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Original article

Propagation of the Black Sea Waters in the Sea of Azov Based on the Satellite Data and the NEMO Model

N. V. Vasilenko ✉, A. A. Aleskerova, A. A. Kubryakov, A. I. Mizyuk, S. V. Stanichny

Marine Hydrophysical Institute of RAS, Sevastopol, Russian Federation
✉ *nadinkot.nk@gmail.com*

Abstract
Purpose. The paper is purposed at studying the dynamics and reasons of the Black Sea water inflows to the Sea of Azov, as well as the features of their seasonal variability.
Methods and Results. Medium and high resolution satellite data, and also the results of numerical modeling the salinity field of the Azov-Black Sea basin for 2008–2009 by the high resolution (1 km) NEMO model were used. The analysis showed that the transparent and salty Black Sea waters were recorded most frequently in the southern and southeastern parts of the Azov Sea during a cold season. Based on the satellite measurements, the maximum number of inflows was observed in November and March, and the minimum one – from June to October. Similar results were obtained from the data of numerical calculations for 2008–2009: in winter, intense salt water inflows to the Sea of Azov (the flow exceeds 20 tons/s) are observed in a third of cases, and in some cases, the estimated salt flux attains 60 tons/s, whereas in summer their number is close to zero. Further the Black Sea waters move predominantly in a cyclonic direction, sometimes reaching the basin center. In some cases, high density gradients induce the development of an intense cyclonic eddy near the strait at the front of the Black Sea water inflows. The simulation data made it possible to assess the relationship between the wind and the salt fluxes to the Sea of Azov. It is shown that this relationship is of a cubic nature that is partly explained by increase of the inflowing water salinity caused by the intensified vertical mixing during the storms.
Conclusions. The main hydrodynamic reasons for the Black Sea water inflows to the Sea of Azov and their seasonal variability are the following: 1) intense wind transfer during the south winds; 2) frontal currents at the boundary of upwellings near the Kerch Peninsula during the western and southwestern winds; 3) orbital currents of the passing anticyclones which are able to induce a northerly water transport in the strait at any wind conditions.

Keywords: Sea of Azov, Black Sea, water exchange, Kerch Strait, MODIS, NEMO, current velocity, eddy dynamics, seasonal dynamics, satellite data, water circulation, numerical modeling, water transport, salinity, sea surface temperature, chlorophyll concentration, drift currents, salt flux, hydrooptical characteristics

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1. Introduction

The Sea of Azov is a shallow and enclosed water area (an average depth is 7 m, a maximum depth – 14.4 m), which is characterized by intense mixing, high concentrations of suspended matter in the waters, and a pronounced effect of river freshwater runoff [1–3]. In recent years, there has been an increase in the average value of the water salinity (about 14) [4–7]. The Sea of Azov is also characterized by high bioproductivity and biodiversity, and it is one of the most important sources of biological resources.

The waters of the Sea of Azov and the Black Sea differ significantly in a number of thermohaline and hydrooptical characteristics [3, 8]. An intensive river runoff into the Sea of Azov leads to a significant desalination of the basin and is an important source of nutrients that cause an increase in the basin bioproductivity. Every year during the warm season, a significant increase in the chlorophyll a concentration takes place, which in some areas can reach 50 mg/m^3 [9]. The shallow Sea of Azov is characterized by low transparency, which is primarily due to the disturbance of near-bottom suspension under effect of strong and moderate winds. Due to shallow depths, during the cold season in the Sea of Azov convection penetrates to the bottom and its temperature becomes much lower than the one in the Black Sea. These characteristics provide effective identification of the inflows of the Black Sea waters from satellite data in the optical and infrared ranges [10]. In the study [11], a configuration of NEMO circulation model for the Azov-Black Sea region with a high resolution (1.2 km) was developed, which allows us to explicitly reconstruct the water exchange through the Kerch Strait, analyze the distribution of salty Black Sea waters and their relationship with the current regime.

The inflows of saline less productive and relatively transparent waters of the Black Sea significantly affect the thermohaline structure of waters, hydrochemical and hydrobiological regime of the Sea of Azov [1, 2, 12]. According to the data averaged over a long-term period [1], the water discharge from the Sea of Azov to the Black Sea is 49.2 km^3, and from the Black Sea to the Sea of Azov – 33.8 km^3 per year. The intensity of water exchange with the Black Sea is determined by the morphological features of the Kerch Strait, as well as by the current regime and fluctuations in the level surface of the sea [1]. The factors that determine water exchange in the Kerch Strait significantly depend on atmospheric circulation and water balance components [13, 14]: formation of currents in the Kerch Strait is to some extent related to the impact of the river runoff, but mainly depends on wind characteristics [15–17].

The features of the Black Sea water distribution into the Sea of Azov are described in [1, 2, 13–15, 17, 18], which present quantitative estimates of water exchange through the Kerch Strait based on field observations and numerical modeling results, and also consider the effect of various hydrological conditions on the occurrence of Black Sea water inflows. The currents in the Kerch Strait were also considered in [13, 19–20] on the basis of integrated satellite monitoring. In particular, it was noted that the use of MODIS-Aqua satellite images containing information on the temperature of the sea surface, the chlorophyll a concentration and the normalized brightness of the ascending radiation at a wavelength of 551 nm makes it possible to detect the transport of the Black Sea and the Sea of Azov waters through the strait. In [1, 14, 16, 20] it was demonstrated that the inflows of the Black Sea waters were observed in the southern and south-eastern parts of the Sea of Azov.

[1] Dobrovolsky, A.D. and Zalogin, B.S., 1982. *Seas of the USSR*. Moscow: Publishing House of Moscow State University, 192 p. (in Russian).

This work is purposed at studying the dynamics of causes of the Black Sea water inflows into the Sea of Azov and the features of their seasonal variability. For the first time, on the basis of long-term satellite optical measurements of medium and high resolution, as well as the results of numerical calculations, an analysis of the temporal and seasonal variability of the Black Sea water inflows into the Sea of Azov was carried out. Based on the modeling data, the relation of these inflows with the wind characteristics and the features of the Black Sea currents was studied. On the basis of satellite and numerical data, the distribution areas of the Black Sea waters in the Sea of Azov were indicated.

2. Data

2.1. Satellite data

A significant difference in the hydrooptical characteristics of the Black Sea and the Sea of Azov provides efficient study of the Black Sea water distributions into the Sea of Azov water area using remote sensing data. To reveal the distribution of the Black Sea waters with lower concentrations of suspended matter, daily satellite data from MODIS-Aqua, MODIS-Terra on the brightness of the ascending radiation at 551 nm wavelength for 2003–2020 were considered. MODIS data on chlorophyll a concentration and sea surface temperature (SST) were also used. The data were obtained from the Ocean Color archive (http://oceancolor.gsfc.nasa.gov/).

For a detailed consideration of the features of the Black Sea water inflows, the satellite data of high spatial resolution OLI (Operational Land Imager) Landsat-7, -8, MSI (MultiSpectral Instrument) Sentinel-2 (30 and 10 m, respectively) were used. The data were obtained from the USGS portal (https://earthexplorer.usgs.gov/).

To analyze the impact of wind conditions on the formation of the Black Sea water inflows into the Sea of Azov, we used the latest generation *ERA5* global atmospheric reanalysis data of the European Center for Medium-Range Weather Forecasts (ECMWF) with a spatial resolution of 0.25° and a discreteness of 1 h.

2.2. Numerical modeling

To study the inflows of the Black Sea waters using numerical modeling data, the results obtained on the basis of NEMO model complex [11, 21] are used. The computational domain of the configuration covers the basin of the Azov, Black and Marmara seas (the so-called Euxinian cascade) with an almost uniform spatial resolution of $\approx$ 1.2 km.

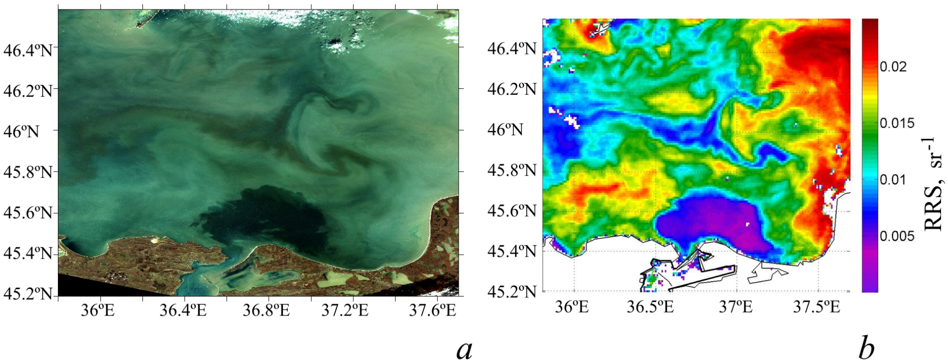
A more detailed description of the configuration we used is presented in [11]. We note a number of assumptions in this work when carrying out a numerical experiment. A vertical discretization was performed using the *z* coordinate with a fractional step on 35 horizons so that there were 5 horizons in the deepest part of the Sea of Azov, and at least 3 horizons in the shallowest part of the Kerch Strait. In this regard, the indicators of water exchange between the basins according to the results of numerical modeling are somewhat overestimated.

