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MARINE PHYSICS

The Atlantic Gateway to the Arctic in the Mirror of the Kola Transect

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Abstract—In situ temperature measurements along the Kola Transect for 1993–2019 are compared to climate indices for the North Atlantic, developed by the authors in earlier works. Five climate indices are considered: PC1, PC2, NAT, NAT1, and NAT2. It is shown that the temperature time series along the Kola Transect correlate well with climate indices PC2, as well as NAT1 and NAT2, which are responsible for warming processes in the cold North European Basin and cooling processes in the warm region south of Iceland. The correlation coefficients reach 0.80. At the same time, there is a low correlation between the temperature along the Kola Transect and the PC1 and NAT indices, which represent the volume flux of water entering the North European Basin from the Atlantic. This implies that the thermal state of the Atlantic waters entering the Barents Sea and the water temperature along the Kola Meridian are determined by the thermal state of the waters rather than the volume flux of Atlantic waters. A high consistency is found between the in situ measurements along the Kola Transect and the corresponding data from the GLORYS12V1 global ocean reanalysis. It is shown that the northern boundary of the Coastal Branch of the Murmansk Current can reach 71.5°–72° N.

Keywords: Kola Transect, Barents Sea, North European Basin, climate indices, GLORYS12V1

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INTRODUCTION

The Kola Meridian (Transect) is a century-old standard transect in the Barents Sea, running from the coast of Kola Bay to 77° N along the 33°30′ E meridian. At present, this transect is one of the world's longest series of oceanographic data: a total observation period on the Kola Meridian is 104 years with respect to short breaks [5]. Kola Meridian consists of 16 stations and extends northward to 77° N, but the most regular observations are made on ten southern stations (up to 74° N), situated in the area where warm Atlantic waters are distributed. The major mass of Atlantic waters is primarily bounded by the parallel of 74° N [7].

The measurement depth on the Kola Meridian varies from 150 to 350 m, 250 m on the average. The most well-studied transect (stations 1–10) is divided into three segments: the transect through stations 1–3 intersects the coastal branch of the Murmansk Current, through stations 3–7, the main branch of the Murmansk Current, and through stations 8–10, the central branch of the North Cape Current. Data from the Kola Meridian are available on the website of the Polar Branch of the Federal State Budgetary Scientific Institution Caspian Fisheries Research Institute (Knipovich Polar Research Institute of Marine Fisheries and Oceanography) http://www.pinro.vniro.ru/ru/razrez-kolskij-meridian/ryady-nablyudenij.

The history of measurements on the Kola Meridian was described in detail in the monograph [5]. We focus on certain moments. The oceanographic operations on this transect were conducted for the first time in May 1900 aboard the expeditionary vessel *Andrey Pervozvanny* under the supervision of N.M. Knipovich [6]. Based on collected data on water temperature and salinity, Knipovich developed a scheme of currents and identified several warm branches on the Kola Meridian, stating that a powerful warm current "brings an enormous amount of heat into the Barents Sea, and at the end of the year we observe intense inflows of this heat at great depths, which significantly mitigates the climate." Temperature and salinity measurements on the Kola Meridian allowed Knipovich to establish a relationship between the distribution and migrations of commercial fish in the Barents Sea with warm currents [6].

In 1907, oceanographic and biological research on the Kola Transect was terminated. It was only in early 1921 that the Scientific Council of the Murmansk Biological Station proposed resuming observations on the transect, realizing their importance for solving problems not only in the oceanography and biology of the Barents Sea, but also in the general climatology of the entire North [3]. Regular oceanographic observations conducted from 1928 to 1941 onboard vessels of

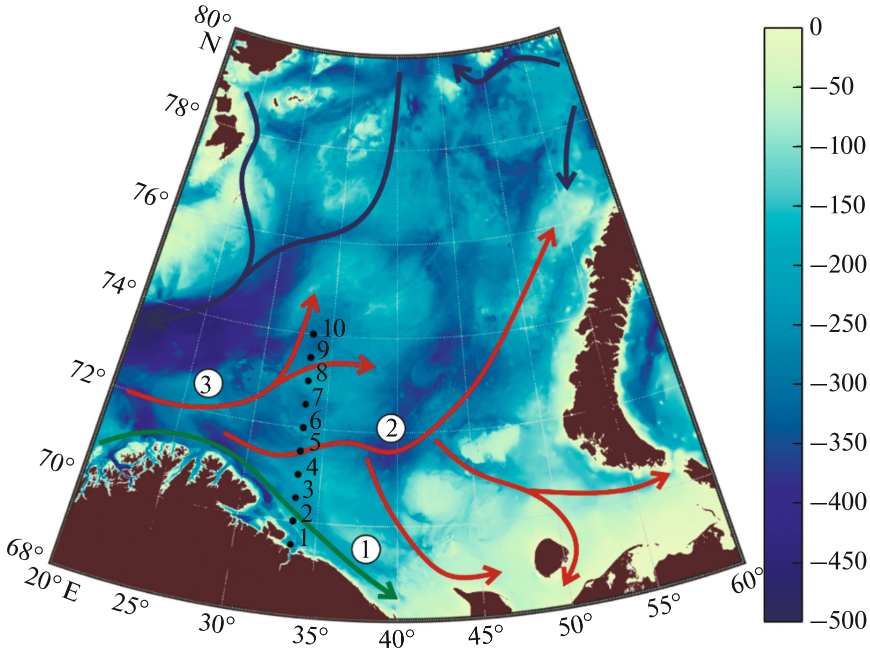

Fig. 1. Study area. Depth (m) is represented by a color scale. Stations along the Kola Meridian are designated by numbers. Arrows depict the main directions of coastal (green), Atlantic (red), and Arctic (blue) water propagation. Circles numbers denote the main currents along Kola Meridian: (1) Murmansk Coastal Current; (2) Murmansk Current; (3) North Cape Current.

