an oceanic mixed layer: A linear analysis. Climate Dynam. 20, 775–787, doi:10.1007/s00382-003-0312-x.

Alexeev, V.A., P.L. Langen, and J.R. Bates, 2005: Polar amplification of surface warming on an aquaplanet in "ghost forcing" experiments without sea ice feedbacks. Climate Dynam., doi:10.1007/s00382-005-0018-3.

AMAP, 2007. Arctic Oil and Gas 2007. Arctic Monitoring and Assessment Programme (AMAP) Oslo, Norway, 40 pp.

Ambaum, M.H.P., B.J. Hoskins, D.B. Stephenson, 2001: Arctic Oscillation or North Atlantic Oscillation? J. Climate, 14, 3495–3507, doi:10.1175/1520-0442(2001)014<3495:AOONAO>2.0.CO;2.

Andersson, A., S. Bakan, K. Fennig, H.Grassl, C. Klepp, and J. Schulz, 2007: Hamburg Ocean Atmosphere Parameters and fluxes from Satellite data – HOAPS3 – monthly mean, doi:10.1594/WDCC/HOAPS3 MONTHLY.

Årthun, M., T. Eldevik, L.H. Smedsrud, Ø. Skagseth, and R.B. Ingvaldsen, 2012: Quantifying the influence of Atlantic heat on Barents Sea ice variability and retreat. J. Climate, 25, 4736–4743, doi:10.1175/JCLI-D-11-00466.1.

Barnes, E.A., 2013: Revisiting the evidence linking Arctic amplification to extreme weather in midlatitudes, Geophys. Res. Lett., 40, 4728–4733, doi:10.1002/grl.50880.

Barnes, E.A., E. Dunn-Sigouin, G. Masato, and T. Woollings, 2014: Exploring recent trends in Northern Hemisphere blocking, Geophys. Res. Lett., 41, 638–644, doi:10.1002/2013GL058745.

Barnston, A.G., and R.E. Livezey, 1987: Classification, Seasonality and Persistence of Low-Frequency Atmospheric Circulation Patterns. Mon. Wea. Rev., 115, 1083–1126, doi:10.1175/1520-0493(1987)115<1083:CSAPOL>2.0.CO;2.

Beesley, J.A., C.S. Bretherton, C. Jakob, E.L. Andreas, J.M. Intrieri, and T.A. Uttal, 2000: A comparison of cloud and boundary layer variables in the ECMWF forecast model with observations at Surface Heat Budget of the Arctic Ocean (SHEBA) ice camp, J. Geophys. Res., 105, 12337–12349, doi:10.1029/2000JD900079.

Belchansky, G., D.C. Douglas, V.A. Eremeev, and N.G. Platonov, 2005: Variations in the Arctic's multiyear sea ice cover: a neural network analysis of SMMR-SSM/I data, 1979–2004. Geophys. Res. Lett, 32, L09605. doi:10.1029/2005GL022395.

Bengtsson, L., S. Hagemann, and K.I. Hodges, 2004a: Can climate trends be computed from reanalysis data? J. Geophys. Res. Atmos., 109, doi:10.2001/2004JD00.

Bengtsson, L., K.I. Hodges, and S. Hagemann, 2004b: Sensitivity of the ERA40 reanalysis to the observing system: Determination of the global atmospheric circulation from reduced observations. Tellus A, 56, 456–471, doi:10.1111/j.1600-0870.2004.00079.x.

Bitz, C.M, and Q. Fu, 2008: Arctic warming aloft is dataset dependent, Nature 455, E3–E4, doi:10.1038/nature07258.

Bjerknes, J., 1964: Atlantic Air-Sea Interaction, In: H.E. Landsberg and J. Van Mieghem, Editor(s), Advances in Geophysics, Elsevier, Volume 10, Pages 1-82, ISSN 0065-2687, ISBN 9780120188109, doi:10.1016/S0065-2687(08)60005-9.

Blüthgen, J., R. Gerdes, and M. Werner, 2012: Atmospheric response to the extreme Arctic sea ice conditions in 2007, Geophys. Res. Lett., 39, L02707, doi:10.1029/2011GL050486.

Boer, G.J. and N.E. Sargent, 1985: Vertically integrated budgets of mass and energy of the globe. J. Atmos. Sci., 42, 1592–1613, doi:10.1175/1520-0469(1985)042<1592:VIBOMA>2.0.CO;2.

Bromwich, D.H., and S.H., Wang, 2005: Evaluation of the NCEP–NCAR and ECMWF 15- and 40-Yr reanalyses using rawinsonde data from two independent arctic field experiments. Mon Wea. Rev., 133, 3562–3578, doi:10.1175/MWR3043.1.

Byrkjedal, O, I. Esau, N.G. Kvamstø, 2008: Sensitivity of simulated wintertime Arctic atmosphere to vertical resolution in the ARPEGE/IFS model. Climate Dynam., 30, 687–701, doi:10.1007/s00382-007-0316-z.

Cattiaux, J., R. Vautard, C. Cassou, P. Yiou, V. Masson-Delmotte, and F. Codron, 2010: Winter 2010 in Europe: A cold extreme in a warming climate. Geophys. Res. Lett., 37, L20704, doi:10.1029/2010GL044613.

Cayan, D.R., 1991: Latent and sensible heat flux anomalies over the Northern Oceans: the connection to monthly atmospheric circulation. J. Climate, 5, 354–369, doi:10.1175/1520-0442(1992)005<0354:LASHFA>2.0.CO;2.

Chen, Y., J.A. Francis, and J.R. Miller, 2002: Surface Temperature of the Arctic: Comparison of TOVS Satellite Retrievals with Surface Observations, J. Climate, 15, 3698-3708, doi:10.1175/1520-0442(2002)015<3698:STOTAC>2.0.CO;2.

Cheung, H.N., W. Zhou, Y. Shao, W. Chen, H.Y. Mok, and M.C. Wu, 2012: Observational climatology and characteristics of wintertime atmospheric blocking over Ural–Siberia. Climate Dynam., 41, 63–79, doi:10.1007/s00382-012-1587-6.

