ISSN 1573-160X, *PHYSICAL OCEANOGRAPHY*, Vol. 32, Iss. 3, pp. 312-325 (2025)
Original Russian Text © The Authors, 2025,
published in *Morskoy Gidrofizicheskiy Zhurnal*, 2025, Vol. 41, Iss. 3, pp. 295–309

Original article

Upwelling Index at the Southern Coast of Crimea in the Black Sea

I. G. Shokurova [1], ✉, T. V. Plastun [1], Yu. V. Simonova [1], V. Yu. Kasianenko [2]

[1] *Marine Hydrophysical Institute of RAS, Sevastopol, Russian Federation*
[2] *V. I. Vernadsky Crimean Federal University, Simferopol, Russian Federation*
✉ *igshokurova@mail.ru*

Abstract
Purpose. The purpose of the study is to analyze wind conditions leading to the occurrence of coastal upwelling events off the Southern Coast of Crimea (Katsiveli) in the Black Sea based on the calculations of wind upwelling index.
Methods and Results. The 6-hour ERA5 reanalysis data of surface wind speed components, long-term measurements of seawater and air temperature near the coast in Katsiveli (1992–2021), as well as satellite maps of sea surface temperature are used. The upwelling index is calculated as Ekman transport driven by alongshore winds. The index is considered to be positive when the transport is directed offshore. For the Katsiveli area, this condition corresponds to winds with a western component. Negative values of the index and onshore water transport correspond to eastern winds. Calculations of the upwelling index shown that the most favorable wind conditions for upwelling events are observed in winter (December and January) and summer (June and July), driven by the high frequency of western winds. The maximum value of the upwelling index is noted in June. The statistical relationship between the monthly mean upwelling index, water temperature, number of upwellings, and the frequency and speed of western winds is analyzed for this month. It is found that the upwelling index in June correlates with the number of low water temperature events (indicative of upwelling). The correlation coefficient between them is 0.88. During the years characterized by high frequency and speed of western winds, the number of upwellings increased, whereas it was minimal when eastern winds predominated. Analysis of the variability of wind index and seawater temperature based on the 6-hour data shows that high positive values of the index correspond to the onset of upwellings, while a negative index indicates their cessation.
Conclusions. Good agreement between the wind index variability and the number of measurements at low water temperature in summer demonstrates the potential of the index for studying wind conditions resulting in the development of upwelling events, as well as for forecasting their occurrence.

Keywords: coastal upwelling, upwelling index, sea water temperature, wind speed, wind direction, Katsiveli, Southern Coast of Crimea, Black Sea

Acknowledgements: the study was carried out within the framework of state assignments of FSBSI FRC MHI: FNNN-2024-0014 and FNNN-2024-0016.

For citation: Shokurova, I.G., Plastun, T.V., Simonova, Yu.V. and Kasianenko, V.Yu., 2025. Upwelling Index at the Southern Coast of Crimea in the Black Sea. *Physical Oceanography*, 32(3), pp. 312-325.

Introduction

The Black Sea waters adjacent to the Southern Coast of Crimea are a natural marine ecosystem [1], and an area for the development of aquaculture [2]. Productivity of the marine waters depends on the concentration of biogenic elements in the upper photic layer of the sea [3]. Since there are no large rivers in this area, the enrichment of surface waters with biogenic elements can be due to the inflow from deeper layers where their concentration is higher [4]. In winter, strong winds and winter convection cause the upper layer to mix well, enriching it with nutrients [5] throughout the entire water area. In summer, however, water mixing is weakened [6]. At this time, the role of coastal upwelling, an important factor in ensuring vertical water exchange, increases significantly [7].

Information on the frequency of upwelling events affecting the living conditions of marine organisms can be used to analyze monitoring results relating to the vital activity of the marine ecosystem off the coast of Crimea [8, 9]. In addition, the Southern Coast of Crimea is a popular tourist destination, so understanding the features and intensity of changes in water temperature during the summer is also of interest to researchers [10].

Upwelling is defined as the movement of water from deeper layers to the sea surface. According to Ekman’s theory, which was formulated for the deep sea, coastal upwelling can be caused by alongshore winds with the coast to the left (in the Northern Hemisphere) or to the right (in the Southern Hemisphere). In this case, Ekman transport, which is perpendicular to the wind and moves from the coast, shifts the upper layer of water towards the sea, resulting in a compensatory rise in deep waters [11]. The shelf off the Southern Coast of Crimea is narrow with a steep drop-off, so upwelling here is caused by alongshore winds. In the Katsiveli area, these are westerly winds. The occurrence and scale of upwelling depend on the wind speed, duration of action, seasonal stratification of waters, and dynamic processes in the sea [12–14].

In winter, upwellings in the Black Sea are not recorded by temperature since the upper layer is mixed [6]. In summer, however, coastal upwelling events can be clearly visible by the lower water temperature in comparison with the surrounding warm waters [15–17]. On the Southern Coast of Crimea, the area of low-temperature water can extend 60–80 km into the sea [17, 18].

A large number of works has been devoted to studying upwelling off the coast of Crimea. The wind conditions associated with upwelling events were studied based on data from coastal weather stations [19], temperature measurements at the Hydrophysical Polygon in Katsiveli [20–23], ship measurements [15], satellite data [16–18], and data from moored buoys [24]. Upwellings were studied based on numerical modeling in [18, 25, 26]. Statistics on the number of upwellings are given in [17, 19, 20]. Statistics on the frequency and speed of winds favorable for upwelling, based on ERA5 reanalysis data, are presented in [21].