the Polar Research Institute of Marine Fisheries and Oceanography, such as the *Nikolay Knipovich*, *Perseus*, and *Explorer*, yielded basic ideas about the seasonal trend and interannual changes in the most important oceanographic parameters of the Kola Transect [1]. In 1960, by order of the Main Department for the Meteorological Service, the Kola Transect was included into the list allotted for monitoring the centennial variability of elements in the oceanographic regime, obtained the status of a "centennial" transect, and monthly observations were recommended [4]. Since the early 1990s, due to the dissolution of the USSR and the subsequent economic downturn, there has been a significant reduction in the number and content of observations. Today, the Kola Transect is the only Russian transect in the Barents Sea for regular oceanographic observations to monitor and study seasonal and interannual changes in the thermohaline state of Barents Sea waters.

It has been found currently that both sensible and latent heat flows into the high-latitude Arctic during winter primarily through the Atlantic part of its southern boundary at 70° N (from 0° to 80° E) in the layer from the surface to 750 hPa [2]. The North Atlantic is one of the most well-studied and well-documented regions of the World Ocean [22]. The region in the North Atlantic where heat is transported into the Arctic is often called by many scientists the "Atlantic gateway to the Arctic" [2, 17]. As soon as climate predictions become a reality, it became necessary to identify systemic characteristics that can best characterize its variability and be considered parameters for forecasting the state of this system.

Principal component analysis (PCA) of water temperature anomalies at a depth of 457 m in the North Atlantic over the period from 1993 to 2019 for the area of 50°–80° N, 50° W– 20° E on a 1° × 1° grid was used in [14] to identify climate indicators characterizing Atlantic heat transfer into the Arctic. The choice of depth for analysis was determined by study [24], which stated that the 400–500 m layer best reflects the attributes of Atlantic waters transported northward. In addition, comparison of parameter values at several depths showed that the chosen depth is characterized by the largest total variance of the first two in the decomposition of the fields into principal components.

Gordeeva et al. [15] calculated two climate variability indices: PC1 (first principal component) and PC2 (second principal component). Since the first two principal components of the decomposition are responsible for 48% of the variability, and all subsequent components are smaller by an order of magnitude, the authors suggested using the first two components as climate system indicators. PC1 is an indicator characterizing advection into the North European Basin. An increase in PC1 values is associated with a decrease in the bulk transport of the northward flow through the Faroe–Shetland and Faroe–Iceland straits and significant warming south of Iceland. PC2 is an indicator characterizing corresponding northward heat fluxes. The increase in PC2 reflects warming processes in the cold North European Basin and cooling in the warm region south of Iceland. The

Table 1. Correlation between water temperature and salinity along Kola Meridian based on in situ and GLORYS12V1 data

	nos. 1–3, 0–50 m	nos. 1–3, 0–200 m	nos. 1–3, 50–200 m	nos. 3–7, 0–50 m	nos. 3–7, 0–200 m	nos. 3–7, 50–200 m	nos. 8–10, 0–50 m	nos. 8–10, 0–200 m	nos. 8–10, 50–200 m
T	0.99	0.96	0.94	0.99	0.98	0.96	0.98	0.97	0.96
S	–	0.80	–	0.80	0.74	0.70	–	0.77	–

decrease in temperature gradients between these regions is accompanied by an increase in PC2 [15].

Principal components are used primarily to identify regions exhibiting major modes of variability. Their construction requires rather extensive and specific calculations, which can be substituted by the characteristic itself, i.e., in this case, temperature anomalies in the regions where the loads are the largest. This approach is used, e.g., to decompose atmospheric pressure fields into principal components, when instead of PC1, the North Atlantic Oscillation (NAO) index is considered to be the pressure difference between the Azores High and the Icelandic Low (Hurrell's NAO Index). In analogy with this approach, three additional climate variability indices were developed in [15], which can be calculated directly from water temperature anomalies:

(1) NAT means water temperature anomalies in the region of 59°–61° N, 28°–30° W (PC1 loading = +0.95). This index can be used instead of PC1.

(2) NAT1 means water temperature anomalies at coordinates of 68°–69° N, 1°–2° E (loading +0.89). The index can be used instead of PC2.

(3) NAT2 means water temperature anomalies at coordinates of 56°–57° N, 30°–31° W (loading –0.85). This index can also be used instead of PC2.

Thus, to study variability in the climate system of the Atlantic gateway to the Arctic, five temperature indices were developed in [15], which we use in this study. The temperature index values are available at: https://esdb.wdcb.ru/doi/2022/2022es000792-data.html.

Conversely, the Kola Meridian project also refers to the estimation of heat transfer from the Atlantic Ocean, but specifically into the Barents Sea. Therefore, temperature series from the Kola Meridian and the five climate indices presented in [15] fulfill the same function. However, data on the Kola Meridian were obtained empirically via regular monthly measurements, whereas the indices in [15] were developed from global ocean reanalysis data.

In our study, along with in situ measurements from the Kola Meridian, we use data from the GLORYS12V1 eddy-resolving global ocean reanalysis (Global Ocean Physics Reanalysis). These data are available on the CMEMS (Copernicus Marine Environment Monitoring Service) portal, https://data.marine.copernicus.eu/product/GLOBAL_MULTIYEAR_PHY_001_030/description. They have a spatial resolution of 1/12° and feature 50 levels for the period when altimetry observations became available (since 1993). The GLORYS12V1 reanalysis is based on the CMEMS real-time global forecasting system. The NEMO model with ECMWF ERA-Interim forcing is used for ocean circulation reanalysis. Observations are assimilated using a low-order Kalman filter. In situ data from satellite altimeters (sea level anomalies), sea surface temperature, sea ice concentration, and vertical temperature and salinity profiles are assimilated together.