It should be noted that in this model the ice cover, which is regularly formed in the Sea of Azov in winter, is absent. The ice was taken into account only by correcting the heat flux in the area in which the calculated sea surface temperature becomes below the freezing point of water, but without correcting the dynamic drag coefficient necessary to determine the wind stress. This affects the results of the analysis of sea water dynamics, mainly in winter. The studies [2] revealed that winters of 2008–2009 period correspond to warm and moderate ice conditions, i.e. not the entire basin was covered with ice, but only its individual parts, and the strait itself was free of ice.

3. Results and discussion

3.1. Inflows of the Black Sea waters into the Sea of Azov according to the satellite data

When considering high-resolution *Landsat* 7, -8, *Sentinel*-2 satellite data in the southern and south-eastern parts of the Sea of Azov northwards of the Kerch Strait, the zones of the Black Sea waters containing less suspended matter are annually observed. For example, the *RGB* composite of the *Landsat*-8 satellite image dated 13.11.2015 (Fig. 1, *a*) is demonstrated. In this image, using visual assessment, one can distinguish a vast area of clear Black Sea waters from the more turbid surrounding waters of the Sea of Azov. The presented Black Sea inflow has a manifestation area on the surface of 1165 km^2 and reaches 45.72° N.



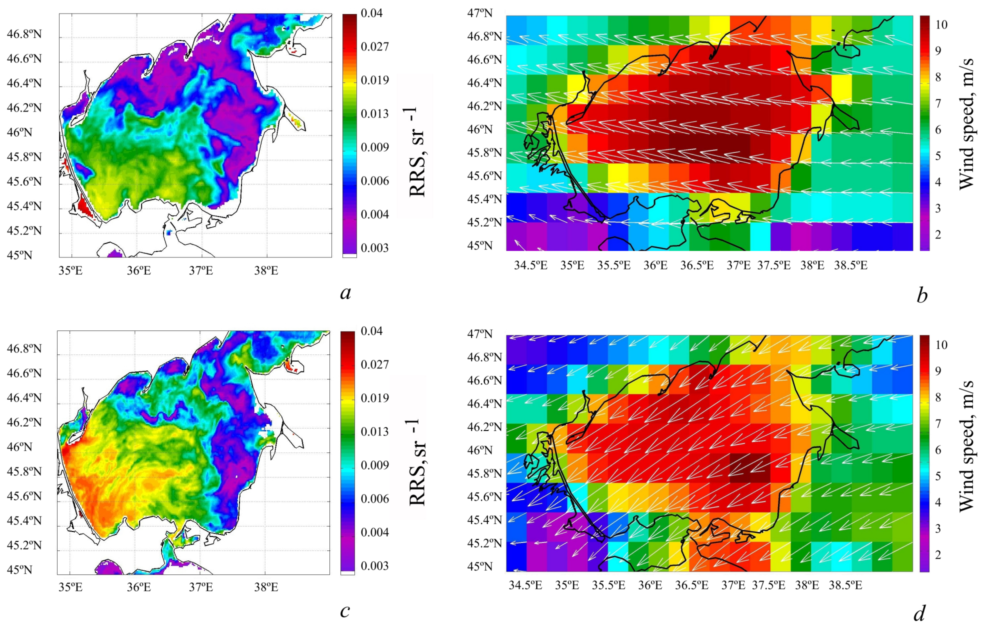
F i g. 1. Example of propagation of the Black Sea waters free of suspended matter in the southern part of the Sea of Azov: *a* is the Landsat-8 data on 13.11.2015, RGB-composite in pseudo-natural colors; *b* is the MODIS-Aqua data on the remote sensing reflectance at the wavelength 551 nm on 12.11. 2015

For comparison, in Fig. 1, *b* the MODIS-Aqua remote sensing reflectance map (RRS) at a wavelength of 551 nm (RRS(551)) is given, which characterizes the amount of scattering suspended matter in waters. It is clearly seen that the areas of clear waters coincide according to the data of high and medium resolution satellites. In the inflow area northward of the Kerch Strait, RRS(551) is four times lower than in the surrounding waters of the Sea of Azov. It should be noted that the Sea of Azov is characterized by a sharp variability of biooptical characteristics, which is associated with rapid changes in the wind and its effect on the disturbance of near-bottom suspension and coastal erosion. The authors considered that the inflow of the Black Sea waters is observed on the satellite data in case of detection of an area with a significantly lower RRS(551) value northward of

[2] Dyakov, N.N., Tymoshenko, T.Y., Belogudov, A.A. and Gorbach, S.B., 2015. [*Atlas of Ice of the Azov and Black Seas*]. Sevastopol: ECOSI-Gidrofizika, 219 p. (in Russian).

the strait and sharp gradients of this parameter. The identification of inflow events was carried out on the basis of a visual analysis of each reflectance map of the daily data set for 2003–2020.

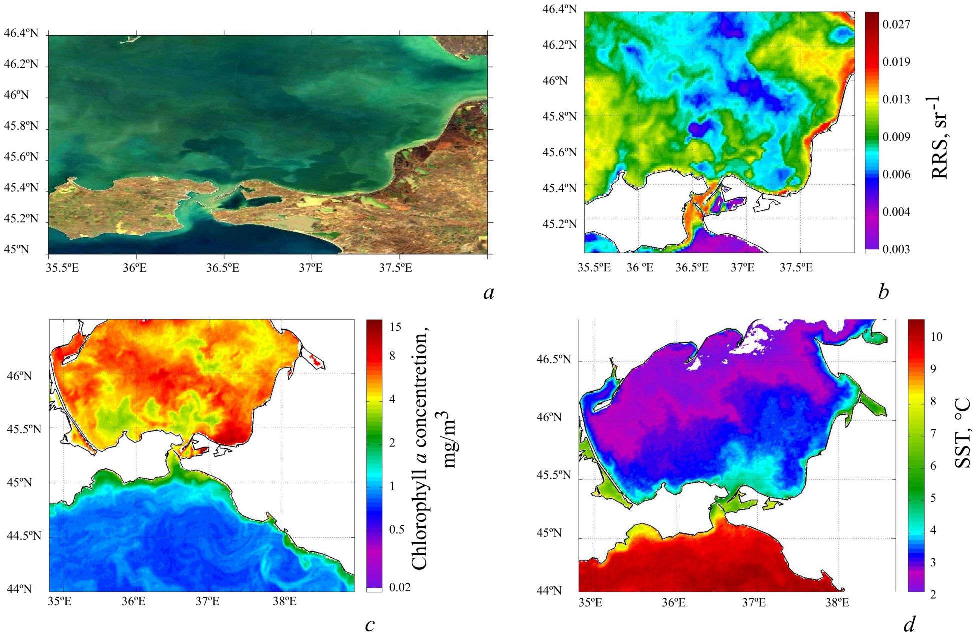
However, the application of data only on the remote sensing reflectance in some cases leads to errors. An example of such ambiguous reflectance maps is given in Fig. 2, *a*, *c*. It is clearly seen that in the southeastern part of the Sea of Azov relatively transparent waters with a reflectance 10 times lower than the one of the waters in the central part of the sea are observed. As the Black Sea waters often move eastward after entering the Sea of Azov, this propagation can be mistaken for an inflow event.



F i g. 2. Field of the remote sensing reflectance at the wavelength 551 nm at the intense northeast and eastern winds: the MODIS-Aqua RRS(551) data on 11.10.2018 (*a*) and 17.10.2018 (*c*); the ERA-5 data on the wind fields on 07.10.2018 (*b*) and 16.10.2018 (*d*)

However, a detailed analysis of such maps showed that such a reflectance distribution has features that are apparently associated with the processes of bottom sediment disturbance. At the windward side of the sea, the wind speed is lower (Fig. 2, *b*, *d*), and, in addition, the waves are young and their lengths are relatively small. As a result, the waters in the eastern coastal part of the sea are relatively transparent. These clean waters are transported off the coast by the wind action and occupy a strip up to 50 km wide near the coast. At the same time, in the central and southwestern parts of the sea, developed waves reach the bottom, and a sharp disturbance of bottom sediments is observed here. This process forms characteristic horizontal inhomogeneities of the water reflectance field, which are not associated with the inflow of the Black Sea waters. After a characteristic structure of the reflectance field with an increase in values at the windward side during and after the action of northeastern and eastern winds was recorded, these cases were excluded from the analysis.

