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ON THE TRANSITION OF TEMPERATURE REGIME OF THE WHITE SEA REGION TO A NEW PHASE STATE

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Abstract

Changes in near surface air temperature and vorticity of the wind speed field of the White Sea and the territory of the Murmansk and Arkhangelsk regions and the Republic of Karelia are investigated. We analyzed the monthly average NCEP/NCAR reanalysis data for the period 1950–2020. The average surface air temperature growth estimated using a linear trend was +0.24 °C/10 years. Against the background of this linear growth, significant interdecadal changes in surface air temperature are observed. The following periods are highlighted: the strengthening of the continentality of the climate (1950–1976), a more maritime climate (1977–1998), and the rapid growth of surface air temperature (1999–2020). The transition from a period of increasing continentality of the climate to a period of a more maritime climate is associated with an increase in the influence of the North Atlantic on the region under study. A hypothesis has been put forward that the period of rapid growth of surface air temperature is caused by the transition of the climatic system of the western part of the Russian Arctic into a new phase state. The observed warming in the Arctic has caused a reduction in sea ice, which has led to an increase in solar energy absorption by the surface of the Barents and White Seas.

Keywords: climate change, temperature, Arctic, White Sea, Barents Sea, sea ice, atmospheric circulation

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О ПЕРЕХОДЕ ТЕМПЕРАТУРНОГО РЕЖИМА РЕГИОНА БЕЛОГО МОРЯ В НОВОЕ ФАЗОВОЕ СОСТОЯНИЕ

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Аннотация

Исследованы изменения температуры воздуха у поверхности и завихренности поля скорости ветра акватории Белого моря и территории Мурманской и Архангельской областей и Республики Карелия. Анализировались среднемесячные данные реанализа NCEP/NCAR за период 1950–2020 гг. Оцененный с помощью линейного тренда средний рост температуры воздуха у поверхности составил +0,24 °С/10 лет. На фоне этого линейного роста наблюдаются существенные междекадные изменения температуры воздуха у поверхности. Выделены периоды: усиления континентальности климата (1950–1976 гг.), более морского климата (1977–1998 гг.), и быстро-

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го роста температуры воздуха у поверхности (1999—2020 гг.). Переход от периода усиления континентальности климата к периоду более морского климата связан с усилением влияния Северной Атлантики на исследуемый регион. Выдвинута гипотеза, что период быстрого роста температуры воздуха у поверхности вызван произошедшим переходом климатической системы западной части российской Арктики в новое фазовое состояние. Наблюдаемое потепление в Арктике вызвало сокращение морского льда, что привело к увеличению поглощения солнечной энергии поверхностью Баренцева и Белого морей.

Ключевые слова: изменения климата, температура, Арктика, Белое море, Баренцево море, морской лед, атмосферная циркуляция

1. Introduction

The subarctic zone of Russia is particularly vulnerable to climate change, as hundreds of billions of dollars of infrastructure is located in the permafrost zone. At the same time, according to observations since the mid-1970s, average temperatures here are growing 2.5 times faster than in the whole planet. If the frozen strata thaw, then due to the significant ice content in them, the average subsidence of soils can be 10—20 cm per year [1]. The railway infrastructure in the subarctic regions is used in extremely difficult engineering-geological and landscape-climatic conditions, being constantly exposed to various external influences, leading to deformations of the track and artificial structures [1]. Among them: coastal abrasion, mudflows, floods, erosion, landslides and slipouts, landslips and screes, karst holes, solution sinkholes, ice, thermokarst, thermal erosion, solifluction, rupturing deformations, frost penetration avalanches, etc.

Island zones of permafrost are located on the Kola Peninsula [2]. The infrastructure of Russian Railways in this region is especially vulnerable to the negative factors of regional climate change, since the main problem of the Volkhovstroy — Murmansk section is the fact that out of 1320 kilometers of its length, more than 340 kilometers are single-track sections, which limits its bandwidth. In addition, on April 30, 2020, the Government of the Russian Federation set a task to increase transportation from 28 to 44 million tons per year on the section of the Murmansk branch of the Oktyabrskaya Railway by 2023, and not by 2035, as previously planned, but by 2035 they should grow to 100 million tons (https://tass.ru/ekonomika/9890949, https://rg.ru/2020/11/10/reg-szfo/propusknaia-sposobnost-zheleznodorozhnoj-infrastruktury-v-zapoliare-vyrastet.html). In this regard, studies of climate change in the Murmansk region, the Republic of Karelia and the Arkhangelsk region are extremely important for the Russian Railways. This study is a continuation of the works begun in [3—5, 1].

Since the beginning of the 2000s, several papers have been published on the study of regional climate change in the region under study, mainly in the area of the White Sea and Karelia drainage basins. However, in most works, the study period was limited to 2000 or 2011, so critical climate changes in the first two decades of the 21st century were almost not reflected in them. In addition, the main efforts were aimed to the study of the White Sea drainage basin, which for the most part is located southeast of the White Sea and the region under study.

For example, it was shown in [6—8] that for the White Sea region since 1985 a period began, which was characterized by positive anomalies of eastern transport, while the frequency of western transport forms was close to the norm. Negative air temperature anomalies in the late 1980s changed to positive ones up to 2.0—2.5 °C, and atmospheric pressure anomalies changed sign from positive to negative. The decrease in atmospheric pressure is explained by an increase in westerly transfers, increased cyclonic activity, and an increase in air temperature is explained by the inflow of warm air masses from the Atlantic. The spectrum of near-surface air temperature fluctuations in Arkhangelsk for 176 years revealed dominant fluctuations with a period of 4—5 and 11—13 years, which indicates the influence of large-scale climatic processes on the formation of long-term variability of hydrometeorological characteristics of the White Sea region. It is expected that the air temperature in the region will rise to 2.8—3.3 °C by 2050, i.e. by 1.8—2.3 °C relative to 1840 or by 0.5—1.0 °C relative to 2000 [8].

