Original Russian Text © A. I. Mizyuk, O. S. Puzina, G. K. Korotaev, 2023,
published in MORSKOY GIDROFIZICHESKIY ZHURNAL, Vol. 39, Iss. 2 (2023)

Original article

Features of Water Exchange through the Kerch Strait Based on the Results of Numerical Modeling of the Circulation with High Spatial Resolution

A. I. Mizyuk ✉, O. S. Puzina, G. K. Korotaev

Marine Hydrophysical Institute of RAS, Sevastopol, Russian Federation
✉ *artem.mizyuk@mhi-ras.ru*

Abstract
Purpose. The work is purposed at studying the synoptic variability of hydrophysical parameters in the basins of the Azov and Black seas induced by the water masses inflow through the strait; at that the inflowing water features differ from the analogous ones in the above-noted basins.
Methods and Results. The results of numerical modeling of circulation in the cascade of seas (the Azov – Black – Marmara seas) for 2008–2009 were analyzed. Regional configuration of the NEMO numerical modeling platform and the results of the ERA5 atmospheric reanalysis were used. The main results were obtained for the configuration with the ~ 1.1 km spatial resolution of the computational grid. The processes of the Azov Sea waters inflow to the Black Sea and their further evolution, as well as the analogous processes with Black Sea waters in the Azov Sea basin are demonstrated. The estimates of water and salt exchange through the Kerch Strait are represented.
Conclusions. Regular change of the water transfer direction through the strait conditioned by the wind significant variability constitutes the basic mechanism for the changes in water exchange between the basins. Having being analyzed, the events with the exceeding average annual values in the unidirectional salt flows through the Kerch Strait permitted to identify significant salt inflows to the Sea of Azov. The portion of such events ranges from 20–25 to almost 70 % of the total number of inflows.

Keywords: numerical modeling, Kerch Strait, Sea of Azov, salt exchange, intermittency, water exchange, water circulation, synoptic variability, water transport

Acknowledgments: The study was carried out within the framework of the state assignment on theme No. 0555-2021-0007.

For citation: Mizyuk, A.I., Puzina, O.S. and Korotaev, G.K., 2023. Features of Water Exchange through the Kerch Strait Based on the Results of Numerical Modeling of the Circulation with High Spatial Resolution. *Physical Oceanography*, 30(2), pp. 125-140. doi:10.29039/0233-7584-2023-2-125-140

DOI: 10.29039/0233-7584-2023-2-125-140

Introduction

Studies of the Sea of Azov and the Black Sea water exchange have been carried out for almost 150 years. This is primarily due to the active use of the Kerch Strait as a transport route. The second, but no less important reason is that the transport of water through the strait largely determines the state of the ecology and hydrology of the Sea of Azov, an important fishing area with a coastline that is attractive enough for the development of the resort business.

As noted in [1], already in the first works, the main factors determining the nature of water exchange through the Kerch Strait were presented. For example, it is postulated that currents in the Kerch Strait are caused by a level difference and a difference in water density at the strait boundaries. It was also noted that the currents in the strait are determined by wind speed and atmospheric pressure changes.

Intensive observations organized in the 1950s, as well as previous, more limited field data, generally confirmed validity of the initial conclusions [1]. Subsequently, on the basis of the obtained instrumental data, various semi-empirical relationships that determine the dependence of water exchange on the difference in levels at its ends and the projection of wind speed on its longitudinal axis [1, 2], were constructed. At the same time, it became clear that the complex configuration of the strait coasts and the topography of its bottom causes a redistribution of currents, as a result of which it is difficult to obtain a complete picture of the variability of fluxes based on a limited amount of contact data.

Water exchange through the Kerch Strait affects hydrological characteristics of the Black Sea and the Sea of Azov in two ways. First of all, together with river runoff, precipitation and evaporation, it contributes to the water and salt balance of the basins. The characteristic time scale of this process is determined by the ratio of the water volume of each of the basins to the discharge through the straits and is several hundred years for the Black Sea. For the shallower Sea of Azov, the characteristic time is much shorter.

Contrasts in the sea surface temperature (SST) and water color characteristics observed from artificial earth satellites by scanners with high spatial resolution make it possible to get an idea of the spatial structure of water transport through the strait [3, 4]. Satellite observations indicate that the water entering through the straits contributes to the synoptic variability of hydrophysical fields of the Azov-Black Sea basin. Synoptic structures that stand out on satellite images appear when volumes of liquid, which differ in their properties from the surrounding waters of the Azov or Black seas, flow through the strait. However, this type of observation does not give an idea of the vertical structure of currents and, thus, provides only an indirect estimate of the volumetric transport magnitude of the Sea of Azov desalinated waters and salty Black Sea waters [4]. At the same time, the dynamics of synoptic structures based on satellite observations can be traced only as long as contrasts in the SST field or sea colors are preserved.

In the last two decades, a detailed study of water exchange in the Kerch Strait has also been carried out on the basis of numerical circulation models. The works [5–7] present calculations in which the circulation of waters in the strait and adjacent water areas is determined depending on the wind strength and direction, which acts for a rather long time. Modern computing resources make it possible to calculate the water exchange through the strait, taking into account the changes taking place both in the Sea of Azov and in the Black Sea under effect of changing atmospheric impact on the marine environment and river runoff [8]. The requirements for a numerical model may be different depending on the time scale of the processes under study. When modeling climate changes in the stratification of the Black Sea, in order to achieve an accurate quantitative description, it is necessary to reconstruct the structure of water exchange through the strait in as much detail as possible, since small systematic inaccuracies in the reconstruction of salt fluxes through the straits during long-term integration accumulate over time and distort the trends in the evolution of the basin fields.

A detailed description of the Kerch Strait currents requires a significant reduction in the step of the computational grid [8, 9]. A feature of [9] is the use of a numerical circulation model implemented on an unstructured grid. This approach provides the introduction of an increased local resolution and takes into account a more detailed coastline and bottom topography not only in the Kerch Strait, but also in the Bosporus and Dardanelles straits.

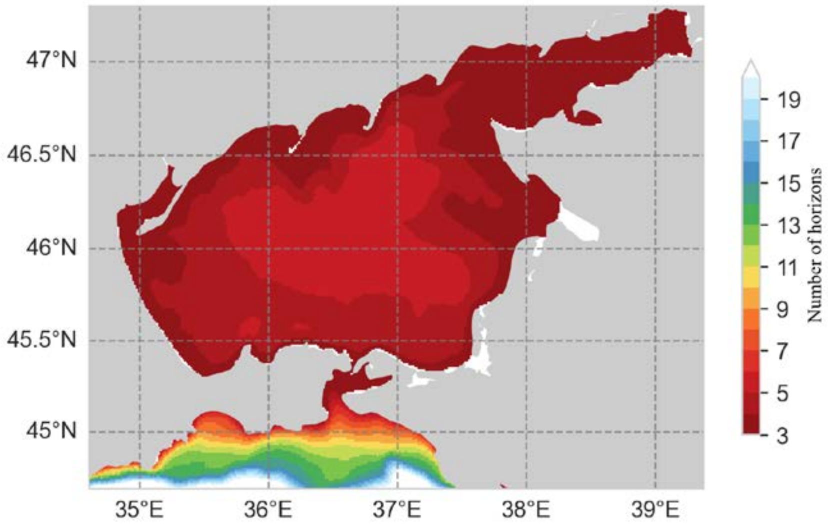
At the same time, to study the contribution of water exchange through the strait to the formation of the synoptic and seasonal variability of the fields of the Azov and Black seas, it seems possible to use a rougher description of the strait than was done in [9]. The purpose of this work is to study synoptic variability of the fields of the Azov and Black seas, based on the results of numerical modeling, caused by the inflow of water masses through the strait, which differ in their properties from those surrounding them in the noted basins.