The wind conditions necessary for upwelling are often studied using the wind upwelling index, which is calculated based on the Ekman transport [27]. This index is widely used to study upwelling in different areas of the World Ocean [28–31], including the Black Sea [32]. There are also improved modifications of the wind index [33]. A criterion for the wind upwelling development taking into account the speed and direction of currents in the sea was proposed in [13] and applied in [14, 24]. A number of studies use the temperature upwelling index [30]. It is defined as the difference in water temperature between the upwelling zone near the coast and open waters, usually at a distance sufficient to avoid the influence of upwelling waters captured by currents or eddies.

Studies of the conditions for upwelling events using indices have not yet been carried out for the Southern Coast of Crimea. This paper analyzes the conditions for upwelling events using the wind upwelling index (UI) [27]. The paper compares natural data on the temperature of the upper layer of seawater with index values. In the future, the index could be used to clarify the features of upwelling occurrence depending on wind conditions, and to investigate the climatic conditions affecting the functioning of the coastal ecosystem in Crimea.

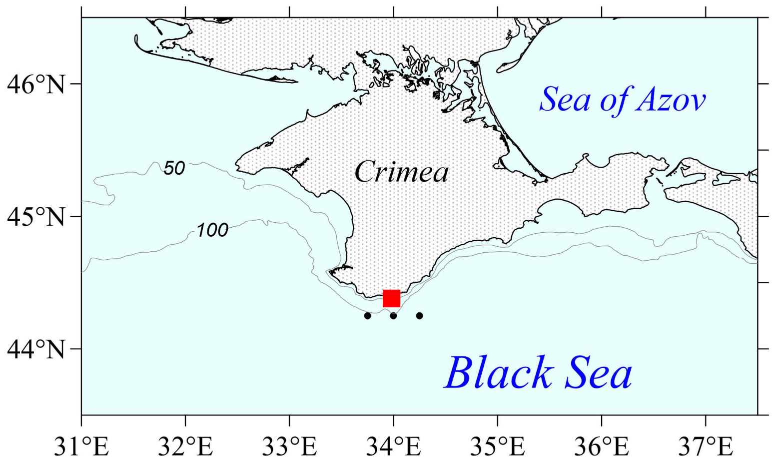
The study aims to analyze the wind conditions that lead to coastal upwelling events off the Southern Coast of Crimea (Katsiveli) in the Black Sea, based on the calculations of wind upwelling index.

Research data and methods

Water and air temperature. To identify upwelling events, we used the following data:

– daytime measurements (08:00, 14:00 and 17:00) of seawater temperature T_w and air temperature T_A (°C) for June 1992–2021, conducted at the Black Sea Hydrophysical Sub-Satellite Polygon of Marine Hydrophysical Institute of the Russian Academy of Sciences in Katsiveli, Crimea [34]. Water temperature was measured near the shore from a pier at a depth of 0.75 m;

– maps of the Black Sea surface temperature from the website archive (http://dvs.net.ru/mp/index_ru.shtml).



F i g. 1. Spatial distribution of ERA5 reanalysis data [36] used to calculate wind characteristics (black dots). Red square indicates the location of the Black Sea Hydrophysical Sub-Satellite Polygon in Katsiveli

Upwelling. It was defined as a sharp drop in water temperature of 5 °C or more, lasting from six hours to several days [19]. *In situ* measurements were taken in Katsiveli. The total number of upwelling events was determined by counting the number of measurements taken at low water temperatures. This included measurements at which the water temperature dropped sharply, corresponding to the onset of upwelling, as well as subsequent measurements at which the low temperature was maintained, indicating the upwelling-supporting effect of the wind. An increase in water temperature and its maintenance at high values meant the termination of upwelling.

Wind. The study employed 6-hourly ERA5 atmospheric reanalysis data on the u and v (m/s) wind speed components at a height of 10 m for the period 1979–2021, with a spatial resolution of 0.25 × 0.25° [35].

Wind characteristics were calculated for each 6-hour period based on wind speed components averaged over three ERA5 grid nodes in the sea area closest to Katsiveli, with coordinates of 44.25° N and 33.75°; 34° and 34.25° E (Fig. 1).

For simplicity, winds with a positive zonal component in the speed vector will be called 'western' or 'westerly' winds, and those with a negative component will be called 'eastern' or 'easterly' winds.

Wind upwelling index. To estimate the wind conditions necessary for an upwelling event, the wind upwelling index was used [27]. This index is based on the calculation of the zonal U^{Ek} and meridional V^{Ek} components of the Ekman transport $\mathbf{V}^{\mathrm{Ek}} = \left(U^{\mathrm{Ek}}, V^{\mathrm{Ek}}\right)$, $m^2 \cdot s^{-1}$, which is an integral flow of 1 m width, directed at a 90° angle to the wind direction:

$$U^{Ek} = \frac{\tau_y}{\rho_w f}, \quad V^{Ek} = -\frac{\tau_x}{\rho_w f},$$

where $\boldsymbol{\tau} = (\tau_x, \tau_y)$ is the wind stress: $\tau_x = \rho_a C_d |\mathbf{v}| u$, $\tau_y = \rho_a C_d |\mathbf{v}| v$, u is the zonal and v is the meridional wind speed components $\mathbf{v} = (u, v)$ at a 10 m height above the sea level; $\rho_a = 1.2\ \mathrm{kg \cdot m^{-3}}$ is the air density; $\rho_w = 1012\ \mathrm{kg \cdot m^{-3}}$ is the sea water density; $C_D = 1.3 \cdot 10^{-3}$ is the dimensionless empirical drag coefficient, was taken as constant; f is the Coriolis parameter.

