Seasonal and Interannual Variability of the Barents Sea Temperature

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Abstract
Analysis of the monthly average temperature data of the Barents Sea at various depths for the period 1948-2016 showed its growth, which accelerated significantly since the mid-1980s. Against the background of this growth, interannual variability was found over periods of 2 to 7 years and about 10 years. It is shown that periods of this variability can be associated, respectively, with El Nino - Southern Oscillation and the North Atlantic Oscillation. It has been hypothesized that the Global Atmospheric Oscillation may be the synchronizing mechanism of the interannual variability of the tropics of the Pacific Ocean, the North Atlantic and the Barents Sea. Interdecadal changes with a period of about 15 years were also found, which are most likely related to surface temperature anomalies carried by the North Atlantic Current.

Key words: climate change, temperature, the Barents Sea, El Nino, North Atlantic Oscillation, Global Atmospheric Oscillation, the North Atlantic Current.

Introduction
The Earth’s modern climate is characterized by a positive trend in changes in global near-surface temperature, which, as is now commonly believed, is associated with an anthropogenic factor in the increase in greenhouse gas concentrations in the atmosphere (IPPC, 2013). Along with this, there are more high-frequency, seemingly chaotic changes in temperature, caused, apparently, by factors of natural origin. These factors include, firstly, the impact on the climate system of such external quasiperiodic forces as the 11-year change in solar activity, the 14-month Chandler oscillation of the Earth’s poles, and the 18.6-year lunar-solar nutation of the Earth’s rotation axis (Sidorenkov, 2009; Serykh and Sonechkin, 2019). Second, global and regional modes of climate variability: El Nino - Southern Oscillation (ENSO) (Byshev et al., 2012a, 2012b, 2016; Serykh et al., 2019), the North Atlantic Oscillation (NAO) (Hurrell and Deser, 2009), the Pacific Decadal Oscillation (PDO) (Dong and Dai, 2015), the Arctic Oscillation (AO), etc. Thirdly, heat redistribution between the upper active layer of the World Ocean and the atmosphere (Byshev et al., 2017). All these factors can influence the regional climatic changes in the temperature of the Barents Sea, which this work is devoted to.

Materials and methods
Monthly average temperature data were analyzed at 22 different depths from 5 to 409 meters of the oceanic reanalysis German contribution of the Estimating the Circulation and Climate of the Ocean project.
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(GECCO2) on a 1×1° grid for the period 1948-2016 (Köhler A., 2015). Monthly mean sea-level pressure (SLP) data were taken from the NCEP/NCAR reanalysis on a 2.5×2.5° grid for the period 1948-2016 (Kalnay et al., 1996).

Data were averaged for the Barents Sea region (68-80°N; 20-55°W). At each grid node, the average seasonal variation for the period under consideration was calculated, which was then subtracted from the initial data to obtain anomalies with respect to the seasonal variation.

The Global Atmospheric Oscillation (GAO) Index was calculated as the algebraic sum of the normalized values of the SLP anomalies in ten geographical areas that coincide with the extrema (highs and lows) in the GAO field: (5°S-5°N, 35-25°W) + (5°S-5°N, 55-65°E) + (55-65°N, 95-85°W) + (65-55°S, 95-85°W) + (5°S-5°N, 145-155°E) - (45-55°N, 175-165°W) - (45-55°N, 15-5°W) - (55-45°N, 15-5°W) - (55-45°S, 175-165°W) - (5°S-5°N, 95-85°W) (Serykh et al., 2019). Under El Niño, this index is positive, while under La Niña it is negative.

The North Atlantic Oscillation Index, calculated using the main component method for atmospheric pressure anomalies at sea level in the North Atlantic, was taken from the NCAR Hurrell North Atlantic Oscillation Index (PC-based) (Hurrell, 2003).

The North Atlantic Current Index, which is part of the Atlantic Meridional Overturning Circulation (AMOC), was calculated as the difference between the normalized anomalies of water temperature at a depth of 5 meters between regions (34-39°N; 58-48°E) and (48°-53°N; 35°-25°E).

Linear trends were calculated using the least squares method. For smoothing and bandpass filtering, the Butterworth filter was used. The spectra were built using the fast Fourier transform method. The wavelet transform was performed using the Morlet wavelet function (Torrence and Compo, 1998). For the wavelet cross-correlations of the two series, a multiplication of their wavelet real components were calculated (Torrence and Webster, 1999).

Results

An analysis of changes in the Barents Sea water temperature anomalies at various depths showed significant differences between the depths of 5 and 105 meters (Fig. 1). The depths from 5 to 105 meters are intermediate, and levels from 105 to 222 meters differ slightly. With a depth of more than 222 meters, there is a strong reduction in the area of the levels, so their comparison with the surface becomes difficult. Based on this, further results are given for depths of 5 and 105 meters.

