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Original article

Steady Winds over the Black Sea and Atmospheric Blocking Events

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Abstract
Purpose. This paper aims at identifying and studying the cases of steady winds of one direction over the Black Sea and analyzing the accompanying conditions in the surface atmosphere and middle troposphere in winter (December–March).
Methods and Results. The situations with extremely steady winds of persistent direction, namely, when the prevailing wind over the sea does not change its direction for 5 days or more, are considered. The analysis is based on the 6-hour data on wind speed at the 10 m height, the 500 hPa geopotential height and the surface pressure from the ERA5 reanalysis of the European Centre for Medium-Range Weather Forecasts for 1979–2021. Within the analyzed period, 10 cases of steady, mostly north-eastern, winds were identified. At the same time there were 3 recorded cases of the eastern, northern and south-western winds. The empirical orthogonal function analysis performed for a set of steady wind cases shows that distribution of the first modes of the geopotential height and surface pressure fields has a spatial structure with a stable high-pressure area over the European territory. The contribution of these modes to the total variability is 65 and 47%, respectively. Analysis of the revealed situations with steady winds shows that in all the cases with northern and north-eastern winds, there was a blocking process in a form of a quasi-stationary anticyclone in the middle atmosphere located over the Northern Europe/Scandinavian Peninsula. In the case of northern wind, an extensive high-altitude anticyclone was located over the northern part of the European Russia. Values of the Tibaldi and Molteni blocking index confirm the fact that the considered cases of long-lasting north-eastern and northern winds correspond to the blocking conditions over the European region. A steady eastern wind was observed when the extensive anticyclone in the middle troposphere was actively moving from the north of the Scandinavian Peninsula to the south-east. In the case of a long-lasting south-western wind, a subtropical high-pressure ridge was presented in the middle troposphere as well as an intense transfer of cyclones took place over the European region that created a prevailing steady wind over the Black Sea.
Conclusions. The analysis results indicate that the considered cases with steady north-eastern and northern winds over the Black Sea are related to the blocking processes in the European region atmosphere.

Keywords: Black Sea, European region, steady winds, 500 hPa geopotential height, atmospheric blocking

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Introduction

In recent years, there has been a trend towards an increase in the total number and intensity of regional hydrometeorological anomalies against the background of global climate change [1] [1, 2]. This is confirmed by relevant data and calculations of global and regional climate models capable of reconstructing observed climate change trends [2] [3], including those in the Black Sea region [4, 5].

It is known that long-term anomalous phenomena in the atmosphere surface layer are often associated with quasi-stationary situations in the mid-troposphere due to its blocking with a typical duration of 5 days or more [1, 3, 5, 6]. Blocking events observed in the atmosphere of the Northern Hemisphere mid-latitudes lead not only to intense regional anomalies in the hydrometeorological fields of the European region [5, 7–9]. Blocking is often accompanied by changes in air quality, for example, abnormally low ozone content, especially pronounced over Scandinavia and Alaska [10]. Extreme conditions and regional anomalies (including those due to atmospheric blocking) result in many negative consequences, in particular, mortality increase [10, 11]. That is why numerous works exceeding greatly the references given in this paper are focused on their study in the European–Black Sea region.

Currently, blocking is understood as a situation in the mid-latitude atmosphere when the jet stream crest becomes especially large and forms a separate anticyclone in the flow creating a large-scale stable weather regime (blocking) which prevents the propagation of Rossby waves [2, 12]. As a result of the quasi-stationary position of the blocking anticyclone, typical cyclone trajectories become redirected. In this case, the regionally stable westerly flow is often replaced locally by a meridional flow lasting from several days to several weeks [3] [6, 13, 14]. Blockings can be different in their structure. In studies, the most frequently mentioned blockings are omega-type ones structured like the Greek letter Ω, when a large anticyclone located in the center is flowed around by cyclones [15, 16], and dipole blockings consisting of an anticyclone and a cyclone located southwards of the anticyclone [17].

According to [13, 17–19], typical region of the most active blocking is located in the 50–60°N band with its maximum amount in the west of the European region

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[1] Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L. [et al.], 2021. Climate Change 2021: The Physical Science Basis. In: *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom: Cambridge University Press, 2339 p. https://doi.org/10.1017/9781009157896

[2] Pörtner, H.-O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S. [et al.], 2022. Climate Change 2022: Impacts, Adaptation and Vulnerability. In: *IPCC Sixth Assessment Report*. Netherlands: IPCC Publisher, 3675 p. https://doi.org/10.1017/9781009325844

[3] Mokhov, I.I., Akperov, M.G., Lupo, A.R., Chernokulsky, A.V. and Timazhev, A.V., 2011. Regional Climate Extremes in Northern Eurasia Associated with Atmospheric Blockings: Interannual Variations and Tendencies of Change. *AGU Fall Meeting Abstracts,* 2011, pp. GC43F-06.

and Scandinavia. In this region, blocking is clearly manifested in extensive anomalies of the geopotential height of 500 hPa isobaric surface [20]. Consideration of such a pressure distribution was applied to create blocking indices [20] which make it possible to determine the presence of blocking at a specific longitude at a specific time based on gradients in the geopotential height field. The Tibaldi and Molteni blocking index is often used to verify calculations of blocking regimes in climate models, reanalyses and observational data [4] [9, 18–22].

