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published in MORSKOY GIDROFIZICHESKIY ZHURNAL, Vol. 39, Iss. 4 (2023)

Original article

Winds Favorable for Upwellings near the Southern Coast of Crimea

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Abstract
Purpose. The study is purposed at analyzing frequency, speed and duration of the alongshore winds inducing the Ekman upwelling near the Southern Coast of Crimea.
Methods and Results. The 6-hour data on the wind speed components at the 10 m height derived from the ERA5 atmospheric reanalysis for 1979–2021, as well as the data of temperature monitoring performed at the Black Sea hydrophysical sub-satellite polygon of Marine Hydrophysical Institute, Russian Academy of Sciences, are used. Frequency and speed of the winds (namely, the southwestern, western and northwestern ones) favorable for development of upwelling near the Southern Coast of Crimea are considered. The multi-year data based calculations show that the seasonal variability in frequency of each of these winds is of an individual character, whereas their average speeds change the same decreasing from winter to summer. In summer, frequency of the western and northwestern winds increases, and that of the southwestern ones – decreases. The total frequency of favorable winds is the highest in June (maximum values), July, January and December. The lowest frequency values occur in August and October. The interannual changes in speed and frequency of the westerly directions winds result in changes in the upwelling numbers and durations. A significant positive relationship was obtained between the mean speed and frequency of these winds in June and the number of upwellings recorded by a water temperature decrease. The correlation coefficients were 0.74 and 0.68, respectively.
Conclusions. The wind conditions for arising of upwelling near the Southern Coast of Crimea are observed in all the months of a year, but the most favorable ones – in June, July, December and January due to the high frequency of westerly winds. High wind speed is also a significant factor for the development of upwelling.

Keywords: upwelling, wind direction, wind frequency, seawater temperature, seasonal variability, interannual variability, Southern Coast of Crimea, Black Sea

Acknowledgments: The study was carried out within the framework of the state assignments of Marine Hydrophysical Institute of RAS on themes FNNN-2021-0002, FNNN-2021-0003, FNNN-2021-0005 and FRC IBSS, RAS 0556-2021-0003 (No. 121041400077-1).

For citation: Shokurova, I.G., Plastun, T.V., Kasianenko, T.E., Stanichnaya, R.R., Krasheninnikova, S.B. and Simonova, Yu.V., 2023. Winds Favorable for Upwellings near the Southern Coast of Crimea. *Physical Oceanography*, 30(4), pp. 398-409.

Introduction

Upwellings affect the productivity of coastal zone ecosystems significantly [1, 2]. Elevation of deep waters saturated with biogenic elements ensures the growth of phytoplankton biomass and other plankton community components [3]. The coastal zone of the Southern Coast of Crimea is characterized by significant dynamic activity, as evidenced by numerous cases of upwellings on the sea surface [4–7].

In the deep-water coastal zone, upwelling appears when the alongshore wind direction deflects surface water from the coast due to the Coriolis force and viscosity, instead of which deep waters are pulled up. At the same time, in the Northern hemisphere, the coast should be situated to the left of the wind direction. The average depth of the Southern Coast of Crimea shelf is over 50 m (Fig. 1), which exceeds the Ekman boundary layer thickness. Therefore, upwellings prevail here, which occur during alongshore winds with a western component in the velocity vector, i.e. southwestern, western and northwestern ones. This is confirmed by the results of numerical experiments using a three-dimensional hydrodynamic model [8–10], an analysis of meteorological observations [4], and temperature measurements on the oceanographic platform in Katsiveli [11].

From April to October, when the surface temperature is higher than that of subsurface waters [12], upwelling is detected in the form of temperature drops due to the elevation of colder deep waters. This is most pronounced in the summer months, when the vertical temperature gradient in the thermocline shows its largest value. Such upwelling is determined from the sea surface temperature obtained from contact measurements [4], including thermal streamers installed in the shelf zones [6, 13, 14], as well as from satellite data [1, 7, 15]. In winter, upwelling is difficult to determine due to an increase in the upper mixed layer thickness [16], in which the vertical temperature gradient is small. Therefore, the water elevated to the surface as a result of upwelling differs slightly in temperature from the surrounding waters.

