# Spatio-temporal regularities of the White Sea ice regime formation

Vyacheslav Baklagin

Northern Water Problems Institute, Karelian Research Centre, Russian Academy of Sciences, Petrozavodsk, Russia

***ABSTRACT***

The paper presents the spatial and temporal regularities of the course of ice processes in the White Sea, derived from satellite data observations, for the period 2004-2020. The dependences, defining indicative dates of the White Sea ice regime of air temperature regime over its water area are given, which can be used for diagnostic and prognostic purposes. It was found that the rate of breaking (2.11%/day) of the Sea ice cover is 1.24 times higher than the rate of formation (1.70%/day). It is noted that the connection with the Barents Sea has a significant impact on the course of the ice regime of the White Sea, in particular on the beginning freeze-up phase and the beginning break-up phase. Comparative analysis of seasonal variations in ice coverage in the White Sea indicates that the course of the ice regime in recent years was slightly different from that recorded in the second half of the XX century. The average duration of the ice period decreased by 10 days, and the average values of the ice coverage decreased by 3-7% throughout the entire period of ice phenomena, which is in line with the global warming trend. Also, the effects of an abnormally warm winter on the formation of the White Sea ice regime in the 2019-2020 period are presented. The differences in the indicative dates of the ice regime, such as the dates of the beginning and the end of the period of ice phenomena in 2019-2020, compared to the average for the period 2004-2019, are +1 and -8 days, respectively.



## INTRODUCTION

The White Sea is an inland sea located in the North of the European part of Russia; it belongs to the Arctic Ocean. Its area is 90.000 km$^2$, and its maximum depth is 343 m. The White Sea communicates with the vast Barents Sea, which has an impact on the formation of the ice cover on the inland sea, due to the warming of climatic conditions (Gluhovskiy, 1991). It should be noted that, every year, the surface of the White Sea in winter is almost completely covered by ice, and in spring the Sea is completely free of ice.

The formation of an ice cover in the water area of many water bodies (as well as the White Sea) of the Northern hemisphere is an integral part of the hydrological cycle. The data about the formation of the ice regime is necessary for planning and organizing the navigation period, as well as the possibility of transporting people and/or cargoes over the stable ice (Assel *et al*., 2004; Karetnikov and Naumenko, 2008; Salo and Nazarova, 2011; Andrews *et al*., 2018). This is particularly important for seas affected by commercial and economic activities.

It is difficult to overestimate the importance of shipping in the White Sea. A lot of shipping routes pass through the White Sea, which connect the cities of Russia located in its Northern part with the central regions of Russia. The largest port is Arkhangelsk, from where flights go to other ports on the coast of the White Sea – Mezen, Severodvinsk, Belomorsk, and others. For example, delivering goods across the White Sea to Kandalaksha is vital for the city-forming enterprise. Also, one of the most important ports is Belomorsk, which is connected with the central regions of Russia thanks to the White Sea-Baltic Canal. For the efficient organization of the transport logistics in the White Sea, it is necessary to have not only information about the ice situation at sea, but also to know the patterns of annually recurring ice phenomena, the average dates of the formation and breaking of ice features (Andrews *et al*., 2018).

It should be noted that some studies of the White Sea ice regime were carried out earlier. The first systematic observations of the state of the ice cover in the White Sea coasts were initiated by the lighthouse service of the Russian Maritime Department at lighthouses (1894-1898). In the period 1918-1985, systematic ice observations were carried out at 30 coastal stations. Also, since 1909, observations of the ice cover were carried out from icebreakers and hunting vessels. And since 1927, air sorties have been undertaken to guide ships through the ice. The most complete information on the course of the ice regime in the White Sea is collected in the works provided by the State Oceanographic Institute of the USSR (Gluhovskiy, 1991), where various statistical characteristics of ice processes occurring in the White Sea, based on aerial reconnaissance materials, ship observations made at coastal stations and posts for the period up to 1985 are described. All these materials are of great scientific and practical interest.

However, many researchers (Magnuson *et al.*, 1990; Latifovic and Pouliot, 2007; Brown and Duguay, 2010; Efremova *et al.*, 2013; Filazzola *et al.*, 2020; Hwang *et al.*, 2020) noted that in recent decades around the world there have been significant changes in climatic conditions associated with global warming, which led to a change in the course of the ice regime on lakes and seas. For example, in the work of Thoman *et al*. (2020), it is noted that in the cold season of 2017-2018, in the Northern Hemisphere, the extent of sea ice in the Bering Sea was less than any other winter in the past.