Despite the large number of works analyzing the relationship between regional climatic anomalies in the European region of Russia and blocking processes in the atmosphere, there are few such studies for the Black Sea region, which are mainly focused on temperature anomalies or precipitation/droughts [3, 5, 23]. Studies of the causes of anomalous situations with steady winds and their relationship with blockings in the mid-troposphere have not been performed. At the same time, the wind regime is one of the important conditions for economic activity and human life. Knowledge of the wind regime and consideration of wind direction are important in the construction of hydraulic structures [24], forecasting wind waves, surge phenomena [25, 26], upwellings and storm conditions [27, 28] in the Black Sea region. In addition, the wind regime largely determines the nature of water circulation and changes in the thickness of the mixed layer [29, 30] and also affects regional weather conditions [31]. The cases where the wind direction is stable for a fairly long time are of particular interest. This determines the relevance of such studies. Therefore, the main purpose of the work is to identify situations with long winds over the Black Sea for the cold period of the year and to determine the relationship between the occurrence of such events and large-scale processes in the surface layer and mid-troposphere.

Materials and methods

In this work, we used the data from the ERA5 atmospheric reanalysis (0.25° × × 0.25°) [32] for 1979–2021:

– 6-h data on wind speed (m/s) at a height of 10 m above the Black Sea;

– 6-h data on surface pressure (hPa) and geopotential of the 500 hPa isobaric surface in the area bounded by coordinates 35–75°N, 10°W–100°E.

The direction of the wind prevailing over the Black Sea was determined for each 6-h period as the velocity vector direction, zonal and meridional components of which were obtained by averaging the wind speed components according to the data covering the sea area. The obtained direction was compared with one of eight main geographical directions: northern (N), north-eastern (NE), eastern (E), south-eastern (SE), southern (S), south-western (SW), western (W), north-western (NW).

[4] Davini, P., 2013. *Atmospheric Blocking and Winter Mid-Latitude Climate Variability: Tesi di Dottorato*. Venezia: Universita Ca' Foscari, 141 p.

From the obtained time series, we identified cases with extremely steady winds, when the wind direction did not change for twenty 6-hour periods (i.e., 5 days) or more. For the identified situations, we calculated additionally the average wind direction by all grid nodes $\overline{\varphi}$ (°)

$$\overline{\varphi} = \frac{1}{NK}\sum_{i=1}^{N}\sum_{j=1}^{K}\varphi_{ij}$$

and its deviation φ^* (°) from the direction of geographic reference. Here, φ_{ij} is wind direction at each grid node; N is number of grid nodes over the sea area; K is number of 6-hour periods in a situation with steady wind.

To identify atmospheric conditions that lead to the occurrence of long-term situations with steady winds, the decomposition of 500 hPa geopotential height fields and surface pressure for a set of cases with these winds into empirical orthogonal functions (EOFs) was performed. The method consists of decomposing the initial field $F(x, t)$ into certain functions $X_n(x)$ with coefficients $T_n(t)$ ($n = 1 \dots N$, where N is number of periods with steady winds) [5] [33]. In this case, only one condition is applied as a basis for determining the unknown functions: the sum of squares of the decomposition errors over all points of a given set of fields must reach a minimum for any n.

To test the hypothesis that the situations with long-lasting winds possibly occur in the mid-troposphere due to blocking, the blocking index was calculated on the dates when the cases with such winds took place. The calculation was carried out according to the method proposed by Tibaldi and Molteni [20]. For each latitude, the northern *GHGN* (north geopotential height gradient) and southern *GHGS* (southern geopotential height gradient) gradients (in m/°) between the values of 500 hPa geopotential height were calculated:

$$GHGN = \left[\frac{Z(\phi_n) - Z(\phi_0)}{\phi_n - \phi_0}\right], \quad (1)$$

$$GHGS = \left[\frac{Z(\phi_0) - Z(\phi_s)}{\phi_0 - \phi_s}\right], \quad (2)$$

where $\phi_n = 80°N + \delta,\ \phi_0 = 60°N + \delta,\ \phi_s = 40°N + \delta,\ \delta = -5°, 0, +5°.$

Blocking occurs when conditions $GHGS > 0,\ GHGN <= -10$ are satisfied at least for one δ value. Southern gradient $GHGS$ determines the measure of blocking intensity, while the northern gradient $GHGN$ eliminates false blocking cases [20].