Materials and methods

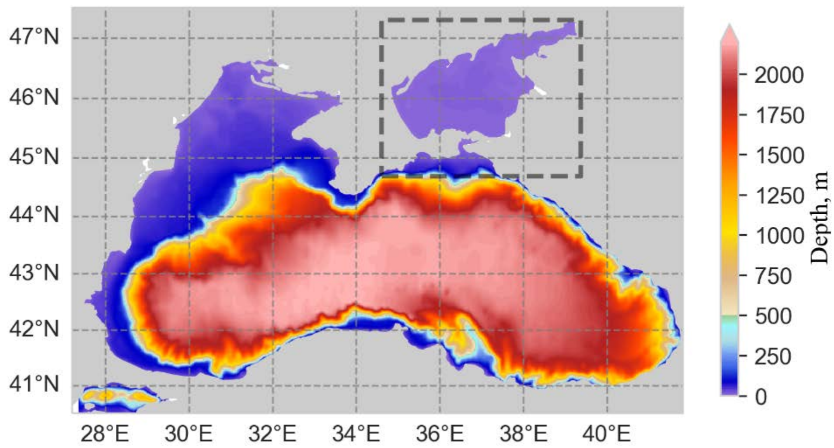
For the analysis, we use the results of circulation numerical modeling of the cascade of the seas (Azov – Black – Marmara), performed using the complex of interdisciplinary modeling of the components of ocean (marine) systems NEMO (Nucleus for European Modeling of the Ocean) [10]. The hydrodynamic block of the complex is based on the system of equations of hydrothermodynamics in the Boussinesq approximation, hydrostatics and fluid incompressibility, described in detail in [10]. Finite-difference analogs of the equations are implemented for an arbitrary curvilinear grid *C* according to Arakawa's terminology [11]. Time discretization is carried out by means of a modified "leapfrog" scheme [12].

In this paper, we use the results from [13, 14], which propose NEMO BAMS (Black, Azov, and Marmara Seas) regional configurations that allow for numerical modeling of the cascade sea circulation with different spatial resolutions. Here we note only some of the features. To calculate the sea level, the model uses a numerical solution of the equation for the kinematic condition on the surface using the scheme of time splitting into fast (barotropic) and slow (baroclinic) modes [15]. The computational domain of the configuration with high spatial resolution is a quasi-regular grid covering the seas of the cascade [14] with latitude and longitude steps of 1/96° and 1/69° (BAMS96). This corresponds approximately to 1.157 km in the meridional direction. In the zonal direction, the step changes uniformly from 1,100 m in the north to 1,230 m in the south. The topography of the computational domain bottom is built on the basis of a digital bathymetry array from the EMODNet project[1] (Fig. 1). Lateral exchange in the equations of motion and transfer – diffusion of heat/salt is described by a biharmonic operator with coefficients of viscosity and diffusion, in modulus equal to $4 \cdot 10^7$ m^4/s and $8 \cdot 10^6$ m^4/s, respectively. To satisfy the Courant – Friedrichs – Lewy criterion, the time step for the baroclinic mode is 60 s, for the barotropic mode it is 4 s. The vertical discretization was performed using the *z*-coordinate with a fractional step on 35 horizons. The values of the horizon depths are set using the analytical function [10] in such a way that there are five horizons in the Sea of Azov (Fig. 1, *b*).

[1] European Commission, 2021. *European Marine Observation and Data Network (EMODnet).* [online] Available at: http://www.emodnet-bathymetry.eu [Accessed: 22 March 2023].



a



b

F i g. 1. *NEMO BAMS96* configuration: bottom topography constructed on the basis of bathymetry data [15] (*a*) and a number of computational horizons in the Azov Sea and Kerch Strait water areas (*b*)

The setting of boundary conditions on the surface is based on the fields of air temperature and humidity at a height of 2 m, the component of the horizontal wind speed at a height of 10 m, radiation fluxes of downward long-wave and short-wave radiation, precipitation in liquid and solid phases obtained from the global atmospheric reanalysis of the European Center for Medium Range Weather Forecasts (ECMWF) of ERA5 [2] latest generation. The spatial resolution of the product fields is 0.25°, and the time discretization is 1 h, which can be very important for reconstructing short-period (intra-diurnal) processes and diurnal variation. The noted meteorological parameters with initial time discreteness were used to calculate

[2] European Commission, 2022. *Climate Data Store – Copernicus*. [online] Available at: https://cds.climate.copernicus.eu/ [Accessed: 22 August 2018].

the total heat fluxes, mass (precipitation minus evaporation) and wind stress using the bulk formulas of the CORE protocol (Coordinated Ocean-ice Reference Experiments) [3]. A general idea of the wind field according to the ERA5 reanalysis data is given in Fig. 2. As can be seen, in 2008–2009 cyclonic vorticity prevails over the water area of the Sea of Azov in most of the year (Fig. 2). It changes sign towards the end of the year in the second half of autumn. Over the Black Sea, the vorticity changes sign in the summer months. The most recurring wind directions over the Sea of Azov are northeastern and east-northeastern (Fig. 2, *b*).

Note that the experiment did not take into account the ice cover, which regularly forms in the Sea of Azov in winter [16]. Ice formation in the Sea of Azov basin was not taken into account. Instead, during the calculations, the heat flux was corrected in the region where the calculated SST becomes below the freezing temperature of water, but without correction of the dynamic resistance coefficient, which is important for determining the wind friction stress. This may partly affect the results of the analysis of the sea water dynamics in winter. On the other hand, the analysis carried out in [16] revealed that the winters of the period 2008–2009 correspond to warm and moderate ice conditions, i.e., not the entire basin (but only its individual parts) was covered with ice, and the strait itself was also free from ice.

To initialize the model in the Black Sea basin, the initial fields were prepared based on the results of temperature and salinity reconstruction in the system of the Center for Marine Forecasts FSBSI FRC MHI [4]. For the Sea of Azov, the initial conditions were obtained based on an objective analysis of *in situ* measurements provided in the oceanographic data bases of Copernicus Marine Environment Monitoring Service (CMEMS) and the SeaDataNet project (available at: https://www.seadatanet.org/). More detailed descriptions of the preparation of initial conditions and the setting of conditions on the open liquid boundary in the Sea of Marmara are given in [13].

A numerical experiment based on a high spatial resolution (HR) configuration started in the summer of 2007, but the presented analysis was performed for 2008–2009. Additionally, we also compared the results of numerical simulation using a similar configuration with a medium spatial resolution (step 4.6 km) (MR) from [13].

