

## Propagation of Waters from the Kerch Strait in the Black Sea

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Turbid and brackish Azov waters penetrating through the Kerch Strait significantly modify the biooptical and thermohaline features in North-Western part of the Black Sea. The Kerch Strait itself is another additional powerful source of suspended matter. Analysis of the high-resolution Landsat imagery and MODIS satellite data on the total suspended matter (TSM) concentration and sea surface temperature is carried out in the present work to study the Kerch waters propagation in the Black Sea.

It is shown that Kerch waters most frequently propagate westward from the strait in the form of a narrow jet having a width of 1-10 km. Turbid waters are mainly observed in shallow areas do not crossing isobaths of 20 meters. In winter such jets are observed in both optical (turbid) and infrared measurements (cold water). On average, they stretch from the Kerch Strait to Cape Meganom and cover the whole Feodosia Bay. Strong north-east storms increase the outflow of the Azov waters from the strait and intensify the western propagation of Azov waters. The propagation area and distance from the source of waters with high TSM are related to the strength and duration of storms.

During southern storms, vast areas with large turbidity, which are not related to the penetration of Kerch waters, are observed in the vicinity of the Kerch Strait along the shores of the Kerch and Taman Peninsulas. Such increase of turbidity is a result of wave action, that lead to the coast erosion and resuspension of bottom sediments near the clay cliffs. High values of TSM are mostly observed up to the isobath of 50 meters. In some cases, Kerch waters can be transported offshore on the large distances upon the action of mesoscale eddies advection.

**Keywords:** remote sensing, the Black Sea, the Azov Sea, the Kerch Strait, suspended matter, thermohaline structure, turbidity

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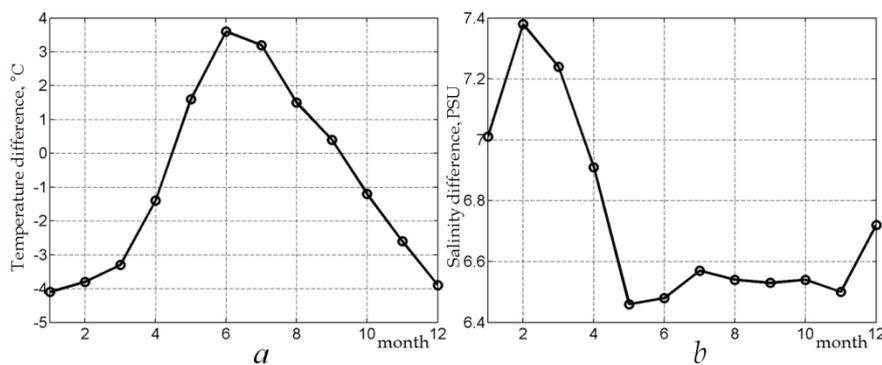
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**Introduction.** Construction of the bridge across the Kerch Strait and its subsequent operation potentially create additional risks of pollution of the Strait and adjacent water areas. Due to this fact, it is important to study the water dynamics not only in the strait itself, but also in the surrounding areas. First knowledge about the Kerch Strait currents was obtained during the expeditions in the 60 s years of the 20<sup>th</sup> century and 00s years of the 21<sup>st</sup> century. Close relation between the dynamics, the wind characteristics and the difference in sea levels at the ends of the strait was shown [1–3]. Later it was confirmed by satellite data [4, 5]. The dynamics of the pre-strait areas is less known. As the resulting annual water transfer from the Azov Sea is  $\sim 17 \text{ km}^3/\text{g}$  [3], their propagation in the Black Sea that is of greatest interest.