In [9, 10], the temperature regime of the territory of Karelia in 1950—2011 is considered, it is shown that since 1989 only positive air temperature anomalies of the order of 1—2 °C have been observed, compared with the average value for 1961—1990. The greatest warming is observed in winter and in March from 0.3 °C to 0.6 °C/10 years. An increase in air temperature obviously leads to an increase in soil temperature. An analysis of observational data from soil thermometer under natural cover at depths from 20 to 320 cm showed that during the 1990 s and 2000 s, the average annual soil temperature at various depths up to 320 cm in the territory of Karelia exceeded the climatic norm by 1.0—1.5 °C in the southern regions and by 0.5—1.0 °C in the northern regions of the republic [10]. It should be noted that the climatic norm in southern Karelia is the soil temperature of −1.5...—2.0 °C at a depth of 20 cm from December to mid-April, however, during 1991—2011 soil freezing was not observed, while it still persisted in the central and northern regions [10]. At other depths, the average monthly temperature values during the year were positive. In [11], according to satellite data for 2002–2019 it is shown that the rate of increase of soil temperature in some areas of the Kola Peninsula can reach +0.1 °C/year.

In [12, 13], to analyze the interannual variability of the thermal and ice regime of lakes in Karelia, data on air temperature from adjacent meteorological stations were also used. Analysis of these series for 1953–2011 showed a positive trend in air temperature of 0.2–0.3 °C/10 years, and in 1976–2014 0.57–0.67 °C/10 years in the area between Lake Ladoga and the White Sea, and at the meteorological station Valaam (Lake Ladoga) up to +1.12 °C/ 10 years in July.

It was shown in [14] for the Kola Peninsula that the air temperature increased from 1878 to 2013 at an average rate of 1 °C/100 years, while the growth rate increased noticeably in 1980–2009 +0.55 °C/10 years. In 2000–2009 the maximum values of average near-surface air temperature anomalies were observed in winter (+1.8 °C), and the minimum values were observed in summer (+0.75 °C). The authors drew attention to the significant heterogeneity of temperature changes on the Kola Peninsula. For example, on the Murmansk coast, facing the Barents Sea, warming is noticeable and statistically significant, while on the Tersky and Kandalaksha coasts of the White Sea, the trend values are much smaller and almost insignificant. This indicates a mosaic of microclimatic conditions, which are more important than regional trends for geomorphological processes in small mountain river basins.

In [15, 16] for the White Sea drainage basin, it is shown that, based on the data of meteorological stations, the average air temperatures for 1991–2017 increased by 0.8–1.2 °C compared with the standard climatic period— 1961–1990. Observational data indicate an almost synchronous nature of the variability of the average annual air temperature over the entire catchment area of the White Sea. As for different seasons of the year, the largest increase in temperature was recorded for the winter months, especially for January (average values for 1991–2017 exceed climatic norms by 1.7–2.5 °C).

In [17], for the drainage basin of Lake Onega, it was shown that in the second half of the 21st century, the air temperature will increase by an average of 4.53 °C compared to the period of 1951–2000, while significant warming is expected in the winter period. It is expected that the increase in average January temperatures in 2001–2050 will be at 5.6 °C, and in 2051–2100 at 8.6 °C.

In [18], the thermal runoff of rivers in the White Sea catchment area and its variability are considered. An increase in the water temperature of the mouths of the rivers of the White Sea catchment for 1956–2015 is shown, which is especially pronounced since 1990. The model experiments performed have shown that an increase or decrease in the average monthly water temperature in the rivers by 2 % as well as change in their runoff by 30 % will not lead to a significant change in the timing of ice formation and ice destruction in the bays of the White Sea, but will only change the water temperature in the warm season.

In the above works, it was noted that the consequences of climate change in the White Sea catchment significantly affect fisheries, agriculture and forestry (mainly due to an increase in air and water temperatures in the White Sea and rivers), and further climate change may affect mining, energy, transport and tourism, which are developing in the White Sea region and on the Kola Peninsula [16].

2. Data and Methods

The paper analyzed monthly average surface air temperature (SAT) and wind speed data at sigma level of 0.995 from NCEP/NCAR Reanalysis on a 2.5°× 2.5° grid over the period 1950–2020 [19]. The sigma level of 0.995 is the closest model level to the surface used in NCEP/NCAR Reanalysis data assimilation, and is approximately 42.2 meters above the surface, with the height referenced from the terrain at each grid point. By surface is meant the solid or liquid surface of the land or ocean, depending on the specific mesh node. At a sigma level of 0.995, the atmospheric pressure at a given grid point at a given time step is 0.995 times the surface atmospheric pressure at that grid point at that time.

As additional data used in the discussion of the results obtained, monthly average values of sea ice concentration (the area covered with ice of any concentration, as a percentage of the total sea area) obtained by averaging daily average values from the CMEMS EUMETSAT OSI SAF SEAICE_GLO_SEAICE_L4_REP_OBSERVATIONS_011_009 array on a grid of 12.5 km over the period 1979–2020 [20]. These data are satellite based and cover the high latitudes of the Northern Hemisphere. Additionally, monthly average ocean temperature data at different depths of the global oceanic reanalysis GECCO3 (German contribution of the Estimating the Circulation and Climate of the Ocean project) on a 1 × 1° grid for the period 1948–2018 were analyzed [21].

