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Original article

Interdecadal Variability of Large-Scale Atmospheric Circulation in the Atlantic-European Sector Conditioning Surface Temperature Anomalies in the Black, Barents and Norwegian Seas

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Abstract
Purpose. The study is aimed at analyzing and assessing the interdecadal variability of winter hydrometeorological fields in the Atlantic-European sector during different phases of the Arctic and North Atlantic Oscillations indices.
Methods and results. The structure of positive (negative) anomalies of the geopotential height was analyzed based on the composite maps of geopotential height anomalies at levels H_{1000} and H_{50}, the North Atlantic Oscillation index was scrutinized using the data from the Climate Prediction Center archives, the sea surface temperature anomalies were surveyed applying the information from the Japan Oceanographic Data Center. The researches covered two periods: a decade of negative and a decade of positive values of the Arctic and North Atlantic Oscillations indices. During a decade of positive values of these indices, the Azores anticyclone and the Icelandic cyclone are intensified, while the Siberian anticyclone weakens. And, on the contrary, during a decade of negative values, the Siberian anticyclone strengthens, while the Azores anticyclone and the Icelandic cyclone wane. Atmospheric circulation in the Atlantic-European sector (the Western Europe subregion) is formed being affected by the Atlantic air masses, and in the Eastern Europe subregion – by the Azores anticyclone and the Siberian anticyclone spur. During a decade of positive phase of the Arctic and North Atlantic Oscillations, the Black Sea surface temperature decreases and becomes lower than the climatic, whereas that of the Barents and Norwegian seas – higher. During a decade of negative phase of the Arctic and North Atlantic Oscillations, the surface temperature of the Black Sea becomes higher, and that of the Barents and Norwegian seas – lower.
Conclusions. During different phases of the Arctic Oscillation, interdecadal variability in the polar vortex intensity affects the redistribution of atmospheric mass between the center of a polar vortex and its boundaries. The consequence of this phenomenon consists in strengthening (weakening) of the Azores, Siberian and Icelandic centers of atmospheric action as well as formation of the interdecadal variability of atmospheric circulation in the Atlantic-European sector. As a result, the pressure structures conditioning the anomalies in surface air and sea surface temperatures with opposite signs are formed in the subregions of the Atlantic-European sector.

Keywords: North Atlantic, hydrometeorological parameters, Black Sea, Barents Sea, Norwegian Sea, temperature anomaly, geopotential, North Atlantic Oscillation, Arctic Oscillation, interdecadal variability

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Introduction

The main atmospheric circulation characteristics influencing weather conditions in Northern Europe are the North Atlantic Oscillation (NAO) and the Arctic Oscillation (AO). The NAO and the AO regulate the intensity of cyclonic and anticyclonic activity in the North Atlantic and Europe [1].

Works [2, 3] note that the AO is involved in the atmospheric mass redistribution between the Arctic and mid-latitudes from the earth's surface to the lower stratosphere and has close ties to the NAO. The correlation coefficient between the NAO and the AO is 0.95 [3]. A characteristic feature of the negative AO phase is high atmospheric pressure over the polar regions and low pressure in the middle latitudes (about 45°N). The picture is opposite with a positive value of the AO index [4–7]. It is shown in [5] that the AO is the dominant variability mode in the field of surface atmospheric pressure and in the field of geopotential heights in the Northern Hemisphere from 20°N to the North Pole. The variability of atmospheric processes is characterized by surface pressure anomalies of the same sign in the Arctic and anomalies of the opposite sign in mid-latitudes 40°–50°N.

A positive surface pressure anomaly is observed in northeast Asia and over Europe during the positive AO phase, and a negative anomaly is observed over Siberia, the Western Arctic and Greenland. An opposite distribution of surface pressure field anomalies is observed during the negative AO phase [5].

Annual NAO index values correlate well with sea surface temperature. The correlation between winter NAO index values and air temperature anomalies in Northern Europe is 0.7–0.8 [8].

In [8], the main features of the hydrometeorological fields of the North Atlantic in the winter months during different NAO phases were summarized based on an analysis of literary sources. The present paper shows that in the Atlantic-European sector, surface pressure and geopotential height at the H_{50} level in the Azores anticyclone and Icelandic cyclone change inphase in different NAO phases [8]. The Azores anticyclone strengthens and the Siberian anticyclone weakens during the positive NAO phase. At the same time, the anomaly of surface pressure and geopotential height in the Icelandic cyclone is negative, and in the Azores anticyclone it is positive [8]. The process of strengthening and weakening of these atmospheric action centers develops in the opposite direction during the negative NAO phase. As shown in [9, 10], this means for Eastern Europe that the Siberian anticyclone effect on the atmospheric circulation [1] increases during the negative NAO phase.

It is known that the interdecadal variability of the NAO index phase occurs in antiphase with the variability of the North Atlantic (AMO index) surface temperature [11].