Large river discharge and the Azov Sea shallowness form significant differences between the thermohaline and optical properties of the waters of the two seas – the Black Sea and the Azov Sea. The mean annual temperature difference of these seas in the winter and summer months reaches  $4 \text{ }^\circ\text{C}$  (Fig. 1). This allows tracking the interpenetration of the waters of both seas through the Kerch Strait on the base of satellite measurements of the sea surface temperature (SST). The annual difference in surface salinity, 6.5–7.5 PSU (Fig. 1), is also rather significant. In [6, 7] it was shown that the seasonal variability of surface water salinity in the

coastal zone of the Southern coast of Crimea is related to the penetration of the Azov Sea waters along the shelf during spring. Particularly, it is the main reason of an annual minimum of salinity in this area in the given period. Additional opportunities for studying the water dynamics near the Kerch Strait are given by a known property of increased turbidity of the Azov Sea waters in comparison with the Black Sea ones. It should be noted that the Kerch Strait itself is also a powerful source of suspended matter. Its coasts on a considerable extent are composed of abrasion-landslide clay cliffs [8]. According to some estimates, abrasion of the cliffs and benches gives solid material in the amount of 340,000 m<sup>3</sup> per year, or 580,000 tons per year [9]. In the strait itself, storms are frequent, especially during the cold period. All these circumstances create additional conditions for the sediment resuspension in the water column. That is why analyzing satellite optical data, we will use the term «the Kerch Strait waters», rather than the «the Azov Sea waters».



**Fig. 1.** Mean long-term temperature difference (*a*) and salinity (*b*) of the Azov and Black Seas according to the data of HMS Mysovoye and Feodosiya

Existed in-situ data on the thermohaline structure of water and currents do not give possibility for reliable description of the water propagation dynamics from the Kerch Strait to the Black Sea. Data of climatic arrays of temperature and salinity allows only obtaining the average situation for a certain period of time, without describing any of the real ones. Differences in the thermal and optical properties of the waters of the two basins make it possible to track their propagation and transformation on the base of satellite infrared and optical measurements.

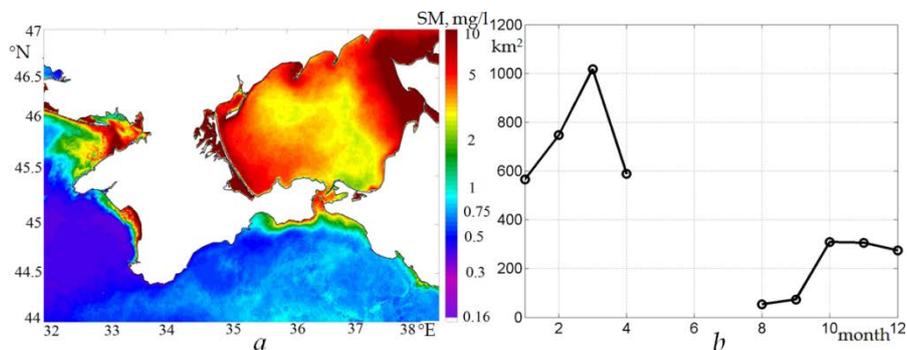
The aim of the present work is to study the features of water propagation from the Kerch Strait in the Black Sea basing on satellite, in-situ data analysis and hydrometeorological information.

**The data applied.** The reflectance data of the *MODIS/Aqua* scanners on the wavelength at 555 nm with a spatial resolution of 1 km and a time resolution of 1 day (*Level-2*) for 2003–2015 were used. The data were obtained in the Remote Sensing Department of Marine Hydrophysical Institute (<http://dvs.net.ru>) and from the archive of <http://oceandata.sci.gsfc.nasa.gov/>. The regional algorithm for determining the concentration of total suspended matter (TSM) based on a combination of spectral brightness at different wavelengths was used [10]. The algorithm was calibrated on the base of measurements made both in coastal waters with high

suspended matter concentrations and in the pure waters [11]. Nevertheless, it can be expected that in some cases, especially at extremely high TSM, the satellite data may be quantitatively different from the real one. The data on the remote sensing brightness from the *Landsat-4*, -5, -7, -8 satellites during 1985–2015 were also used (<http://glovis.usgs.gov>). *Landsat-7* and -8 have a spatial resolution of 15–30 m for the visible and near infrared (IR) ranges and 100 m – for the far infrared range. The time resolution is 16 days. *Landsat-8 TIRS* device measures in two channels in the far infrared range. This allows performing the atmospheric correction of measurements and reconstructing the real SST. Such an algorithm for the Black Sea was developed on the basis of a comparison with the *MODIS* calibrated data [12].