The occurrence of upwelling and its coverage depend on wind conditions (wind direction, speed and duration), as well as on stratification and dynamic processes at sea [13, 17–20]. A critical task is to analyze the seasonal and interannual variability of wind conditions favorable for upwelling. In the absence of retrospective data on water temperature, information on the frequency and speed of the winds causing them can be indirect evidence of possible upwellings. Wind conditions statistics also make it possible to evaluate the probability of occurrence of upwellings in the cold season, when they cannot be identified from the sea surface temperature in the absence of salinity data. Such studies are carried out in all areas of the World Ocean [21, 22]. Despite the large number of works devoted to the upwelling phenomenon study near the Southern Coast of Crimea, the issue of statistics of winds causing upwelling remains poorly understood.

The preset paper is aimed to analyze the intraannual and interannual variability in the frequency, speed and duration of westerly winds that are favorable for the occurrence of upwellings near the Southern Coast of Crimea.

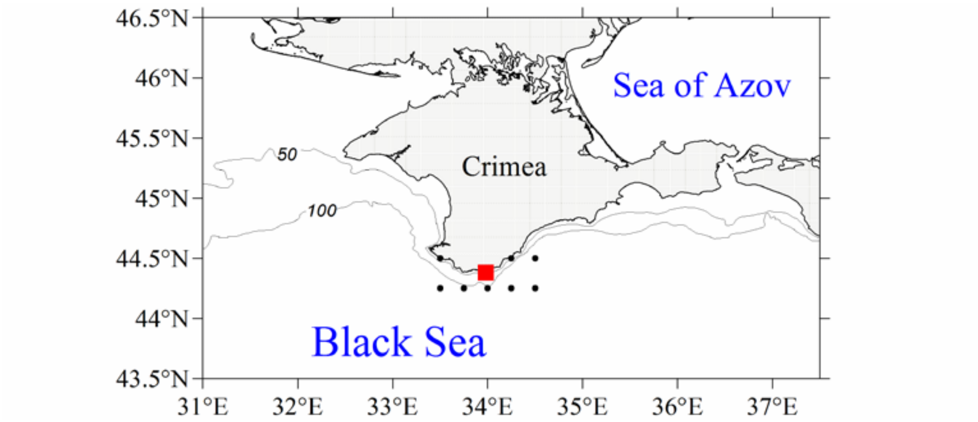
Data and research methods

The following data were used in the work:

– 6-hour data on wind speed components (u, v) at a height of 10 m with a spatial resolution (0.25° × 0.25°) of the *ERA5* atmospheric reanalysis for 1979–2021 [23];

– one-minute data on the sea water temperature from a measuring thermistor chain installed on a stationary oceanographic platform of the Black Sea hydrophysical sub-satellite polygon of Marine Hydrophysical Institute [6, 24]. The platform is located in the Black Sea coastal zone in Katsiveli at a distance of ~ 450 m from the coast, the polygon depth is ~ 30 m (Fig. 1);

– contact measurement data of sea water temperature (three measurements per day at 08:00, 14:00 and 17:00) at a depth of ~1 m near the coast (Katsiveli), obtained in June 1992–2021.



F i g. 1. Spatial distribution of the ERA5 reanalysis data [23] used to calculate wind direction. Red square indicates the position of the oceanographic platform

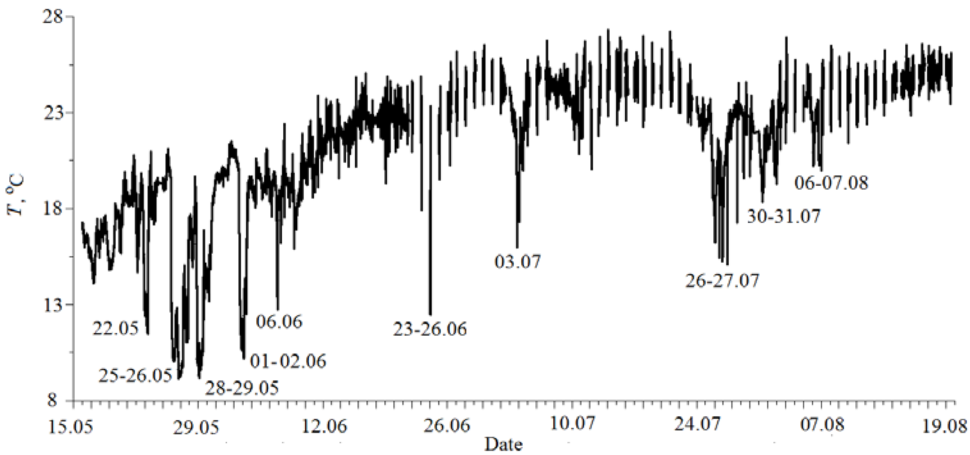
Wind characteristics are given for the following area: 44.25–44.5°N, 33.5–34.5°E (Fig. 1). The wind direction was determined for each 6-hour period by averaging the wind speed components in the specified area and comparing the resulting vector with one of the eight main geographical directions: northern (N), northeastern (NE), eastern (B), southeastern (SE), southern (S), southwestern (SW), western (W) and northwestern (NW). Frequency of each wind direction was determined as a percentage of the total number of cases in all directions.

