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published in MORSKOY GIDROFIZICHESKIY ZHURNAL, Vol. 35, Iss. 6 (2019)

Dynamics of the Caspian Sea Waters over the Apsheron Sill in 2003

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Purpose. The paper is aimed at studying water exchange between the Middle and South Caspian, at assessing its intensity, spatial-temporal structure and variability.
Methods and Results. The study includes the numerical model of the Caspian Sea general circulation; it is of sufficiently high resolution for reproducing mesoscale structure of the currents – 2 km. Due to the model, the Caspian Sea circulation in 2003 was reconstructed and the basic characteristics of water transfer between the Middle and the South Caspian were calculated. This specific year was chosen since in all its months, the wind fields in the Middle and South Caspian water areas were in good agreement with the average climatic ones. The simulated structure of the currents over the Apsheron Sill represents the following pattern: the northward currents are most often formed over the eastern shelf slopes, and the southward ones – over the western shelf slope. The latter are usually more intense and regular. From mid-July to October, the easterly winds regularly occur over the Caspian Sea strengthening the northward currents, which, in their turn, transfer relatively salty and warm South Caspian waters to the Middle Caspian along the eastern coast. A fairly stable southward stream resulted from the density gradient between the cold Middle and the warm South Caspian, is located along the western shelf slope at the depths 100–150 m. On the whole, the water flow above the sill is directed from north to south. At that the southward flows are distributed rather evenly throughout the year, whereas the major part of the northward currents' flow is observed from late July to December.
Conclusions. Since the South Caspian waters on all the depths are warmer and more salty than those in the Middle, water exchange between the two basins in course of the whole year, contributes to increase both of temperature and salinity in the Middle Caspian, and to their decrease in the South Caspian. The current-originated salt flows in the region are sufficient to make salinity grow in the Middle Caspian upper layer by 0.5 psu within 100 days, at that the corresponding temperature increase does not exceed 0.01–0.03 °C per day. The reverse southward currents transfer relatively fresh water to the South Caspian that lowers salinity of its upper layer by 0.2 psu per month. However, such intense intrusions are noted only in March and December. The impact of these currents on the South Caspian heat balance is more uniform throughout the year and does not exceed 0.17 °C/day.

Key words: Caspian Sea, Apsheron Sill, water exchange, hydrodynamic modeling.

Acknowledgments: The work was carried out within the framework of the state task of FASO, Russia (No 0149-2019-0002) and at financial support of the Russian Fund for Basic Research (project No 17-05-01282-a).

For citation: Dyakonov, G.S. and Ibrayev, R.A., 2019. Dynamics of the Caspian Sea Waters over the Apsheron Sill in 2003. *Physical Oceanography,* [e-journal] 26(6), pp. 557-568. doi:10.22449/1573-160X-2019-6-557-568

DOI: 10.22449/1573-160X-2019-6-557-568

Introduction

The Caspian Sea consists of three basins: the North, Middle and South Caspian partially separated from each other by peninsulas. Due to the large differences in the bottom topography the uneven spatial distribution of the river runoff and the large meridional length of the sea, the waters of these basins have different thermohaline structures and circulation patterns. In the extremely shallow Northern Caspian, which is the estuary zone of a large river – the Volga, the salinity varies from zero to 12 psu and is generally a few units lower than in the Middle and Southern Caspian. Average salinity of their surface waters is about 12 and 13 psu, respectively. The differences in the thermal regime of three sea basins are even more significant. The average surface water temperature in the Middle Caspian is 5–6 °C lower than in the South Caspian: in summer due to strong upwelling along the coasts, in winter due to the cold water influx from the North Caspian, the surface of which completely freezes. As a result, water masses intruding from one Caspian basin to another have a contrasting temperature, salinity and density relative to the surrounding waters, as a result of which they greatly affect the thermal and salt balances of the basin in which they end up and modulate the thermohaline structure of its waters. This circumstance causes a special interest in the dynamics of the Caspian Sea in areas where such water exchange occurs, in particular in the region of the Apsheron Sill separating the deep-sea basins of the Middle and Southern Caspian. The bottom relief here is formed by the merger of the western and eastern shelves and is a saddle-shaped one. For the conditional boundary between the Middle and South Caspian we take a zonal vertical section passing through the saddle point of the bottom, as well as through the tip of the Apsheron Peninsula (40° 12′ N). The sea depth in this section is on average only 63 m and reaches a maximum value of 165 m at the saddle point.

