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NORTH ATLANTIC OSCILLATION: DESCRIPTION, MECHANISMS, AND INFLUENCE ON THE EURASIAN CLIMATE

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The present work is devoted to the characteristic of the North-Atlantic Oscillation and the analysis of the state-of-the-art of this problem. In the survey section of the work, we deal with the following issues: the definition of the North Atlantic and Arctic Oscillations, their interaction with oceanic processes, and their influence on the variations of climate in Eurasia. In addition, by using the *COADS* (Comprehensive Ocean Atmosphere Data Set) data and the data on the discharge of European and Asian rivers, we establish some new original results. It is confirmed that the anomalies of the sea-surface temperature are consequences of the integral response of the ocean to the preceding atmospheric actions and that the spectra of these anomalies are characterized by the presence of significant peaks within the band of periods of 10–20 yr. These periods correspond to inherent oceanic variability. The atmospheric response manifests itself in the form of abnormal conditions over the catchment areas of European and Asian rivers, which leads to oscillations of their discharges. As a result of the intensification of the North Atlantic Oscillation and the displacement of the centers of action of the atmosphere in the 60–90s of the previous century, the influence of this oscillation on the climatic conditions in the European-Asian region became more intense.

Introduction. Basic Definitions

The general atmospheric circulation in the North Atlantic is characterized by the following basic specific features [1]: Trade winds are located between the region of high pressure at subtropical latitudes (Azores High) and the region of low pressure in the vicinity of the intratropical convergence zone [ITCZ (tropical depression)]. The drop of pressure between these zones characterizes the intensity of trade winds. Due to the asymmetry of the distribution of land area over the Globe, the subtropical regions of high pressure in the Northern and Southern Hemispheres and the zone of tropical depression are located asymmetrically about the equator. In the Atlantic Ocean, these centers of atmospheric action (CAA) are shifted northward (by several degrees). Moreover, the indicated shift is more pronounced in the east part of the Atlantic than in its west part. As a result, on the average (over a year), the axis of the ITCZ is located in the Northern Hemisphere. It is inclined to latitudinal circles and, thus, lies between 3 and 4°N at 45°W and between 6 and 7°N at 15°W. West winds are predominant to the north of the Azores High and up to about 60°N. At 60°N, a region of low pressure is formed near Iceland (Iceland Low). The gradient of pressure between the Azores High and Iceland Low specifies the intensity of west transfer at mid latitudes and weather over the European continent. The change in the direction of zonal atmospheric circulation from eastward in tropics to westward at middle latitudes is caused by the instability of the Hadley cell at mid latitudes. This instability leads to the development of cyclones and anticyclones in which the wind velocity is much higher than the velocity of the mean flow. The North-Atlantic cyclones traveling in the northeast direction prove to be especially intense. They carry relatively warm and humid air from the regions of the Atlantic close to the Gulf Stream and North-Atlantic Current to Europe and form, at middle latitudes, the predominant westerly over the European continent [2].

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Table 1. Monthly Average Characteristics of the North-Atlantic Centers of Atmospheric Action for 1890–1990

Month	Azores High			Iceland Low		
	P, mbar	°N	°W	*P*, mbar	°N	°W
1	1024	35	19	994	62	27
2	1024	36	20.5	996	60	29
3	1022.5	35	29	1000	59	31
4	1022	34	30	1005	61	28
5	1023	34	33	1007	58	34
6	1024	34	34.5	1008	61	46
7	1025	33.5	37	1009	63	39
8	1023	35	35.5	1007	64	25
9	1022	36	31	1004	64	26
10	1020.5	35	34	1001	62.5	27.5
11	1022	35	30	998.5	62	24
12	1023	34	26	999	63	24

The quasisynchronous low-frequency oscillations of pressure in the Azores High and Iceland Low are called the North-Atlantic Oscillation (NAO). This phenomenon was described for the first time in [3]. As a quantitative characteristic of the NAO, it is customary to use either the so-called NAO index [defined as the normalized difference between the surface pressures recorded at one of the hydrometeorological stations on the Azores (or in Lisbon) and at one of the stations in Iceland] or the Rossby index (more precisely, its analog [4] defined as the difference between the sea-level pressures in the analyzed CAA; however, for the sake of brevity, we use the term "Rossby index"). The climatic characteristics of the CAA obtained according to the data of the VNIIGMI-MTsD [5] are presented in Table 1. It is easy to see that, for a typical seasonal cycle, the CAA shift in the space by more than 10°. Their displacements are especially pronounced along the latitudinal circles. As a result, the coefficient of correlation between the monthly values of the NAO and Rossby indices varies from 0.54 to 0.77 and attains its maximum value in winter [2]. The spectra of both indices contain significant peaks corresponding to periods of 2–4 and 6–10 yr. Oscillations with characteristic periods of 50–100 yr can be distinguished on a significant level according to the paleodata. The long-term trends also detected in the spectra reflect the decrease in the distance between the CAA and the intensification of the NAO in the 20th century [5–9]. As an indirect proof of the existence of 65–70-yr oscillations of the NAO index, one can mention the results obtained in [10]. In this work, the oscillations of temperature of the corresponding periods were detected for the North Atlantic. In numerous works, it is shown that the intensification of the NAO on the annual and decadal scales is accompanied by the displacement of the Azores High and Iceland Low in the northeast and north directions, respectively. At the same time, the process of weakening of the NAO results in their displacements in the southwest and south directions, respectively [4, 5, 8, 11–13]. The variations of the intensity of zonal circulation over the North Atlantic and the displacement of CAA promote significant changes in the climatic conditions over Europe [4, 6, 11–14].

In [15], one can find a different definition of the NAO. Barnston and Livezey used the term NAO to denote one of the leading empirical orthogonal functions (EOF) in the expansion of the large-scale field of atmospheric pressure in the Northern Hemisphere. The appearance of this definition is explained by the fact that the space structure of this EOF is characterized by the presence of extrema in the regions of the Azores High and Iceland Low. In addition, it was discovered that this is the sole mode detected in all seasons of the year. In winter (of the Northern Hemisphere), this mode contains the maximum fraction of variance of the field, i.e., this is the first EOF. In [16], this mode is called Arctic Oscillation (AO) because, in the expansion of the pressure field constructed in the cited work, it is characterized by a high degree of zonal symmetry with extremum attained in the Arctic basin. In the literature [17, 18], the problem of different definitions of the NAO caused by different structures of the EOF is a matter of active discussions. In the present work, we also discuss the causes of the appearance of different structures of the EOF in the expansions of the field of atmospheric pressure constructed in different works.