In the Northern Hemisphere, the Ekman transport $\mathbf{V}^{\mathrm{Ek}} = \left(U^{\mathrm{Ek}}, V^{\mathrm{Ek}}\right)$ is directed at a 90° angle to the right of the wind direction. If the coastline is inclined at the α angle relative to the line of latitude, the $V^{\mathrm{Ek}'}$ transport component (perpendicular to the coastline) is calculated using the zonal and meridional components of the Ekman transport as $V^{\mathrm{Ek}'} = V^{\mathrm{Ek}} \cos\alpha - U^{\mathrm{Ek}} \sin\alpha$. In this paper, we do not take into account the small slopes of the coastline from Cape Sarych to Cape Ai-Todor (Fig. 1). It is assumed that the coastline runs parallel to the line of latitude; therefore $\alpha = 0$, and $V^{\mathrm{Ek}'} = V^{\mathrm{Ek}}$.

The upwelling index is defined as a transport V^{Ek} ($m^3 \cdot s^{-1} \cdot km^{-1}$) and calculated per kilometer of the coastline [29, 30]. In addition, the upwelling index is usually defined as positive when the Ekman transport is directed offshore. In the present case, however, the negative transfer is directed offshore, so the index will be defined as $UI = -V^{\mathrm{Ek}}$. Positive values of the UI index correspond to the presence of a western wind. In this case, the Ekman transport is directed offshore, creating conditions for the rise of deep waters (upwelling). Conversely, negative *UI* values correspond to an eastern wind, indicating that the Ekman transport is directed onshore, creating conditions for the sinking of surface waters (downwelling).

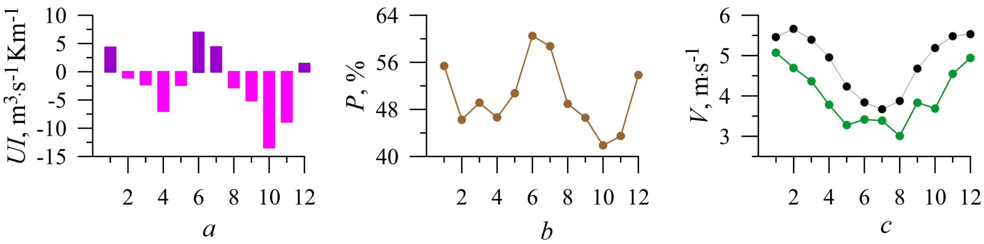
Results and discussion

Seasonal variability of the upwelling index

Calculations of the upwelling index revealed two seasons near the Southern Coast of Crimea during which the wind most often creates conditions conductive to upwelling events: winter (December, January) and summer (June, July) (Fig. 2, *a*). During these months, the zonal component of wind speed is dominated by the westerly direction. Dependence of the seasonal variability of the index on the frequency of westerly winds is clearly evident when comparing Figs. 2, a and 2, *b*. The correlation coefficient between them is 0.95. Despite the higher wind speeds in December and January (Fig. 2, *c*), the absolute value of the upwelling index in these months is lower than in June (Fig. 2, *a*). Therefore, on seasonal timescales, the frequency of winds favorable to upwelling events plays a more important role than wind speed.

The most favorable conditions for upwelling are observed in June, when the positive upwelling index reaches its maximum absolute value (Fig. 2, *a*). During this month, the frequency of westerly winds exceeds 60% (Fig. 2, *b*). A local increase in the speed of westerly winds is also observed in June (Fig. 2, *c*). By August, the speed decreases sharply.

Meanwhile, negative values of the upwelling index prevail throughout the year, caused by winds with an easterly component in the velocity vector (Fig. 2, *a*). In other words, downwelling occurs more frequently than upwelling, which is consistent with long-term water temperature observations conducted at the offshore stationary platform in Katsiveli [20]. In addition, eastern winds are faster than western ones in all months (Fig. 2, *c*). Wind conditions favorable for downwelling occur most frequently in October (Fig. 2, *a*, *b*), as confirmed by observation data [20].



F i g. 2. Monthly average values of the upwelling index (*a*), frequency of western winds (*b*), speed of western (green curve) and eastern (black curve) winds (*c*) near the Southern Coast of Crimea in 1979–2021

Taking into account the obtained feature of seasonal variability of the upwelling index, the interannual variability of the conditions for an upwelling event was analyzed based on the data for June. It was considered that, in June:

– the maximum positive upwelling index is reached, corresponding to surface water transfer from the coast and deep-water rise;

– the highest frequency of alongshore westerly winds is observed near the Southern Coast of Crimea (Fig. 2, *b*) [21];

– upwelling is well detected by water temperature [17], since in summer the rising waters from the underlying layers have a lower temperature compared to the temperature of the heated surface waters;

– stratification in the thermocline, which prevents vertical exchange, has not yet reached its maximum value, observed in August [6].

Interannual variability of the number of upwelling events and the upwelling index in June

During the period under consideration (1992–2021), 467 measurements corresponded to upwelling events were recorded in Katsiveli in June. This equates to 17.3% of the total number of measurements (2,700). There were 74 independent upwelling events. On average, 2.4 independent upwelling events and 15.6 low-temperature measurements were observed per month (Table 1). The highest number of upwellings occurred in June in 1993, 2000, 2001, 2005, 2011 and 2021 (Fig. 3, *a*). The maximum number was recorded in 2005: 43. A small number of upwellings or their complete absence were noted in 1999, 2009 and 2016.

