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Original article

Features of Water Exchange between the Black and Marmara Sea Basins based on the Results of Numerical Simulation with a Simplified Representation of the Strait

A. I. Mizyuk ✉, **G. K. Korotaev**

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

Abstract
Purpose. The study is purposed at analyzing the adequacy of reconstruction of mass, heat and salt transfer processes through the Bosphorus Strait based on the results of numerical simulation of joint circulation of the Euxine Cascade waters involving a simplified description of the strait due to the model spatial resolution.
Methods and Results. A regional configuration for the *NEMO* model (spatial resolution is about 1 km) which allows simulating the meso- and submeso-scale variability of hydrophysical fields in the Euxine Cascade seas is used. It is briefly described. The numerical experiment covers the period 2008–2009. The salinity and current velocity fields in the strait cross-section reconstructed in the experiment confirm a two-layer structure of water circulation, i.e. the presence of upper and lower Bosphorus currents. Besides, they show the availability of periods of complete or partial blocking both the upper and lower currents. Despite a somewhat rough configuration of the strait, the reconstructed salt exchange features are in good agreement with the similar ones obtained on the basis of a finite-element model with a higher spatial detailing in the strait, and as for temperature, the agreement is to some extent worse. At the same time, the reconstructed current velocities show a fairly accurate correspondence of the blocking events when compared to the earlier performed measurements.
Conclusions. The previously revealed mechanism for maintaining the upper Bosphorus Current in winter conditioned by a rise of the Black Sea level in the Bosphorus region due to the Rim Current intensification has been confirmed. The model qualitatively correctly describes the strait response to the changes both in wind forcing and seawater density in the vicinity of the northern and southern inlets to the strait. Blockings of the upper Bosphorus Current occur and can be induced by the intensification of currents in the Marmara Sea due to the wind forcing and subsequent weakening of the Black Sea Rim Current. In a winter-spring period, the Marmara Sea circulation weakens, and one can observe the reverse phenomena in which the lower Bosphorus current blockings take place.

Keywords: numerical modeling, Black Sea, Bosporus, Sea of Marmara, salt exchange, high resolution

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Introduction

Water exchange through the Bosphorus Strait has two effects on the Black Sea regime. Firstly, together with river runoff, precipitation and evaporation, and including the Kerch Strait, it contributes to the water and salt balance of the Black

Sea basin. The specific time scale of this process spans several hundred years, with the balance determined by the ratio of the volume of the Black Sea waters to the amount of discharge through the straits.

However, recent observations indicate that the waters entering through the straits also contribute to the mesoscale variability of the basin fields. This phenomenon is observed in the dispersion of liquid volumes that differ in their properties from the surrounding waters over considerable distances [1].

It can be assumed that the requirements for the strait model vary depending on the time scale of the phenomenon under consideration. In order to accurately model long-term changes in Black Sea stratification, it is essential to simulate the geometry of the straits with a high degree of detail, thereby enabling a precise quantitative description of water exchange. Otherwise, minor discrepancies in the simulation of salt flows through the straits over extended periods will accumulate, resulting in the distortion of the evolution trends of the basin fields. A comprehensive description of the strait geometry requires a substantial refinement of the computational grid [2]. However, in order to keep the calculation time reasonable, the authors have reduced the model resolution for the open part of the Black Sea basin in the noted work.

At the same time, to study the contribution of water exchange through the straits to the mesoscale variability of the Black Sea fields, it seems possible to use a rougher description of the straits compared to work [2].

It should also be noted that a spatial resolution of about 1 km should be sufficient to adequately simulate the dynamics of the waters of the Marmara Sea [3]. The present work aims to demonstrate that a simpler description of the strait, obtained using a grid with such a resolution, nevertheless allows the simulation of the essential features of the temporal variability of the processes of mass, heat and salt transfer in the strait. Thus, it is possible to model the contribution of water exchange through the strait to the relatively high-frequency variability of the Black Sea fields. The choice of an appropriate spatial resolution of the model allows to adequately describe the variability of the Black Sea fields caused by the spreading of saline Mediterranean waters entering through the strait.

Materials and methods

The paper uses the results obtained in the regional configuration of the interdisciplinary framework Nucleus for European Modeling of the Ocean (NEMO) [4] for modeling the components of the ocean (marine) system with high spatial resolution. It allows the simulation of meso- and submesoscale variability of hydrophysical fields in the seas of the Euxine Cascade. The computational domain is a quasi-regular grid covering the basins of the Marmara, Black and Azov Seas with steps of 1/96° × 1/69° in the meridional and zonal directions, respectively [5]. The resolution is approximately 1.157 km in the meridional direction. In the zonal direction, the step varies uniformly from 1100 m in the north to 1230 m in the south. The bottom topography is based on the EMODnet digital bathymetry array [1] (Fig. 1, *a*).