The principal unsolved problem in the analysis of the mechanism of formation of the indicated peaks in the spectrum of the NAO index is connected with the role of the ocean in the annual and decadal variability of the NAO. The efficiency of action of the oceanic anomalies on the atmospheric circulation at middle latitudes is also unclear. What excites the corresponding climatic modes: the oceanic processes or oscillations inside the atmosphere? The problem is connected, in particular, with the detection of relatively weak signals against the background of intense noises caused by the internal variability of the atmosphere. The leading role of the atmosphere on the analyzed scales is emphasized by some authors [19]. At the same time, one can also find indications of the important role played by oceanic anomalies in the generation of interannual variability at extratropical latitudes [20–22]. The discussion of this problem is the main aim of the present work. Finally, we consider the manifestations and efficiency of the influence of the NAO/AO on climate in Eurasia by analyzing the variability of river discharge. Our work continues the general discussion about the mechanisms maintaining the NAO/AO and climatic consequences of this phenomenon originated in [23].

Characteristic of the Used Data and the Procedure of Their Processing

In the present work, we used the *COADS* (Comprehensive Ocean Atmosphere Data Set) data (version of 24.06.1999) on the sea-surface temperature (SST) and sea-level pressure for 1950–1997 with monthly resolution on a 2×2° regular grid. We studied a region of the Atlantic between 0–60°N and 0–70°W. The data were averaged over time for consecutive couples of months (January–February, March–April, etc.) and over space at the nodes of a 10-degree grid for five 2-degree squares in the vicinity of each point. This procedure was performed to improve the statistical significance of the results and reduce the amount of processed data.

The original data array was analyzed by the EOF method frequently used in practice for data processing on a regular grid [24, 25]. According to this method, the original field $F(x, t)$ is expanded in a series in certain functions $X_n(x)$ with coefficients $T_n(t)$ $(n = 1, 2, 3, \dots)$ varying from one field to another:

$$F(x, t) = \sum (T_n(t) X_n(x)).$$

In this case, the procedure of determination of unknown functions is based on a single condition that the sum of squared errors of the expansion over all points of a given collection for the analyzed field must be minimum for all n. The empirical orthogonal functions minimizing the sum of squared errors of the expansion form the best possible basis for the representation of the original ensemble. This basis is specific for each individual case of expansion.

Later, this method was developed in numerous works. First, it was generalized to the case of complex variables, which, in principle, made it possible to detect nonstationary modes. Second, several modifications of the traditional expansion were proposed. As one of the most popular, we can mention the method of rotating components used, in particular, in [15]. In [26], one can find the critical comparison of these and some other generalizations as applied to the analysis of hydrometeorological fields.

In the present work, we used the traditional method of EOF. Indeed, the expansion of the *COADS* data was constructed with the help of this method. At the same time, the accumulated results were compared with the results of expansions obtained by using different methods. Prior to the application of the EOF method, the average climatic field was subtracted from the obtained ensemble of points. After this, the linear trend was subtracted from the fields obtained as a result and they were expanded in the EOF. Finally, we obtained the distributions of SST averaged over two months, the field of trends in the investigated region, the leading five space modes whose contribution to the variance is maximum, and the time coefficients corresponding to each mode.

The monthly values of the NAO and Southern-Oscillation (SO) indices were found as the differences between, respectively, the values of sea-level pressure (normalized to the standard deviation) at the hydrometeorological stations in Iceland (Reykjavik) and on the Azores (Ponta-Delgada) and the values of sea-level pressure at the stations on Tahiti and in Darwin (Australia). The Rossby index and the characteristics of displacements of the CAA in the North Atlantic were computed according to 100-yr monthly series studied in detail in [5].

The data on the surface temperature of air in the European region for 1979–1993 were borrowed from the data of reanalysis of the European Center of Medium-Range Weather Forecasts (ERA). Their characteristic is given in [14].

The monthly values of the flow rates of European and Asian rivers determined according to the individual empirical relationships between the level and flow rate (the so-called hodographs) can be regarded as an integral parameter of the hydrometeorological conditions over their water-catchment areas. In the present work, we used data on the monthly average flow rates of the Danube (for 1947–2002), Dnieper, Dniester, and Yuzhnyi Bug (for 1947–1993), Garonne (for 1921–1994), Loire (for 1891–1994), Volga (for 1932–1995), Severnaya Dvina (for 1881–19850, Ob (for 1930–1994), and Yenisey (for 1936–1995) as well as data on the annual average flow rates of the Danube for 1855–2001.

The time series and the coefficients of expansion in EOF were subjected to statistical analysis based on the use of standard algorithms and software. The spectral estimates obtained by using nonparametric methods were smoothed with the help of the Parzen window. After this, we computed the coefficients of correlation between the interannual (with periods of 2–7 yr), decadal (7–20 yr), and low-frequency (> 20 yr) oscillations in the fields of pressure and SST and between the oscillations of the flow rates of rivers with these periods for different time shifts. To detect these oscillations, all time series were subjected to filtering with the help of the corresponding time filters.

Results, Their Analysis, and Discussion

Characteristic and Possible Causes of Trends in the Behavior of Temperature and Pressure. The obtained fields of trends in the behavior of SST for the couples of months can be conventionally split into the following two structures: winter (November–April) and summer (May–October).

The winter structure is characterized by the presence of a large zone in the north of the region (bounded between 45 and 60°N) with negative trends of temperature. For the major part of points in this zone, which approximately coincides with the subpolar cyclonic gyre, we observe a significant (at the 95% level) negative trend of SST. This trend exceeds (in the absolute value) $-0.3°$ per 10 yr for January–February in the region of formation of Labradorean waters. The winter structure is also characterized by the presence of the second zone of significant negative trends in the behavior of SST located in the northwest part of the Equatorial Atlantic. However, these trends are much less pronounced (in the absolute values) than the trends observed in the subpolar region (up to $-0.1°$ per 10 yr). The region with positive values of trends approximately coincides with the subtropical anticyclonic gyre and the zone of upwelling in the east part of the North Atlantic (Fig. 1a). The number of significant points in this region increases from January to April. The maximum values of the positive trends are attained in January–February ($>0.1°$ per 10 yr). Thus, it is clear that the subpolar region of the North Atlantic undergoes cooling, whereas the temperature of the northern tropical and subtropical waters increases. The intensity of the negative trend at equatorial latitudes is three times lower (in the absolute value) than in the subpolar gyre. This must lead to the intensification of the meridional thermohaline circulation in the ocean and atmospheric circulation (Hadley cells). Actually, there are two zones of significant trends in the field of trends of atmospheric pressure. One of these zones is located near the Azores High. In this zone, positive trends (>1 mbar per 10 yr) are observed in winter (in spring, these trends can be even more intense: >1.2 mbar per 10 yr). The second zone with negative trends (up to -2.25 mbar per 10 yr in winter) is located near the Iceland Low (Fig. 1b). In this way, the Rossby index determined according to the first EOF of the winter pressure field increased by about 15 mbar for 50 yr. This is about 50% of the average value of this index in 1890–1990. Note that this estimate is several times greater the value of trend of the Rossby index established in [5, 8] according to the 100-yr series of pressure at the CAA.

