On the climatic changes of the surface air temperature in the White Sea region

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Abstract. Analysis of the monthly average surface air temperature (SAT) data of the White Sea showed its significant growth over the past decades. Against the background of this growth, the interannual variability was revealed with periods close to the periods of El Niño – Southern Oscillation (2-7 years) and the North Atlantic Oscillation (7-10 years). The effect of these oscillations on the interannual variability of the SAT of the White Sea is shown and the periods of their synchronization and desynchronization are found. During the periods of 1960s and from the second half of the 1980s to the mid-2010s during the El Niño events in the White Sea negative SAT anomalies were usually observed, and during the La Niña events – positive anomalies. In the period from the late 1960s to the mid-1990s, NAO had a strong positive effect on the SAT anomalies of the White Sea, in the second half of the 1990s this influence changed its sign, but from the beginning of the 2000s it became positive again.

1. Introduction

The White Sea is of particular importance for the Russian Federation, since it is fully included in its territorial waters and is actively used for sea transport, fishing, and recreation. Therefore, the study of the variability of physical and biological processes in the White Sea region is necessary for the development of the Northern Economic Region.

Over the White Sea air masses coming from the North Atlantic prevail. They cause a fairly warm long winter, a cool short summer, with significant cloud cover and high humidity. Unstable weather conditions are observed in all seasons of the year: a frequent change in air masses is characteristic. Intensive cyclonic activity and relatively fast change of synoptic processes are manifested in a noticeable variability of the values of meteorological quantities [1]. Some parts of the territories of the constituent entities of the Russian Federation, washed by the White Sea, are equated to the Arctic zone by climatic conditions.

An analysis of the impact of climate variability on processes in the White Sea is given, for example, in [1-4]. In these works, a general tendency to warming was observed, which is also observed at present in the White Sea region [5]. The analysis of time series of the temperature of the surface water layer of the White Sea, including using data from RIHMI-WDC (http://meteo.ru), was
performed earlier and is presented in the monograph [4]. This work focuses mainly on the surface water temperature of the White Sea.

The North Atlantic Oscillation (NAO) is an important mechanism for the formation of long-period variability of climate elements. NAO is characterized by the difference of the atmospheric pressure between the Azores maximum and the Icelandic minimum, which in turn affects the intensification of Western transport in the Northern Hemisphere. In [6] it is shown that NAO affects the main parameters: wind speed, latent and sensible heat fluxes, evaporation and precipitation.

In recent years, more and more works have appeared that show the relationship between NAO and the El Niño – Southern Oscillation (ENSO) phenomenon [7-8]. Although El Niño events take place in the tropical Pacific Ocean, nevertheless, their influence through long-distance links (teleconnections) affects the NAO. So, for example, a relationship was found between the events of El Niño and the deepening of the Icelandic Depression [9]. The Barents Sea according to V.I. Byshev [10] responds to El Niño by lowering the heat content of water and increasing ice cover. Therefore, the task of finding links between the NAO, ENSO and the temperature regime of the White Sea looks relevant.

The paper [11] presented the spatial structure of sea level atmospheric pressure (SLP) anomalies, called the Global Atmospheric Oscillation (GAO), arising long before the next El Niño events. This structure is symmetrical relative to the equator, despite differences in the configurations of the continents of the northern and southern hemispheres. It covers almost the entire Earth, including the anomalies attributed to the manifestation of long-distance links with El Niño.

In a later paper [12] the Student’s t-test was applied to differences in spatial structures between the events of El Niño and La Niña. The test showed that the SLP and near-surface temperature differences inherent in the El Niño and La Niña events are statistically highly significant almost everywhere on Earth, and not only in the Pacific tropics (the El Niño region). Thus, additional formal proof of the existence of GAO was obtained. Although the problem of causality of GAO and El Niño was not specifically considered in [12], its authors based on the foregoing formulated and substantiated the working hypothesis that the Southern Oscillation (SO) should be considered as a structural element of the GAO in the Pacific.

It was shown in [13] that the GAO includes both SO and extratropical oscillations, such as NAO, as its elements. A GAO index was proposed, calculated as a combination of the normalized values of the SLP anomalies in ten geographical areas coinciding with the extrema (highs and lows) in the GAO spatial structure. During El Niño, this index is positive, while during La Niña it is negative. A study of the GAO index shows that the extratropical components of the GAO can be independent of the SO, while the latter accompanies the GAO in all cases. Moreover, in view of the general spread of GAO from west to east as a spatial structure, some of its extratropical components demonstrate changes in their features even before El Niño begins to form.