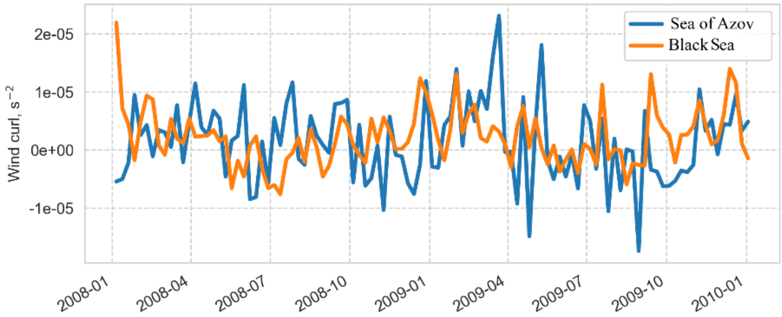
The water exchange of the Black Sea and the Sea of Azov is carried out through the shallow (no more than 18 m deep) and rather wide (from 4 to 42 km wide in its different parts) Kerch Strait. Therefore, the grid step size of 1.2 km provides the use of a fairly detailed coastline in the calculations.

To reconstruct the process of salinization of the Sea of Azov waters, in this work, as well as in [13], we used observational data on the volumetric runoff of the Don and Kuban rivers from the database [2]. Note that its value has been noticeably decreasing since 2006. This made it possible to obtain a very adequate agreement between simulation results and observational data in long-term prognostic calculations [13].

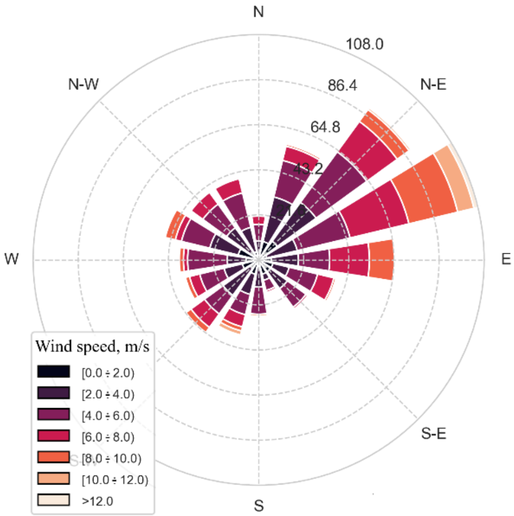
---

[3] Large, W.G. and Yeager, S., 2004. *Diurnal to Decadal Global Forcing for Ocean and Sea-Ice Models: The Data Sets and Flux Climatologies*. NCAR/TN-460+STR. Boulder, Colorado, USA: NCAR. [online] Available at: http://dx.doi.org/10.5065/D6KK98Q6 [Accessed: 28 March 2022]

[4] MHI, 2019. *Black Sea Marine Forecasting Centre. MyOcean*. [online] Available at: http://mis.bsmfc.net:8080/thredds/catalog.html [Accessed: 28 March 2022].



a



b

F i g. 2. Sea area averaged vorticity of the wind speed field (c^{-2}) (a) and the wind frequency in the Azov Sea basin in 2008–2009 (b)

Results and discussion

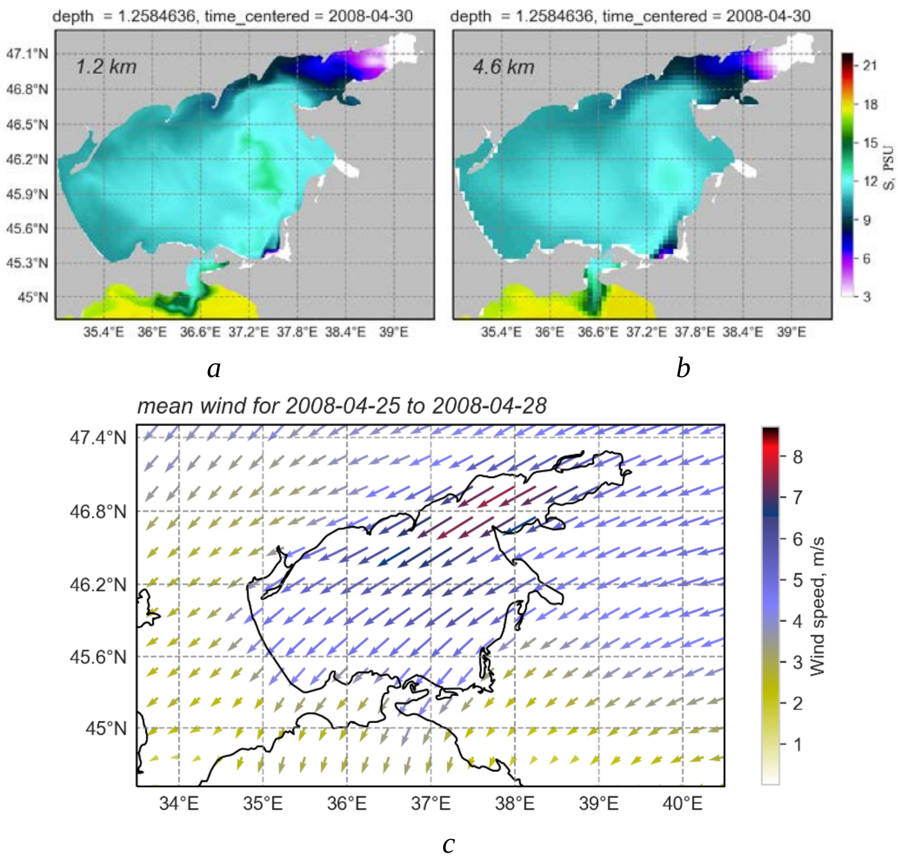
We consider the spatial variability of currents in the strait obtained on the basis of numerical simulation results. Based on the analysis of the available observations, it was previously assumed [1] that two oppositely directed streams simultaneously exist in the Kerch Strait. The flow of water from the Sea of Azov to the Black Sea occurs along the coast of Crimea. The reverse transfer is carried out along the Taman Peninsula. However, due to the shallowness of the strait, the movement of waters is significantly affected by the drift and gradient transport caused by the wind. As a result, the nature of water exchange through the strait changes significantly depending on the type of wind field. In the further analysis, the main attention will be paid to the consideration of intense water inflows, similar to those observed on satellite images [3, 4].

