On assessment of the relationship between changes of sea ice extent and climate in the Arctic

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On assessment of the relationship between changes of sea ice extent and climate in the Arctic

Genrikh Alekseev, Natalia Glok, Alexander Smirnov

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Abstract:

An increase of surface air temperature (SAT) in the marine Arctic (part of the Arctic covered with sea ice in winter) shows a good relationship with reduction of sea ice extent (SIE) in summer. For instance, strong correlation (a coefficient equals to -0.93) was found between the summer SAT in the marine Arctic and satellite-derived 1980-2014 September sea ice index. Based on this finding anomalies of Arctic September SIE were reconstructed from the beginning of twentieth century using linear regression relationship. This reconstructed SIE shows substantial decrease in the 1930-40s with a minimum occurred in 1936, which constitutes, however, only a half of the SIE minimum in 2012. An impact of the inflow of warm and salty Atlantic water on winter SIE was evaluated on an example of the Barents Sea. This evaluation reveals coherent spatial pattern of the Atlantic water spreading, presented by surface salinity distribution, and the position of sea-ice edge and significant correlation between the inflow of the Atlantic water and maximal SIE. The strong relationship between the summer SAT and September SIE was used to assess the onset of summer sea ice disappearance in the Arctic Ocean. According to the estimates made with a simple regression model we can expect the seasonally ice-free Arctic Ocean as early as in the mid-2030s.

Key words: Arctic, Barents Sea, sea ice, surface air temperature, Atlantic water, climate feedbacks, sea ice disappearance
1. Introduction

The earliest systematic information about arctic sea ice is available for the Atlantic sector of the Arctic Ocean since the twentieth century (Zakharov, 1997; Vinje, 2001; Løyning et al., 2003; Divine and Dick, 2006). The first sea ice charts have been prepared in Danish Meteorological Institute based on ship observations in the Greenland and Barents Seas in spring and summer months (i.e., from April to August). A growth of shipping along the coast of Siberia, which is occurred in the 1930s, motivates further extension of sea ice observations toward the Siberian Arctic seas. Since this decade aircraft-based surveys become the primary source of ice observations, typically synthesized as ice charts. These ice charts including those produced for the period since 1933 are an important part of historical archive (Borodachev and Shilnikov, 2001), which is collected in Arctic and Antarctic Research Institute (AARI), and was used successfully to reconstruct specific historical ice series for the Arctic seas (e.g., Mahoney et al., 2008). In this archive the earliest historical ice data in the Barents and Siberian Arctic seas are available from 1924 (Zakharov, 2003a; Frolov et al., 2007).

The longest SIC dataset starts in 1870 (Rayner et al., 2003) and covers the oceans with a one-degree resolution (http://hadobs.metoffice.com.hadstt). Historical Arctic sea ice data in this dataset were taken from (Chapman and Walsh, 1993), and cover the period since 1901 (http://www.nsidc.colorado.edu). Another long-term sea ice dataset can be found at http://www.aari.ru/projects/ECIMO/index.php.

Analysis of historical sea ice data had been carried out many times using continuously growing available observations. This analysis likely suggests significant long-term changes in ice distributions. For example, Zakharov (2003b) reported four stages in the development of the Arctic sea ice cover for the twentieth century: two
stages of expansion (1900-1918 and 1938-1968), and two stages of ice cover reduction
(1918-1938 and 1968-1999), accompanied by a secular decline of sea ice extent.

According to the finding by Vinje (2001) the sea ice extent in the Greenland and
Barents Seas in April have steadily declined since 1864, and in 1998 was reduced by
33%.

A comparison of historical ice series from various sources shows significant
differences between them, which disappear rapidly after transition to satellite
observations (Alekseev et al., 2007) - the major source of information for sea ice
monitoring since 1978. Assessments of sea ice observations from satellites show
reduction of the sea ice extent, which was accelerated over the past two decades (e.g.,
Smolyanitsky, 2003; Johannessen et al., 2004; Stroeve et al., 2007; Comiso et al., 2008;
Kwok and Rothrock, 2009; Alekseev et al., 2009; Stroeve et al., 2011; Ivanov et al.,
2013).