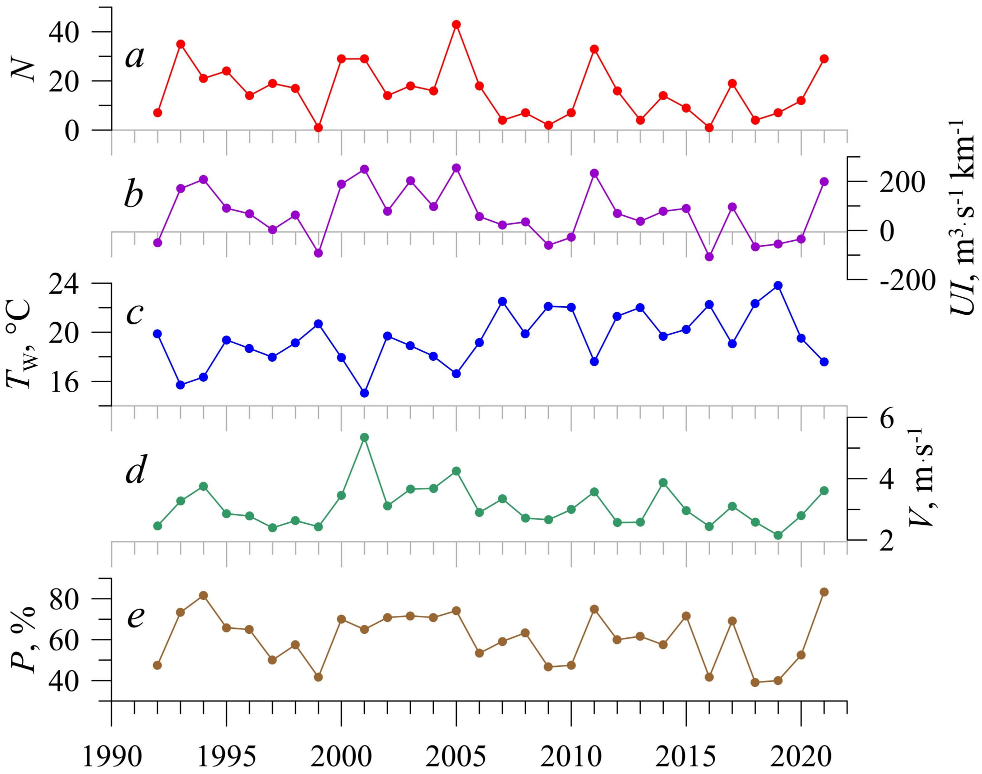
T a b l e 1

Monthly average characteristics of upwelling conditions in June, 1992–2021

Characteristic	Average	Maximum	Minimum
Total number of daytime observations of low water temperature (upwelling) in month, *N*	15.6	43.0	1.0
Water temperature, T_w, °C	19.5	23.8	15.0
Speed of western winds, *V*, $m \cdot s^{-1}$	3.1	5.3	2.1
Frequency of western winds, *P*, %	73.0	83.3	39.2
Upwelling index, $m^3 \cdot s^{-1} \cdot km^{-1}$	70.0	255	−107.0

The average water temperature in June during the years under study was 19.5 °C. The highest maximum temperature was recorded in 2019 at an average of 23.8 °C per month (Fig. 3, *c*). Temperatures over 22 °C were also observed in 2007, 2009, 2010, 2013, 2016 and 2018. The lowest average temperature was recorded in 1993 and 2001, at 15 °C.

The most frequent occurrence of winds with a westerly component in the velocity vector (83.3%) was observed in 2021 (Fig. 3, *e*), while the minimum (39.2%) was observed in 2018. The average monthly speed of westerly winds peaked at 5.3 $m \cdot s^{-1}$ in 2001 (Fig. 3, *d*). The lowest speed of 2.1 $m \cdot s^{-1}$ was recorded in 1998.



F i g. 3. Total number of daytime observations of low water temperature (upwelling) for June (*a*); June average values of upwelling index *UI* (*b*), water temperature T_W (*c*), speed *V* (*d*) and frequency *P* (*e*) of westerly winds

The excess of positive values of the upwelling index over negative values indicates stable wind conditions favorable for upwelling near the Southern Coast of Crimea in June (Table 1, Fig. 3, *b*). The maximum number of upwellings, in combination with low water temperature, occurred in 2001 and 2005, which correspond to the maximum positive values of the upwelling index (Fig. 3, *a*, *b*). The absence of upwelling in 1999 and 2016 is consistent with the low values of the upwelling index.

T a b l e 2

Correlation coefficients between the time series (1992–2021): number of observations of low water temperature (upwelling) *N*, June average water temperature T_w, upwelling index *UI*, speed *V* and frequency *P* of the westerly winds

Time series	T_w	*UI*	*V*	*P*
N	−0.84	0.88	0.69	0.71
T_w	1.00	−0.81	−0.68	−0.71
UI	−0.81	1.00	0.83	0.89

There is a highly significant relationship between the time series of the monthly total number of upwelling measurements and the upwelling index. The correlation coefficient is 0.88 (Table 2). The correlation coefficient of the upwelling index with the average water temperature is −0.81, and with the speed and frequency of western winds is 0.83 and 0.89, respectively.

Therefore, the upwelling index describes effectively the variability of wind conditions conductive to upwelling based on monthly averages and can be employed in climate studies in areas where regular measurements are unavailable.