Thus, the study of the relationships of NAO, ENSO and GAO with temperature anomalies of the near-surface air layer above the White Sea is the aim of this study.

2. Materials and methods of the study

For a detailed analysis of individual regions of the White Sea, we used the monthly average data of surface air temperature (SAT) from the reanalysis of satellite measurements by NASA MERRA-2 on a grid of 0.5°x0.625° for the period 1980-2017 [14]. The data were averaged for the White Sea region (63.75°-68.75°N; 32.1875°-44.6875°E), the coordinates of which were selected taking into account the MERRA-2 grid.

We also studied the SAT data from reanalyses: NOAA CIRES 20th Century Global Reanalysis Version 2c (20thC_ReanV2c) on a 2°x2° grid for the period 1851-2014 [15], ECMWF ERA-20C on a 1°x1° grid for the period 1900-2010 [16], JMA JRA-55 on a grid of 1.25°x1.25° for the period 1958-2013 [17], NCEP/NCAR Reanalysis on a 2.5°x2.5° grid for the period 1948-2018 [18], NCEP-DOE on the global Gaussian grid T62 (192x94) for the period 1980-2013 [19], ERA-Interim on a 0.75°x0.75° grid for the period 1980-2016 [20] and NCEP-CFSR on a 0.5°x0.5° grid for the period 1980-2016 [21].
The SAT of the White Sea is characterized by a strong seasonal variation of 22-30 °C: on average, from -10 °C to +15 °C. Moreover, in some years, the average monthly SAT dropped below -15 °C. Therefore, to analyze interannual changes, the seasonal variation was excluded from consideration. For this, the average seasonal variations for the period under consideration were calculated at each grid node, which were then subtracted from the initial data to obtain SAT anomalies with respect to the seasonal variations. The linear trends of the SAT anomalies thus obtained were calculated using the least squares method. For smoothing and band-pass filtering of the series of the studied characteristics, a Butterworth filter was used. The spectra were built using the fast Fourier transform method.

A comparative analysis of all chosen data has been performed. To do this, cross-correlation matrices were calculated for changes in the average SAT anomalies without smoothing and with annual moving smoothing between different reanalyses in the White Sea region for a single period for all considered reanalyses of 1980-2010. The interannual changes in the mean SAT anomalies in the White Sea region for 1980-2010, calculated from various reanalyses, were well correlated with each other. At the same time, two reanalyses turned out to be closest to the rest of the data sources: MERRA-2 with high resolution for the period of satellite observations, and NCEP/NCAR with lower resolution, but for a longer period. Therefore, for a detailed analysis of the SAT changes in various regions of the White Sea MERRA-2 was chosen, and for the study of longer-term SAT changes in the entire White Sea region data from the NCEP/NCAR reanalysis were chosen.

The White Sea region was divided into 7 districts according to [22], into which the following nodes of the MERRA-2 grid fall: Voronka (66.5°-68°N; 40.625°-44.5°E), Gorlo (65.5°-66.5°N; 39.375°-42°E), Kandalakshskiy Bay (66°-67°N; 32.5°-35.625°E), Dvinskiy Bay (64.5°-65.5°N; 37.5°-40°E), Onegshski Bay (64°-65°N; 35°-38°E), Mezenski Bay (66.5°-67°N; 42.5°-44.5°E), The Bassein (65.5°-66°N; 35°-40°E). The changes in the SAT anomalies in each region were calculated, and a cross-correlation matrix of the variability of the SAT anomalies between the regions was constructed. Their analysis showed weak differences in the changes in the SAT anomalies between individual regions and the White Sea region as a whole. Therefore, with a further analysis of interannual fluctuations, it was decided to investigate the mean anomalies of the SAT throughout the entire White Sea.

To analyze the long-term climatic variability of the entire White Sea, we used the monthly average sea surface temperature (SST) from the NOAA Extended Reconstructed Sea Surface Temperature v5 (ERSSTv5) archive on a 2°x2° grid for the period 1854-2018 [23]. The Oceanic Niño Index (ONI), calculated as the 3-month running mean of ERSSTv5 SST anomalies in the Niño 3.4 region (5°N-5°S, 120°-170°W), based on centered 30-year base periods updated every 5 years, was taken from the NOAA Climate Prediction Centre site (https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php) for the period 1950-2019. NAO Index for 1900-2019 was taken from the NCAR Hurrell North Atlantic Oscillation Index (PC-based) [24].