Of 794 *MODIS* images analyzed, a band of turbulent waters along the Crimean coast is observed in 461 images. 250 of them refer to the cold season, when the winds of the northern points have the greatest strength and repeatability facilitating the water transfer from the Kerch Strait to the Black Sea. On 18 images, zones of turbulent waters are related to the south winds. Information on the wind velocity at a height of 10 m of *MERRA* reanalysis with spatio-temporal resolution  $0.5^\circ \times 0.66^\circ$ ; 6 hours was used. The spatial distribution of wind in the northeastern part of the Black Sea was analyzed for the date of the satellite image and for three to five days before it. Hydrometeorological data of HMS Opasnoye, Mysovoye, Kerch, Feodosiya and data hydrological survey in the Feodosiya Bay on the R/V *Experiment* in December 2006 were also analyzed.

**Results and discussion.** Fig. 2, *a* shows the time-averaged TSM concentration obtained from *MODIS/Aqua* data in 2003–2015. Almost all of the Azov Sea is characterized by elevated TSM concentrations exceeding 3 mg/l. They are especially high near the eastern shores and in the Don mouth area. In the northern Black Sea three zones with increased water turbidity are distinguished. These are areas of shallow Karkinitzky and Kalamitsky bays, as well as of the Kerch Strait with water areas adjacent to the Kerch and Taman Peninsulas. Typical mean long-term SM concentration values here are 5 – 10 mg/l with the highest ones recorded near the coast. The greatest part of the shores of these areas is of abrasion-landslide type in clay rocks, which the intense abrasion is typical for.



**Fig. 2.** Mean annual TSM concentration (mg/l) according to *MODIS/Aqua* data for 2003–2015 (*a*) and the area (km<sup>2</sup>) occupied by waters with TSM concentration > 1.5 mg/l near the Kerch Strait (*b*)

Typical speed of the retreat of the cliffs of this type of coast is 0.5–1.0 m/g. It ensures the release of  $\sim 10 \text{ m}^3/\text{g}$  soil per the running meter of the shore to the sea, at that, up to 95 % is a well-stirred fine fraction of  $\leq 0.1 \text{ mm}$  [8]. Thus, the main source of the TSM elevated concentrations in the coastal area of the Russian sector of the Black Sea is associated with the destruction of clay cliffs in the Karkinitsky and Kalamitsky bays and in the Kerch Strait. In the latter there is an additional TSM source – the Azov Sea. The application of SST as a tracer makes it possible to determine the cases when the Kerch Strait waters are released into the Black Sea and distinguish it from other situations.

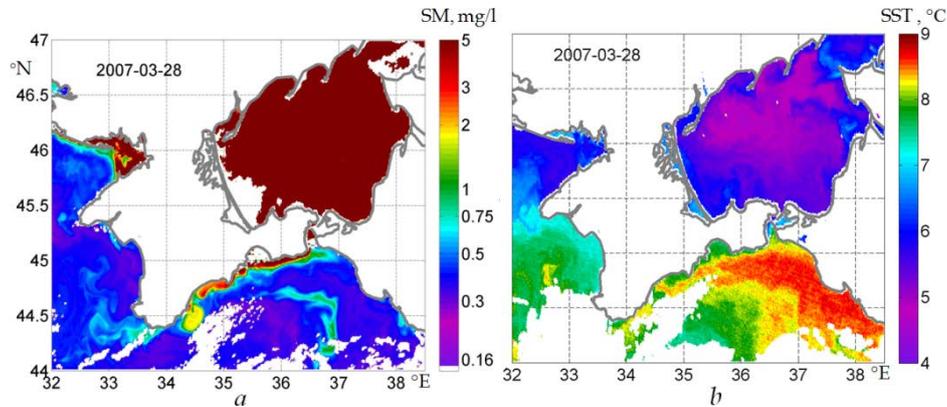
The area of the Kerch waters in the Black Sea can be estimated as part of the sea with high SM concentration. As a criterion, the TSM concentrations of  $> 1.5 \text{ mg/l}$  were chosen. Note that the suspended matter comes not only from the Kerch Strait, it also can be formed due to the destruction of clay cliffs. The seasonal variability of the Kerch waters area ( $\text{km}^2$ ) calculated according to the *MODIS* data is shown in Fig. 2, *b*. In May – July the coccolithophoride blooms are the reason of elevated TSM concentrations that are not associated with the Kerch waters. Therefore, values in this period were not considered. Fig. 2, *b* shows that the area occupied by waters with the SM concentration  $> 1.5 \text{ mg/l}$  in the area of the Kerch Strait in autumn is no more than  $350 \text{ km}^2$  on average, in winter – up to  $600\text{--}700 \text{ km}^2$ . The maximum area is observed in March, however, in this period the effect of the destruction of cliffs on SM is the highest. The minimum area is observed in the summer and is only  $50 \text{ km}^2$ .