In this context, we can assume that the previously obtained patterns of ice phenomena occurring in the White Sea should be updated, taking into account the most recent climatic conditions. In addition, it should be noted that modern methods of monitoring the state of the ice cover of lakes and seas include the use of satellite observations (Karetnikov and Naumenko, 2008; Baklagin, 2018; Filazzola *et al.*, 2020), which were not fully available to researchers in the XX century. Satellite observations data on the state of the ice cover of water bodies (lakes and seas) make it possible to significantly expand and update knowledge and information about the formation of the ice regime of water bodies, since satellite observations have an undeniable advantage, due to the high spatial and temporal resolution of the obtained data compared with the observation methods which were used by researchers in the XX century. For example, owing to unfavourable weather conditions, the frequency of air reconnaissance missions to the White Sea was only 10-15 per year, and the information received from the coastal observation posts described only a small part of the sea area, that is, that in the visibility zone. Conversely, satellite observations are conducted daily and cover the entire area of the White Sea. This facilitates accurate assessment of the dynamics of ice formations change and, as a result, it is a determining factor for establishing patterns of ice processes.

The purpose of this study is to establish the spatiotemporal regularities of the course of ice processes in the White Sea, to clarify and update the statistical characteristics of the ice regime on the basis of modern satellite observation data (for the period 2004-2020), as well as to identify the dependences of the course of ice processes on temperature control over the White Sea water area.

## MATERIALS AND METHODS

### Identification of the ice regime in the White Sea

The analysis and assessment of the course of ice regime in the White Sea in this study was carried out on the basis of satellite data sets for the period 2004-2020, provided by the USA National Aeronautics and Space Administration (NASA) (MODIS sensor, with a spatial resolution of up to 250 m), the National Snow and Ice Data Center (NSIDC) (4-6 km), the Center for Satellite Applications and Research NOAA NESDIS (4-6 km). To assess the state of the Sea ice cover, the ice coverage values for each day of the observed period were calculated as area ratio of ice formations to the total area of the water area. This characteristic is very often used during observations of the state of the ice cover of lakes (Karetnikov and Naumenko, 2008; Baklagin, 2018, 2019). The methodology for the formation of a daily series of ice coverage values based on the listed sets of satellite data was the same as that used in Lake Onego (Baklagin, 2018).

For a comprehensive assessment of changes in ice coverage in each period of ice phenomena in this study, the sums of daily values of ice coverage, which correspond to the RICI value described by Karetnikov and Naumenko (2008), were calculated for each period of ice phenomena (Σ*ice*), following Baklagin (2018).

### Method of formation schemes of the development of ice processes in the White Sea

The formation schemes of the development of ice processes in the White Sea was carried out by averaging the indicative dates of the period 2004-2020 for each section of the sea water area (corresponding to the spatial resolution of satellite data). In particular, the average indicative dates for each section of the sea area with geographic coordinates (*lat, lon*) were determined by the formulas:

$$(Dice_{lat,\ lon})_{ave} = \frac{\sum_{y=sy}^{fy}(Dice_{lat,\ lon})_y}{fy-sy}, \quad (1)$$

$$(Dfree_{lat,\ lon})_{ave} = \frac{\sum_{y=sy}^{fy}(Dfree_{lat,\ lon})_y}{fy-sy}, \quad (2)$$

where $(Dice_{lat,\ lon})_{ave}$ is the average duration of the period from the 1st of December to the beginning of complete ice formation in the section of sea area with geographic coordinates (*lat, lon*), days; $(Dice_{lat,\ lon})_y$ is the duration of the period from the 1st of December to the beginning of complete ice formation in the section of sea area with geographic coordinates (*lat, lon*) in hydrological year *y*, days; $(Dfree_{lat,\ lon})_{ave}$ is the average duration of the period from the 1st of April to complete ice clearance in the section of sea area with geographic coordinates (*lat, lon*), days; $(Dfree_{lat,\ lon})_y$ is the duration of the period from the 1st of April to complete ice clearance in the section of sea area with geographic coordinates (*lat, lon*) in hydrological year *y*, days; *sy* is the starting year of the observed period; *fy* is the last year of the observed period.

### Estimation of meteorological conditions above the White Sea

In calculating the indicative ice regime, the establishment of full freeze-up in the White Sea was assumed to be achieved when the ice coverage was 90% and above. To assess the temperature regime over the White Sea, we used daily data on the average daily air temperature for the period 2004–2020, which is provided by the National Climatic Data Center NOAA USA (NCDC NOAA) (ftp://ftp.ncdc.noaa.gov/pub/data/noaa/).

For this purpose, meteorological centers were selected that are equidistant from each other and located on the coast of the White Sea (with the WMO index) (Figure 1): the city of Kandalaksha (222170), the village of Shojna (22710), the village of Umba (223240), the settlement of Pjalica (223490), Zizgin Island (224380), the city of

Mezen (224710), the airport of Talagi Arkhangelsk (225500), the city of Onega (226410). The estimation of the temperature regime over the water area of the White Sea was carried out by averaging the data on the air temperature obtained at the centres listed above.

## Statistical analysis

The work establishes statistical relationships between the characteristics of the ice regime and temperature regime using correlation and regression analyses. The method of selection of significant input features of regression models includes the use of the "Forward selection" procedure, based on an F-test (Larose, 2006).

