LETTER

Warming in the Nordic Seas, North Atlantic storms and thinning Arctic sea ice

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Abstract

Arctic sea ice over the last few decades has experienced a significant decline in coverage both in summer and winter. The currently warming Atlantic Water layer has a pronounced impact on sea ice in the Nordic Seas (including the Barents Sea). More open water combined with the prevailing atmospheric pattern of airflow from the southeast, and persistent North Atlantic storms such as the recent extremely strong Storm Frank in December 2015, lead to increased energy transport to the high Arctic. Each of these storms brings sizeable anomalies of heat to the high Arctic, resulting in significant warming and slowing down of sea ice growth or even melting. Our analysis indicates that the recently observed sea ice decline in the Nordic Seas during the cold season around Svalbard, Franz Joseph Land and Novaya Zemlya, and the associated heat release from open water into the atmosphere, contributed significantly to the increase in the downward longwave radiation throughout the entire Arctic. Added to other changes in the surface energy budget, this increase since the 1960s to the present is estimated to be at least 10 W m⁻², which can result in thinner (up to at least 15–20 cm) Arctic ice at the end of the winter. This change in the surface budget is an important contributing factor accelerating the thinning of Arctic sea ice.

Introduction

Several driving factors have been implicated in the well-documented retreat of Arctic sea ice over the past decade. The long-term trend in Arctic sea ice over the last few decades includes a dramatic decrease in the summer extent and a significant decline in the proportions of multi-year thick ice (Rothrock et al 1999, Kwok et al 2009). The consensus is that a combination of factors, including anthropogenic warming and natural variability, has contributed to this loss of sea ice (Kattsov et al 2010). Natural variability manifests itself in anomalous wind forcing, with variations of oceanic heat inflow from both the North Pacific (Shimada et al 2006, Woodgate et al 2012) and the North Atlantic (Bengtsson et al 2004, Semenov 2008, Polyakov et al 2011, Schlichtholz et al 2013, Walczowski et al 2012, Alexeev et al 2013, Carmack et al 2015). The ice retreat is enhanced by increased absorption of solar radiation in areas that are newly free of sea ice (Perovich et al 2008). The latter is part of the so-called ice-albedo-temperature feedback, which is one of the key contributors to the polar amplification of temperature changes, especially over the Arctic Ocean.

Processes in the North Atlantic Ocean have been identified as very important for variability of air temperature and sea ice in the Northern Hemisphere (Schlesinger and Ramankutty 1994, Delworth and Mann 2000, Zhang et al 2007, Semenov et al 2010).
Mahajan et al, 2011, Wyatt et al, 2012, Smedsrud et al, 2013, Miles et al, 2014). Feedback loops linking changes in the atmosphere, ocean circulation and sea ice have been suggested to explain decadal to multi-decadal variability in the Arctic (e.g. Ikeda, 1990, Mysak and Venegas, 1998, Polyakov and Johnson, 2000, Proshutinsky and Johnson, 1997, Bengtsson et al, 2004). A dynamical feedback loop contributing to the enhanced decadal climate variations in the Arctic has been suggested by empirical data analysis (Polyakov et al, 2003, Alekseev et al, 2009, Miles et al, 2014) and by model reconstructions (Semenov and Latif, 2012). It should also be noted that recently found indications of nonlinear atmospheric response to sea ice forcing in the Barents Sea (Petoukhov and Semenov, 2010, Semenov and Latif, 2015) as well as a non-stationary link between the North Atlantic Oscillation (NAO) and Arctic climate indices (Semenov et al, 2009, Smedsrud et al, 2013) add more complexity in the hypothesized dynamical links.