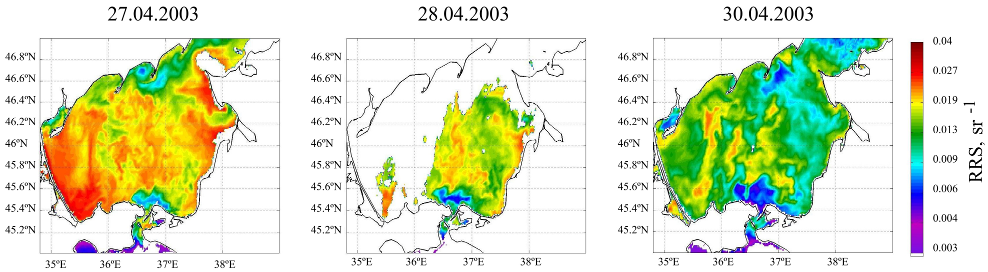
For more accurate identification of the Black Sea inflows, additional satellite measurements were used. In case of the Black Sea waters entering the Sea of Azov, there is a simultaneous sharp decrease in the remote sensing reflectance (difference from 0.003 and above to 0.03 sr^{-1}) and a decrease in the chlorophyll a concentration (the contrast reaches 2–10 mg/m^3). For example, a similar difference in values can be observed in the case of the Black Sea water inflow in satellite images from 18.02.2016 (Fig. 3, *b*, *c*).



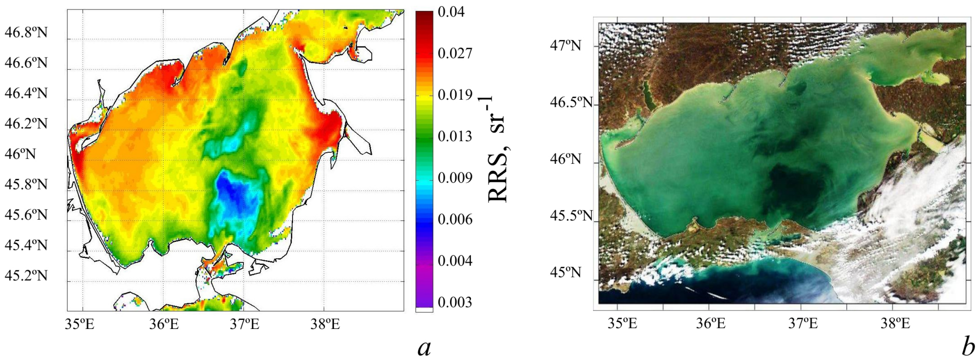
F i g. 3. Area of the Black Sea water inflows propagation in the southeastern part of the Sea of Azov based on the MODIS-Aqua data for 18.02. 2016: a is the RGB-composite in pseudo-natural colors; *b* is the remote sensing reflectance at the wavelength 551 nm; *c* is the chlorophyll a concentration; *d* is SST

During the cold season, the Sea of Azov cools faster than the Black Sea. These differences in temperature in some cases also make it possible to identify the Black Sea inflows in the Sea of Azov waters according to SST data. Thus, in a satellite image containing information on SST (Fig. 3, *d*), one can observe rather significant difference in values for the waters of the Sea of Azov and the Black Sea (up to 9 °C). At the same time, in the southern and southeastern parts of the Sea of Azov adjacent to the Kerch Strait, the surface temperature is much higher than in the rest of the water area. Since in this area there is also a zone with a small amount of suspended matter (Fig. 3, *a*, *b*) and low chlorophyll a concentration (Fig. 3, *c*), the increased temperature values are most likely associated with the inflow of the warmer Black Sea waters.

The duration of the Black Sea inflow manifestation, according to optical satellite data, averages from 1 to 3 days, but in some cases, it can be observed within a week. In Fig. 4 an example of the Black Sea water distribution dynamics in the south of the Sea of Azov for 26.04.2003–30.04.2003 is given. Thus, on April 26–27, after a long period of cloud cover over the study area in the southern part of the Sea of Azov, it an inflow of relatively clear Black Sea waters was recorded, which correspond to the region of low values of the remote sensing reflectance. In the following days (April 28–30), this area becomes larger and moves northward along the water area. Subsequently, either an extensive cloud cover was observed over the region under study, or manifestation of the Black Sea waters was not detected on the surface.

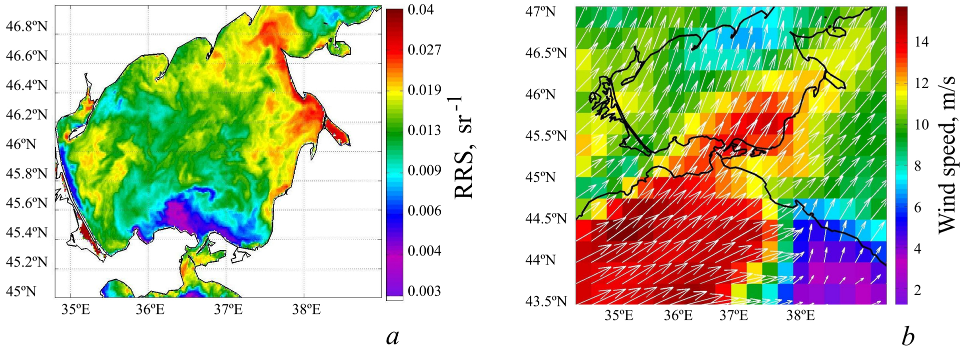


F i g. 4. Dynamics of the Black Sea water propagation in the south of the Sea of Azov based on the MODIS-Aqua data on the remote sensing reflectance at the wavelength 551 nm



F i g. 5. Manifestation of extensive inflow of the Black Sea waters on 20.03.2013 based on the MODIS-Aqua data on the remote sensing reflectance at the wavelength 551 nm (*a*); RGB-composite in pseudo-natural colors (*b*)

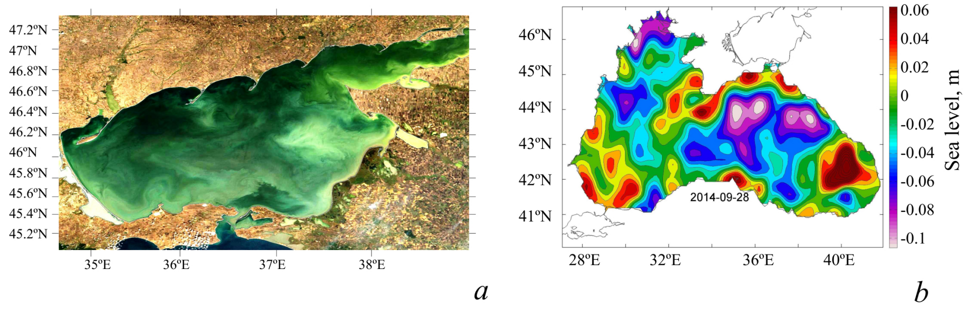
As a rule, according to satellite data, the Black Sea waters are observed in the southern, southeastern and eastern parts of the Sea of Azov after a transport through the Kerch Strait. The area of their manifestation can reach more than 2000 km^2. At the same time, according to optical satellite images, the Black Sea waters regularly manifest themselves on the surface of the Sea of Azov at a distance of more than 10 km north of the Kerch Strait, as, for example, in the case shown in Fig. 5, where a Black Sea inflow manifests itself on the surface at a distance of about 15 km from the Kerch Strait in the northerly direction.



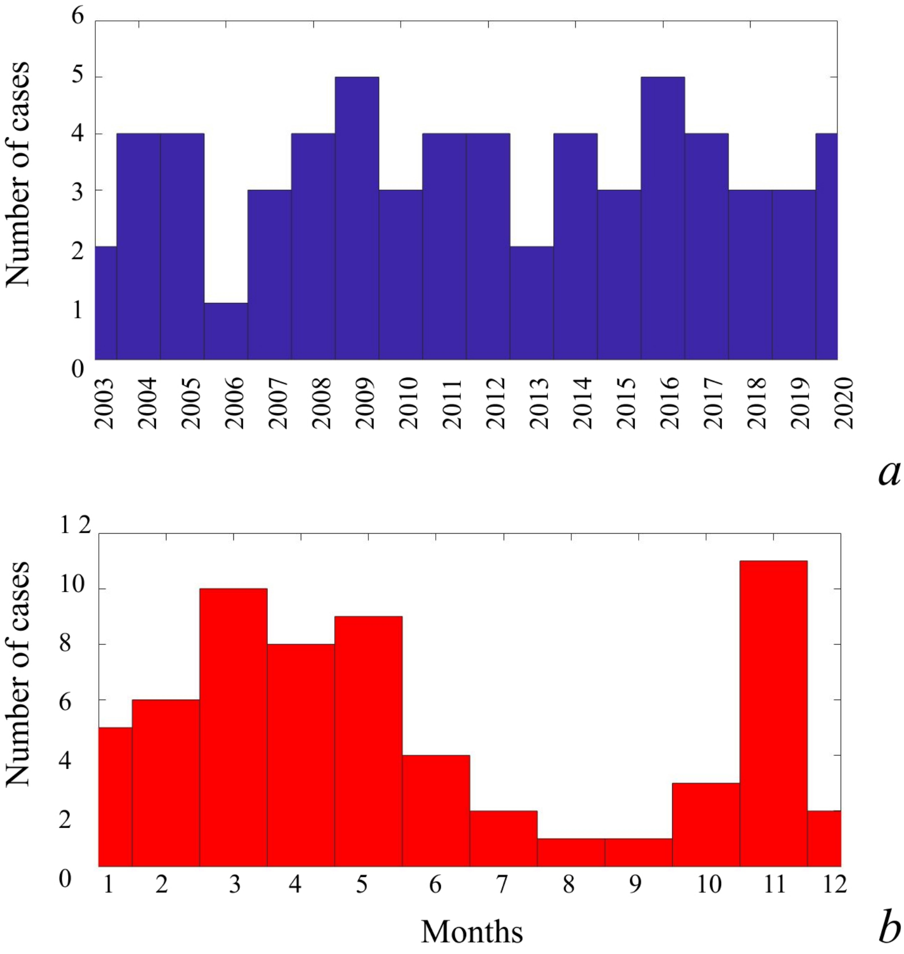
F i g. 6. MODIS-Aqua data on the remote sensing reflectance at the wavelength 551 nm for 12.11.2016 (*a*); the NCEP wind field data for 10.11.2016 (*b*)