At each grid node, the average annual course of the studied characteristics over the period under consideration is calculated. The average annual variation obtained separately for each grid node was subtracted from the initial data to obtain anomalies at each grid node relative to the average annual variation (hereinafter simply anomalies). Linear trends were calculated using the least squares method.

The SAT anomalies were averaged for the extended region of the White Sea (61.25°–71.25° N; 28.75°–46.25° E). The coordinates are specified taking into account the NCEP/NCAR Reanalysis grid, since each grid node contains data averaged over its vicinity ±1.25°. The region under study includes grid nodes with latitudes 62.5°, 65°, 67.5°, 70°N and longitudes 30°, 32.5°, 35°, 37.5°, 40°, 42.5°, 45°E. Thus, the study region includes the entire water area of the White Sea, part of the south of the Barents Sea, the entire territory of the Murmansk region and the Republic of Karelia, and most of the Arkhangelsk region.

To analyze the type of atmospheric circulation in small regions, the concept of vorticity is used, which is $\zeta = \partial V/\partial x - \partial U/\partial y$, where U and V are the zonal and meridional components of the wind speed. On the other hand, vorticity is a rotor from streamlines $\zeta = \mathrm{rot}(\psi)$. A positive value of ζ characterizes the predominance of cyclonic circulation, while a negative value characterizes anticyclonic circulation. This approach made it possible to analyze the variability of the type of circulation over the water area of the Black and Caspian Seas [22–25], where the analysis of the interannual variability of the vorticity of both the circulation of the sea and the atmosphere above it was carried out. This technique was used to analyze the temporal variability of the average monthly wind speed vorticity at the level of sigma 0.995 to identify periods of changes in atmospheric circulation over the study area for 1950–2020.

3. Results

Figure 1 (green line) shows the time series of changes in the average SAT in the study region. The variability of the average monthly SAT is ~35 °C: from –18 °C to +17 °C. At the same time, the variability of the local minima of the SAT is ~13 °C: from –18 °C to –5 °C, which is stronger than the variability of the local maxima of the SAT ~6 °C: from +11 °C to +17 °C.

In the time period under consideration, global climate warming occurred, apparently caused mainly by anthropogenic impact [26]. However, both global and regional climate systems are non-linear, and therefore their responses to anthropogenic impact are also non-linear. But at present, to reliably and accurately separate the nonlinear response of the climate system to anthropogenic forcing from its nonlinear responses to other external influences (for example, to changes in solar activity) and from the own oscillations of the system (modes of climatic variability), in our opinion, seems to be a very difficult task.

A linear approximation of the time series of changes in the average SAT of the White Sea region demonstrates its growth by an average of +0.24 °C over 10 years (purple line in Fig. 1). Thus, over the 71 years under consideration, the increase in SAT was approximately +1.7 °C. However, it should be taken into account that the least squares method used to estimate the linear trend is very sensitive to the edge values. And the boundary values, in turn, are affected by the interannual and interseasonal variability of the series under study. Moreover, it will be shown that the changes in the SAT of the region under consideration can be divided into three different periods, and to analyze such behavior of the system, it is better to use a step function approximation.

Interannual (Fig. 1, black curved line) and interseasonal (Fig. 1, red and blue circles) variability of average SAT anomalies in the region under consideration demonstrates a large range of values, both between individual years and individual seasons. At the same time, the variability of SAT anomalies between winter periods (December-February) is stronger than between summer periods (June — August).

Figure 2 shows the variability of the average SAT anomalies of the study region after applying low-pass filters to highlight longer-term changes. On the time series (Fig. 2), against the background of a linear increase in SAT anomalies, three periods with different characteristics can be distinguished. First period 1950–1976 characterized by strong positive SAT anomalies in the warm half-years (May — October). In the second period 1977–1998 the situation changed and strong positive anomalies of the SAT began to be observed mainly in the cold half-years, and in the warm half-years mainly negative anomalies began to be observed. Third period 1999–2020 characterized by a sharp increase in SAT anomalies both in the cold (up to +3 °C) and in the warm period of the year (up to +2 °C).

The existence of these three periods of different climate confirms the behavior of the graph of the accumulated sum of SAT anomalies after the removal of the linear trend (Fig. 2, green). The accumulated amount allows to highlight long-term (interdecadal) changes without applying large-window filtering, which can distort the result, especially at the edges of the series under study. The graph of the accumulated amount of SAT