For northwestern, western and southwestern winds favorable for upwelling near the Southern Coast of Crimea [4, 8, 9, 11], an analysis of the seasonal and interannual variability of the frequency of individual directions, the total frequency, and duration of situations with these winds is carried out. Time series of frequency and speed of westerly winds are compared with the number of upwellings obtained based on a long-term time series of observations of sea water temperature in Katsiveli.

Results and discussion

Upwellings in the area of the Southern Coast of Crimea in the summer of 2013 according to the thermistor chain data. Let us consider an example of situations with upwellings in the area of the Black Sea polygon according to the thermistor chain data installed on the platform (Fig. 1). From a number of water temperature values at a depth of 0.75 m, cases were distinguished with its sharp decrease by more than 5 °C, which corresponds to the generally accepted criterion for determining temperature upwelling [4, 7].

In the summer of 2013, mid-May to mid-August, 10 cases of a sharp temperature decrease were recorded. Their analysis showed that all the above events had been preceded by southwestern, western and northwestern winds (Fig. 2, Table) with a maximum speed of 5–9 m/s. Winds of other directions caused a complete or temporary upwelling termination. An analysis of the time sequence of wind directions preceding upwelling shows the presence of a continuous wind of one direction only in some cases. The situations with variable wind direction are more frequent. Note that all cases with a temperature decrease were preceded by a sequence of events with westerly winds during a day or more.



F i g. 2. Temperature time series at the 0.75 m depth in summer 2013 according to the thermistor chain data [6]. The dates on the graph indicate the upwelling duration

Upwelling characteristics in the region of the oceanographic platform in summer 2013

Month	Date	Duration, days	Minimum water temperature, ºC	Maximum wind speed, m/s	Wind directions preceding upwellings
May	22	1	11.5	5	NW, W, SW
	25-26	2	8.2	8	
	28-29	1.5	9.5	6	
June	01-02	2	10.2	7	NW, W, SW
	06	1	13.1	7	
	23-26	4	17.3	6	
July	03	1	16.2	9	NW, W, SW
	26-27	2	16.0	6	
	30-31	2	18.5	6	
August	06-07	2	19.5	7	NW, W, SW

A comparison of the series of water temperatures and wind characteristics also showed that the action of winds with a western component was not always accompanied by a decrease in the sea surface temperature. In two situations (June 9–10 and June 15–16), there was a wind favorable for upwelling, but a sharp decrease in temperature was observed at depths of 6 and 8 m and was not manifested at a depth of 0.75 m. This indicates incomplete upwelling, when deep waters do not reach the sea surface [6, 13].

Therefore, the above analysis corresponds to the results of studies [4, 8, 9, 11] and shows that near the Southern Coast of Crimea, a sharp decrease in sea surface temperature due to the elevation of cold deep waters in most cases is a result of the action of the southwestern, western and northwestern winds.