A comparative analysis of the results was performed with the temperature data of the surface water layer and near-surface air at the coastal and island hydrometeorological stations of the White Sea contained in the integrated database of the White Sea and its catchment of Northern Water Problems Institute of the Karelian Research Centre of the Russian Academy of Sciences (NWPI KarRC RAS) [25]. In particular, it contains long-term series of measured values obtained through the RIHMI-WDC (http://meteo.ru/) and data from complex expeditions to the White Sea at the NWPI KarRC RAS. The trends and fluctuations of hydrological and meteorological parameters were evaluated. A detailed analysis of the temperature variability of the surface layer of the White Sea water according to measurement and modeling data is presented earlier in the monograph [4].

The rather high consistency of the results obtained from various sources made it possible to use in further work the SAT data from the NCEP/NCAR reanalysis for 70-years period 1950-2019, during that there were more observations than in the previous years.
3. Results

Analysis of the NCEP/NCAR data showed an increase in the average SAT of the White Sea for the period 1950-2019 approximately 1.6 °C (figure 1), which is most likely caused by global warming [26]. Against the background of the general growth of the SAT, a strong interannual variability of its anomalies relative to the seasonal signal is observed. Moreover, the variability of the SAT in the cold season exceeds the variability in the warm season, which may be due to the increased influence of NAO on the White Sea region in winter. When considering the schedule of short-period interannual fluctuations in the SAT anomalies, short, lasting 1-2 years, abnormally cold and warm periods are distinguished (figure 1, blue line). One of such periods of negative anomalies of 1997-1998 can be attributed to the strong El Niño event that occurred at that time [4].

![Figure 1](image1.png)

**Figure 1.** Changes in average surface air temperature anomalies of the White Sea, smoothed by 2-years (blue line) and 7-years (red line) low-pass Butterworth filters, and their linear trend (black line).

When considering the graph of long-period fluctuations of the SAT anomalies of the White Sea (figure 1, red line), it is seen that in the mid-1970s, inter-decade changes occurred. This transition between long periods of anomalies of opposite signs falls on the global climate shift 1976/77 [27]. The reverse global climate shift occurred in the late 1990s [27], which is also traced on the graph of long-period fluctuations. Since 1999, there has been a sharp increase not only in the SAT, but also in the surface temperature of the White Sea, which continues to the present [28]. Short periods of negative anomalies during this growth can be attributed to the El Niño events 2002/03, 2009/10 and 2015/16.

A spectral estimate of the time series of the normalized (by the standard deviation of this series) SAT anomalies of the White Sea (figure 2) shows 2 peaks over periods of more than 1 year that are formally statistically significant (with a probability of more than 95%): ~3 years and ~8 years. Therefore, let us turn our attention to these formally statistically significant periods of White Sea’s SAT fluctuations. To understand the factors affecting the interannual variability of the SAT of the White Sea, it is necessary to establish the sources of these oscillations.

The calculation of spectral estimates (figure 2) showed that a period of about 3 years is characteristic of the interannual variability of the White Sea’s SAT, which is typical for the ENSO [29-31]. In the works [11-13, 32-33] showed that the Southern Oscillation (SO) is an element of the baric structure of the Global Atmospheric Oscillation (GAO), which partially explains the links between such remote regions as the Pacific tropics and the White Sea.
Figure 2. The energy spectrum (blue line) of average surface air temperature anomalies of the White Sea after normalizing of the series by its standard deviation. The confidence interval from 5% (black line down) to 95% (black line above) and the spectrum of red noise (red line) are noted. The vertical scale is not signed, because the spectral estimate was made using the normalized data.

The time-series of the White Sea’s SAT and the El Niño index (ONI) is shown in figure 3. Preliminary removal of linear trends, centering and normalization of the series by their standard deviations were performed. The figure 3a shows the time-series in question after applying the Butterworth bandpass filter from 2 to 3 years. The purpose of all these transformations was to preserve only fluctuations in the periods of 2-3 years, and try to remove the variability at the remaining periods. In figure 3a it is seen that there are periods of synchronization and desynchronization of oscillations of the series in question. During the periods of 1960s, the second half of the 1980s and in the mid-2000s, during the El Niño events (positive phase of the GAO) in the White Sea negative SAT anomalies were usually observed, and during La Niña events (negative phase of GAO) – positive anomalies. In the remaining periods, the indicated negative links were not observed, or they were positive.