An evidence of significant Arctic sea ice reduction during the first warming of
the Arctic in the 1930s is a subject for discussion (e.g., Semenov and Latif, 2012). The
authors have conducted numerical experiments with a global atmospheric circulation
model, using prescribed sea ice boundaries and concentrations taken from the Hadley
Centre Sea Ice and Sea Surface Temperature (HadSST) dataset. The simulations did not
reproduce the Arctic warming in the 1930s, while it was prominently developed in the
period when the sea ice in the model is reduced. In this connection it is interesting to
estimate the state of the sea ice in the Arctic in the 1930s, when the warming in the
Arctic has been observed. Some indications of the reduced ice extent in the 1930s are
discussed in papers (Viese 1937; 1944), written directly in the period of the
development of the first Arctic warming. Our paper presents an evaluation of the past
and future changes in sea ice in the twenty and twenty-first centuries and their interplay
with other components of the Arctic climate system on basis of sea ice, air and water
temperature observations in the Arctic and the Northern Hemisphere.

2. Data

Sea ice data are presented by the sea ice index (the average of sea ice extent in the
Arctic since 1978, in millions sq. km) taken from the National Snow and Ice Data
Center (NSIDC) site (http://www.nsidc.colorado.edu). The average sea ice extent data
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(http://wdc.aari.ru/datasets). The average monthly air temperatures for the Arctic
meteorological stations are derived from "Surface Meteorology for the North Polar
Region" archive, which was prepared in AARI, and from the NCEP/NCAR reanalysis
(http://www.esrl.noaa.gov/psd/data/reanalysis/). The sea surface temperature (SST) is
taken from the HadSST dataset (http://www.metoffice.gov.uk/hadobs/hadisst/data/).
The average Atlantic water temperatures in the 0-200 m layer at the Kola section (along
33°30’ E) in the Barents Sea are taken from the Polar Research Institute of Marine
Fisheries and Oceanography (PINRO) website (http://www.pinro.ru).

3. Discussion of results

3.1. Empirical assessment of external impacts and feedbacks on the reduction of Arctic
SIE

There are many reasons likely responsible for amplification of the warming and decline
of sea ice extent (SIE) in the Arctic. We speculate that the primary reason is an increase
of heat and moisture transports into the northern polar region due to global warming,
which triggers feedbacks in the Arctic climate system. All of them accelerate the

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warming and degradation of the SIE in the Arctic. The Arctic warming was most
evident as an increase of SAT. Air temperature changes in the marine Arctic, which is
defined as a part of the Arctic with sea ice cover in winter (Alekseev et al., 2009),
primarily affect the growth of ice cover in winter and its melting during the summer. To
estimate the average air temperature over the marine Arctic we used meteorological
records at 41 stations with observations started not later than in 1951 (Fig. 1).

Fig. 1 shows rapid growth of summer SAT since 1996 with an absolute
maximum in 2012. The winter temperatures before 1991 and the summer temperatures
before 1996 had weak negative trends, which changed to significant positive trends for
the period after these years. In agreement with the rapid growth of summer air
temperatures, the shrinking of sea ice extent in the end of summer was accelerated (Fig.
2), and reached its absolute minimum in 2012. A correlation coefficient between the
changes of summer air temperature in the marine Arctic and September sea ice extent
equals to -0.93, suggesting that the summer SAT can be considered as an integral
indicator (or index) of external influences on the SIE.

Dependence of the September SIE from the summer SAT decreased in the
Siberian Arctic seas under influence of sea ice dynamics. The correlation between the
summer SAT and September SIE in those seas is characterized by a coefficient of -0.75
estimated for 1951-2013. This correlation is responsible for ~60% of variability of the
September SIE. The rest of SIE variability is accounted by ice dynamics induced by
impact of winds and currents, which form ice massifs – areas of compact ice spreading
out the Arctic Basin.