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[1] Roshydromet, 2008. *Assessment Report on Climate Change and Its Consequences in Russian Federation*. Moscow: Roshydromet, 2008. Vol. 1: Climate Change. 227 p. Available at: http://climate2008.igce.ru/v2008/htm/index00.htm [Accessed: 09 January 2024] (in Russian).

The study is purposed at analyzing and assessing the interdecadal variability of winter hydrometeorological fields in the Atlantic-European sector during different phases of the Arctic and North Atlantic Oscillations indices.

Materials and methods

The work analyzed mean values of hydrometeorological characteristics for January – March from the archives of the Climate Prediction Center and the Japan Oceanographic Data Center.

The mean values of the NAO index, geopotential height anomalies (Monthly/Seasonal Maps and Composites: NCEP/NCAR Reanalysis and other datasets from NOAA Physical Sciences Laboratory) in the selected climate centers of the Azores (25°–40°N, 15°–45°W) and Siberian (5°–55°N, 85°–105°E) anticyclones and the Icelandic cyclone (60°–75°N, 15°–50°W) were retrieved from the Climate Prediction Center archive (https://ftp.cpc.ncep.noaa.gov/wd52dg/data/indices/tele_index.nh). Geopotential height anomalies were analyzed in the surface layer at levels H_{1000} and in the lower stratosphere H_{50}.

Surface temperature values in the Atlantic-European sector were accessed in the Japan Oceanographic Data Center (https://ds.data.jma.go.jp/tcc/products/elnino/cobesst/cobe-sst.html).

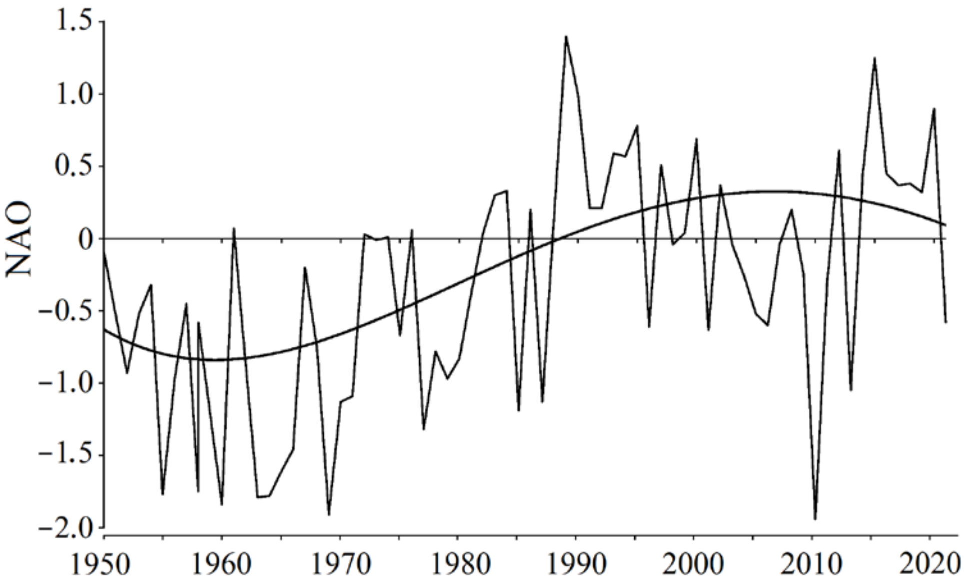
Results and discussion

Hydrometeorological processes in the Atlantic-European sector in different NAO phases in 1950–2020 were studied. It was noted in [8] that the negative NAO phase was observed in 1960–1970 and the positive – in 1980–1990. Fig. 1 shows the interannual variability of the mean NAO index value for January – March. Negative mean values of the NAO index were observed in 1960–1970, positive ones in 1980–2000 (Fig. 1).