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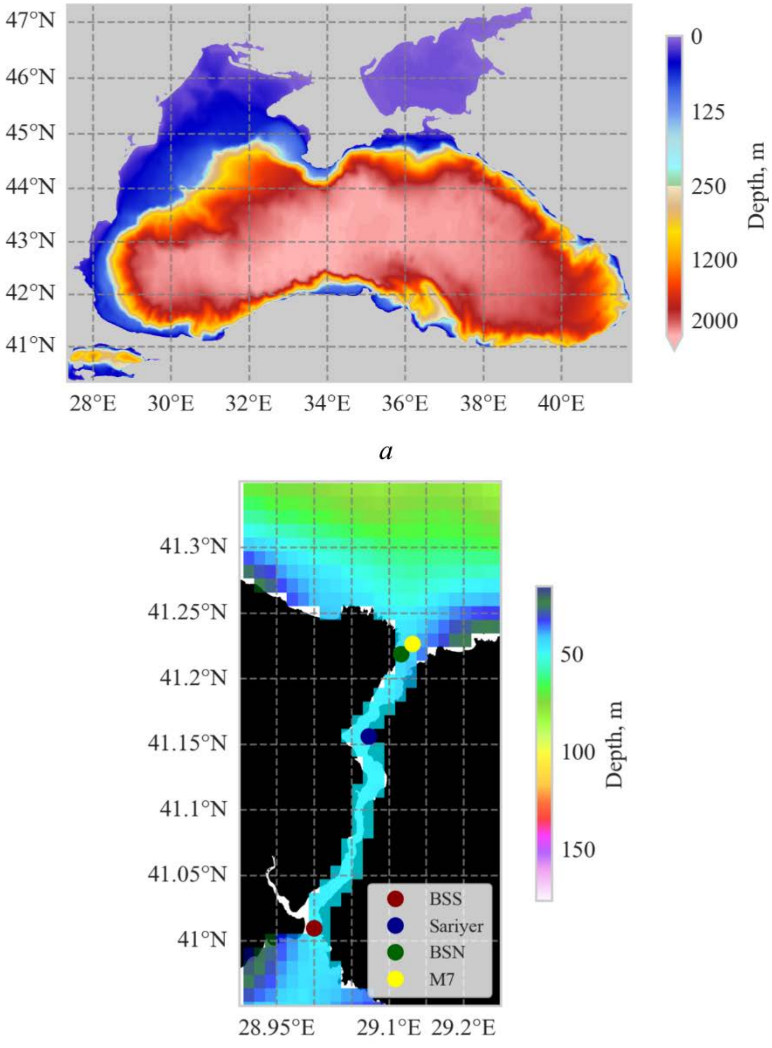
[1] European Commission. *European Marine Observation and Data Network (EMODnet).* [online] Available at: http://www.emodnet-bathymetry.eu [Accessed: 16 October 2016].



a

b

F i g. 1. Bottom topography for the *NEMO* regional configuration: for the entire numerical domain (*a*) and the strait water area (*b*). Configuration of the strait coasts is given according to the data from https://www.openstreetmap.org/; dots on fragment *b* indicate the station positions by analogy with [2]: *BSS – Bosphorus Strait South*, Sariyer – Cape Sarrier, *BSN – Bosphorus Strait North*; station *M*7 is taken from [6]

Modeling the water exchange through the Bosphorus is a complex task due to the significant difference in the spatial scales of the processes occurring in the strait and in the basins it connects. However, using this framework and taking into account the spatial discretization adopted, it is possible to carry out calculations in the strait area and consider the joint dynamics of the Black and Marmara seas. In the constructed topography, the configuration of the strait was roughly taken into account (Fig. 1, *b*, *c*), only the position of the main thresholds at the northern and southern entrances to the strait was taken into account. In this case, the depth in the strait was set at 48.5 m.

The hydrodynamic block of the framework is founded upon the system of equations of hydrothermodynamics in the Boussinesq approximation, hydrostatics and incompressibility of liquid, which are described in detail in reference [4]. The finite-difference equivalents of the equations are implemented for an arbitrary quasi-orthogonal grid in accordance with the template ‘C’ as defined by Arakawa. The time-discretization is performed using a modified leapfrog scheme [7].