The summer structure of trends of SST resembles the winter structure with the sole exception of a region of insignificant negative trend in the Equatorial Atlantic. In addition, we also observe the displacements of the regions with positive trends in the Subtropical Gyre. The maximum number of significant trends and the maximum absolute values of these trends in summer are observed in July–August in the Subpolar Gyre, where their level is close to the winter values ($-0.3°$ per 10 yr). On the whole, the accumulated results confirm the estimate of trends made in [27] according to different data for 1957–1990.

Thus, it is easy to see that, for a period of 48 yr, the temperature drop between the equator and the pole increased and the zonal atmospheric circulation became more intense both in winter and in summer, mainly as a result of cooling of the west part of the Subpolar Gyre. These phenomena manifest themselves in the growth of the NAO index in the 60–90s of the previous century described in numerous works.

Note that, for the climatic changes in the Euro-Asian region, the role played by the long-term variations of the coordinates of the North-Atlantic CAA is in no case less significant than the role of trends in the NAO index. Thus, for a period of 100 yr (since 1890), the Iceland Low shifted to the southwest by about 10° and the Azores High shifted to the northwest by more than 6° [5]. This was the main cause of strengthening of the influence of the NAO on climate in Eurasia (see below).

The correlated character of trends in the behavior of SST and sea-level pressure is obvious. It was studied in numerous works [2, 5, 8, 27–29]. Nevertheless, the main causes of these trends remain unclear. Some authors believe that the analyzed long-term trends are anthropogenic. The other authors insist on their natural origin and assume that these trends are mainly caused by slow variations of the thermohaline circulation cell in the World Ocean controlled by the rate of formation of abyssal waters. In view of the absence of the data of long-term deep-water observations, it is now impossible to solve this problem completely (see [30] and the discussion in [31]). The contemporary state of simulation of the long-term variability of NAO within the framework of combined models of the ocean and atmosphere is often insufficient to reproduce the observed changes even qualitatively [32, 33]. In fact, this was also recognized in [34, p. 633], despite general optimistic conclusions concerning the quality of simulation of the time structure of NAO. Moreover, there are different points of view even concerning the estimates of trends of the characteristics of NAO on the 100-yr scale. Thus, as indicated in [28], the trends of pressure at the CAA over the ocean interior are partially caused by the gradual improvement of the means of observations, i.e., they are artificially overestimated. The analysis of the results presented in [5, 8, 18] definitely show that the 100-yr trend in the behavior of the characteristics of NAO is mainly caused by their abrupt changes in the 60–90s of the previous century. If we remove the variations with a typical period of 70 yr definitely present in the 100-yr series for the North Atlantic [10, 35], then the level and significance of the analyzed trends become much lower [5].

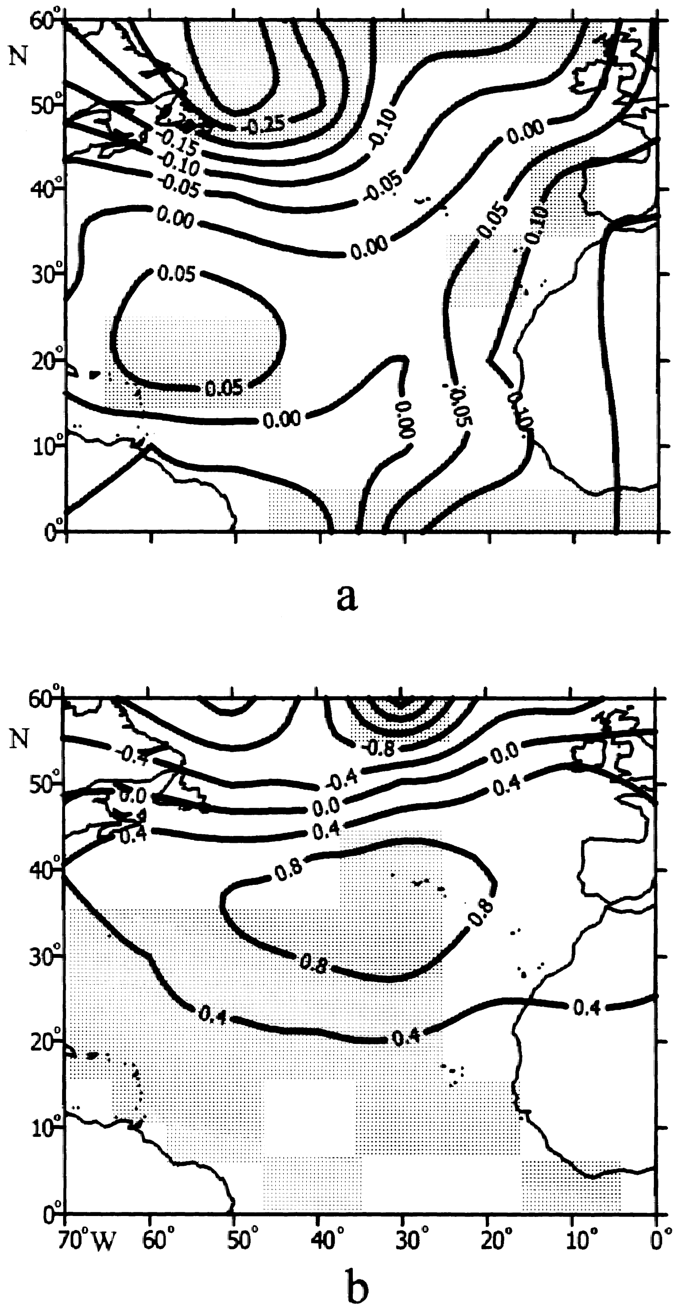

Fig. 1. Trends in the behavior of SST (degrees per 10 yr) (a) and sea-level pressure (mbar per 10 yr) (b) averaged over January–February for the North Atlantic in 1950–1997. Regions with significant trends (at the 95% level) are shaded.

Thus, the problem of the relative roles of natural and anthropogenic factors in the formation of the observed climatic variability on the 100-yr scale in the North Atlantic remains open. Moreover, this problem can hardly be solved in the nearest future due to the absence of long-term data on the state of the entire climatic system and the complexity of this system. At the same time, it is clear that the role of the ocean on the analyzed scale is of principal importance in even if the anthropogenic factor is predominant. This observation is, in particular, confirmed by the fact that the maximum values of the trends of SST are observed in the region of formation of abyssal waters in the North Atlantic (Fig. 1a).