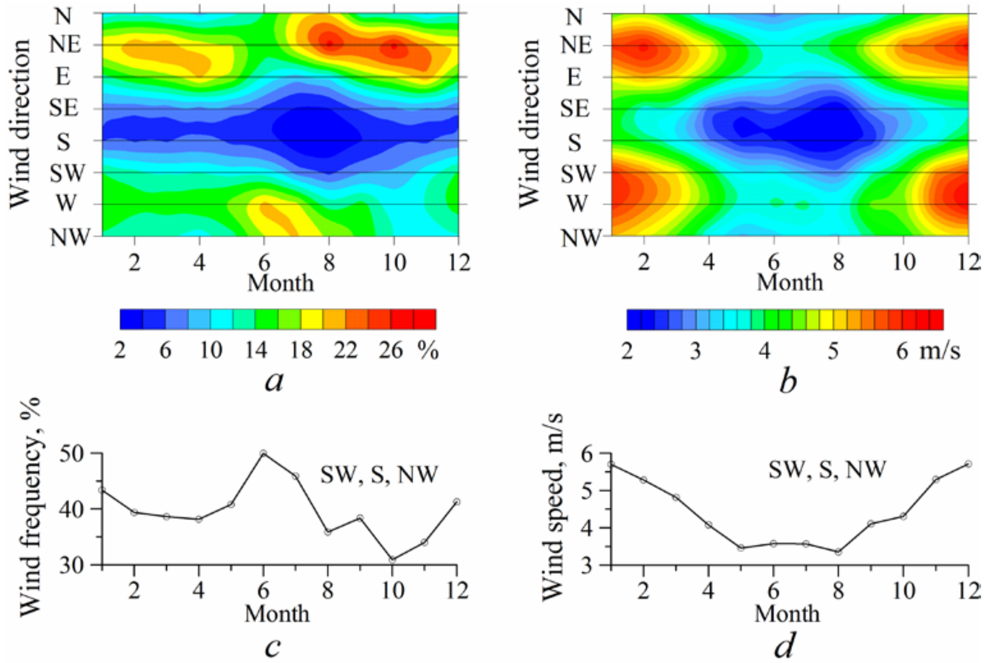
Seasonal variability of the frequency and speed of southwestern, western and northwestern winds in the area of the Southern Coast of Crimea. Based on the ERA5 reanalysis data, the seasonal variability in the frequency and speed of winds that can cause upwelling in the indicated Black Sea area are considered. Since, on average, the frequency of occurrence of each of these winds varies depending on the season [12], not only their total frequency, but also the contribution of each direction will be analyzed.

The northwestern wind is most often observed in the summer months with a maximum frequency in July (Fig. 3, *a*). The western wind prevails in the first half of the year with a maximum frequency in June, and in August its frequency decreases. The frequency of the western wind in June and the northwestern one in July is more than 20% and exceeds the contribution of the northeastern wind, which dominates during all other months (Fig. 3, *a*). The southwestern wind is more often observed in the winter and spring months, while from July to September it has a low frequency with the minimum in August.

The maximum total frequency of westerly winds is observed in June and amounts to 50% of the total number of cases (Fig. 3, *c*), which creates favorable conditions for upwelling. The high frequency of such winds is also observed in July, December, and January. The low total frequency of western winds is observed in August, October and November, which is associated with an increase in the proportion of the northeastern wind in these months (Fig. 3, *a*) [25].

The intraannual variability of the frequency of westerly winds obtained using the ERA5 reanalysis is in good agreement with the results of long-term data processing of water temperature measurements at meteorological stations of the Southern Coast of Crimea and the oceanographic platform in Katsiveli in the summer season [4, 11]. In Yalta, Alushta and Katsiveli, the largest number of upwellings is observed in June, when there is the maximum frequency of westerly winds. In August, there is a decrease in the number of upwellings compared to June and July, which is consistent with a decrease in the frequency of these winds (Fig. 3, *a*).

The average wind speed with the western component has the highest values in November–February (5.3-6.0 m/s), which is a favorable factor for the development of upwellings at this time of the year. In May–August, low values of the average speed are observed, 3–4 m/s (Fig. 3, *b*, *d*).



