

Original article

Distribution of Suspended Matter in Karkinitzky Bay Based on Satellite Data

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Abstract

Purpose. The purpose of the work is to study the spatial-temporal distribution of total suspended matter in the Karkinitzky Bay water area using high- and medium-resolution satellite data.

Methods and Results. The data of MODIS/Aqua, OLI Landsat-8, -9 and MSI Sentinel-2 satellites on the brightness of upwelling radiation and the total suspended matter concentration for 2003–2024 were applied in the study. To analyze the wind and wave regime, the retrospective calculations of wind and wave conditions were statistically analyzed based on the ERA-Interim, ERA5 and SWAN-ERA reanalysis data for the same period, and the typical wave fields were mathematically modeled for the most wave-hazardous regions. The following maps of total suspended matter distribution were compiled: long-term average one, those for each month, for prevailing storm winds and for various wind-wave situations. It was revealed that the lowest values (up to 0.75 mg/L) were typical of the by western deep part, its eastern part was characterized by a more complex structure of distribution and a higher (by 2–4 times) total suspended matter concentrations. Within the seasonal variation, the following periods are distinguished: warm period (May – October) with relatively transparent waters (0.6–0.9 mg/L), cold season (December – March) with maximum total suspended matter concentrations (5.4–6 mg/L), and the periods of spring and autumn off-seasons. The dominant factor in seasonal variability is the storm wind-wave impact. As for the interannual variability, no direct relationship between the annual average values of suspended matter concentration and total storm power index was identified due to the limit of satellite data in cloudy conditions. It is found for the first time that the Small Phyllophora Field constitutes a significant factor influencing the distribution of suspended matter in the eastern part of the bay (lower brightness values above it are recorded in most images).

Conclusions. The waters of Karkinitzky Bay are characterized by high dynamics and spatial heterogeneity of suspended matter distribution. The seasonal variation of total suspended matter concentration is conditioned by the wind-wave regime.

Keywords: suspended matter, satellite data, MODIS-Aqua, Landsat, Karkinitzky Bay, Black Sea, wind-wave regime, retrospective calculations, Small Phyllophora Field

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Introduction

Karkinitzky Bay, located on the northwestern shelf of the Black Sea, is of considerable ecological and economic importance. Approximately half of its area and part of the adjacent coastal zone are included in five specially protected natural areas



(SPNAs) of different categories and statuses [1, 2]. The Golitsynskoye and Arkhangelskoye gas fields and the Kalanchatskoye sand deposit are located within its waters, and industrial and agricultural enterprises are situated along its shores. In the context of growing anthropogenic pressure and climate change, the importance of monitoring the bay's ecosystems is indisputable.

The bay has a complex shoreline configuration and underwater relief (Fig. 1). The coastline varies in origin and structure. The Bakalskaya Spit and its underwater continuation divide the bay into a western part (with depth of up to 36 m) and a shallow eastern part (depths of up to 10–11 m).

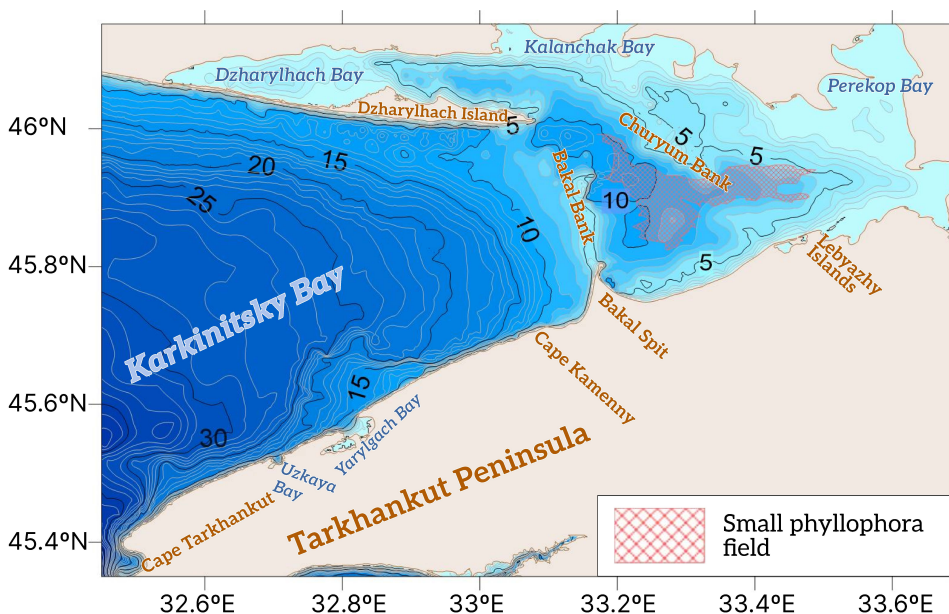


Fig. 1. Bathymetric map of Karkinitsky Bay

The Tarkhankut Peninsula is characterized by abrasion and abrasion-landslide coastlines in limestones with a cliff-foot blocky bench. The bars of Yarylgachskaya and Uzkaya bays are composed of sands. East of Vladymirovka village, the cliff becomes clayey. At the root of the western branch of the Bakalskaya Spit, the cliff (8–10 m high) and the underwater slope are composed of easily erodible loess-like loams¹ [3]. The Bakalskaya Spit and the shoal of the same name are accumulative forms composed of quartz sand with admixtures of limestone sand, gravel, pebbles, and oolitic grains [3, 4]. The adjacent shelf is a gentle plain with a westward slope. Depths on the Bakalskaya Bank range from 2.5 to 5 m [5].

The southern shores of the eastern part of the study area up to Kalanchak Bay are represented by accumulative forms composed mainly of shell material and eelgrass deposits. On the northern shores, in addition to shell detritus, quartz sand is present. The bottom of the shallows is leveled by a cover of silty deposits and is occupied by phytocenoses of seagrasses and phyllophora [6], as a result of which the wave impact on the shore is weakened².

¹ Zenkovich, V.P., 1958. *Shores of the Black and Azov Seas*. Moscow: State Publishing House of Geographical Literature, 374 p. (in Russian)

² Pravotorov, I.A., 1967. *Geomorphological Characteristics of the Coastal Zone. Biology of the North-Western Part of the Black Sea*. Kyiv: Naukova Dumka, Chapter 1. pp. 6–13 (in Russian).

The northern coast of the western part of Karkinitsky Bay is represented by sandy accumulative forms – the Dzharylhach spit-island and the Tendra Spit. Between them, there is an 18-km long abrasion coast [7].

The spatial distribution of water transparency in the bay is formed under the influence of bottom sediments of biological and mineral origin and depends on the amount of incoming total suspended matter and water dynamics. The composition and concentration of suspended matter in the study area are determined by wind-wave resuspension of bottom sediments, abrasion of shores and benches, aeolian processes, production and die-off of phytoplankton, inflow of waters from the northwestern shelf and transformed river waters into the bay, and anthropogenic factors (coastal runoff and runoff from irrigation systems of Northern Crimea) [8, 9].

The main factor affecting the concentration and spatial distribution of total suspended matter is wind-wave impact. A substantial input of mineral particles occurs during shore erosion and resuspension of bottom sediments as a result of storms. According to [10, 11], wind speed and storm wave activity have a well-defined annual cycle with a maximum in the cold period. Waves from northern directions prevail, but the highest wave heights are produced by winds from the west and southwest. Deep cyclones, occurring approximately once every 7–10 years, are particularly destructive.

The suspended matter dynamics in Karkinitsky Bay remains a poorly studied problem, which is associated with the limited amount of *in situ* data. Regular expeditionary studies of the area were conducted until the 1990s; later, the amount of measurement data decreased significantly [12]. *In situ* measurements are possible only in relatively calm sea conditions. Since 2020, access to the study area has been closed, so remote sensing remains the only available research method.

Satellite methods make it possible to track the spatial-temporal distribution of suspended matter, identify sources of its input, and assess anthropogenic impact. The advantage of satellite monitoring is the ability to study the suspended matter dynamics at selected temporal and spatial scales under various hydrometeorological conditions. The only limitation is the presence of cloud cover over the study area.