[5] Björnsson, H. and Venegas, S.A., 1997. A Manual for EOF and SVD Analyses of Climatic Data. *CCGCR Report,* 97(1), pp.112-134.

Time series of 500 hPa geopotential height were previously smoothed by a 5-day moving average at each point of the spatial grid to ensure the search for prolonged blocking events.

Results and their discussion

Cases with long-lasting winds over the Black Sea. During the cold period of the year, 10 cases with extremely steady winds, when the prevailing wind direction over the sea did not change for 5 days or more (twenty or more 6-hour periods) (Table), were identified. In seven of all the identified cases, the north-eastern (NE) wind prevailed, in one case the northern (N) one, in one case the eastern (E) and in one case the steady south-western (SW) wind. Wind direction $\overline{\varphi}$ deviates from that of the geographic reference by an average of −6.6° (Table). The most frequent cases are the ones with steady north-eastern winds, they accounted for ~ 62% of all identified situations. Note that north-eastern winds also have the highest frequency per year – 18% according to long-term data [34, 35].

Characteristics of long-lasting wind cases over the Black Sea region

Case	Date	Wind direction	Duration, day	φ^*, °	Blocking index	max *GHGS*, m/°	V_{mean}, m/s	$V_{\max}$, m/s
1	11–16.03.1986	NE	5.75	–8.2	+	7.0	7.0	11.6
2	01–07.01.1993	NE	6.50	4.3	+	5.0	9.7	16.6
3	07–14.12.1995	NE	8.75	–7.8	+	7.0	6.4	11.9
4	23–28.12.1995	SW	5.00	–4.9	-	<0	10.3	16.0
5	14–19.01.2001	NE	6.50	–7.3	+	5.0	7.7	13.6
6	28.11–03.12.2002	E	6.25	1.5	-	<0	6.3	16.7
7	07–12.02.2008	NE	5.75	–7.8	+	7.0	7.1	12.6
8	28.01–02.02.2012	N	5.25	–9.1	+	11.0	7.4	14.8
9	08–13.02.2017	NE	5.25	–10.2	+	8.0	6.5	16.9
10	22–27.03.2020	NE	5.25	–4.9	+	6.8	6.1	16.4

It is known that blocking events in the mid-troposphere are not rare. According to [16, 21, 36], the total number of days with atmospheric blocking in Europe during the winter season is 33 days and three independent blocking episodes on average. We identified only 10 cases with extremely steady winds lasting for 5 or more days. However, there can be more cases with steady winds of shorter duration (e.g., 3–4 days). At the same time, not all possible situations with a sufficiently stable wind direction over the sea caused by blocking processes can be detected, since regional atmospheric processes can distort the wind direction at certain times.

It should be noted that, according to the results of calculations [21], a number of climate models presented in the sixth assessment report of the Intergovernmental Panel on Climate Change predict a slight decrease in the average number of atmospheric blockings in Europe in winter during the 21st century [1].

Large-scale atmospheric conditions for a set of situations with steady winds

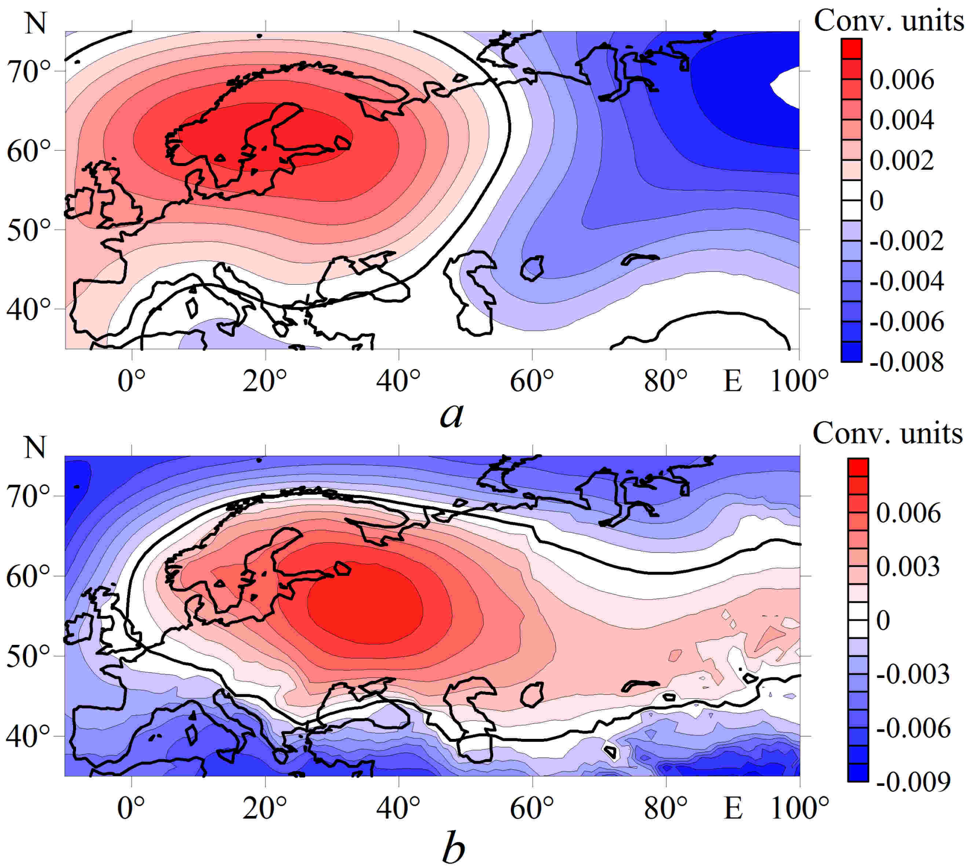
The EOF method made it possible to identify the leading spatial modes for cases with steady winds in the Black Sea. As a result of the analysis, we obtained the first-mode spatial structure of 500 hPa geopotential height containing 65% of the variability (Fig. 1, *a*). Distribution includes a large area of positive geopotential height anomalies covering the north of Europe and extending to the Ural Mountains/Caspian Sea. The anticyclone center is located in the Scandinavian Peninsula which is typical for the position of a blocking anticyclone (blocking).