Figure 1. Series of monthly average temperature anomalies for the Barents Sea at depths of 5, 55, 105, 154 and 222 meters for the period 1948-2016 after applying the 2-year low-frequency Butterworth filter.
In the average fields of the Barents Sea water temperature for depths of 5 and 105 meters (Fig. 2), the influx of warm waters from the North Atlantic and their spread eastward along the Scandinavian coast are clearly visible (Rodionov and Kostianoy, 1998; Kostianoy et al., 2004). The difference in surface water temperature between the west and east of the Barents Sea at latitudes of 70-75°N is about 5°C. While at latitudes 75-80°N the difference is practically absent. At a depth of 105 meters off the coast of Scandinavia, the water temperature is approximately 1°C lower than at the surface. However, at a depth of 105 meters, warm intermediate Atlantic waters extend farther to the northeast than at the surface, and the temperature difference between the west and east of the Barents Sea becomes smaller. Also, with the depth, the influence of the bottom topography begins to have a stronger effect.

**Figure 2.** Fields of average temperature of the Barents Sea at depths of 5 meters (above) and 105 meters (below) for 1948-2016.

An analysis of the data showed a significant increase in the average temperature of the Barents Sea for the period 1948-2016 (Figs. 3 and 4), caused, most likely, by global warming on the planet (IPPC, 2013). Moreover, the surface temperature grew faster than at depth. The temperature of the Barents Sea increased by an average of 0.2°C over 10 years, and thus increased by an average of approximately 2°C over the period 1948-2016. However, this growth occurred unevenly across the Barents Sea (Fig. 3). Thus, the largest
An increase in temperature near the surface took place in 2 regions of the Barents Sea: (75-77°N; 22-35°E) and (72-77°N; 40-55°E) - approximately 0.5-0.7°C over 10 years. Apparently, this is due to a decrease in the area of sea ice in these regions (Lind et al., 2018). At a depth of 105 meters, the highest temperature increase was observed in the region (70-75°N; 35-47°E) – approximately 0.4-0.5°C over 10 years.

Figure 3. Fields of changes in the average monthly temperature of the Barents Sea (°C over 10 years) at depths of 5 meters (above) and 105 meters (below) calculated from the linear trends of its monthly average anomalies for 1948-2016.

The seasonal variation in average water temperature at the surface of the Barents Sea is of 5–6°C, and at a depth of 105 meters, it is of 1-2°C (Fig. 4). For the considered period 1948-2016, an increase in the seasonal variation at depth is observed, that is, a deepening of the upper active layer of the Barents Sea occurs. Also interesting is the fact that in the 21st century the average monthly surface temperature averaged over the entire Barents Sea did not fall below 0°C. Moreover, in the warm season, the surface temperature in 2013 and 2016 rose above a record of 8°C. To analyze interannual changes, the seasonal variation was excluded from further consideration.
Against the background of a general increase in the average temperature of the Barents Sea, strong interannual variability of its anomalies with respect to the seasonal course is observed (Fig. 5). Moreover, the variability of temperature in the warm season (May-October) exceeds the variability in the cold one (November-April), which may be caused by partial screening of the signal from the atmosphere with ice cover in the cold season. So in addition to the already mentioned summer semesters of 2013 and 2016, the years of 1973, 1984, 1990 and 1995 were abnormally warm. The summer semesters of 1966, 1968, 1969, 1978, and 1982 were abnormally cold.

Strong anomalies of the same sign lasting more than a year are also observed: the cold periods of 1978-1982 and 1994-1999, and the warm periods of 1973-1976, 1983-1985, 1990-1992 and 2011-2013. It is interesting that the transitions between periods of anomalies of opposite signs account for global climatic shifts of the mid 1970s and late 1990s - early 2000s (Byshev et al., 2009; Byshev et al., 2017). Also, the periods of negative anomalies are confined to the strongest El Niño events of 1982/1983 and 1997/1998. (Byshev and Neiman, 2000).

Figure 4. Changes in the monthly average temperature of the Barents Sea (red) and their linear trend (blue) at depths of 5 meters (above) and 105 meters (below) for the period 1948-2016.
Figure 5. Changes in the monthly average temperature anomalies of the Barents Sea at depths of 5 meters (above) and 105 meters (below) for the period 1948-2016, smoothed by 2-year (orange) and 7-year (purple) low-frequency Butterworth filters. Their linear trend is shown by black line and the accumulated sum of anomalies after the removal of the linear trend by a green line. The circles indicate the average values of the anomalies for the warm (May-October) (red) and cold (November-April) (blue) seasons.