The k-ε model of closure level 2 is employed for the description of vertical mixing processes [8]. The horizontal exchange is described by a biharmonic operator acting along the geopotential surface, with negative coefficients of viscosity and diffusion of heat and salt of equal absolute value, namely 4×10^7 and 8×10^6 m^4/s, respectively. The UNESCO formula[2] is used as the equation of state. The configuration employed in this study represents a ‘downscaling’ of the configuration with a resolution of 1/24° as presented in [9]. The principal distinctions between the two models lie in the parameters employed to describe the horizontal turbulent exchange and the time step, which is 60 seconds in the present study.

The boundary conditions on the surface are specified based on the air temperature and humidity fields at a height of 2 metres, the horizontal wind speed components at a height of 10 metres, the downward long-wave and short-wave radiation fluxes, and the liquid and solid precipitation, which have been obtained from the latest generation of the European Centre for Medium-Range Weather Forecasts (ECMWF) global atmospheric reanalysis, referred to as ERA5[3]. The product has a sufficiently high spatial (1/4°) and temporal (1 h) resolution, which is of great significance for the simulation of short-period (intra-daily) processes and diurnal variation. The aforementioned meteorological parameters, which were initially recorded at discrete time points, were employed to calculate the total heat, mass and wind friction stress fluxes using the bulk formulas outlined in the Coordinated Ocean-ice Reference Experiments (CORE) protocol.

The objective of the present work was not to provide a comprehensive account of the process of ice formation in winter. In order to reproduce adequate temperature values on the northwestern shelf of the Black Sea and in the Sea of Azov, a heat flux correction was employed. Once the freezing temperature is reached at the surface, no heat flux condition is set, which, in effect, permits omission of any description of the formation of ice fields.

In the Marmara Sea basin situated to the west of Marmara Island (approximately along 27.38°E), the conditions characterizing an open liquid boundary are specified.

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[2] Fofonoff, N.P. and Millard, Jr., R.C., 1983. *Algorithms for the Computation of Fundamental Properties of Seawater*. UNESCO Technical Papers in Marine Sciences; vol. 44. Paris, France: UNESCO, 53 p. https://doi.org/10.25607/OBP-1450

[3] ERA5: Fifth Generation of ECMWF Atmospheric Reanalyses of the Global Climate. *Copernicus Climate Change Service Climate Data Store (CDS).* 2017. [online] Available at: https://cds.climate.copernicus.eu/ [Accessed: 22 August 2018].

The boundary conditions for temperature and salinity, level and current velocities were obtained based on the daily products of the Copernicus Marine Environment Monitoring System (CMEMS) [4]. In order to achieve this, the long-term average climate values were obtained from the analysis data for the period between 2007 and 2016 (Fig. 2). It is evident that the temperature exhibits a distinct pattern of cooling during the winter months, followed by a period of warming in spring and summer, along with the formation of the thermocline (Fig. 2, *a*).

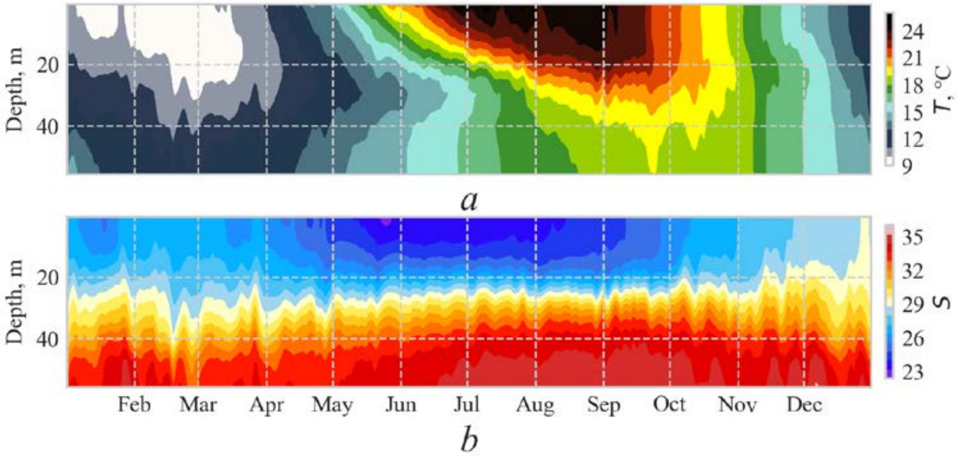

Fig. 2. Intra-annual variability of temperature (*a*) and salinity (*b*) in the Marmara Sea averaged along 27.38°E based on the *CMEMS* products [4] for 2007–2016

The salinity fields according to CMEMS data demonstrate a typical vertical haline structure of waters in the Marmara basin, where the salinity of the upper layer is determined by the inflow and subsequent transformation of less saline Black Sea water masses. Salinity increases significantly with depth due to the influx of Mediterranean waters, with a salinity difference of over 12 between the deep and surface waters (Fig. 2, *b*).