Despite the importance of this sea region for the general circulation of the Caspian, the dynamics of the waters in it have not been sufficiently studied. In the works [1, 2] analyzing the data on measurements of current profiles, it is pointed out that there are currents of opposite directions in the west and east: part of the waters of the Middle Caspian cyclonic circulation turns south, crossing the sill in its western part, while in the east the inflow of relatively heavy waters of the South Caspian to the Middle Caspian occurs [3]. At the same time, twice as high velocities are observed in the west than in the east. This pattern of currents is also confirmed by satellite monitoring of the surface sea waters [4]. However, as noted in [1, 2], for an accurate assessment of the water exchange between the Middle and South Caspian, it is necessary to carry out a section of currents along the entire length of the sill in different seasons of the year. Such assessments are absent up to date. Also, according to measurements in this region, an increased variability in the water column characteristics is observed here [5]. In February – March, when northern winds (which create a drift transport to the southwest on the surface) blow, a northern countercurrent in the subsurface waters along the eastern shelf, which forms the tongue of warm waters on the surface of the Middle Caspian [6], takes place. In the bottom waters a quasi-constant inflow of cold water into the South Caspian, generated by the baroclinic pressure gradient associated with a large temperature difference between the Middle and South Caspian [7, 8], is observed. This flux renews the South Caspian abyssal waters every 15–25 years.

The present study is aimed at studying the features of water exchange between the Middle and South Caspian: its intensity, spatial-temporal structure and variability. In this regard a numerical model of the Caspian Sea general circulation, which has a sufficiently high resolution to describe the mesoscale structure of the currents, is used. This work is a continuation of our studies on the Caspian Sea hydrophysics on time scales from climatic to synoptic using the ocean thermohydrodynamics model SZ-COMPAS [9, 10], developed within the framework of the seamless prediction paradigm [11, 12].