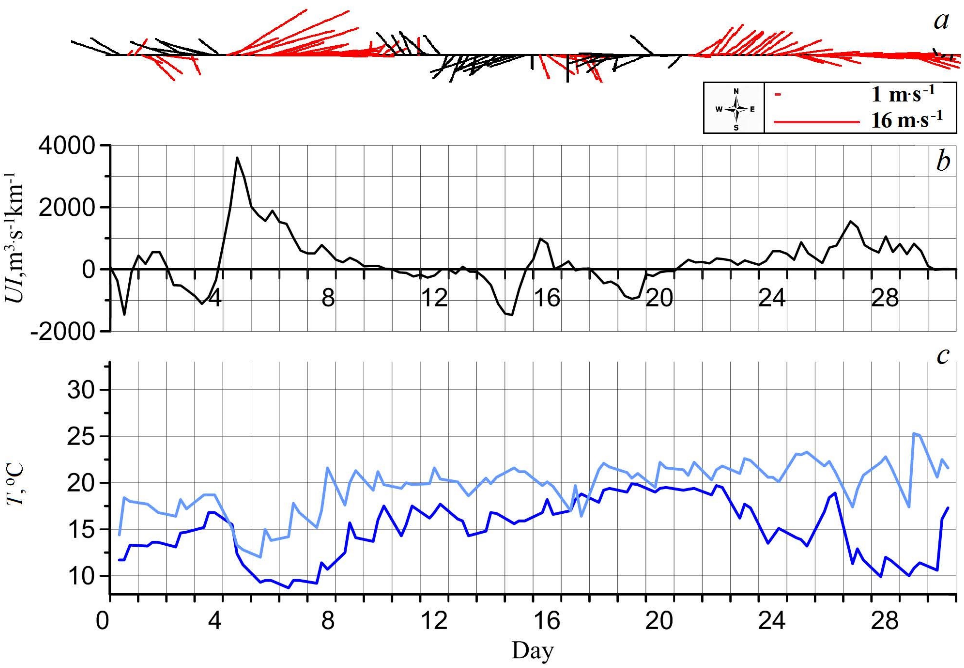
Upwelling events in June 2001 and 2019

The conditions for the occurrence of upwellings in individual years are considered in more detail in cases:

– high speed and frequency of westerly winds and minimum average water temperature (2001);

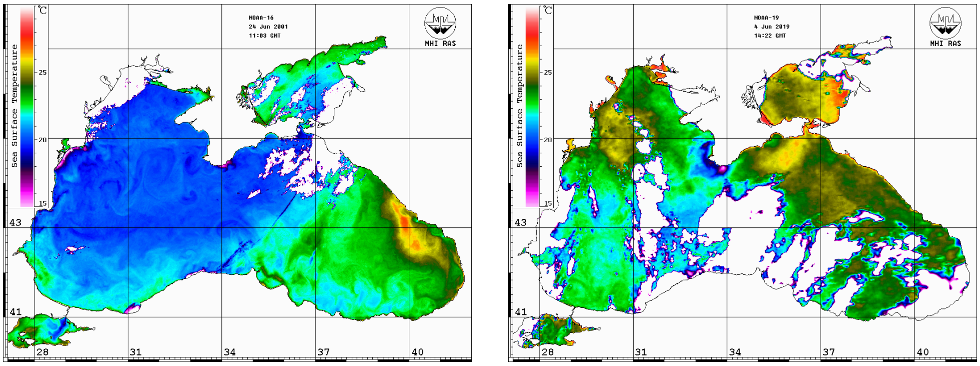
– low frequency of westerly winds and maximum average water temperature (2019).

Upwellings in June 2001. In June 2001, the lowest average water temperature (15 °C) and the highest average wind speed (5.3 m·s^{-1}) were observed during the study period. Two independent upwellings were recorded in this month (Fig. 4, *c*). The first, which was accompanied by a sharp drop in temperature from 17 to 9.3 °C, developed on 5 June during the day with a stable southwesterly wind (Fig. 4, *a*). The upwelling occurred after an increase in wind speed to 16 m·s^{-1}. At the same time, the upwelling index reached an unusually high value of 3600 m^3·s^{-1}·km^{-1} (Fig. 4, *b*). The upwelling ended on 10 June when the wind direction changed to the southeasterly.



F i g. 4. Wind direction (red color indicates westerly winds, black color – easterly winds) (*a*), upwelling index *UI* (*b*), water temperature T_W (blue line) and air temperature T_A (light blue line) based on the daytime measurements in Katsiveli (*c*) in June 2001

Similar wind conditions (a prolonged southwesterly wind with speeds over 6–10 m·s^{-1}) caused long-term upwelling from 23 to 30 June, resulting in a decrease in water temperature of almost 10 °C (Fig. 4, *a*, *c*). The onset of upwelling at Katsiveli is clearly visible in the 24 June satellite image (Fig. 5, *a*). On 26 June, a short-term weakening of the western wind (no more than half a day) was followed by an increase in the surface water temperature near the shore. On 27 June, when the western wind increased to a speed of 10 m·s^{-1}, the temperature dropped again to 10 °C. Positive values of the index during the third ten-day period of June are consistent with a decrease in water temperature during this period (Fig. 4, *b*).