In addition to the boundary conditions, the global CMEMS analysis results were also employed to establish the initial conditions of the fields. To initialize the model in the Black and Azov seas, the procedure of combining different sources, as outlined in reference [9], was employed. The temperature and salinity data for the Azov Sea were constructed using optimal interpolation of *in situ* observations. The temperature and salinity fields from the reanalysis of the hydrophysical parameters of the Black Sea Marine Forecasting Center were employed as the initial fields for the Black Sea basin [10]. Furthermore, in order to obtain the initial fields

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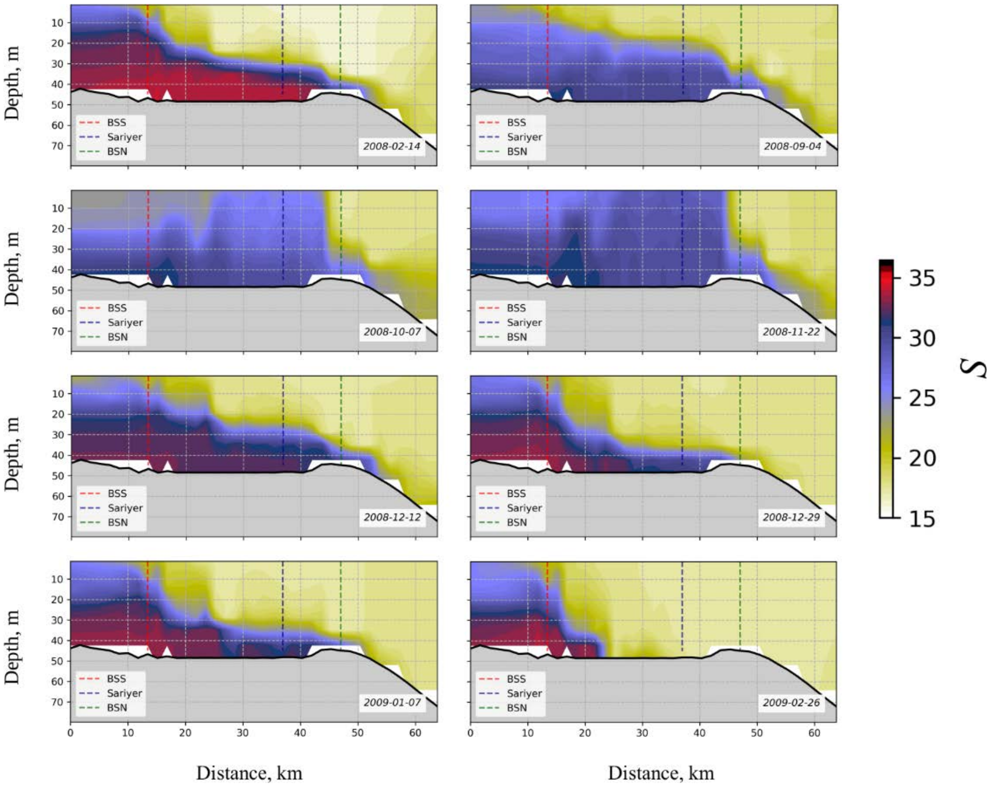
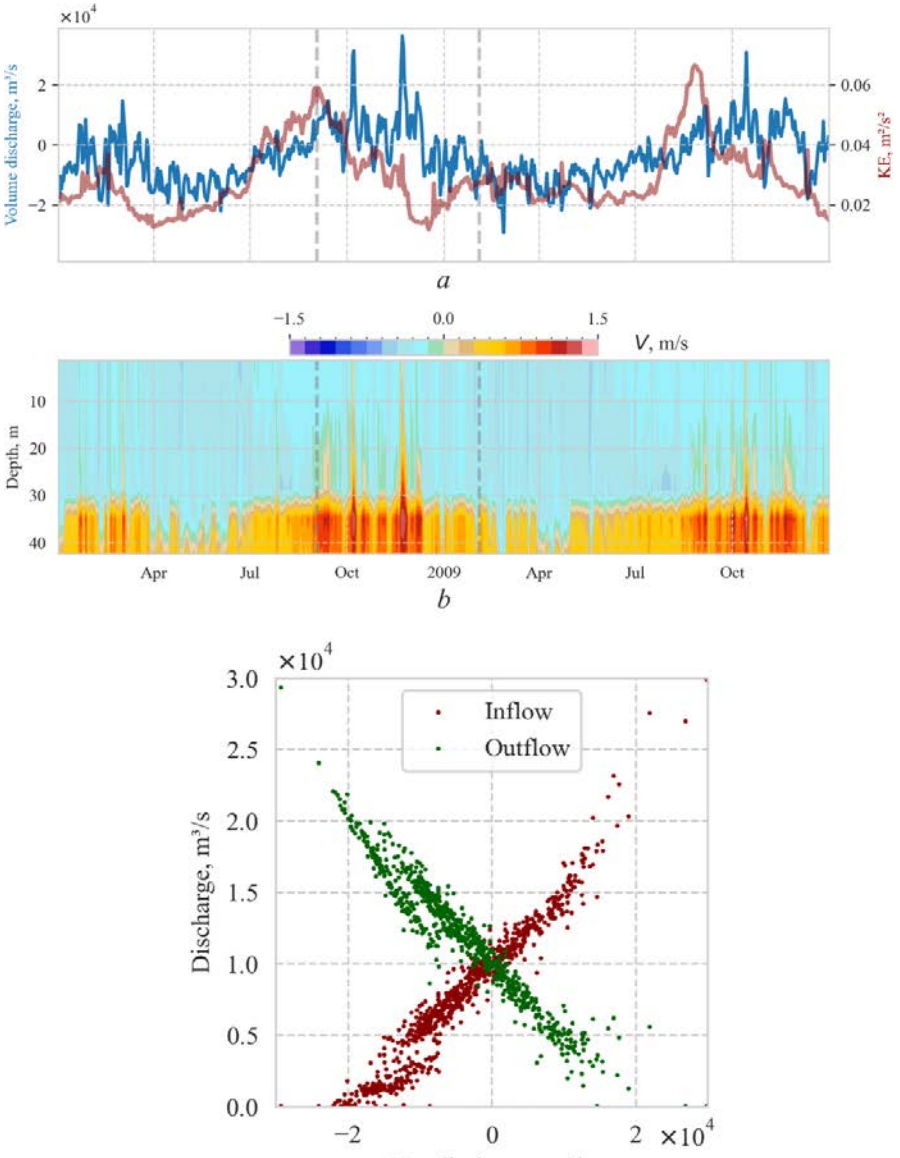
[4] Copernicus Marine Service. *Global Ocean 1/12° Physics Analysis and Forecast Updated Daily*. 2018. [online] Available at: http://marine.copernicus.eu/services-portfolio/access-to-products/?option=com_csw&view=details&product_id=GLOBAL_ANALYSIS_FORECAST_PHY_001_02 [Accessed: 22 August 2018].