The contribution of subsequent spatial modes of 500 hPa geopotential height from the second through the fifth is noticeably smaller; it was 9, 7, 6 and 4%, respectively.

Decomposition of the set of surface pressure fields into empirical orthogonal functions yields similar results. In the spatial structure of the first mode, a vast area of positive surface pressure anomalies is located over Central Europe and the European part of the Russian Federation in all seasons (Fig. 1, *b*); the first mode accounts for 47% of the surface pressure field variability at that. The contribution of subsequent modes, from the second to the fifth, of the surface pressure field for all cases of steady winds was 21, 9, 5, and 4%, respectively, in the cold season. Note that due to the greater spatiotemporal variability of surface fields, contribution of the leading first mode is less than that in the mid-troposphere.

The first mode distribution obtained for surface pressure generally corresponds to the typical pressure field characteristic of northern, north-eastern and eastern winds over the Black Sea [34, 37]. Winds of such directions arise on the periphery of a large-scale anticyclone located northwards and north-eastwards of the Black Sea.

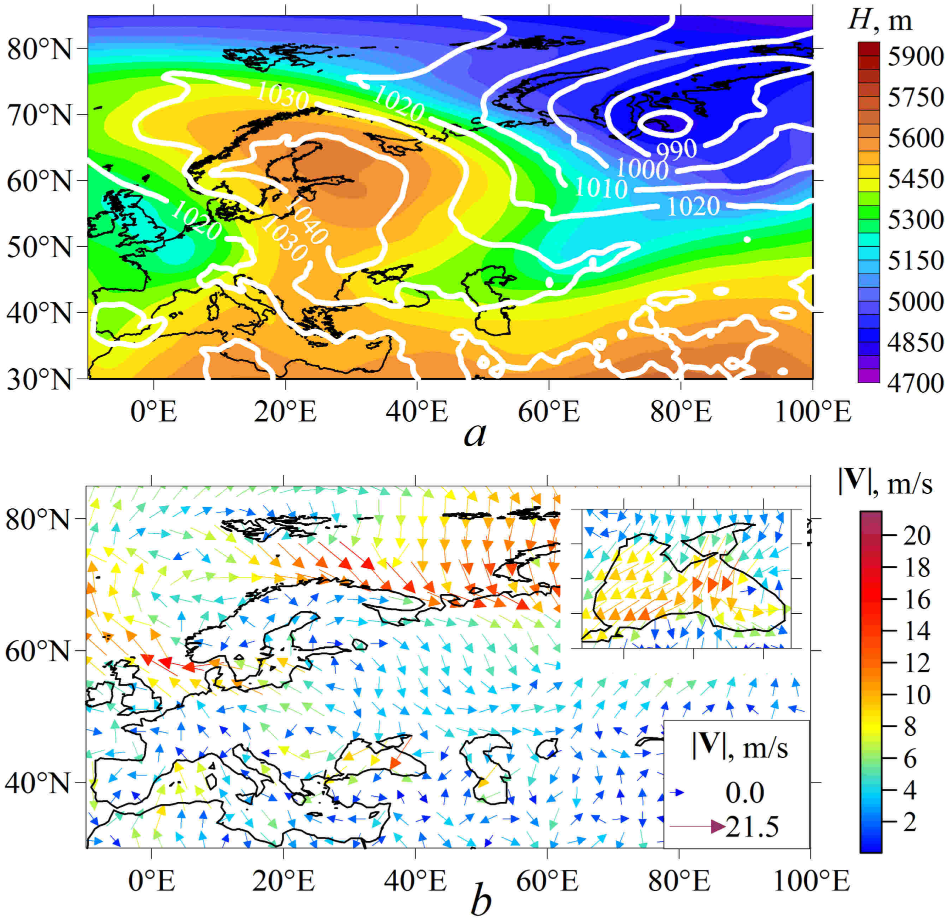
It is known that the removal of cold/arctic air from high latitudes to the eastern/south-eastern periphery of anticyclone is typical for such atmospheric conditions in winter [4]. The results [3] show that blocking anticyclones arising in the Central European region result in the emergence of negative air temperature anomalies near the Black Sea northern coast. At the same time, blocking events over the north-eastern part of Europe/Urals form areas of positive temperature anomalies covering the Black Sea region.