Wind forcing of ice motion is one of the several ways in which the atmosphere affects sea ice (Wang et al, 2009). It represents the atmosphere’s direct mechanical effect in driving sea ice dynamically from its normal areas of coverage into areas more conducive to melt (i.e. the North Atlantic). Another manifestation of wind forcing is ice divergence in response to storm events (Parkinson and Comiso, 2013). The atmosphere also drives sea ice thermodynamically by advecting warmer or colder air over areas of sea ice and adjacent open water. Thermodynamic driving by the atmospheric circulation also includes the advection of moisture, which impacts the downward longwave radiative flux to the sea ice surface, and the presence or absence of clouds, which are key determinants of the longwave radiative balance in winter (when cloud radiative forcing is positive) and in summer (when cloud radiative forcing is negative). Warm air advection is an important factor affecting the ‘fabric’ of the Arctic atmosphere (Francis and Hunter, 2007), including clouds and vertical distribution of temperature and moisture. While other drivers of Arctic warming have been identified, poleward atmospheric heat transport alone is an important mechanism that can explain a significant portion of polar (or Arctic)
amplification in a system without any snow or ice-albedo feedbacks (Flannery 1984, Schneider et al 1997, Alexeev et al 2005, Alexeev and Jackson 2013). In an evaluation of the relative strengths of these feedbacks in coupled global climate models, Pithan and Mauritsen (2014) found that the albedo and temperature feedbacks were indeed the strongest contributors to Arctic warming in the aggregate of the models. Feedbacks involving changes in vertical lapse rates, the Planck effect, water vapor, clouds and atmospheric transports were all positive, while the feedback arising from oceanic heat transports was found to be negative in most models (i.e. as the Arctic warms, oceanic heat transport into the Arctic decreases over the century scale in the model simulations). For the purposes of the present paper, it is noteworthy that the atmospheric transport feedback is positive in the majority of the models, but negative in a sizeable minority of the models.

Warming in the North Atlantic together with the decline in winter sea ice in the Atlantic sector of the Arctic Ocean result in a greater open water area, which serves as a source of heat and moisture during the long cold season when the atmosphere quickly becomes significantly colder than the ocean surface. Atmospheric heat from the North Atlantic is transported to the high Arctic by large-scale circulation and North Atlantic cyclones, such as the recent Storm Frank, for example. These storms bring enormous amounts of sensible and latent heat. Recent work shows that transient eddies are responsible for about 90% of total moisture transport to the Arctic (Dufour et al 2016). Temperature and moisture anomalies associated with heat brought by the atmosphere to the high Arctic will inevitably impact the sea ice budget via changes in both the turbulent and radiative heat fluxes.

The present paper focuses on these high-latitude heat budget changes in order to assess the drivers underpinning the loss of Arctic sea ice. It does so by examining the feedback between variations of key metrics of the high-latitude atmospheric circulation and sea ice. The analysis is framed in terms of surface energy flux variations and their impacts on both sea ice and the atmosphere. Our focus is on the North Atlantic sector because (1) horizontal oceanic exchanges are much greater in the Atlantic than in the Pacific sector, and (2) the ice edge and the marginal ice zone have much greater longitudinal extents in the North Atlantic than in the North Pacific.

**Scope of the paper**

The main idea is to propose a conceptual mechanism that could be a significant contributor to the long-term thinning of sea ice in the high Arctic. Our hypothesis is that more open water in the winter in the Nordic Seas, due to warmer AW and overall warming, results in extra heat and moisture brought to the central Arctic by atmospheric circulation. The induced warming and moistening of the Arctic atmosphere results in increased downward longwave (DLW) radiation at the surface, which reduces winter ice growth.

The paper identifies the types of atmospheric circulation regimes responsible for bringing the extra heat and moisture to the Arctic, and their sources. It also addresses the question of whether the heat and moisture originate locally or remotely. EOF analysis is performed on sea level pressure (SLP) and DLW from NCEP/NCAR Reanalysis (NNRP, Kalnay et al 1996) in order to identify circulation patterns responsible for transporting heat and moisture into the Arctic. Time behavior of corresponding EOFs (SLP and DLW) are compared against one another and against AW in order to delineate the response in the surface heat budget to sea ice retreat in the Nordic Seas (including the Barents Sea). These anomalies in the surface heat budget in the high Arctic are then used to estimate their potential effect on sea ice thickness at the end of the winter.

Most of the analysis related to the impacts of AW on sea ice is not new. What is new is the linking of AW and declining sea ice to the atmospheric heat transports. Significant storm activity transporting large amounts of energy happens on the opposite side of the Arctic, but our focus in this paper is the Atlantic sector and processes linked to receding winter sea ice in the Nordic (including Barents) Seas.