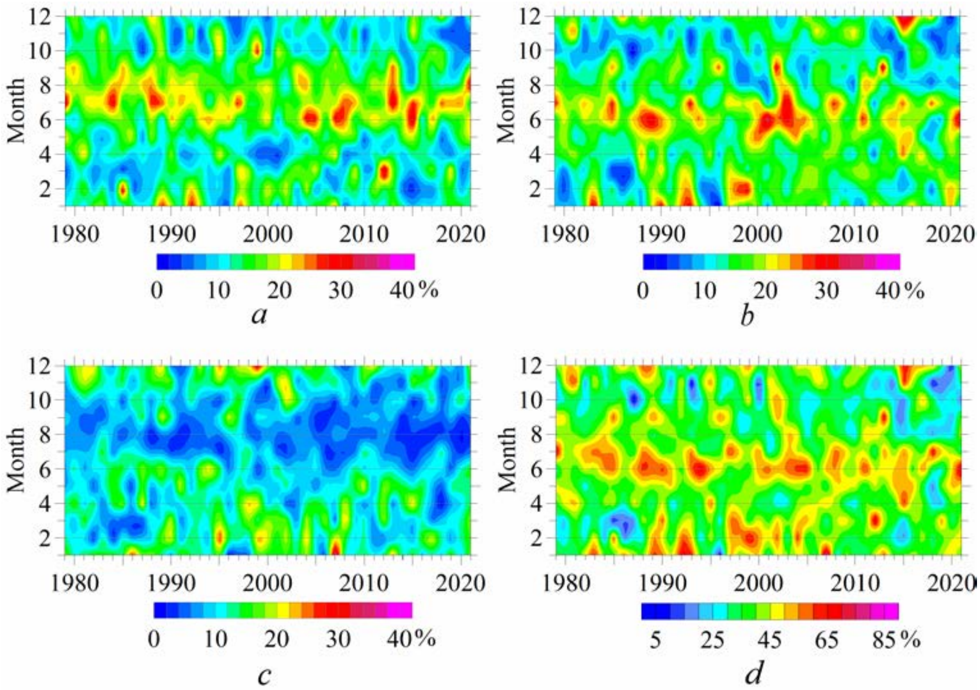
F i g. 3. Seasonal variability of wind direction frequency (*a*) and average speed (*b*) of all winds; total frequency (*c*) and average speed (*d*) of the southwestern, western and northwestern winds near the Southern Coast of Crimea based on the ERA5 data for 1979–2021

Interannual variability of the frequency and speed of southwestern, western and northwestern winds in the area of the Southern Coast of Crimea. Diagrams in Fig. 4 show that the interannual variability in the frequency of westerly winds is mainly manifested in a significant change in the frequency values themselves. At the same time, the seasonal variability features are preserved throughout the entire period under consideration.

The northwestern wind frequency increases in summer months (Fig. 4, *a*) with high values in July, and the western wind frequency increases from April to July with high values in June (Fig. 4, *b*).

The southwestern wind has a consistently low frequency from July to September (Fig. 4, *c*), which makes a negative contribution to the total frequency of western winds in July and August. As a result, the total frequency maximum is observed in June (Fig. 3, *a*; Fig. 4, *d*). High values of total frequency are also noted in winter months (Fig. 4, *d*).

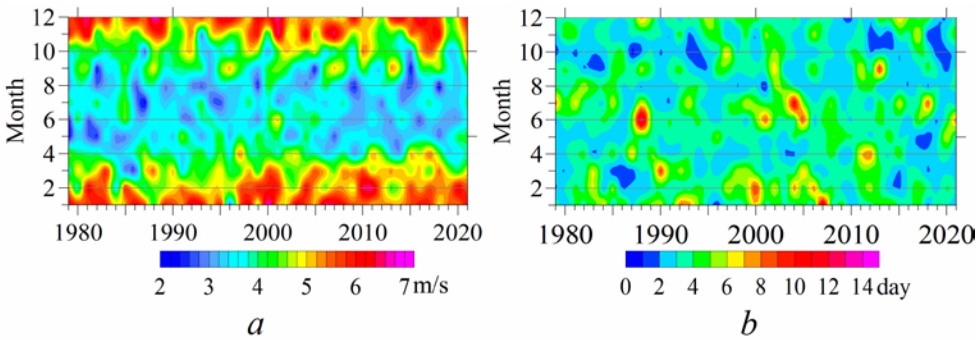
The features of the frequency of northwestern and southwestern winds in summer months (Fig. 4, *a*, *c*) are associated with the predominance of a low-pressure area (Asiatic low) over the southern part of Asia, extending to the Black Sea [26]. With such a distribution of surface pressure, conditions are created for an increase in the frequency of northwestern winds, and southwestern winds become rare [12, 27].



F i g. 4. Monthly average frequency of northwestern (*a*), western (*b*) and southwestern (*c*) winds, and their total frequency (*d*) near the Southern Coast of Crimea in 1979–2021 based on the ERA5 data

In all years, the high speed of westerly winds prevails from November to March (Fig. 5, *a*). High average monthly velocity values are also observed in the warm season. For example, the average wind speed increased in June 2001, September 1988, 1996, 2007 and 2013 (Fig. 5, *a*).

Thus, in each season, years with high and low values of frequency and wind speed, which can be accompanied by a change in the number and duration of upwelling events, are distinguished.