An assessment of hydrometeorological conditions in the area under study showed that the predominant impact on the occurrence of the Black Sea water inflows is exerted by an intense wind effect. Most often, the Black Sea water inflows were found in optical satellite images of the Sea of Azov with a continuous southerly wind with a velocity of more than 6–8 m/s. An example of the Black Sea water inflow in the MODIS-Aqua image for 12.11.2016, where low values of the remote sensing reflectance are observed in the southern part of the water area up to a latitude of 45.7°N, is given in Fig. 6, *a*. At the same time, from November 6 to November 10, an intense southern wind with a velocity of up to 10–11 m/s was recorded (Fig. 6, *b*). Similarly, the wind conditions were considered for all the alleged cases of the Black Sea waters transport to the Sea of Azov.

However, in a number of cases, inflows of the Black Sea waters were observed in the absence of strong winds. An example of such an inflow for 28.09.2008 is shown in Fig. 7, *a*. As demonstrated in [22], the water exchange in the strait can be significantly affected by changes in the Black Sea level associated with its large- and mesoscale dynamics. In winter, an increase in the Black Sea cyclonic circulation causes a surge at the southern tip of the Kerch Strait, accompanied by a decrease in the flux of the Sea of Azov waters into the Black Sea. According to the satellite altimetry data (Fig. 7, *b*), it is clearly seen that at that time, a pronounced increase in the level was observed near the strait, which was associated with the passage of coastal anticyclonic eddies (rounded positive anomalies in Fig. 7, *b*). As will be shown below, such a process can be one of the causes for the inflows of the Black Sea waters.



F i g. 7. RGB-composite in pseudo-natural colors for 28.09.2008 (*a*); satellite altimetry data for 28.09.2008 (*b*)



F i g. 8. Average annual (*a*) and average monthly (*b*) numbers of the detected cases of the Black Sea water inflows to the Sea of Azov based on the satellite data for 2003–2020

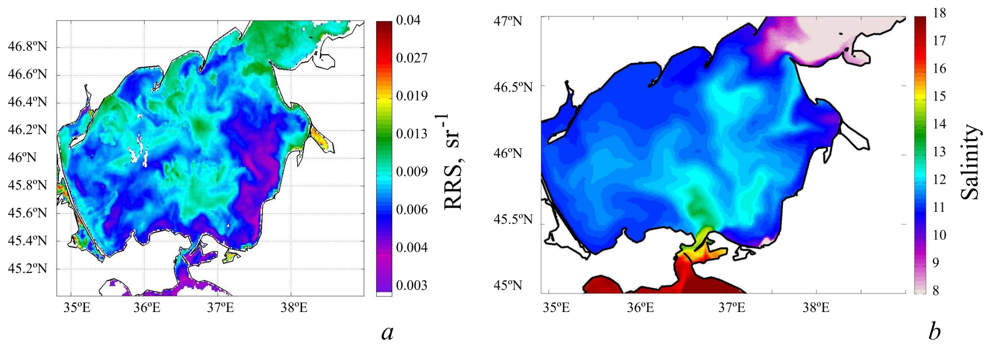
According to the daily satellite data for 2003–2020, excluding the days with a cloud cover, 62 cases of the Black Sea water inflows were recorded. The number of inflows is relatively constant over the entire period with a slight upward trend. On average, in all years, except for 2006 and 2013, according to the satellite data, 3–4 clear cases of the Black Sea water propagation in the Sea of Azov are annually observed (Fig. 8, *a*).

The frequency of inflow observation has significant seasonal variability (Fig. 8, *b*). Most often for the entire study period, the Black Sea inflows were recorded in the cold season. The maximum number of inflows was observed in November (11 cases) and in March (10 cases). The Black Sea inflows occurred least of all in the period from June to October (up to 4 cases for the entire study period). Note that the number of inflows is determined from cloudless satellite images. The cloudiness over the Black Sea has a pronounced seasonal variation with a maximum in December – January (80%) and a minimum in July – August (40%) [23]. Therefore, it can be expected that in winter the number of inflows should be greater than was identified from satellite data, and the seasonal variation can be even more pronounced.

3.2. Inflows of the Black Sea waters to the Sea of Azov according to numerical modeling results

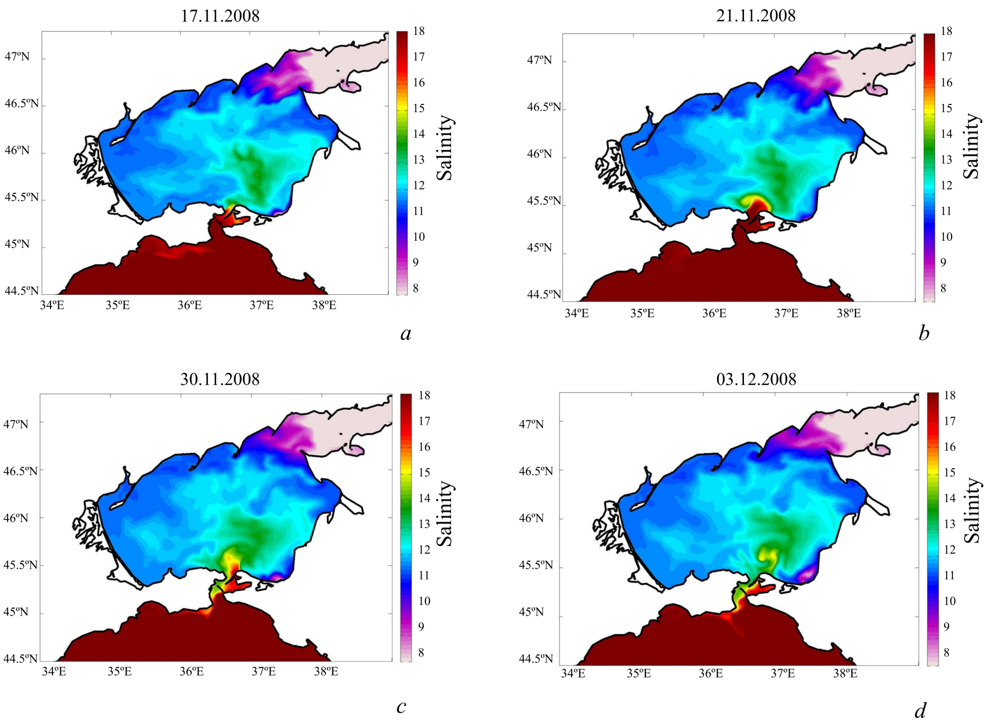
The numerical modeling data provide clear observation of the Black Sea water inflows and track their evolution in the salinity field. The zones of more saline Black Sea waters in the southern part of the Sea of Azov identified by the model data correspond to the zones of low values of remote sensing reflectance detected according to MODIS-Aqua satellite data. When comparing the cases of inflows identified from satellite and model data, four distinct coincidences are observed in 2008 and five in 2009.

One example of such a comparison for 18.08.2008 is given in Fig. 9. Thus, in the MODIS-Aqua satellite image in the southern part of the water area, the waters cleaner from suspended matter are traced. On the same date, according to the NEMO model calculations, a propagation area of more saline Black Sea waters (S > 12) similar in location is noted.



F i g. 9. Comparison of the case of the Black Sea water propagation in the southern part of the Sea of Azov on 18.08.2008 based on the MODIS-Aqua data on the remote sensing reflectance at the wavelength 551 nm (*a*) and the results of calculating the salinity fields using the NEMO model (*b*)

However, some of the identified cases (six during 2008–2009) of the Black Sea inflows to the Sea of Azov, obtained from numerical simulation data, are not recognized from satellite data. Such cases, in particular, are observed in May – June, when optical properties of the Black Sea waters change significantly due to the intensive blooming of coccolithophores. In addition, many cases of inflows according to NEMO model occur on days with a developed cloud cover over the study area, which does not allow them to be compared with satellite data.