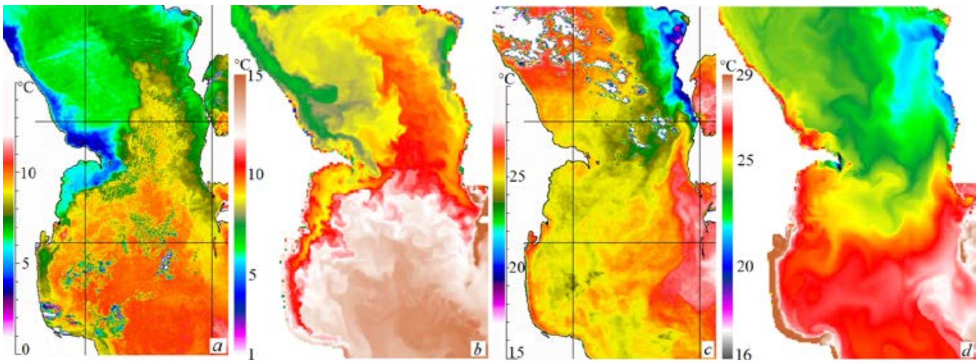
Numerical experiment

The currents were calculated according to the model described in [9], which was previously used to study climatic changes in the level and thermohaline structure of the Caspian Sea [10, 13]. The horizontal resolution is 2 km, which is sufficient to describe the mesoscale water dynamics: in the Caspian Sea the baroclinic radius of Rossby deformation is estimated at 17–22 km in deep water regions and 3–8 km at the shelf in the eastern part of the Middle Caspian [14]. The vertical resolution is from 2 to 30 m. In order to describe the horizontal turbulent viscosity, a fourth-order operator with the Smagorinsky parameterization [15] is used with the minimum dimensionless coefficient $C = 2$ recommended by the authors. Among the known numerical models of the Caspian Sea, only two [16, 17] have higher resolution (about 1.5 km). However, the model we use has a significantly lower level of dissipation and, therefore, a larger effective resolution, which allows us to reconstruct a wide range of movements: from large- to mesoscale ones. In order to parameterize the vertical turbulent viscosity, the Munk – Anderson scheme with a maximum coefficient of $K_m = 10^{-3}$ m^2/s is applied. In [18] it was demonstrated that, despite its simplicity, the application of the Munk – Anderson scheme yields the results that are not qualitatively different from the model with Mellor – Yamada parameterization of 2.5 level of closure. The model is initialized by three-dimensional climatic temperature and salinity fields [19] and “spun-up” for three years until their realistic distribution in the coastal areas is established. To set the boundary conditions on the sea surface, we used the data of *European Center for Medium-Range Weather Forecasts* (*ECMWF*) *ERA-Interim* [20], which have a spatial resolution of 80 km – high for global reanalysis but rough relative to the size of the Caspian Sea. It should be noted that such a step does not always allow us to describe the coastline contours and correctly reconstruct all the physical processes in the sea coastal areas. An alternative to using global reanalysis data is their regionalization described in [21].

In the model calculation, the circulation of the Caspian Sea in 2003 was reconstructed. That year in the Middle and South Caspian the near-surface wind, the main factor in the formation of currents, were rather close to average climatic in all months. This allows us to obtain a characteristic picture of the water exchange of these basins without calculating for a large number of years and the need for additional averaging of the results.

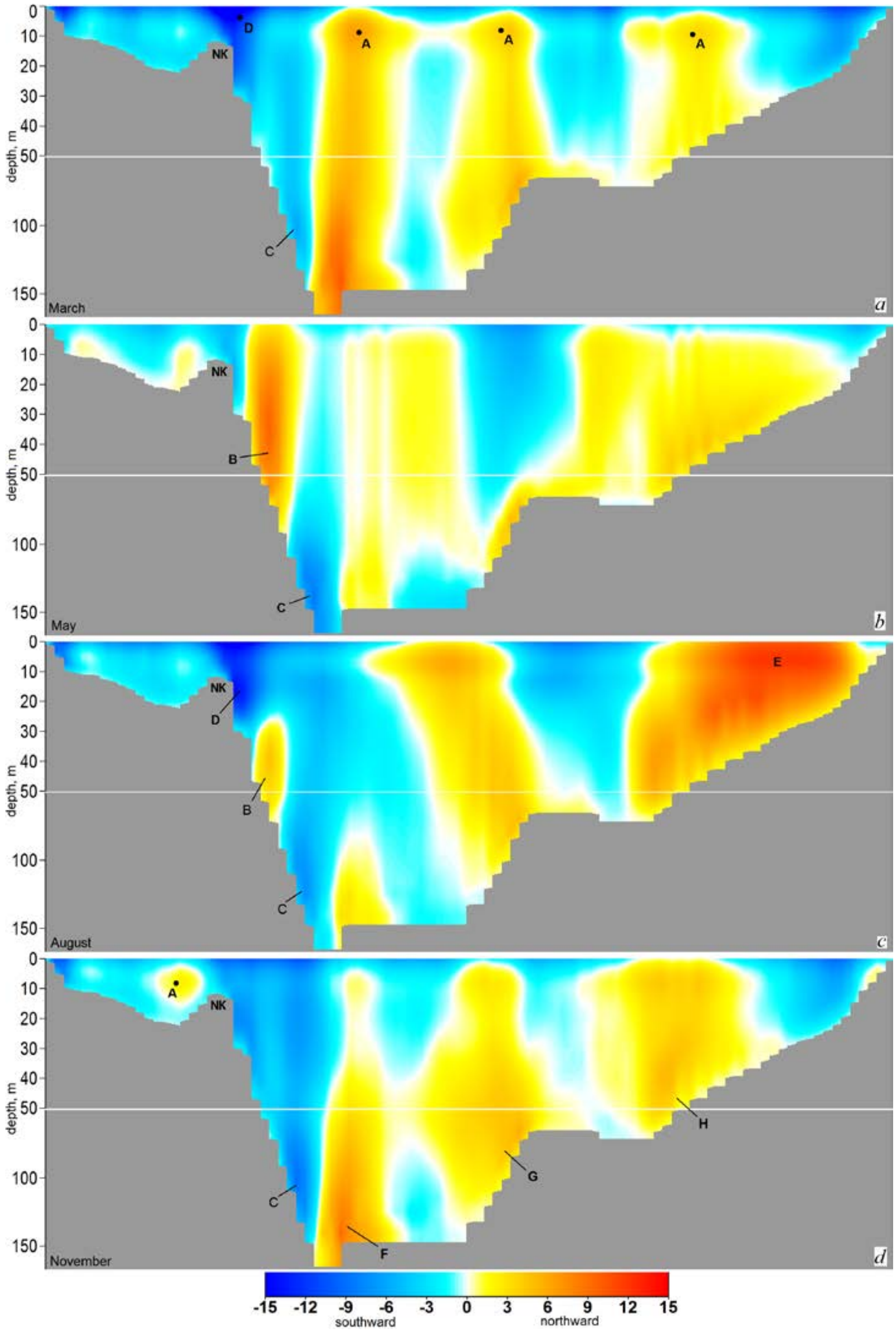
The structure of currents above the Apsheron Sill