for 15 August 2007, an adaptation calculation was conducted utilising the methodology proposed by A. S. Sarkysyan. The initial resolution of the prepared fields was 1/24°, as they were originally designed for long-term numerical experiments with a coarse resolution. Subsequently, the arrays were interpolated onto a grid of a new configuration, and a preliminary prognostic calculation of the general circulation of the cascade for the period between 15 August and 31 December 2007 was carried out in order to adapt the model to high resolution. Prior numerical experiments had demonstrated that this occurs over a period of approximately four months [11].

The principal numerical experiment using the developed configuration was conducted over the period from 1 January 2008 to 31 December 2009. The results of this study correlate temporally with the calculations presented in reference [2]. This allows for a comparison to be made, thus enabling an evaluation of the quality of the straight modeling in its schematized representation. Furthermore, the duration of the numerical experiment partially coincided with the time frame of the measurements taken from work [6], which will also be employed for comparison. The position of the M7 station, as defined in the aforementioned work, is illustrated in Fig. 1, *b*.



F i g. 3. Distribution of seawater salinity along the Bosphorus Strait on certain dates in 2008–2009



a

b

c

Fig. 4. Water dynamics in the Bosporus Strait: *a* – mean kinetic energy (CE) of surface currents in the Marmara Sea and net barotropic meridional transport in the vicinity of point *BSN*; *b* – meridional currents in the northern part (*BSN*); *c* – inflow and outflow values as the functions of total transport. Vertical dashed lines indicate the period of observations from [6]