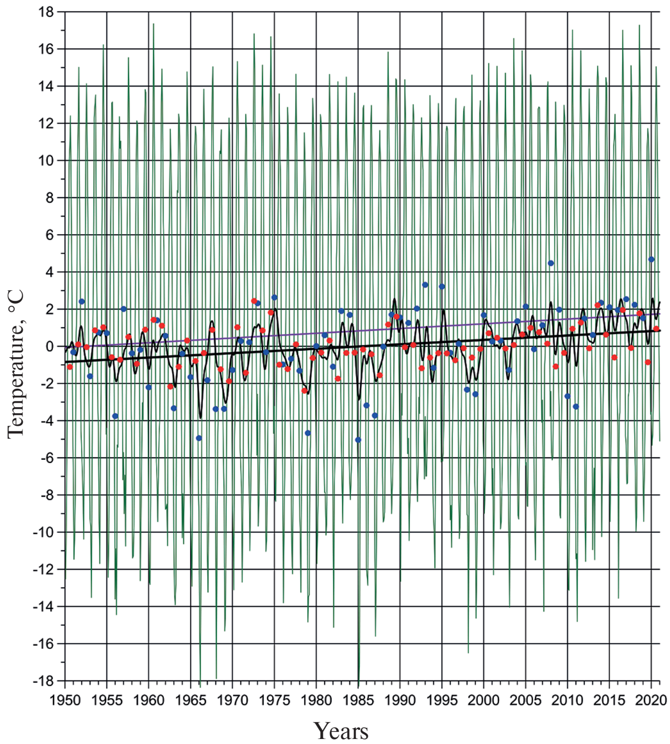

Fig. 1. Changes in mean near surface air temperature (SAT) in the White Sea region (green), and a linear approximation of this time series (purple) for 1950–2020. Changes in mean SAT anomalies in the White Sea region, smoothed by a 1-year low-pass Butterworth filter (black), and their linear trend (black straight line). The circles indicate the mean values of the SAT anomalies for summer (June — August) (red) and winter (December — February) (blue)

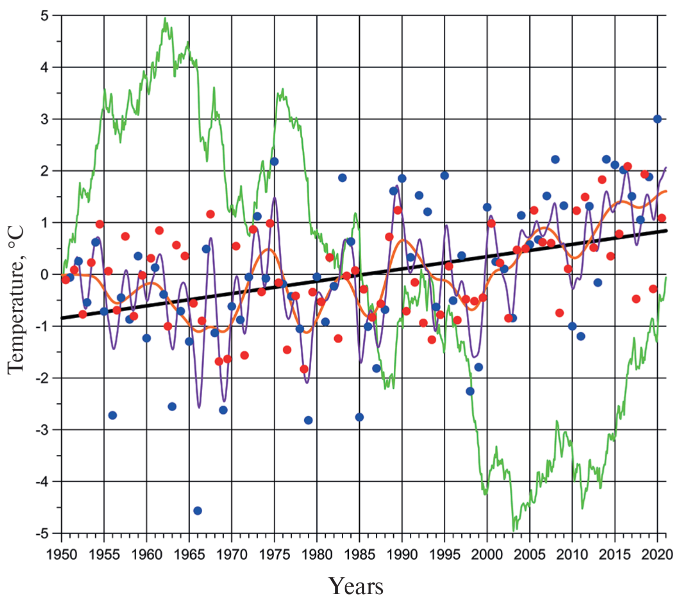

Fig. 2. Changes in mean near surface air temperature (SAT) anomalies in the White Sea region for 1950–2020, smoothed by 2-year (purple) and 7-year (orange) low-pass Butterworth filters. Their linear trend (black) and the accumulated sum of anomalies after the removal of the linear trend (green) are drawn. The circles mark the average values of the anomalies for the warm (May — October) (red) and cold (November — April) (blue) seasons

anomalies generally decreases from 1977 to approximately 1999, stabilizes in the 2000s, and begins to grow rapidly in the 2010s. Thus, confirming the sharp increase in SAT in the third period (1999–2020), which was 2–3 times higher than the average increase in SAT for the entire study period (+0.24 °C for 10 years).

An analysis of the temporal variability of the average monthly wind speed vorticity at the level of sigma 0.995 (Fig. 3) showed that three periods of its increase and decrease can be distinguished in the vorticity field. These periods are associated with a weakening of the cyclonic circulation or its intensification. So, in the periods 1950–1972 and 1999–2020 there is a period of weakening of the cyclonic circulation, and in the period 1973–1998 its strengthening.

Figure 4 shows the fields of average SAT for the entire period under consideration (Fig. 4, *a*) and for the selected three periods (Fig. 4, *b*–*d*). Note that all grid nodes that are used in plotting Fig. 1–3 are presented

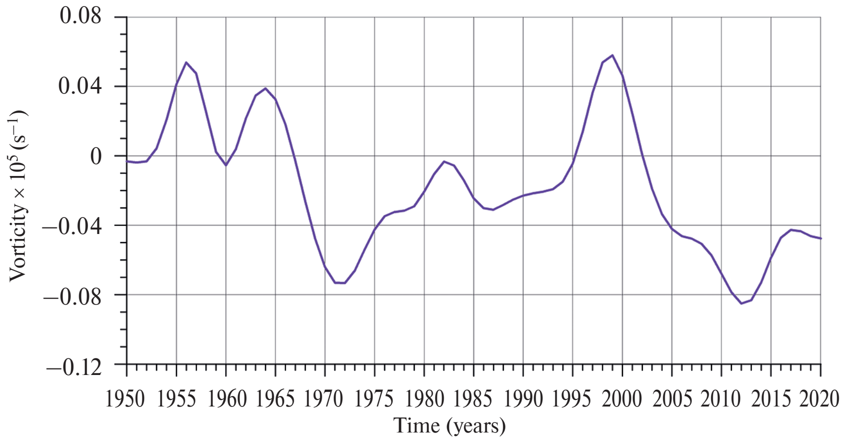

Fig. 3. Temporal variability of the mean annual (after the median filtration) vorticity of the wind speed field at a sigma level of 0.995 for 1950–2020

in these fields, but these fields are extended to the south, and additionally include data from grid nodes with latitudes of 60.0 °N. On Fig. 4, it is noteworthy that in the first two periods (1950–1976 and 1977–1998) the average SAT did not differ much, but in the third period (1999–2020) there was a significant shift in the average SAT compared to the two previous periods. In the first two periods, in the southwest of the Kola Peninsula in