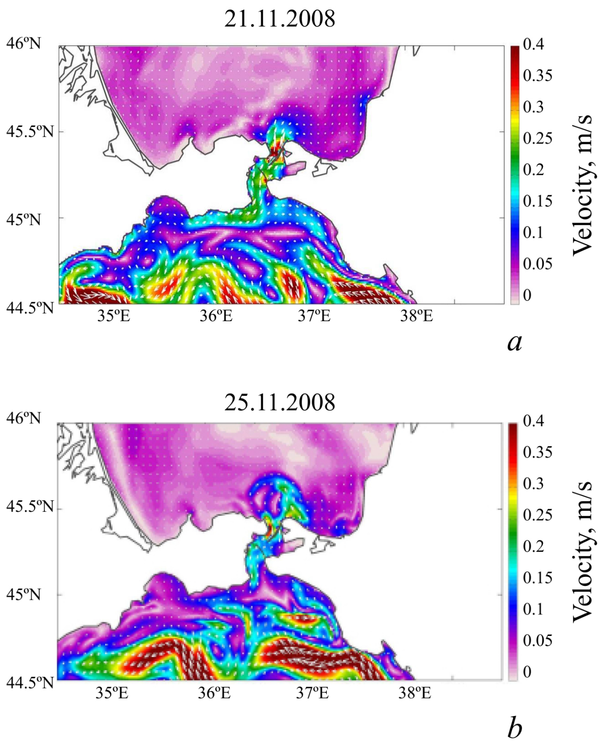


F i g. 10. The Black Sea water propagation in the southern part of the Sea of Azov based on the data on salinity fields in the Sea of Azov resulted from numerical modeling on 17.11.2008 (*a*), 21.11.2008 (*b*), 30.11.2008 (*c*), and 03.12.2008 (*d*)

According to the NEMO model calculations, more than 20 cases of propagation of more saline Black Sea waters in the Sea of Azov are presumably detected per year (25 and 22 for 2008 and 2009, respectively). The duration of manifestation of the Black Sea water inflows, according to model calculations, ranges from 1–2 to 5–7 days. In accordance with satellite information, according to model calculations, more saline waters of the Black Sea origin are distinguished mainly in the southern and southeastern parts of the Sea of Azov. In Fig. 10, an example of such a distribution of the Black Sea inflow and an increase in its area for 13.11.2008–29.11.2008 is demonstrated. Thus, according to the data for 17.11.2008 (Fig. 10, *a*), the waters with salinity values of more than 16 are observed only southward of the Kerch Strait. Further, in the image dated 21.11.2008 (Fig. 10, *b*), we observe an initial stage of propagation of the Black Sea waters with a salinity of 16–18, which propagate for 10 km, forming a mushroom-shaped structure north of the strait tip. The velocity field at this time clearly shows a fairly intense flow in the strait directed northwards (Fig. 11, *a*).

The simulation data, in accordance with [2, 22], show that in most cases (90%) the cause of such inflows was intense southeastern and southern storms. In this example, an intense movement of these waters northward of the Kerch Strait is observed under the effect of a southeastern wind with a velocity of more than 10 m/s, which was observed from 20.11.2008.

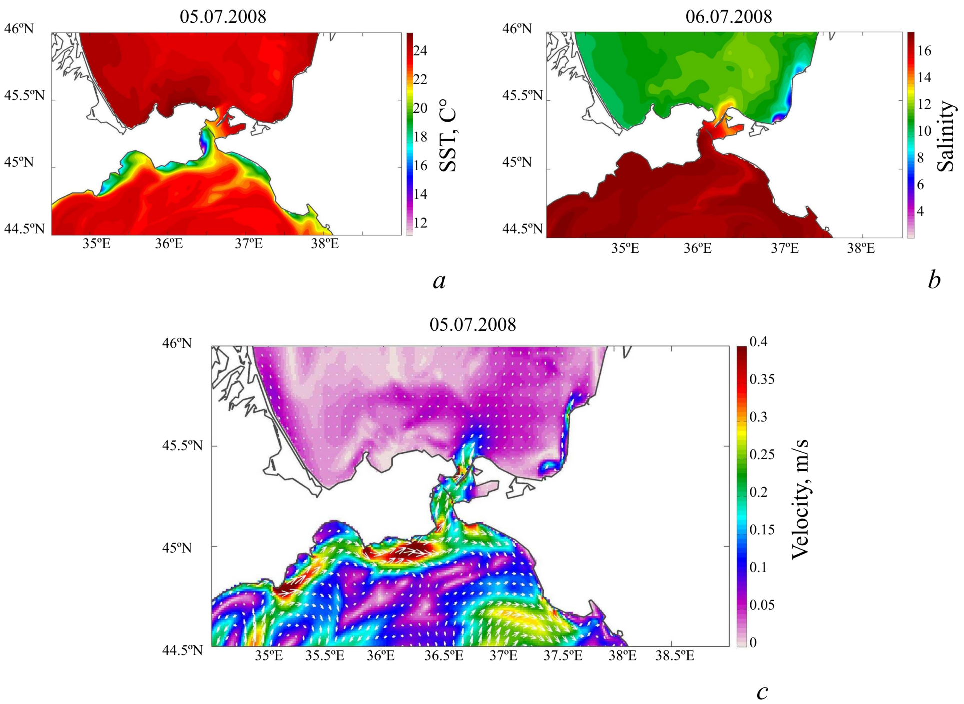
Subsequently, from 22.11.2008, the waters with salinity values of more than 16 penetrate into the Sea of Azov at a distance of 20–30 km from the strait and then move to the northeast. After a significant decrease in wind speed (less than 7 m/s) and a change in direction, an intensive movement of the Black Sea waters through the strait stops on 29.11.2008. However, the tongue of brackish waters with salinity values of 14, formed during the mixing process, can be observed for a long time (Fig. 10, *c*, *d*). Basically, during the cold period of the year, they move in a cyclonic direction, reaching the latitudes of 46–46.5°N. Due to a significant difference in density, the saline water flow becomes unstable, and on its periphery one can observe the development of small eddies (10–20 km in diameter). The most frequently recorded cyclonic eddy is observed near the northern part of the strait (Fig. 10, *b*, *d*; 11, *b*). Its formation is apparently associated with baroclinic instability that occurs at the boundary of the inflow of denser Black Sea waters.



F i g. 11. Current velocity fields in the Sea of Azov based on the results of the NEMO model calculations for 21.11.2008 and 25.11.2008

The analysis showed that the increase in southern and especially southwestern winds is often accompanied by the occurrence of intense eastern currents at the entrance to the strait and near the southern part of the Kerch and Taman peninsulas. In summer, it is clearly seen that the occurrence of such currents is associated with coastal upwelling caused by these winds. At a sharp thermal boundary, a cyclonic eastern frontal current arises, which is directed to the northeast in the strait. An example of such a case, identified by the simulation results at the beginning of July 2008, is shown in Fig. 12.

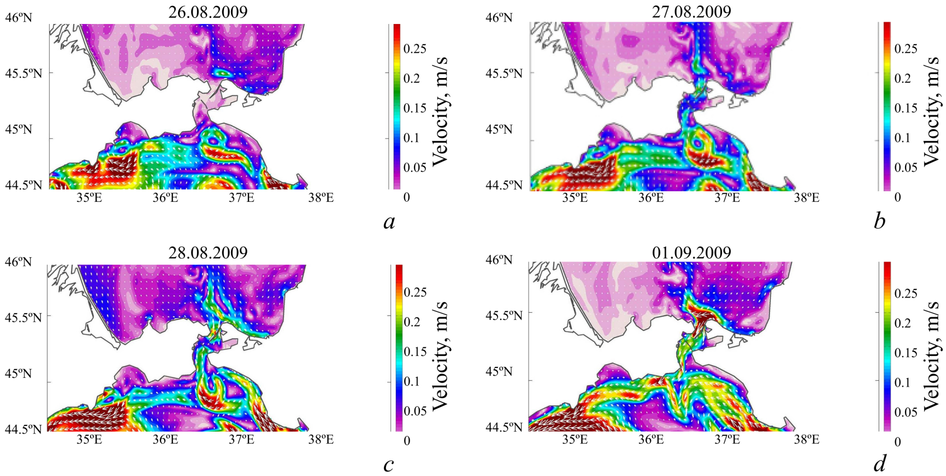
On the temperature map (Fig. 12, *a*), a surge on the southern coast of the Kerch Peninsula, which arose as a result of the action of southwestern winds, is clearly observed. The sharpest upwelling is observed in the western part of the Kerch Peninsula, where the temperature of the raised cold waters is 10° lower than the temperature of the surrounding waters. Easterly currents with velocities of 20–40 cm/s, which formed at the upwelling front as a result of sharp density drops, are clearly visible in Fig. 12, *c*. Northern currents arise at the periphery of the surge in the Kerch Strait. They cause an inflow of the Black Sea waters with salinity values of more than 16 into the Sea of Azov (Fig. 12, *b*) with a delay of 1–2 days. This example shows that frontal upwelling currents arising under the action of western and southwestern winds, along with purely drift currents, are one of the important causes for the intensification of the Black Sea water inflows into the Sea of Azov.