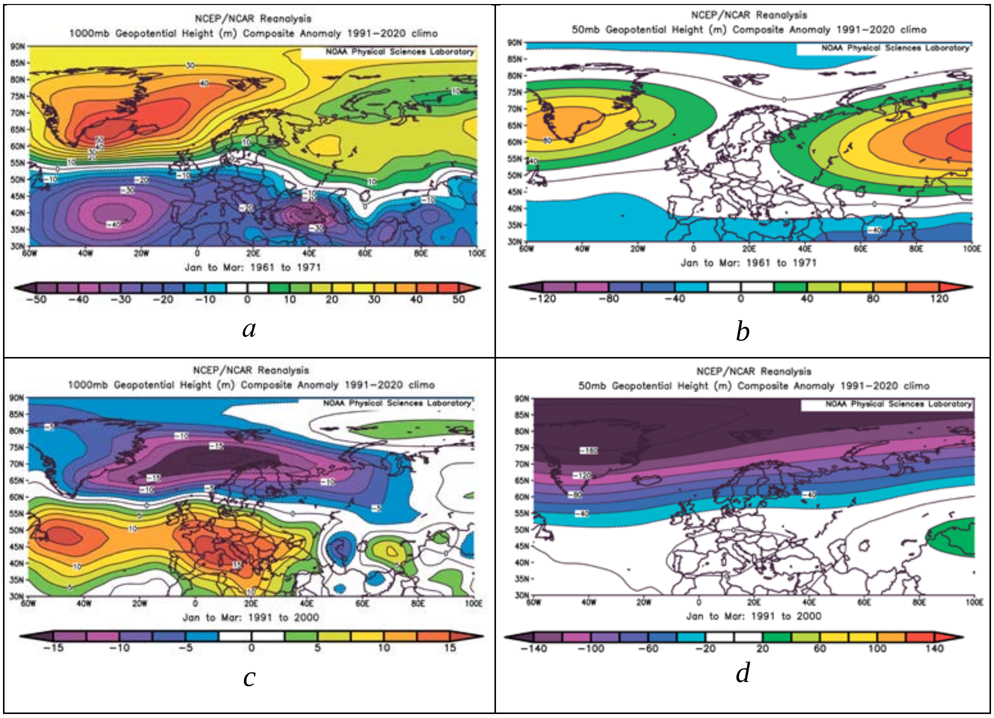
Values of hydrometeorological characteristics averaged over ten-year time intervals were analyzed which made it possible to show the main differences in the values of these characteristics in the studied subregions of the Atlantic-European sector in the indicated decades.

To assess the extreme states of the winter spatial structure of hydrometeorological fields in the Atlantic-European sector, their variability was considered in two ten-year intervals: negative (1961–1970) and positive (1991–2000) NAO index values. The spatial structure of the geopotential height anomaly at the earth’s surface (H_{1000}) and in the lower stratosphere (H_{50}) on the Eurasian continent was considered taking into account that the values of the NAO and AO (stratospheric polar vortex) indices are positive in winter months [7]. Geopotential height anomalies at these levels were calculated relative to the 1991–2020 climate series and are shown on composite maps during various NAO phases (Fig. 2).

The geopotential height anomalies near the earth’s surface and in the lower stratosphere are similar in structure (Fig. 2) in the decade of negative and decade of positive values of the NAO index, which is consistent with the results of [2, 7].



F i g. 1. Interannual variability of the NAO index average values for January – March (thin line) and polynomial trend line (thick line)



F i g. 2. Composite maps of the geopotential height anomalies at H_{1000} (*a*, *c*) and H_{50} (*b*, *d*) during the decade (1961–1970) of the NAO index negative phase (*a*, *b*) and the decade (1991–2000) of its positive phase (*c*, *d*)

In the decade of NAO index negative values (1961–1970), the positive geopotential height anomaly (H_{1000}) extended over the entire Arctic, eastern Europe and Siberia while its negative anomaly was located over Central and Southern Europe (south of 50°N). Fig. 2, *a* shows that in this decade two areas with maximum positive geopotential height anomalies were formed in the subregions of Greenland and Iceland (40–50 m) and in the region of the Siberian anticyclone (20 m). The positive maximum geopotential height anomaly over Greenland is well known as Greenland blocking [12]. According to [1], frequent winter blockings over the North Atlantic are observed in the NAO negative phase. The process of strengthening the Greenland blocking and weakening the Icelandic cyclone occurs simultaneously with the strengthening of the Siberian and weakening of the Azores anticyclone (Fig. 2, *a*). The negative geopotential height anomaly of 40 m occurred in the region of the climatic position of the Azores anticyclone. Another extreme negative anomaly of 30 m was localized near the southeastern part of the Black Sea.

Positive geopotential height anomalies in the subregions of Greenland and the Siberian anticyclone are clearly visible in the lower stratosphere at the H_{50} level. This is especially noticeable in the subregion of the Siberian anticyclone where positive geopotential height anomaly H_{50} exceeds corresponding anomaly H_{1000} by 6–7 times (Fig. 2, *b*).

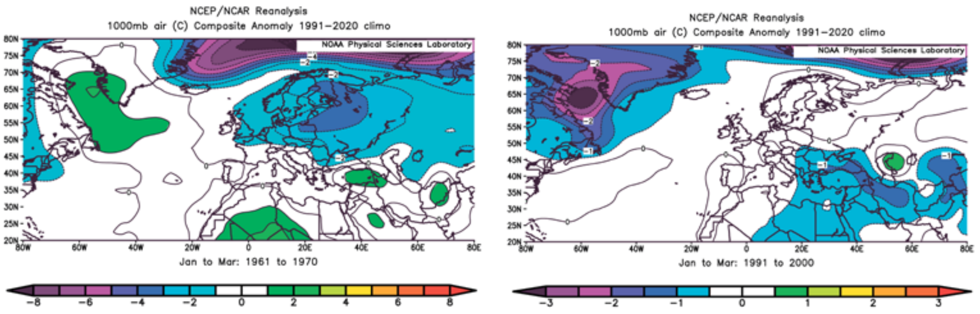
Distribution features of the geopotential height anomaly (Fig. 2, *a*, *b*) lead to the provisional conclusion that these anomalies are well expressed in the atmosphere from the surface layer to the lower stratosphere in the decade of NAO index negative values.