It is assumed that the temperature regime of the air for the previous 6-month period has a significant impact on the onset of the considered indicative date of the ice regime. Therefore, the input candidate features are the values of the average monthly air temperatures for each month (6 values). The algorithm for checking the significance of these input features is as follows:

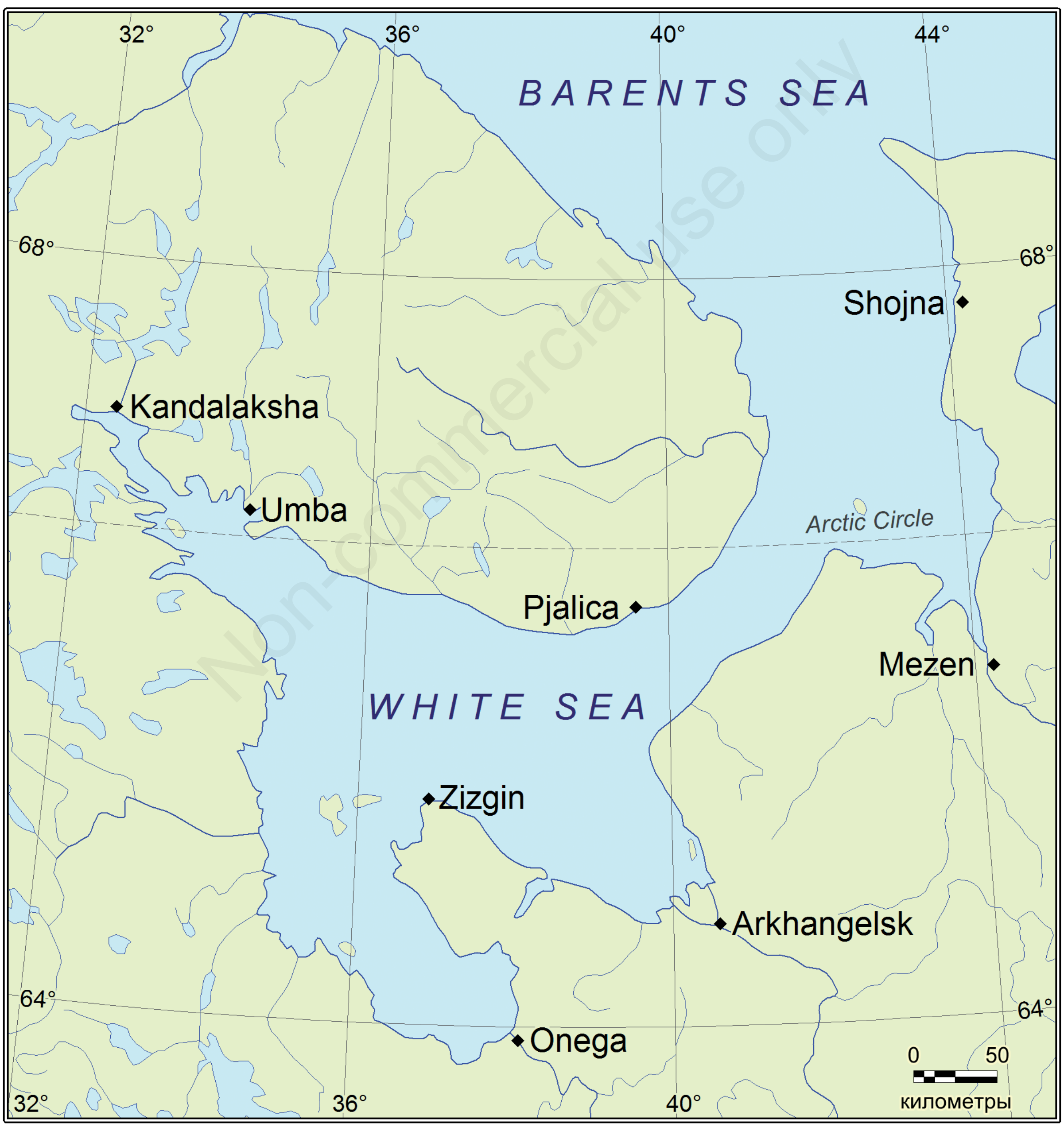



**Figure 1.** The location of meteorological observation points on the coast of the White Sea.

1. As the first feature of the model, a $\overline{T}_i$ is selected that best correlates with the considered indicative date of the ice regime.
2. Then, all other input features $\overline{T}_i$ are sequentially checked for significance according to the following algorithm:
   a. A feature $\overline{T}_i$ from the list of candidate features is included in the model as a new feature and the value of the statistic is calculated:

$$\gamma = \frac{SSR_{extra}}{MSE_{full}}, \quad (3)$$

where $SSR_{extra}$ is an increase of the sum of squares regression taking into account the introduction of the feature $X_{extra}$:

$$SSR_{extra} = SSR_{full} - SSR_{initial}, \quad (4)$$

where $SSR_{full}$ - the sum of squares regression, taking into account the introduced feature $X_{extra}$; $SSR_{initial}$ - the sum of the squares regression without taking into account the feature $X_{extra}$; $MSE_{full}$ - the sum of squares error, taking into account the feature $X_{extra}$, per one degree of freedom:

$$MSE_{full} = \frac{SSE_{full}}{n-k-2}, \quad (5)$$

where $n$ is the sample size, $k$ is the number of model variables.

   b. The value of $\gamma$ is compared with the value of F-test ($F_\alpha$), chosen for the significance level $\alpha = 0{,}05$ and degrees of freedom: $d1 = 1$, $d2 = n - k - 2$. If $\gamma > F_\alpha$, then a conclusion is made about the significance of $X_{extra}$ and this feature is included in the model, otherwise the feature is excluded.