The structure of the currents in the Apsheron Sill region obtained by the model is in good agreement with the observational data [1–5, 7, 8]. In general, the following picture is noted: the prevailing northern winds create an influx of relatively fresh and cold waters from the Middle Caspian to the South Caspian along the western shelf, while water masses move northward along the eastern shelf. This division is most clearly seen in December when the monthly average currents of the southern and northern directions divide the sill into two halves: western and eastern, respectively. In this case, the most intense currents form on the slopes of the shelves and are directed along the isobaths. Since the western shelf has a steeper continental slopes (from Neftyanyye Kamni archipelago to the saddle point of the bottom), the current here is more coherent and has higher velocities than in the east. It is traced well in Fig. 1, *a*, *b* (and also in Fig. 2 (element *D*) and Fig. 3, *a*) in the form of a jet of cold waters enveloping the Apsheron Peninsula and extending to the south. Following the isobaths of 30–100 m, this current sharply turns southwest to the east of Neftyanyye Kamni, regularly forming an anticyclonic eddy with a diameter of about 20 km in their vicinity.



F i g. 1. IR-images of the Caspian Sea surface temperature from the *NOAA*-16 satellite (*a, c*) and those model-derived at the 1 m depth (*b, d*). Time points of satellite images and model data coincide: *a, b* – March 31, 2003, 9:46 *GMT*; *c, d* – August 1, 2003, 22:33 *GMT*. The fragments *a* and *c* are taken from [4]

Fig. 2 represents the sections of the meridional component of current velocities along the Apsheron Sill averaged over the months in which the circulation typical of the four seasons of the year is observed. Northern winds generate on the surface the drift currents of a southwestern direction from February to mid-July, as well as in November. Simultaneously, the northern countercurrents with the cores at 7–10 m depths are formed in the subsurface layer of the sea (elements *A* in Fig. 2). They carry the warm South Caspian waters to the Middle Caspian, which, having a relatively low density, rise to the surface and manifest themselves in the form of a tongue of warm waters (Fig. 1, *a*, *b*). These subsurface currents are not observed in average monthly fields only in December – January. From mid-July to October the winds of eastern directions are frequent. They strengthen several times the northern current along 10–60 m isobaths of the eastern shelf (Fig. 2, element *E*). This current is clearly seen in Fig. 1, *c*, *d* in the form of an elongated tongue of warm waters off the east coast.