Christensen, J.H., O.B. Christensen, P. Lopez, E. van Meijgaard, and M. Botzet (1996), The HIRHAM4 Regional Atmospheric Climate Model, Tech. Rep. 96–4, Danish Meteorological Institute.

Chylek, P., C.K. Folland, G. Lesins, M.K. Dubey, and M.-Y. Wang, 2009: Arctic air temperature change amplification and the Atlantic Multidecadal Oscillation, Geophys. Res. Lett., 36, L14801, doi:10.1029/ 2009GL038777.

Cohen, J.L., D.A. Salstein, and R.D. Rosen, 2000: Interannual Variability in the Meridional Transport of Water Vapour, J. Hydromet. 1, 547–553, doi:10.1175/1525-7541(2000)001<0547:IVITMT>2.0.CO;2.

Comiso, J.C., 2006: Arctic warming signals from satellite observations. Weather, 61, 70–76, doi: 10.1256/wea.222.05.

Comiso, J.C., 2012: Large decadal decline of the Arctic multiyear ice cover. J. Climate, 25 1176–93, doi:10.1175/JCLI-D-11-00113.1.

Coumou, D., and S. Rahmstorf, 2012: A decade of weather extremes. Nature Climate Change, 2, 491–496, doi:10.1038/nclimate1452.

Covey, C., K.M. AchutaRao, M. Fiorino, P.J. Gleckler, K.E. Taylor, and M.F. Wehner, 2002: Intercomparison of climate datasets as a measure of observational uncertainty. Report No. 69, Program for Climate Model Diagnosis and Intercomparison, Livermore, CA 94550, USA, 38 pp.

Croci-Maspoli, M., and H.C. Davies, 2009: Key dynamical features of the 2005/06 European winter. Mon. Wea. Rev., 137, 664–678, doi:10.1175/2008MWR2533.1.

Cullather R.I., D.H. Bromwich, and M.C. Serreze, 2000: The Atmospheric Hydrologic Cycle over the Arctic from Reanalyses. Part I. Comparison with Observations and Previous Studies. J. Climate, 13, 923–937, doi:10.1175/1520-0442(2001)014<2414:TAHCOT>2.0.CO;2.

Dee, D.P., et al. 2011: The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Q.J.R. Meteorol. Soc., 137, 553–597, doi:10.1002/qj.828.

Deser, C., A.S. Phillips, V. Bourdette, and H. Teng, 2012: Uncertainty in climate change projections: The role of internal variability. Climate Dynam., 38, 527–546, doi:10.1007/s00382-010-0977-x.

Deser, C., G. Magnusdottir, R. Saravanan, and A. Phillips, 2004: The effects of North Atlantic SST and sea ice anomalies on the winter circulation in CCM3. Part II: Direct and indirect components of the response. J. Climate, 17, 877–889, doi:10.1175/1520-0442(2004)017<0877:TEONAS>2.0.CO;2.

Deser, C., J.E. Walsh, and M.S. Timlin, 2000: Arctic sea ice variability in the context of recent atmospheric circulation trends. J. Climate, 13, 617–633, doi:10.1175/1520-0442(2000)013<0617:ASIVIT>2.0.CO;2.

Deser, C., R. Tomas, M. Alexander, and D. Lawrence, 2010: The seasonal atmospheric response to projected Arctic sea ice loss in the late twenty-first century. J. Climate, 23, 333–351, doi:10.1175/2009JCLI3053.1.

Deser, C., R.A. Tomas, and S. Peng, 2007: The Transient Atmospheric Circulation Response to North Atlantic SST and Sea Ice Anomalies. J. Climate, 20, 4751–4767, doi:10.1175/JCLI4278.1.

Dickson, R.R., et al., 2000: The Arctic Ocean response to the North Atlantic Oscillation. J. Climate, 13, 2671-2696, doi:10.1007/s00382-013-1875-9.

Esau, I.N. 2007, Amplification of turbulent exchange over wide Arctic leads: Large-eddy simulation study, J. Geophys. Res. Atmos., 112, doi: DOI: 10.1029/2006JD007225.

Flannery, B.P., 1984: Energy-balance models incorporating transport of thermal and latent energy. J. Atmos. Sci., 41, 414–421, doi:10.1175/1520-0469(1984)041<0414:EBMITO>2.0.CO;2.

Francis, J.A., and E. Hunter, 2007: Drivers of declining sea ice in the Arctic winter: a tale of two seas. Geophys. Res. Lett., 34, L17503, doi:10.1029/2007gl030995.

Francis, J.A., and S.J. Vavrus, 2012: Evidence linking Arctic amplification to extreme weather in mid-latitudes, Geophys. Res. Lett., 39, L06801, doi:10.1029/2012GL051000.

Francis, J.A., W. Chan, D.J. Leathers, J.R. Miller, and D.E. Veron, 2009: Winter Northern Hemisphere weather patterns remember summer Arctic sea-ice extent, Geophys. Res. Lett., 36, L07503, doi:10.1029/2009GL037274.

Gaffen, D.J., 1996: A Digitized metadataset of global upper-air station histories, NOAA, Technical Memorandum ERL-ARL 211, Silver Spring, MD, 38 pp.

Gerber, F., J. Sedláček, and R. Knutti, 2014: Influence of the western North Atlantic and the Barents Sea on European winter climate, Geophys. Res. Lett., 41, 561–567, doi:10.1002/2013GL058778.

Ghatak, D., A. Frei, G. Gong, J. Stroeve, D. Robinson, 2010: On the emergence of an Arctic amplification signal in terrestrial Arctic snow extent. J. Geophys. Res., 10.1029/2010JD014007.

Göber, M., R. Hagenbrock, F. Ament, and A. Hense, 2003: Comparing mass-consistent atmospheric moisture budgets on an irregular grid: An Arctic example. Q.J.R. Meteorol. Soc., 129, 2383–2400, doi:10.1256/qj.02.104.