3.2. Reconstruction of the past Arctic SIE based on temperature index
Taking into account strong relationship between the summer SAT and the Arctic SIE, state of September SIE in previous year can be estimated. Unfortunately, most of the weather stations in the marine Arctic began their work after 1950, and only seven of them were operated until the beginning of the 20th century (Fig. 3). A correlation between the summer temperatures at these stations and the Arctic SIE in September over 1980-2013 equals to -0.81. The reconstruction of the September SIE for the past years based on the regression model between the SAT and SIE shows (Fig. 3) significant SIE decrease in 1930-40s, which is close to the Viese’s estimate (Viese, 1944), who found decrease of about 1 million km$^2$. However, the strongest reconstructed SIE reduction for 1930-40s, which was occurred in 1936, constitutes only a half of the ice reduction in 2012.

3.3. Ocean influence on winter sea ice distribution

In spite of fact that winter SAT increases faster than the summer SAT, reduction of winter SIE in the Arctic is much slower in comparison with summer shrinking. One of the reasons is that the Arctic seas in winter are completely covered with ice. Therefore, changes in the Arctic winter SIE are associated with a shift in the sea ice edge in the Nordic Seas and the Northwestern Atlantic that is determined by the boundary between the Arctic water and the salt and warm Atlantic water (Zakharov, 1997, Smedsrud et al., 2013). Consequently, variations of winter SIE include the component determined by changes of Atlantic Water (AW) spreading in the Nordic Seas and the Northwestern Atlantic.

An influence of this component on the winter SIE is clearly evident in the Barents Sea from analysis of interrelation between long-term historical datasets of SIE,
AW temperatures at the Kola section, and sea surface temperatures (Table 1). The correlation of the monthly mean AW temperature at the Kola section and SIE for 1951-2009 reaches its maximal value of 0.86 in May (Table 2). Shift of the correlation maximum to May can be explained by significant impact of AW inflow occurred in southern part of the Barents Sea that prevents southward spreading of sea ice edge in winter. A correspondence between distributions of the AW and the sea ice in the Barents Sea can be seen from Fig. 4, showing similar spatial pattern of surface salinity distribution and sea ice edge in June 1969 and June 1987. In June 1969 the salty AW occupies smaller area, and sea ice goes further to south in comparison with June 1987.

3.5. Effect of summer SIE reduction on winter air temperature in the Arctic

One of the feedbacks that amplify the warming in the Arctic is the result of summer SIE reduction, which increases the air temperature in late autumn and early winter (Fig. 5). In the period with negative air temperatures, the heat accumulated in ice-free areas releases to the atmosphere. An additional contribution to the warming is due to increase of the water vapor content in the air surface layer, accompanied by increased downward long-wave radiation. As a consequence, the largest SAT trends are found from October through February, exceeding background value (the average for March-September). Amplification of the trend caused by this feedback formed up to 75% of background value.

3.6. Disappearance of summer sea ice

Close relationship between the summer air temperature and reduced SIE in September (Fig. 3) allows predicting an evolution of September SIE using statistical modeling. According to the elaborated statistical model the arctic summer sea ice can disappear in
the middle of the 2030s (Fig. 6). The date of disappearance of the summer ice cover was also estimated using simple extrapolation of the September SIE record. This extrapolation shows the same result - the disappearance of ice in the middle of the 2030s, that confirms robustness of both predictions. Derived empirical estimates include influence of both anthropogenic and natural factors, which are responsible for the rapid decline of summer ice in the Arctic. They both are close to the earliest dates of disappearance of September sea ice, estimated from global climate models (e.g., Overland and Wang, 2013).

4. Conclusions

We propose to use summer SAT in the marine Arctic as an indicator for estimates of September SIE changes. Based on high correlation between this SAT and the Arctic SIE, September SIE anomalies were reconstructed for 1900-2013. The reconstructed SIE dataset shows significant reduction in 1930-40s with a minimum of ice extent registered in 1936. However, it was just a half of the reduction found in 2012.

The close relationship between the increase of summer air temperature and the reduction of September SIE is used to assess the onset of summer Arctic ice disappearance. Remaining the current rate of warming of air temperature we found that such an event can happen as early as the mid-2030s. An impact of sea ice dynamics on September SIE variability is evident in the Siberian Arctic seas, where about 40% of the SIE variability is governed by winds and currents.