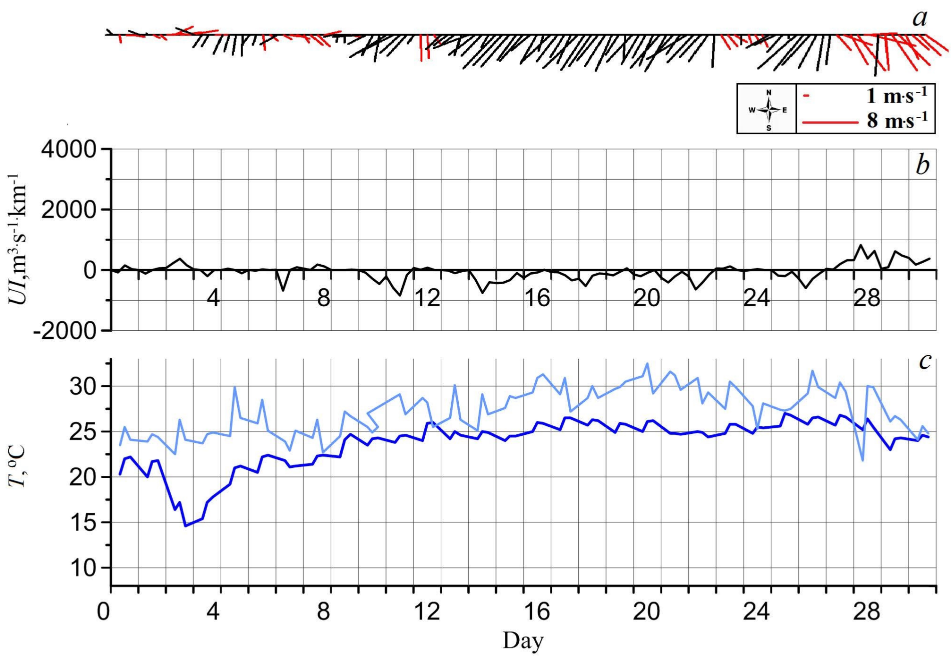
a *b*

F i g. 5. Sea surface temperature at 11:03 GMT on June 24, 2001 (NOAA 16) (*a*) and at 14:22 GMT on June 4, 2019 (NOAA-19) (*b*) taken from the satellite map archive (available at: http://dvs.net.ru/mp/index_ru.shtml)

Upwelling events in June 2019. According to coastal measurements, the maximum average water temperature of 23.8 °C was observed in June 2019 (Table 1). The only upwelling occurred at the beginning of the month, from 3 to 5 June (Fig. 6, *c*). During this period, the temperature fell from 22 to 14 °C. This was caused by a sharp increase in the westerly wind to 5 m·s^{-1} (Fig. 6, *a*). The decrease in water temperature on 4 June is clearly seen in the satellite image (Fig. 5, *b*). No upwelling was observed during the remaining days of the month. The northwesterly winds observed at the end of the month, from 27 June, were accompanied by only a slight decrease in temperature.

This situation, characterized by a small number of upwelling events, was associated with the low frequency of westerly winds (Fig. 6, *a*). During the month, the northeasterly wind contributed to a surge of warm surface water towards the shore and its subsequent descent (downwelling). The upwelling index was negative for most of the month (Fig. 6, *b*).

An analysis of June data from all years (1992–2021) showed that the wind speed leading to upwelling in June mostly exceeds 5–6 m·s^{-1}, with an index value exceeding 520 m·s^{-1}·km^{-1}. This wind speed is consistent with the results obtained in [13]. It should be noted that these values may increase with a growth in the thickness of the heated sea layer and increased stratification of waters in the thermocline in July and August.



F i g. 6. The same as in Fig. 4, June 2019

According to daytime measurements, the air temperature in June was generally higher than the water temperature. In the absence of upwelling, the difference is 1–5 °C; with upwelling, it increases to 10 °C or more.

Conclusion

This paper studies the wind conditions necessary for upwelling to occur near the Southern Coast of Crimea, in the Katsiveli area, using the wind upwelling index. This index represents the value of Ekman water transfer towards or away from the coast depending on the direction and speed of the alongshore wind.

It was found that conditions for an upwelling event vary by season. In December, January, June and July, the average upwelling index is positive, and the Ekman transport is mainly directed offshore due to the high frequency of westerly winds. This creates favorable conditions for the development of upwelling. In other months, the index is negative. The Ekman transfer of water to the coast predominates, which creates conditions for the development of downwelling.

A comparison of the interannual variability of the monthly average values of the upwelling index and the number of *in situ* coastal upwelling observations in June showed a high correlation between these characteristics, with a correlation coefficient of 0.88. Analysis of 6-hour observation data demonstrated good agreement between upwelling index values and measured water temperature. A decrease in temperature starts with a sharp increase in westerly wind speed. High positive values of the wind index, corresponding to high wind speeds, precede the appearance of low sea surface temperatures in summer. Stable westerly winds can support long-term upwelling. A weakening of the westerly winds or a change in wind direction to the east leads to the termination of upwelling.

The results of this paper demonstrate the potential for using the wind index to study and forecast coastal Ekman upwelling, as well as for climate studies along the Southern Coast of Crimea. However, further analysis of wind-driven upwelling processes on hourly and daily time scales is actual.

REFERENCES

1. Eremeev, V.N., Boltachev, A.R., Aleksandrov, B.G., Alyomov, S.V., Zagorodnya, Yu.A., Karpova, E.P., Manzhos, L.A. and Gubanov, V.V., 2012. *Biological Diversity of the Coastal Zone of the Crimean Peninsula: Problems, Preservation and Restoration Pathways*. Sevastopol: Institute of Biology of the Southern Seas, 92 p.

2. Massa, F., Aydın, I., Fezzardi, D., Akbulut, B., Atanasoff, A., Beken, A.T., Bekh, V., Buhlak, Y., Burlachenko, I. [et al.], 2021. Black Sea Aquaculture: Legacy, Challenges & Future Opportunities. *Aquaculture Studies*, 21(4), pp. 181-220. http://doi.org/10.4194/2618-6381-v21_4_05

3. Arrigo, K.R., 2005. Marine Microorganisms and Global Nutrient Cycles. *Nature*, 437(7057), pp. 349-355. https://doi.org/10.1038/nature04159

4. Varenik, A.V., Kondratyev, S.I., Medvedev, E.V., Khoruzhiy, D.S. and Orekhova, N.A., 2023. Characteristics of State and Evolution of the Black Sea Hydrochemical Structure. *Physical Oceanography*, 30(6), pp. 826-850.