F i g. 1. Distribution of the first modes of the 500 hPa geopotential height anomalies (*a*) and the surface pressure field (*b*) for the cases of long-lasting northern, north-eastern and eastern winds in a cold season

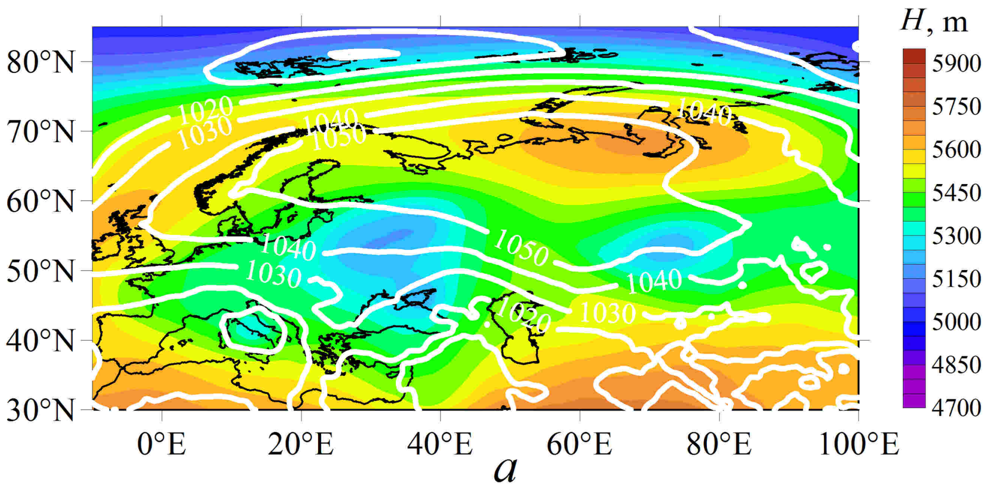
North-eastern wind. Atmospheric conditions in the mid-troposphere for all cases with the long-lasting north-eastern wind over the Black Sea (cases *1–3*, *5*, *7*, *9*, *10*, Table) satisfy the blocking conditions determined by the Tibaldi and Molteni index. This is the largest number of cases with long-lasting winds. The maximum southern gradient of 500 hPa geopotential height representing the measure of blocking intensity is 5–7 m/°. In these cases, a low-mobility blocking structure of omega shape or close to it is observed in the geopotential height distribution (Fig. 2).

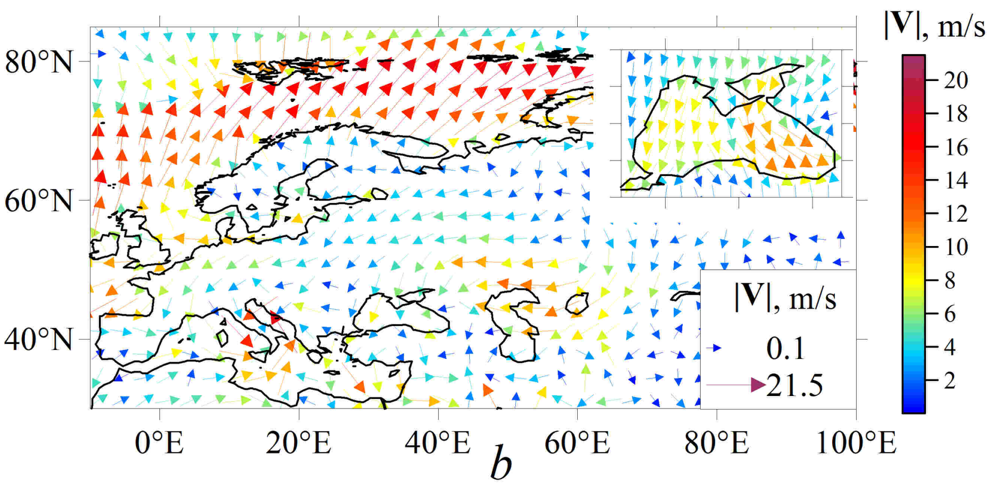
The analysis of geopotential height fields revealed that the blocking anticyclone center was stably located over Eastern Europe in cases *1* (11–16.03.1986) and *2* (02–07.01.1993). The blocking cyclone dominated over the Scandinavian Peninsula in cases *3* (07–14.12.1995) and *9* (08–13.02.2017). The blocking anticyclone center was located over the north-western part of Europe in cases *5* (14–19.01.2001), *7* (07–12.02.2008) and *10* (22–27.03.2020). High-pressure area extended slowly eastwards, where the blocking conditions were also met (formulas (1) and (2)) in cases *2*, *5*, and *10*. In the listed cases, a high-pressure area was present in the surface layer, and north/northeast winds prevailed on the south-eastern periphery [34, 37].