Changes of the Arctic winter SIE are associated with a shift of sea ice edge in the Nordic Seas and in the Northwestern Atlantic, which is determined by the boundary between the Arctic water and the salt and warm Atlantic water. An impact of the inflow of warm and saline Atlantic water and shift of AW distribution on the winter SIE is
evident in the Barents Sea. A correlation coefficient between the monthly Atlantic water
temperatures and SIE in the Barents Sea reaches to -0.86 in May. We argue this shift of
highest negative correlation to May by significant influence of the AW inflow, which
prevents southward spreading of ice edge in the Barents Sea.

The largest positive trends were found in SAT in the marine Arctic during the
last decade for late autumn and early winter, when the heat accumulated in ice free
water areas releases to the atmosphere. This process is responsible for up to 75% of the
trend in this period.

Acknowledgements

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Figure captions

Figure 1. Average surface air temperature in winter (DJF, left), in summer (JJA, right) at meteorological stations in the marine Arctic (center) during 1951-2013. Dotted line shows a 6th order polynomial approximation.

Figure 2. (1) Average Arctic sea ice extent in September taken from NSIDC site (http://www.nsidc.colorado.edu). (2) The average surface air temperature in summer (JJA) in the marine Arctic (temperature scale is inverted). R is a correlation coefficient between (1) and (2) for 1980-2014. Value in brackets is a correlation coefficient between the residuals of (1) and (2) with quadratic polynomial approximations.

Figure 3. (Left) Positions of seven meteorological stations in the marine Arctic with collected observations since 1900. (Right) 1 – reconstructed September SIE in the Arctic from 1900 to 2013. 2 – observed SIE for 1980-2013.

Figure 4. Sea surface salinity and the sea ice edge in the Barents Sea in June 1969 (left) and 1987 (right). Sea surface salinity is taken from the digital “Climatological Atlas of the Nordic Seas and Northern North Atlantic” issued by NOAA in the International Ocean Atlas and Information Series in 2014. Ice edge position (black curve) is taken from HadSST dataset.

Figure 5. Trend of the monthly mean SAT in the marine Arctic for 1993-2012. Period of 1993-2013 was chosen as a period of rapid SAT increase.

Figure 6. (Left panel) 2nd degree polynomial extrapolation of the SIE in September (coefficient of determination is of 0.78); (center panel) extrapolation of relationships between the summer temperatures and SIE in September (coefficient of determination for linear model is 0.85; for quadratic model is 0.89); (right panel) quadratic
extrapolation of the summer air temperature (coefficient of determination is 0.65),
indicating achievement of 7.1 and 8.4 °C in 2027 and 2038, respectively.
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214x58mm (300 x 300 DPI)
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92x70mm (300 x 300 DPI)
Figure 3. (Left) Positions of seven meteorological stations in the marine Arctic with collected observations since 1900. (Right) 1 – reconstructed September SIE in the Arctic from 1900 to 2013. 2 – observed SIE for 1980-2013.

168x73mm (300 x 300 DPI)
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93x68mm (300 x 300 DPI)
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Table 1. Correlation coefficients derived between the mean annual AW temperature in 0-200 m layer along the Kola section, HadSST in the Barents Sea, and the monthly SIE in the Barents Sea for 1928-2013. (95% level of significance of the coefficients is 0.21).

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Table 2. Correlation coefficients derived between the monthly mean AW temperature in 0-200 m layer along the Kola section and the monthly SIE in the Barents Sea for 1951-2009. (95% level of significance of the coefficients is 0.26).

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1. Introduction

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in the period when the sea ice in the model is reduced (Belleflamme et al., 2015). In this
connection it is interesting to estimate the state of the sea ice in the Arctic in the 1930s,
when the warming in the Arctic has been observed. Some indications of the reduced ice
extent in the 1930s are discussed in papers (Viese 1937; 1944), written during the
period of the development of the first Arctic warming. Our paper presents an evaluation
of the past and future changes in sea ice extent in the 20th and 21st centuries and their interplay with other components of the Arctic climate system on the basis of sea ice, air and water temperature observations in the Arctic and the Northern Hemisphere.