For comparison with the water temperature on the Kola Meridian, which is presented as averaged values for the 0–50, 0–200, and 50–200 m layers for groups of stations, similar spatial averaging was performed using GLORYS12V1 data. Additionally, anomalies for all characteristics were obtained by removing the seasonal trend using a 12-month moving average smoothing method.

In this study, we seek answers to the following questions:

(i) What is the correlation between measurements on the Kola Meridian and data from the global ocean reanalysis along a similar (closely located) transect?

(ii) Is there a relationship between data from the Kola Meridian and five climate indices presented in [15]?

(iii) What portion of heat transported across 64.5° N is reflected in transport through the Kola Meridian?

1. RESULTS

1.1. Correlation Analysis of Water Temperature on the Kola Meridian with Climate Indices

At the first stage, we established that the in situ measurements on the Kola Meridian (KS) are in good agreement with the GLORYS12V1 reanalysis data (KS-GLORYS). Information indicating that Kola Meridian data were assimilated into the GLORYS12V1 product is not available in open sources. The high correlation values of temperature on the Kola Meridian and according to the GLORYS12V1 data are within 0.94–0.99, which indicates perfect consistency between the datasets (Table 1). However, the correlation coefficients between the in situ salinity measurements on the Kola Meridian and the corresponding GLORYS12V1 series are significantly lower and vary within 0.70–0.80. The lower values of these coefficients are likely to be determined by several gaps in salinity measurements in the in situ data. Alternatively, there may be another reason: the Kola Meridian data were not considered by the assimilation algorithm, or the algorithm itself is not perfect. In any case, the correlation coefficients presented in Table 1 generally indicate good agreement between the in situ data and model datasets.

Table 2. Cross-correlation matrix between water temperature along Kola Meridian (seasonal trend removed) based on in situ data and climate indices

	PC1	PC2	NAT	NAT1	NAT2
nos. 1–3, 0–50 m	0.34	0.75	0.37	0.70	–0.66
nos. 1–3, 0–200 m	0.30	0.77	0.35	0.71	–0.69
nos. 1–3, 50–200 m	0.27	0.75	0.33	0.70	–0.69
nos. 3–7, 0–50 m	0.32	0.76	0.34	0.69	–0.69
nos. 3–7, 0–200 m	0.24	0.80	0.27	0.72	–0.73
nos. 3–7, 50–200 m	0.22	0.80	0.26	0.71	–0.72
nos. 8–10, 0–50 m	0.22	0.76	0.21	0.63	–0.65
nos. 8–10, 0–200 m	0.24	0.80	0.23	0.69	–0.68
nos. 8–10, 50–200 m	0.22	0.80	0.21	0.69	–0.68

Table 3. Cross-correlation matrix between water temperature along the Kola Meridian (seasonal trend removed) based on GLORYS12V1 data and climate indices

	PC1	PC2	NAT	NAT1	NAT2
nos. 1–3, 0–50 m	0.29	0.76	0.30	0.68	–0.66
nos. 1–3, 0–200 m	0.22	0.77	0.25	0.67	–0.68
nos. 1–3, 50–200 m	0.19	0.76	0.23	0.66	–0.67
nos. 3–7, 0–50 m	0.24	0.78	0.26	0.70	–0.69
nos. 3–7, 0–200 m	0.18	0.81	0.22	0.71	–0.71
nos. 3–7, 50–200 m	0.16	0.80	0.20	0.71	–0.70
nos. 8–10, 0–50 m	0.14	0.76	0.13	0.63	–0.63
nos. 8–10, 0–200 m	0.18	0.80	0.17	0.67	–0.67
nos. 8–10, 50–200 m	0.19	0.81	0.18	0.68	–0.68

Next, we establish the relationship between water temperature anomalies on the Kola Meridian and the PC1, PC2, NAT, NAT1, NAT2 indices (Tables 2 and 3). The correlation of PC1 (and NAT) with the measurements on the Kola Meridian is small, the maximum coefficients of correlation with the data at the surface in the coastal branch of the Murmansk Current amount to 0.37. Since the main component PC1 (and NAT) are responsible for the advection of waters flowing from the Atlantic into the North European Basin, the low correlation between PC1 (NAT) and the temperature on the Kola Meridian suggests that the thermal state of Atlantic waters entering the Barents Sea is not determined by the transport (advection) of Atlantic water but depends on other factors. The weak correlation between PC1 (NAT) and the temperature on the Kola Meridian is also evident in Fig 2a.

Conversely, there is a high correlation of PC2 (NAT1 and NAT2) with water temperature on the entire Kola Transect, which reaches 0.80 for the in situ data and 0.81 for the GLORYS12V1 data in the 0–200 m layer in the main branch of the Murmansk Current (Tables 2, 3, and Fig. 2b). This means that the temperature of the North European Basin is determined by the transport of heat with Atlantic waters. As shown in Fig. 2b, the plots of time variation of PC2 and water temperature of KS No. 3–7 (0–200 m) until 2008 are in good agreement, which is evidently due to a general increase in water temperature in the entire North European Basin. Long-wave oscillations with a period of 5–6 years are distinguished in the plot (Fig. 2b). However, it is also evident from Fig. 2b that the decrease in correlation is primarily associated with the asynchrony of PC2 and KS oscillations in 2009–2016 affected by a weakening positive trend. Since PC1 has a negative correlation with water transport at the southern boundary of the North European Basin [15], the decrease in PC1 in the same period (Fig. 2a) reflects an increase in this flow into the North European Basin. Therefore, a disturbance in the correlation between water temperature on KS and PC2 is likely related to this process. Mutual cross-correlation coefficients of PC2 and water temperature on the KS nos. 8–10 (0–200 m) reach 0.83 with a time lag of 9–10 months.