In the decade of NAO index positive values (1991–2000), the Azores anticyclone intensified (Fig. 2, *c*) and the positive geopotential height anomaly was about 10 m in its climatic location subregion (near Newfoundland). At the same time, a second center of the Azores anticyclone with a positive geopotential height anomaly of 15 m is formed in the south of Central Europe (in the north of the Apennine Peninsula). The formation of two Azores anticyclone centers can be explained by the Icelandic cyclone intensification. In this decade, the negative geopotential height anomaly in the Icelandic anticyclone reached 15 m (Fig. 2, *c*), its pressure trough divided the Azores anticyclone into two cores. At the same time, the Icelandic cyclone (Fig. 2, *c*) extended its influence to the seas of the North European basin, including the Barents Sea. A stratospheric polar vortex with a negative geopotential height anomaly of 160 m is formed at high latitudes in the lower stratosphere (Fig. 2, *d*).

Assessment of the geopotential height anomaly value is approximate like all the above assessments, since it depends on the choice of climatic average. For the same reason, the geopotential height anomaly was close to zero in the subregion of the Azores anticyclone and the positive anomaly was 20 m in the subregion of the Siberian anticyclone. In this decade, the features of the vertical structure of the geopotential height anomaly in the Azores, Iceland and Siberian centers of atmospheric action were weakly expressed.

Distribution of geopotential height anomalies (Fig. 2) in the surface layer of the Eurasian region gives an idea of the way how the atmospheric circulation changes in the Atlantic-European sector in the decade of negative and decade of positive values of the NAO index. Consequently, changes appear in the spatial distribution of large-scale anomalies of hydrometeorological fields.

Further, we studied the spatial distribution of the air temperature anomaly in the surface atmosphere layer in the Atlantic-European sector (Fig. 3)



a *b*

F i g. 3. Anomaly of surface air temperature in the Atlantic-European sector during the decades of negative (1961–1970) (*a*) and positive (1991–2000) (*b*) NAO index values

Distribution of the surface temperature anomaly in the Atlantic-European sector (Fig. 3) shows a good relationship with the distribution of the geopotential height anomaly (Fig. 2). Note that the geopotential height anomaly and atmospheric pressure are closely related [8].

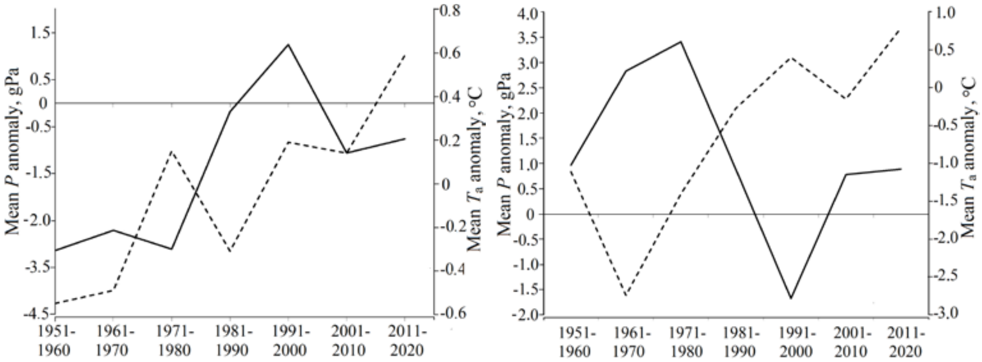
The anticyclonic circulation of the surface atmosphere represented by a positive geopotential height anomaly at the H_{1000} level in the area between Greenland and Iceland “pumped” warm Atlantic air into the Labrador Sea region during the decade of NAO index negative values (1961–1970). A positive anomaly of surface air temperature was formed in this area. This is consistent with the results of [13]. Arctic air was “pumped” into the region of Scandinavia and northern Europe along the eastern periphery of the anticyclone near Greenland and Iceland (Fig. 2, *a*) which led to the formation of a negative anomaly of surface air temperature [13]. In subtropical latitudes (Fig. 3, *a*), the cyclonic circulation formed during the decade of NAO index negative values generated air temperatures in the Southern Europe regions that were close to the climatic.

In the decade of NAO index positive values (1991–2000), the surface air temperature anomaly in the Atlantic-European sector was negative (Fig. 3, *b*). With the strengthening of the Newfoundland core (Fig. 2, *c*), the Azores anticyclone “pumped” Arctic air into the Labrador Sea region forming a negative anomaly of surface air temperature in this area.