5. Kubryakov, A.A., Belokopytov, V.N., Zatsepin, A.G., Stanichny, S.V. and Piotukh, V.B., 2019. The Black Sea Mixed Layer Depth Variability and Its Relation to the Basin Dynamics and Atmospheric Forcing. *Physical Oceanography*, 26(5), pp. 397-413. https://doi.org/10.22449/1573-160X-2019-5-397-413

6. Ivanov, V.A. and Belokopytov, V.N., 2013. *Oceanography of the Black Sea*. Sevastopol: MHI, 210 p.

7. Checkley, D.M. and Barth, J.A., 2009. Patterns and Processes in the California Current System. *Progress in Oceanography*, 83(1-4), pp. 49-64. https://doi.org/10.1016/j.pocean.2009.07.028

8. Stelmakh, L.V., 2020. Methodology of Comprehensive Monitoring of Modern Black Sea Phytoplankton Community Status. *Monitoring Systems of Environment*, (1), pp. 21-26. https://doi.org/10.33075/2220-5861-2020-1-21-26 (in Russian).

9. Finenko, Z.Z., Mansurova, I.M., Kovalyova, I.V. and Georgieva, E.Yu., 2021. Development of Phytoplankton in the Winter-Spring Period in the Coastal Waters of Crimea. *Marine Biological Journal*, 6(1), pp. 102-114. https://doi.org/10.21072/mbj.2021.06.1.08 (in Russian).

10. Kostianaia, E.A. and Kostianoy, A.G., 2021. Regional Climate Change Impact on Coastal Tourism: A Case Study for the Black Sea Coast of Russia. *Hydrology*, 8(3), 133. https://doi.org/10.3390/hydrology8030133

11. Kämpf, J. and Chapman, P., 2016. *The* Functioning of Coastal Upwelling Systems. In: J. Kämpf and P. Chapman, 2016. *Upwelling Systems of the World. A Scientific Journey to the Most Productive Marine Ecosystems*. Cham: Springer, pp. 31-65. https://doi.org/10.1007/978-3-319-42524-5_2

12. Jacox, M.G. and Edwards, C.A., 2011. Effects of Stratification and Shelf Slope on Nutrient Supply in Coastal Upwelling Regions. *Journal of Geophysical Research: Oceans*, 116(C3), C03019. https://doi.org/10.1029/2010JC006547

13. Zatsepin, A.G., Silvestrova, K.P., Piotoukh, V.B., Kuklev, S.B. and Podymov, O.I., 2016. Observations of a Cycle of Intense Coastal Upwelling and Downwelling at the Research Site of the Shirshov Institute of Oceanology in the Black Sea. *Oceanology*, 56(2), pp. 188-199. https://doi.org/10.1134/S0001437016020211

14. Silvestrova, K.P., Zatsepin, A.G. and Myslenkov, S.A., 2017. Coastal Upwelling in the Gelendzhik Area of the Black Sea: Effect of Wind and Dynamics. *Oceanology*, 57(4), pp. 469-477. https://doi.org/10.1134/S0001437017040178

15. Gawarkiewicz, G., Korotaev, G., Stanichny, S., Repetin, L. and Soloviev, D., 1999. Synoptic Upwelling and Cross-Shelf Transport Processes along the Crimean Coast of the Black Sea. *Continental Shelf Research*, 19(8), pp. 977-1005. https://doi.org/10.1016/S0278-4343(99)00003-5

16. Goryachkin, Yu.N., 2018. Upwelling nearby the Crimea Western Coast. *Oceanography*, 25(5), pp. 368-379. https://doi.org/10.22449/1573-160X-2018-5-368-379

17. Stanichnaya, R.R. and Stanichny, S.V., 2021. Black Sea Upwellings. *Current Problems in Remote Sensing of the Earth from Space*, 18(4), pp. 195-207. https://doi.org/10.21046/2070-7401-2021-18-4-195-207 (in Russian).

18. Kubryakov, A., Aleskerova, A. and Mizyuk, A., 2024. Submesoscale Features of Coastal Upwellings in the Black Sea: Observations and Modeling. *Continental Shelf Research*, 279, 105291. https://doi.org/10.1016/j.csr.2024.105291

19. Lovenkova, E.A. and Polonskii, A.B., 2005. Climatic Characteristics of Upwelling near the Crimean Coast. *Russian Meteorology and Hydrology*, (5), pp. 31-37.

20. Kuklin, A.K., Kuklina, N.Ya. and Shabalina, O.A., 2014. [Sea Water Temperature near the Oceanographic Platform in Katsiveli]. *Ecological Safety of Coastal and Shelf Zones and Comprehensive Use of Shelf Resources*, 28, pp. 186-194 (in Russian).

21. 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.

22. Tolstosheev, A.P., Motyzhev, S.V. and Lunev, E.G., 2020. Results of Long-Term Monitoring of the Shelf Water Vertical Thermal Structure at the Black Sea Hydrophysical Polygon of RAS. *Physical Oceanography*, 27(1), pp. 69-80. https://doi.org/10.22449/1573-160X-2020-1-69-80

23. Simonova, Yu.V., Stanichny, S.V. and Lemeshko, E.M., 2024. The Features of Anomalies in Surface Temperature of the Black Sea in the Area of the Southern Coast of Crimea. *Sovremennye Problemy Distantsionnogo Zondirovaniya Zemli iz Kosmosa*, 21(3), pp. 234-243. https://doi.org/10.21046/2070-7401-2024-21-3-234-243 (in Russian).