Grant, A.N., S. Broennimann, and L. Haimberger, 2008: Recent Arctic warming vertical structure contested, Nature, 455, E2–E3, doi: 10.1038/nature07257.

Graversen, R.G., T. Mauritsen, M. Tjernström, E. Källén, and G. Svensson, 2008: Vertical structure of recent Arctic warming, Nature, 451, 53–56, doi: doi:10.1038/nature06502.

Gulev, S.K., M. Latif, N. Keenlyside, W. Park, and K.P. Koltermann, 2013: North Atlantic Ocean control on surface heat flux on multidecadal timescales. Nature, 499, 464–467, doi:10.1038/nature12268.

Heininen, L. (ed.), 2013: Arctic Yearbook 2013. Akureyri, Iceland: Northern Research Forum. Available from, http://www.arcticyearbook.com.

Holland, M.M, C.M. Bitz, M. Eby, and A.J. Weaver, 2001: The role of ice-ocean interactions in the variability of the North Atlantic thermohaline circulation, J. Climate, 14, 656–675, doi:10.1175/1520-0442(2001)014<0656:TROIOI>2.0.CO;2.

Holland, M.M., and C.M. Bitz, 2003: Polar amplification of climate change in coupled models, Climate Dynam., 21, 221–232., doi: 10.1007/s00382-003-0332-6.

Holzworth, G.C., 1964: Estimates of mean maximum mixing depths in the contiguous United States, Mon. Weather Rev., 92, 235–242, doi:10.1175/ 1520-0493(1964)092<0235:EOMMMD>2.3.CO;2.

Holzworth, G.C., 1967: Mixing depths, wind speeds and air pollution potential for selected locations in the United States, J. Appl. Meteor., 6, 1039–1044, doi:10.1175/1520-0450(1967)006<1039:MDWSAA>2.0. CO;2.

Honda, M., J. Inoue, and S. Yamane, 2009: Influence of low Arctic sea-ice minima on anomalously cold Eurasian winters. Geophys. Res. Lett., 36, L08707, doi:10.1029/2008GL037079.

Hopsch, S., J. Cohen, and K. Dethloff, 2012: Analysis of a link between fall Arctic sea ice concentration and atmospheric patterns in the following winter. Tellus A, 64, 18624, doi:10.3402/tellusa.v64i0.18624.

Hori, M.E., J. Inoue, T. Kikuchi, M. Honda, and Y. Tachibana, 2011: Recurrence of intraseasonal cold air outbreak during the 2009/2010 winter in Japan and its ties to the atmospheric condition over the Barents-Kara Sea. SOLA, 7, 25–28, doi:10.2151/sola.2011-007.

Hurrell, J.W., 1995: Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. Science, 269, 676–679, doi:10.1126/science.269.5224.676.

Hwang, Y.T., D.M.W. Frierson, and J.E. Kay, 2011: Coupling between Arctic feedbacks and changes in poleward energy transport. Geophys. Res. Lett., 38, L17704, doi:10.1029/2011gl048546.

Inoue, J., M.E. Hori, and K. Takaya, 2012: The role of Barents Sea ice in the wintertime cyclone track and emergence of a warm-Arctic cold-Siberian anomaly. J. Climate, 25, 2561–2568, doi:10.1175/JCLI-D-11-00449.1.

IPCC, 2001: Intergovernmental Panel for Climate Change 2001. The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881 pp.

IPCC, 2007: Intergovernmental Panel for Climate Change 2007. Fourth assessment report. The physical sciences basis. Contribution of working group I to the fourth assessment report of the IPCC, Cambridge University Press, ISBN 978-0-521-88009-1, 996p.

Ivanov, I., 2000: The Northern Sea Route Tariff System – Present Practice and Future Requirements – The ARCDEV Experience. The 21st Century – Turning Point for the Northern Sea Route? Eds.: Ragner, C.L. Springer Netherlands p. 135–145, doi:10.1007/978-94-017-3228-4_23.

Jacobson, A.R., and B. Medeiros, 2012: Climatology of the planetary boundary layer over the continental United States and Europe. J. Geophys. Res., 117, D17106, doi:10.1029/2012JD018143.

Jaiser, R., K. Dethloff, D. Handorf, A. Rinke, and J. Cohen, 2012: Impact of sea ice cover changes on the Northern Hemisphere atmospheric winter circulation. Tellus A, 64, 11595, doi:10.3402/tellusa.v64i0.11595.

Jeong, J.-H., and C.-H. Ho, 2005: Changes in occurrence of cold surges over East Asia in associated with Arctic Oscillation. Geophys. Res. Lett., 32, L14704, doi:10.1029/2005GL023024.

Kalnay, E., et al., 1996: The NCEP/NCAR 40-Year Reanalysis Project, Bull. Amer. Meteor. Soc., 77, 437–470, doi:10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2.

Kanamitsu, M, W. Ebisuzaki, J. Woollen, S.-K. Yang, J.J. Hnilo, M. Fiorino, and G.L. Potter, 2002: NCEP–DOE AMIP-II Reanalysis (R-2). Bull. Amer. Meteor. Soc., 83, 1631–1643, doi:10.1175/BAMS-83-11-1631.

Kaufman, D.S. et al., 2009: Recent warming reverses long-term Arctic cooling. Science, 325, 1236-1239, doi:10.1126/science.1173983.

Kauker, F., R. Gerdes, M. Karcher, C. Köberle, and J.L. Lieser, 2003: Variability of Arctic and North Atlantic sea ice: A combined analysis of model results and observations from 1978 to 2001. J. Geophys. Res., 108(C6), 3182, doi:10.1029/2002JC001573.

Khrol, V.P. (Ed.), 1992: Atlas of the Energy Balance of the Northern Polar Area, Arctic, and Antarctic. Res. Inst., p. 72, St. Petersburg, Russia.