Optical scanners make it possible to estimate sources of suspended matter input, spatial variability, and quantitative indicators of suspended matter of various origins in the surface layer [13–19]. For the western Crimea area, the authors conducted studies of suspended matter distribution under strong winds and the influence of submesoscale eddies on suspended matter transport [9, 20, 21].

In Karkinitsky Bay, the variability of the beam attenuation coefficient and water transparency based on archival observational data on Secchi disk depth was studied in [8, 22]. Numerical modeling of bottom sediment resuspension, transport, and deposition under storm conditions was performed in [23, 24]. An integrated approach to studying bottom dynamics near the Bakalskaya Spit was applied in [25], where, based on *in situ* measurements with the “Bottom Station” complex [26, 27], MODIS data, and numerical modeling of surface waves and currents, characteristics of sediment resuspension in coastal and deep waters with relatively high transparency were obtained.

This work aims to study the spatio-temporal distribution of suspended matter in the Karkinitsky Bay water area using high- and medium-resolution satellite data.

Materials and methods

The study of suspended matter distribution in Karkinitsky Bay was carried out using satellite images from MODIS/Aqua (Moderate Resolution Imaging Spectroradiometer) with a spatial resolution of 1 km and a temporal resolution of 1 day (Level-2) for 2003–2024. Data on the brightness of upwelling radiation (RRS at a wavelength of 551 nm) and total suspended matter (TSM) concentration were used. To determine the concentration of suspended matter, a regional algorithm based on a combination of spectral brightness values at different wavelengths from MODIS/Aqua data was applied [28]. The algorithm was calibrated based on measurements in open sea waters and in coastal waters with high TSM concentrations [29, 30].

A detailed study of individual cases of TSM propagation in the study area was carried out using high-resolution data from OLI (Operational Land Imager) Landsat-8, -9 (resolution 30 m) and MSI (Multispectral Instrument) Sentinel-2 (resolution 10 m); the temporal resolutions are 16 and 10 days, respectively. Images with cloud cover not exceeding 30% of the study area were selected. In total, 4826 MODIS images for 2003–2024 and 258 Landsat-8, -9 images for 2013–2025 were analyzed. Sentinel-2 scenes were used to examine individual cases, in particular to study the position of the Small Phyllophora Field in Karkinitsky Bay. The data were obtained from the Remote Sensing Department of Marine Hydrophysical Institute (<http://dvs.net.ru>) and from the NASA archive (<http://oceandata.sci.gsfc.nasa.gov/>).

Estimates of the statistical characteristics of wind and waves in the study area were obtained based on retrospective wind-wave calculation data for 2003–2024 with a temporal resolution of 1 hour. Wind fields were taken from the global atmospheric reanalyses ERA-Interim and ERA5 (<https://www.ecmwf.int/en/forecasts>). The wind-wave data array (hereinafter, the SWAN-ERA array) was obtained using the numerical spectral-discrete model SWAN (Simulating Waves Nearshore)³ [31] on an unstructured computational grid with refinement in the coastal zone of Crimea. From the SWAN-ERA array, two grid nodes were selected; they were located at the entrance to the bay (at a depth of 30 m) and in the eastern part of the bay (at the 5 m isobath). For these points, long-term series of parameters were formed, including wind speed and direction at a height of 10 m; significant wave height (h_s); mean wave period ($\bar{\tau}$); mean wave direction ($\bar{\theta}$); peak wave period (τ_p).

To analyze the impact of storms, stationary wave fields (typical wave fields) formed by spatially uniform and temporally constant wind with a wind speed of 10 m/s for six of the most wave-hazardous directions were calculated using the spectral wave model SWAN. Increased computational accuracy was achieved using a three-step nested grid method; the spatial resolution was ~ 200 m. The modeling technology is described in more detail in [11]. Mathematical calculations were performed on the computing cluster of Marine Hydrophysical Institute in the Department of Computational Technologies and Mathematical Modeling.

³ The SWAN Team, 2018. *SWAN Cycle III Version 41.20*. Delft, Netherlands: Delft University of Technology, 121 p. (SWAN User Manual).

Results and discussions

Based on the analysis of MODIS satellite images for 2003–2024, a map of the long-term average distribution of suspended matter concentration in Karkinitzky Bay was constructed (Fig. 2). The heterogeneity of suspended matter distribution in the study area was revealed. In this work, for the analysis of the suspended matter field, the bay was divided by a conventional line from Cape Dzharylhach to Cape Kamenny.

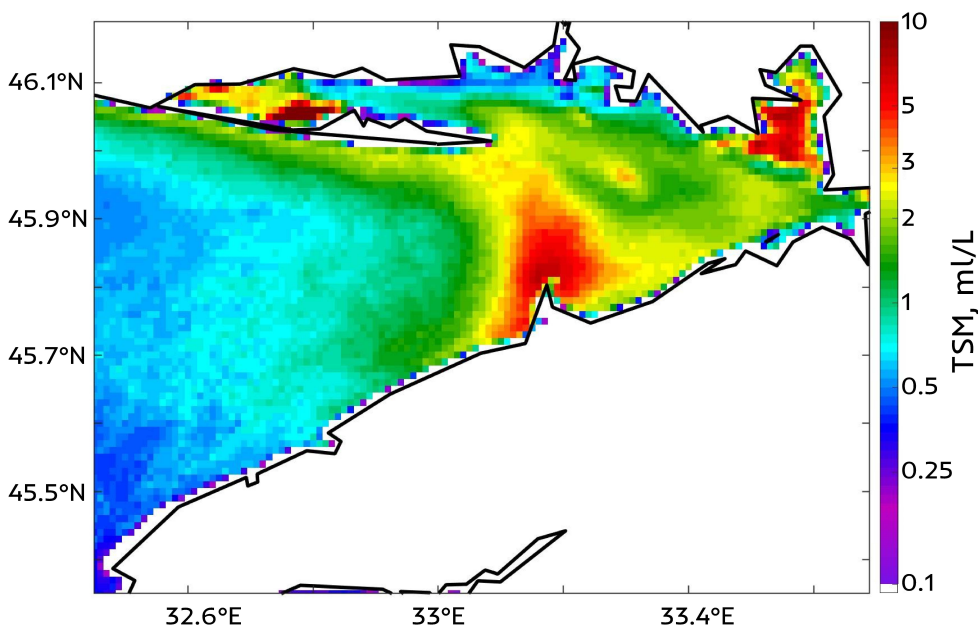


Fig. 2. Average TSM concentration in the Karkinitzky Bay waters based on the MODIS/Aqua data for 2003–2024

The lowest values of TSM concentration (up to 0.75 mg/L) were recorded in the western part of the water area, which is characterized by depths greater than 25 m and active water exchange with the sea. In the coastal zone, the most transparent waters are located in the area of the limestone coastline from Yarylhach Bay to Cape Tarkhankut. As depth decreases, the concentration of suspended matter increases; near the northern coast of the bay (along the Dzharylhach spit-land and Tendra Spit), it reaches 2.5 mg/L.

The eastern part of Karkinitzky Bay has a more complex structure of TSM distribution. Over almost the entire area, TSM concentrations are elevated; only along the northern shore of Dzharylhach Bay are low values (less than 1 mg/L) recorded. TSM concentrations reach a maximum (4–10 mg/L) in the shallow areas of Bakalskaya Spit and the Bakalskaya Bank, Perekop Bay, and the innermost part of Dzharylhach Bay.

Wind-wave impact on TSM distribution. The TSM distribution depends significantly on the impact of storms, which lead to resuspension of bottom sediments. Analysis of the wind-wave regime of the region showed that winds from land (sector 0°–90°) have the highest frequency (~ 36–38%) (Fig. 3, a).