F i g. 2. Distribution of the 500 hPa geopotential height, sea level pressure (hPa, white isolines) (*a*) and wind field at the 10 m height (*b*) for 07.12.1995, 12:00 (a case of long-lasting north-eastern wind)

As an example illustrating cases with a steady north-eastern wind, Fig. 2 demonstrates the distribution of 500 hPa geopotential height anomalies (Fig. 2, *a*) and surface pressure distribution (Fig. 2, *a*) for case *3*, 07–14.12.1995 (Table). The high-altitude blocking anticyclone was located over the northern part of the European territory of Russia and the Scandinavian Peninsula. The blocking structure in the mid-troposphere had a well-defined shape of the Greek letter Ω with low-pressure areas at the base on the eastern and western sides. At this time, a north-eastern wind with a maximum speed of 12 m/s blew over the Black Sea (Fig. 2, *b*, Table) and surface temperature anomalies reached minus 6–7 °C, according to the following websites: https://psl.noaa.gov/cgi-bin/data, https://www1.wetter3.de/archiv_gfs_dt.html.





F i g. 3. The same as in Fig. 2, for 01.02.2012, 12:00 (a case of long-lasting northern wind)

Northern wind. A case with long-lasting northern wind (case *8* from the Table) was recorded for the period of 29 January – 2 February 2012. At this time, there was a steady blocking of the westerly transport in the mid-troposphere over the North Atlantic and Eurasia, characterized by the most intense, compared to all other cases, southern gradient (formula (2)) in the 500 hPa geopotential height (11 m/°). The blocking process which started in the third ten-day period of January and continued in February was accompanied by abnormal snowfalls and cold waves in Europe and the European part of Russia. These events are described in numerous publications [6] [7, 38–40].

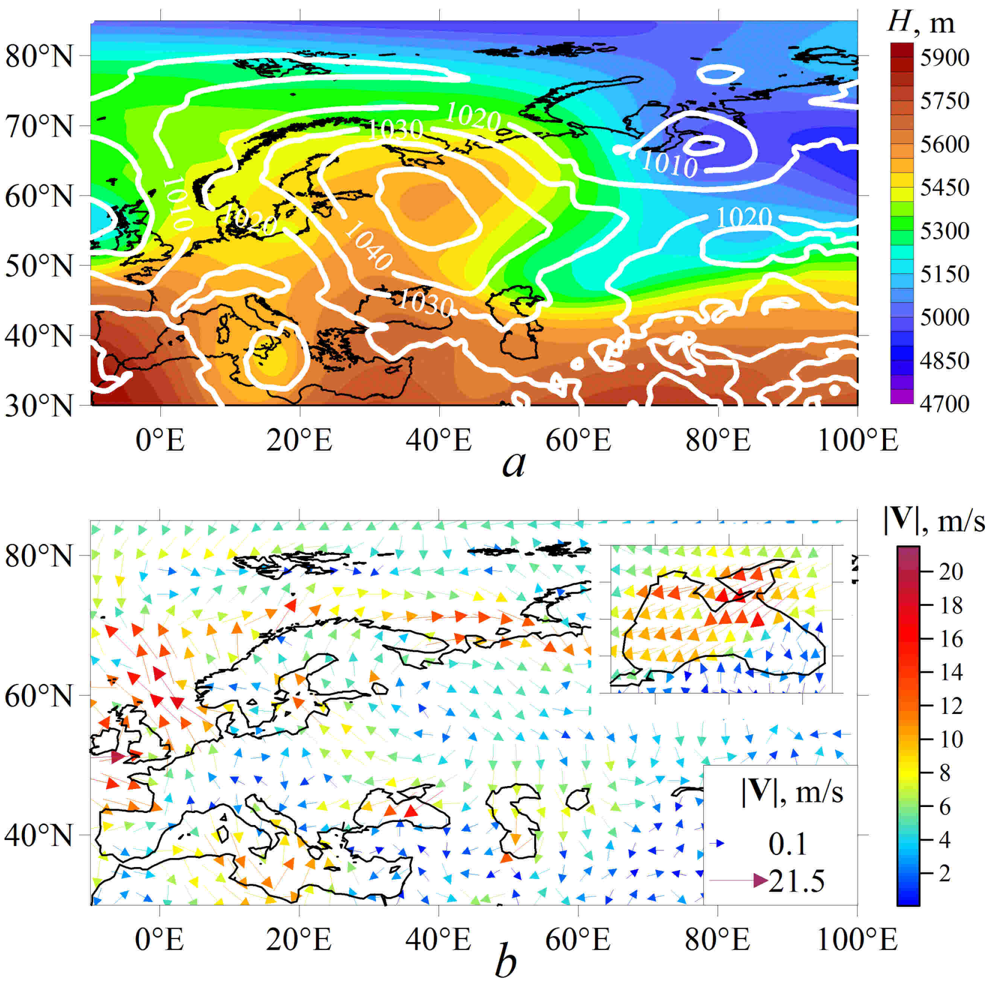
[6] Grazzini, F., 2013. Cold Spell Prediction beyond a Week: Extreme Snowfall Events in February 2012 in Italy. *ECMWF Newsletter*, (136), pp. 31-35.