Satellite data analysis showed that during storms the zone of elevated SM concentrations localized in the form of a band along the Kerch Peninsula – Feodosiya Bay coast, and in some cases – to the west of it, or in the form of two bands simultaneously to the west and east of the Kerch Strait. Comparison of satellite images with specific hydrometeorological situations indicates that the TSM concentration and its spatial localization in the near-Kerch area of the Black Sea depends on the direction and intensity of the storms. In this case, two most typical situations occur: the first one is associated with the impact of storms of the northern points, the second – with the storms of the southern ones.

During north storms in the Kerch Strait area, satellite images most often show bands of water with elevated SM concentrations having a width of 1 to 10 km, extending along the Crimean Peninsula. In some cases, commonly in winter, these bands can be traced up to the western extremity of the Crimea (Cape Chersonese) and even westward of it, to  $31\text{--}32^\circ \text{E}$ . The propagation area and the distance from the source of waters with elevated SM concentrations are closely related to the strength and duration of storms. The propagation area is usually maximal in the cold period under the northeastern winds. Below a specific example is given.

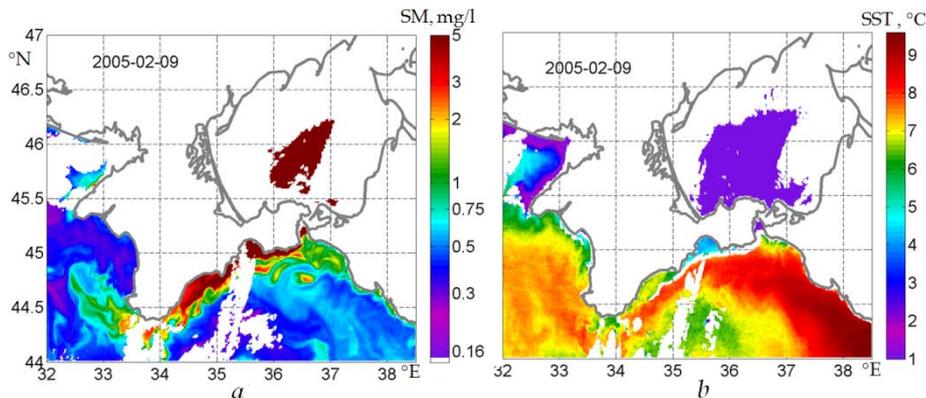
In the Kerch Strait on March 23–24, 2007, the northeastern storm wind was observed. Its speed reached  $15\text{--}18 \text{ m}\cdot\text{s}^{-1}$ , and the wave height was 1.4 m. The sea level in the Kerch Strait began to rise rapidly and to the end on March 24, it increased by 20 cm. The level difference between the Black and Azov Sea was  $\sim 25 \text{ cm}$ . The steady north-eastern wind remained stable for the next three days, but it weakened to  $6\text{--}10 \text{ m}\cdot\text{s}^{-1}$ . In the image taken after the end of the storm (Fig. 3, *a*), a band of relatively turbid waters with a width of  $\sim 10 \text{ km}$ , stretching for 150 km along the coast from the Kerch Strait to Alushta, can be seen.