Obviously, the processes affecting the temperature regime on the Kola Meridian are determined by numerous factors that are not equivalent with time and simple linear correlations, evaluated along the entire length of time series; they cannot describe many aspects of the variability of these processes. This will require research that considers regional specifics among other things. The conducted analysis implies that the temperature regime in the Barents Sea Basin is influenced by heat carried by waters from the Atlantic Basin and not directly by transport (advection) of these waters. This is confirmed by high correlation coefficients between the variability of the second principal component PC2 (NAT1 and NAT2) and water temperature on the Kola Meridian.

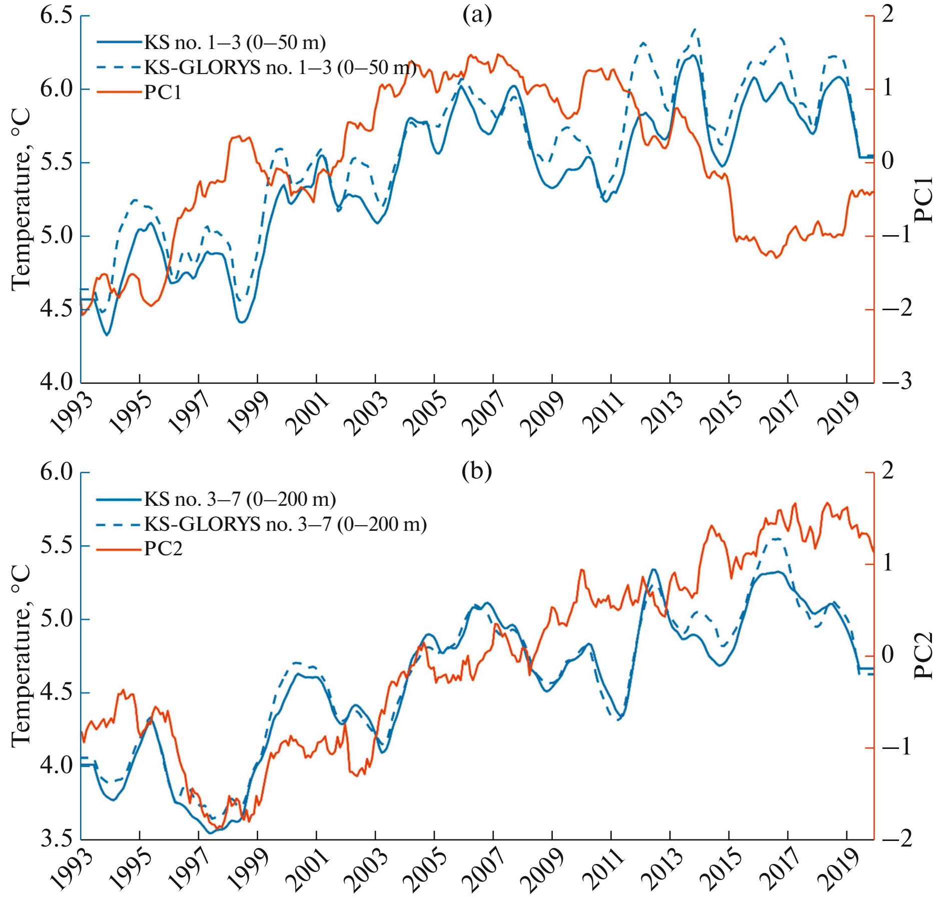

Fig. 2. Temporal variability of water temperature along Kola Meridian (with seasonal trend removed) and climate indices (a) PC1 and (b) PC2.

1.2. Lagrangian Analysis of Waters in the North European Basin

To study the water structure of the North European Basin, we use Lagrangian modeling over the period of 1993–2019 with the construction of different indicators calculated based on particle tracking. The main aspects of the applied method are presented in [18–20]. Successful instances of applying this method for studying water structures in the Lofoten Basin are given in [12, 13, 23].

The area of 64.5°–75° N, 14° W – 33.5° E is seeded with a patch of passive particles on a uniform grid with 500 × 500 nodes. The initial material is flow characteristics at a depth of 109.73 m, obtained from the GLORYS12V1 reanalysis. Figure 3 shows the tracking map of passive markers obtained by Lagrangian modeling. The color of the shaded particles on the map characterizes their origin (O-map). We can see that a significant number of particles in Fig. 3 is colored in red or yellow, which corresponds to waters entering the region from the south and the west, i.e., North Atlantic Current waters. In the northern part of the region, there are patches of blue-colored waters of Arctic origin. All of this agrees with the basic ideas of current circulations in the region. The eastern boundary of the region corresponds to the longitude of the Kola Meridian. The particles move also westward through the Kola Meridian, (green waters), which evidently enter the region with the meanders of the Murmansk Coastal, Murmansk, and North Cape Currents (Fig. 1). We constructed similar maps of particle origin for each month of 2017 (not shown) and established that the seasonal variability in current circulation in the region is not pronounced, and O-maps differ slightly from each other in different months.

Lagrangian particle tracking methods make it possible not only to determine the origin but also the age of particles within the region. Figure 4 shows that young waters correspond to Norwegian Current waters, which is quite expectable. The Norwegian Current, an extension of the North Atlantic Current, transports warm and saline waters from the Atlantic. In the streamlines of the Norwegian Current branches, velocities reach 60–70 cm/s [8, 9, 13, 21]. Figure 4 shows that most of the particles did not cross the boundaries of the region during the year, remaining within its limits.