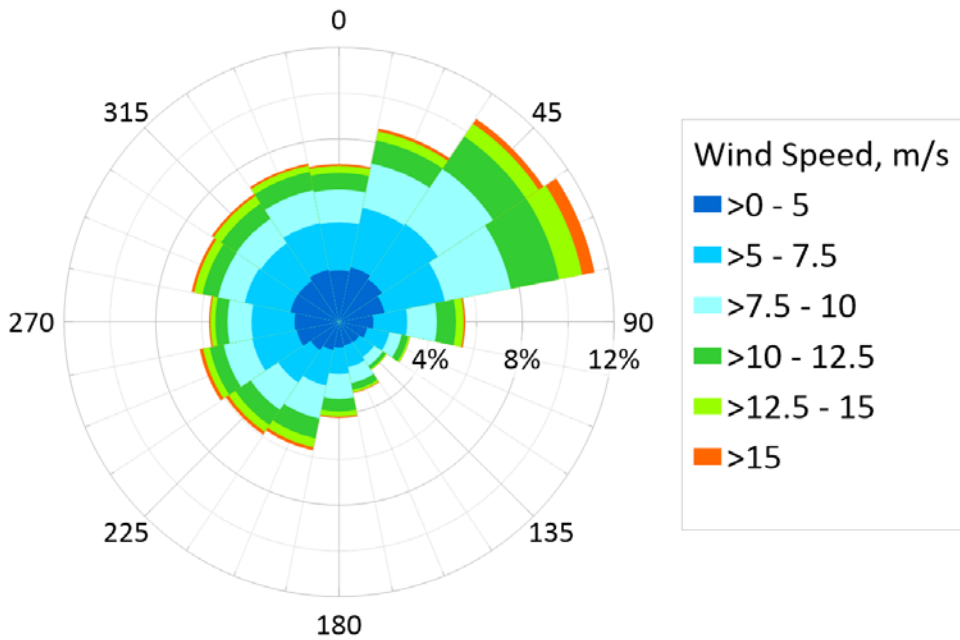
The maximum frequency of strong winds (speeds more than 15 m/s) corresponds to the east-northeast direction. From the sea, the most wave-hazardous sector is southwest – northwest (225° – 315°), the frequency of wind from this sector is ~ 24 – 26% . At the entrance to the bay, waves coming from the open sea from the southwest – northwest sector (240 – 285°) have the highest frequency ($\sim 40\%$), most often from the southwest (14%). Waves from the northeast have a frequency of 23% (Fig. 3, *b*). Waves with periods of 7 s or more enter Karkinitsky Bay from the sector 190° – 270° . In the eastern part of the bay, waves with periods of 2–5 s predominate, entering this part of the water area through the strait between Bakalskaya Spit and Dzharylhach Island.

The key factors determining the wave regime in the study area are wind speed, depth distribution, and effective fetch lengths [10]. Due to the shallowness of Karkinitsky Bay, the complex coastline configuration, and bottom topography, waves undergo significant transformation. According to numerical modeling data (Fig. 4), the most intense waves (coming from the southwest – northwest sector) at the entrance to the bay have heights up to 1.7 m (Fig. 4, *a* – *c*). When interacting with bottom irregularities, wave heights decrease and their direction changes: above Bakalskaya Bank, the heights are ~ 0.9 m, whereas farther east they do not exceed 0.8 m. In this area, wave-height contours largely follow the isobaths, forming minima above the Bakalskaya and Chumryuyskaya banks. Refracted waves with heights not exceeding 0.6 m penetrate into Dzharylhach Bay. During storm winds from the northeast, due to the small fetch (no more than 30 km), wave heights in the eastern part of the bay do not exceed 0.8 m; in the western part, where the fetch is larger, they reach 1.2 m (Fig. 4, *d* – *f*).

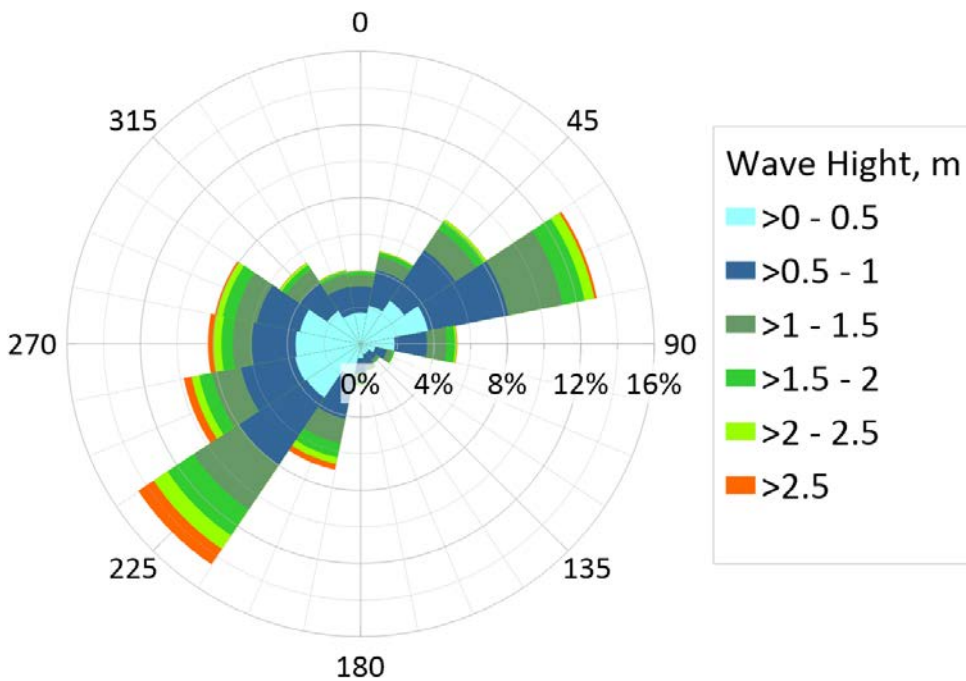
To construct maps of TSM distribution in Karkinitsky Bay under prevailing storm winds (Fig. 5), all cases in which the wind speed at the point with coordinates $\varphi = 45.9^{\circ}\text{N}$, $\lambda = 31.2^{\circ}\text{E}$ exceeded 8 m/s were selected from ERA-Interim data. The TSM concentration on the selected dates and over the following seven days was averaged, after which average values for each direction were calculated.

As expected, under winds from wave-hazardous directions (from the southwest – northwest sector), the TSM concentration over most of the bay exceeds 7 mg/L (Fig. 5, *a* – *c*). The most frequent southwest storms lead to the spread of suspended matter over almost the entire study area (Fig. 5, *a*). Only in the wave shadow of Dzharylhach Island are the waters more transparent.

Under winds from northern and northeastern directions (Fig. 5, *d*, *e*), the spatial distribution of TSM concentration is similar to the long-term average distribution (see Fig. 2). Although winds of these directions are not capable of developing strong waves in the study area, they have the highest frequency. During storm winds from the east, TSM concentrations are low over most of the water area; zones of increased concentration are localized near the tip of Bakalskaya Spit, in Dzharylhach Bay, and in the innermost part of Karkinitsky Bay (Fig. 5, *f*).



a



b

Fig. 3. Roses of wind based on the ERA-Interim and ERA5 data (*a*) and waves based on the SWAN-ERA data (*b*) in Karkinitsky Bay for 2003–2024