Since mid-January, a typical westerly movement of Atlantic cyclones over Central Europe was disrupted due to the strengthening of the Siberian anticyclone ridge, stretching from the south of the Urals, its subsequent movement to the north-west and merging with the high-altitude ridge over the north-eastern Atlantic [39, 40]. An extreme increase in positive surface pressure anomalies took place in the lower layer of the troposphere [41]. By the end of January – early February, an extensive high-altitude blocking anticyclone was located in the north of the European part of Russia (Fig. 3, *a*). At the Black Sea coast, frosts were accompanied by strong winds (Fig. 3, *b*). During the period under review, from 29 January to 2 February 2012, a northerly wind blew over the Black Sea with a mean speed of 7.4 m/s and maximum values of up to 15 m/s.

The opposite situation developed in the Arctic region at that time. The realigning of large-scale circulation that took place during these months created favorable conditions for intensive advection of warm air from Western Europe and from the Atlantic Ocean to the central region of the Arctic Basin (Fig. 3, *b*). In the Arctic region, average monthly air temperature anomalies exceeded 15 °C [39]. At the same time, a polar air invasion from northern Siberia to the European part of Russia, central and southern Europe (Fig. 3, *b*) accompanied by severe frosts took place and a cold wave was also observed in eastern Asia [41].

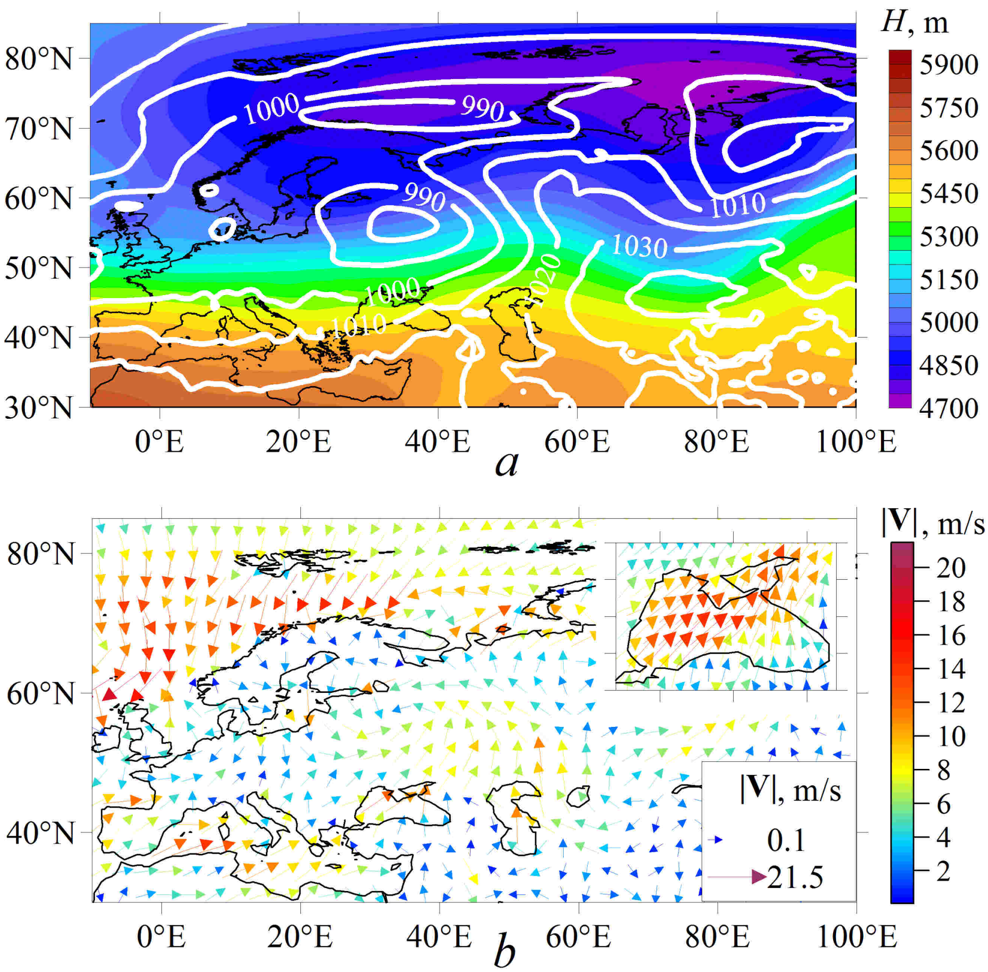
Eastern wind. In the case of the long-lasting eastern wind (28.11–03.12.2002), the anticyclone center in the mid-troposphere shifted actively starting from 28 November for several days, from the north of the Scandinavian Peninsula in a south-easterly direction to the central part of the European territory of Russia. The spatial structure of the anticyclone changed significantly. For example, as of 1 December, it corresponded to the omega-type blocking (Fig. 4, *a*), but shifted quickly and was characterized by a less-than-zero southern gradient, which did not make it possible to identify it as a blocking anticyclone according to the Tibaldi and Molteni criterion [20]. By the end of the period, the anticyclone was located north/north-eastwards of the Black Sea and then gradually moved east. Easterly winds prevailed on its southern periphery over the Black Sea (Fig. 4, *b*). In general, the steady eastern wind with a mean speed of ~ 6.3 m/s and maximum values reaching 17 m/s prevailed over the sea area during the specified period according to ERA5 reanalysis data.

