An empirical method for the prediction of extreme low winter sea ice extent in the Barents Sea

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Abstract. This study addresses a possibility to use surface air temperature (SAT) of the Northern Hemisphere as a potential predictor for winter sea ice concentration (SIC) in the Barents Sea. The areas of most significant correlation between the leading modes of joint variability of the observed SIC in January-March and the SAT in the autumn, winter, and spring months in the 1979-2019 period are determined using a method of singular value decomposition (SVD) of covariance matrices. An analysis of the structure of this linkage has shown its robustness for SIC in the Barents Sea. The most strongly related areas are found in the first leading mode of the SVD analysis of the SIC in January-March and the SAT in November-January. The first SVD-mode explains in total 55\% of covariation of both parameters. It has been revealed that the January-March SIC in the northern part of the Barents Sea is strongly correlated with the November-January SAT in Scandinavia and over the Barents Sea (the correlation coefficient is -0.8). The relationship between the SIC and SAT in key areas has allowed obtaining estimates of SIC in the northern part of the Barents Sea in the 21\textsuperscript{st} century from an ensemble of 30 CMIP5 GCMs by using models’ SAT data. It has been found that the RCP 4.5 scenario results in a strong reduction in the sea ice in the northern part of the Barents Sea by 2041-2050. At the same time, no complete disappearance of sea ice is expected until the end of the century. According to the aggressive scenario RCP 8.5, almost free-ice Barents Sea is expected by the middle of the 21\textsuperscript{st} century.

1. Introduction
The late decades of the 20\textsuperscript{th} century and early 21\textsuperscript{st} century were characterized by significant global warming. The most dramatic changes occurred in the northern high latitudes in wintertime. Higher rates of the warming in the Arctic relative to the temperature changes in the middle and low latitudes called Arctic amplification (e.g., [2]) can lead to a transformation of atmospheric circulation regimes with an increased probability of stationary weather regimes and weather extremes [6, 16]. Along with the increase in global temperature, there was a rapid reduction of the Arctic Sea ice extent, which accelerated at the beginning of the 21\textsuperscript{st} century [8, 17]. The strongest sea ice retreat is observed in September, whereas the winter sea ice decrease is about three times slower. However, the winter sea ice changes result, due to high temperature and humidity contrasts and stronger wind speed, in much larger ocean-atmosphere heat flux anomalies that strongly impact atmospheric circulation [14]. The greatest loss of winter sea ice extent was observed in the Barents Sea [11, 12]. The extrapolation of the
current ice coverage trends in the Barents Sea into the future implies the ice-free conditions already in 2023 and 2036 for quadratic and linear trends, respectively [13].

The sea ice in numerical experiments with climatic models is linked to the sea surface temperature. At the same time, climate models do not always realistically reproduce processes in the ocean and, in particular, the multidecadal variability of sea surface temperature in the North Atlantic [1]. Results of model estimates of the sea ice coverage in the Arctic have a significant intermodel spread. For example, ice-free conditions in the Barents Sea “are projected to occur for the first time in 2028 in GFDL CM3, 2061 in MPI-ESM-MR, and 2063 in NorESM1-M” [13]. Researchers have noted that “the Barents Sea is currently almost ice free in summer, while the models in average simulate such conditions by the end of the 21st century or around 2050 in the CMIP3 and CMIP5 ensembles, respectively” [17]. The overestimation of sea ice can be associated with an underestimation of the ocean heat transport to the Barents Sea in CMIP5 models [10]. The importance of prediction of the sea ice cover extent in the Barents Sea is rising, because it is one of the major regions of offshore oil and gas exploration and an important part of the marine sea routes. Therefore, it seems plausible to use sea ice concentration and the surface air temperature over a vast part of the Northern Hemisphere.