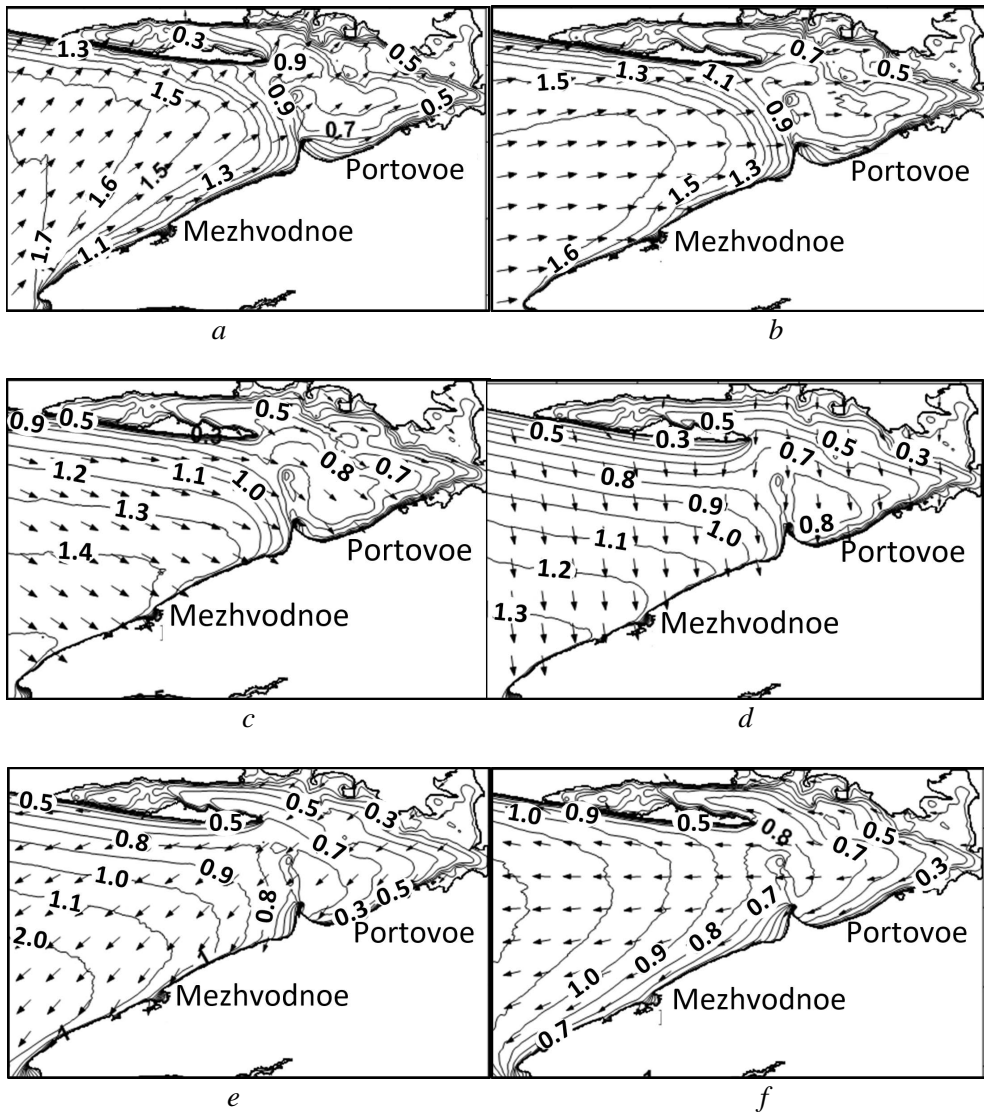


Fig. 4. Height of significant waves (m) and average direction of waves in Karkinitsky Bay at the southwest (*a*), west (*b*), northwest (*c*), north (*d*), northeast (*e*) and east (*f*) winds of speed 10 m/s

In all situations considered, areas of high TSM concentrations exist in the region of Bakalskaya Spit and Bakalskaya Bank (Fig. 5). These morphological structures protrude far into the bay and serve as a barrier for waves, both those penetrating from the open sea and those formed by winds from northern and eastern directions, as a result, the sand-shell sediments of this part of the water area are subject to wave resuspension under the impact of winds from various directions. This is clearly visible when analyzing satellite images.

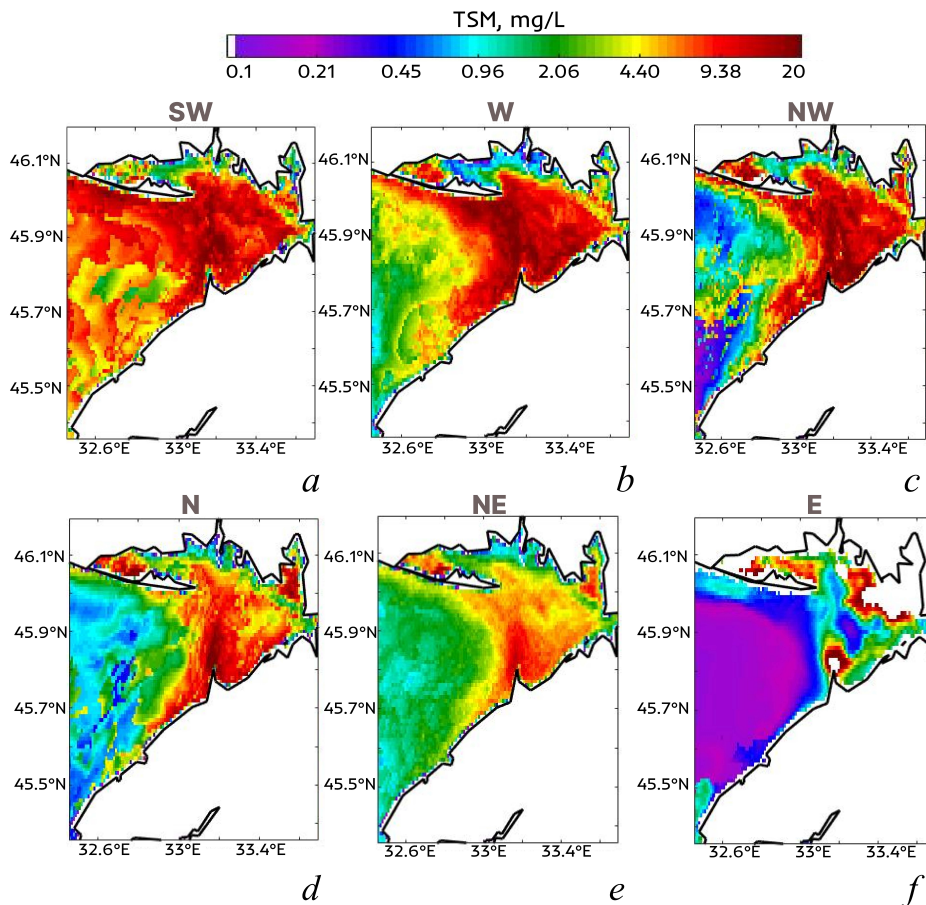


Fig. 5. Average values of TSM concentration in the Karkinitzky Bay waters (2003–2024) based on the MODIS/Aqua data during the period of storm southwest (*a*), west (*b*), northwest (*c*), north (*d*), northeast (*e*) and east (*f*) winds of speed 10 m/s

Fig. 6 presents maps of the spatial variability of TSM concentration under various wind-wave situations.

The MODIS/Aqua image of 07.10.2003 (Fig. 6, *a*) was taken after the action of a southwest storm (04.10.2003–07.10.2003); at the time of image acquisition, wind speed was 5 m/s. High concentrations of TSM were observed over most of the bay. The image of 26.03.2003 (Fig. 6, *b*) captured the situation the day after a southwest storm (from 0 to 14 h on 25.03.2003, wind speed was 8–9 m/s; at the time of the image acquisition, a northwest wind of 2–3 m/s was blowing). It can be seen that most of the resuspended material had settled. Increased concentrations of TSM were recorded along Bakalskaya Spit, along the southeastern coast of the bay, and in Perekop Bay. In the western part of the bay off the coast of Crimea, elevated concentrations are apparently formed by the transport of TSM by currents.

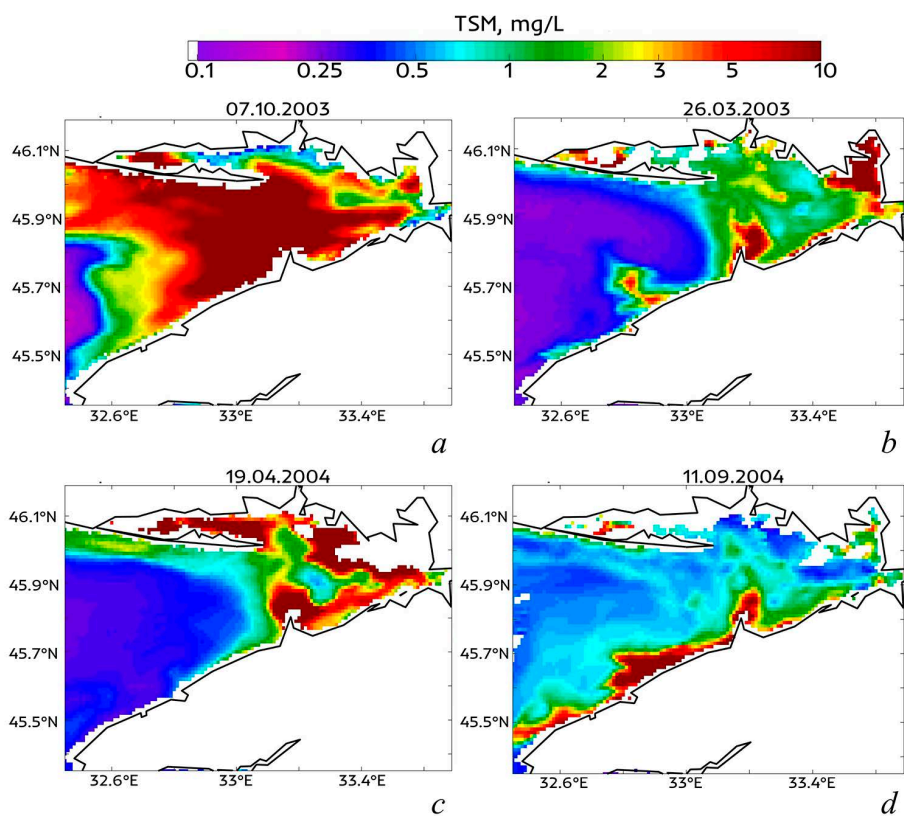


Fig. 6. Examples of TSM distribution in the Karkinitzky Bay waters based on the MODIS/Aqua data: 07.10.2003 (a); 26.03.2003 (b); 19.04.2004 (c); 11.09.2004 (d)