2. Data

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3. Analysis and discussion of results

3.1. Empirical assessment of external impacts and feedbacks on the reduction of Arctic sea ice extent

There are many reasons that are likely to be responsible for amplification of the warming and decline of sea ice extent (SIE) in the Arctic. We speculate that the primary
reason is an increase of heat and moisture transports into the northern polar region due
to global warming, which triggers feedbacks in the Arctic climate system. All of them
accelerate the warming and degradation of the SIE in the Arctic. Screen et al. (2012)
believe that the surface-intensification of recent Arctic warming is due to Arctic sea ice
loss (and associated local SST change) and that warming aloft is driven by changes in
poleward heat transport. We believe that the Arctic warming as near surface and as well
as aloft is caused by increase of heat and moisture poleward transport. Sea ice loss and
SST increase act as feedbacks in summer and during sea ice formation in autumn and
early winter. The Arctic warming is most evident as an increase of SAT. Air
temperature changes in the marine Arctic affect the growth of ice cover in winter and its
melting during the summer. The marine Arctic domain is defined (Alekseev et al.,
2009), as maximal area with sea ice in the end of winter. The border of this area is
But the set of meteorological station that is used to estimate average summer air
temperature is constant. Consequently average temperature characterizes conditions as
shrinking as well growth of September sea ice extent and it can be used as an index of
atmospheric influence on summer sea ice. To estimate the average air temperature over
the marine Arctic we used meteorological records at 41 stations with observations that
started not later than in 1951 (Fig. 1). The average summer air temperature was derived
from the monthly mean air temperature (at 2 m height) in June, July and August at
every station by averaging over 3 months and then by averaging over 41 stations. The
stations are located on the periphery of the winter sea ice cover where there is a stronger
heat forcing on ice in summer. A strong correlation between the determined temperature
index and September ice extent confirms efficiency of this index and it is consistent
with the results reported in [Screen et al., 2013] about strong the atmospheric impacts of
Arctic sea ice loss within the maritime and coastal Arctic and in the lowermost
atmosphere.

Fig. 1 shows rapid growth of summer SAT since 1996 with an absolute
maximum in 2012. The winter temperatures before 1991 and the summer temperatures
before 1996 had weak negative trends, which changed to significant positive trends for
the period after these years. In agreement with the rapid growth of summer air
temperatures, the shrinking of sea ice extent at the end of summer was accelerated (Fig.
2), and reached its absolute minimum in 2012. A correlation coefficient between the
changes of summer air temperature in the marine Arctic and September sea ice extent
equals -0.93, suggesting that the summer SAT can be considered as an indicator (or
index) of external influences on the SIE. Value in brackets is a correlation coefficient (-
0.78) between curves (1) and (2) that are the departures of from quadratic polynomial
trends.

Dependence of the September SIE from the summer SAT decreased in the
Siberian Arctic seas under influence of sea ice dynamics. The correlation between the
summer SAT and September SIE in those seas is characterized by a coefficient of -0.75
estimated for 1951-2013. This correlation is responsible for 56% of the variability of the
September SIE. Hence almost half of the variance is explained in this region by the
other processes in particular winds and cyclonic activity (Rudeva and coauthors, 2012;
Rudeva et al., 2014).

3.2. Reconstruction of the past Arctic SIE based on temperature index

http://mc.manuscriptcentral.com/joc
Taking into account a strong relationship between the summer SAT and the Arctic SIE, the state of September SIE in the previous year can be estimated. Unfortunately, most of the weather stations in the marine Arctic began their work after 1950, and only seven of them were operating at the beginning of the 20th century (Fig. 3). Therefore time series of the average summer temperature in the marine Arctic for the period 1900-2013 could be estimated at these stations only. A correlation between the summer temperatures and the Arctic SIE in September over 1980-2013 equals -0.81. Based on the correlation the regression equation of September SIE on summer SAT was performed and used for calculating September SIE for 1900-2013. The result of calculations is presented on figure 3 where data for 1900-1980 show the reconstruction of September SIE. These data show significant SIE decrease in 1930-40s, which is close to the Viese’s estimate (Viese, 1944), who found a decrease of about 1 million km$^2$. However, the strongest reconstructed SIE reduction for 1930-40s, which occurred in 1936, constitutes only a half of the ice reduction in 2012. Reconstruction includes as trend as year-to-year changes that confirms close agreement between reconstructed and observed curves for 1980-2013 in fig. 3.