Under the action of intense northeast winds, water transfer from the Sea of Azov is observed across the entire width of the strait. The flow of water into the Black Sea has the form of a jet that changes the direction of propagation from south to east

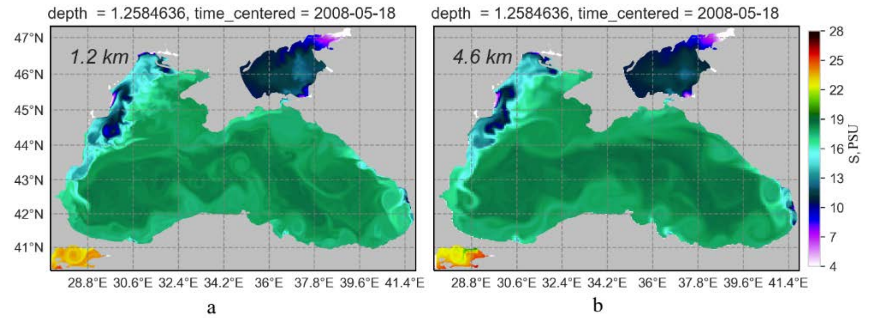
(Fig. 3). The water getting from the strait to the Black Sea, as a rule, moves further to the west along the Crimean coast, without crossing the Black Sea Rim Current. The distance from the strait, where the Sea of Azov water is still visible, depends on the duration of the wind in the desired direction. In some cases, the transformed water mass, moving from the Sea of Azov, can be traced in the surface temperature or color of the sea up to the central part [3, 4]. For the first time, the manifestation of this process, apparently, was identified on the basis of water transparency observations at the oceanographic platform in Katsiveli [17].

In the numerical experiment HR, we succeeded in reconstructing the process of propagation of the Sea of Azov waters for a long distance along the Crimean coast (Fig. 4). In the area of Cape Ai-Todor, the coastal jet turned into the open sea. Further, freshened waters can still be traced in the form of a jet at some distance from the coast, but then they mix with the surrounding Black Sea waters.

The use of a coarser spatial resolution (MR experiment) leads to a noticeable smoothing of contrasts in salinity fields, as well as a less pronounced process of jet formation near the Crimean coast. As a result, in the fields of salinity from the noted experiment, it is almost non-existent by mid-May 2008 (Fig. 4).

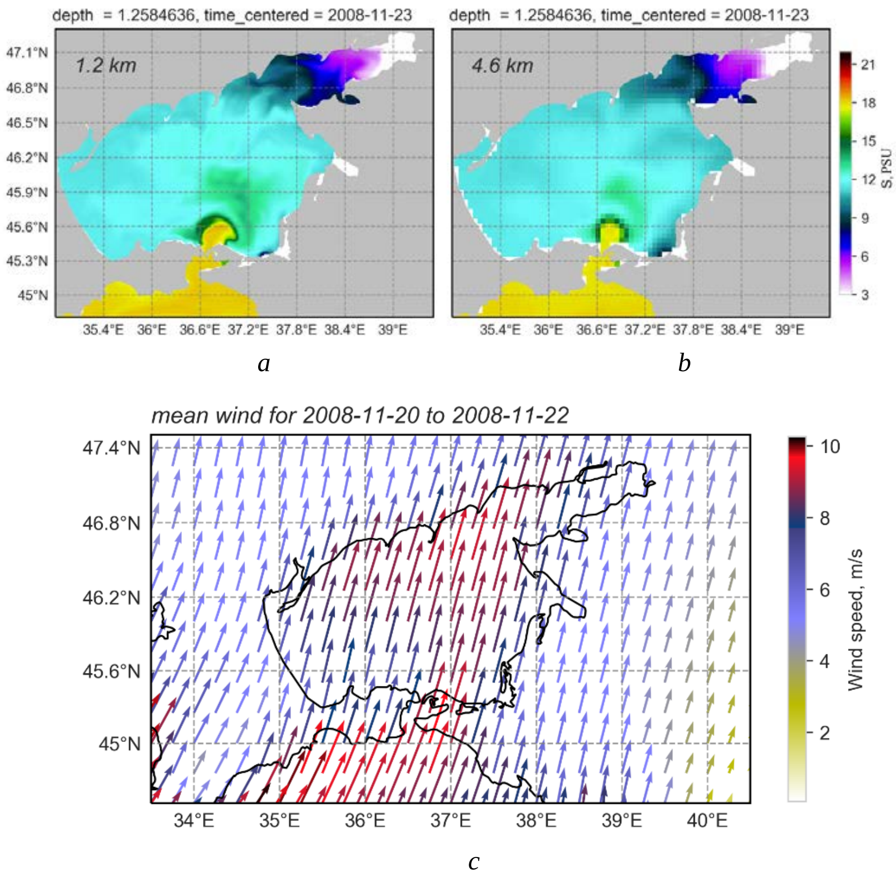


F i g. 3. The Azov Sea waters inflow to the Black Sea in late April, 2008: distribution of surface salinity based on the results of the HR (*a*) and AR (*b*) experiments, average wind circulation (*c*) preceding the event



F i g. 4. Propagation of the Azov Sea water flow along the coast of Crimea and its mixing in the open sea: distribution of surface salinity on May 18, 2008 based on the results of the HR (*a*) and AR (*b*) experiments

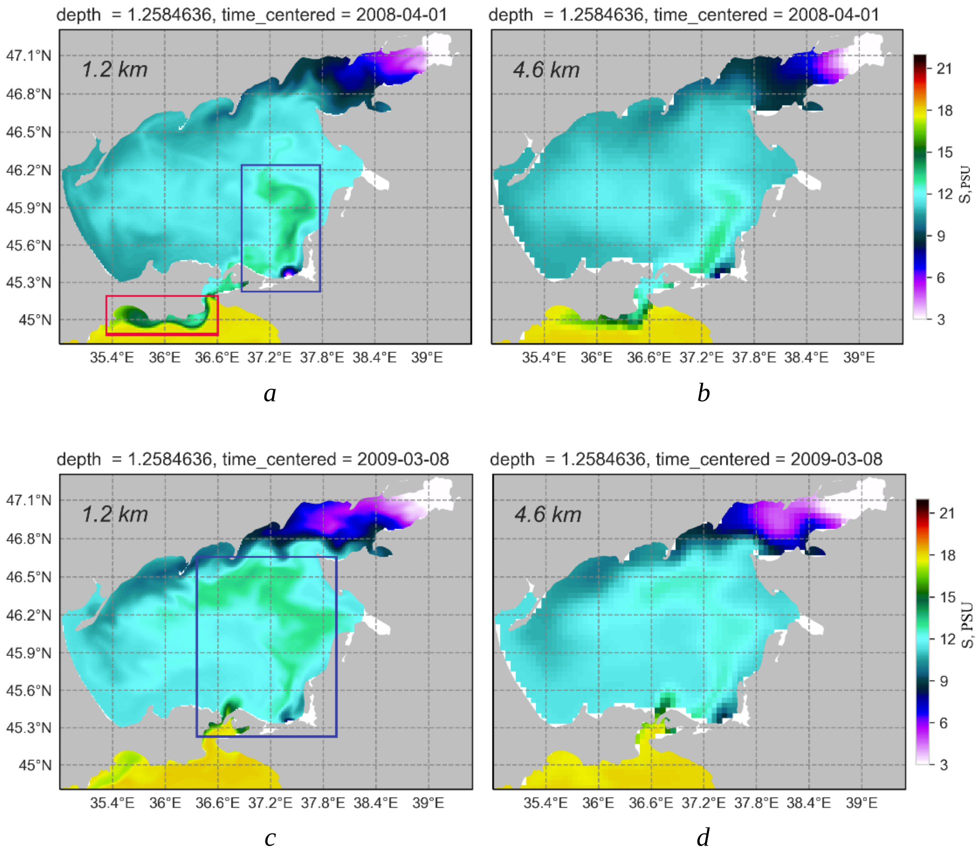
At intense winds of the opposite direction, the Black Sea water in a wide flow, occupying the entire strait, inflows the Sea of Azov (Fig. 5). It can be seen that the salinity difference at the inflowing water front reaches 3 PSU. The salt water penetrating into the Sea of Azov is partially transformed due to mixing with surrounding waters. Nevertheless, for four months, in a significant part of the Sea of Azov, a spot of saline water, stretching for more than 100 km (Fig. 5), is distinguished.