The image of 19.04.2004 (Fig. 6, c) characterizes the situation during a storm generated by an easterly wind with speeds of 8–11 m/s that lasted more than one day. Coastal areas of the eastern part of the bay were subjected to resuspension. The image of 11.09.2004 (Fig. 6, d) shows a situation in which, during a two-day northerly storm with wind speeds up to 13 m/s, areas of increased TSM concentration formed along the Crimean coast (Fig. 6, d).

Seasonal variability. Monthly average values of TSM concentration were calculated both for the entire study area and separately for the eastern and western parts (Fig. 7, a). For each month, maps of the distribution of average suspended matter concentration and prevailing storm wind directions (speeds of 8 m/s and above) were constructed (Fig. 8). It can be seen that throughout the year, the main features of the TSM spatial distribution in the bay, described above, are preserved. TSM concentrations in different parts of the bay differ by a factor of 2–4. The highest values were recorded in the cold period (December to March): for the entire bay, they are 5.4–6 mg/L; for the eastern part, 9–10 mg/L; for the western part, 3–4.6 mg/L. In the warm period (May to October), the waters of the bay are relatively transparent: for the entire bay, average suspended matter concentrations are 0.6–0.9 mg/L; for the eastern part, 0.8–1.5 mg/L; for the western part, 0.4–0.6 mg/L.

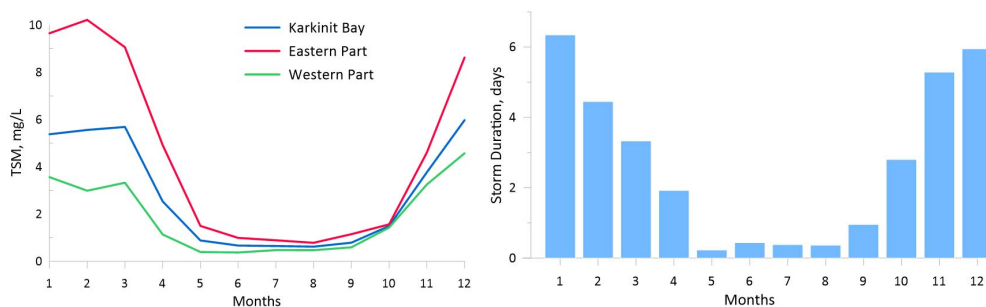


Fig. 7. Seasonal variation of TSM concentration based on the MODIS/Aqua images (a), and distribution by months of average storm duration based on the SWAN-ERA data (b) in the Karkinitzky Bay waters for 2003–2024

Seasonal variation in TSM concentration is in good agreement with the monthly distribution of average storm duration (Fig. 7, b). Thus, the dominant factor in the seasonal distribution of suspended matter in Karkinitzky Bay is the wind-wave regime.

The increase in storm activity in the cold period leads to active mixing of waters, resuspension of bottom sediments in shallow waters, abrasion of shores, and transport of suspended matter towards the deeper parts of the bay by currents. On the maps of average TSM concentration, the largest spatial extent of high values in the study area was recorded from December to March (Fig. 8).

It should be taken into account that the winter months are characterized by a high proportion of images with cloud cover, which reduces the representativeness of the averaged data for this period. Thus, on the January map constructed (Fig. 8), an apparent decrease in TSM concentration values is likely observed.

In April, October and November, the concentrations of suspended matter over the entire water area are somewhat lower; high values remain in the areas of Bakalskaya Bank, Perekop Bay and Dzharylhach Bay (Fig. 8). Such a spatial distribution of TSM is characteristic of the spring and autumn seasons. Under comparable wind-wave conditions in October and November, resuspension of bottom sediments occurs less actively than in April, which may be due to strong stratification of the water column during this period of the year.

In the summer season (May – September), the weakening of bottom sediment resuspension is associated with a decrease in wind activity and an increase in water column stratification, which hinders the penetration of wind-wave energy to the bottom. Areas of increased TSM concentration remain only in the shallow areas: near Bakalskaya Spit, in Perekop Bay and Dzharylhach Bay (Fig. 8).

On the July average map (Fig. 8), increased TSM concentrations are recorded in the western part of the bay, which may be due to the inflow of water from the northwestern shelf of the Black Sea, characterized by intense algal blooms. An example of such a situation is shown in Fig. 9. In the MODIS/Aqua and Landsat images of 25 and 27 July 2017, it can be seen that in the western part of the bay, the values of chlorophyll concentration (Fig. 9, a) and brightness in the first channel (*RRS* 560) are elevated (Fig. 9, b). This combination of values does not indicate the presence of mechanical suspended matter or products

of coccolithophore blooms in the western part of the bay. According to the studies ⁴ [32], during coccolithophore blooms, high brightness values in the *RRS 555* channel and low chlorophyll concentration values would be observed. In Fig. 9, *b*, the inflow of such water extends to Bakalskaya Bank and does not penetrate further. Blooms may also affect the waters of the shallowest part of the bay (the area of the Lebyazhye Islands, Perekop Bay, and Dzhyrylhach Bay).