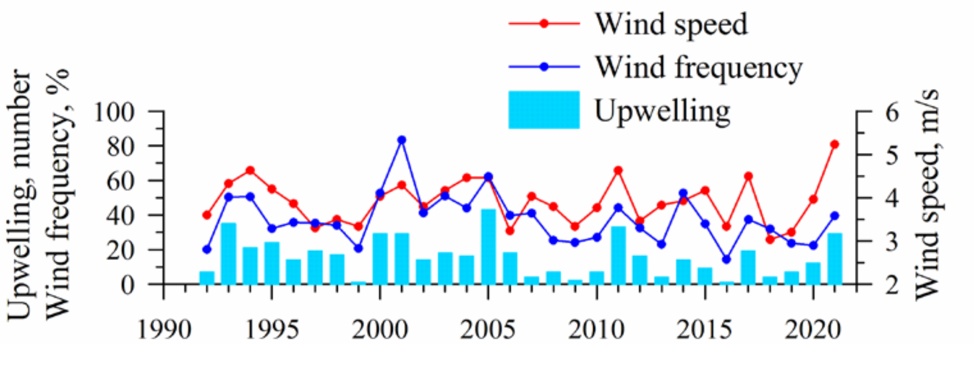
F i g. 5. Monthly average speed of southwestern, western and northwestern winds (*a*), and maximum duration of their action (*b*) near the Southern Coast of Crimea in 1979–2021

The duration of situations with the action of winds favorable for upwelling. Western winds of different duration (from a 6-hour period to several days) are observed in all months of the year. On average, each month 4–5 situations are observed with the action of southwestern, western and northwestern winds lasting a day or more.

The longest situations were obtained for the following dates: June 12–26, 1988 (more than 14 days), June 1–13, 2021 (13 days), January 10–22, 2007 (12 days), June 21–July 2 2004 (11 days) and August 29–September 8, 2013 (10 days) (Fig. 5, *b*).

Interannual variability in the number of upwellings in June based on long-term observations. To compare the number of upwellings with the frequency and speed of favorable winds, a series of long-term observations of the June sea water temperature for 1992–2021 is considered. The choice of the month is due to the fact that in June the upper heated layer thickness is less than in other summer months [12]. In addition, the highest frequency of westerly winds is observed at this time (Fig. 3, *c*). These factors are favorable for the manifestation of upwelling on the sea surface.

The sum of measurements with a sharp decrease in temperature (corresponding to the beginning of upwelling) and measurements with a persistently low temperature, which indicates the upwelling effect of the wind, will be taken into account. Let us compare the interannual variability of these values with the frequency and average speed of westerly winds (Fig. 6).



F i g. 6. Total frequency and average speed of southwestern, western and northwestern winds based on the ERA5 reanalysis data, and total number of the measurements with low temperature (upwelling) in Katsiveli in June, 1992–2021

The correlation coefficient between the number of measurements with upwellings and the values of the average speed of westerly winds is 0.74, the frequency values of these winds is 0.68. Consequently, high frequency and high wind speed are accompanied by an increase in the number of situations with a lower water temperature, such as in June 2001, 2005, 2011 and 2021 (Fig. 4, *d*; Fig. 5, *a*; Fig. 6). The low frequency of westerly winds and their low speed led to a decrease in the number of upwellings in June 1999, 2009 and 2016. Thus, interannual changes in the frequency and speed of westerly winds lead to a change in the number of upwellings.

Conclusion

Comparison of the occurrence of upwellings (according to sea water temperature data) with the wind direction (according to the ERA5 reanalysis) shows that upwellings in the area of the Southern Coast of Crimea are mainly caused by synoptic situations with westerly winds.

Wind conditions favorable for the Ekman upwelling near the Southern Coast of Crimea exist throughout the year, but each season has its own characteristics, shown in a change in the speed and frequency of winds favorable for upwelling. The speed of the southwestern, western and northwestern winds has maximum values in winter months, which, together with the high frequency of these winds, should lead to an increase in the number of upwellings. In summer months, the wind speed decreases, but in June the total frequency of favorable winds increases, which can also contribute to an increase in the number of upwellings. This is confirmed by a statistically significant positive relationship between the number of upwellings in June and the frequency and speed of westerly winds. The lowest values of speed and frequency of these winds are observed in August and October.

The issues of the analysis of the relationship between upwelling characteristics and wind and temperature indices, as well as with stratification conditions and dynamic processes in the sea, are urgent for further research.

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The authors have read and approved the final manuscript.
The authors declare that they have no conflict of interest.