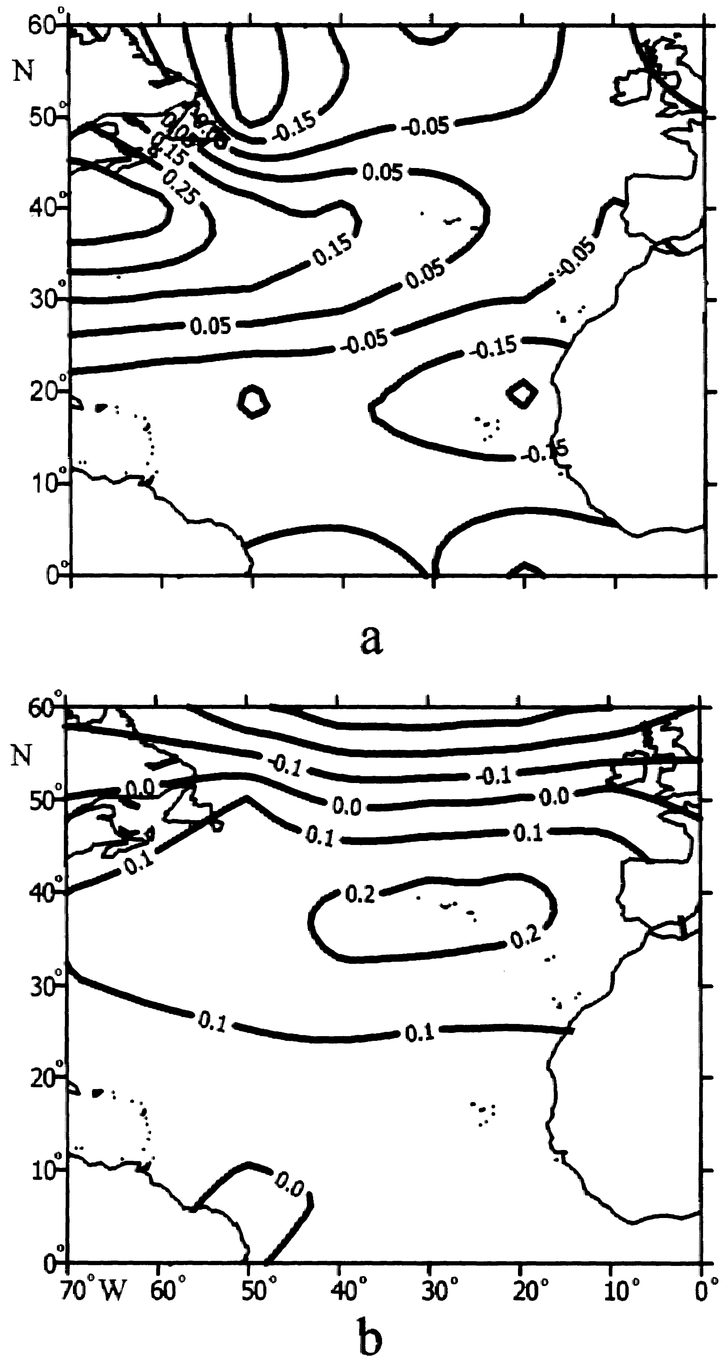

Fig. 2. Space structure of the first EOF in January–February according to the data accumulated in 1950–1997: (a) SST (20.1% of the total variance of the field), (b) pressure (40.5% of the total variance of the field).

Characteristic and Analysis of Space and Time Modes. The main space and time modes of SST and pressure for the winter-spring period are presented in Figs. 2 and 3. The structure of these modes and their time dependences confirm the data obtained in [15, 16, 18] according to which the first mode of SST and pressure in this period is associated with the NAO/AO. Its contribution to the total variance varies for different fields and months from ~20 to ~40% with maxima of the SST and pressure fields attained in March–April (24.8%) and January–February (40.5%), respectively.

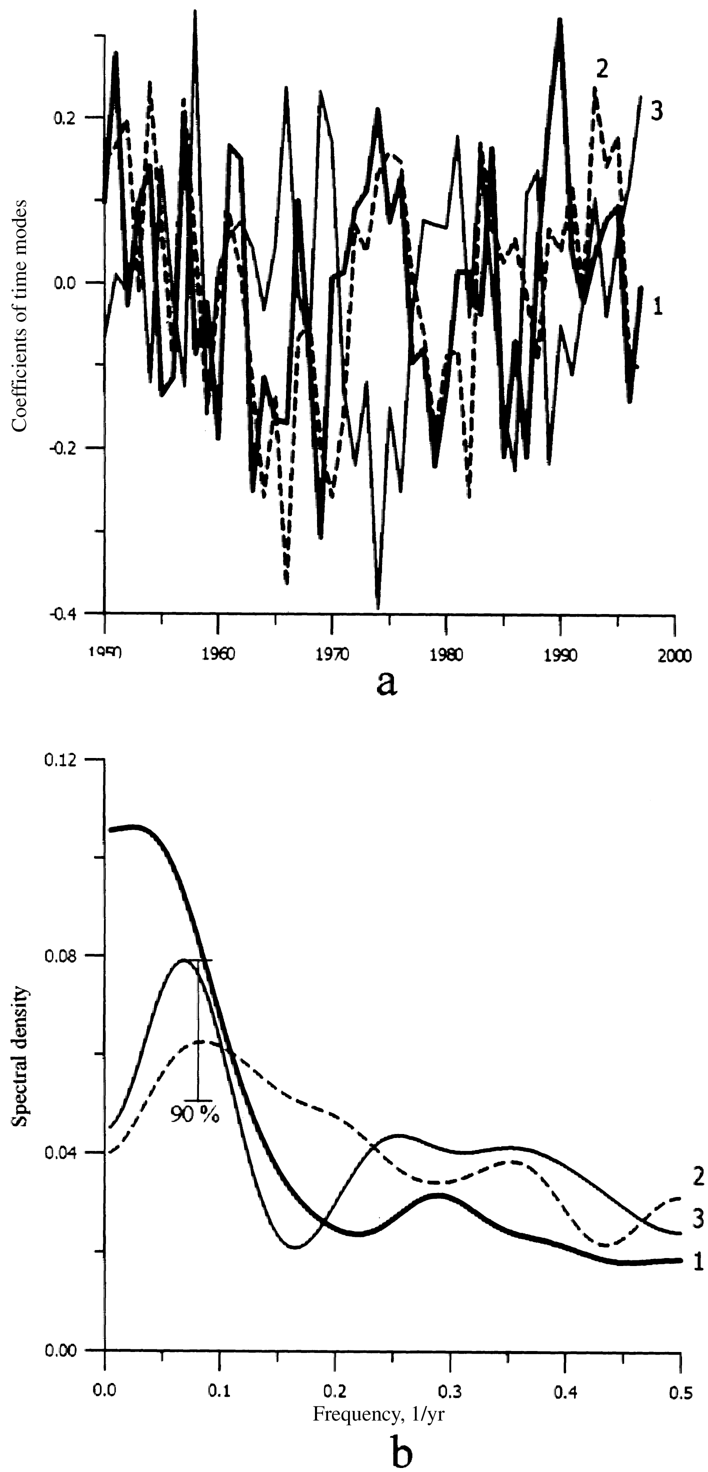

Fig. 3. Time coefficients of the first EOF presented in Fig. 2 (a) and their spectra (b): (1) SST, (2) pressure, (3) time coefficient of the first EOF for SST in March–April and its spectrum.