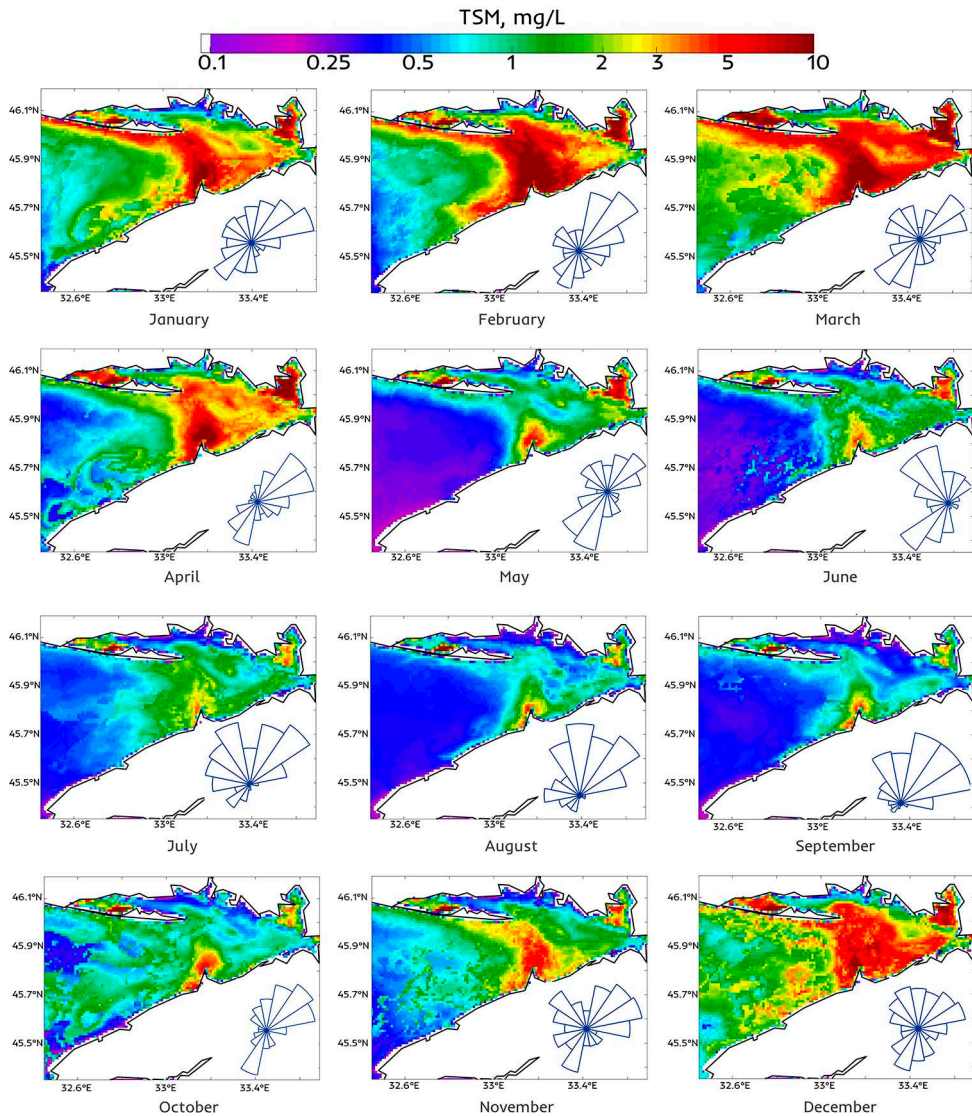


Fig. 8. Maps of average TSM concentration in the Karkinitzky Bay waters based on the MODIS/Aqua data and wind rose (wind speed exceeding 8 m/s) by months for 2003–2024

⁴ Gordon, H.R. and Balch, W.M., 1999. *MODIS Detached Coccolith Concentration Algorithm Theoretical Basis Document Version 4*. Coral Gables, Florida: University of Miami, 27 p.
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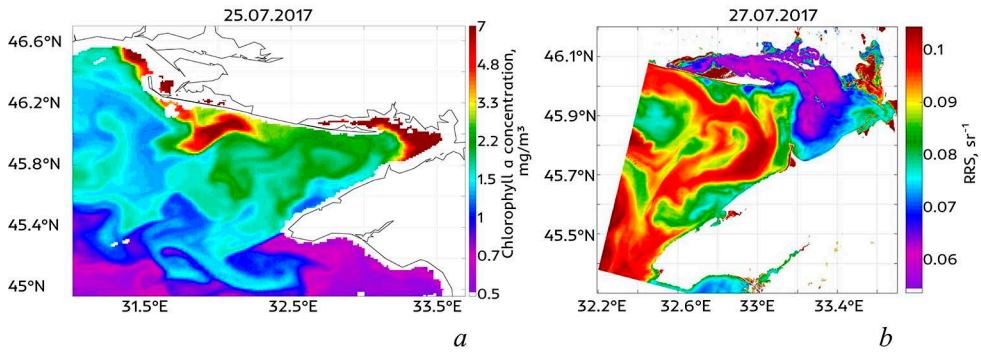


Fig. 9. An example of water inflow into Karkinitzky Bay from the northwestern shelf from the satellite images of MODIS/Aqua on July 25, 2017 (based on chlorophyll concentration) (a) and Landsat on July 27, 2017 (based on RRS 560 channel) (b)

Influence of the Small Phyllophora Field. On the maps of average TSM concentration for the entire study period (see Fig. 2), for the summer season (see Fig. 8) and during storm winds from the northeast sector (see Fig. 5, *d–f*; 6, *b, c*), an area of more transparent waters is clearly distinguished in the eastern part of the bay. According to the literature⁵ [1], the Small Phyllophora Field is located in this area. It is clearly distinguished in satellite images and is characterized by reduced brightness values. To delineate its boundaries, maps of the brightness difference between the near-infrared (0.845–0.885 μm) and green (0.525–0.600 μm) channels were constructed. This combination makes it possible to obtain more accurate indicators of radiation emerging from below the water surface. In high- and medium-resolution Landsat and MODIS/Aqua images (Fig. 10), an area of reduced brightness values is clearly distinguished above the Small Phyllophora Field.

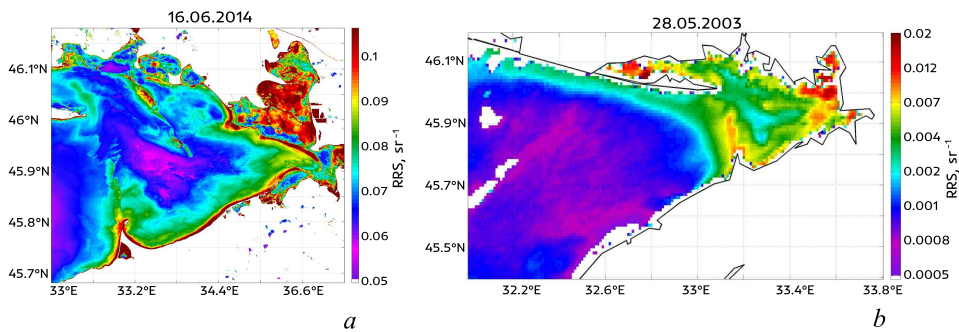


Fig. 10. An example of highlighting the Small Phyllophora Field in the eastern part of Karkinitzky Bay in the images: *a* – Landsat on 16.05.2014 (difference between the green and near IR channels); *b* – MODIS/Aqua on 28.05.2003 (RRS value at a wavelength 555 nm)

⁵ Aleksandrov, B.G., Boltacheva, N.A., Bushuev, S.G., Kolesnikova, E.A., Litvinenko, N.M., Milchakova, N.A., Minicheva, G.G., Sinegub, I.A. and Terent'ev, A.S., 2010. Habitat Specification for a Small Phyllophoran Field in the Karkinitzky Gulf of the Black Sea. *Environmental Collaboration for the Black Sea*. Georgia, Moldova, Russia and Ukraine; EuropeAid/120117/C/SV/Muilt; Contract No. 111779, 34 p. (in Russian).

Interannual variability. Annual average values of TSM concentration from 2003 to 2024 were calculated for the entire study area and separately for the western and eastern parts (Fig. 11, *a*). The greatest contribution to the average values for the entire bay is made by the eastern part. The long-term average TSM concentration for the western part is 1.5 mg/L, and for the eastern part, 3.5 mg/L.

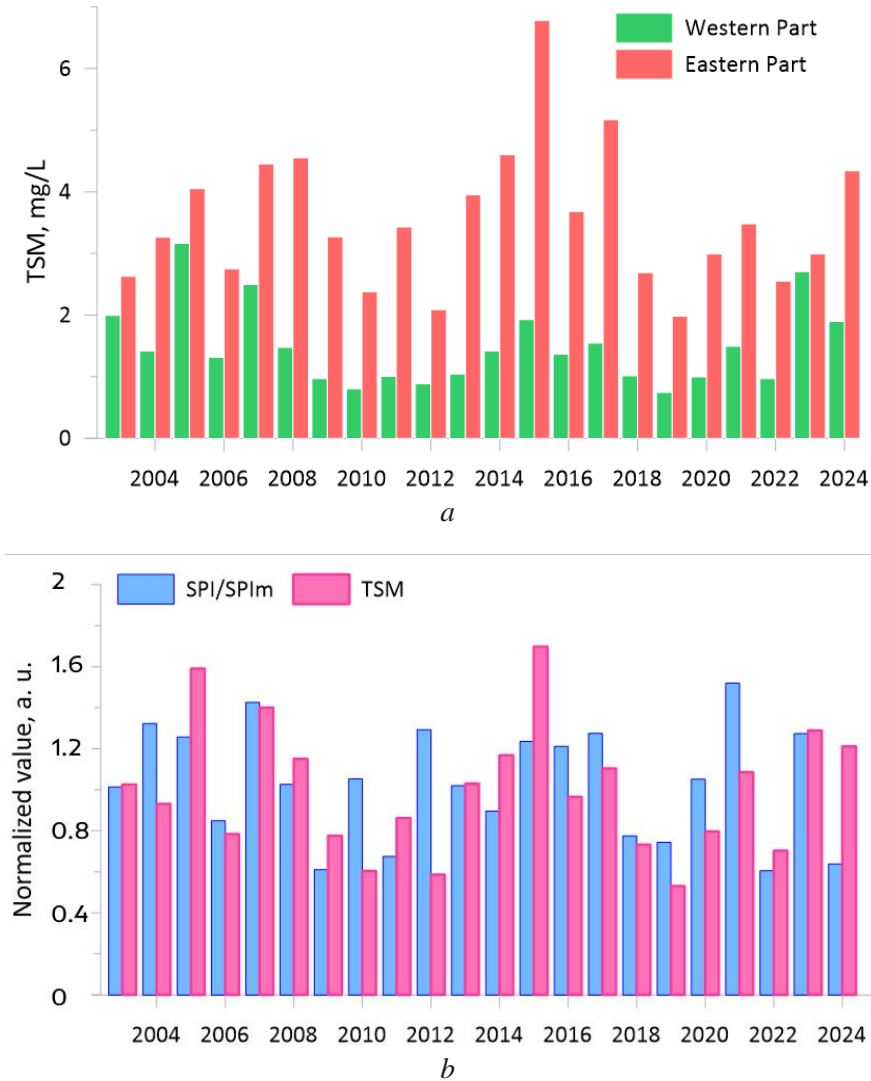


Fig. 11. Interannual variability of TSM concentration for the western and eastern parts of Karkinitzky Bay based on the MODIS/Aqua data (*a*), and interannual variability of storm intensity (SPI) and TSM concentration over the entire bay normalized to long-term average values (2003–2024) (*b*)