Figures 5 and 6 show the temperature and salinity distributions in the region on April 17 and July 31,

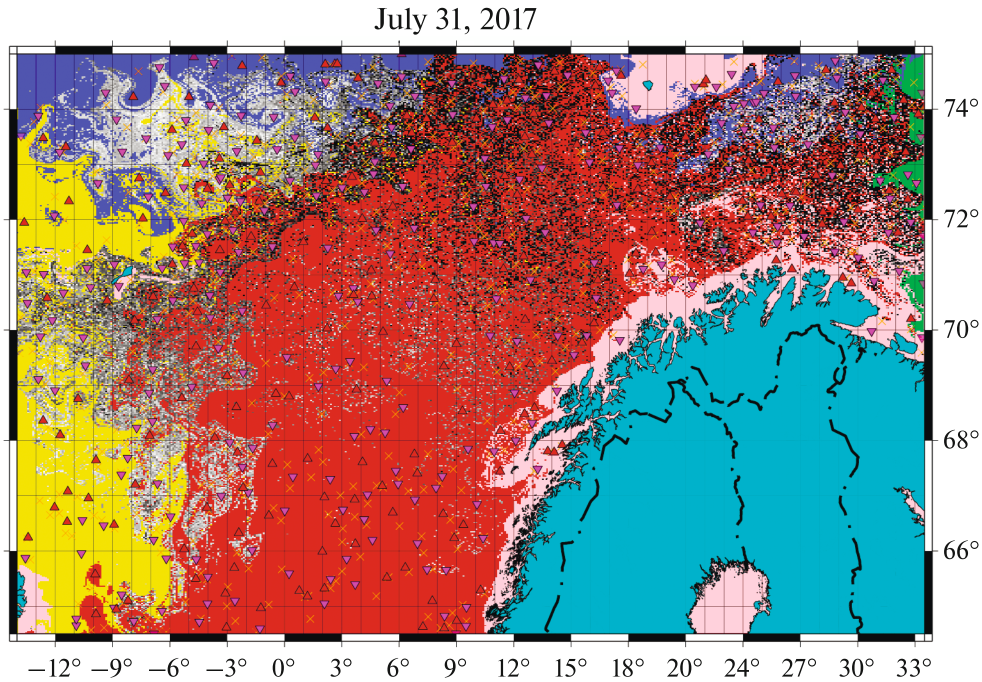

Fig. 3. Map of particle origin (O-map). Red represents particles intersecting the southern boundary of the region at 64.5° N (from south to north); blue, the northern boundary at 75° N (from north to south); yellow, the western boundary at 14° W (from west to east); and green, the eastern boundary at 33.5° E (from east to west). Pink corresponds to particles of coastal origin (Scandinavian Peninsula, Svalbard). Gray denotes particles that resided in the region during the year until the specified date. Triangles denote elliptic points: red triangles ▲ are anticyclone centers; bright purple ▼, cyclones. Orange crosses mark hyperbolic points that are nonstability points.

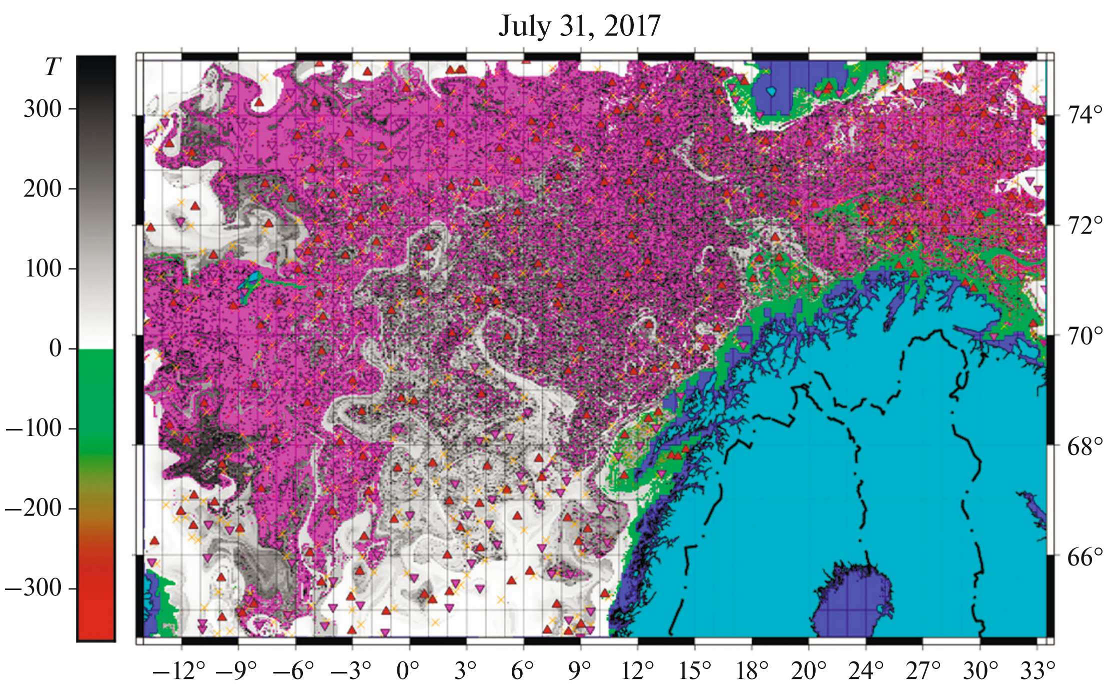

Fig. 4. Map illustrating the number of days required by particles to reach boundaries of the region (positive values on scale) or coastline (negative scale values). Light gray, young waters; dark gray, waters that resided in the region for up to 365 days. Bright purple, particles that resided in the region during a year until July 31, 2017. Blue, areas with depths less than 109.73 m. Triangles, eddy centers (red ▲, anticyclones; bright purple ▼, are cyclones); crosses, hyperbolic points.