**Methods and data**

This study uses AW data in conjunction with satellite observations of sea ice and atmospheric reanalysis data to establish a link between the recent warming in the North Atlantic and sea ice retreat. The use of NNRP is justified by the availability of data in this product before the satellite era. NNRP has been used before in conjunction with other products (models and satellite observations) to study components of the Arctic Climate System (e.g. Serreze et al 2007). AW data goes back to the 1930s and the use of NNRP allows the inclusion of as many cycles of variability on the AW as possible. NNRP assimilates radiosondes and other upper air products, which lead us to believe that this is a better product than the 20th Century Reanalysis based only on surface products, since many meteorological fields are functions of air properties of the whole atmospheric layer. Another argument in favor of NNRP is that it is necessary to use a dynamically self-consistent product for all atmospheric fields (that includes SLP, air temperature, air moisture and surface fluxes). Reanalysis products are designed to make model fields as close as possible to observations while keeping those fields constrained by the basic laws of physics. The large-scale atmospheric dynamics in the Arctic are captured relatively well (Serreze et al 2007). Therefore, the following factors played a role in our
choosing of NNRP for the analysis: (1) length; (2) dynamic self-consistency of product fields in terms of reanalysis using the same 'frozen' data assimilation system, and; (3) assimilation of upper-air fields.

The quality of the surface fluxes from any reanalysis products or observations must be addressed when applying them to the study of long-term time series. It can be an even bigger problem in the case of observations. The main problem here is the consistency of flux products: platforms and instruments change with time. These statements apply both to well-measured locations and the Arctic, scarcely covered with stations. Moreover, there is no surface flux product available for the central Arctic that was consistently measured over some prolonged period of time. Downward longwave radiation (DLW) from NNRP is a product that is consistent with changes in the upper-air fields (air temperature and moisture) because DLW is a function of those values. More moisture in the air and warmer atmosphere above the surface will result in more DLW at the surface. The quality of DLW can be questionable, but the consistency of the upper-air fields (temperature and moisture) with DLW gives us more confidence in our search for a remote signal in the high Arctic as a function of changes in the atmosphere above the surface. One way to check the hypotheses that we present in this study would be to use models, and this is our next step. While a more detailed analysis of model performance is not a part of this study, in order to assess the robustness of the results based on NNRP we repeated parts of the analysis below, using ERA Interim (Dee et al 2011) over the shorter (1979 to present) period.

With regard to the impact of the choice of NNRP reanalysis on the validity of the calculations, we note that similar findings concerning increased water and its role in DLW-driven warming of the surface have been obtained for different parts of the Arctic by Cullather et al (2016). In that study, satellite-derived products provided the water vapor information used to deduce the downward longwave radiation anomalies associated with record warmth in the Arctic, especially the Alaskan region, during a single winter, 2015–16.

Results

North Atlantic Storm Frank reached maximum intensity on December 30, 2015, causing strong winds in Europe, as was widely reported in the media. The intensity of that cyclone was quite impressive, with a central pressure of 937 hPa at the time of peak intensity (figure 1(a)), although this was not the strongest winter storm according to our analysis of sea level pressure from NNRP. We were able to find two stronger storms in the past, in December 1986 and 1999 (details are given in the supplementary materials section available at stacks.iop.org/ERL/12/084011/ mmedia). A list of the strongest North Atlantic cyclones with some statistics is compiled in table S1 of the supplementary section. Storm Frank was accompanied by a strong southerly flow from the North Atlantic to the high Arctic. Our simple estimates using daily NNRP data show that the anomaly in the air temperature over the polar cap (defined as the area north of 80°N) on December 30, 2015, reached a record high of about 16°C, and the corresponding downward radiation anomaly was about 60 W m⁻² (table S1). Table S1, which could be incomplete, contains only the strongest detected events in the North Atlantic (we chose cyclones with SLPs in the center lower than 960 hPa). Another conclusion from table S1 is that an anomaly of 1°C in the upper air temperature (anomaly averaged over 1000–100 hPa layer of the atmosphere) corresponds to a downward radiation anomaly of roughly 6 W m⁻². This was obtained by performing a linear regression of temperature against DLW.