To analyze the influence of storms on the interannual variability of TSM concentration, the total storm power index for each year was calculated. Annual values of TSM concentration and storm power were normalized to the long-term

average values for the entire study period (Fig. 11, *b*). The highest TSM concentrations (more than 3 mg/L for the entire bay) were obtained for 2015, 2005, and 2007. These years corresponded not to maximum but to high storm power values. The minimum TSM concentrations (less than 1.5 mg/L for the entire bay) were observed in 2010, 2012, and 2019. At the same time, in 2012, the total storm power index was high. This discrepancy is partly explained by a methodological limitation: during periods of maximum storm activity, especially in winter, significant cloud cover is usually observed, which excludes the possibility of obtaining satellite data and retrieving TSM concentration values. The most intense storm events may not be fully accounted for in satellite data, leading to biases in TSM concentration estimates.

As shown earlier, the greatest influence on TSM concentration is exerted by storms from the southwest-northwest sector (sector 225°–315°), since they form the strongest wave impact on shallow areas of the bay and contribute to the resuspension of bottom sediments. Storms from the east, despite high storm power index values, have a smaller effect on TSM increase due to the small wave fetch.

Thus, for a correct interpretation of the interannual variability of TSM concentration, it is necessary to take into account not only the total power of storms, but also their direction, as well as the limitations of satellite data under continuous cloud cover conditions.

Conclusion

A study of the spatio-temporal distribution of TSM in Karkinitsky Bay was carried out based using an array of satellite data from MODIS, Landsat-8, and Sentinel-2. It was revealed that the water area of the bay is characterized by high dynamism and spatial heterogeneity of suspended matter distribution. Storm wind-wave impact, complex bottom topography, and coastline configuration play a significant role in the spatial distribution of TSM.

A map of the long-term average distribution of TSM concentration in Karkinitsky Bay for 2003–2024 based on MODIS/Aqua images was constructed. The lowest values (up to 0.75 mg/L) are characteristic of the deep western part of the water area; as depth decreases, the concentration increases, reaching a maximum (4–10 mg/L) in shallow areas. The eastern part of the bay is characterized by a more complex distribution structure compared to the western part, and by TSM concentration values higher by a factor of 2–4.

A statistical analysis of retrospective wind-wave calculations based on ERA-Interim, ERA5, and SWAN-ERA reanalysis data for 2003–2024 and mathematical modeling of typical wave fields for the most wave-hazardous directions showed that, despite the highest frequency of winds from the northeast sector (~ 38–36%), most waves enter the bay from the southwest direction (14%). The highest wave heights are formed by winds from the southwest – northwest sector, and the lowest ones from the north–east sector. When interacting with bottom irregularities, waves are transformed: in the eastern part of the bay, wave height contours follow

the isobaths, with minima above the Bakalskaya and Chumryukskaya banks; waves with heights not exceeding 0.6 m penetrate into Dzharylhach Bay.

Analysis of the dependence of the spatial distribution of TSM concentration on prevailing storm winds revealed the following: under winds from wave-hazardous directions (the southwest – northwest sector), the TSM concentration exceeds 7 mg/L; winds from northern and northeastern directions form suspended matter concentration fields similar to the long-term average distribution; during easterly storm winds, zones of increased concentration are localized near the tip of Bakalskaya Spit, in Dzharylhach Bay, and in the innermost part of Karkinitsky Bay.

It was revealed that the wind-wave regime is the dominant factor in the seasonal variation of suspended matter distribution in Karkinitsky Bay. In the warm period (May to October), the waters of the bay are relatively transparent (TSM concentration ranges within 0.6–0.9 mg/L), with local increases in shallow waters. In the spring and autumn seasons (April, October, and November), the TSM concentrations over the entire water area are somewhat higher, while, due to water column stratification under comparable wind-wave conditions in October and November, resuspension of bottom sediments is less intense than in April. With increased storm activity in the cold period (December to March), as a result of active resuspension of bottom sediments, abrasion of shores, and TSM transport by currents, the TSM concentrations reach maximum values (5.4–6 mg/L).

It was found for the first time that a significant factor influencing the spatial distribution of TSM concentration in the eastern part of the bay is the Small Phyllophora Field: in most of the analyzed images, reduced brightness values were recorded in this area.

The interannual variability of TSM concentration does not show an obvious direct relationship with the total storm power index. This is partly explained by a methodological limitation: during periods of maximum storm activity, especially in winter, extensive cloud cover excludes the possibility of obtaining satellite data and retrieving TSM concentration values. For a correct interpretation of the data, not only the power of storms but also their direction should be taken into account.

REFERENCES

1. Milchakova, N.A. and Alexandrov, V.V., 2018. Marine Conservation Areas and Problems of Nature Management in the Karkinitsky Bay (the Black Sea). *Ecological Safety of Coastal and Shelf Zones of Sea*, (4), pp. 50-58. <https://doi.org/10.22449/2413-5577-2018-4-50-58> (in Russian).
2. Pankeeva, T.V., Mironova, N.V., Goryachkin, Yu.N. and Kharitonova, L.V., 2022. Distribution of Bottom Vegetation of the Shallow Water Zone in Karkinitskiy Bay of the Crimean Peninsula. *South of Russia: Ecology, Development*, 17(2), pp. 62-75. <https://doi.org/10.18470/1992-1098-2022-2-62-75> (in Russian).
3. Goryachkin, Yu.N., ed., 2015. [*Current State of the Crimean Coastal Area*]. Sevastopol: ECOSI-Gidrofizika, 252 p. (in Russian).