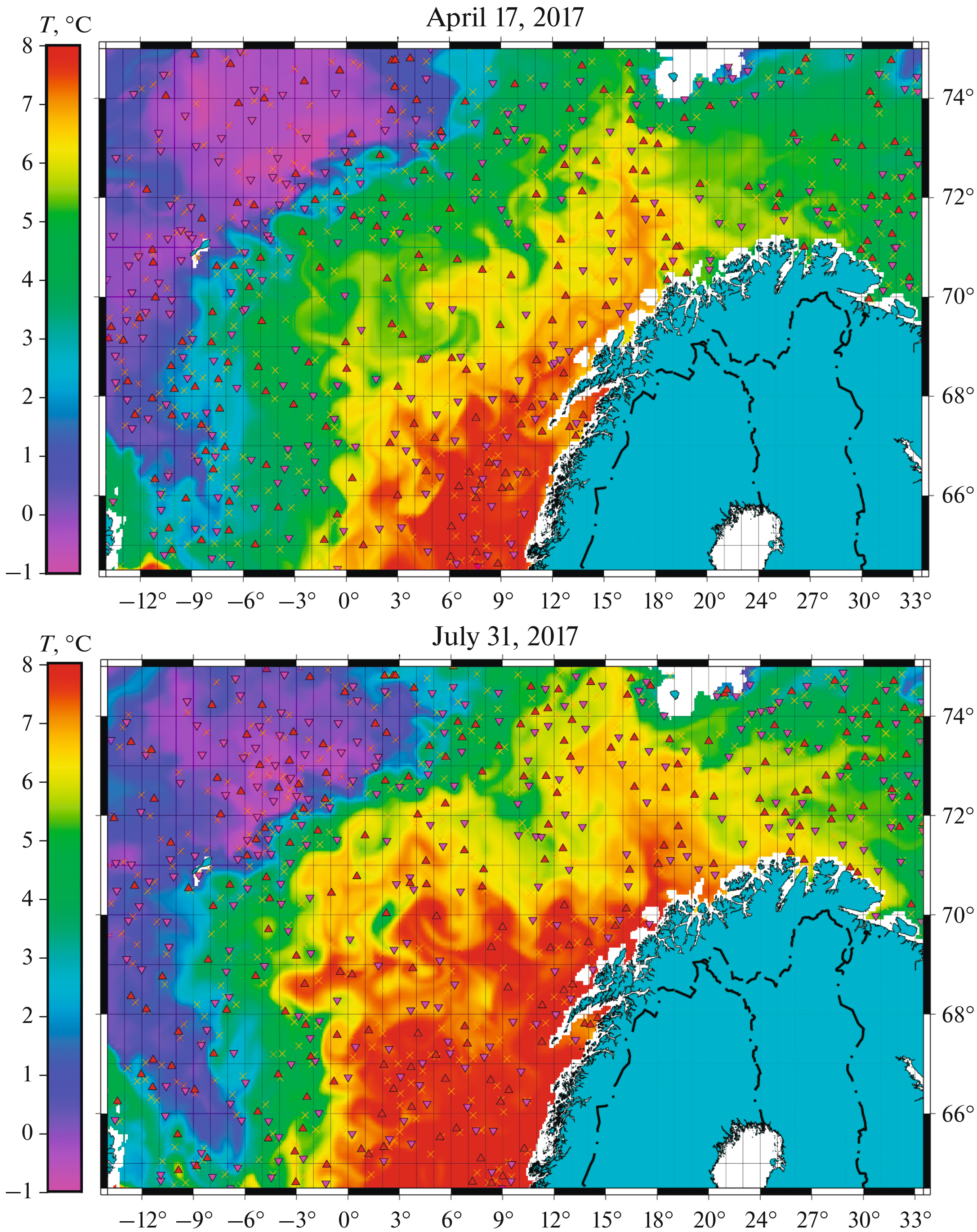

Fig. 5. Distribution of water temperature the North European Basin at depths of 109.73 m on April 17 (top) and July 31 (bottom) 2017. Triangles, eddy centers (red ▲, anticyclones; purple ▼, cyclones); crosses, hyperbolic points.

2017, at a depth of 109.73 m. Clearly, cold waters entering the region from the west, the Greenland Sea, have low temperatures from –1 to +1°C. Waters entering from the south and associated with the Norwegian Current are usually warm and salinel and temperature exceeds 8 °C, and the salinity is 35.15 PSU. We should focus on the eastern boundary of the region, the Kola Meridian. The salinity maps clearly differentiate different water masses by color gradation. Along the Kola Meridian, the area with low salinity values up to 34.85 PSU extends northward to 72° N. These waters with a salinity of 34.85 PSU are evidently correspond to the Coastal Branch of the Murmansk Current. Northward are the Main Branch of the Murmansk Current and the Central Branch of the North Cape Current. Note that this is not consistent with the division of current branches according to [5], where three segments were identified, each correlated with a