The western periphery of the Apennine core of the Azores anticyclone (Fig. 2, *c*) “pumped” Atlantic air into high latitudes forming there an air temperature close to the climatic. The eastern periphery of the Apennine core of the Azores anticyclone transported Arctic air to subtropical latitudes forming a negative anomaly of surface air temperature in this region (Fig. 3, *b*).

The pressure field in Western and Eastern Europe differed widely in the decade of negative and the decade of positive values of the NAO index (Fig. 2, *a*, *b*).

To identify differences in the structure of thermobaric characteristics in the European part, two subregions were selected: western (40°–70°N, 10°W – 10°E) and eastern (50°–70°N, 30°E – 50°E) ones. Fig. 4 shows surface pressure and air temperature variability in these subregions.



a *b*

F i g. 4. Anomalies of surface pressure P' (solid line) and air temperature T_a (dashed line) in the western (*a*) and eastern (*b*) subregions

The western subregion was in the area of negative surface pressure anomaly (it corresponds to the area of negative geopotential height anomaly at the H_{1000} level in Fig. 2, *a*) in the decade of NAO index negative values (Fig. 4, *a*). The eastern subregion (Fig. 4, *b*) was located in the area of positive surface pressure anomaly (it corresponds to the area of positive geopotential height anomaly at the H_{1000} level in Fig. 2, *a*). Atmospheric processes in this subregion were influenced greatly by the Siberian anticyclone.

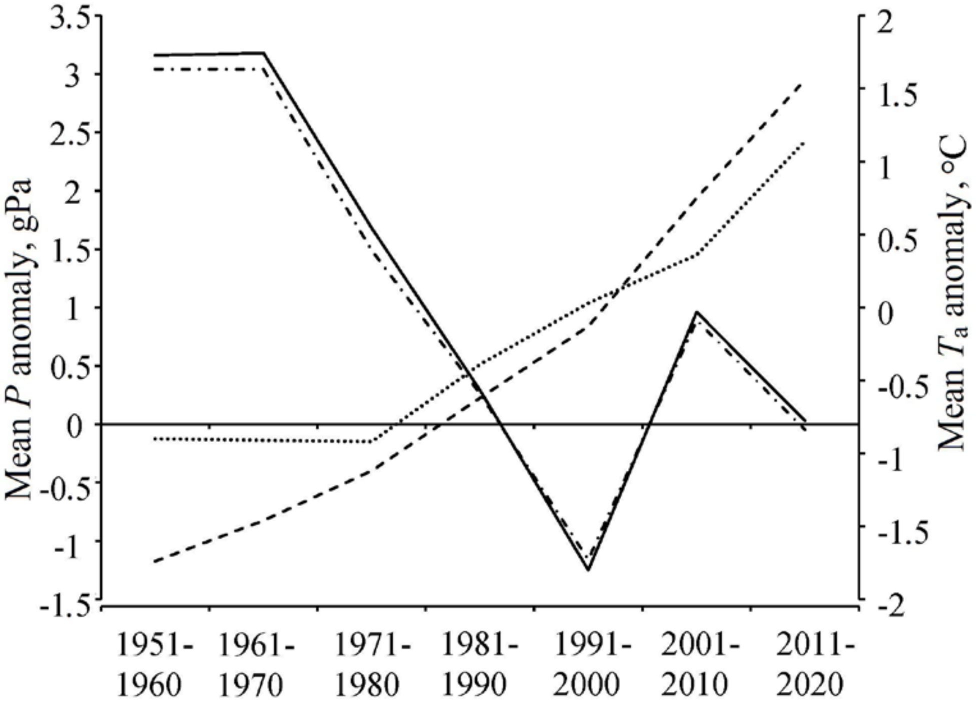
On the contrary, the western subregion (Fig. 4, *a*) was in the region of a positive surface pressure anomaly (positive geopotential height anomaly at H_{1000}) (Fig. 2, *c*) and the eastern subregion (Fig. 4, *b*) – in the area of negative surface pressure anomaly (negative geopotential height anomaly at H_{1000}) (Fig. 2, *c*) in the decade of NAO index positive values. Therefore, it can be said that the interdecadal variability of the surface pressure anomaly occurred in antiphase in these subregions.

The interdecadal variability of the air temperature anomaly in the western and eastern subregions reflects the thermal influence characteristics of the North Atlantic on the Eurasian continent. It was determined by the variability of the North Atlantic surface temperature anomaly (AMO index [14]) in the western subregion (Fig. 4, *a*) and it was influenced by processes determined by the Azores anticyclone and the Siberian anticyclone in the eastern subregion (Fig. 4, *b*).

A negative air temperature anomaly was formed during the Arctic air invasion with the weakening of the Azores and the strengthening of the Siberian anticyclone in the decade of NAO index negative values (Fig. 4, *b*).

The opposite process was observed in the decade of NAO index positive values (Fig. 4, *b*): the strengthening of the Azores and weakening of the Siberian anticyclone created a positive air temperature anomaly in the eastern subregion.