South-western wind. Case *4* with the steady south-western wind was recorded in the period from 23 December to 28 December 1995 (Fig. 5). It can be noted that this year appears twice in the cases with steady winds identified by us (Table). The winter of 1995–1996 is one of the longest in the 20th century second half with an increased number of extremes which is partly associated with blocking activity intensification [3] [14]. During this period, from 23 December, the cold trough in the north-east of Eastern Europe was gradually filled while shifting to the east; an intense zonal transfer took place over the south of Europe bringing Atlantic warmth to the Black Sea region. This transfer was associated with a cyclone passage across northern Europe. Later, from 27 December, we observed a cooling over the Black Sea region associated with the passage of a cold front of another fast moving cyclone which moved quickly eastwards across the region. In addition, a pronounced quasi-stationary subtropical high-pressure ridge took place (Fig. 5, *a*) and a relatively high stable temperature gradient was observed between the north and south of Europe throughout the period under consideration.



F i g. 4. The same as in Fig. 2, for 01.12.2002, 06:00 (a case of long-lasting eastern wind)

Thus, it can be concluded that the passage of cyclones one after another across the European region accompanied by an intense westerly transfer of air masses and a stable high-pressure ridge in the subtropical latitudes (Fig. 5, *a*) created conditions for the prevalence of the south-western wind over the Black Sea (Fig. 5, *b*). In general, the steady south-western wind with a mean speed of ~ 10.3 m/s with maximum values reaching 16 m/s prevailed over the sea.



F i g. 5. The same as in Fig. 2, for 24.12.1995, 12:00 (a case of long-lasting south-western wind)

Conclusion

The paper identifies and examines cases of extremely steady winds over the Black Sea during the cold season (December to March). In total, 10 cases of winds lasting for 5 days or more were identified over 1979–2021. Atmospheric conditions in the surface layer and mid-troposphere were analyzed for all identified cases.

All cases with long-lasting north-eastern winds and the case with northern one were accompanied in the atmosphere by blocking events confirmed by the blocking index. Typically, a slow-moving high-altitude blocking anticyclone located over northern Europe/Scandinavia or over northern European Russia was present so that the Black Sea region was on its south-eastern periphery. In the surface layer, such an anticyclone position was accompanied by northern and north-eastern winds. Thus, atmospheric blockings located predominantly over northern Europe can be accompanied by steady north-eastern and northern winds over the Black Sea.

The case with the south-western steady wind is characterized by distinctive atmospheric conditions compared to the previous listed cases. At this time, there was an intense westerly transfer with the passage of cyclones one after another across Europe. In the subtropical belt, a well-defined quasi-stationary high-pressure ridge was observed, and at the same time, a relatively high steady temperature gradient between the north and south of Europe occurred. Such a pressure distribution contributed to the presence of a steady south-western wind over the Black Sea.

In the future, it is of interest to identify and analyze events with long-lasting winds for the warm season. The results of this work can be used for studying currents and wind waves in the Black Sea during the periods of identified extremely steady winds via numerical modeling.

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