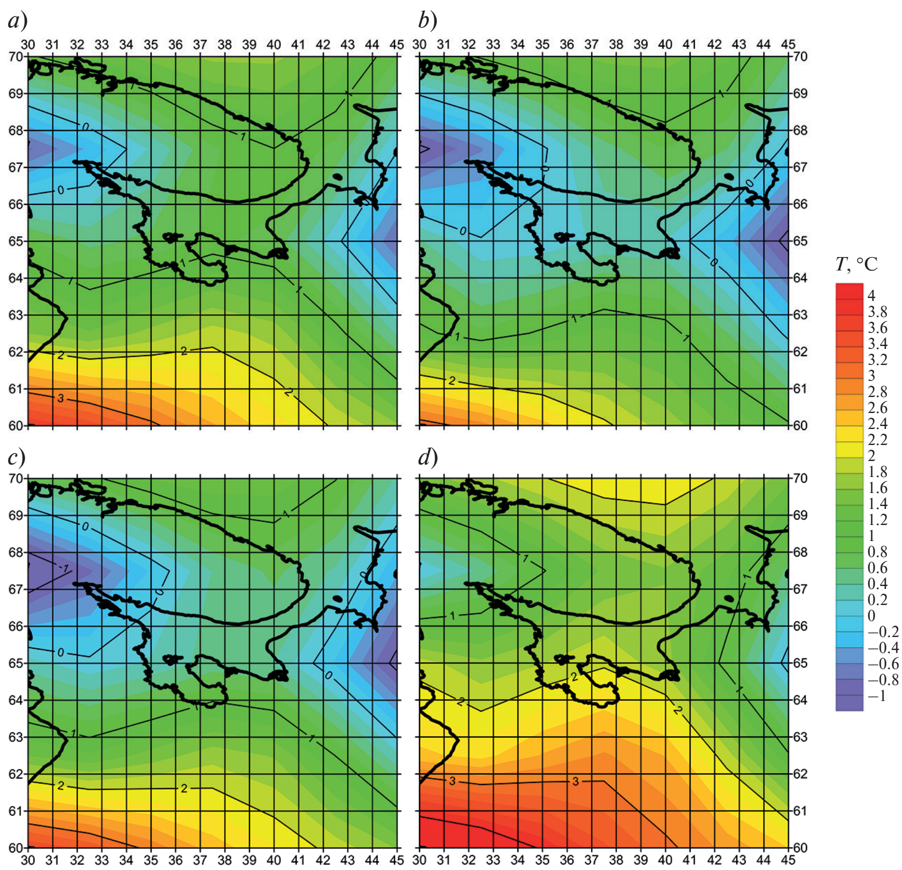

Fig. 4. Fields of mean near surface air temperatures (SAT) for the periods:
a — 1950–2020; *b* — 1950–1976; *c* — 1977–1998; *d* — 1999–2020

the region (66.5°–68.5°N; 30°–34°E) and in the east of the Arkhangelsk region (64°–67°N; 43°–45°E) the average SAT were slightly below zero (Fig. 4, *b–c*), because of which island zones of permafrost could exist there [2]. In the third period, the average SAT became above zero in the entire study area (Fig. 4, *d*), due to which permafrost thawing in these regions should be expected. An interesting feature of the changes that have occurred is the fact that the movement of heat from south to north (for example, the 2 °C isotherm at longitude 38°E rose from 60°N to almost 65°N) did not lead to displacement of cold regions to the north, and to their squeezing to the west and east, respectively. In addition, the atmosphere over the southern part of the Barents Sea also warmed by a degree (Fig. 4, *d*).

Figure 5 shows the fields of changes in SAT anomalies estimated using a linear approximation for the entire period under consideration and for the selected three periods. It can be seen that over the entire period under consideration, the increase in SAT averaged from +0.1 to +0.4 °C over 10 years (Fig. 5, *a*). However, in the first selected period, a decrease in SAT was observed over a larger area of the study region, especially in the above-mentioned areas of permafrost existence (Fig. 5, *b*). In the second period, an increase in SAT was observed on average from +0.1 to +0.4 °C over 10 years (Fig. 5, *c*). In the third period, this growth accelerated significantly and averaged from +0.4 to +1.0 °C over 10 years (Fig. 5, *d*). Moreover, the strongest increase in SAT was observed in the northeastern part of the region under consideration, in the waters of the White and Barents Seas.

Fig. 6 shows the fields of changes (differences) in the average SAT between the selected periods. In the second period (1977–1998), as compared to the first one (1950–1976), the average SAT increased mainly in the southern part of the region under consideration (Fig. 6, *a*). In the northern part, the average SAT in the second period became lower than in the first. In the third period (1999–2020), the average SAT increased significantly