The coefficient of correlation between the first time mode of pressure and the NAO index in winter can be as high as 0.9. This mode of the SST field was repeatedly described in the literature beginning with [36]. In the North Atlantic, it has a triple character. The variations of SST in the Tropical and Subpolar Gyres are of the same sign. In the Subtropical Gyre, the indicated variations have the opposite sign. The time coefficients of the first EOF for the SST and pressure fields in winter have the following basic spectral peaks: for SST, within the range of periods 14–25 yr (about 20% of the total variance in the corresponding modes) and, for pressure, within the range of periods 6–13 yr (up to 30% of the total variance in March–April; see Fig. 3). In general, these results confirm the data obtained in [2, 5, 8, 10, 15, 35, 36].

The difference between the space structures of the EOF for pressure fields (one of the causes of extensive discussions about the definitions of NAO and AO and the difference between these two oscillations) is, for the most part, explained by the following two circumstances: First, by the methodological causes. Indeed, in different works, the results of expansions of the fields are not always studied by using the same procedure. Thus, in the expansions of pressure and SST fields in EOF by using the traditional approach and the method of rotating components, the space structures of the first EOF and their contributions to the total variance of the field can be substantially different [15, 18, 26, 35]. However, this difference is, in fact, formal. The second circumstance seems to be more important. As follows from the results of numerous works devoted to the analysis of the expansions of pressure fields in EOF, the space structure of the NAO mode suffered significant changes for the analyzed 100-yr period. The mode separated according to the data accumulated for the last 30–40 yr is characterized by a greater degree of zonal symmetry. This can partially be explained by the space-time structure of the data array because the data arrays used in recent years are much larger and, in addition, often subjected to much more sophisticated procedures of processing (e.g., to reanalysis). At the same time, it is also clear that the process of strengthening of zonal circulation indeed exists (this process manifests itself, in particular, in the increase in the NAO index observed beginning from the 1960s and especially well pronounced from the second half of the 1970s till the first half of the 1990s). It was recorded according to data of different types and leads to numerous climatic consequences. As one of these consequences, one can mention the growth of temperature in Northern Europe in winter often described in the literature (see surveys [2, 23] and Fig. 4). Another consequence of this process, i.e., the variability of the flow rates of European and Asian rivers, is analyzed in what follows. The variations of the space structure of the NAO served as the main cause of introducing the notion of Arctic Oscillation in [16]. Thus, the problem of difference between the NAO and AO is, in fact, the problem of character and causes of long-period variability of the characteristics of zonal atmospheric circulation in the Northern Hemisphere. This problem is discussed in the next subsection.

Mechanism of Formation of the Space-Time Structure of the NAO/AO. Up to now, there is no common viewpoint concerning the predominant mechanism of formation of the described space-time structure of SST and pressure fields in the North Atlantic. Many researchers follow Hasselmann's idea that the ocean simply integrates the atmospheric actions whose spectrum is close to white noise [37]. In this case, the response of the ocean is nothing but a passive reaction to atmospheric actions and has the form of red noise (see, e.g., [38]). This concept explains the concentration of the major part of energy in the low-frequency band of the spectra of oceanic characteristics but fails to explain the observed peaks in the spectra of SST on the decadal scale (Fig. 3). To explain oscillations of this sort, it is necessary to use hypotheses based on the assumption of more active participation of the ocean in the formation of these anomalies. Thus, the so-called Stommel's concept (in [2], this concept was named after the author of the fundamental monograph [39] and other pioneer works in the theory of oceanic circulation) is based on similar ideas. According to this concept, the spectra of oceanic fields are characterized by the presence of peaks in the low-frequency band caused by the existence of certain space-time scales in the ocean. These scales can be connected, e.g., with the character of baroclinic adjustment of oceanic gyres depending on the parameters of Rossby waves. Stommel's concept explains the spectral structure of fluctuations of SST but does not explain the inphase character of these fluctuations in the Tropical and Subpolar Gyres and the opposite phase of fluctuations in the Subtropical Gyre.

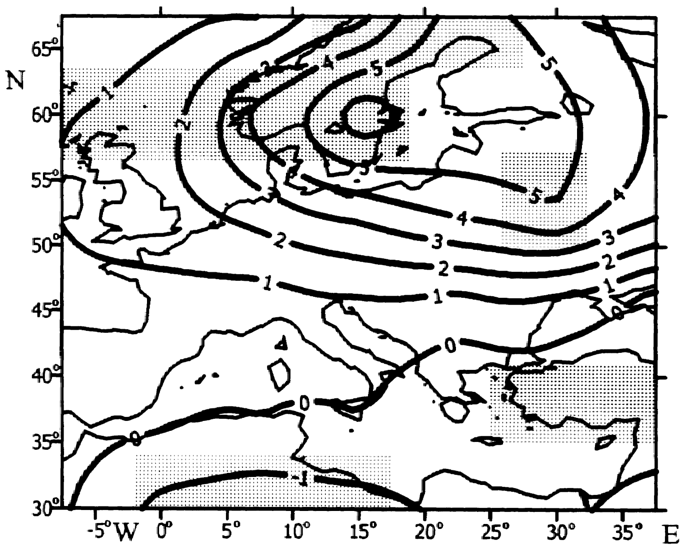

Fig. 4. Spatial distribution of trends in the behavior of sea-surface temperature (deg. per 10 yr) in January–February in Europe for 1979–1993 according to the ERA data of reanalysis. Regions with significant trends (at the 95% level) are shaded.

Finally, the third group of authors treats the large-scale interaction between the ocean and atmosphere at low frequencies and coupled modes in the ocean–atmosphere system as the most important factors of climatic variability on the interannual and decadal scales. In this case, the spectra of oceanic and atmospheric fields are characterized by the presence of peaks in the region of relatively low frequencies caused by the influence of coupled modes in the ocean–atmosphere system. In [2], these ideas were called Bjerknes' concept after the author of the fundamental work [40]. However, this approach fails to explain the following fact well known from the data of observations and confirmed by our own results: The characteristic period of fluctuations of the NAO index corresponding to the main spectral peak is 6–10 yr, whereas the oscillations predominant in the spectra of SST have lower frequencies (see [23, 41] and Fig. 3). At present, most authors interpret the observed variations of the NAO as the response of the atmosphere to slow variations of SST caused by internal processes in the ocean. At the same time, the possibility of realization of coupled modes is also not denied [20–23, 41–43]. In addition, it is customary to believe that the internal oceanic variability is generated by the integral action of the atmosphere.