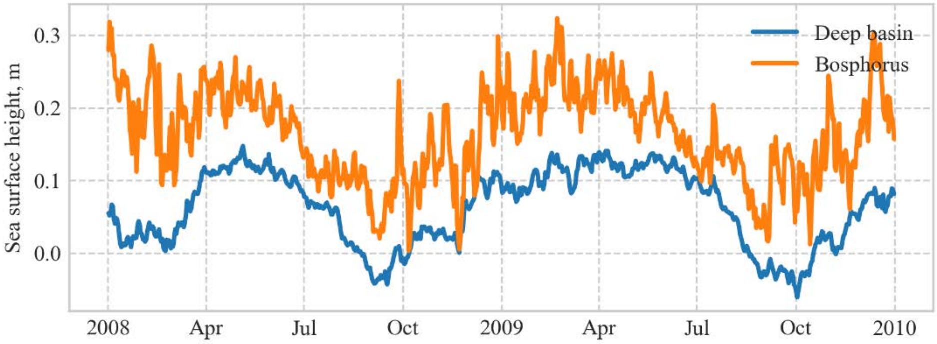
Analysis of the results

Notwithstanding the inaccuracies in the strait configuration simulation (Fig. 1, *b*), the model provides a highly plausible distribution of hydrological characteristics along the strait axis. In the thermohaline fields, two distinct layers of homogeneous water masses, separated by a thin layer of high gradients, are clearly discernible. This is illustrated in the vertical salinity sections along the strait (Fig. 3, fragment from 14 February 2008). The locations of the stations along which the sections are constructed are illustrated in Fig. 1, *b*.

It is important to note that the calculation accurately reproduces the seasonal course of total transport through the Bosphorus Strait (Fig. 4, *a*), which is primarily influenced by the intensification of river runoff in the Black Sea during the months of May and June [12]. The ratio of the flow rates of the upper and lower Bosphorus currents is consistent with the findings presented in reference [2] (Fig. 4, *c*).

Furthermore, the currents within the strait exhibit a two-layer structure (Figs. 3 and 4, *b*). In the upper layer, the currents are directed from the Black Sea to the Marmara Sea. This layer is comprised of Black Sea waters, which undergo gradual transformation as they are transported along the strait. The current in the lower layer is oriented towards the Black Sea. The water in this layer is derived from the Marmara Sea and undergoes transformation as it is transported along the strait. However, an analysis of the meridional velocity over time reveals the occurrence of periods during which the upper Bosphorus or lower Bosphorus current is obstructed in the strait (Fig. 4, *a*, *b*).

Furthermore, our calculations confirm the mechanism for maintaining the upper Bosphorus Current during the winter period, as previously established in work [2]. The elevation of the Black Sea level in the Bosphorus region is the determining factor. This is caused by the intensification of the Black Sea Rim Current at this time (Fig. 5).

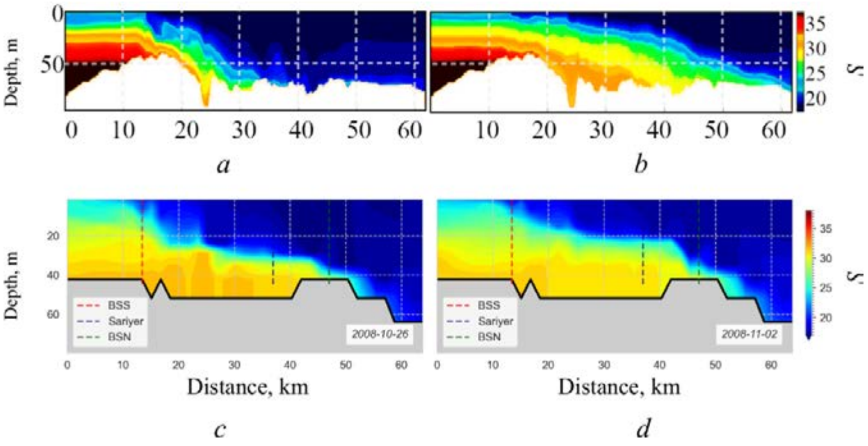


F i g. 5. The Black Sea surface level averaged over the deep-sea (deeper than 500 m) and near-Bosphorus areas

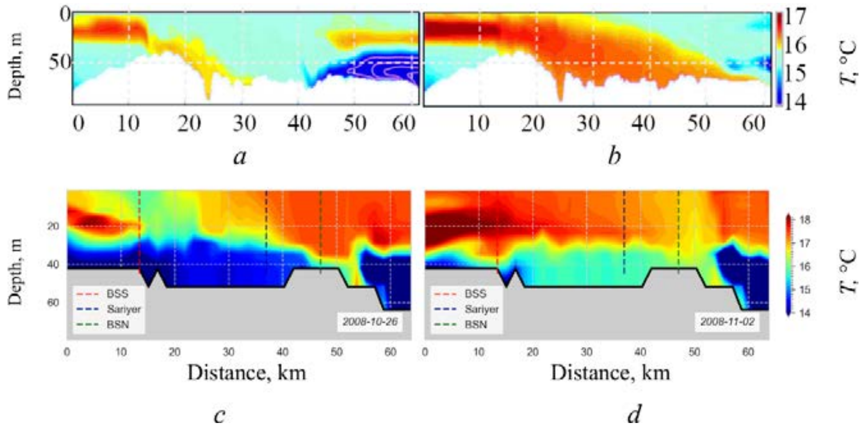
Furthermore, the salinity of the lower layer is also subject to seasonal variation in our calculations. During the winter months, the salinity can reach 30–35 (Fig. 3). In this instance, the salinity of the water reaches the threshold at the point of exit from the Bosphorus along the seabed. In general, the boundary between the layers expands and rises to the surface as the area approaches the Marmara Sea (Fig. 3). In certain periods, the salinity at the bottom reaches 25–30 (Fig. 3, fragment from 09 April 2008).