The energy spectrum of the monthly average temperature anomalies of the Barents Sea at a depth of 105 meters contains formally statistically significant peaks (exceeding the 95% confidence level) for periods of 2.4 and 3.6 years (Fig. 6, lower part). Serykh and Sonechkin (2016, 2017, 2019) showed that these periods, which are sub-harmonics of 1:2 and 1:3 of the Chandler oscillation of the Earth’s poles, are characteristic of the El Nino - Southern Oscillation.
Figure 6. Energy spectra (blue) of the monthly average temperature anomalies of the Barents Sea at depths of 5 meters (above) and 105 meters (below) for 1948-2016. A confidence level from 5% (black line at the bottom) to 95% (black line at the top) and a spectrum of red noise (red line between them) were drown. The preliminary normalization of the series to their standard deviations was made.

Since the data sets under consideration are non-stationary, it is appropriate to apply wavelet analysis to them. The calculation of wavelet transforms showed that periods from 2 to 7 years, about 10 years and about 15 years are distinguished in the interannual variability of temperature anomalies in the Barents Sea (Fig. 7). Which can be associated with the El Nino - Southern Oscillation (Serykh, Sonechkin, 2017), the North Atlantic Oscillation (Moron et al., 1998) and changes in the North Atlantic Current (Arthun et al., 2017), respectively. In the picture of the wavelet transform of the monthly average temperature anomalies of the Barents Sea at a depth of 5 meters (Fig. 7, upper part) at the time of the global climate shift of the mid-1970s, one can see the energy transfer upward in scale from fluctuations with periods of 2-3 years to fluctuations with periods of 3-4 years. At the time of the global climate shift of the late 1990s - early 2000s we observe down scale from fluctuations with periods of 8-10 years to fluctuations with periods of 3-7 years. This fact indicates the presence of non-linear mechanisms that led in the beginning 21st century toward
weakening of fluctuations associated with the North Atlantic Oscillation, and enhancing of fluctuations caused by El Nino.

![Wavelet transform of monthly average temperature anomalies of the Barents Sea](image)

**Figure 7.** Pictures of the wavelet transform of the monthly average temperature anomalies of the Barents Sea at depths of 5 meters (above) and 105 meters (below) for the period 1948-2016. The preliminary normalization of the series to their standard deviations was made.

Serykh et al. (2019) showed that the El Nino - Southern Oscillation is an element of the Global Atmospheric Oscillation (GAO), which explains the connection between such remote regions as the Pacific tropics and the Barents Sea, as well as the occurrence of negative temperature anomalies in Barents Sea
before the events of El Nino. During the events of La Niña (negative GAO phase), positive temperature anomalies are observed in the Barents Sea. Let’s consider separately each of the above modes of climatic variability.

The relationship of temperature anomalies of the Barents Sea near the surface with GAO is shown in Fig. 8. There are periods of desynchronization of the two sets of data at the beginning of the study period (1948-2016) and the mid-1970s. The period of weak dependencies at the beginning of the period under study can be caused by the boundary effects of the transformations and insufficiently detailed and qualitative observational data at this time. The second period in the mid-1970s can be attributed to the transition between the phases of the Pacific Decadal Oscillation and the associated global climate shift (Hare and Mantua, 2000; Byshev et al., 2009). In other periods, synchronization is observed between temperature fluctuations in the Barents Sea and GAO. Moreover, on periods of fluctuations from 2 to 4 years, before the climatic shift of the mid-1970s, changes occurred in antiphase, and after the mid-1970s - in phase. On periods of fluctuations from 4 to 7 years, before the climatic shift of the mid-1970s, changes were weakly correlated, and after the shift there is a strong antiphase correlation. Also, the relationship between the temperature of the Barents Sea and GAO is confirmed by the presence of high energies of fluctuations around 1982/1983 and 1997/1998, when the strongest El Niño events occurred. In the late 1990s and early 2000s, there was a reverse transition between the phases of the PDO and the related global climate shift (Bond et al., 2003; Byshev et al., 2017), which led to a shift in the periods of positive relationships between GAO and the temperature of the Barents Sea. Thus, unsteady relationships are observed between the GAO and the temperature of the Barents Sea, but mostly positive for periods from 2 to 4 years, and negative for periods from 4 to 7 years.

Figure 8. Interannual variability of the Global Atmospheric Oscillation Index (red) and monthly average temperature anomalies of the Barents Sea (blue) at a depth of 5 meters for the period 1948-2016 after applying the Butterworth bandpass filter from 2 to 7 years (above), and the cross-correlation picture of their material transformations without
filtering (below). Preliminary removal of linear trends, centering and normalization of the data sets to their standard deviations were performed.