The surface thermobaric field in the Atlantic-European sector was manifested in surface pressure and air temperature anomalies in the subregions of the Black Sea and the North European basin seas. Fig. 5 shows the interdecadal variability of the winter anomaly of these characteristics in the Norwegian and Barents Seas.



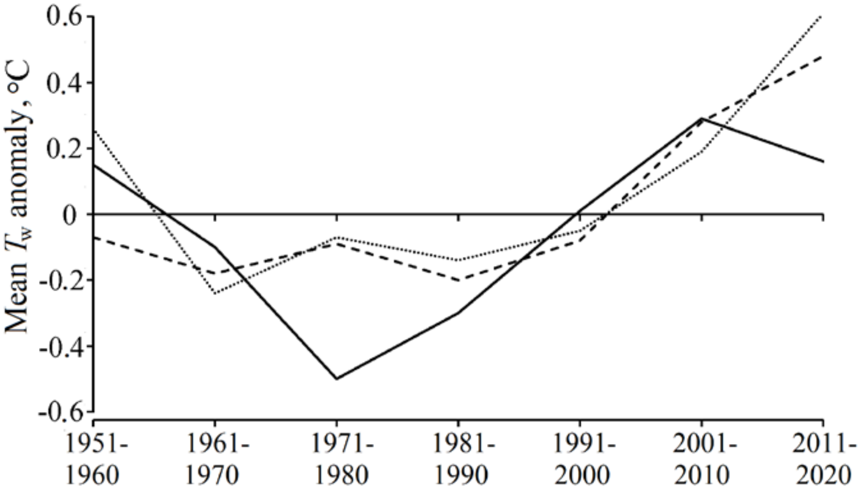
F i g. 5. Interdecadal variability of the atmospheric pressure anomaly P' in the Barents (dash-dotted line) and Norwegian (solid line) seas and the surface air temperature anomalies in the regions of the Barents (dotted line) and Norwegian (dashed line) seas

A positive anomaly of surface pressure was noted during the AO and NAO negative phase (1950–1970) with the developed Greenland blocking [7]. Anticyclonic atmospheric circulation conditions characterized by low air temperatures prevailed during these years over the Norwegian and Barents seas (Fig. 5).

A negative surface pressure anomaly which created cyclonic atmospheric circulation conditions supporting a positive surface air temperature anomaly prevailed in the region of these seas during the decades of the AO and NAO positive phase (1981–2020). The correlation between surface pressure anomalies and air temperature in the region of the Norwegian and Barents Seas is significant and equal to − 0.68.

The formation of the sea surface temperature anomaly occurred with the Atlantic water mass participation brought to the region by the Norwegian Current. Therefore, the interdecadal variability of the surface temperature anomaly of the Norwegian and Barents Seas was largely determined by the corresponding AMO index variability (the mean North Atlantic surface temperature anomaly for January – March).

The AMO index analogue – the mean North Atlantic surface temperature anomaly for January – March – was used to assess the interdecadal variability of the sea surface temperature anomaly. The water area determining this anomaly was limited to coordinates of 30°– 60°N, 10°– 55°W (Fig. 6).



F i g. 6. Interdecadal variability of surface temperature anomaly of the North Atlantic (solid line) and surface temperature of the Norwegian (dashed line) and Barents (dotted line) seas

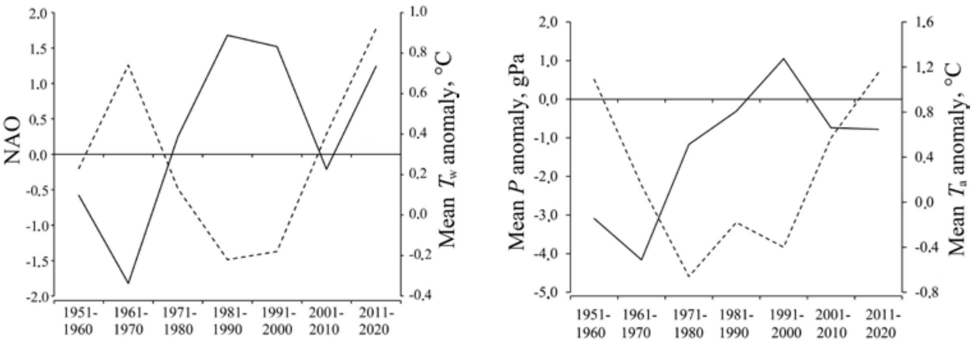
North Atlantic surface temperatures were below the climatic in 1960–1990 and above it in 1950 and 2000–2020 (Fig. 6). Corresponding anomalies in the surface temperature of the Norwegian and Barents seas were observed in the same decades. The correlation coefficient between the surface temperature anomaly of these seas and the surface temperature anomaly of the North Atlantic is significant and equal to 0.64. It can be assumed that the interdecadal variability in the surface temperature of the Norwegian and Barents Seas was determined mainly by the corresponding variability in the surface temperature of the North Atlantic.