The seasonal and high-frequency variability of salinity in the lower layer of the strait can be attributed to the distinctive vertical structure of salinity in the Marmara Sea. The influx of fresher Black Sea waters into the upper layers of the basin and highly saline Aegean Sea waters into the lower layers results in the formation of a two-layer stratification in the Marmara Sea. Fluctuations in the position of the boundary between the layers in the vicinity of the Bosphorus strait in the Marmara Sea result in alterations to the salinity of the lower layer.

In comparison with the findings of the study [2], salinity profiles along the strait on 26 October and 2 November 2008 (Fig. 6) will be considered. In comparison to the results presented in work [2], our calculations indicate that the Marmara Sea waters extended to the north to a somewhat greater extent in October. Nevertheless, as in the aforementioned work, our calculation also reveals the obstruction of Black Sea waters at the boundary with the Marmara Sea. In both calculations, there is a tendency for the boundary to rise during the October–November period. The temperature of the bottom waters in our results was found to be lower (Fig. 7). The process of incorporating more saline, yet warmer Marmara Sea waters into the Black Sea basin is less discernible in terms of temperature.

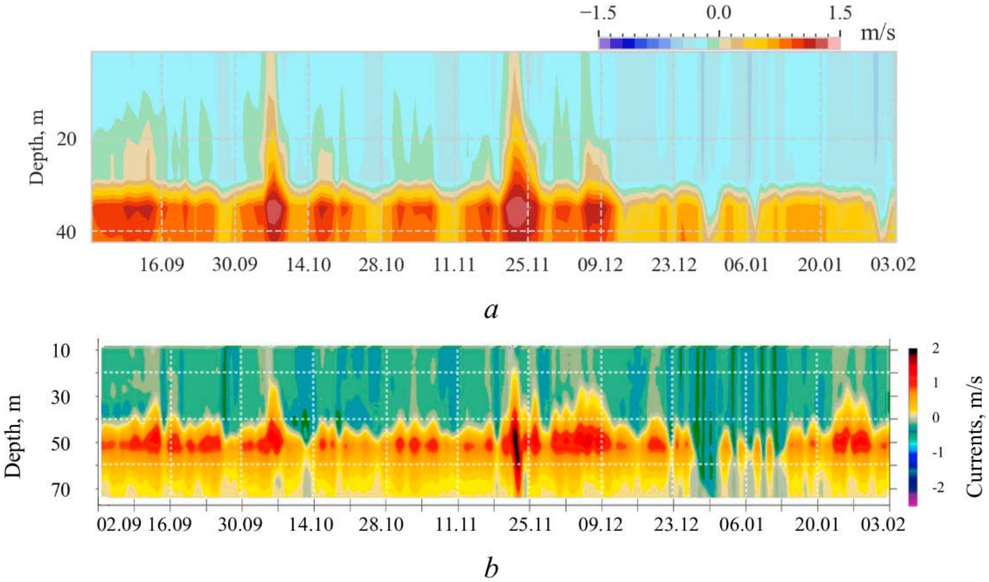


F i g. 6. Distribution of seawater salinity along the strait on 26.10.2008 and 02.11.2008 based on simulations in [2] (*a*, *b*) and in this paper (*c*, *d*)



F i g. 7. Distribution of seawater temperature (°C) along the strait on 26.10.2008 and 02.11.2008 based on simulations in [2] (*a*, *b*) and in this paper (*c*, *d*)

The boundary between the layers is subject to significant fluctuations over time. On occasion, the boundary rises to the free surface, resulting in the complete obstruction of the upper Bosphorus Current (Fig. 3, fragment from 26 February 2009). In reference [6], it is demonstrated that such occurrences are linked to the wind effect. Based on direct observations of current velocity, periods during which the upper Bosphorus Current was completely blocked were identified. A comparison of the results of the present work (Fig. 8) with those of previous studies demonstrates good agreement. During the observation period, the events of blocking the upper and lower Bosphorus currents are consistent. It is important to note that the position of the boundary between these currents differs significantly due to the discrepancy between the depth of the model and the actual depth at a given station.