24. Silvestrova, K.P., Myslenkov, S.A. and Repkov, D.S., 2022. Wind Upwelling Forecast for the Russian Black Sea Coast. *Hydrometeorological Research and Forecasting*, 1(383), pp. 89-107. https://doi.org/10.37162/2618-9631-2022-1-89-107

25. Ivanov, V.A. and Mikhailova, E.N., 2008. *Upwelling in the Black Sea*. Sevastopol: ECOSI-Gidrofizika, 92 p. (in Russian).

26. Polonskii, A.B. and Muzyleva, M.A., 2016. Modern Spatial-Temporal Variability of Upwelling in the North-Western Black Sea and off the Crimea Coast. *Izvestiya Rossiiskoi Akademii Nauk.*

Seriya Geograficheskaya, (4), pp. 96-108. https://doi.org/10.15356/0373-2444-2016-4-96-108 (in Russian).

27. Bakun, A., 1973. *Coastal Upwelling Indices, West Coast of North America, 1946–71*. NOAA Technical Report NMFS SSRF. Seattle, WA: National Marine Fisheries Service, 103 p.

28. Pérez, F.F., Padín, X.A., Pazos, Y., Gilcoto, M., Cabanas, M., Pardo, P.C., Doval, M.D. and Farina-Busto, L., 2010. Plankton Response to Weakening of the Iberian Coastal Upwelling. *Global Change Biology*, 16(4), pp. 1258-1267. https://doi.org/10.1111/j.1365-2486.2009.02125.x

29. González-Nuevo, G., Gago, J. and Cabanas, J.M., 2014. Upwelling Index: A Powerful Tool for Marine Research in the NW Iberian Upwelling System. *Journal of Operational Oceanography*, 7(1), pp. 47-57. https://doi.org/10.1080/1755876X.2014.11020152

30. Ferreira, S., Sousa, M., Picado, A., Vaz, N. and Dias, J.M., 2022. New Insights about Upwelling Trends off the Portuguese Coast: An ERA5 Dataset Analysis. *Journal of Marine Science and Engineering*, 10(12), 1849. https://doi.org/10.3390/jmse10121849

31. Zhabin, I.A., Dmitrieva, E.V., Dubina, V.A. and Luchin, V.A., 2022. Variability of Summer Wind-Driven Upwelling along the Koryak Coast in the Northwestern Bering Sea Based on Satellite Data. *Izvestiya, Atmospheric and Oceanic Physics*, 58(12), pp. 1438-1449. https://doi.org/10.1134/S0001433822120283

32. Mihailov, M.E., 2024. *The* Black Sea Upwelling System: Analysis on the Western Shallow Waters. *Atmosphere*, 15(8), 999. https://doi.org/10.3390/atmos15080999

33. Jacox, M.G., Edwards, C.A., Hazen, E.L. and Bograd, S.J., 2018. Coastal Upwelling Revisited: Ekman, Bakun, and Improved Upwelling Indices for the U.S. West Coast. *Journal of Geophysical Research: Oceans*, 123(10), pp. 7332-7350. https://doi.org/10.1029/2018JC014187

34. Zhuk, E., Khaliulin, A., Zodiatis, G., Nikolaidis, A. and Isaeva, E., 2016. Black Sea GIS Developed in MHI. In: SPIE, 2016. *Proceedings of SPIE*. Volume 9688, Fourth International Conference on Remote Sensing and Geoinformation of the Environment (RSCy2016), 96881C. https://doi.org/10.1117/12.2241631

35. Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R. [et al.], 2020. The ERA5 Global Reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146(730), pp. 1999-2049. https://doi.org/10.1002/qj.3803

Submitted 18.11.2024; approved after review 29.11.2024;
accepted for publication 13.03.2025.

About the authors:

Irina G. Shokurova, Senior Researcher, Marine Hydrophysical Institute of RAS (2 Kapitanskaya Str., Sevastopol, 299011, Russian Federation), CSc. (Geogr.), **ORCID ID: 0000-0002-3150-8603**, **WOS ResearcherID: C-8223-2016**, igshokurova@mail.ru

Tatyana V. Plastun, Junior Researcher, Marine Hydrophysical Institute of RAS (2 Kapitanskaya Str., Sevastopol, 299011, Russian Federation), **ORCID ID: 0000-0001-7685-7455**, **WOS ResearcherID: AAC-1888-2022**, ptv63@inbox.ru

Yulia V. Simonova, Junior Researcher, Black Sea Sub-Satellite Polygon, Marine Hydrophysical Institute of RAS (2 Kapitanskaya Str., Sevastopol, 299011, Russian Federation), **ORCID ID: 0000-0002-8075-8748**, **WoS ResearcherID: GYU-2700-2022**, julia.simonova.0502@gmail.com

Valeria Yu. Kasianenko, Student, V.I. Vernadsky Crimean Federal University (5/7 Lenina Blvd., Simferopol, 295051, Russian Federation)

Contribution of the co-authors:

Irina G. Shokurova – wind and temperature data processing, visualization, writing and editing of the text, literature review, discussion of results

Tatyana V. Plastun – wind and temperature data processing, visualization, writing and editing of the text, literature review, discussion of results

Yulia V. Simonova – water and air temperature data collection and processing, visualization, text editing, discussion of results

Valeria Yu. Kasianenko – work with satellite map archive, visualization, discussion of results

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