The relationships between the surface temperature anomalies of the Barents Sea and the North Atlantic Oscillation (NAO) are shown in Fig. 9. These relations are more stationary than with the GAO, but there are periods of strengthening and weakening of them. Due to the global climate shift in the mid-1970s, a change in the NAO phases occurred, which led to changes in the number of cyclones and near-surface temperature in the North Atlantic, as well as heat transfer from this region to the Euro-Asian continent (Jung et al., 2003). This can also be clearly seen in the cross-wavelet diagram (Fig. 9), where the strongest cross-correlations in the quasi-8-year period are traced from the early 1970s to the late 1990s. A distinctive feature of this period is the advancing changes in the NAO to changes in the temperature of the Barents Sea. After the global climatic shift of the late 1990s, a shift in the energies of the oscillation links is observed downward from 7–10 years to 5–7 years, that is, the influence of the El Niño – Southern oscillation intensifies. This can be explained by the fact that both the Southern Oscillation and the NAO are elements of the GAO (Serykh et al., 2019), which plays the role of a synchronizing link between them and the temperature of the Barents Sea.

Figure 9. Interannual variability of the North Atlantic Oscillation Index (red) and monthly average temperature anomalies of the Barents Sea (blue) at a depth of 5 meters for the period 1948-2016 after applying the Butterworth bandpass filter from 7 to 10 years (above), and the cross-correlation picture of their material transformations without filtering (below). Preliminary removal of linear trends, centering and normalization of the series to their standard deviations were performed.
The relationships between the surface temperature anomalies of the Barents Sea and the changes in the North Atlantic Current are shown in Fig. 10. They are characterized by a quasi-15-year oscillation period (Arthun et al., 2017), which can be traced on the cross-wavelet diagram in Fig. 10. Unfortunately, the lengths of the considered series are not enough for reliable estimates of these interdecadal oscillations. However, according to available data, it is possible to conclude that these relations are positive. This is explained by the transfer of temperature anomalies of the water by the North Atlantic to the Barents Sea region. Violation of these connections is noticeable only at the beginning and end of the considered calendar period, but this is most likely due to boundary effects during filtering and the construction of a cross-wavelet diagram for these low-frequency oscillations.

![Figure 10. Interannual variability of the North Atlantic Current Index (red) and monthly average temperature anomalies of the Barents Sea (blue) at a depth of 5 meters for the period 1948-2016, after applying the Butterworth bandpass filter from 12 to 16 years (above), and the cross-correlation picture of their material transformations without filtering (below). Preliminary removal of linear trends, centering and normalization of the series to their standard deviations were performed.](image)

Conclusions

The obtained results indicate the influence of planetary and regional modes of climatic variability on interannual and interdecadal changes in temperature anomalies of the Barents Sea.
Analysis of monthly average temperature of the Barents Sea at various depths showed its significant increase for the period 1948-2016. Moreover, the temperature increase has markedly accelerated since the mid-1980s.

Against the background of this growth, temperature fluctuations were found over periods of 2-7 years, about 10 years and about 15 years. An assumption has been put forward that these fluctuations are related to the El Niño - Southern Oscillation, the North Atlantic Oscillation and changes in the North Atlantic Current, respectively.

It is shown that temperature anomalies associated with El Niño, the North Atlantic Oscillation and changes in the North Atlantic Current affect the upper 100-meter layer of the Barents Sea.

The relationship between El Niño and the temperature of the Barents Sea is positive for periods from 2 to 4 years, and negative for periods from 4 to 7 years. Moreover, the unsteady behavior of these connections is observed: a shift in the time periods of oscillations, as well as calendar periods for their synchronization and desynchronization.

The relationship between the temperature of the Barents Sea and the North Atlantic Oscillation over periods of about 10 years is positive and also demonstrates unsteady behavior: since the beginning of the 2000s, energy has been transferred downward in time scales - to periods of 5-7 years, more typical for El Niño - Southern Oscillation.

It has been hypothesized that the Global Atmospheric Oscillation, whose elements are the Southern and North Atlantic Oscillations, can serve as the synchronizing mechanism of interannual fluctuations in the tropics of the Pacific Ocean, the North Atlantic, and the Barents Sea.

The relationship between the interdecadal temperature fluctuations of the Barents Sea and changes in the North Atlantic Oscillation over a period of about 15 years is positive for periods from 15 years, about 10 years and about 15 years. An assumption has been made that these connections is observed: a shift in the time periods of oscillations, as well as calendar periods for their synchronization and desynchronization.

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