All of the above calculations were executed in Excel 2010.

## RESULTS

The analysis of satellite observation data showed that the White Sea is almost completely covered by ice every year (on 93-99%). However, unlike for example Lake Onego, throughout the entire period of ice phenomena, the ice cover had breaks and cracks, which is explained by the presence of drifting ice arising from strong winds and tidal currents. Statistical analysis of the indicative dates and durations of the phases of the White Sea ice regime (Figure 2, Table 1) for the period 2004-2020 showed that the rate of breaking (2.11%/day) of the Sea ice cover is 1.24 times higher than the rate of formation (1.70%/day). A similar pattern was shown for the two largest lakes in Europe located in this geographical area, namely Ladoga (1.5), and Onego (1.65) (Karetnikov and

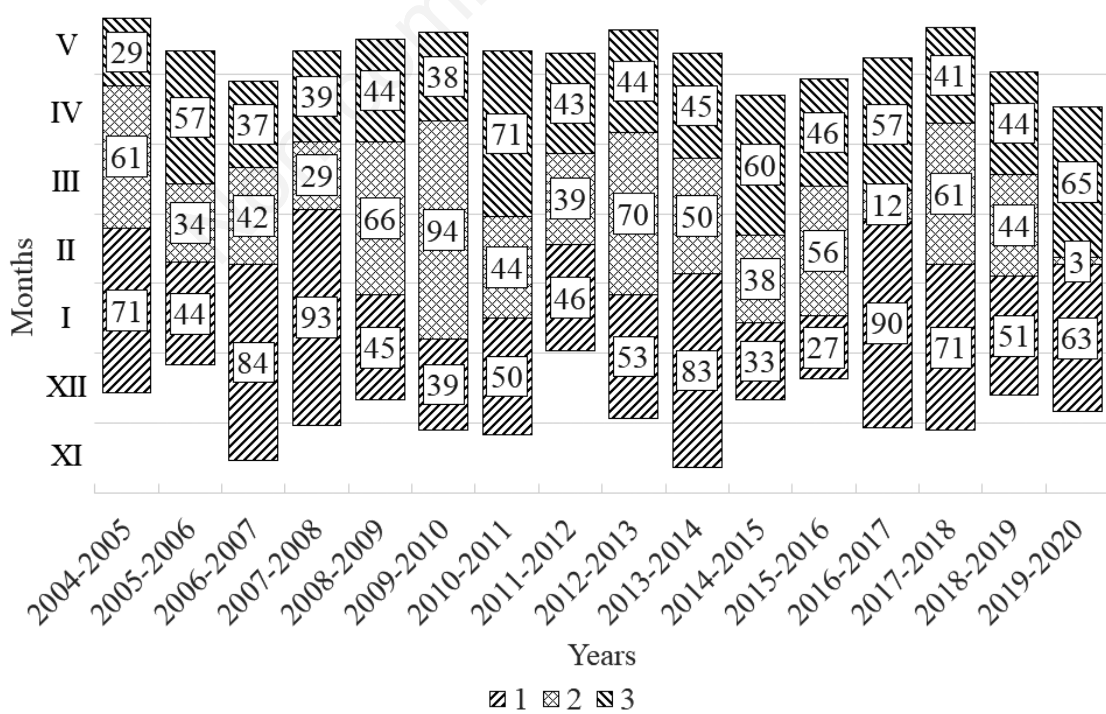


**Figure 2.** Dates of the beginning and the ending of phases and the duration (the number of days) of ice freezing (1), complete freeze-up (2), and break-up (3) on the White Sea for the period 2004-2020.

Naumenko, 2008; Baklagin, 2018). The distinctive course of the ice regime of the White Sea in 2019-2020 is due to abnormal warm winter conditions recorded all over the world (GISS Surface Temperature Analysis (GISTEMP), version 4 NASA Goddard Institute for Space Studies (https://data.giss.nasa.gov/gistemp/maps/index.html)). The accumulated sum of negative air temperatures over the water area of the White Sea for the cold season was only -692°C, while the average value for the period 2004-2019 is -1067°C. At the same time, the sum of daily values of ice coverage ($\Sigma_{ice}$) for the period of ice phenomena in 2019-2020 was 4352%, with an average value of 9132% for the period 2004-2019. It should be noted that the minimum value of $\Sigma_{ice}$ for the period 2004-2019 is 7141% (2007-2008), which indicates a significant update of the record minimum during the period of anomalous winter. It should also be noted that the differences in the indicative dates of the ice regime, such as the dates of the beginning and the end of the period of ice phenomena in 2019-2020, from the average for the period 2004-2019 are only +1 and -8 days, respectively.