F i g. 5. Intensive saline water inflow to the Sea of Azov in November, 2008: surface salinity distribution in the HR (*a*) and MR (*b*) experiments; average wind circulation (*c*) preceding the event

The long-term existence of zones with increased (for the case of the Sea of Azov) or decreased (for the Black Sea) salinity after the events of inflows through the strait is manifested most clearly in the results of the HR experiment.

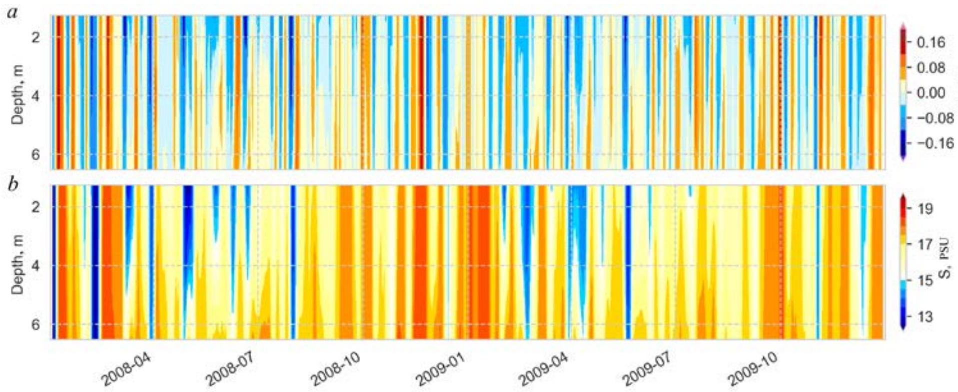
The performed calculations demonstrate that the regular change in the direction of water transfer through the Kerch Strait, due to significant wind variability, is the main mechanism for the intermittency of water exchange between the Black Sea and the Sea of Azov. The result of the effect of water exchange intermittency on hydrophysical fields is shown in Fig. 5. As can be seen, in the Sea of Azov, due to successive "injections" of Black Sea waters through the Kerch Strait, a spot of more saline waters is formed (Fig. 6). At the same time, one can see the movement of a jet of desalinated Sea of Azov waters along the Crimean coast after a wind direction change (red rectangle in Fig. 6, *a*) and the subsequent formation of a new inflow of salty waters near the Taman Peninsula.



F i g. 6. Propagation of the Black Sea waters in the Azov Sea basin in 2008 (*a*, *b*) and 2009 (*c*, *d*) in the fields of surface salinity in the HR (*a*, *c*) and MR (*b*, *d*) experiments. Red rectangle indicates the area of distribution of the Azov Sea waters in the Black Sea basin, the blue one – formation of the salt water inflow

Successive inflows of Black Sea waters into the Sea of Azov lead to the formation of a saline water spot in the basin, which is well pronounced and can be traced for a long time in the results of the HR experiment (blue rectangle in Fig. 6, *a*, *c*). As can be seen, the transport of saline water by currents occurs in a cyclonic direction. Comparison of the simulation results of two numerical experiments allows us to note that the more saline Black Sea waters in the MR experiment appear in the fields not so clearly and mix with the surrounding waters much faster.

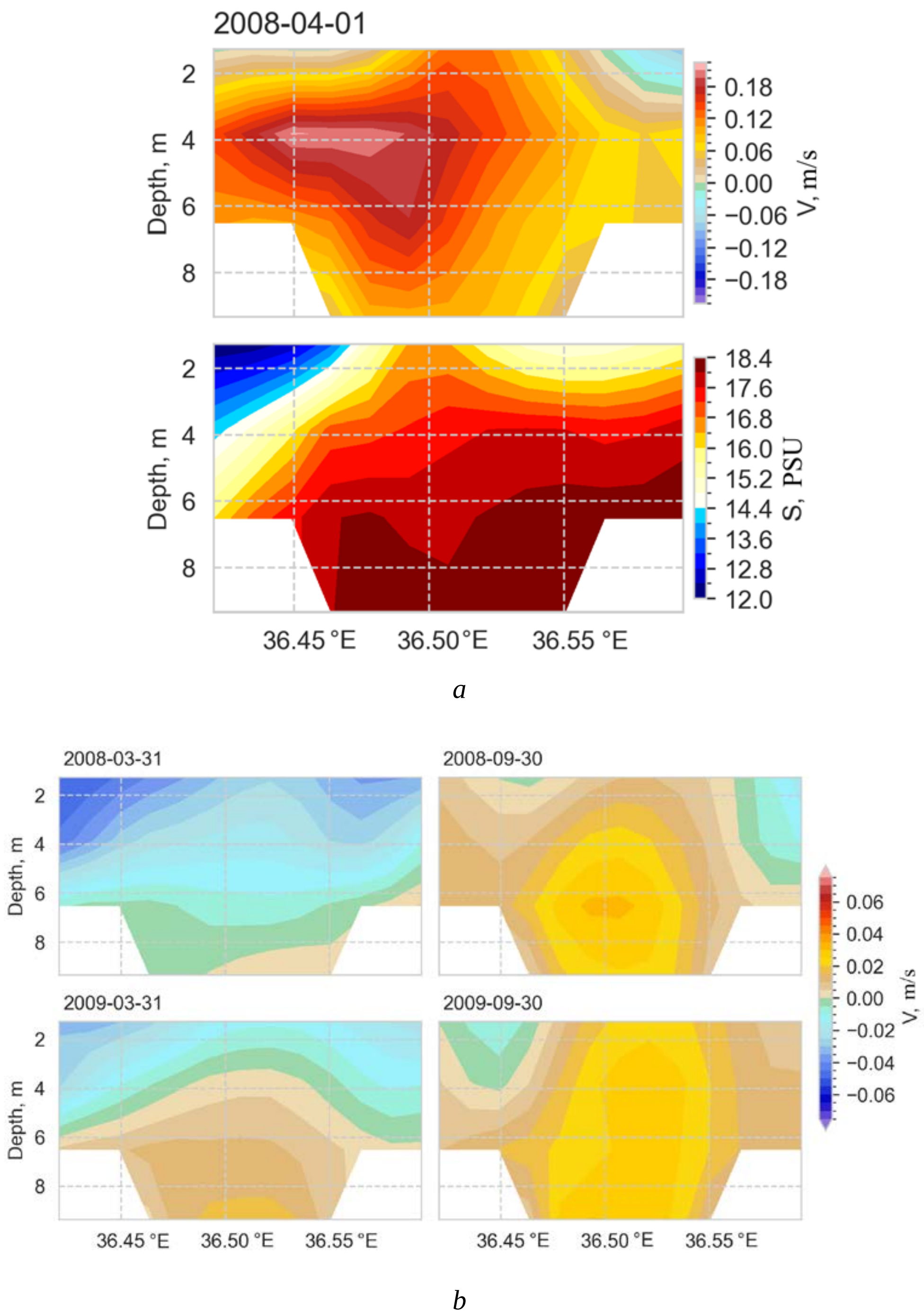
The intermittency of water exchange in the Sea of Azov and the Black Sea, determined by the change in the wind regime, is clearly demonstrated by the depth – time diagrams for hydrophysical parameters in the area of the Kerch Strait (Fig. 7, *a*). With stable winds, the current velocities in the strait are quite high and can reach more than 0.3 m/s in modulus. During the periods of the greatest intensification of water exchange, the velocity profile changes very little along the depth and across the strait. At the same time, during periods of weakening winds, the direction of the integral transport changes sign with depth, i.e. a pronounced two-layer transport structure in depth is formed in the strait (Fig. 7, *b*). The number of events of intense inflow of salty Black Sea waters (positive velocities) increases in autumn – winter.