Our results demonstrate that the role played by internal oceanic processes (integrating external actions) in the formation of anomalies of SST is extremely important and confirm the existence of significant response of the atmosphere to these anomalies. Indeed, the coefficient of correlation between the first time modes of SST and pressure reaches 0.55 in winter and, in the case of a time delay of SST relative to the atmospheric pressure for a period from one season to 3 yr, varies within a fairly broad range (from 0.52 to 0.33, respectively). The cross spectrum of the first mode of SST for March–April and pressure for January–February contains a significant peak corresponding to a period of about 14 yr. For this period, the coherence function can be as high as 0.77 for a phase shift close to zero. A significant level of coherence (> 0.6) for a phase shift close to zero is observed between the ~ 9-yr oscillations of the first time coefficients for pressure in March–April and SST in May–June. These results demonstrate that the response of the ocean to the winter-spring anomalies of atmospheric pressure is significant. At the same time, the correlation between the time dependences of SST and pressure in the case of time delay of the latter is also significant, which is especially well pronounced in winter. This fact confirms the existence of the counterresponse of the atmosphere to the low-frequency anomalies of SST. Moreover, for a 1–2-yr time delay of pressure in January–February relative to the SST in winter, the correlation coefficient remains significant (up to -0.34).

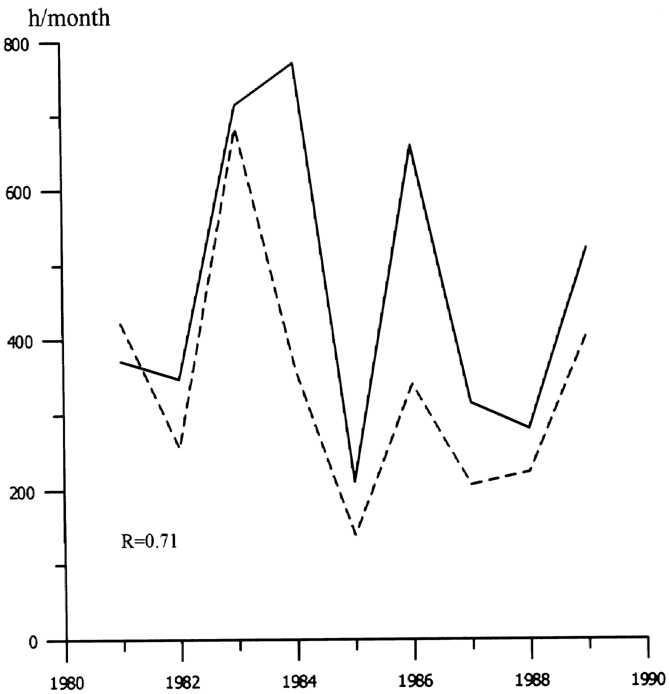

Fig. 5. Duration (h/month) of stay of January North-Atlantic cyclones and anticyclones in the zones bounded between 60 and 70°N (solid line) and 40 and 50°N (dashed line), respectively. The correlation coefficient is denoted by R. The curves are plotted according to the VNIIGMI-MTsD data for the 1980s [54].

This means that the influence of the ocean on the interannual variations of atmospheric circulation is of primary importance for the North Atlantic in winter. The mechanism of this influence is quite clear. It is connected with the fact (well known from the data of observations) of reemergence of the winter anomalies of SST next year in the process of development of the autumn-winter convection [44]. The results presented in [45] demonstrate the efficiency of this mechanism in vast regions of the North Atlantic without intense large-scale currents. At the same time, it should be emphasized that the summer-autumn anomalies of SST in the North Atlantic also affect winter characteristics of the atmospheric circulation in the Atlantic-European sector, although not so efficiently as the autumn-winter anomalies [46]. Most likely, this influence is partially connected with the action of Pacific anomalies on the North-Atlantic anomalies in the periods of El Niño–La Niño [46–50].

The existence of decadal oscillations of the NAO is, in principle, explained by the interaction of the upper mixed layer with deeper layers and the transfer of SST anomalies by oceanic currents [2, 51]. At the same time, as shown in [52], the variations of NAO with typical periods of 5–10 yr are, in fact, coupled oscillations in the North-Atlantic ocean–atmosphere system. The typical time of delay of the oceanic response to the action of the atmosphere (NAO) is equal to 1–3 yr for different areas of the Tropical, Subtropical, and Subpolar Gyres. The complete cycle of interaction of the NAO with temperature anomalies in the active layer of the ocean with regard for the time of their advection is about 8 yr, which leads to the formation of a spectral peak in the analyzed time series at the corresponding frequencies. Moreover, the interaction of oceanic gyres, including the process of advection of anomalies in the meridional direction and feedbacks in the ocean–atmosphere system, is also important for the maintenance of the NAO [41].

We can demonstrate the difference between coupled and uncoupled modes by using, as an example, the results obtained in [53], where different terms of the heat balance equation were evaluated for the subtropical thermocline in the North Atlantic and all fields were represented as the sum of their mean values (marked by overbars) and fluctuations on the decadal scale.

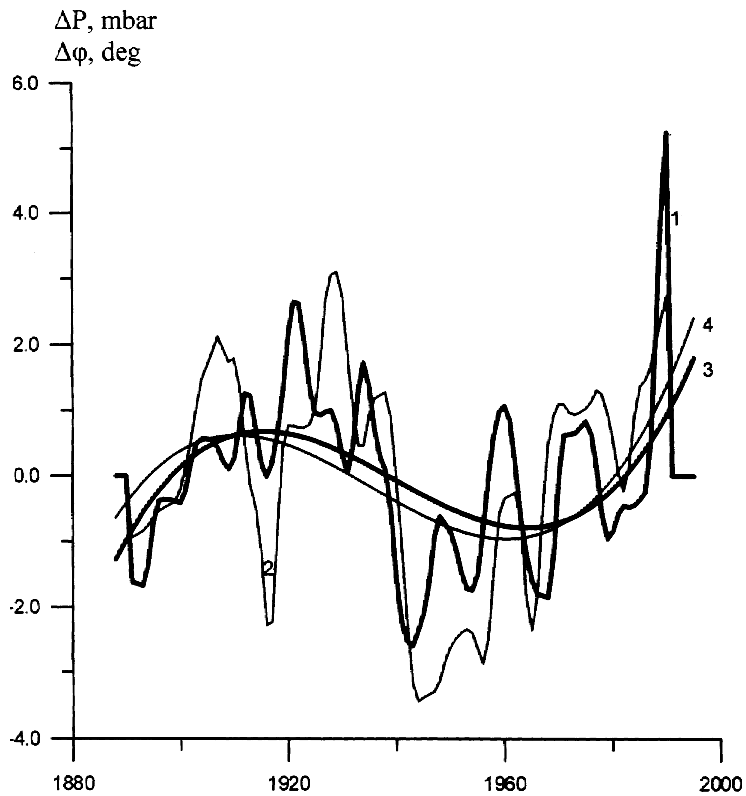

Fig. 6. Variations of the annual winter values of the Rossby index ΔP (1) and the latitudinal distance $\Delta\varphi$ between the centers of the Azores High and Iceland Low (2) and their trends approximated by cubic polynomials (3 and 4, respectively). The mean values and oscillations with periods smaller than 5 yr were preliminarily removed from the series.