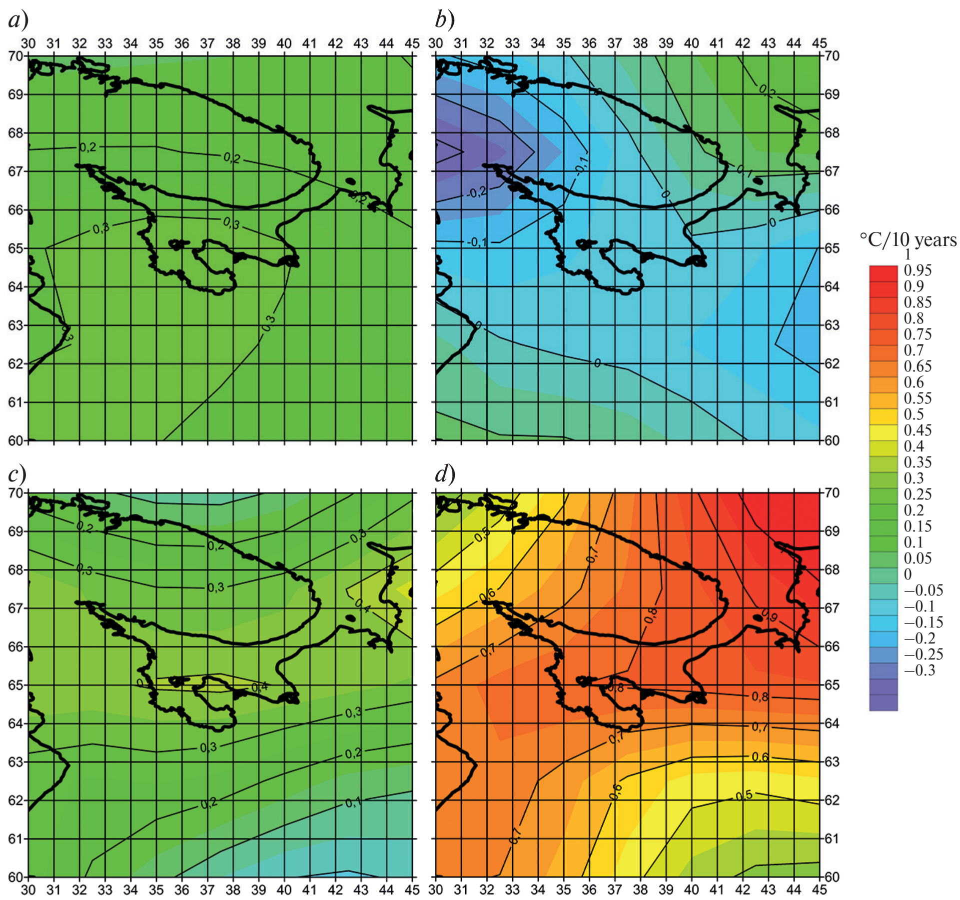

Fig. 5. Fields of changes in near surface air temperature (SAT) anomalies estimated using linear trends for the periods: *a* –1950–2020; *b* — 1950–1976; *c* — 1977–1998; *d* — 1999–2020

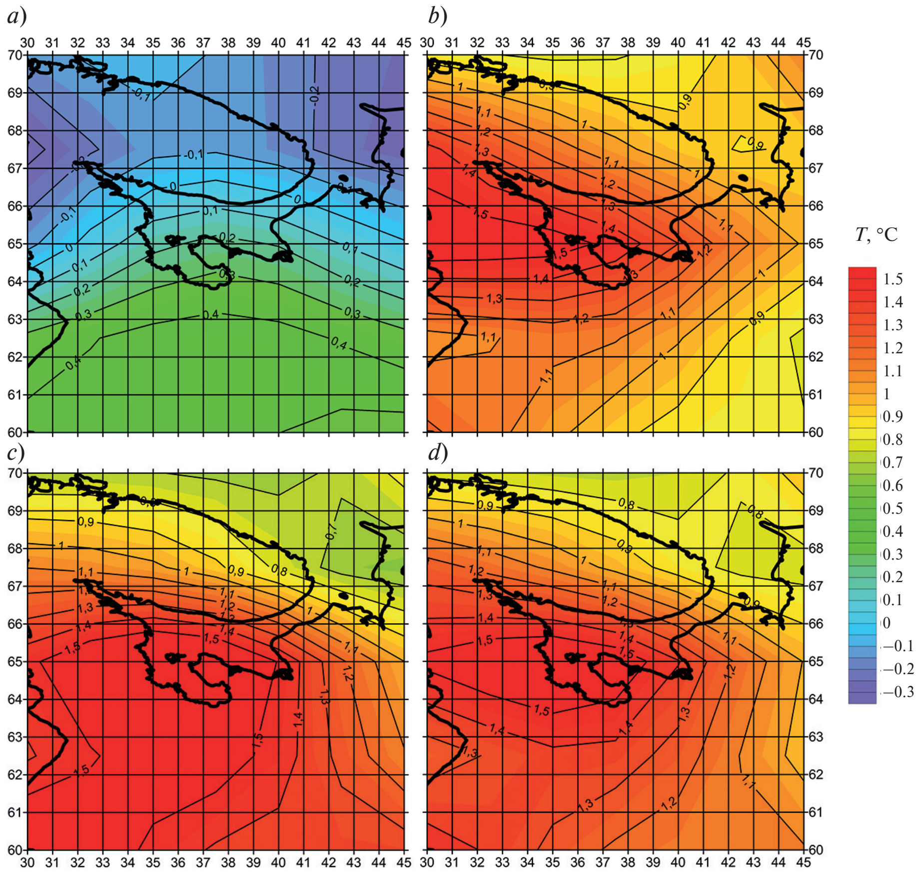

Fig. 6. Fields of changes in mean near surface air temperature (SAT) between the periods: *a* — 1977–1998 and 1950–1976; *b* — 1999–2020 and 1977–1998; *c* — 1999–2020 and 1950–1976; *d* — 1999–2020 and 1950–1998

in the entire region under consideration in relation to the second (Fig. 6, *b*), first (Fig. 6, *c*) and the entire previous period (Fig. 6, *d*). The most significant increase in the average SAT in the third period was in the center of the western part of the region under consideration, including the White Sea.