Koenigk, T., U. Mikolajewicz, J.H. Jungclaus, and A. Kroll, 2009: Sea ice in the Barents Sea: Seasonal to interannual variability and climate feedbacks in a global coupled model. Climate Dyn., 32, 1119–1138, doi:10.1007/s00382-008-0450-2.

Kolstad, E.W., T. Breiteig, and A.A. Scaife, 2010: The association between stratospheric weak polar vortex events and cold air outbreaks in the Northern Hemisphere, Q.J.R. Meteorolog. Soc., 136(649), 886–893, doi:10.1002/qj.620.

Kutzbach, J.E., 1970: Large-scale features of monthly mean Northern Hemisphere anomaly maps of sea-level pressure. Mon. Wea. Rev., 98, 708–716, doi:10.1175/1520-0493(1970)098<0708:LSFOMM>2.3.CO;2.

Kvamstø, N.G., Skeie, P. and Stephenson, D.B., 2004: Impact of Labrador sea-ice extent on the North Atlantic oscillation. Int. J. Climatol., 24, 603–612. doi:10.1002/joc.1015.

Kwok, R., and D.A. Rothrock, 2009: Decline in Arctic sea ice thickness from submarine and ICESat records: 1958–2008, Geophys. Res. Lett., 36, L15501, doi:10.1029/2009GL039035.

Kwok, R., G. Cunningham, and S. Pang, 2004: Fram Strait sea ice outflow, J. Geophys. Res., 109, C01009, doi:10.1029/2003JC001785.

L'Heureux, M.L., A. Kumar, G.D. Bell, M.S. Halpert, and R.W. Higgins, 2008: Role of the Pacific-North American (PNA) pattern in the 2007 Arctic sea ice decline. Geophys. Res. Lett., 35, L20701, doi:10.1029/2008GL035205.

Langen, P.L., and V.A. Alexeev, 2005: Estimating $2\times CO$ warming in an aquaplanet GCM using the fluctuation-dissipation theorem, Geophys. Res. Lett., 32, L23708, doi:10.1029/2005GL024136.

Langen, P.L., and V.A. Alexeev, 2007: Polar amplification as a preferred response in an aquaplanet GCM. Climate Dynam., 29, 305–317, doi:10.1007/s00382-006-0221-x.

Liptak, J., and C. Strong, 2014a: The Winter Atmospheric Response to Sea Ice Anomalies in the Barents Sea. J. Climate, 27, 914–924, doi:10.1175/JCLI-D-13-00186.1.

Liptak, J., and C. Strong, 2014b: A Model-Based Decomposition of the Sea Ice-Atmosphere Feedback over the Barents Sea during Winter. J. Climate, e-view, doi:10.1175/JCLI-D-13-00371.1.

Liu, J., J.A. Curry, H. Wang, M. Song, and R.M. Horton, 2012: Impact of decliningArctic sea ice on winter snowfall. Proc. Natl. Acad. Sci. USA, 109, 4074–4079, doi:10.1073/pnas.1114910109.

Liu, Z., and M. Alexander, 2007: Atmospheric bridge, oceanic tunnel, and global climatic teleconnections. Rev. Geophys., 45, RG2005, doi:10.1029/2005RG000172.

Lorenz, E.N., 1950: Seasonal and irregular variations of the Northern Hemisphere sea-level pressure profile. J. Meteor., 8, 52–59, doi:10.1175/1520-0469(1951)008<0052:SAIVOT>2.0.CO;2.

Magnusdottir, G., C. Deser, and R. Saravanan, 2004: The effects of North Atlantic SST and sea ice anomalies on the winter circulation in CCM3. Part I: Main features and storm track characteristics of the response. J. Climate, 17, 857–876, doi:10.1175/1520-0442(2004)017<0857:TEONAS>2.0.CO;2.

Mauritsen, T., G. Svensson and B. Grisogono, 2005: Wave flow simulations over Arctic leads, Boundary Layer Meteorology, 117(2), 259–273, doi:10.1007/s10546-004-1427-2.

Mauritsen, T., G. Svensson, S. Zilitinkevich, I. Esau, L. Enger, and B. Grisogono, 2007. A total turbulent energy closure model for neutrally and stably stratified atmospheric boundary layers. J. Atmos. Sci., 64, 4113–4126, doi:10.1175/2007JAS2294.1.

Michaud, R., and J. Derome, 1991: On the mean meridional transport of energy in the atmosphere and oceans as derived from six years of ECMWF analyses. Tellus, 43A, 1–14, doi:10.1034/j.1600-0870.1991.00001.x.

Moore, G.W.K., and I.A. Renfrew, 2011: Cold European winters: interplay between the NAO and the East Atlantic mode. Atmosph. Sci. Lett., 13, 1–8. doi:10.1002/asl.356.

Murphy, S.J., and R. Washington, 2001: United Kingdom and Ireland precipitation variability and the North Atlantic sea-level pressure field. Int. J. Climatol., 21, 939–959, doi:10.1002/joc.670.

Nakamura, N., and A.H. Oort, 1988: Atmospheric Heat Budgets of the Polar Regions. J. Geophys. Res., 93, 9510–9524, doi: 10.1029/JD093iD08p09510.

Ogi, M., and J.M. Wallace, 2007: Summer minimum Arctic sea ice extent and the associated summer atmospheric circulation. Geophys. Res. Lett., 34, L12705, doi:10.1029/2007GL029897.

Ogi, M., and J.M. Wallace, 2012: The role of summer surface wind anomalies in the summer Arctic sea ice extent in 2010 and 2011. Geophys. Res. Lett., 39, L09704, doi:10.1029/2012GL051330.

Ogi, M., K. Yamazaki, and J.M. Wallace, 2010: Influence of winter and summer surface wind anomalies on summer Arctic sea ice extent. Geophys. Res. Lett., 37, L07701, doi:10.1029/2009GL042356.

Oort, A.H., 1983: Global atmospheric circulation statistics, 1958–1973, NOAA Prof. Pap., 14, Washington, D.C.