2. Data and methods
The method of singular value decomposition of covariance matrices (SVD) [4] was used to determine areas of the most significant linkage between the leading modes of joint variability of the sea ice concentration (SIC) in January-March and the surface air temperature (SAT) of the Northern Hemisphere in autumn, winter, and spring during 1979-2019; (2) to determine the periods in which this linkage is the strongest; (3) to predict the timing of the ice free conditions in the Russian Arctic seas using statistical methods based on the observed link between the sea ice concentration and the surface air temperature over a vast part of the Northern Hemisphere.

According to the method, the covariance matrix $C(X, Y)$ of the time series of spatial vectors $X(t)$, $Y(t)$ can be represented by the following formula:

$$C(X, Y) = U S V^T$$ (1),

where $S$ is the diagonal matrix of singular values, $U$ is the unitary matrix of left singular vectors, and $V$ is the unitary matrix of right singular vectors.

The singular value decomposition analysis method helps to reduce the dimension of the investigated links between time varying spatial fields and, therefore, to identify the leading modes that make the largest contribution to the explanation of the covariation variability. Previously, analysis of the covariation of precipitation in Europe, the North Atlantic sea surface temperature, the Arctic sea ice, and the geopotential height in winter revealed two leading modes responsible for the major part of co-variability of these variables; the first one is associated with the North Atlantic Oscillation, while the second mode indicates a significant contribution of the Atlantic Multidecadal Oscillation [5].

The method identifies pairs of the most related space-time structures [3; 4]. In this study, the leading components of the SVD decomposition of covariance matrices of SAT and SIC were analyzed. Covariance matrices of SAT of the Northern Hemisphere north to $30^\circ$ N in autumn, winter, and spring in the 1979-2019 period and SIC in the Arctic seas in January-March were calculated based on the three-month averaged anomalies of the considered parameters with a linear trend removed. For each SVD mode, two temporal scores (or vectors) and two spatial patterns were obtained for each considered parameter. The heterogeneous influence of the considered parameters was analyzed. The heterogeneous correlation maps are associated with the coupled modes between the two parameters, i.e. the correlation between the temporal vector of one of the parameters and time-series of the other field at each grid point. The spatial patterns of the results of the SVD analysis were obtained as a
correlation of the matrix of each considered parameter with the corresponding SVD mode (Figures 1a-1b). The high correlation between the averaged SAT and SIC over these areas reflects the strength of the linkage. The statistical significance of the correlation was determined at a level of 0.05.

The data of monthly SAT anomalies of the Northern Hemisphere were obtained from datasets of NOAA GHCN v4 (meteorological stations) and ERSST v5 (ocean areas) with a spatial resolution of 2°x2°, combined as described in [9]. The data from the UK Met Office Hadley Center dataset (HadISST1.1) on monthly mean sea concentration in the Arctic with a spatial resolution of 1°x1° were analyzed [15].

To explain the linkage between SAT and SIC, a regression model was designed based on the average values in the areas of the strongest correlation revealed by SVD analysis for the 1979-2019 period. The changes in SIC in the 21st century were calculated using the model parameters at the assumption that the found linkage between SAT and SIC will persist for several decades. The data of numerical experiments with the global coupled atmosphere-ocean general circulation models (GCMs) from a CMIP5 (Coupled Model Intercomparison Project Phase 5) model ensemble taken from the global archive of the Center for Environmental Data Analysis [7] were used for these calculations. The results show that most of the GCMs overestimate the SAT in November-January in Scandinavia and over the Barents Sea during 1979-2019 (Figure 2b). 30 GCMs out of 33 climate models were selected based on an estimate of minimum of the bias of different GCMs with regard to the observed SAT in the same period (Figure 2b).