The maximum TSM concentrations were  $\sim 5$  mg/l with background values in the surrounding waters of 0.5 mg/l. On the satellite images characterizing the SST distribution, a band with decreased temperature of the same configuration is manifested (Fig. 3, *b*). The contrast of SST with the surrounding waters was up to 1.5 °C. It can be concluded that relatively turbid waters are a product of mixing of the Black Sea with the Azov Sea ones. At the same time the penetration of water from the Kerch Strait to the east in this case is relatively small.



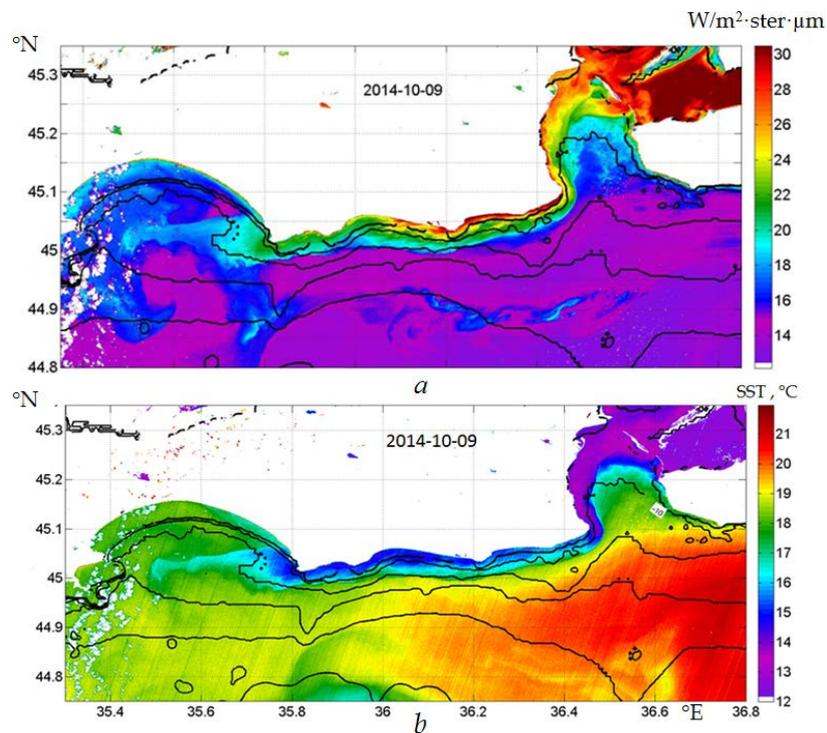
**Fig. 3.** The SM concentration according to *MODIS/Aqua* data (*a*); SST according to *MODIS/Terra* (*b*) in 2007

The greater intensity and duration of north storms leads to larger areas of water propagation from the Kerch Strait. So, on February 3–9, 2005, the storm northeastern wind (10–16 m/s) was observed in the strait. Its effect caused the surge of waters in the strait, the level elevation by 22 cm; the level difference with the Black Sea was 33 cm. The water temperature in the Kerch Strait fell down to the negative values (from 3.5 to  $-0.4$  °C). In the satellite images taken after the end of the storm, a band of turbulent waters, stretching along the Crimean coast to Cape Chersonese is seen (Fig. 4, *a*).