Orsolini, Y.J., R. Senan, R.E. Benestad, and A. Melsom, 2012: Autumn atmospheric response to the 2007 low Arctic sea ice extent in coupled ocean–atmosphere hindcasts. Clim. Dynam., 38, 2437–2448, doi:10.1007/s00382-011-1169-z.

Outten, S., and I. Esau, 2012: A link between Arctic sea ice and recent cooling trends over Eurasia. Climatic Change, 110, 1069–1075, doi:10.1007/s10584-011-0334-z.

Overland, J.E. and P. Turet, 1994: Variability of the Atmospheric Energy Flux across 70 °N Computed from the GFDL Data Set, Nansen Centennial Volume. Geophys. Monogr. American Geophys. Union, No. 84, 313–325, doi:0.1029/GM085p0313.

Overland, J.E., 2014: Long-range linkage. Nature Climate Change. 4, 11–12, doi:10.1038/nclimate2079.

Overland, J.E., and M. Wang, 2005: The Arctic climate paradox: the recent decrease of the Arctic Oscillation. Geophys. Res. Lett., 32(6), L06701, doi:10.1029/2004GL021752.

Overland, J.E., and M. Wang, 2010: Large-scale atmospheric circulation changes associated with the recent loss of Arctic sea ice. Tellus, 62A, 1–9, doi:10.1111/j.1600-0870.2009.00421.x.

Overland, J.E., K.R. Wood, and M. Wang, 2011: Warm Arctic–cold continents: Impacts of the newly open Arctic Sea. Polar Res., 30, 15787, doi:10.3402/polar.v30i0.15787.

Overland, J.E., P. Turet, and A.H. Oort, 1996: Regional Variations of Moist Static Energy Flux into the Arctic. J. Climate, 9, 54–65, doi:10.1175/1520-0442(1996)009<0054:RVOMSE>2.0.CO;2.

Park, T.-W., C.-H. Ho, and S. Yang, 2011: Relationship between the Arctic Oscillation and cold surges over East Asia. J. Climate, 24, 68–83, doi:10.1175/2010JCLI3529.1.

Perovich, D.K., B. Light, H. Eicken, K.F. Jones, K. Runciman, and S.V. Nghiem, 2007: Increasing solar heating of the Arctic Ocean and adjacent seas, 1979–2005: Attribution and role in the ice-albedo feedback. Geophys. Res. Lett., 34, L19505, doi:10.1029/2007GL031480.

Petoukhov, V., and V.A. Semenov, 2010: A link between reduced Barents–Kara Sea ice and cold winter extremes over northern continents. J. Geophys. Res., 115, D21111, doi:10.1029/2009JD013568.

PolyakoI, I.V., et al., 2005: One more step toward a warmer Arctic. Geophys. Res. Lett., 32, L17 605, doi:10.1029/2005GL023740.

Rahmstorf, S., and D. Coumou, 2011: Increase of extreme events in a warming world, Proc. Natl. Acad. Sci. U. S. A., 108(44), 17905–17909, doi:10.1073/pnas.1101766108.

Rhines, A. and P. Huybers, 2013: Frequent summer temperature extremes reflect changes in the mean, not the variance, Proceedings of the National Academy of Sciences, 110(7), E546-E546, doi:10.1073/pnas.1218748110.

Rigor, I.G., and J.M. Wallace, 2004: Variations in the age of Arctic sea-ice and summer sea ice extent. Geophys. Res. Lett., 31, L09401, doi:10.1029/2004GL019492.

Rigor, I.G., J.M. Wallace, and R.L. Colony, 2002: Response of sea ice to the Arctic Oscillation. J. Climate, 15, 2648–2663, doi:10.1175/1520-0442(2002)015<2648:ROSITT>2.0.CO;2.

Rigor, I.G., R.L. Colony, S. Martin, 2000: Variations in surface air temperature observations in the Arctic, 1979-97, J. Climate, 13, 896–914, doi:10.1175/1520-0442(2000)013<0896:VISATO>2.0.CO;2.

Rinke, A. et al., 2006: Evaluation of an ensemble of Arctic regional climate models: Spatial patterns and height profiles. Climate Dynam., doi:10.1007/s00382-005-0095-3.

Rodgers, K.B., G. Lohmann, S. Lorenz, R. Schneider, and G.M. Henderson, 2003: A tropical mechanism for Northern Hemisphere deglaciation, Geochem. Geophys. Geosyst., 4, 1046, doi:10.1029/2003GC000508.

Rogers, J.C., and H. van Loon, 1979: The Seesaw in Winter Temperatures Between Greenland and Northern Europe. Part II: Some Oceanic and Atmospheric Effects in Middle and High Latitudes. Mon. Wea. Rev., 107, 509–519, doi:10.1175/1520-0493(1979)107<0509:TSIWTB>2.0.CO;2.

Savijärvi, H.I., 1988: Global Energy and Moisture Budgets from Rawinsonde Data. Mon. Wea. Rev., 116, 417–430, doi:10.1175/1520-0493(1988)116<0417:GEAMBF>2.0.CO;2.

Schlichtholz, P., 2011: Influence of oceanic heat variability on sea ice anomalies in the Nordic Seas, Geophys. Res. Lett., 38, L05705, doi:10.1029/2010GL045894.

Schneider, E.K., R.S. Lindzen, and B.P. Kirtman, 1997: A tropical influence on the global climate. J. Atmos. Sci., 54, 1349–1358, doi: 10.1175/1520-0469(1997)054<1349:ATIOGC>2.0.CO;2.

Screen, J.A., and I. Simmonds, 2013: Exploring links between Arctic amplification and mid-latitude weather, Geophys. Res. Lett., 40, 959–964, doi:10.1002/grl.50174.

Screen, J.A., and I. Simmonds, 2010: The central role of diminishing sea ice in recent Arctic temperature amplification. Nature, 464, 1334–1337, doi:10.1038/nature09051.