The figure 3b shows the series of the ONI and the SAT anomalies of the White Sea after applying the Butterworth bandpass filter from 3 to 7 years. The strong negative links between the ONI and the SAT of the White Sea are characteristic from the mid-1960s to the beginning of the 1970s for the time-scales of oscillations from 3 to 7 years. Then, in the first half of the 1980s positive links can be traced between the characteristics under consideration. From the second half of the 1980s until the first half of the 2010s strong negative links between the ONI and the SAT of the White Sea were observed for the time-scales from 3 to 7 years. What caused the synchronization, desynchronization and change of sign of the links of the oscillations under consideration on the different time scales?
Figure 3. The time-series of the El Niño index (ONI) (red lines) and average surface air temperature anomalies of the White Sea (blue lines) after applying Butterworth band-pass filter from 2 to 3 years (a) and from 3 to 7 years (b), and sliding cross-correlations (with the window of 8 years) between these time series (black lines).

In the works [29-33] all the main peaks in the ENSO and GAO spectra in the range of time-scales from 2 to 7 years were correlated with three external periodic forces on the climate system: 1) Chandler wobble, 2) lunar-solar nutation, 3) the cycle of solar activity. The main periods of these external forces are ~1.2, ~18.6 and ~11.5 years, respectively. Therefore, it can be assumed that synchronization and desynchronization of the periods of influence of these external forces may be the reason for such a complex picture of cross-correlations of the ONI and the SAT anomalies of the White Sea.

Another possible reason may be the state of the North Atlantic, as a link between the Pacific Ocean and the White Sea region. Consider the periods from 7 to 10 years characteristic of NAO [34-35], which has a direct impact on the White Sea region. The links of the NAO with the SAT of the White Sea are shown in figure 4. Here, preliminary removal of linear trends, centering and normalization of the time-series by their standard deviations were also performed.

In figure 4b, there are positive links between the NAO and the SAT anomalies of the White Sea at periods of oscillations from 7 to 10 years. Moreover, from the late 1960s to the mid-1990s, these links are most clearly traced – at this time the influence of the North Atlantic on the White Sea region was strengthened. In the second half of the 1990s, there was a breakdown of these positive links, and even their replacement with negative ones. After the beginning of the 2000s, positive links are restored in time-scales of 7-10 years. It is possible that this shift in the second half of the 1990s was due to the strong El Niño event of 1997/98 and the ensuing global climate shift.

An interesting result is that the positive links between the NAO index and the SAT anomalies of the White Sea are observed both for time-scales of 7–10 years and for time-scales of 2–3 years (figure 4a). Since the SO, which is characterized by fluctuations in periods from 2 to 3 years [30], and NAO are elements of the GAO [13], then the positive links between the NAO and the SAT of the White Sea
for time-scales of 2-3 years can be a signal of the SO transmitted through the GAO. This is confirmed by the fact that in the 1960s, when the positive links of NAO and SAT of the White Sea were strengthened on the 2-3 years time-scales (figure 4a), strong negative links of ONI and SAT of the White Sea were observed on these same time-scales (figure 3a). Thus, in these years the SO and the NAO had an antiphase effect on the SAT of the White Sea.

**Figure 4.** The time-series of the North Atlantic Oscillation Index (red lines) and average surface air temperature anomalies of the White Sea (blue lines) after applying Butterworth band-pass filter from 2 to 3 years (a) and from 7 to 10 years (b), and sliding cross-correlations (with the window of 8 years) between these time series (black lines).

During the global climate shift 1976/77 the positive links between the NAO and the White Sea’s SAT on the 2-3 years time-scales disappeared, and negative links of ONI and SAT of the White Sea on these same time-scales became positive. After that, from the mid-1980s to the end of 1990s and from the second half of 2000s the positive links between the NAO and the White Sea’s SAT on the 2-3 years time-scales were observed.

**4. Conclusions**

Over 1950-2019 period of observations of the surface air temperature (SAT) of the White Sea, its pronounced positive trend stands out, which indicates the manifestation of global warming processes in this region.

Against the background of the positive trend of the SAT of the White Sea, its fluctuations are observed with different periods associated, most likely, with the influence of planetary and regional modes of climatic variability.

It was found that in the interannual variability of the White Sea SAT at periods from 2 to 7 years and from 7 to 10 years are distinguished, associated, respectively, with El Niño - Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO).
During the periods of 1960s and from the second half of the 1980s to the mid-2010s during the El Niño events in the White Sea negative SAT anomalies were usually observed, and during the La Niña events – positive anomalies.

In the period from the late 1960s to the mid-1990s, NAO had a strong positive effect on the SAT anomalies of the White Sea, in the second half of the 1990s this influence changed its sign, but from the beginning of the 2000s it became positive again.

The detected changes in the relationships between ENSO, NAO, and the SAT of the White Sea suggest that the Global Atmospheric Oscillation (GAO) is the synchronizing mechanism of these processes.

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