Regression analysis made it possible to establish dependencies that determine the indicative dates of the ice regime of the White Sea on the average monthly air temperatures over the seawater area, preceding these dates (Table 2):

$$D_{freezing} = 2.6334 \cdot \bar{T}_{XI} + 3.3234 \cdot \bar{T}_{X} - 4.2861 \cdot \bar{T}_{IX} - 5.3886, \quad (6)$$

$$D_{ice} = 3.3962 \cdot \bar{T}_{I} + 1.1015 \cdot \bar{T}_{XII} - 0.7002 \cdot \bar{T}_{XI} + 4.1129 \cdot \bar{T}_{X} + 90.5148, \quad (7)$$

$$D_{breaking} - 3.5685 \cdot \bar{T}_{III} - 0.4592 \cdot \bar{T}_{II} - 5.5847, \quad (8)$$

$$D_{free} = -1.7132 \cdot \bar{T}_{IV} - 2.3886 \cdot \bar{T}_{III} + 22.9301, \quad (9)$$

where $D_{freezing}$ is the duration of the period from the 1st of November to the beginning of ice phenomena formation, days; $D_{ice}$ is the duration of the period from the 1st of December to the beginning of the complete freeze-up phase, days; $D_{breaking}$ is the duration of the period from the 1st of March to the beginning of the ice cover break-up, days; $D_{free}$ is the duration of the period from the 1st of April to complete ice clearance, days; $\bar{T}_i$ is the average air temperature over the Sea water area in the i-th month, °C.

The analysis of the values of the accumulated sums of air temperature during the phases of ice phenomena in the White Sea is given in Table 3. A special fact is that the ice cover break-up of the White Sea begins before the beginning of the warm season (period of positive air temperatures), which is not typical, for example, for Onego and Ladoga lakes. The statistical characteristics of the warm and cold seasons in the White Sea are shown in Table 4.

The accumulated sums of negative air temperatures at the complete freeze-up phase $\sum T_{ice}$ showed a strong negative correlation (r=-0.73; p<0.05) with the accumulated



**Table 1.** Statistical characteristics of phases of the White Sea ice regime for the period 2004–2020.

| Characteristic | Average date of the beginning and the end of the period | Mean value of the duration, days | Standard deviation, days | Coefficient of variation, % |
|---|---|---|---|---|
| Freeze-up phase | December 6 – February 2 | 59 | 21 | 35 |
| Complete freeze-up | February 3 – March 21 | 46 | 22 | 48 |
| Break-up phase | March 22 – May 8 | 48 | 11 | 24 |
| Period of ice phenomena | December 6 – May 8 | 153 | 18 | 12 |

**Table 2.** Statistical details of regressions.

| Equations | The coefficient of determination $R^2$ | Explained sum of squares (ESS) | Residual sum of squares (RSS) | Mean squared error (MSE) | p-value | Observations |
|---|---|---|---|---|---|---|
| Eq. 3 | 0,42 | 1337,41 | 1817,53 | 11,82 | 0,04954 | 17 |
| Eq. 4 | 0,76 | 1209,12 | 595,94 | 9,11 | 0,00114 | 17 |
| Eq. 5 | 0,46 | 2642,65 | 3123,80 | 14,43 | 0,01008 | 17 |
| Eq. 6 | 0,67 | 1209,12 | 595,94 | 6,52 | 0,00043 | 16 |
| Eq. 7 | 0,54 | 114949,05 | 99901,31 | 81,61 | 0,00085 | 17 |
| Eq. 8 | 0,61 | 21936,69 | 21936,69 | 30,53 | 0,00021 | 17 |

sums of positive air temperatures for the warm season preceding the period of ice phenomena $\sum T_+$ (on the Chaddock scale). Furthermore, a strong negative correlation was observed (r=-0.78; p<0.05) between the accumulated sums of positive air temperatures at the complete ice clearance on the Sea $\sum T_{free}$ and the accumulated sums of temperatures for the cold season (period of negative air temperatures). Similar statistical relationships between the accumulated sums of air temperatures at the beginning of the formation of ice cover $\sum T_{freezing}$ and at the beginning of the break-up phase $\sum T_{breaking}$ were not obtained.

Based on previous results, regression analysis made it possible to reveal the equations that determine the accumulated sums of air temperatures necessary for the onset of indicative dates of the ice regime of the White Sea (Table 2):

$$\sum T_{ice} = -0.53 \sum T_+ + 351.74, \quad (10)$$

$$\sum T_{free} = -0.16 \sum T_- - 106.19, \quad (11)$$

The results of assessing the degree of influence of the accumulated sums of negative temperatures during the cold season $\sum T\_$ on various indicators of the ice regime of the White Sea based on the correlation analysis are as follows (Table 5): weak (on the Chaddock scale) correlation is observed between the accumulated sums of negative temperatures during the cold season $\sum T\_$ and the duration period of ice phenomena L in the White Sea; the correlation is somewhat stronger between the values of $\sum T\_$ and the duration of freeze-up S in the White Sea; the strongest correlation was observed between the values of $\sum T\_$ and the sums of daily values of the ice coverage for the period of ice phenomena $\sum_{ice}$. Similar results were obtained earlier in the study of the ice regime of Lake Onego (Baklagin, 2019). These results confirm that the $\sum_{the\ ice}$ value is the most sensitive to changes induced by the temperature regime.