The regions of the Norwegian and Barents Seas were characterized by anomalously high surface pressure in the decade of NAO index negative values (1961–1970) while the Black Sea region – by anomalously low surface pressure. The same antiphase in the distribution of the surface pressure anomaly was observed in the decade of NAO index positive values (1991–2000).

The Black Sea region and the regions of the Norwegian and Barents Seas differ as changes in the surface temperature anomaly of the Atlantic waters do not have a direct impact on the surface temperature formation of the Black Sea [15]. The main contribution to the formation of the surface temperature and Black Sea surface temperature anomalies is made by atmospheric circulation.

In the Black Sea region, cyclonic atmospheric circulation prevailed in the decade of NAO index negative values and anticyclonic circulation prevailed in the decade of NAO index positive values [15].

Fig. 7 shows interdecadal variability of surface air temperature, sea surface temperature and atmospheric pressure in the Black Sea. Atmospheric circulation is represented by the NAO index in this figure.



a *b*

F i g. 7. Interdecadal variability of the NAO index (solid line) and the anomalies of sea surface temperature (dashed line) (*a*), surface pressure (solid line) and surface air temperature (dashed line) (*b*) of the Black Sea

Fig. 7 shows that the interdecadal variability of the surface pressure anomaly is consistent with the NAO index variability in the Black Sea region. The correlation coefficient between NAO and atmospheric pressure is 0.90. Accordingly, cyclonic atmospheric circulation conditions prevailed in the region and the sea surface temperature was above the climatic in the decade of NAO index negative values (1961–1970). Anticyclonic atmospheric circulation conditions prevailed in the region and the sea surface temperature was below the climatic in the decade of NAO index positive values (1980–2000).

The interdecadal variability of surface air temperature corresponds to the variability of the sea surface temperature anomaly with a correlation coefficient of 0.64. However, negative values of the surface temperature anomaly in the 1971–1980 and 1991–2000 decades confirm that surface air temperature is formed in the Black Sea region under the influence of the Arctic air intrusion.

Large-scale atmospheric circulation restructuring determined by the AO and NAO indices forms the main features of the surface pressure field structure in the Atlantic-European sector. The mutual influence of the Azores and the Siberian anticyclone on the pressure fields of these subregions is clearly visible in the correlations (Table).

Correlation coefficient between the NAO index and the surface pressure anomaly, hPa, in the western and eastern subregions of Europe

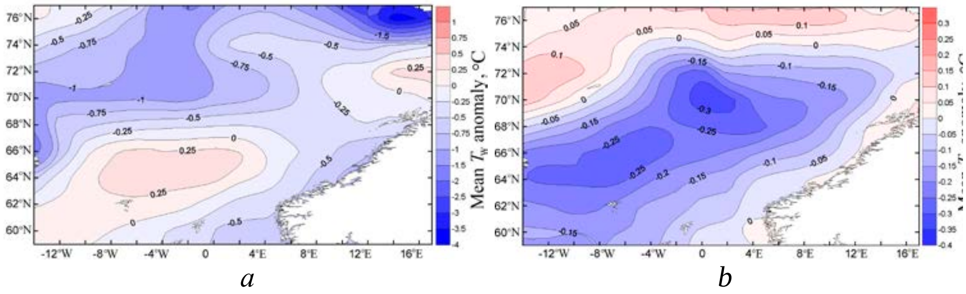
Parameter	P'_{W}	P'_{E}
NAO	0.78	−0.73
P'_{W}	–	−0.79
P'_{E}	−0.79	–

Note: P'_{W} is surface pressure anomaly in the western subregion of Europe; P'_{E} is surface pressure anomaly in the eastern subregion of Europe.

Surface pressure in the western subregion changes in phase with the NAO index, while in the eastern subregion it is in antiphase. Accordingly, surface pressure in the western subregion is higher than the climatic value in the decade of NAO positive values and lower in the decade of its negative values and vice versa in the eastern subregion.

Therefore, it is advisable to consider the spatial structure using composite maps of the surface temperature anomaly of the Norwegian, Barents and Black Seas in the decade of negative (1961–1970) and decade of positive (1991–2000) NAO index values (Figs. 8–10). Fig. 8 shows the values of the surface temperature anomaly of the Norwegian Sea in various NAO phases averaged over January – March.

During the decade of NAO index negative values (Fig. 8, *a*), a positive surface temperature anomaly in the Norwegian Sea was recorded in its southern part, approximately in the localization area of the Norwegian Current. A negative surface temperature anomaly was observed in the northern part of the sea, in the area where the Norwegian and Lofoten gyres are located.