Screen, J.A., and I. Simmonds, 2011: Erroneous Arctic Temperature Trends in the ERA-40 Reanalysis: A Closer Look. J. Climate, 24, 2620–2627,doi: http://dx.doi.org/10.1175/2010JCLI4054.1.

Screen, J.A., C. Deser, and I. Simmonds, 2012: Local and remote controls on observed Arctic warming, Geophys. Res. Lett., 39, L10709, doi:10.1029/2012GL051598.

Screen, J.A., I. Simmonds, and K. Keay, 2011: Dramatic interannual changes of perennial Arctic sea ice linked to abnormal summer storm activity. J. Geophys. Res., 116, D15105, doi:10.1029/2011JD015847.

Seidel, D.J., C.O. Ao, and K. Li, 2010: Estimating climatological planetary boundary layer heights from radiosonde observations: Comparison of methods and uncertainty analysis, J. Geophys. Res., 115, D16113, doi:10.1029/2009JD013680.

Seidel, et al., 2012: Climatology of the planetary boundary layer over the continental United States and Europe, J. Geophys. Res., 117, D17106, doi:10.1029/2012JD018143.

Seierstad, I., and J. Bader, 2009: Impact of a projected future Arctic Sea Ice reduction on extratropical storminess and the NAO. Climate Dynam., 33, 937–943, doi:10.1007/s00382-008-0463-x.

Semmler, T., D. Jacob, K.H. Schlunzen and R. Podzun, 2005: The Water and Energy Budget of the Arctic Atmosphere. J. Climate. 18, 2515–2530, doi:10.1175/JCLI3414.1.

Serreze, et al., 2007: The Large-Scale Energy Budget of the Arctic. J. Geophys. Res., 112, D11122, doi:10.1029/2006Jd008230.

Serreze, M.C., A.P. Barrett, J.C. Stroeve, D.N. Kindig, and M.M. Holland, 2009: The emergence of surface-based Arctic amplification. The Cryosphere, 3, 11–19, doi: 10.5194/tc-3-11-2009.

Serreze, M.C., and J.A. Francis, 2006: The arctic amplification debate. Climatic Change, 76, 241-264, doi:1007/s10584-005-9017-y.

Serreze, M.C., and R.G. Barry, 2005: The Arctic Climate System. UK. Cambridge University Press, Cambridge.

Shaffrey, L., and R. Sutton, 2006: Bjerknes Compensation and the Decadal Variability of the Energy Transports in a Coupled Climate Model. J. Climate, 19, 1167–1181, doi:10.1175/JCLI3652.1.

Shimada, K., T. Kamoshida, M. Itoh, S. Nishio, E. Carmack, F. McLaughlin, S. Zimmerman, and A. Proshutinsky, 2006: Pacific Ocean inflow: Influence on catastrophic reduction of sea ice cover in the Arctic Ocean. Geophys. Res. Lett., 33, L08605, doi:10.1029/2005GL025624.

Simmons, A.J. et al., 2004: Comparison of trends and low-frequency variability in CRU, ERA-40, and NCEP/ NCAR analyses of surface air temperature, J. Geophys, Res., 109, D24115, doi:10.1029/2004JD005306.

Singarayer, J. S., J.L. Bamber, and P.J. Valdes, 2006: Twenty-firstcentury climate impacts from a declining Arctic sea ice cover. J. Climate, 19, 1109–1125, doi:10.1175/JCLI3649.1.

Smedsrud L.H., A. Sorteberg, and K. Kloster, 2008: Recent and Future Changes of the Arctic Sea Ice Cover. Geophys. Rev. Lett. 35, L20503, doi:10.1029/2008GL034813.

Smedsrud, L.H., A. Sirevaag, K. Kloster, A. Sorteberg, and S. Sandven, 2011: Recent wind driven high sea ice area export in the Fram Strait contributes to Arctic sea ice decline. Cryosphere, 5, 821–829, doi:10.5194/tc-5-821-2011.

Smedsrud, L.H., et al., 2013: The role of the Barents Sea in the Arctic climate system, Rev. Geophys., 51, 415–449, doi:10.1002/rog.20017.

Steele, M., W. Ermold, and J. Zhang, 2008: Arctic Ocean surface warming trends over the past 100 years, Geophys. Res. Lett., 35, L02614, doi:10.1029/2007GL031651.

Steeneveld, G.J., B.J.H. van de Wiel and A.A.M. Holtslag, 2006: Modeling the Arctic stable boundary layer and its coupling to the surface. Bound.-Layer Meteorol. 118, 357–378, doi:10.1007/s10546-005-7771-z.

Stendel, M., J.H. Christensen, G. Aðalgeirsdóttir, N. Kliem, and M. Drews, 2007: Regional climate change for Greenland and surrounding seas part I: Atmosphere and land surface, in Danish Climate Centre Report, vol. 07-02, Danish Meteorological Institute.

Stroeve, J., M.M. Holland, W. Meier, T. Scambos, and M. Serreze, 2007: Arctic sea ice decline: Faster than forecast, Geophys. Res. Lett., 34, L09501, doi:10.1029/2007GL029703.

Stroeve, J.C., J. Maslanik, M.C. Serreze, I. Rigor, W. Meier, and C. Fowler, 2011: Sea ice response to an extreme negative phase of the Arctic Oscillation during winter 2009/2010. Geophys. Res. Lett., 38, L02502, doi:10.1029/2010GL045662.

Stroeve, J.C., M.C. Serreze, M.M. Holland, J.E. Kay, J. Maslanik, and A.P. Barrett, 2012: The Arctic's rapidly shrinking sea ice cover: A research synthesis, Climate Change, 110, 1005–1027, doi:10.1007/ s10584-011-0101-1.

Strong, C., and G. Magnusdottir, 2010: Modeled winter sea ice variability and the North Atlantic Oscillation: a multi-century perspective. Climate Dynamics, 34(4), 515–525. doi:10.1007/s00382-009-0550-7.