Spatiotemporal statistical analysis of satellite data for the period 2004-2020 (Figs 3, 4a) showed that the formation of the ice cover in the White Sea proceeds from the tops of the bays to the centre of the White Sea. The formation of ice features begins in early December in the



**Table 3.** Values of the accumulated sums of air temperatures over the water area of the White Sea at the indicative dates of the ice regime.

| Characteristic | Accumulated sums of air temperatures over the waters of White Sea: | | | |
|---|---|---|---|---|
| | At the beginning of the formation of ice cover $\sum T_{freezing}$, °C | At the complete freeze-up phase $\sum T_{ice}$, °C | At the beginning of break-up phase $\sum T_{breaking}$, °C | At the moment of complete ice clearance on the sea $\sum T_{free}$, °C |
| Mean value | -112 | -583 | -884 | 61 |
| Standard deviation | 62 | 119 | 323 | 49 |
| Coefficient of variation | -0,55 | -0,20 | -0,36 | 0,81 |

**Table 4.** Statistical characteristics of warm and cold season on the White Sea for the period 2004-2020.

| Characteristic | Warm season | Cold season |
|---|---|---|
| Average date of the beginning and the end of the period | April 14 - November 5 | November 6 - April 13 |
| Accumulated sums of air temperatures,°C: | | |
| Min value | 1460 | -692 |
| Average value | 1747 | -1055 |
| Max value | 2006 | -1555 |

**Table 5.** The results of the correlation analysis between the accumulated sums of negative temperatures in the cold season and various indicators of the ice regime of the White Sea.

| Variables | Observations (n) | The correlation coefficient (r) | Student's test (T) | p value |
|---|---|---|---|---|
| The duration period of ice phenomena | 16 | -0,37 | -1,51 | 0,07537 |
| The duration of complete freeze-up | 17 | -0,58 | -2,77 | 0,00653 |
| The sums of daily values of the ice coverage for the period of ice phenomena | 16 | -0,84 | -5,81 | 0,00001 |

form of fast ice in the coastal zone of the Mezen and Onego Bays (Figure 3a, T1, 5-10%). By January, the area of ice features increases, and the waters of the Mezen, Onego and Dvina Bays are entirely covered with ice (Figure 3a, T2, 35-45%). By February, the 92-98% of the White Sea is covered by ice (Figure 3a, T3). From early to mid-March, the ice sheet breaks down in the White Sea Funnel (Figure 3a, T4, 82-84%). In mid-April, the ice sheet breaks in the waters of the Basin, the White Sea Throat, and Onego, Dvina and Kandalaksha Bays (Figure 3a, T5, 40-46%). Finally, in mid-May, the water area of the Mezen Bay is freed from ice, thereby ending the period of ice cover in the White Sea (Figure 3a, T6).

In general, Mezen and Onego Bays are under the ice for the longest time (90-100 days a year), whereas in the White Sea Basin and the White Sea Throat and the Dvina Bay, the ice stays for a shorter time (80 days a year). The White Sea Funnel is covered with ice only 30-40 days a year.

Figure 3b shows a diagram of the seasonal variation of the White Sea ice coverage, obtained by roughly digitizing the results of the analysis of ice aerial reconnaissance for the period 1951-1985 (Gluhovskiy, 1991). Unfortunately, we do not have the initial data that were used to construct this diagram (Figure 4). Therefore, it is possible to carry out only a visual assessment of the comparability of the ice coverage dynamics for the period of