**Fig. 4.** The TSM concentration according to *MODIS/Aqua* data (*a*); SST according to *MODIS/Terra* (*b*) in 2005

Up to Cape Meganom it has a width of ~ 10 km and extends to 30 km behind it. The TSM concentration is 5 mg/l and more. To the west of the Yalta Gulf, the band, apparently captured by the Black Sea Rim Current, expands, acquiring the form of a spot that can be traced to 32.5 °E, however, the SM concentration reduces to 1 mg/l. The SST field also has a similar configuration (Fig. 4, b): in the Feodosiya Bay SST is ~ 4 °C, near Cape Sarych – 7 °C. According to HMS Feodosiya, the temperature dropped from 6.6 to 2.9 °C, HMS Yalta – from 8.7 to 6.7 °C. At the same time the salinity decreased from 18.1 to 16.8 PSU in Feodosiya and from 18.0 to 17.6 PSU in Yalta. Taking into account the initial salinity in the Azov Sea ~ 10 PSU (HMS Opasnoe), it can be roughly estimated that ~ 20 % of the volume in the Feodosiya Bay was occupied by waters from the Kerch Strait; in the Yalta Gulf they were no more than 5 %. Unlike the TSM, no anomalies westward the Yalta Gulf are observed in the SST field, which is explained by the high gradients of the TSM propagation and the difference in the rates of the processes of thermal mixing and TSM sedimentation.



**Fig. 5.** Brightness difference in the channels 3–5 (a) and simulated SST (b) according to Landsat-8 data

The examples above can be characterized as extreme ones. Much more often penetrations of waters from the Kerch Strait into the Black Sea are smaller. They usually spread to Cape Chauda or Meganom, where they separate from the shore. The effect of a relatively weak storm is shown in Fig. 5. In the Kerch Strait on October 6–8, 2014, a steady northeastern wind with a strength of 8–12 m·s<sup>-1</sup> was observed. The image dated October 9, 2014 shows that as a result a band of relatively

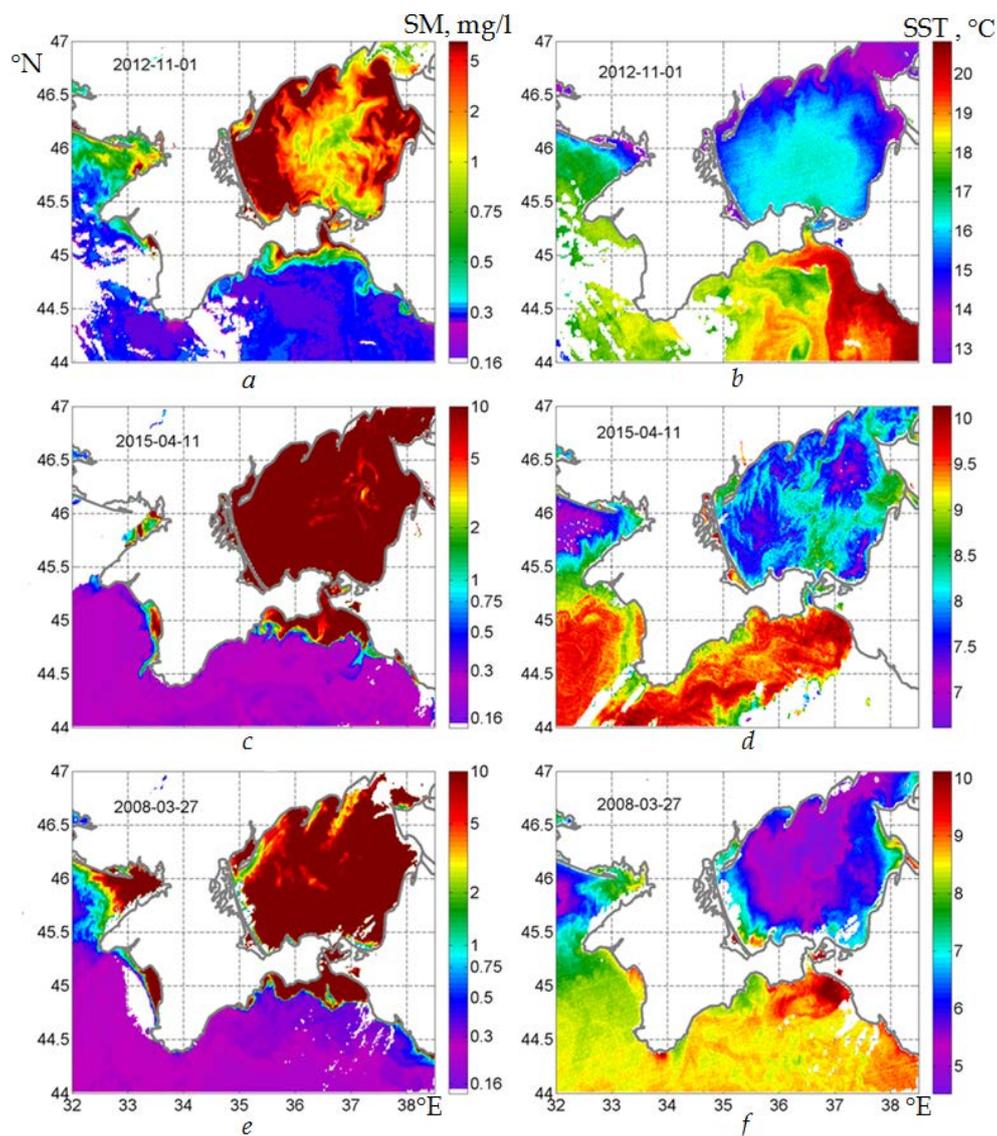
turbid and cold waters with a width of 4–5 km was formed along the coast from the Kerch Strait to Cape Chauda. It is localized in shallow areas along the isobaths (black lines in Fig. 5, *b*) and does not through 20 m isobaths. Near Cape Chauda, the large part of the jet separates from the shore and reaches the middle of the Feodosiya Gulf. The SST distribution shows that the contrast of temperatures with the surrounding waters is the most significant near the Cape Takil and is ~ 6–7 °C, near Cape Chauda it decreases to 3–4 °C.