F i g. 7. Depth-time diagrams of the parameters averaged over the strait cross section at the latitude 45.186 °N based on the results of the HR experiment: *a* – of the meridional current velocity (positive values correspond to the movement from the Black Sea to the Azov Sea); *b* – of water salinity

In the MR experiment, a similar vertical structure of the integral transport in the strait was noted at its high intensity, but the formation of a two-layer structure was traced much worse.

In contrast to the Bosphorus Strait, where a two-layer structure of currents along the vertical with practically constant thicknesses of the layers of the upper and lower currents [14] exists almost always, in the Kerch Strait the flows of different signs can occupy an arbitrary fraction of the cross-sectional area (Fig. 8, *a*). For representativeness, this figure shows the pattern of currents on April 1, 2008, corresponding to Fig. 6. As can be seen, a relatively powerful inflow of water into the Sea of Azov is observed a little deeper than a very thin surface layer (the meridional velocity is more than zero). In the upper layer, in the opposite direction (the meridional velocity is less than zero), low-salinity water is transported (see Fig. 6; 8, *a*).



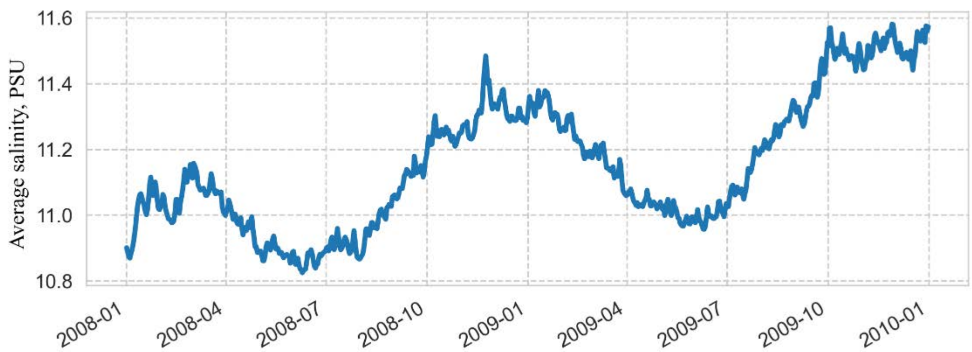
F i g. 8. Zonal sections of hydrophysical parameters in the Kerch Strait (along the latitude 45.186 °N) based on the results of the HR experiment: daily average salinity and daily average meridional current velocity ($V > 0$ – current is directed to the Sea of Azov) (*a*); monthly average meridional currents in March and September for two years (*b*)

The situations of simultaneous development of currents of different signs are also manifested in the distributions of mean monthly currents. For example, in March 2008, the average water transport is carried out mainly in one direction (from the Sea of Azov), and in March 2009, the water flow into the Sea of Azov is much better expressed (Fig. 8, *b*). In September 2008 and 2009, the average monthly distributions of velocities are more similar to each other, and in both cases a multidirectional water transport in the cross-section of the strait takes place.

The salinity averaged over the strait width has a very similar vertical structure with meridional transport (see Fig. 6, *c*, *d*). With a formal division into more (above 15 PSU) and less (13–15 PSU) saline waters, the periods of predominant transport of the Black Sea and the Sea of Azov water masses, respectively, become well pronounced. During these periods, the salinity profile is almost uniform along the vertical. In the case of a constantly changing wind, the two-layer vertical structure of the average salinity becomes more pronounced.

Comparison of the positions of the current intensification moments (see Fig. 6, *a*, *b*) and the maximum/minimum of water salinity (see Fig. 6, *c*, *d*) on the time axis allows to state that there is an insignificant lag (1–2 days) between the events, probably due to the characteristic time of saline or desalinated water inflow to the location of the selected section. The diagram in Fig. 6, *c*, *d*, also confirms the thesis about an increase in the number of the Black Sea water inflow events in the period from autumn to the end of winter.

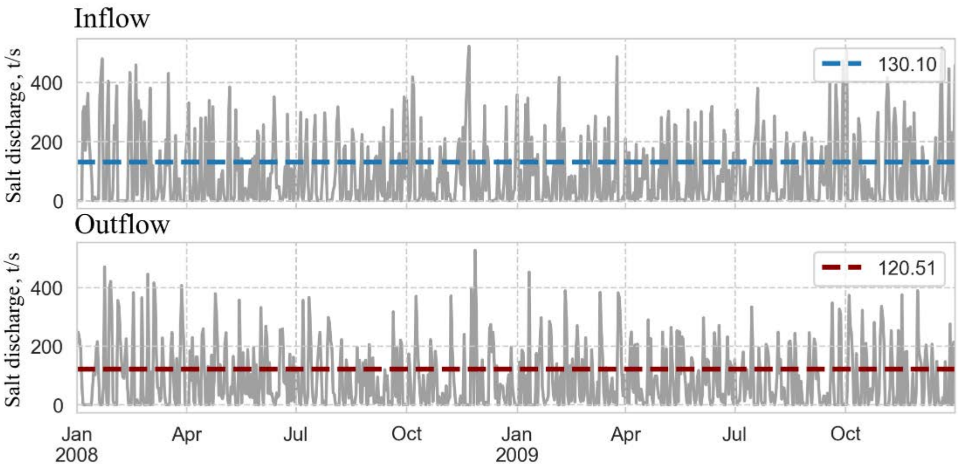
The results of numerical modeling provide the estimation of the magnitude of unidirectional flows of water Q_V and salt Q_S through the strait in the direction of the Sea of Azov and the Black Sea. We use the relations $Q_V = \iint v dxdz$ and $Q_S = \iint \rho_0 v S dxdz$, where S is salinity; ρ_0 is an average seawater density; v is the meridional velocity component; x and z are zonal and vertical coordinates. The quantitative values for the Sea of Azov and the reverse Black Sea flows obtained from various data are presented in [18]. Our estimates based on the results of the HR experiment turned out to be somewhat different: the average annual outflow of water (172.3 km^3/year) from the Sea of Azov slightly exceeds the inflow of the Black Sea water masses into the Sea of Azov (165.4 km^3/year). The resulting difference agrees qualitatively with the estimates from [1, 18] (about 20 km^3/year), but is somewhat smaller. Note that if we talk about 2008–2009, then the magnitude of such an outflow can be compensated by river runoff. However, by 2018 the value of the latter will be halved.