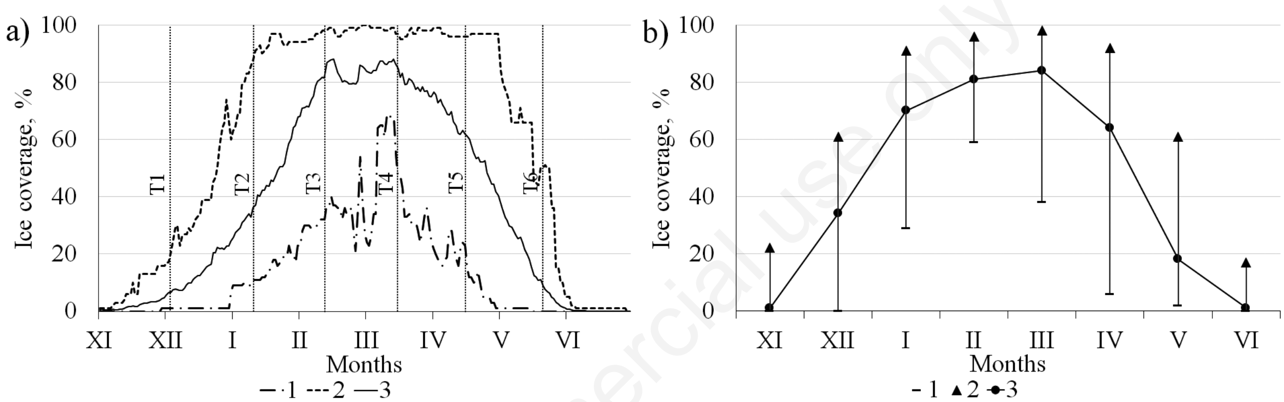


**Figure 3.** Seasonal variation of the White Sea ice coverage (1 – minimum, 2 – maximum, 3 – average values): a) according to satellite observations for the period 2004-2020; b) according to air reconnaissance data 1951-1985 (Gluhovskiy, 1991).



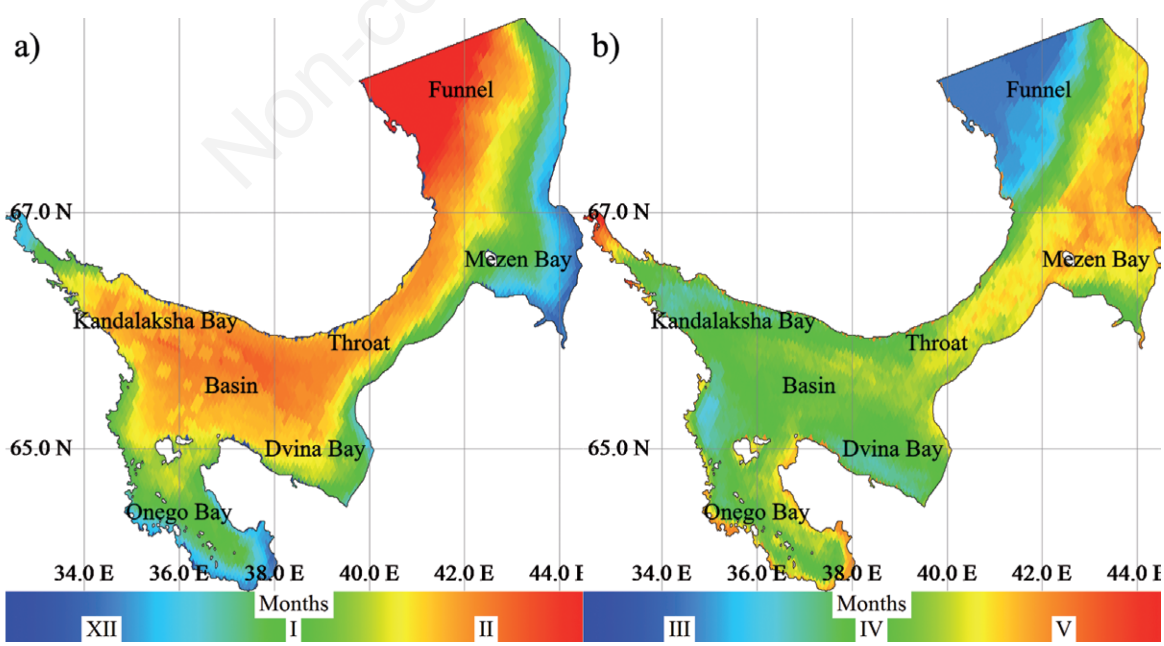


**Figure 4.** Schemes of the development of ice processes in the White Sea, averaged over the period 2004-2020, characterizing phases: a) freeze-up; b) break-up.

ice phenomena in the White Sea. It should be noted that the authors of the work (Gluhovskiy, 1991) were somewhat limited in the time resolution of the data when plotting the seasonal variation diagram of the White Sea ice coverage due to the irregularity of aerial reconnaissance missions; therefore, monthly intervals were used in plotting the diagram. It is noted that the seasonal course of ice cover in the White Sea in recent years is slightly different from what could be observed in the second half of the XX century (Figure 3). This is due to slight discrepancies between the indicative dates of the ice regime, in particular, later freeze-up (3 days) and earlier breakup (7 days). In addition, the average value of ice coverage for the entire period of ice phenomena has been reduced by 3-7%.

The seasonal variations in ice coverage (Figure 3a) showed that the minimum values in the period 2004-2020 were documented during the abnormal warm winter in 2019-2020.

## DISCUSSION

The results obtained in this study indicate that the course of the ice regime in the White Sea is similar to that of the largest lakes located in this geographic region (Onego and Ladoga). The duration of ice phenomena period in the White Sea varied from 128 to 178 days, with the average value of 153 days (from December to May), complete freeze-up period - from 3 to 94 days, with the average value of 46 days. While the average duration of the period of ice phenomena is 171, and that of complete freeze-up period is 90 days in Lake Onego (Baklagin, 2019), they are respectively 172 and 34 days in Lake Ladoga (Karetnikov and Naumenko, 2008).