Then the characteristics of decadal oscillations in the fields of temperature, wind, and horizontal and vertical currents were estimated by using the archive data accumulated for the region of the Subtropical Atlantic with the maximum amount of available data of measurements. If the characteristics of decadal variations of the vertical Ekman velocity W' and the temperature of thermocline T' are such that the terms $W'\partial\bar{T}/\partial z$ and $\partial T'/\partial t$ (these terms balance each other and/or the other terms describing the horizontal advection and vertical and horizontal turbulent exchange) play a significant role in the heat balance of the thermocline on the decadal scale, then these oscillations can be regarded as coupled (since the low-frequency variations of the wind field over the ocean are generated by the large-scale anomalies of SST at the corresponding frequencies). It turns out that the decadal oscillations can be regarded as a correlated process in the ocean–atmosphere system, mainly in the east part of the Subtropical Atlantic. In the other zones of the central part of the Subtropical Gyre, the variations of temperature in the thermocline on the decadal scale are determined mainly by the processes of horizontal advection and diffusion on a subgrid scale. In turn, the low-frequency variations of the wind field over the ocean are generated by large-scale thermal inhomogeneities in the upper layer of the ocean (mainly of the advective origin). However, the direct influence of the corresponding decadal oscillations of Ekman "pumping" on the temperature of thermocline can be weak in the main part of the gyre. In other words, the decadal variations can be regarded as correlated oscillations in the ocean–atmosphere system whose typical time scale is determined by the advective processes in the ocean. However, the indicated correlation is observed not in all regions.

The feedbacks existing in the ocean–atmosphere system are extremely important for the maintenance of decadal oscillations. One of possible types of positive feedback in the North-Atlantic ocean–atmosphere system, which directly affects the variations of climate in Europe, is described in [2] as follows:

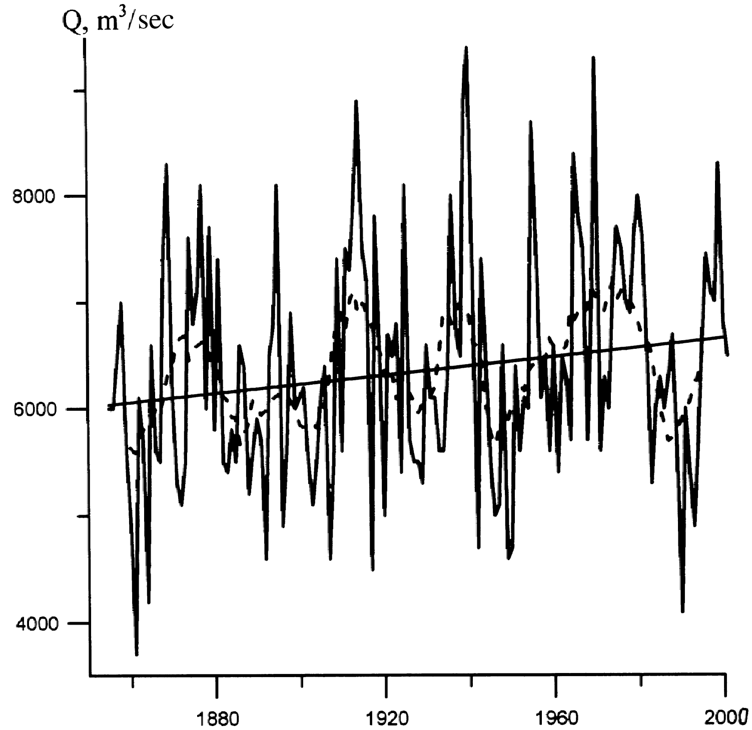

Fig. 7. Variations of the annual discharge Q of the Danube (solid line) and the quantities smoothed by an 11-yr sliding filter (dashed line). The straight line corresponds to the linear trend.

Strengthening of the wind with cyclonic vorticity in the atmosphere (negative anomaly of sea-level pressure) results in a drop of SST caused by the increase in the velocity of entrainment and additional heat transfer from the ocean into the atmosphere. On the contrary, in the zones of elevated anticyclonic activity in the atmosphere (positive anomaly of sea-level pressure), the SST increases due to the decrease in the velocity of entrainment and an additional inflow of heat to the surface of the ocean. If, in addition, the cyclonic activity increases at high latitudes and the anticyclonic activity in subtropics [this is in good agreement with the well-known (from the data of observations) fact of quasisynchronous intensification of the Azores High and Iceland Low at low frequencies, satisfies the condition of conservation of absolute vorticity in the atmosphere, and is confirmed by our data (see Fig. 5)], then the meridional temperature gradient and, hence, the intensity of zonal circulation in the atmosphere increase. The intensification of zonal circulation is accompanied by the growth of instability and elevation of synoptic activity in the atmosphere. The orders of typical anomalies of SST and sea-level pressure of this sort are $1°$ and 1 mbar, respectively, and the corresponding anomalies of the Rossby index can be as large as 2 mbar, i.e., about 10% of its normal level. This mechanism manifests itself, in particular, in the quasiperiodic inphase oscillations of the Rossby index and the latitudinal distance between the centers of the Azores High and Iceland Low (Fig. 6).

Thus, we can conclude that all described mechanisms of maintenance of oscillations on the decadal scale are realized in the North Atlantic. However, their relative role varies from region to region. Thus, the intensification of convection in the Subpolar Gyre is accompanied by an almost inphase strengthening of trade winds as a result of the increase in the drop of temperature between the pole and equator. This promotes a relatively fast (as compared with the decadal scale) response of the upper mixed layer at low latitudes as a result of relatively high rates of the Ekman transfer, planetary waves at low latitudes, and vertical advection. At the same time, the intensification of the Subtropical Gyre is delayed by several years as compared with the Tropical Gyre due to its slower baroclinic adjustment.

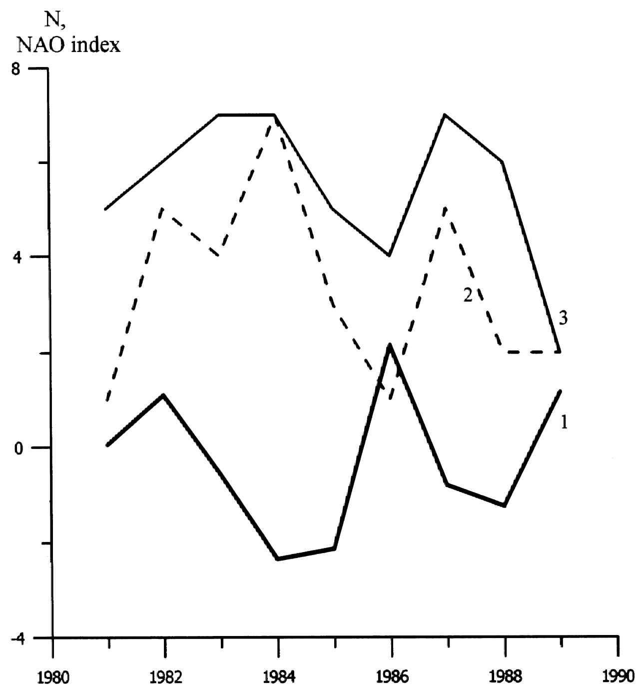

Fig. 8. NAO index (1) and the number of cyclones N over the water-catchment areas of the Dnieper (2) and the Danube (3) in the 1980s of the previous century (on the basis of the VNIIGMI-MTsD data [54] for May).