4. Rudnev, V.I., 2018. Peculiarities of the Bottom Relief of the Bakalskaya Spit Foreshore. *Ecological Safety of Coastal and Shelf Zones of Sea*, (4), pp. 15-21. <https://doi.org/10.22449/2413-5577-2018-4-15-21> (in Russian).
5. Krylenko, V.V., Krylenko, M.V. and Aleinikov, A.A., 2019. Research of the Bakalskaya Bank Underwater Relief by Sentinel-2 Satellite Images. *Ecological Safety of Coastal and Shelf Zones of Sea*, (2), pp. 30-39. <https://doi.org/10.22449/2413-5577-2019-2-30-39> (in Russian).
6. Milchakova, N.A., ed., 2015. *Marine Protected Areas of Crimea. Scientific Handbook*. Simferopol: N. Orianda, 312 p. (in Russian).
7. Davydov, A., Kotovskiy, I. and Roskos, N., 2018. Features of Evolution Coastal Lithodynamic System Tendra – Jarylgach in Conditions of Anthropogenic Transformation. In: *Materials of XXVII International Coastal Conference “Arctic Shores: Shore-up to Sustainability”*. Academus Publishing, pp. 56-59. https://doi.org/10.31519/conferencearticle_5cebbb8aaef595.14822649
8. Kukushkin, A.S., 2009. Variability of Water Transparency Distribution in the Karkinit Bay. *Morskoy Gidrofizicheskiy Zhurnal*, (2), pp. 67-79 (in Russian).
9. Aleskerova, A.A., Kubryakov, A.A., Goryachkin, Yu.N., Stanichny, S.V. and Garmashov, A.V., 2019. Distribution of Suspended Matter off the Western Coast of the Crimea under Impact of the Strong Winds of Various Directions. *Issledovanie Zemli iz Kosmosa*, (2), pp. 74-88. <https://doi.org/10.31857/S0205-96142019274-88> (in Russian).
10. Goryachkin, Yu.N. and Repetin, L.N., 2009. Storm Wind and Wave Regime near the Black Sea Coast of Crimea. *Ecological Safety of Coastal and Shelf Zones and Comprehensive Use of Shelf Resources*, 19, pp. 56-69 (in Russian).
11. Kharitonova, L.V. and Fomin V.V., 2011. Numerical Modeling of Wind Waves near the Western Crimea Coast. *Ecological Safety of Coastal and Shelf Zones and Comprehensive Use of Shelf Resources*, 25(1), pp. 26-37 (in Russian).
12. Godin, E.A., Ingerov, A.V. and Galkovskaya, L.K., 2018. Information Support of Coastal Research: The Karkinitzky Bay and the Bakalskaya Spit. *Ecological Safety of Coastal and Shelf Zones of Sea*, (4), pp. 92-100. <https://doi.org/10.22449/2413-5577-2018-4-92-100> (in Russian).
13. Miller, R.L. and McKee, B.A., 2004. Using MODIS Terra 250 m Imagery to Map Concentrations of Total Suspended Matter in Coastal Waters. *Remote Sensing of Environment*, 93(1–2), pp. 259-266. <https://doi.org/10.1016/j.rse.2004.07.012>
14. Zhang, M., Tang, J., Dong, Q., Song, Q.T. and Ding, J., 2010. Retrieval of Total Suspended Matter Concentration in the Yellow and East China Seas from MODIS Imagery. *Remote Sensing of Environment*, 114(2), pp. 392-403. <https://doi.org/10.1016/j.rse.2009.09.016>
15. Burenkov, V.I., Goldin, Yu.A. and Kravchishina, M.D., 2010. The Distribution of the Suspended Matter Concentration in the Kara Sea in September 2007 Based on Ship and Satellite Data. *Oceanology*, 50(5), pp. 798-805. <https://doi.org/10.1134/S0001437010050164>
16. Loisel, H., Mangin, A., Vantrepotte, V., Dessailly, D., Ngoc Dinh, D., Garnesson, P., Ouillon, S., Lefebvre, J.-P., Mériaux, X. [et al.], 2014. Variability of Suspended Particulate Matter Concentration in Coastal Waters under the Mekong’s Influence from Ocean Color (MERIS) Remote Sensing over the Last Decade. *Remote Sensing of Environment*, 150, pp. 218-230. <https://doi.org/10.1016/j.rse.2014.05.006>
17. Nechad, B., Ruddick, K., Schroeder, T., Oubelkheir, K., Blondeau-Patissier, D., Cherukuru, N., Brandt, V., Dekker, A., Clementson, L. [et al.], 2015. CoastColour Round Robin Data Sets: A Database to Evaluate the Performance of Algorithms for the Retrieval of Water Quality Parameters in Coastal Waters. *Earth System Science Data*, 7(2), pp. 319-348. <https://doi.org/10.5194/essd-7-319-2015>
18. Kopelevich, O.V., Vazyulya, S.V., Sheberstov, S.V. and Bukanova, T.V., 2016. Suspended Matter in the Surface Layer of the Southeastern Baltic from Satellite Data. *Oceanology*, 56(1), pp. 46-54. <https://doi.org/10.1134/S0001437016010069>

19. Lisitzin, A.P., Klyuvitkin, A.A., Burenkov, V.I., Kravchishina, M.D., Politova, N.V., Novigatsky, A.N., Shevchenko, V.P. and Klyuvitkina, T.S., 2016. Distribution and Composition of Suspended Particulate Matter in the Atlantic Ocean: Direct Measurements and Satellite Data. *Doklady Earth Sciences*, 466(1), pp. 78-81. <https://doi.org/10.1134/S1028334X16010116>
20. Aleskerova, A.A., Kubryakov, A.A. and Stanichny, S.V., 2015. Propagation of Suspended Matter under the Influence of Storm Winds off the Western Coast of Crimea by High-Resolution Optical Data. *Sovremennye Problemy Distantionnogo Zondirovaniya Zemli iz Kosmosa*, 12(1), pp. 63-71 (in Russian).
21. Kubryakov, A., Aleskerova, A., Plotnikov, E., Mizyuk, A., Medvedeva, A. and Stanichny, S., 2023. Accumulation and Cross-Shelf Transport of Coastal Waters by Submesoscale Cyclones in the Black Sea. *Remote Sensing*, 15(18), 4386. <https://doi.org/10.3390/rs15184386>
22. Kukushkin, A.S., 2012. Seasonal Variability of Water Transparency Distribution in the Karkinit Bay. *Optika Atmosfery i Okeana*, 25(2), pp. 181–189 (in Russian).
23. Alekseev, D.V., Ivanov, V.A., Ivancha, E.V., Fomin, V.V. and Cherkesov, L.V., 2007. Investigation of the Fields of Concentration of the Suspension on the Northwest Shelf of the Black Sea in the Case of Roiling of the Bottom Sediments by a Moving Cyclone. *Physical Oceanography*, 17(1), pp. 1-16. <https://doi.org/10.1007/s11110-007-0001-0>
24. Alekseev, D.V., Ivanov, V.A., Ivancha, E.V., Fomin, V.V. and Cherkesov, L.V., 2009. Erosion and Deposition of Sediments in the Karkinitsky Bay during the Storm on the 10–11 of November 2007. *Ecological Safety of Coastal and Shelf Zones and Comprehensive Use of Shelf Resources*, 19, pp. 93-105 (in Russian).
25. Kushnir, V.M., 2013. Characteristics of Coastal Dynamics Benthic According Satellite Imagery Optical Scanner. *Issledovanie Zemli iz Kosmosa*, (3), pp. 13-21. <https://doi.org/10.7868/S0205961413030020> (in Russian).
26. Ivanov, V.A., ed., 2006. *Modern Methods and Tools for Monitoring the Marine Environment*. Sevastopol: ECOSI-Gidrofizika, 112 p. (in Russian).
27. Dykman, V.Z., Ivanov, V.A. and Kushnir, V.M., 2012. Nonlinear Waves and Turbulence in the Coastal Zone of the Island Kosa Tuzla. *Morskoy Gidrofizicheskiy Zhurnal*, (4), pp. 3-21 (in Russian).
28. Kremenchutskiy, D.A., Kubryakov, A.A., Zav'yalov, P.O., Konovalov, B.V., Stanichniy, S.V. and Aleskerova, A.A., 2014. Determination of the Suspended Matter Concentration in the Black Sea Using to the Satellite MODIS Data. *Ecological Safety of Coastal and Shelf Zones and Comprehensive Use of Shelf Resources*, 29, pp. 5-9 (in Russian).
29. Zavialov, P.O., Makkaveev, P.N., Konovalov, B.V., Osadchiev, A.A., Khlebopashev, P.V., Pelevin, V.V., Grabovskiy, A.B., Izhitskiy, A.S., Goncharenko, I.V. [et al.], 2014. Hydrophysical and Hydrochemical Characteristics of the Sea Areas Adjacent to the Estuaries of Small Rivers of the Russian Coast of the Black Sea. *Oceanology*, 54(3), pp. 265-280. <https://doi.org/10.1134/S0001437014030151>
30. Kos'yan, R.D., Podymov, I.S. and Pykhov, N.V., 2003. *Dynamical Processes in the Sea Nearshore Zone*. Moscow: Scientific World, 326 p. (in Russian).
31. Booij N., Ris R.C. and Holthuijsen, L.H., 1999. A Third-Generation Wave Model for Coastal Regions. 1. Model Description and Validation. *Journal of Geophysical Research: Oceans*, 104(C4), pp. 7649-7666. <https://doi.org/10.1029/98JC02622>
32. Smyth, T.J., Moore, G.F., Groom, S.B., Land, P.E. and Tyrrell, T., 2002. Optical Modeling and Measurements of a Coccolithophore Bloom. *Applied Optics*, 41(36), pp. 7679-7688. <https://doi.org/10.1364/AO.41.007679>

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