F i g. 9. Water salinity average over the Azov Sea basin

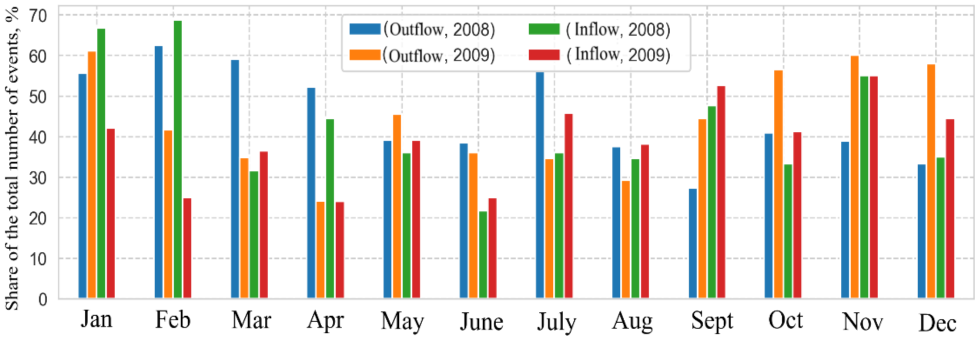
Analysis of changes in unidirectional salt flows (Q_S) through the Kerch Strait over time (Fig. 8) revealed the following. An intensification of salt exchange is noted in the autumn – winter period, which has already been mentioned and, apparently, is a consequence of wind strengthening. Note that the difference in the average annual values of unidirectional salt fluxes through the strait is opposite in sign to the difference in volumetric fluxes: the inflow of salt exceeds its outflow from the Sea of Azov by ≈ 10 t/s (Fig. 8). As a result of this excess, an increase in the average salinity over the basin, similar to that presented in [19], is observed (Fig. 9). As we can see, for 2008–2009 this value grows by almost 0.7 PSU. Note that, according to the results of the HR experiment, the flux values turned out to be higher than in the MR experiment.

To estimate the contribution of salt flux intermittency caused by intense wind events, we estimated the proportion of such events in the total number of inflows and outflows. In this work we considered events with an excess of the average annual values of unidirectional salt fluxes in the Kerch Strait to be intense. This value was estimated without taking into account the days on which the flux for the analyzed direction was absent. Thus, the values of ≈ 130 and ≈ 120.5 t/s were obtained for inflows (to the Sea of Azov) and outflows (to the Black Sea), respectively.



F i g. 10. Variability of salt flow through the Kerch Strait based on the results of the HR experiment (solid line denote the instantaneous values; dashed line – two-year average ones)

An idea of the seasonal variability of the proportion of intense salt fluxes is given in Fig. 10. As can be seen, the events of anomalous salt inflow into the Sea of Azov prevail in the autumn – winter period. On average, per month, the amount of salt received during the events under study can range from approximately 20–25% in June to almost 70% in February (Fig. 11). Moreover, in 2008 this was expressed to a greater extent. A high proportion of anomalous salt outflow events is observed in January (about 60%). Thus, in the Kerch Strait, there is a rather significant contribution of the intermittency of mass and salt exchange to the long-term changes in thermohaline parameters and the stratification of waters in the water area near the strait.



F i g. 11. Portion of the events with the exceeding average annual values in unidirectional salt flows from the total number of events

Conclusion

In this work, based on the results of numerical simulation of the joint dynamics of the Sea of Azov and the Black Sea with high spatial resolution, a number of features of mass and salt exchange through the Kerch Strait are revealed. Their behavior over time has a pronounced seasonal character with intensification in the autumn-winter period. The main factor determining the variability of water exchange between the seas is the wind regime in the region. In general, the magnitude of water exchange is determined by the direction, speed and duration of the wind.

The transport of the Sea of Azov waters through the strait to the Black Sea (outflow) mainly occurs in the form of a jet that spreads along the eastern and southern coasts of the Crimean Peninsula, initially entering Feodosiya Bay. Less saline waters can then be traced at fairly large distances from the strait (more than 200 km) in full accordance with satellite observations.

A noticeable penetration of the Black Sea waters into the Sea of Azov occurs at a very intense wind action, mainly southwestern points. This process leads to the formation of an extensive patch of high salinity waters within a few days. The patch further moves along the basin cyclonically. Despite mixing with the surrounding waters, the patch can be traced in the basin for quite a long time. The noted results with the reconstruction of jet streams and inflows of the Black Sea waters into the Sea of Azov were not noted earlier in numerical modeling of the cascade water dynamics due to the use of a rather rough spatial resolution. At the same time, the developed regional configuration can be very useful in planning experiments to identify waters in the area of Katsiveli on the basis of the Black Sea branch of the FSBSI FRC MHI. Obviously, it is impossible to achieve such a quality in modeling dynamic processes in relatively shallow coastal and shelf zones with a resolution of about 5 km.

If we analyze the vertical structure of the strait hydrophysical parameters, we can see that it is also determined by the intensity and duration of the wind impact. At strong and prolonged winds, the distributions of current velocity and salinity of seawater in the strait are practically uniform along the vertical. However, under conditions of frequent changes in wind circulation, currents weaken and the subsequent formation of a vertical structure with water advection in both directions takes place. Such multidirectional fluxes can divide the cross-section of the strait not only vertically, but also horizontally in an arbitrary ratio. Despite the fact that it is difficult to identify situations with such simultaneously existing fluxes from measurements, the model demonstrates a pronounced inhomogeneity of currents in the strait even on synoptic time scales.

Although the estimates of the inflows and outflows of water through the strait based on the modeling results are somewhat higher than the values obtained earlier on the basis of other sources from information (observations, reanalyses), nevertheless, they qualitatively agree with the generally accepted fact – their difference is negative, i.e., the Sea of Azov basin through the Kerch Strait loses an average volume of ≈ 20 km^3 per year (the estimates based on the modeling results provide a value of about 8 km^3). This feature of water exchange through the strait can be considered as one of the causes for the basin salinization in recent years, especially taking into account the observed decrease in river runoff. If in 2008 the value of the river runoff was close to the value of the outflow through the Kerch Strait, then already in 2018, the river runoff decreased by half, which is likely to increase the observed salinization of the basin waters.

The analysis of salt fluxes through the strait showed that, although there was a small difference in unidirectional total water flows, the difference in salinity values between the Sea of Azov and the Black Sea water masses leads to the predominance of the salt flux into the Sea of Azov (inflow). This also contributes to the salinization of the basin waters. If we single out events of intense salt inflows into the Sea of Azov, then the share of such events ranges from 20–25% to almost 70%. Note that the use of high spatial resolution in this work for numerical simulation of the circulation provided new results. However, they should be taken with some caution and need to be compared with more regular observations of thermohaline parameters in the strait.