F i g. 12. Intensification of the Black Sea water inflows during the development of upwelling near the Kerch Peninsula coast based on the NEMO data: a is the SST map for July 5, 2008; *b* is the salinity map for July 6, 2008 and *c* is the current velocity map for July 5, 2008

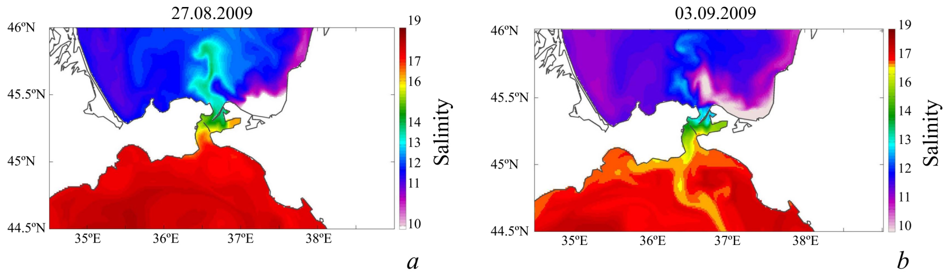
In addition, apparently, it is these currents that carry the impurity that came earlier from the Sea of Azov to the east, which causes a sharp increase in turbidity near the Taman Peninsula, as was shown in [8].

At the same time, according to the modeling results, in some cases (~ 10%), as well as according to satellite data, the Black Sea water inflows were noted during northerly winds. An analysis of numerical modeling data showed that the cause of this phenomenon is probably the effect of mesoscale dynamics southward of the strait. A similar process was observed during 24.08.2009–30.08.2009, when an intense anticyclone with orbital velocities of 0.2–0.3 m/s was observed on the Kerch-Taman shelf (Fig. 13, *a*). The eddy moved to the west with a velocity of about 0.05 m/s. In the western part of the anticyclone, intense currents were directed to the north. During the passage of the periphery of this eddy in the Kerch Strait, a rather strong northern current with velocities of 0.1–0.2 m/s (Fig. 13, *b*) arose. Such a current was observed for three days from 27.08.2009 to 30.08.2009, which probably led to a significant penetration of the saline Black Sea waters into the Sea of Azov (Fig. 14). More saline waters of the Black Sea penetrated 50–60 km into the Sea of Azov (Fig. 13, *b*, *c*; 14, *b*). At the same time, during the presented period, the wind of the northeastern direction prevailed.



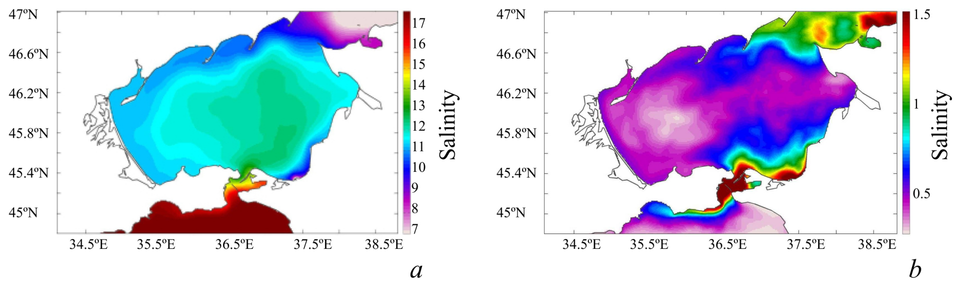
F i g. 13. Current velocity maps in the Kerch Strait region during passing of the anticyclone on the Kerch-Taman shelf: a – before the anticyclone – strait interaction; *b*, *c* – during interaction with the western periphery and *d* – when passing of the eastern periphery of an anticyclone

As in the previous case, dense waters became unstable after the inflow, resulting in the formation of a cyclonic eddy structure at the boundary of the salt water area. Subsequently, the anticyclonic eddy that caused this disturbance shifted to the west and the current changed direction to the opposite one (see Fig. 13, *d*). During this period, there is an increased flow of desalinated waters of the Sea of Azov into the Kerch Strait. This example demonstrates a significant effect of mesoscale circulation on water exchange pulsations between the Sea of Azov and the Black Sea.



F i g. 14. Salinity fields on August 27, 2009 during intensification of the northern currents at interaction with the anticyclone western periphery (*a*) and on September 3, 2009, after the southern currents intensified and the Azov Sea fresh waters were trapped by the anticyclone (*b*)

The maps of salinity averaged for 2008–2009 (Fig. 15, *a*) and its dispersion (Fig. 15, *b*) clearly demonstrate the main features of the saline Black Sea water propagation. In Fig. 15, a one can observe the tongue of saline waters, which moves northeastwards from the strait mouth, exerting a significant effect, at least, on the entire eastern part of the Sea of Azov. The tongue is most pronounced in the southeastern region of the basin with 45.2°– 46°N, 36.5°–37.5°E coordinates. The Black Sea water inflows cause significant increase in salinity dispersion (Fig. 15, *b*), which has a maximum in the northeastern and southeastern parts of the sea. In the first region, such a dispersion is largely related to the dynamics of the propagation of the Don River freshened waters in the shallow Taganrog Bay. In the southeastern part of the Sea of Azov, there is a much less extensive area of high values of the salinity root-mean-square deviation, associated with the water discharge from the Kuban River. To the north and east of the strait, there is another zone of high variability, which is caused by periodic inflows of the Black Sea waters. Note that this area has a symmetrical part in the Black Sea southward of the Kerch Peninsula. It is associated with periodic intense inflows of the Sea of Azov waters into the Black Sea, which subsequently propagate mainly to the west, often to the Feodosia Bay [8].



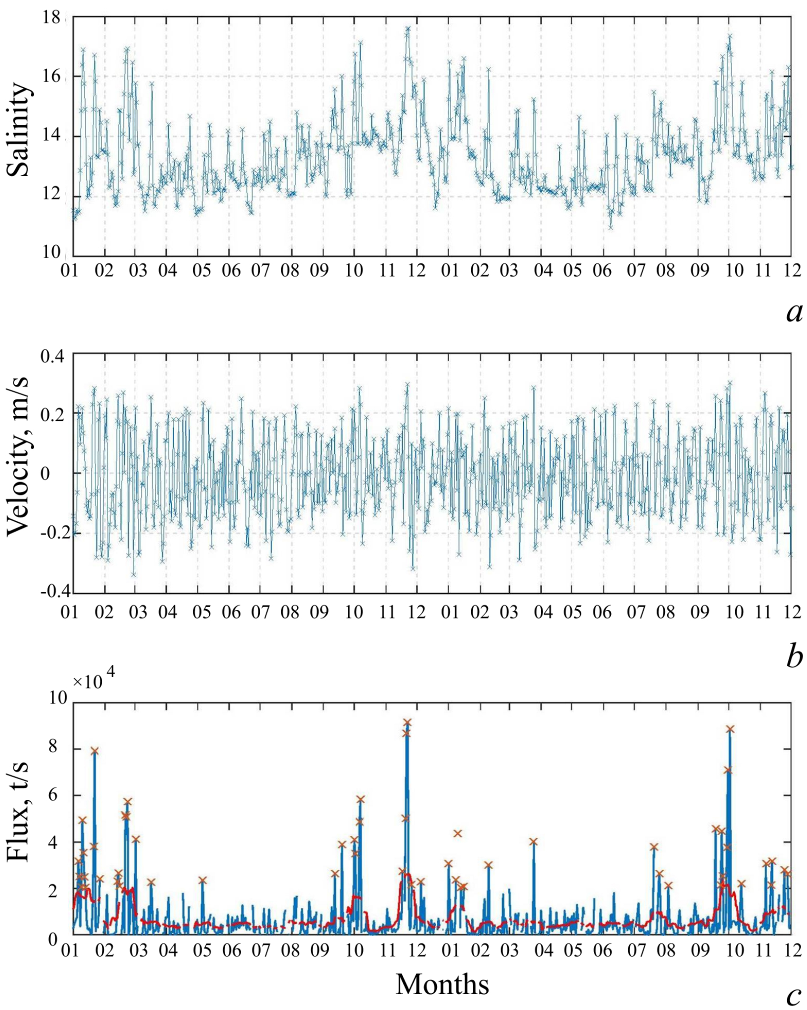
F i g. 15. Averaged for 2008–2009 salinity (*a*) and standard deviation of salinity (*b*)

3.3. Seasonal and interannual variability of the Black Sea water inflows

Analysis of the results of model calculations also confirms pronounced seasonality of the Black Sea waters distribution in the Sea of Azov. Temporal variability of currents averaged over the salinity depth and meridional velocity, as well as an unidirectional salt flux in the upper layer through the section of the Kerch Strait along 45.4°N from 36.65° to 36.8°E according to the modeling results, is shown in Fig. 16. A unidirectional salt flux F was calculated only for cases $V_y > 0$, i.e. when the current velocity (V_y) was directed to the north according to the formula