3. Results and discussion

3.1. Changes in the concentration of sea ice in the Arctic seas of Russia in 1979-2019

It was found that the highest SIC in the seasonal cycle in the seas of the Russian Arctic was observed in January-March in 1979-2019 (Figure 2a). A significant decrease of the sea ice cover in January-March was observed in the Barents and Kara Seas in 1999-2019 compared to 1979-1998 (see Table 1). The sea ice cover shrank most rapidly in the Barents Sea (up to 16% per year). The rate of the sea ice cover reduction in the Kara Sea did not exceed 5% per year so far. The increase in SIC in the remaining seas of the Russian Arctic in practically all months from January to March in the same period was insignificant (less than 1%) (see Table 1). Thus, the Kara Sea is the next candidate for the “sea without ice” status after the Barents Sea.

Table 1. The difference in SIC (%) in the Russian Arctic between the 1999-2019 and 1979-1998 periods in January (1), February (2), and March (3).

| region       | Barents Sea | Kara Sea | Laptev sea | East-Siberian Sea | Chukchi Sea |
|--------------|-------------|----------|------------|-------------------|-------------|
| month        | 1           | 2         | 3          | 1                 | 2           |
| %            | -15.1*      | -16.3*    | -11.4*     | -5.01*            | -3.6*       |
|              | -3.6*       | -1.8*     | -0.08      | 0.09              | 0.25        |
|              | 0.33        | 0.2       | 0.13       | 0.28              | 0.55        |
|              | 0.58        |           |            |                   |             |

* Significant changes

3.2. The linkage between the leading modes of joint variability of SIC in January-March and SAT in autumn, winter, and spring in 1979-2019

An analysis of the structure of the linkage between the leading modes of joint variability of SIC in the Russian Arctic in January-March and SAT of the Northern Hemisphere in autumn, winter, and spring in 1979-2019 showed robustness of such a linkage for SIC in the Barents Sea. On the other hand, the system of linkages between the studied parameters changed in the late 1990s in other seas of the Russian Arctic. The most strongly related areas are found in the pattern of the first leading mode of SVD analysis of joint variability of SAT in November-January and SIC. The SVD mode in total explains 55% of the covariation of the both parameters (Figure 1c). The spatial structure of the first leading mode of SVD analysis is represented by a zonal dipole highlighting changes in SAT and SIC of the opposite sign in the eastern and western regions of the Arctic (Figures 1f-1b). A similar pattern

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* Table 1: The difference in SIC (%) in the Russian Arctic between the 1999-2019 and 1979-1998 periods in January (1), February (2), and March (3).

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* Significant changes
of the anomalies, called the Arctic Dipole Anomaly (DA), is associated with the second leading mode of EOF-analysis of variability in the monthly mean sea level pressure to the north of 70° N, and is an “important driving force” for the transport of the Arctic Sea ice from the western Pacific to the North Atlantic [18, 20]. The ice movement in the Arctic seas occurs mainly due to meridional wind anomalies accompanying SLP anomalies in the opposite phases of the Arctic Dipole [19]. The prevailing west winds in the western regions of the Arctic during the positive DA phase enhance the transpolar transport, contributing to the drift of sea ice from the central Arctic through the Fram Strait to the Greenland Sea [19, 20]. As shown in Figure 1d, the average January-March SIC in the north of the Barents Sea (inside the area indicated by green dots in Figure 1a) in 1979-2019 was strongly correlated with the average November-January SAT in Scandinavia and over the Barents Sea (the correlation coefficient is -0.8) inside the area indicated by green dots in Figure 1b. Note that the linkage between the time series of the leading SVD-mode of SIC variability and the SIC time series (with a correlation coefficient of 0.64) does not take into account the influence of the global warming trend.

Figure 1. Spatial patterns (a, b) and time series (c) of the first leading mode of SVD analysis of SIC observed in the Arctic seas in January-March (1) and SAT observed in the Northern Hemisphere in November-January (2) in 1979-2019, as well as variability of SIC in the north of the Barents Sea (3) and SAT anomalies in Scandinavia and over the Barents Sea (4) (d) in the same periods in the areas marked with green dots in Figures (a) and (b).