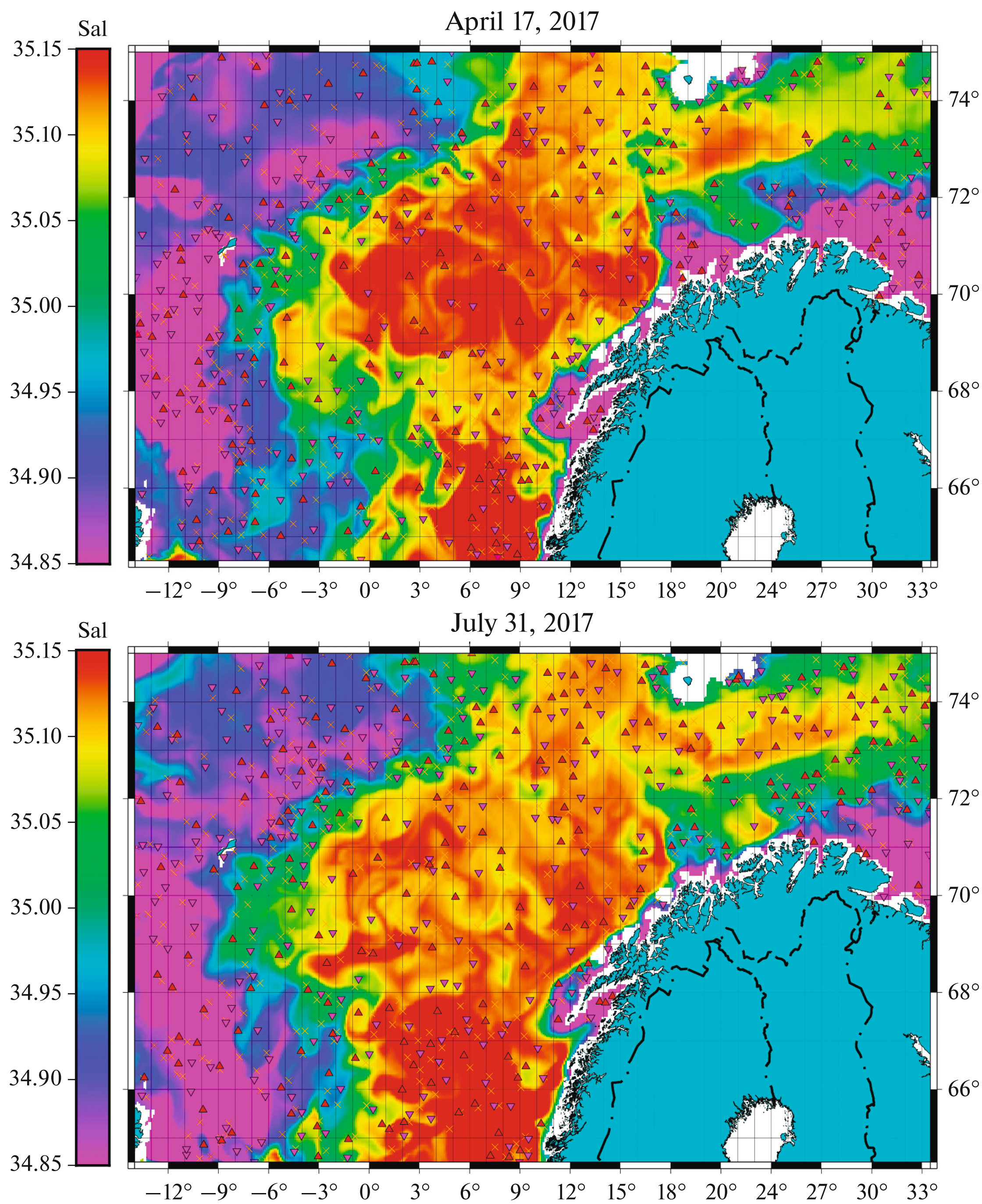

Fig. 6. Distribution of water salinity in the North European Basin at a depth of 109.73 m on April 17 (top) and July 31 (bottom) 2017. Triangles, eddy centers (red ▲, anticyclones; purple ▼, cyclones); crosses mark hyperbolic points.

specific current: stations nos. 1–3 (69.5°–70.5° N)—Coastal Branch of the Murmansk Current, stations nos. 3–7 (70.5°–72.5° N)—Main Branch of the Murmansk Current, and stations nos. 8–10 (73°–74° N)—Central Branch of the North Cape Current. However, based on the salinity characteristics at a depth of 109.73 m obtained from the GLORYS12V1 reanalysis, the Coastal Branch of the Murmansk Current extends much further northward, by more than 150 km. The Main Branch of the Murmansk Current is characterized by lower salinity values (up to 35.05 PSU) compared to the Central Branch of the North Cape Current (up to 35.10 PSU). All of this is clearly shown in Fig. 6.

Figure 7 presents the spatial distribution of the mixed layer depth (MLD) during the winter period