F i g. 8. Comparison with observational data: meridional currents (m/s) in the northern part of the strait in the period September 9, 2008 – February 3, 2009 based on the results of simulation (*a*) and measurements from [6] (*b*)

On approximately 7 October and 22 November 2008, the upper Bosphorus Current was observed to be blocked at both the southern and northern ends of the strait, where buoys equipped with current meters were deployed [6]. The results of the analysis indicate that on the aforementioned days, the Marmara Sea waters occupied the entire depth of the Bosphorus Strait, extending from the southern mouth to the northern end (Fig. 3, fragments from October 7 and November 22, 2008). Furthermore, the observations presented in [6] indicate that three additional instances of the upper Bosphorus current being blocked at the southern end of the strait were recorded between September 2008 and February 2009. At the same time, in the northern section of the strait, the customary transport of the Black Sea waters in the direction of the Marmara Sea was observed in the upper layer. Our calculations indicate that on these days, in the area of the southern end of the strait, there was either a disappearance of the upper layer or a significant decrease in its thickness.

Furthermore, the observations presented in [6] demonstrated that between the end of December 2008 and mid-January 2009, a series of instances of obstruction to the lower Bosphorus Current were recorded in the northern end of the strait. As evidenced in [6], the complete obstruction of maritime traffic in the Black Sea direction was observed at the end of December (Fig. 8). The salinity sections along the strait (Fig. 3) demonstrate that at this time, the lower Bosporus Current is entirely obstructed at its northern end.

It can be observed that between the dates of 5 and 14 January 2009, the lower Bosphorus Current in the northern section of the strait is obstructed to a significant extent, as evidenced by the findings presented in reference [6] (see Fig. 8). Our calculations indicate that the lower layer does not entirely disappear during this period, but its thickness does decrease significantly. At the same time, the calculations also demonstrate a complete blockage of the lower Bosphorus Current along the entire length of the strait (Fig. 3, fragment from 26 February 2009).

The two-year analysis of meridional currents in the strait reveals that blockages of the upper Bosporus Current start in September (Fig. 4, *b*). This phenomenon is apparently caused by the intensification of currents in the Marmara Sea by this time (Fig. 4, *a*), which is a consequence of wind action. At the same time, the Rim Current undergoes a reduction in strength (Fig. 5). A reduction in the circulation of the Marmara Sea results in the occurrence of blockages in the lower Bosporus Current.

Discussion

The analysis of meridional currents in the strait reveals that blockages of the upper Bosphorus Current occur from September onwards. This phenomenon may be attributed to the intensification of wind-driven currents in the Marmara Sea, which subsequently results in the weakening of the Rim Current. This results in the influx of saline Marmara waters into the Black Sea basin, leading to the formation of saltwater lenses, as demonstrated in the numerical experiment presented herewith [5]. This may also provide an explanation for the saltwater intrusions that have been detected during this period by means of profiling buoy measurements [1]. As the Marmara circulation weakens during the winter and spring, the reverse phenomenon of lower Bosporus current blockage can be observed.

Conclusions

A comparison of the hydrophysical fields in the Bosphorus Strait with observations presented in the present paper demonstrates that the proposed model accurately reproduces the blockage of the upper Bosphorus or lower Bosphorus Current. This is in contrast to finite-element models, which allow for a more complex configuration of the strait, and which do not reproduce these situations as accurately. Furthermore, the ratios of the flow rates of the upper and lower Bosphorus currents obtained on the basis of finite-element models and according to the results of our numerical experiment are in quantitative agreement. The mechanism by which the upper Bosphorus Current is maintained during the winter months has been confirmed. This is determined by the rise in the Black Sea level in the Bosphorus region caused by the intensification of the Rim Current.

The results of the proposed regional configuration of the NEMO model calibration indicate that the model is capable of qualitatively accurately representing the response of the strait to changes in wind action and seawater density near the northern and southern entrances.

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About the authors:

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

Gennady K. Korotaev, Marine Hydrophysical Institute of RAS (2 Kapitanskaya Str., Sevastopol, 299011, Russian Federation), DSc. (Phys.-Math.), Corresponding Member of the Russian Academy of Sciences, Professor, **ResearcherID: K-3408-2017**, **Scopus Author ID: 7004998153**, gkorotaev@gmail.com

Contribution of the co-authors:

Artem I. Mizyuk – investigation, methodology, validation, visualization, writing, review and editing

Gennady K. Korotaev – supervision, writing of the original draft, review, editing, conceptualization

The authors have read and approved the final manuscript.

The authors declare that they have no conflict of interest.