As noted above, these storms are not unique. In order to find out whether this pattern changed over time, we calculated EOFs of winter mean (December–January–February, or DJF) sea levels pressure fields from NCEP/NCAR Reanalysis. EOFs were calculated for the Arctic domain north of 65°N in order to remove variability induced by the mid-latitudes. The first EOF (not shown) explaining 34% of variability represents the familiar Arctic Oscillation (AO) pattern, while the second EOF (figure 1(b), shaded, explaining about 16% of variability) has an ‘anti-dipole’ structure. The ‘anti-dipole’ term is used in order to contrast it with the Arctic Dipole (Wu et al 2006, Wu et al 2012), the map of which has a very similar pattern but an opposite sign. The second EOF’s structure also represents a circulation pattern with the strong flow from the North Atlantic to the central Arctic. These anti-dipole situations are associated with lower pressure anomalies on the North Atlantic side of the Arctic. Contour lines in figure 1(b) represent mean composite SLP calculated from all episodes listed in table S1 corresponding to low-pressure systems like Storm Frank. The composite of all identified ‘Frank’ events (contours) compares well with the second EOF of the DJF SLP field. ‘Frank’ events happen on a daily timescale, while EOFs were calculated for seasonal means, which is a significantly longer timescale. The similarity between these two fields suggests that the second EOF characterizes the composite Frank-type of circulation anomaly. These situations can vary in intensity and the locations of the minima can vary geographically as well, but a negative SLP anomaly on the North Atlantic side of the Arctic corresponds to a situation favoring an occurrence of a storm with a circulation anomaly bringing warm and moist air to most of the central Arctic. The time behavior of this anti-dipole pattern will be compared with trends in other fields later in this section.
Figure 1. (a) Sea level pressure on Dec 30, 2015 (hPa); (b) shading: 2nd EOF of SLP; contours: mean SLP during Storm Frank events; (c) contours: DLW regressed on the principal component of the 2nd EOF (W m⁻²); shading: change in 1979–2015 DJF sea ice concentration (fraction, darkest blue color corresponds to −0.9); color bar is omitted for simplicity; (d) principal component of the 2nd EOF as a function of time (black line), normalized anomaly (multiplied by −1, green line) of ERA Interim sea ice concentration averaged over area 50°W–90°E, 65–90°N. EOFs and other variables were calculated using winter means (December–January–February).
The second EOF’s principal component has no obvious long-term trend for the NNRP period (figure 1(d)), although it seems to have spent more time in the positive phase since the 1980s. A more detailed analysis of this pattern with daily data in the supplementary section gives a similar result (figure S1) with no obvious long-term trend.

The strong southerly flow in the second EOF of SLP is linked to a strong positive anomaly in the DLW radiation with a maximum collocated with the margin of winter sea ice (figure 1(c)). The shape of the DLW anomaly suggests that the maximum is of local origin; there is practically no signal upstream of the dominant southerly flow until it reaches the area of sea ice degradation. A similar composite picture based on all strong North Atlantic storm events is given later in the article. The corresponding anomalies during Frank (December 30, 2015) and the storm of December 22, 2016 are given in the supplementary section (figure S7). EOF analysis with ERA Interim fields similar to that conducted above with NNRP show very similar results, both in the shape of EOFs and the behavior of DLW_PC1 (figures S8 and S9), which indicates the robustness of the pattern.

In order to understand what causes DLW anomalies at the surface we first look at the atmospheric vertical structure. Analysis of the vertical distribution of temperature and humidity during the cold season (November–December–January–February–March, or NDJFM) from the NNRP dataset averaged over the polar cap north of 80°N as a function of time shows that both quantities exhibit oscillatory behavior, with a positive increasing trend over recent years. The warming episodes are accompanied by corresponding increases in DLW radiation (figure 2). What is shown in figure 2 are not anomalies, but the absolute values of temperature and humidity; therefore the strong elevated signal suggests that it is of non-local origin. The magnitudes of DLW anomalies are quite significant and the overall change since the mid-1960s constitutes around 10 W m⁻². Notably, surface air temperature at 2 m averaged over the same area increases too, with a change of about 5 °C corresponding to the 10 W m⁻² change in DLW. More precise calculations with detailed estimates of the statistical significance of this trend is given in the text below. These are sizeable changes in the radiative budget and air temperature at the surface. In order to
understand their origin, we will first look at the changes in winter sea ice extent in the Nordic Seas and try to link the changing sea ice extent to changes in other variables.