The practice of equations (6)-(9) can be limited. The indicative dates of the ice regime in the White Sea may occur earlier than the possibility of calculating the input parameters of the models. However, they can be served for diagnostic purposes. In this case, equations (10)-(11) allow to make a short-term forecast of the indicative dates of the ice regime of the White Sea, based on the expected data on the air temperature.

Comparative analysis of seasonal variations in the ice cover of the White Sea for the period 2004-2020 and 1951-1985 (Figure 3), based on a visual assessment of the graphic material of the work by Glukhovsky (1991), recognized a decrease in the duration of the period of ice phenomena in the White Sea by about 10 days. The shortening of the average duration of the ice period is about 0.22 days per year for the White Sea. In addition, the average values of the seasonal course of ice coverage are reduced by 3-7% within each month of the period of ice phenomena. This is consistent with the opinion of many researchers about a decrease in the duration of the period of ice phenomena on water bodies over the past decades, associated with the effects of global warming (Assel *et al*., 2004; Karetnikov and Naumenko, 2008; Efremova *et al*., 2013; Comiso *et al*., 2017; Andrews *et al*., 2018; Ptak *et al*., 2019). For example, in the offshore waters of Hudson Bay, Andrews *et al*. (2018) documented an increase of 0.97 days per year in the open water season between 1980 and 2014. Stammerjohn *et al*. (2012) identified a shortening of the sea ice season by about 2.8 days per year in the Kara and Barents Sea regions and in the East Siberian Sea and Chukchi Sea. A similar trend was noted by Jensen *et al*. (2007) in 65 waterbodies across the Great Lakes region during a period of rapid climate warming (1975-2004); in this group of lakes, the average duration of the ice period decreased by 0.53 days per year. Furthermore, compared to the second half of the XX century, Baklagin (2019) identified a monthly shift in the indicative dates of the ice regime for Lake Onego between 2000 and 2018.

Correlation analysis showed that there is a strong negative correlation between the values of $\sum_{ice}$ and the accumulated sums of negative temperatures during the cold season over the water area of the White Sea $\sum T\_$. A similar result was recorded, for example, in lake Onego (r=-0.89) (Baklagin, 2019). This fact indicates that the temperature regime of the air above the water area in the cold season has a decisive influence on the dynamics of areas and volumes of ice formations in the White Sea.

However, it should be noted that the temperature regime of the air over the White Sea area does not always play the main role in the formation of the ice regime, unlike, for example, the Baltic Sea (Sooäär and Jaagus, 2007) and Caspian Sea (Ivkina *et al*., 2017), the Onego, Ladoga lakes (Karetnikov and Naumenko, 2008; Baklagin, 2019), and also Lake Baikal (Kouraev *et al*., 2007). This is evidenced by the results of correlation and regression analysis when studying the regularities of the dates of the onset of the periods of ice formation $D_{freezing}$ and the breaking of the ice cover $D_{breaking}$, while the dates of the end of these periods ($D_{ice}$, $D_{free}$) correlate well with the temperature regime of the air over the sea area. This is also evidenced by the analysis of the accumulated sums of air temperatures (Table 3). In particular, at the beginning of the ice cover breaking $\sum T_{breaking}$ , the break-up phase on the White Sea occurs before the onset of the warm season (Table 4), which indicates that the breaking of the ice cover is caused not only by the local meteorological conditions. We assume that flows of relatively warm waters of the Barents Sea have a significant impact on the beginning of the ice formation and the beginning of the ice breaking. This is also confirmed by the fact that the ice cover breaking (Figure 4) starts from the White Sea Throat, at the junction with the Barents Sea. This is consistent with observations carried out in many other inland water bodies (Karetnikov and Naumenko, 2008; Baklagin, 2018), where freezing and breaking did not occur evenly from the coast to the center of the sea (and *vice versa*). Consistently, the northern coast of the White Sea is the last to be covered with ice, even after the establishment of ice in the central part of the sea. Thus, the forecast of indicative dates of the ice regime of the White Sea can only be carried out by taking into account the influence of the Barents Sea.

## CONCLUSIONS

The regularities of the ice regime and the schemes of the development of ice processes in the White Sea documented in this work significantly expand and supplement the data and knowledge in this geographical area, providing a basis for planning and organizing the navigation period. Significant results include:

The formation of the ice regime of the White Sea is significantly influenced not only by the air temperature regime, but also by the direct communication with the Barents Sea, which affects the dates of the beginning of the formation of the ice cover and the beginning of its breaking.

- Results of research indicate that the course of the ice regime in the White Sea is also subject to global warming trends. These trends are less pronounced in comparison with Lake Onego.
- The abnormal winter 2019-2020 significantly influenced the course of the ice regime in the White Sea. The value of the sum of daily values of ice coverage for the period of ice phenomena amounted to only 61% of the previous low record, and 49% of the mean value for the period 2004-2019. Nevertheless, the differences between the dates of the beginning and the end of the ice phenomena in 2019-2020 and the corresponding average dates in the period 2004-2019 show insignificant values, namely +1 and -8 days respectively.

Corresponding author: Vyacheslav Baklagin.
E-mail: slava.baklagin@mail.ru.

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