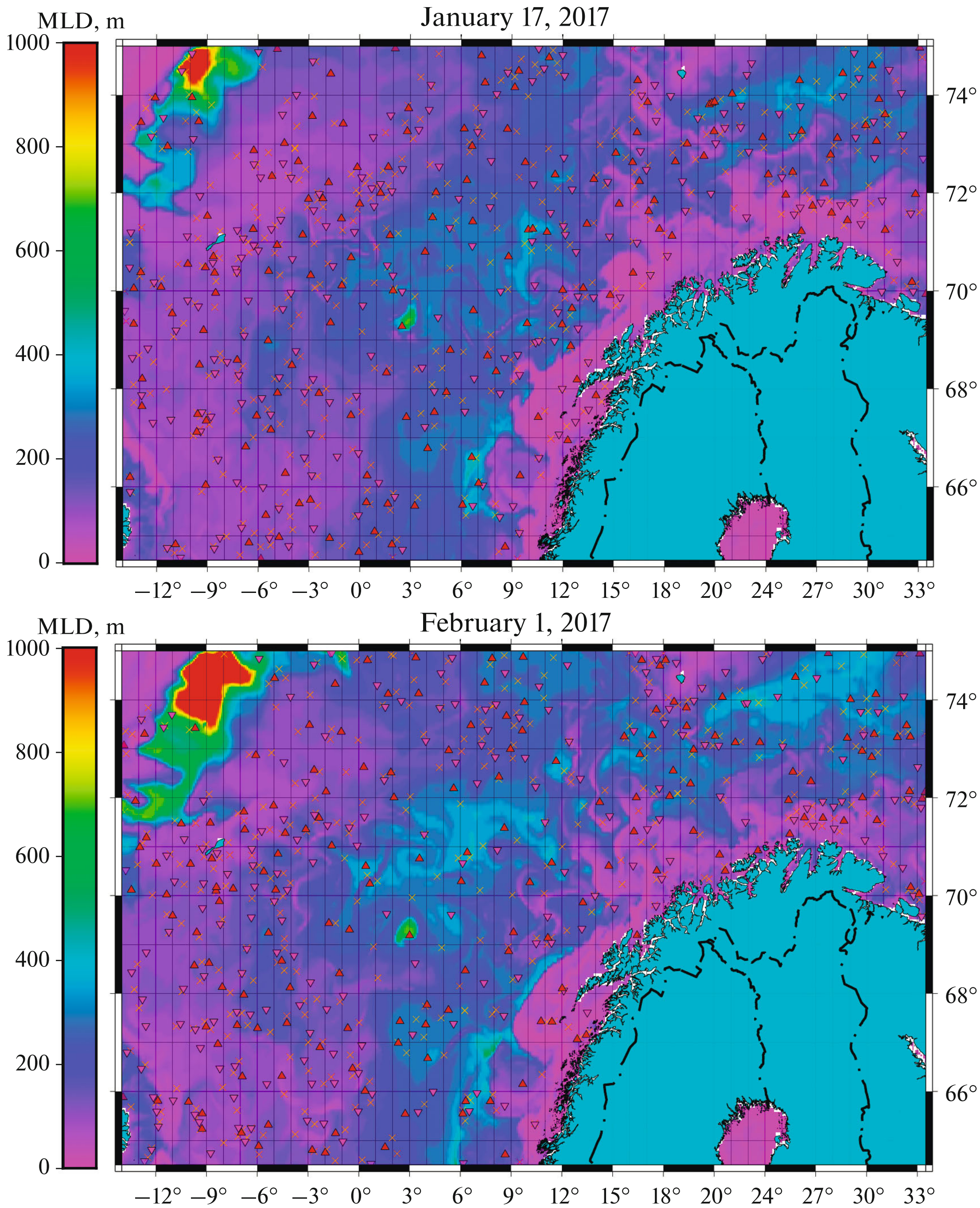

Fig. 7. Distribution of thickness of mixed layer in the North European Basin during winter period on January 17 (top) and February 1 (bottom) 2017. Triangles, eddy centers (red ▲, anticyclones; purple ▼, cyclones); crosses, hyperbolic points.

based on the data of the GLORYS12V1 ocean reanalysis. According to the product documentation,[1] MLD was calculated using the method [16] as the depth at which the density increase compared to the density at a depth of 10 m corresponds to a temperature decrease by 0.2°C [10, 11]. In the coastal zone, the MLD values on the Kola Meridian did not exceed 100 m, while in more northern regions, they reached 300 m. During the summer, the MLD values (not shown) were spatially homogeneous and did not exceed 50 m everywhere. The distributions of the mixed layer depth in the winter period (Fig. 7) also confirm the conclusion about the more northern extent of the Coastal Branch

[1] https://catalogue.marine.copernicus.eu/documents/PUM/CMEMS-GLO-PUM-001-030.pdf.

of the Murmansk Current, up to 71.5°–72° N. The positions of the branches indicated in earlier works (references in the review [5]) were likely determined by the temperature values. However, as shown in Fig. 5, the positions of the current branches based on the temperature distributions on the transect can hardly be determined.

2. CONCLUSIONS

(1) The variability of water temperature along the Kola Transect reflects the processes occurring in the North European Basin. We found that the temperature time series along the Kola Meridian agree well with climate indices PC2, as well as NAT1 and NAT2, which are responsible for warming processes in the cold North European Basin and cooling processes in the warm region south of Iceland. The correlation coefficients for the water temperature measurements (with the seasonal trend removed) along the Kola Meridian and indices PC2, NAT1, and NAT2 reach 0.80. The cross-correlation coefficients for PC2 and water temperature along the Kola Meridian (station nos. 8–10, depths of 0–200 m) reach 0.83 with a lag of 9–10 months.

(2) The low correlation between water temperature along the Kola Meridian and indices PC1 and NAT responsible for the volume flow of waters entering from the Atlantic into the North European Basin indicates that the thermal state of Atlantic waters flowing into the Barents Sea is governed by the thermal state of Atlantic waters rather than by their volume.

(3) The spatial distribution of water salinity at a depth of 109.73 m is sufficient to quite accurately localize the Coastal Branch of the Murmansk Current. Low salinity values (up to 34.85 PSU) characterize the position of the northern boundary of the Coastal Branch of the Murmansk Current in the region of 71.5°–72° N in 2017. This finding does not agree with the existing ideas about the position of this boundary within the limits of 70.5° N.

(4) The spatial distribution of the thickness of the mixed layer during winter 2017 also confirms the conclusion that the Coastal Branch of the Murmansk Current extends more northward, up to 71.5°–72° N.

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ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This work does not contain any studies involving human and animal subjects.

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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