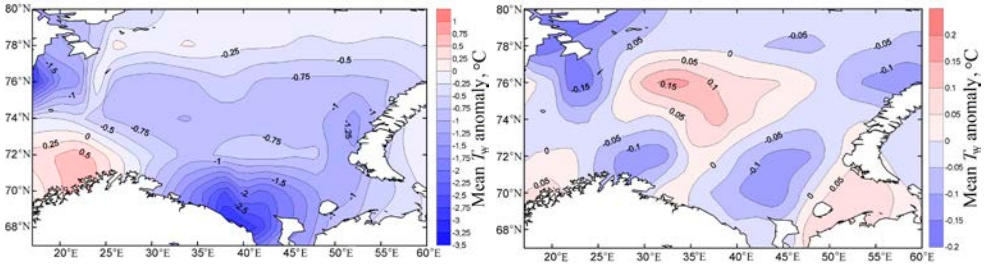


F i g. 8. Surface temperature anomaly in the Norwegian Sea during the decades of negative (*a*) and positive (*b*) values of the NAO index

The positive temperature anomaly shifted to the north of the Norwegian Sea while the negative one – to the south of the sea in the Norwegian Current area in the decade of NAO positive index values (Fig. 8, *b*). One of the reasons for the change in the sign of the surface temperature anomaly in the Norwegian Current could be an increase in the Atlantic water flow through the Faroe-Shetland Strait into the Polar Basin in the years of NAO index negative values [16, 17]. At the same time, the inflow of Atlantic waters into the Norwegian Sea through the Iceland-Faroe threshold and the Denmark Strait increased [18]. The pattern of currents in the Norwegian Sea [18] suggests that the Norwegian Current branch generated cyclonic and anticyclonic gyres in the Norwegian and Lofoten basins in the years of NAO index negative values. This could be the reason for the increase in the negative surface temperature anomaly in the Norwegian Basin and its decrease in the Lofoten Basin (Fig. 8, *a*). The weakening of the Atlantic waters inflow into the Norwegian Sea which is typical for a decade of NAO index positive values [16, 17] could be the reason for the change in the sign of the gyres in the Norwegian and Lofoten basins as a result of which the sign of the surface temperature anomaly in these areas changed (Fig. 8, *b*).

In the Barents Sea, a negative sea surface temperature anomaly with the coldest waters located in its southern and eastern regions was observed during the decade of NAO index negative values (Fig. 9, *a*). Colder waters occupied the eastern and western peripheries of the sea and warmer waters occupied the central part of the Barents Sea in the decade of NAO index positive values (Fig. 9, *b*).

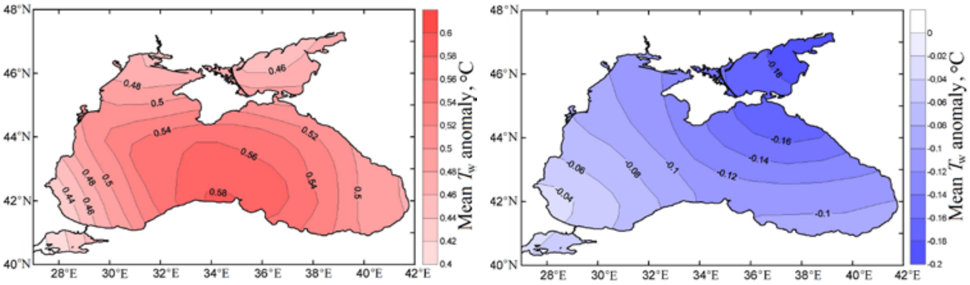
It can be assumed that in this case the localization of areas with warmer and colder water was also determined by the existence of anticyclonic and cyclonic gyres in the Barents Sea region. Thus, it is known that a transformation of the thermohaline characteristics of water masses takes place in the eastern part of the Barents Sea [19]. As a result, a water mass with components of the Fram and Barents Sea branches of Atlantic water is formed [20].



a *b*

F i g. 9. Surface temperature anomaly in the Barents Sea during the decades of negative (*a*) and positive (*b*) values of the NAO index

Fig. 10 shows the spatial distribution of the Black Sea surface temperature anomaly in the decade of negative and decade of positive NAO index values.



a *b*

F i g. 10. Surface temperature anomaly of the Black Sea during the decades of negative (*a*) and positive (*b*) values of the NAO index

The surface temperature of the Black Sea is above the climatic in the years of NAO index negative values and cyclonic atmospheric circulation (Fig. 10, *a*) and below the climatic in the years of NAO index positive values with anticyclonic circulation (Fig. 10, *b*) which is consistent with the results given in [15].

Conclusion

1. Interdecadal variability of winter hydrometeorological characteristics in the Atlantic-European sector is regulated by atmospheric circulation. Its large-scale fluctuation is formed to a large extent by the polar vortex dynamics.

2. The Azores, Siberian and Icelandic centers of atmospheric action strengthen or weaken depending on the stage of polar vortex development (AO phase).

3. Local regions with different characteristics of atmospheric circulation are formed in the Atlantic-European sector. They create corresponding anomalies in surface pressure, air temperature and surface temperature in the subregions of Europe and the seas of the North European basin.

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