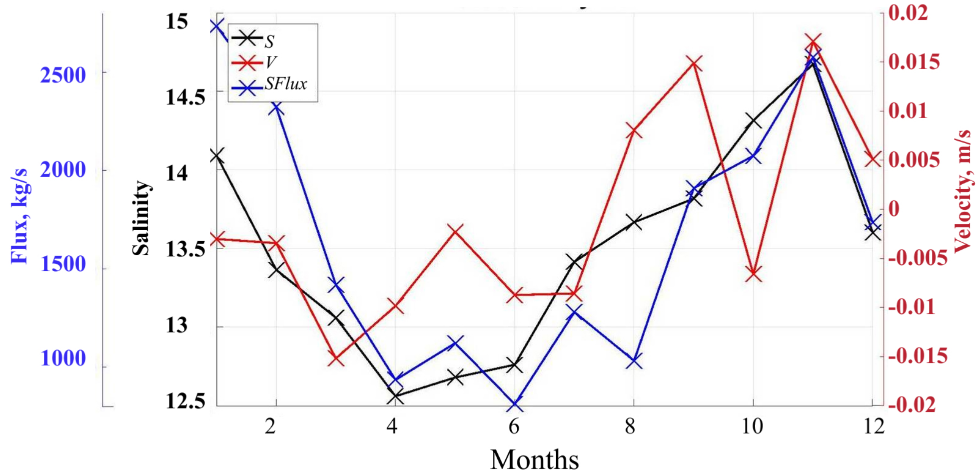
$$F = \int_0^z \int_{x_1}^{x_2} (S - \langle S \rangle) \cdot v dz dx.$$

Here S is salinity; v is meridional velocity of currents; $\langle S \rangle = 13.5$ is average salinity at the section; x_1 and x_2 are the section boundaries.



F i g. 16. Temporal variability of the depth-average salinity (*a*), meridional current velocities (*b*) and salt flux (*c*) on the section along 45.4°N. Red crosses show the selected cases of inflows; red curve is smoothed variability

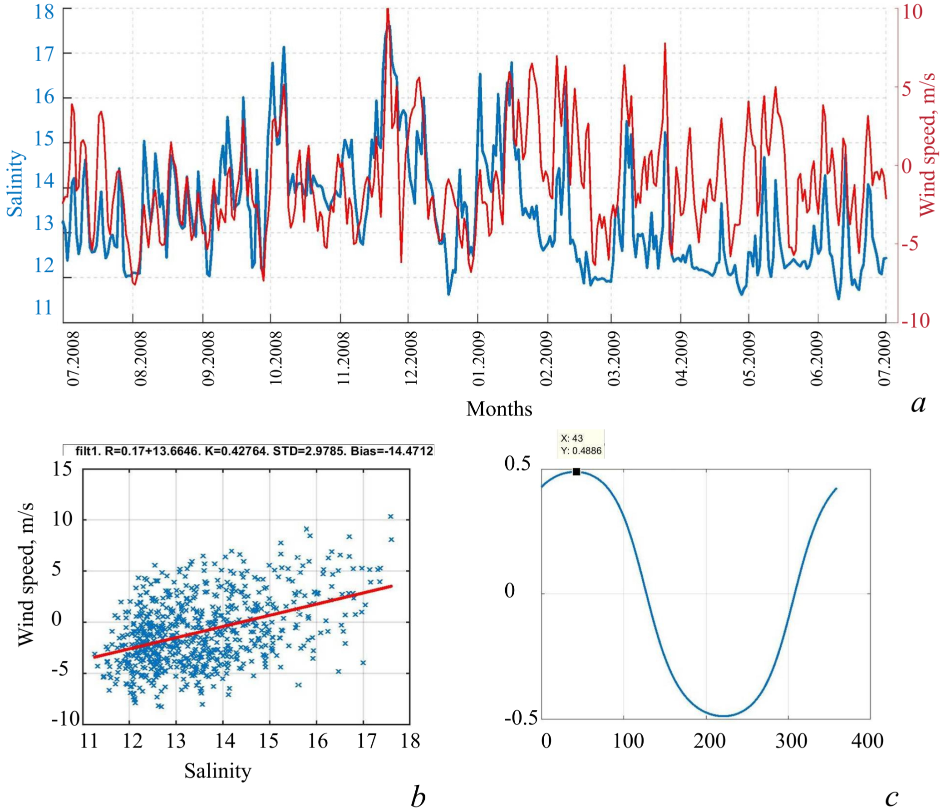
The velocity of waters in the Kerch Strait is characterized by a pronounced high-frequency variability associated with wind speed fluctuations (Fig. 16, *b*). When averaging over depth (Fig. 17), a seasonal variation with relatively small amplitudes manifests itself: the largest positive values (0.02 m/s) are observed in the autumn period (September and November), negative values – in spring and summer (−0.02 m/s).



F i g. 17. Seasonal variations of the depth-average salinity (*S*), meridional current velocities (V_y) and salt flux along 45.4°N

Similar, but more pronounced features of seasonal variation are observed in the salinity field (Fig. 17). In winter, salinity in the strait increases on average from 13 to 14.5. Such an increase in salinity is associated with a decrease in river runoff and an increase in evaporation. In addition, the intensification of vertical mixing due to winter convection, starting from autumn storms, leads to the involvement of deep waters in the Black Sea upper layers, contributing to a significant increase in salinity. These changes are superimposed by salinity fluctuations associated with the Black Sea water inflows, which are much more pronounced in the winter season, when an average salinity in the section can reach values of 16–17 (Fig. 16, *b*).

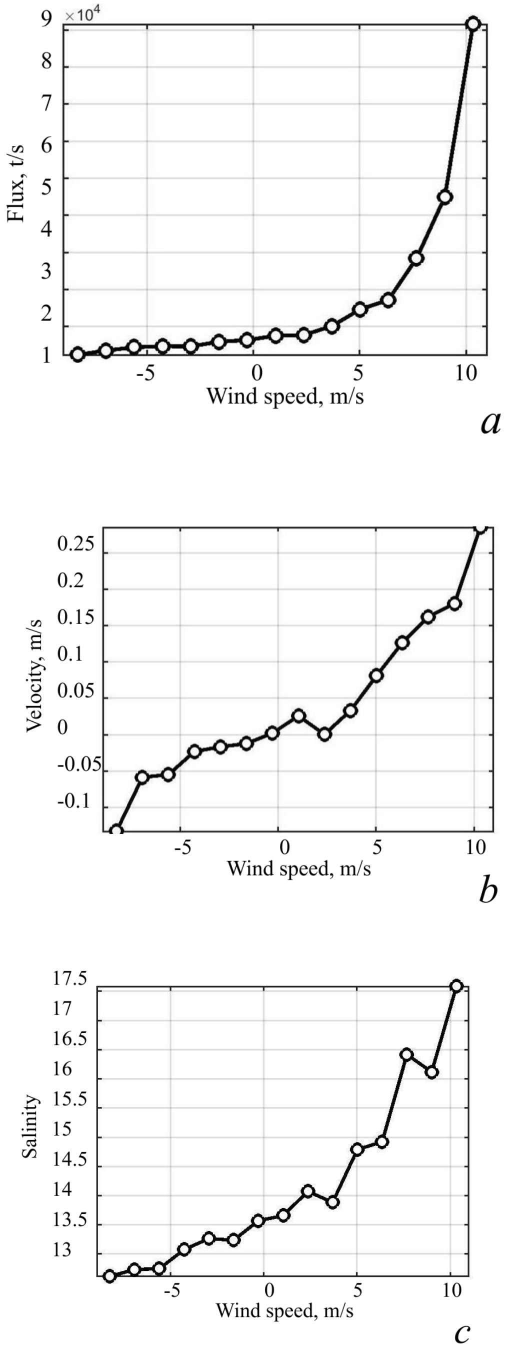
In addition, such variability features are associated with an increase in southerly storm winds during this period of the year [22]. A correlation between the average daily values of the meridional wind speed (W_y) and salinity is ~ 0.45 (Fig. 18, *a*, *b*). The dependence of this correlation on winds of different directions is demonstrated in Fig. 18, *c*. The highest correlation value is observed when the velocity vector rotates by 43° (clockwise), if counted from the northern direction, i.e. it is associated with the action of southwestern winds. As shown in the previous section, this dependence is associated with the wind impact on the occurrence of surges in the Kerch Strait, which contribute to the northern transfer of salt water under the effect of intense frontal upwelling currents.