Table 2. **Maximum Coefficients of Correlation (I) of the Discharges of European and Asian Rivers in March–April and May–June with the NAO and SO Indices for the Corresponding Delays of Discharges (II)**

River	NAO				SO			
	March–April		May–June		March–April		May–June	
	I	II	I	II	I	II	I	II
Dnieper	**– 0.71**	2	**– 0.63**	1	**– 0.66**	0	– 0.42	2
Dniester	– 0.6	3	**– 0.63**	1	**– 0.71**	1	– 0.61	3
Danube	**– 0.77**	3	– 0.56	1	**– 0.65**	0	– 0.55	3
Garonne	**– 0.72**	2	**– 0.77**	1	**– 0.58**	1	**– 0.65**	3
Loire	**– 0.72**	2	**– 0.52**	1	**– 0.56**	0	**– 0.62**	2
Ob	**0.53**	2–3	0.43	1–2	0.35	4	0.48	2–3
Severnaya Dvina	**0.40**	3	**– 0.44**	3	– 0.21	1–2	0.32	0

Comment: The original series were subjected to band-pass filtration transmitting oscillations with periods of 5–20 yr. The bold type is used for the quantities significant at the 95% level. The computations were carried out for the delays of discharges by 1–6 months.

The indicated phenomena lead to the formation of almost inphase oscillations of SST at high and low latitudes and antiphase oscillations in subtropics, i.e., to the observed space structure of the first mode of SST (Fig. 2a). The anomalies of SST formed as a result affect, in turn, the characteristics of atmospheric circulation by changing the conditions over the water-catchment areas of European and Asian rivers. This phenomenon manifests itself in variations of the discharges of rivers studied in what follows by analyzing, as an example, the behavior of discharges of several large rivers.

Effect of the NAO/AO on the Discharges of European and Asian Rivers. The intense interannual and decadal variations of the river discharge Q are well visible in Fig. 7, where the annual flow rates of the Danube are analyzed as an example. As shown in [55], the extreme (in the amount of water) years for the largest Black-Sea rivers in spring coincide with the following combination of circulation conditions expressed in terms of the NAO and SO indices: stable low NAO indices in the previous winter and anomalous SO indices in the winter-spring periods (i.e., the events of El Niño or La Niño). Stable negative NAO indices in winter show that the zonal circulation becomes weaker and the trajectories of cyclones shift southward, which leads to abundant precipitation and the formation of anomalous snow-cover water equivalent in the water-catchment areas of the Black-Sea rivers. The opposite relationship between the NAO index and the flow rates should be true for the northern rivers. Our results confirm this conclusion. Actually, as shown above, during the period of intense phase of the NAO, the trajectories of cyclones shift northward. Therefore, in particular, the number of cyclones running over the water-catchment areas of the Dnieper and (especially) the Danube increases for low values of the NAO indices (Fig. 8). On the contrary, for the water-catchment area of the Severnaya Dvina, the number of cyclones in this case decreases. As a result, the correlation between the NAO indices in winter and the spring discharge of the Danube is negative. For the Severnaya Dvina, the indicated correlation is positive. Since the major part of the annual discharge of these rivers is formed by the spring discharge, the correlations of their annual average flow rates with the NAO index are also significant, although the values of the correlation coefficient become lower as a result of the annual averaging of the series. Note that the coefficient of correlation between the NAO index in January and the discharge of the Severnaya Dvina in April successively increased from 0.25 in 1881–1985 to 0.6 in 1966–1985. The correlation coefficient computed according to the annual average values of the NAO index and the flow rate of the Danube after removing linear trends increased (in modulus) from -0.21 in 1864–1995 to -0.59 for 1976–1995. The indicated strengthening of the effect of NAO on the discharges of the Severnaya Dvina and the Danube is explained by the decrease in the distance between the CAA for a period of 100 yr described above and, hence, by the closer location of storm tracks to the water-catchment areas.

As a result of the intensification of zonal circulation and the displacement of the North-Atlantic CAA in the last third of the 20th century, the influence of the NAO on the discharges of Asian rivers became stronger. Thus, the coefficient of correlation between the spring discharges of the Ob and Yenisey and the NAO index in winter attains 0.37 and 0.33, respectively, or even 0.56 if we remove oscillations whose periods are greater than 7 yr. All these correlations are significant (at the 99% level). The phenomenon of strengthening of the effect of NAO on climate in Asia is also studied in [56].

At the same time, it should be emphasized that the years with extremely large amounts of water coincide with the maxima of interdecadal oscillations (see [55]). The data presented in Table 2 reflects the fact that the variations of the discharges of European and Asian rivers on the decadal scale directly depend on the decadal variations of both the NAO and SO (reflecting the Pacific decadal oscillation). Their combined action is responsible for more than a half of the total low-frequency variability of the discharges of most European rivers in spring and about a half of this quantity for the Asian rivers. The analysis of the mechanism of this effect, however, lies beyond the scope of the present work. We only note that the time delay of river discharges by several months is insignificant as compared with the decadal variations of the NAO and SO. Nevertheless, this delay is observed practically for all rivers and serves as an indication of the corresponding trend.

CONCLUSIONS

The NAO and AO are two terms used to denote the same phenomenon caused by the regularities of formation of the general atmospheric circulation in the Northern Hemisphere. This phenomenon manifests itself in the form of a certain space-time structure of the EOF of pressure and temperature fields in the North Atlantic. The process of strengthening of the zonal atmospheric circulation for the last 40 yr and the corresponding changes in the space structure of the NAO mode are the principal manifestations of low-frequency variations in the ocean–atmosphere system. They lead to numerous climatic consequences in the Euro-Asian region. As the main consequences, we can mention the increase in temperature in the north of Eurasia in winter and the changes in the amount of water in rivers. The problem of relative roles of natural and anthropogenic factors in the formation of the observed climatic variability in the North-Atlantic region with time scales varying from several tens to one hundred years remains open. Moreover, one can hardly expect that this problem will be solved in the nearest future due to the absence of long-term data on the state of the entire climatic system and the complexity of the analyzed system. At the same time, it is clear that the role of the ocean on the investigated scales is of principal importance even if the anthropogenic factor is predominant.

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