3.3. Ocean influence on winter sea ice distribution

In spite of fact that winter SAT increases faster than the summer SAT, reduction of winter SIE in the Arctic is much slower in comparison with summer shrinking. One of the reasons is that the Arctic seas in winter are completely covered with ice. Therefore, changes in the Arctic winter SIE are associated with a shift in the sea ice edge in the Nordic Seas and the Northwestern Atlantic that is determined by the boundary between the Arctic water and the salty and warm Atlantic water (Zakharov, 1997, Smelserud et al., 2013). Consequently variations of winter SIE include the component determined by
changes of the Atlantic Water (AW) spreading in the Nordic Seas and the Northwestern
Atlantic.

An influence of this component on the winter SIE is clearly evident in the Barents Sea from analysis of interrelation between long-term historical datasets of SIE, AW temperatures in the Kola section, and sea surface temperatures. (Table 1). The correlation of the monthly mean AW temperature occurring in the Kola section and the sea ice edge for 1951-2009 reaches its maximal value of 0.86 in May (Table 2). Shift of the correlation maximum to May can be explained by significant impact of AW inflow occurred in southern part of the Barents Sea that prevents the southward spreading of sea ice edge in winter. A correspondence between distributions of the AW and the sea ice in the Barents Sea can be seen from Fig. 4, showing a similar spatial pattern of surface salinity distribution and sea ice edge in June of 1969 and 1987. In June 1969 the salty AW occupies a smaller area, and sea ice goes further to the south in comparison with June 1987.

3.4. Effect of summer SIE reduction on winter air temperature in the Arctic

One of the feedbacks that amplify the warming in the Arctic is the result of summer SIE reduction, which increases the air temperature in late autumn and early winter (Fig. 5). In the period with negative air temperatures, the heat accumulated in ice-free areas releases to the atmosphere. An additional contribution to the warming is an increase of the water vapor content in the surface atmospheric layer, accompanied by increased downward long-wave radiation. As consequence, the largest SAT trends are found from October through February, exceeding background value (the average for March-September). Amplification of the trend caused by this feedback formed up to 75% of background value.
3.5. Disappearance of summer sea ice

Close relationship between the summer air temperature and reduced SIE in September (Fig. 3) allows predicting an evolution of September SIE using statistical modeling. According to the elaborated statistical model (Fig. 6), the arctic summer sea ice will disappear in the middle of the 2030s. The points and curves on center panel in Fig. 6 depict the dependence between the summer SAT (x-axis) and September SIE (y-axis) and linear (1) and quadratic (2) approximations of this dependence. The extrapolation both curves up to SIE=0 shows the summer temperatures by which it can happen. The date of disappearance of the summer ice cover was also estimated using simple extrapolation of the September SIE record. This extrapolation shows the same result - the disappearance of ice in the middle of the 2030s, that confirms the robustness of both predictions. Derived empirical estimates include the influence of both anthropogenic and natural factors, which are responsible for the rapid decline of summer ice in the Arctic. They both are close to the earliest dates of disappearance of September sea ice, estimated from global climate models (e.g., Overland and Wang, 2013).

4. Conclusions

We propose to use summer SAT in the marine Arctic as an indicator for estimates of September SIE changes. Based on high correlation between SAT and the Arctic SIE, September SIE anomalies were reconstructed for 1900-2013. The reconstructed SIE dataset shows a significant reduction in the 1930-40s with minimum of ice extent registered in 1936. However, it was just a half of the reduction found in 2012.

The close relationship between the increase of summer air temperature and the reduction of September SIE is used to assess the onset of summer Arctic ice disappearance. If we keep the current rate of warming of air temperature we found that
such an event can happen as early as the mid-2030s. An impact of sea ice dynamics on September SIE variability is evident in the Siberian Arctic seas, where about 40% of the SIE variability is governed by winds and currents.