Figure 3 summarizes the analysis of variability in sea ice concentration during the cold season and how it corresponds to changes in DLW and temperature of the Atlantic Water layer based on data collected at two locations—the Fram Strait and the Barents Sea (see supplementary section for details). The upper panel shows the first EOF of sea ice concentration calculated for three months of the cold season (DJF) from a satellite product (Cavalieri et al. 1996). Ice extent and area in this satellite product were calculated on the basis of daily data from the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) and the Defence Meteorological Satellite Program (DMSP) Special Sensor Microwave/Imager (SSM/I) Passive Microwave Data dataset (Cavalieri et al. 1996, http://nsidc.org/data/nsidc-0051.html), updated yearly from 1979. The spatial resolution of the regular grid is 25 km.

Sea ice concentration EOFs were also calculated using an identical algorithm for gridded ERA Interim (Dee et al. 2011) DJF fields. Their analysis gives very similar results because ERA Interim sea ice is based on satellite era products, which is why for the sake of simplicity (it is easier to handle gridded fields) we use ERA Interim product hereinafter.

The EOF shape illustrates the recent decline in sea ice coverage in areas along the pathways of propagation of AW into the Arctic Ocean, loosely indicated by the arrows. Also shown in figure 3 are the March ice margin (drawn at 20% sea ice concentration) for the years before 2004 (black line) and for 2012 (red line), based on ERA Interim. The retreat of the ice margin is very consistent with the warming of AW. This first EOF explains almost 50% of the variability in sea ice, and the corresponding principal component (PC) highly correlates with the decline in the area (at 96%)
calculated for the box bounded by 90°W–90°E and 70°N–90°N. Therefore, this EOF along with the corresponding PC can serve as a measure of the decline in sea ice coverage in the Atlantic sector of the Arctic in the winter.

The lower panel of figure 3 clearly illustrates that the AW temperature has been increasing since the mid-1960s. The warming peaked in the 2000s (around 2005) and it was observed both in Fram Strait, on the pathway along the continental shelf break, and in the Laptev and East Siberian seas, with the maximum of the observed warming in 2006–2007 (Polyakov et al 2011). This warming has been suggested to be an important factor for the overall thinning of Arctic sea ice (Polyakov et al 2010) by providing more heat to the ice from the AW layer as the AW temperature in the Arctic Ocean has been increasing.

The individual lines in the lower panel of figure 3 show a certain similarity but still exhibit some independent variability. In order to identify a pattern in the DIW radiation at the surface linked to the declining sea ice, we independently calculated EOFs of DIW using NCEP/NCAR Reanalysis. Figure 4 shows that its first PC (DLW_PC1) is highly correlated with ICE_PC1 (89%) and SLP_PC2 over the period of availability of ICE_PC1 in 1979–2014. As expected, DLW_EOF1 has a maximum over the area of sea ice retreat, which can be attributed to higher temperature and moisture in the atmosphere. DLW_EOF1 in figure 4 also has a very specific feature—an area of positive non-zero amplitude extending far downstream of the region of ice retreat over almost the entire Arctic Ocean, which, as argued later, is due to the atmospheric circulation. DLW_PC1 (which was calculated independently) starts increasing together with AW around the mid-1960s. Because of the high

\[ N = 37 \] (37 years is length of our sea ice time series) correlation becomes significant at 0.325. Correlation values higher than .8 with number of points larger than 30 give values of \( p \ll 0.0001 \).
correlation between PCs of sea ice and DLW and the fact that the maximum of DLW EOF1 is collocated with the area of sea ice retreat, we conclude that this mode of variability in DLW is linked to the decline in sea ice and the warming in the Atlantic sector, with some additional 'help' from a stronger anti-dipole type of circulation anomaly. The two PCs (ICE_PC1 and DLW_PC1) follow each other very closely although ICE_PC1 seems to increase faster than DLW_PC1, which could be due to other factors (overall warming, for example, due to increasing CO₂ concentration). The causation between the sea ice decline in the Nordic Seas and DLW over the Arctic Ocean will be considered next.