All the aforementioned arguments concern only the surface sea layer. The vertical distribution of the waters flowing from the Kerch Strait into the Black Sea can be estimated only on the basis of the currently available hydrological surveys that recorded waters from the Kerch Strait in the Feodosiya Gulf in parallel with satellite observations. According to this data, on December 14–15, 2006, the main feature characterizing the horizontal surface thermohaline structure of the gulf was the presence of relatively cold and freshened waters. They were separated by a local frontal zone from the open sea waters, having the temperature of 2 °C, and the salinity of 1 PSU less than in the open sea.

Typical values of horizontal gradients on the frontal section were 0.2–0.3 °C and 0.2–0.3 PSU/km. Upper layer to a depth of 10 m was occupied by waters with temperature of 9.3 °C and salinity of 16.4 PSU, the frontal zone with the Black Sea waters was at a depth of 10–15 m. The concentration of the total suspended matter measured by the turbidimeter in the background was 0.2–0.8 mg/l, in the anomalous waters – 2.2 mg/l. Distribution of the other characteristics (SST, water transparency and chlorophyll *a* concentration), according to the *MODIS/Aqua* satellite, confirmed their origin. According to these data, a band of waters, 10 km wide, stretched from the southern boundary of the Kerch Strait, to the Feodosiya Gulf, and fills it almost completely. During this period there was a moderate northeastern wind (up to 6 m·s<sup>-1</sup>). However, the frontal zone between the Kerch and the Black Sea waters was located directly on the southern boundary of the strait. Analysis of the previous hydrometeorological information does not permit to relate this fact to the wind field.

Under the action of strong southern winds, bands of turbulent waters both in the Kerch Strait and along the shores of the Kerch and Taman Peninsulas are also observed. However, in these cases such zones are not a marker of the penetration of water from the Azov Sea. This is the result of wave action and stirring of the bottom sediments in clay cliffs. An example of such a process is evident in the image dated November 1, 2012 after the action of the south wind (8–10 m·s<sup>-1</sup>) on October 28–30. Fig. 6, *a* shows the bands of turbid waters stretching on the same distance westward to the Feodosiya Gulf and eastward to Anapa. However, the SST distribution indicates that these areas are occupied by the Black Sea waters with a temperature of 18–20 °C, also penetrating into the Kerch Strait (Fig. 6, *b*). Even more intense sediment resuspension, which was preceded by a strong and prolonged south-western wind with a speed of up to 15 m·s<sup>-1</sup>, was noted in this area on April 11, 2015. Water with the elevated TSM content spread more than 30 km off the coast, occupying a considerable area from Novorossiysk to the Feodosiya Gulf (Fig. 6, *c*). The areas of elevated TSM concentrations (5–10 mg/l) follow the bottom topography configuration to some extent, mainly up to an isobath of 50 m. This apparently reflects the wave action penetration and indirectly indicates the

wavelength of surface waves. The SST distribution clearly shows that the stormy areas are occupied by the Black Sea waters with a temperature of  $\sim 10\text{ }^{\circ}\text{C}$  (Fig. 6, *d*).