Changes of the Arctic winter SIE are associated with a shift of sea ice edge in the Nordic Seas and in the Northwestern Atlantic, which is determined by the boundary between the Arctic water and the salty and warm Atlantic water. An impact of the inflow of warm and saline Atlantic water and shift of AW distribution on the winter SIE is evident in the Barents Sea. A correlation coefficient between the monthly Atlantic water temperatures and SIE in the Barents Sea reaches -0.86 in May. We argue that this shift of highest negative correlation to May is due to significant influence of the AW inflow, which prevents southward spreading of ice edge in the Barents Sea.

The largest positive trends were found in SAT in the marine Arctic during the last decade for late autumn and early winter, when the heat accumulated in ice free water areas releases to the atmosphere. This process is responsible for up to 75% of the trend in this period.

Acknowledgements

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Table 1. Correlation coefficients derived between the mean annual AW temperature in 0-200 m layer along the Kola section, HadISST in the Barents Sea, and the monthly SIE in the Barents Sea for 1928-2013. (95% level of significance of the coefficients is 0.21).

<table>
<thead>
<tr>
<th>Months</th>
<th>1</th>
<th>2</th>
<th>3</th>
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<th>9</th>
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<tbody>
<tr>
<td>$T_{AW}$</td>
<td>-0.54</td>
<td>-0.64</td>
<td>-0.59</td>
<td>-0.66</td>
<td>-0.79</td>
<td>-0.75</td>
<td>-0.67</td>
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<td>-0.37</td>
<td>-0.34</td>
<td>-0.51</td>
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<tr>
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<td>-0.65</td>
<td>-0.75</td>
<td>-0.80</td>
<td>-0.79</td>
<td>-0.74</td>
<td>-0.67</td>
<td>-0.57</td>
<td>-0.48</td>
<td>-0.33</td>
<td>-0.47</td>
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</tbody>
</table>

Table 2. Correlation coefficients derived between the monthly mean AW temperature in 0-200 m layer along the Kola section and the monthly SIE in the Barents Sea for 1951-2009. (95% level of significance of the coefficients is 0.26).

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>$T_{AW}$</td>
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<td>-0.70</td>
<td>-0.68</td>
<td>-0.77</td>
<td>-0.86</td>
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<td>-0.41</td>
<td>-0.30</td>
<td>-0.40</td>
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</tr>
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</table>
References


Figure captions

Figure 1. Average surface air temperature in winter (DJF, left), in summer (JJA, right) at meteorological stations in the marine Arctic (center) during 1951-2013. Dotted line shows a 6th order polynomial approximation.

Figure 2. (1) Average Arctic sea ice extent in September taken from NSIDC site (http://www.nsidc.colorado.edu). (2) The average surface air temperature in summer (JJA) in the marine Arctic (temperature scale is inverted). R is a correlation coefficient between (1) and (2) for 1980-2014. Value in brackets (-0.78) is a correlation coefficient between the departures of (1) and (2) from quadratic polynomial trends (3) and (4).

Figure 3. (Left) Positions of seven meteorological stations in the marine Arctic with collected observations since 1900. (Right) 1 – reconstructed September SIE in the Arctic from 1900 to 2013. 2 – observed SIE for 1980-2013.

Figure 4. Sea surface salinity and the sea ice edge in the Barents Sea in June 1969 (left) and 1987 (right). Sea surface salinity is taken from the digital “Climatological Atlas of the Nordic Seas and Northern North Atlantic” issued by NOAA in the International Ocean Atlas and Information Series in 2014. Ice edge position (black curve) is taken from HadISST dataset.

Figure 5. Trend of the monthly mean SAT in the marine Arctic for 1993-2012. Period of 1993-2013 was chosen as a period of rapid SAT increase.

Figure 6. (Left panel) 2-nd degree polynomial extrapolation of the SIE in September (coefficient of determination is 0.78); (center panel) extrapolation of relationships between the summer temperatures and SIE in September (coefficient of determination for linear model is 0.85; for quadratic model is 0.89); (right panel) quadratic...
extrapolation of the summer air temperature (coefficient of determination is 0.65), indicating achievement of 7.1 and 8.4 °C in 2027 and 2038, respectively.
updated figure 6
163x41mm (300 x 300 DPI)