In order to see how the DLW anomaly is formed on the pan-Arctic scale, we regressed DLW_PC1 on other fields that may contribute to it. Figure 5 shows a map of lower-tropospheric air temperature (color) regressed on DLW_PC1 along with vectors of regressions of components of the sensible heat transport within 1000–700 hPa layer with DLW_PC1. (b) same as in figure (a), except color represents regression of anomaly in specific humidity (g kg⁻¹); vectors represent correlations of transport of latent heat UQ, VQ with DLW_PC1.

Figure 5. (a) Regression of air temperature anomaly, averaged within 1000–700 mb layer on DLW_PC1 (color, °C), and vectors representing correlations of component of the sensible heat transport within 1000–700 hPa layer with DLW_PC1. (b) same as in figure (a), except color represents regression of anomaly in specific humidity (g kg⁻¹); vectors represent correlations of transport of latent heat UQ, VQ with DLW_PC1.
transport in the lower troposphere (represented by vectors) on the same PC. One can see a pronounced temperature anomaly over the Barents and Kara Seas. The heat transport anomaly corresponding to DLW_PC1 favors the propagation of extra heat and moisture (figure 5) to the northeast from the open water area.

Both extra temperature and moisture will contribute to the shape of DLW EOF1 and figure 5 explains how this kind of anomaly is formed. Flow from the south brings air to the Nordic Seas, where it picks up more moisture and heat over the area of ice retreat (this is why air and moisture anomalies are highest in that area). This warmer and moister air is then spread out by the atmospheric anti-dipole. A DLW EOF1 type of anomaly is thus driven by both the decline in sea ice (represented by the maxima in DLW, air temperature and humidity shown in figures 4 and 5 over the area of sea ice decline) and changes in the circulation. The DLW EOF1 anomaly will contribute to thinning of ice both in the area of sea ice retreat and downstream of it over the entire Arctic. It is important to notice that all manipulations were done with seasonal means, which explains the blurred nature of anomalies in DLW and air temperature in figures 4 and 5.

Figure 6 provides further insight into the origin of anomalies in the central Arctic associated with south winds and events like Storm Frank. We averaged anomalies of temperature and DLW for all the events listed in table S1 of the supplementary section. Strong southerly winds associated with storm events bring an average temperature anomaly of up to 25°C and a 70 W m⁻² DLW anomaly at their maximum. It is obvious that the maxima of the anomalies lie downstream of the area of open water. Pictures corresponding to the events of December 30, 2015 and December 22, 2016 (figure S7) are given in the supplementary section and they tell a very similar story. DLW anomalies corresponding to these storms start right above the anomalies in sea ice in the Barents and Kara Seas. The DLW anomalies following closely the atmospheric circulation anomalies are further spread by the flow into the central Arctic. It is highly unlikely that these DLW anomalies were formed independently of the anomalies in sea ice, or that the anomalies in sea ice were influenced or formed by the DLW anomalies.

Heat transport from the south results in a widespread air temperature anomaly of 0.4°C and higher. The anomaly in moisture (figure 5(a)) is more localized because excess moisture does not travel far, but its magnitude is still quite a significant way from the open water area. Anomalies in both air temperature and moisture will result in the increase in DLW. The increase in the air temperature will also contribute to changes in the sensible heat fluxes (figures S2 and S3). The regression maps (of DLW_PC1 on the corresponding field) for air temperature and specific humidity look very similar to EOFs of the corresponding quantities calculated in exactly the same way as DLW (supplementary section, figure S4). The fact that the corresponding PCs are also highly correlated with DLW_PC1 leads us to conclude that the same physics is behind all those quantities—more open water associated with recent ice retreat. The regression of DLW_PC1 on 850 hPa geopotential height (figure S5 in the supplementary section) gives a picture of anomalies in the atmospheric circulation very

![Figure 6](image-url)
consistent with the anomalies in the sensible and heat transports in figure 5. It is interesting to note that maps of regression of temperature and moisture on the AO index (figure S6) significantly differ from those given here in figure 5. The AO impact on the temperature and moisture gives us a familiar picture of strong zonal flow bringing warm and moist air to Europe and further inland.