4. Discussion

The detected changes in the SAT of the White Sea region between the selected periods can be associated with both anthropogenic global warming and the influence of natural modes of climatic variability on the region under study. In the Pacific Ocean, climate shifts occurred in 1976/1977 and 1998/1999 [27–31]. They manifested in transitions between opposite phases of the Pacific Decadal Oscillation (PDO) and the Interdecadal Pacific Oscillation (IPO) [32–34]. These climatic shifts had a global impact, including the North Atlantic region [34, 35].

The North Atlantic has a significant impact on the considered region of the White Sea. The first distinguished period (1950–1976) is characterized by cold winters and hot summers, that is, a more continental climate. As shown in [36, 37], this is due to the weakening of the influence of the North Atlantic on the region under study during this period, which is also confirmed by the weakening of cyclonic vorticity (Fig. 3). In the second selected period (1977–1998), winters became milder, and summer anomalies of SAT became mostly negative. That is, the climate of the region under study has become more maritime compared to the previous period. This is due to the increased influence of the North Atlantic on the region under study in the second period [36, 37]. As shown in [35], the increase in the influence of the North Atlantic in 1977–1998 to the White Sea region was the result of changes in atmospheric circulation over the North Atlantic and Europe. This was also manifested in an increase in the cyclonic vorticity of the atmosphere in the White Sea region (Fig. 3).

In the third selected period (1999–2020), there is a sharp increase in SAT in the region under study. It can be assumed that this is due to a sharp increase in temperature in the Arctic during this period [38], and a significant reduction in the area of sea ice in the Barents Sea (Fig. 7) [39]. This caused an increase in positive feedback in the form of a weakening of the stratification of the upper layer of the water of the Barents Sea, increased mixing, and the rise of warmer and saltier Atlantic waters to the surface [40]. Also, an additional contribution to the increase in water temperature in the upper layer of the Barents and White Seas is made by a positive feedback from the absorption of solar radiation: with the warming of the Arctic, the ice area decreases, and this leads to a greater absorption of solar radiation by the surface [41]. Thus, the sharp increase in SAT in the third selected period, apparently, is associated with an increase in the effect of positive feedback, which means that the climate system of the White Sea region under study has moved to a new phase state.

Unfortunately, data on sea ice concentration at grid nodes containing coastlines are strongly affected by errors in the satellite data processing algorithm [20]. This raises doubts about the reliability of data on sea ice concentration for a significant part of the White Sea due to its small size and complex configuration. Therefore, the results of changes in sea ice concentration (Fig. 7) should primarily be considered for the Barents and Kara Seas. The field of change in mean sea ice concentration (Fig. 7) is shown in the Lambert azimuthal equal-area projection, which accurately represents the area in all areas of the sphere. This makes it possible to more correctly estimate the area of reduction in sea ice concentration in the region of the Barents and Kara Seas.

The warming of the Arctic climate and the reduction of the ice cover of the Barents and Kara Seas could not affect the climate of the White Sea region. Based on this, the region under study was expanded to include the waters of the Barents Sea and partially the Kara Sea (65°–82°N; 15°–70°E). For this entire extended region, charts of changes in the average SAT anomalies and ocean temperature anomalies at various depths were plotted (Fig. 8). In the case of ocean temperature anomalies, those grid nodes were selected that fall into the region (65°–82°N; 15°–70°E) and are not land.

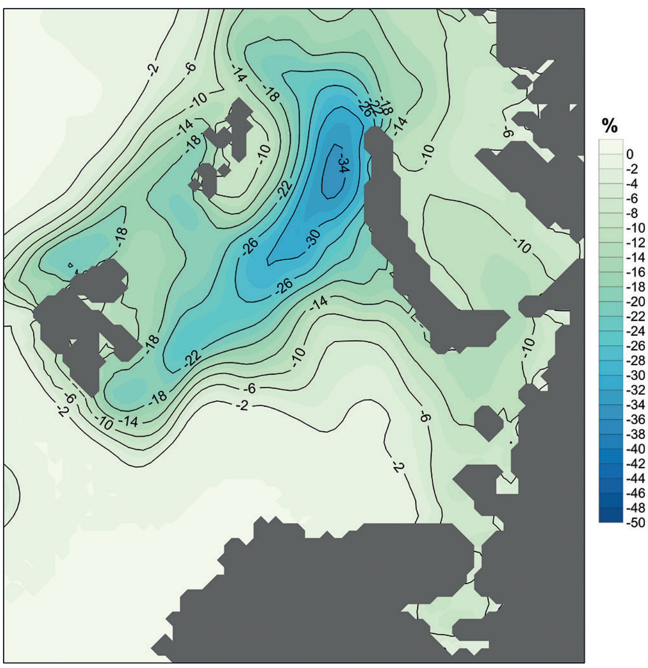

Fig. 7. Field of changes (difference) in the average concentration (%) of the sea ice in the White, Barents and Kara seas between the periods 1999–2020 and 1979–1998 in Lambert azimuthal equal-area projection

On Fig. 8, there has been a rapid increase in temperature in the region (65°–82°N; 15°–70°E) since 1999. Moreover, the temperature increases from 1999 to 2007 at depths of 47–100 m began earlier and surpassed the rise in temperature near the surface at depths of 6–27 m. In the Barents Sea region, there is a quasi-15-year temperature fluctuation caused primarily by heat advection from the North Atlantic [41]. It is possible that this fluctuation was one of the reasons for the rapid rise in temperature in the 2000s. Thus, the presence of feedback between regional changes in air temperature over the water area and sea ice concentration in the Barents and Kara Seas requires additional research.