**Fig. 6.** The SM concentration according to *MODIS/Aqua* data (*a*, *c*, *e*); SST according to *MODIS/Aqua* (*b*, *f*) and *MODIS/Terra* (*d*) data

The similar distribution was observed on March 27, 2008 after the action of the southwestern storm wind ( $8\text{--}16\text{ m}\cdot\text{s}^{-1}$ ). And in this case, the turbid waters were localized off the coast of the Kerch Strait at an equal distance westward to the Feodosiya Gulf and eastward to Anapa, but the SST distribution surely indicates that these are the Black Sea waters with a temperature of  $\sim 10\text{ }^{\circ}\text{C}$  (Fig. 6, *e*, *f*). It should be noted that in all the three cases described above, areas with elevated TSM concentrations are observed in both Karkinitsky and Kalamitsky Gulfs. Un-

der the action of the north winds, they are not observed, since such winds do not generate significant waves and do not disturb the bottom sediments. Therefore, in the absence of SST distribution data, the presence of elevated SM concentration zones in the areas of the Karkinitzky and Kalamitsky bays may indirectly indicate the source of TSM in the near-Kerch area of the Black Sea.

The presented features of the Kerch Strait water propagation to the Black Sea have pronounced seasonal variability, which is associated with the seasonal wind variability. In general, the first of the two situations prevails, since the frequency of the northern quarter winds with a speed of  $\geq 6 \text{ m}\cdot\text{s}^{-1}$  in the Kerch Strait is 19.0 % (HMS Opasnoe), the southern quarter ones – 6.7 %. The mesoscale eddies passing in this region [13–16] and the upwellings [17], play a certain role in the propagation of waters from the Kerch Strait contributing to their cross-shelf transport. Eddies are capable of trapping the Kerch waters into their orbital motion and transferring them on a distance equal to the diameter of the eddies (10–80 km) to the south to the deep sea or to the east along the eastern coast. Cross-shelf transport of waters rich in terrigenous substances from the Kerch Strait can have a significant impact on the balance of nutrients and phytoplankton bloom in the central part of the basin [18]. The study of the seasonal variability of the propagation of the Kerch Strait waters from to the Black Sea, the effects of eddy and upwelling motions, as well as situations not falling under the described above, is beyond the scope of this paper due to the limited volume of the article.

**Conclusions.** The analysis carried out in the preset paper permits to make the following general conclusions.

1. The three most significant areas with increased turbidity of the waters are distinguished in the Black Sea waters of the Russian sector. These are areas of shallow Karkinitzky and Kalamitsky bays, as well as the Kerch Strait with water areas adjacent to the Kerch and Taman Peninsulas. According to satellite data, here the typical mean long-term values of the TSM concentration are 5–10 mg/l with the highest ones recorded near the coast and decreasing moving away from it

2. During the north storms in the Kerch Strait area, satellite images most often show water bands 1–10 km wide stretching along the Crimean Peninsula with elevated TSM concentrations. In this case, the Kerch Strait waters are a product of mixing of the Black and Azov Sea waters, which is identified by the differences in their thermohaline properties.

3. Under the action of strong southern winds, there are also bands of turbulent waters both in the Kerch Strait and along the shores of the Kerch and Taman Peninsulas. However, in this case such zones do not serve as a marker for the penetration of the Azov Sea waters, but are the result of wave action and stirring of the bottom sediments in clay cliffs.

4. The propagation area and the distance from the source of the waters with elevated concentrations are closely related to the strength and duration of storms.

The TSM propagation area is maximal in the cold period during the storm north-eastern winds.

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