Based on this analysis we conclude that the warm AW is the major driver behind the change in the radiative budget and the air temperature in the central Arctic, mediated by the decrease in sea ice coverage in the Nordic Seas and anti-dipole atmospheric circulation anomalies. Figure 7 illustrates that DLW_PC1 very well explains the changes in the DLW component of the surface budget over the entire period of the Reanalysis. The positive growth in DLW over the central Arctic seems to start accelerating around the mid-1990s, as indicated by the dashed green line.

The effects of the shortwave radiation and latent heat flux over the ice in the Arctic Ocean during the winter are significantly less important (by an order of magnitude), which is why they were omitted from the analysis. However, the Supplementary section contains regression maps for both sensible and latent heat fluxes.

Simple analysis (see the supplementary section) suggests that a positive imbalance of 10 W m\(^{-2}\) at the surface can result in a change in the surface temperature of about 3 \(^\circ\)C in order to compensate for the imbalance by higher upward LW. The rate of ice thickness growth is proportional to the square root of time and difference between the ocean water temperature, which is taken here as freezing point and ice surface temperature. The square root dependence of ice thickness on time and surface temperature is consistent with Lebedev’s formula for thermodynamic ice growth (Lebedev 1938, also see the supplementary section). Therefore, the increase in the ice surface temperature will result in a proportional decrease in ice thickness:

\[
\frac{\Delta h}{h_0} = \frac{1}{2} \frac{\Delta T}{T_{\text{ice}}},
\]

where \(h_0\) is the climatological ice thickness, \(\Delta T\) is the difference of temperature of ice at the surface and the ocean temperature, and \(\Delta h\) is the change in \(h_0\) as a result of change in \(\Delta T\) (referenced as \(\Delta T\) here).

Discussion/conclusions

Warming in the Nordic Seas caused by the warming of Atlantic Water has widespread consequences for the whole Arctic region. We have looked at one particular aspect of how the heat from the currently opening Nordic and Barents Seas (caused by the retreat of sea ice because of the warmer AW) is redistributed throughout the Arctic by the changing atmospheric

\[\text{Figure 7. NNRP DLW anomaly averaged over the polar cap (north of 80°N, black) and DLW explained by the first EOF (DLW}_{-}\text{PC1 multiplied by the mean of DLW}_{-}\text{EOF1 over the polar cap, green line). Dashed green line is added to show change in long-term trends.}\]
circulation. The southerly meridional flow across the Barents Sea spreads warmer and moister air over almost the entire Arctic. This results in changes in the energy budget leading to warmer temperatures at the surface and in the troposphere, which in turn slows down ice growth during the cold season. Changes in the surface budget include increases in the downward longwave radiation (due to the warmer and moister air) and in the downward sensible heat (a warmer atmosphere heats up the surface more). The sea ice retreat in the Nordic Seas became more and more active in mid-2000s (after 2004) and together with the ongoing global warming is very likely to be an important contributor to the long-term thinning of Arctic sea ice (Rothrock et al 1999). Altered conditions at the ocean surface facilitate extra ocean heat to be spent on ice melt along the AW pathways northeast of Svalbard and in the Barents-Kara Seas, thus providing positive feedback to further ice decay (Ivanov et al 2016). Several studies looked at pathways and consequences of moisture intrusions into the Arctic (Doyle et al 2011, Woods et al 2013, Woods and Caballero 2016, Park et al 2015a, Park et al 2015b, Boisvert and Stroeve 2015, Johansson et al 2017, Luo et al 2017). Results of the present study are consistent with those from the references above. This study also links the impacts of changes in the atmospheric circulation and associated moisture and warm air intrusions in the Arctic with more open water in the Nordic Seas caused by the warmer Atlantic Water. The importance of the more local source region has not been identified in previous studies.