Strong, C., G. Magnusdottir, and H. Stern, 2009: Observed Feedback between Winter Sea Ice and the North Atlantic Oscillation. J. Climate, 22, 6021–6032, doi:10.1175/2009JCLI3100.1.

Takaya, K., and H. Nakamura, 2005: Mechanisms of intraseasonal amplification of the cold Siberian high. J. Atmos. Sci., 62, 4423–4440, doi:10.1175/JAS3629.1.

Tang, Q., X. Zhang and J.A. Francis, 2014: Extreme summer weather in northern mid-latitudes linked to a vanishing cryosphere, Nature Climate Change 4, 45–50, doi:10.1038/nclimate2065.

Tang, Q., X. Zhang, X. Yang, and J.A. Francis, 2013: Cold winter extremes in northern continents linked to Arctic sea ice loss. Envir. Res. Lett., 8, doi:10.1088/1748-9326/8/1/014036.

Tedesco, M., X. Fettweis, T. Mote, J. Wahr, P. Alexander, J.E. Box, and B. Wouters, 2013: Evidence and analysis of 2012 Greenland records from spaceborne observations, a regional climate model and reanalysis data, The Cryosphere, 7, 615-630, doi:10.5194/tc-7-615-2013.

Thompson, D.W.J., and J.M. Wallace, 1998: The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. Geophys. Res. Lett., 25(9), 1297–1300, doi:10.1029/98GL00950.

Thompson, D.W.J., and J.M. Wallace, 2000: Annular modes in the extratropical circulation. Part I: Month-to-month variability. J. Climate, 13, 1000–1016, doi:10.1175/1520-0442(2000)013<1000:AMITEC>2.0.CO;2.

Thompson, D.W.J., J.M. Wallace, and G.C. Hegerl, 2000: Annular modes in the extratropical circulation: Part II: Trends. J. Climate, 13, 1018-1036, doi:10.1175/1520-0442(2000)013<1018:AMITEC>2.0.CO;2.

Thorne, P.W., 2008: Arctic tropospheric warming amplification? Nature, 455, E1–E2, doi:10.1038/ nature07256.

Thorne, P.W., D.E. Parker, S.F.B. Tett, P.D. Jones, M. McCarthy, H. Coleman, and P. Brohan, 2005: Revisiting radiosonde upper air temperatures from 1958 to 2002, J. Geophys. Res., 110, D18105, doi:10.1029/2004JD005753.

Tjernström, M. and T. Mauritsen, 2009: Mesoscale Variability in the Summer Arctic Boundary Layer. Boundary Layer Meteorology, 130, 383–406, doi: 10.1007/s10546-009-9354-x.

Tjernström, M., 2005: The summer Arctic boundary layer during the Arctic Ocean Experiment 2001 (AOE-2001). Boundary-Layer Meteorology 117, 5–36, doi:10.1007/s10546-004-5641-8.

Tjernström, M., C. Leck, P.O.G. Persson, M.L.J. Jensen, S.P. Oncley, A. Targino, 2004: The Summertime Arctic Atmosphere. Meteorological Measurements during the Arctic Ocean Experiment 2001. Bull. Am. Meteorol. Soc., 1305–1321, doi:10.1175/BAMS-85-9-1305.

Trenberth, K.E, and A. Solomon, 1994: The global heat balance: Heat transports in the atmosphere and ocean. Climate Dynam., 107–134, doi:10.1007/BF00210625.

Trenberth, K.E., 1981: Seasonal variations in global sea level pressure and the total mass of the atmosphere. J. Geophys. Res, 86, doi:10.1029/JC086iC06p05238.

Trenberth, K.E., and D.P. Stepaniak, 2003a: Co-variability of components of poleward atmospheric energy transports on seasonal and interannual timescales. J. Climate, 16, 3691–3705, doi:10.1175/1520-0442(2003)016<3691:COCOPA>2.0.CO;2.

Trenberth, K.E., and D.P. Stepaniak, 2003b: Seamless poleward atmospheric energy transports and implications for the Hadley circulation. J. Climate, 16, 3706–3722, doi:10.1175/1520-0442(2003)016<3706:SPAETA>2.0.CO;2.

Trenberth, K.E., and J.M. Caron, 2001: Estimates of Meridional Atmosphere and Ocean Heat Transports. J. Climate, 14, 3433–3443. doi:10.1175/1520-0442(2001)014<3433:EOMAAO>2.0.CO;2.

Trenberth, K.E., and J.T. Fasullo, 2009: Global warming due to increasing absorbed solar radiation. Geophys. Res. Lett., 36, L07706, doi:10.1029/2009GL037527.

Trenberth, K.E., J.M. Caron, and D.P. Stepaniak, 2001a: The atmospheric energy budget and implications for surface fluxes and ocean heat transports. Climate Dynam., 17, 259–276, doi:10.1007/PL00007927.

Trenberth, K.E., D.P. Stepaniak, J.W. Hurrell, and M. Fiorino, 2001b: Quality of reanalyses in the Tropics. J. Climate, 14, 1499–1510, doi:10.1175/1520-0442(2001)014<1499:QORITT>2.0.CO;2.

Trenberth, K.E., J.W. Hurrell, and A. Solomon, 1995: Conservation of mass in three dimensions. J. Climate, 8, 692–708, doi:10.1175/1520-0442(1995)008<0692:COMITD>2.0.CO;2.

Trenberth, K.E., 1991: Climate diagnostics from global analyses: conservation of mass in ECMWF analyses. J. Climate, 4, 707–722, doi:10.1175/1520-0442(1991)004<0707:CDFGAC>2.0.CO;2.

Trenberth, K.E., 1997: Using atmospheric budgets as a constraint on surface fluxes. J. Climate, 10, 2796–2809, doi:10.1175/1520-0442(1997)010<2796:UABAAC>2.0.CO;2.

Treshnikov, A.F., 1985: Atlas of the Arctic. Arctic and Antarctic Institute, USSR State Committee on Hydrometeorology and Environment, and The Arctic and Antarctic Research Institute, Central Administrative Board of Geodesy and Cartography of the Ministereal Council of the USSR, Moscow, 204 pp.