3.3. Changes in the ice concentration in the north of the Barents Sea in the current century based on modelled data

Based on the empirical linkage (Table 2) between SIC in January-March in the north of the Barents Sea, SAT in November-January in Scandinavia and over the Barents Sea in the late 20th - early 21st
centuries, and the changes in SAT according to the climate model projections, the expected changes in the ice concentration were estimated for the north of the Barents Sea up to the end of the 21st century.

Table 2. Parameters of the regression model with SIC in January-March in the north of the Barents Sea (in the area with green dots in Figure 1b) as a dependent variable and SAT in November-January in Scandinavia and over the Barents Sea (in the area with green dots in Figure 1a) as an independent factor in 1979-2019.

| model independent variable | regression coefficient | constant | Std.Err. | t(30) | R² | F | p-value |
|-----------------------------|------------------------|----------|----------|-------|----|---|---------|
| SAT                        | -13.35                 | 67.11    | 1.6      | -8.36 | 0.64 | 69.95 | 0.0000000003 |

The multimodel ensemble estimates of SIC based on the expected changes in SAT showed that the RCP 4.5 scenario assumes a reduction in the ice cover in the northern part of the Barents Sea in 2041-2050 to values less than 10% (Figure 2c). However, the complete disappearance of ice is not expected until the end of this century. According to the RCP 8.5 scenario, 10% SIC values in the region will be achieved approximately five years earlier than in the RCP 4.5 scenario, and almost complete sea ice removal should be expected by the middle of the 21st century (Figure 2d).

The proposed method of empirical linkage was also applied to SAT data predicted by HadGEM2-ES, and the result was compared to SIC predicted by this climate model. The HadGEM2 was chosen since it most realistically reproduces SAT in 1979-2019. The comparison showed that the
underestimation of modelled SIC values in the north of the Barents Sea is the consequence of a sharper increase in SAT in the model (Figure 3a).

According to the RCP4.5 scenario and the revealed linkage between SAT and SIC in the last decades of the 20th century and the beginning of the 21st century, a warming of 5.2 °C in Scandinavia and over the Barents Sea in November-January is expected to lead to complete disappearance of the ice cover in the north of the Barents Sea by the mid-2050s (Figure 3b). This conclusion is in good agreement with the results of simulation of the sea ice cover concentration according to HadGEM2-ES projections. However, the climate model assumes insignificant variability (less than 9%) in the concentration in the second half of the 21st century (Figure 3b). At the same time, changes in the sea ice cover in the coming decades are expected to be more unstable according to the HadGEM2-ES SIC data.

The warming by 5.5 °C in Scandinavia and over the Barents Sea in November-January in 2041-2050 under the RCP 8.5 scenario is expected to lead to complete ice disappearance in January-March in the north of the Barents Sea by the early 2050s according to the revealed linkage between SIC and SAT (Figure 3c). A projection of the regional climate by the HadGEM2-ES scenario demonstrated year-round ice-free conditions to be expected soon in the Barents Sea. It was found that the SIC simulated by the model under both anthropogenic forcing scenarios has higher values than the SIC estimated using the relationship between the SIC and SAT. Note that the RCP 4.5 scenario assumes sharper than in RCP 8.5 inter-annual fluctuations in the sea ice concentration after 2022.
4. Conclusions
The above study of the leading modes of joint variability of the observed SIC in the Arctic and the SAT of the Northern Hemisphere in the 1979-2019 period revealed areas of the most strongly related January-March SIC in the northern part of the Barents Sea and the November-January SAT in Scandinavia and over the Barents Sea. The relationship between the SIC and SAT allowed obtaining semi-independent estimates of the SIC in the northern part of the Barents Sea in the 21st century from an ensemble of 30 CMIP5 GCMs by using models’ SAT data. It was found that the RCP 4.5 scenario leads to a significant decrease in the sea ice in the northern part of the Barents Sea by 2041-2050. On the other hand, no complete disappearance of sea ice is expected until the end of the century. Almost free-ice Barents Sea is expected by the middle of the 21st century according to the most aggressive scenario, RCP 8.5.

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