The year 2017 saw the lowest winter sea ice in the Arctic, followed by 2016 and 2015. Most of the winter decline happened in the North Atlantic sector of the Arctic, leading to more open ocean surface exposed to air. This open water serves as a source of heat and moisture that travels with the dominant ‘anti-dipole’ pattern of southerly flow into the central Arctic. Dominant downward longwave radiation’s mode of variability (first EOF) has a shape with a maximum collocated with the area of maximum sea ice retreat, which tells us about the local origin of processes (heat and moisture from the surface) contributing to that shape. This mode has a significant non-zero amplitude over most of the Arctic and is associated with the positive phase of the anti-dipole. All of the identified strong storm events in the North Atlantic result in a pronounced anti-dipole type of circulation anomaly. The mechanism responsible for the anti-dipole mode and its role in sea ice decline has also been interpreted in connection with Ural blockings interacting with the positive phase of the North Atlantic Oscillation (Luo et al 2016, Gong and Luo 2017). Weaker anti-dipole situations may or may not be a result of storms in the North Atlantic, but they will also contribute to the transport of heat and moisture to the central Arctic.

It is well documented and widely published (see references above) that AW entering the Barents Sea serves as a significant contributor to the corresponding sea ice retreat, with increased turbulent heat fluxes from the ocean to the atmosphere. This extra heat and moisture are redistributed by the atmospheric pattern that has an anti-dipole shape (figure 1). At the same time warm AW is favoring this anti-dipole response in SLP corresponding to stormier conditions in the North Atlantic sector of the Arctic, although this correlation is rather weak. Such a response is also indicated by the analysis of atmospheric circulation response to oceanic heat anomalies in the Nordic Seas (Schlichtholz 2014). This type of response is not directly linked to AO/NAO processes. AO/NAO are a part of the large-scale coupled system (Marshall et al 2001, Dickson et al 2000, Polyakov et al 2010) regulating multi-decadal scales. A positive AO/NAO phase results in a different type of circulation anomaly than one associated with the anti-dipole. Analysis is given in figure S6 of the supplementary section. An AO/NAO positive phase brings about a stronger zonal flow of mild Atlantic air into Europe, in accordance with other studies (e.g. Thompson and Wallace 1998).

In a warming world, a poleward deflection of the Atlantic storm tracks is generally expected according to climate model simulations, suggesting an increasing number of North Atlantic storms reaching the inner Arctic (e.g. Yin 2005, Chang et al 2012, Woolings and Blackburn 2012). The observed tendencies are not very clear due to high natural variability. However, some tendency to the poleward shift is indicated by reanalysis data (Tilinina et al 2013). Thus we may expect that the seeming tendency towards an increased number of extreme cyclones in the Arctic in recent years reflects the climate trend and can be projected into the future. North Atlantic cyclone statistics combined with surface conditions in the Nordic Seas will be the variables to track in order to better understand the atmospheric impact on growth of winter sea ice in the Arctic Ocean in the future.

Storm Frank (December 29–30, 2015, calculations below are based on NNRP product) brought an anomaly of surface temperature of 16°C and an extra 60 W m\(^{-2}\) of DLW radiation at the surface. At least one more North Atlantic storm occurred after Storm Frank (Storm Gertrude, see table S1) in the winter of 2015–16, bringing a DLW anomaly of about 26 W m\(^{-2}\). Boisvert et al (2016) also looked at the effect of Storm Frank on sea ice and concluded that this individual cyclone could have resulted in a 10 cm loss of ice thickness. Each of these individual storm events and an overall increasing DLW trend in the Central Arctic inevitably contribute to further ‘preconditioning’ of ice before the melt season. Thinner ice is easily moved around by the wind; therefore if a situation analogous to 2007 develops this year, we might see a new low in the autumn sea ice extent. Documenting the mechanism for how DLW anomalies over the Arctic Ocean are formed because of more open water in the Nordic Seas is the main outcome of this article. The North
Atlantic seems to be acting more and more as an active pre-conditioner for thinning of the sea ice during winter and subsequent easier melt during the warm season. Is this how the collapse of summer ice in the Arctic will happen?

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