REFERENCES

1. Simonov, A.I. and Altman, E.N., eds., 1991. *Hydrometeorology and Hydrochemistry of Seas in the USSR. Vol. IV. Black Sea. Issue 1. Hydrometeorological Conditions*. Leningrad: Gidrometeoizdat, 429 p. (in Russian).
2. Altman, E. and Tolmazin, D., 1970. Method for Computing Currents and Water Exchange in Kerch Stait. *Oceanology*, 10(3), pp. 333-340.
3. Aleskerova, A.A., Kubryakov, A.A., Goryachkin, Yu.N. and Stanichny, S.V., 2017. Propagation of Waters from the Kerch Strait in the Black Sea. *Physical Oceanography*, (6), pp. 47-57. doi:10.22449/1573-160X-2017-6-47-57
4. Zavialov, I., Osadchiev, A., Sedakov, R., Barnier, B., Molines, J.-M. and Belokopytov, V., 2020. Water Exchange between the Sea of Azov and the Black Sea through the Kerch Strait. *Ocean Science*, 16(1), pp. 15-30. doi:10.5194/os-16-15-2020
5. Ivanov, V.A. and Shapiro, N.B., 2004. Modeling of Currents in the Kerch Strait. In: MHI, 2004. *Ekologicheskaya Bezopasnost' Pribrezhnoy i Shel'fovoy Zon i Kompleksnoe Ispol'zovanie Resursov Shel'fa* [Ecological Safety of Coastal and Shelf Zones and Comprehensive Use of Shelf Resources]. Sevastopol: MHI. Iss. 10, pp. 207–232 (in Russian).
6. Fomin, V.V., Lazorenko, D.I. and Fomina, I.N., 2017. Numerical Modeling of Water Exchange through the Kerch Strait for Various Types of the Atmospheric Impact. *Physical Oceanography*, (4), pp. 79-89. doi:10.22449/1573-160X-2017-4-79-89
7. Ivanov, V.A., ed., 2010. *Modeling of Water Dynamics in the Kerch Strait and Pre-Strait Zones*. Sevastopol: MHI, 206 p. (in Russian).
8. Diansky, N.A., Fomin, V.V., Korshenko, E.A. and Kabatchenko, I.M., 2020. Hindcast and Operational Forecasting System of Hydrometeorological Characteristics for the Sea of Azov

and Kerch Strait. *Ecology. Economy. Informatics. Geoinformation Technologies and Space Monitoring*, 2(5), pp. 131-140. doi:10.23885/2500-123X-2020-2-5-131-140 (in Russian).

9. Stanev, E.V., Grashorn, S. and Zhang, Y.J., 2017. Cascading Ocean Basins: Numerical Simulations of the Circulation and Interbasin Exchange in the Azov-Black-Marmara-Mediterranean Seas System. *Ocean Dynamics*, 67, pp. 1003-1025. doi:10.1007/s10236-017-1071-2
10. Madec, G. and the NEMO team, 2016. *NEMO Ocean Engine*. Note du Pôle de Modélisation de l'Institut Pierre-Simon Laplace, No. 27. France: Institut Pierre-Simon Laplace. Available at: https://www.nemo-ocean.eu/doc/node1.html [Accessed: 5 March 2023].
11. Mesinger, F. and Arakawa, A., 1976. *Numerical Methods Used in Atmospheric Models*. WMO-ICSU Joint Organizing Committee. Vol. 1, 64 p.
12. Leclair, M. and Madec, G., 2009. A Conservative Leapfrog Time Stepping Method. *Ocean Modelling*, 30(2-3), pp. 88-94. doi:10.1016/j.ocemod.2009.06.006
13. Mizyuk, A.I., Korotaev, G.K., Grigoriev, A.V., Puzina, O.S. and Lishaev, P.N., 2019. Long-Term Variability of Thermohaline Characteristics of the Azov Sea Based on the Numerical Eddy-Resolving Model. *Physical Oceanography*, 26(5), pp. 438-450. doi:10.22449/1573-160X-2019-5-438-450
14. Mizyuk, A.I. and Korotaev, G.K., 2020. Black Sea Intrapycnocline Lenses according to the Results of a Numerical Simulation of Basin Circulation. *Izvestiya, Atmospheric and Oceanic Physics*, 56(1), pp. 92-100. doi:10.1134/S0001433820010107
15. Roullet, G. and Madec, G., 2000. Salt Conservation, Free Surface, and Varying Levels: A New Formulation for Ocean General Circulation Models. *Journal of Geophysical Research: Oceans*, 105(C10), pp. 23927-23942. doi:10.1029/2000JC900089
16. Mizyuk, A.I. and Puzina, O.S., 2019. Sea Ice Modeling in the Sea of Azov for a Study of Long-Term Variability. *IOP Conference Series: Earth and Environmental Science*, 386, 012023. doi:10.1088/1755-1315/386/1/012023
17. Tolkachenko, G.A., Man'kovsky, V.I. and Solov'ev, M.V., 2001. Hydrooptical Observations in the Coastal Waters of the Crimean South Coast on Summer and Fall of 2001. In: MHI, 2001. *Ekologicheskaya Bezopasnost' Pribrezhnoy i Shel'fovoy Zon i Kompleksnoe Ispol'zovanie Resursov Shel'fa* [Ecological Safety of Coastal and Shelf Zones and Comprehensive Use of Shelf Resources]. Sevastopol: MHI. Iss. 2(7), pp. 93-99 (in Russian).
18. Ivanov, V.A. and Belokopytov, V.N., 2013. *Oceanography of the Black Sea*. Sevastopol, 210 p.
19. Mizyuk, A.I., Lishaev, P.N. and Puzina, O.S., 2020. Estimation of the Azov Sea State Based on the Black Sea Hydrography. *Journal of Physics: Conference Series*, 1675, 012120. doi:10.1088/1742-6596/1675/1/012120

About the authors:

Artem I. Mizyuk, Senior Research Associate, Marine Hydrophysical Institute of RAS (2 Kapitanskaya Str., Sevastopol, 299011, Russian Federation), Ph.D. (Phys.-Math.), **ORCID ID: 0000-0003-4885-354X**, **ResearcherID: C-6125-2016**, artem.mizyuk@mhi-ras.ru

Oksana S. Puzina, Junior Research Associate, Marine Hydrophysical Institute of RAS (2 Kapitanskaya Str., Sevastopol, 299011, Russian Federation), **ORCID ID: 0000-0002-1637-4475**, oksana_puzina@mhi-ras.ru

Gennadiy K. Korotaev, Research Supervisor of Marine Hydrophysical Institute of RAS (2 Kapitanskaya Str., Sevastopol, 299011, Russian Federation), Corresponding Member of RAS, Dr.Sci. (Phys.-Math.), Professor, **ResearcherID: K-3408-2017**, gkorotaev@gmail.com

Contribution of the co-authors:

Artem I. Mizyuk – problem formulation, text preparation and editing, statistical analysis, visualization, numerical simulation

Oksana S. Puzina – text preparation and editing, statistical analysis, visualization

Gennadiy K. Korotaev – formulation of the idea, approval of the final version

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