Tsukernik, M., C. Deser, M. Alexander, and R. Tomas, 2010: Atmospheric forcing of Fram Strait sea ice export: A closer look. Climate Dynam., 35, 1349–1360, doi:10.1007/s00382-009-0647-z.

Uppala, S.M. et al., 2005: The ERA-40 reanalysis, Q.J.R. Met Society, 61, 3493-3512, doi:10.1256/qj.04.176.

Uttal, T. et al., 2002: Surface Heat Budget of the Arctic Ocean, Bull. Amer. Meteor. Soc., 81, 255–275, doi:10.1175/1520-0477(2002)083<0255:SHBOTA>2.3.CO;2.

Vallis, G.K. and R. Farneti, 2009: Meridional energy transport in the coupled atmosphere–ocean system: scaling and numerical experiments. Q.J.R. Meteorol. Soc., 135, 1643–1660, doi:10.1002/qj.498

van Loon, H. and J.C. Rogers, 1978: The Seesaw in Winter Temperatures Between Greenland and Northern Europe. Part I: General Description. Mon. Wea. Rev., 106, 296–310, doi:10.1175/1520-0493(1978)106<0296:TSIWTB>2.0.CO;2.

Vinje, T., 2001: Anomalies and trends of sea-ice extent and atmospheric circulation in the Nordic Seas during the period 1864–1998. J. Climate, 14, 255–267, doi:10.1175/1520-0442(2001)014<0255:AATOSI>2.0.CO;2.

Vinogradova A.A., 2007: Meridional Mass and Energy Fluxes in the Vicinity of the Arctic Border, Izv. Atmos. Ocean. Phys., 43, 281–293, doi:10.1134/S0001433807030036.

Walker, G.T., and E.W. Bliss, 1932: World Weather V. Mem. Roy. Meteor. Soc., 4, No. 36, 53–84.

Wallace, J.M., 2000: North atlantic oscillation / annular mode: Two paradigms – one phenomenon. Q.J.R. Meteorol. Soc., 126: 791–805. doi:10.1002/qj.49712656402.

Wallace, J.M., and D.S. Gutzler, 1981: Teleconnections in the Geopotential Height Field during the Northern Hemisphere Winter. Mon. Wea. Rev., 109, 784–812, doi:10.1175/1520-0493(1981)109<0784:TITGHF>2.0.CO;2.

Wallace, J.M., I.M. Held, D.W.J. Thompson, K.E. Trenberth, and J.E. Walsh, 2014: Global Warming and Winter Weather. Science, 343, 729–730, doi:10.1126/science.343.6172.729.

Wang, J., J. Zhang, E. Watanabe, M. Ikeda, K. Mizobata, J.E. Walsh, X. Bai, and B. Wu, 2009: Is the Dipole Anomaly a major driver to record lows in Arctic summer sea ice extent? Geophys. Res. Lett., 36, L05 70, doi:10.1029/2008GL036706.

Woollings, T., A. Hannachi, and B. Hoskins, 2010: Variability of the North Atlantic eddy-driven jet stream. Q.J.R. Meteorol. Soc., 136, 856–868. doi:10.1002/qj.62.

Woollings, T., B. Harvey and G. Masato, 2014: Arctic warming, atmospheric blocking and cold European winters in CMIP5 models. Environ. Res. Lett., 9, 014002, doi:10.1088/1748-9326/9/1/014002.

Wu, B., J. Wang, and J.E. Walsh, 2006: Dipole anomaly in the winter Arctic atmosphere and its association with sea ice motion. J. Climate, 19, 210–225, doi:10.1175/JCLI3619.1.

Xiong, X., Stamnes, K., and Lubin, D., 2002: Surface Albedo over the Arctic Ocean Derived from AVHRR and Its Validation with SHEBA Data. J. Appl. Meteor., 41, 413–425. doi:10.1175/1520-0450(2002)041<0413:SAOTAO>2.0.CO;2.

Yang, H., Y. Wang, and Z. Liu, 2013: A modelling study of the Bjerknes compensation in the meridional heat transport in a freshening ocean, Tellus A, 65, 18480, doi:10.3402/tellusa.v65i0.18480.

Yang, H.J., 2013: Assessing the meridional atmosphere and ocean energy transport in a varying climate. Chin. Sci. Bull., 58, 1737-1740, doi:10.1007/s11434-013-5665-x.

Yang, S., and J.H. Christensen, 2012: Arctic sea ice reduction and European cold winters in CMIP5 climate change experiments, Geophys. Res. Lett., 39, L20707, doi:10.1029/2012GL053338.

Yoshimori M., M. Watanabe, A. Abe-Ouchi, H. Shiogama, and T. Ogura, 2014: Relative contribution of feedback processes to Arctic amplification of temperature change in MIROC GCM. Climate Dynam., 42, 1613–1630, doi:10.1007/s00382-013-1875-9.

Yu, L., X. Jin, and R.A. Weller, 2008: Multidecade Global Flux Datasets from the Objectively Analyzed Air-sea Fluxes (OAFlux) Project: Latent and sensible heat fluxes, ocean evaporation, and related surface meteorological variables. Woods Hole Oceanographic Institution, OAFlux Project Technical Report. OA-2008-01, 64 pp. Woods Hole. Massachusetts.

Zhang, J., M. Steele, D.A. Rothrock, and R.W. Lindsay, 2004: Increasing exchanges at Greenland-Scotland Ridge and their links with the North Atlantic Oscillation and Arctic Sea Ice, Geophys. Res. Lett., 31, L09307, doi:10.1029/2003GL019304.

Zilitinkevich, S.S. and I.N. Esau, 2005: Resistance and Heat Transfer Laws for Stable and Neutral Planetary Boundary Layers: Old Theory, Advanced and Re-evaluated, Q.J.R. Meteorol. Soc., 131, 1863–1892, doi:10.1256/qj.04.143.