F i g. 18. Temporal variability of salinity and meridional wind speed on the section along 45.4°N (*a*); scatterplot between salinity and meridional component of wind speed (*b*), and variability of the correlation coefficient between salinity and wind speed for the winds of different directions (*c*)

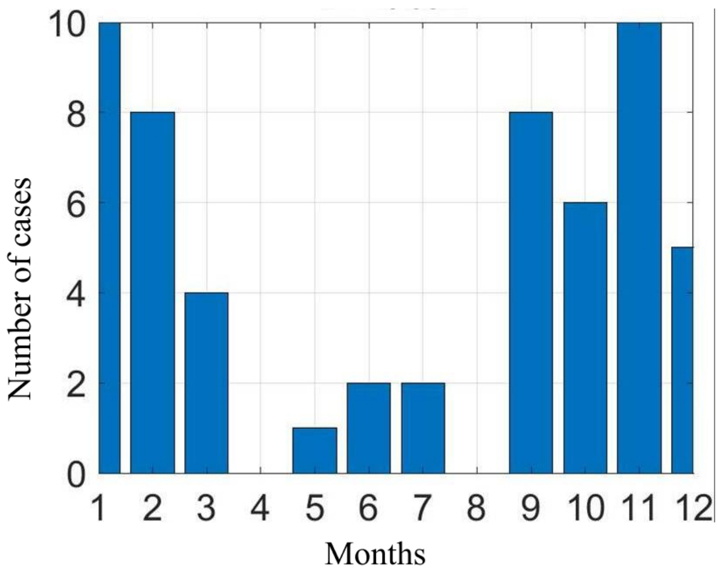
The average dependence of V_y on W_y is linear (Fig. 19, *a*), while the dependence of S on W_y is quadratic (Fig. 19, *b*). A sharp increase in salinity with an increase in wind is associated with at least three processes: horizontal advection of salty Black Sea waters under the effect of wind, intensification of turbulent mixing under the wind effect, and intensification of vertical advection under effect of offshore winds. The last two processes cause an inflow of deep waters into the upper layers and increase the salinity of the inflowing Black Sea waters.

Since a salt flux is the product of velocity and salinity, its dependence on wind velocity is a power function and the flux increases sharply during the strongest winds (Fig. 19, *c*). The strengthening of the northern currents and an increase in the salinity of the upper layer lead to the intensification of salt fluxes in winter (Fig. 19, *a*). At this time, the flux on some days can reach 60–80 t/s. Such inflows are observed for a longer time.



F i g. 19. Average dependence of the salt flux (*a*) from the Azov Sea to the Black Sea, velocity (*b*) and salinity (*c*) upon the meridional wind speed

To assess seasonal variability in the number of inflows, we calculated the number of days in a year in which *F* exceeded 20 t/s. Such events are marked with red crosses in Fig. 16, *c*. A seasonal variation of the number of days in a month when an inflow was observed is shown in Fig. 20. As according to the satellite data, these events demonstrate a seasonal pattern, with a maximum in winter and a minimum in summer. Their largest number is generally observed from September to February, and the smallest – from April to August. The maximum number of days with inflows, is 10, i.e. the third of the entire month, and it corresponds to January and November; however, in April and August of 2008–2009 the inflows are not recorded. In November and January, the average monthly estimates of the salt flux through the strait are 3 t/s. Note that in this part of the work, the analysis was carried out on the basis of a rather short two-year calculation period, and the obtained estimates of the seasonal variation may have features in other years.



F i g. 20. Average number of days in the months during which the Black Sea water inflows to the Sea of Azov were observed (based on the NEMO model calculations for 2008–2009)

Conclusion

In this paper, the spatiotemporal variability of the Black Sea water inflows into the Sea of Azov is studied for the first time on the basis of long-term satellite data and the results of numerical modeling.

The inflows of the Black Sea waters are well distinguished by the field of satellite reflectance (at 551 nm wavelength), which characterizes the presence of scattering suspension, since the Black Sea waters are generally much more transparent than those of the Sea of Azov, except for the events of intense blooming of coccolithophores. At the same time, when analyzing, it is necessary to discard situations associated with inhomogeneity of the wave effect on the disturbance of the near-bottom suspension under the effect of northeasterly winds. Additional information about inflows is provided by data on SST and chlorophyll a concentration.

According to daily satellite data for 2003–2020, excluding the days with a cloud cover, 3–5 clear cases of the Black Sea water propagation in the Sea of Azov are recorded annually. At the same time, the duration of manifestation of the Black Sea water inflows according to the satellite data is on average 1–3 days. According to the salinity data for 2008–2009, obtained from the numerical modeling results, the number of such events is estimated to be about 20 per year, and the duration can be up to 5–7 days. Such differences between the results are probably related to the shortcomings of the satellite data: cloudiness effect, specifics of the variability of water optical characteristics.

According to the satellite data over 2003–2020, the Black Sea waters after the transport through the Kerch Strait are observed mainly in the southern, southeastern, and eastern parts of the Sea of Azov. At the same time, the area of their manifestation can reach more than 2000 km^2. According to the numerical modeling data for 2008–2009, the saline Black Sea waters in the Sea of Azov move eastwards and then northwards in a cyclonic direction and reach the northern part of the Sea of Azov, which is associated with a predominant cyclonic circulation of the basin. At the same time, eddy structures are likely to form at the front of inflowing saline water. Particularly intense cyclonic eddies can form northward of the Kerch Strait. The Black Sea waters have an important effect on the average characteristics of the salinity field of the Sea of Azov, which is significant in its central and eastern parts. The inflow of these waters is one of the important causes for the maximum variability of salinity in the Sea of Azov southeastern part.

The satellite data and the modeling results demonstrate that the most intense inflow of the Black Sea waters into the Sea of Azov can be observed in the autumn-winter period. The Black Sea water inflows were detected most often by satellite measurements during the cold season. The maximum number of inflows was observed in November (11 cases) and March (10 cases). The Black Sea inflows occurred least frequently from June to October (up to 4 cases for the entire study period). Similar results were obtained from the data of numerical calculations for 2008–2009: in winter, intense saline water inflows into the Sea of Azov (with a flow of more than 20 t/s) should occur in a third of the days of the month, while in summer their number is close to zero. According to the calculations, in winter, an increase in the salt flux to the Sea of Azov, which in November and January reaches an average of 3 t/s, and on some days, it is up to 60 t/s, is possible. Such an increase in salt fluxes is probably largely due to an increase in the salinity of the incoming waters of the Black Sea upper layer due to winter mixing, which causes the involvement of deep saline waters into the upper layers.

An analysis of hydrometeorological conditions in the study area showed that the predominant impact on the occurrence of the Black Sea water inflows is exerted by the intense effect of wind of southern directions, especially of the southwestern one. According to the model calculations, the dependence of salt fluxes on wind speed has a cubic character. Such winds should cause the emergence of intense northern currents in the strait, the velocity of which are 15–25 cm/s during storms with a wind speed of 7–10 m/s. An increase in wind speed should cause an increase in salinity associated with the intensification of vertical mixing and the involvement of deep waters in the upper layers of the Black Sea, which additionally contributes to an increase in salt fluxes.

In the warm period of the year, frontal currents at the boundary of coastal upwellings near the Kerch Peninsula, which arise under effect of southwestern and western winds, have an important impact on the intensification of inflows. Sharp temperature gradients cause the development of eastern and northeastern currents, which increase the inflows of the Black Sea waters.

In a number of cases, satellite and model data make it possible to assume the probability of the Black Sea water inflow under unfavorable wind conditions, for example, during northerly winds. An analysis of the numerical modeling data showed that the cause for this phenomenon is probably the passage of synoptic anticyclones southward of the strait. These anticyclones cause formation of northern currents on their western periphery and can contribute to the transport of the Black Sea waters to the Sea of Azov.

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About the authors:

Nadezhda V. Vasilenko, Senior Engineer-Researcher, Marine Hydrophysical Institute of RAS (2 Kapitanskaya Str., Sevastopol, 299011, Russian Federation), **SPIN-code: 4710-2532 AuthorID: 1114885, Scopus Author ID: 57358387000**, nadinkot.nk@gmail.com

Anna A. Aleskerova, Research Associate, Marine Hydrophysical Institute of RAS (2 Kapitanskaya Str., Sevastopol, 299011, Russian Federation), Ph.D. (Geogr.), **SPIN-code: 5796-2254 AuthorID: 1020460, Scopus Author ID: 57021552600**, annete08@mail.ru

Arseniy A. Kubryakov, Leading Research Associate, Marine Hydrophysical Institute of RAS (2 Kapitanskaya Str., Sevastopol, 299011, Russian Federation), Ph.D. (Phys.-Math.), **SPIN-code: 4371-8879 AuthorID: 722633, Scopus Author ID: 37072750100**, arskubr@yandex.ru

Artem. I. Mizyuk, **Senior Research Associate,** Marine Hydrophysical Institute of RAS (2 Kapitanskaya Str., Sevastopol, 299011, Russian Federation), Ph.D. (Math.), **SPIN-code: 8285-8260 AuthorID: 854379, Scopus Author ID: 36446217200**, artem.mizyuk@mhi-ras.ru

Sergey S. Stanichny, Senior Research Associate, Marine Hydrophysical Institute of RAS (2 Kapitanskaya Str., Sevastopol, 299011, Russian Federation), Ph.D. (Phys.-Math.), **SPIN-code: 8146-9454 AuthorID: 442139, Scopus Author ID: 6602344280**, sstanichny@mail.ru

Contribution of the co-authors:
Nadezhda V. Vasilenko – literature review on the research topic, preparation and editing of text, illustrations, statistical analysis, processing of satellite data

Anna A. Aleskerova – processing of satellite and model data, statistical analysis

Arseniy A. Kubryakov – research goal setting, research methodology, text preparation and editing, interpretation of results, statistical analysis, processing of satellite and model data

Artem. I. Mizyuk – providing numerical calculations of the NEMO model

Sergey S. Stanichny – scientific consulting, interpretation of results

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