5. Conclusion

The study showed that in the White Sea region in the last 2 decades (1999–2020) there has been a significant variability of the regional climate, which was expressed in the warming of this region from +0.9 to +1.5 °C compared to previous years (1977–1998), in a sharp increase in air temperature growth (+0.4 — +1.0 °C in 10 years), to a shift of the +2 °C isotherm by 550 km to the north up to the southern part of the White Sea and to the complete disappearance of average negative temperatures.

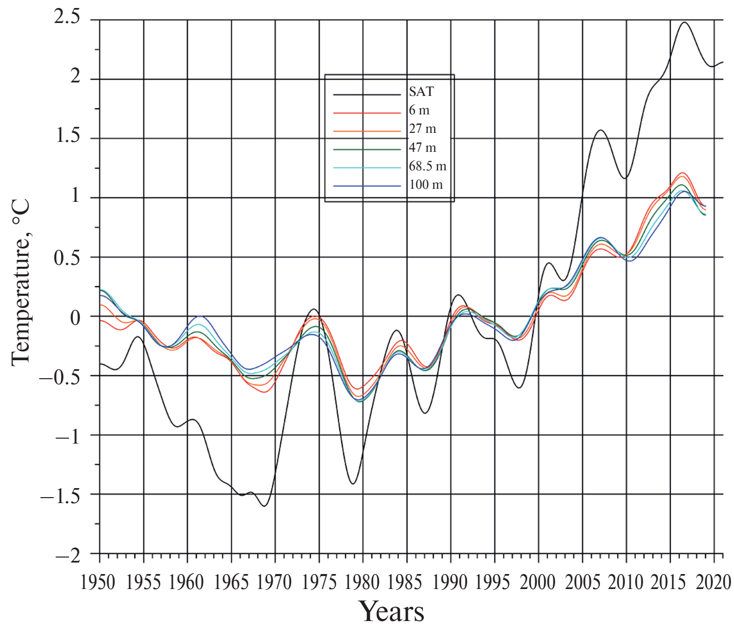

Fig. 8. Changes in mean anomalies of surface air temperature (SAT) for 1950–2020 (black), and ocean temperature anomalies at depths of 6 m (red), 27 m (orange), 47 m (green), 68.5 m (blue) and 100 m (dark blue) for 1950–2018 in the region (65°–82° N; 15°–70° E), smoothed with a 7-year Butterworth low-pass filter

The sharp increase in SAT in the region under study is probably associated with a sharp increase in air and sea temperatures in the Barents and Kara Seas since 1999 (Fig. 8), as well as with a significant reduction in the ice cover of the Barents and Kara Seas (Fig. 7). The sharp increase in SAT in the third selected period, apparently, is associated with an increase in the action of positive feedback between the ocean and the atmosphere. The weakening of the stratification of the upper layer of the Barents Sea water as a result of warming, and increased mixing and upwelling of warmer and saltier Atlantic waters to the surface could lead to a significant increase in sea surface temperature. An additional contribution to the increase in water temperature in the upper layer of the Barents and Kara Seas is made by a positive feedback from the absorption of solar radiation as a result of a decrease in the area of ice cover. Besides, interannual variability of water temperature anomalies in the Barents and Kara Seas showed that there are periods of time when water temperature anomalies at depths of 47–100 m exceed the corresponding anomalies in the near-surface layer (Fig. 8), which means periodic (quasi-15-year fluctuation) dominating influence of heat advection brought by currents from the Norwegian Sea. It is this effect in the period 1999–2007 made a significant contribution when, against the background of a sharp increase in water and air temperatures, water temperature anomalies at depths of 47–100 m exceeded the corresponding anomalies at depths of 6–27 m.

The disappearance of average negative air temperatures is an extremely important fact, since this means a phase transition that will lead to the thawing of permafrost soils throughout the Murmansk and Arkhangelsk regions. The thawing of permafrost soils and a significant increase in average temperatures will lead to a change in the water balance of numerous rivers and lakes in the study region, to an increase in such geomorphological processes as water-snow flows (a kind of mudflows) and landslides-flotations [14] and may have a negative impact on the transport infrastructure [42] including the infrastructure and performance of Russian Railways in the region under study.

It was shown in [42] that for the territory of the Kola Peninsula, which is characterized by high-temperature permafrost of a rare island nature, objects which foundation is formed by piles with a depth of 5 m or less are at very high risks of reducing their functionality, down to zero. So, for example, with a relatively small warming up to +1 °C, piles 5 m deep, still provide functionality $U = 0.65–0.85$ ($U = 1$ corresponds to the maximum level of functionality for a basic, unchanged climate), which is considered an average level of climate risk in relation to the object of transport infrastructure. Warming up to +2 °C often already leads to a decrease in functionality to $U < 0.5$ (in the presence of soils of low humidity), and warming up to +3 °C for objects of this group can be considered catastrophic; functionality decreases to the level $U = 0–0.35$, which corresponds to an unacceptably high level of climatic risks. An extremely important conclusion follows from the study: objects on piled foundations with a depth of less than 6 m are at increased risk even when the temperature rises to +2 °C, so the engineering protection of these objects should be carried out at a pace that outpaces the warming of the regional climate [42].

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