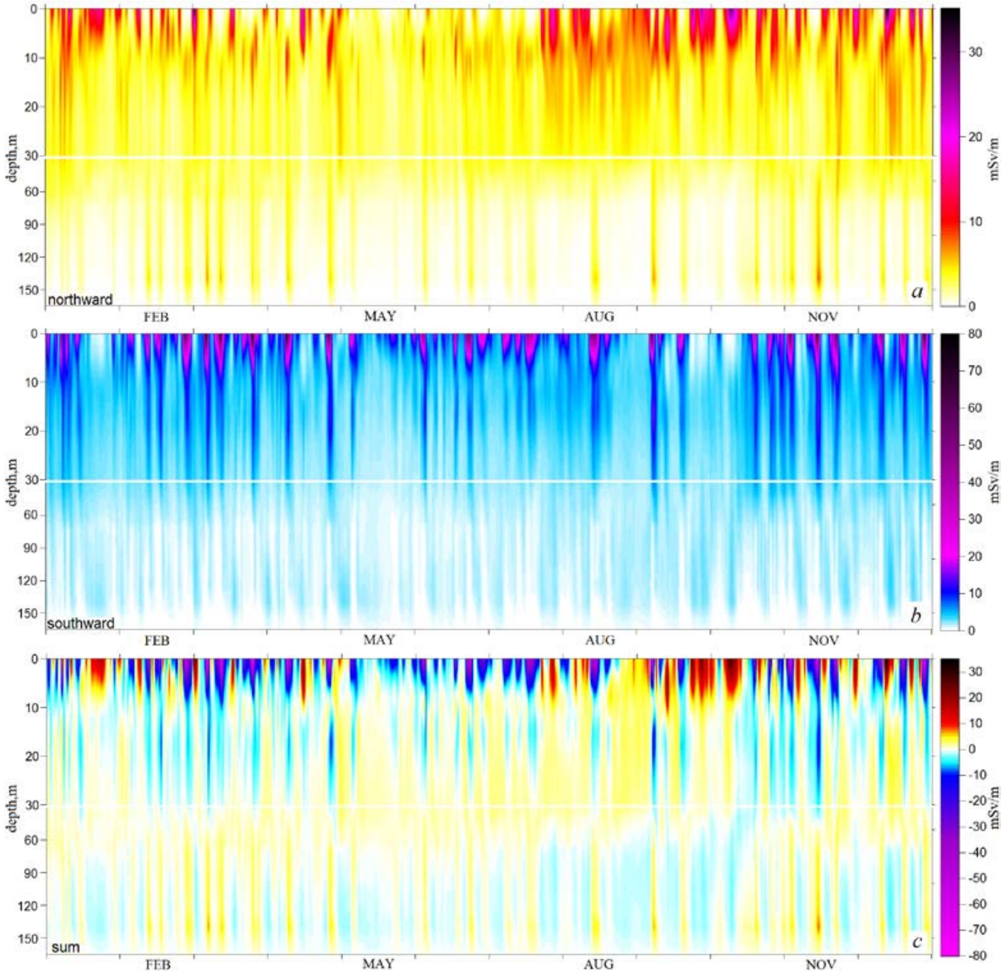
F i g. 2. Monthly average meridian velocity component on the vertical-zonal section at the latitude of the Apsheron Peninsula tip (40° 12′ N) in March – *a*, May – *b*, August – *c*, November – *d*. Latin letters denote individual elements of the currents' structure. NK – location of Neftyanyye Kamni archipelago

From Fig. 2 we can see a general regularity: the northern currents are most often formed above the eastern shelf slope (Fig. 2, elements *E*, *F*, *G*, *H*), the southern ones – above the western shelf slope (Fig. 2, elements *C*, *D*) and partly over the plateau formed by the bottom. A current along the western shelf at up to 70 m depths, which has a predominantly northern direction (Fig. 2, element *B*) in the warm part of the year (from April to September), is an exception. In the remaining 6 months of the year it is also subjected to the indicated regularity and merges with the southern current existing at 100–150 m depths throughout the year (Fig. 2, element *C*; Fig. 3, *b*). The latter, according to [7], is formed by the density gradient between the Middle and the South Caspian due to the large temperature difference between their waters.

F i g. 3. Model instantaneous currents (m/s): *a* – at the 8 m depth on October, 16; *b* – at the 100 m depth on July, 6. Contours designate the bottom depth, (m)

The Middle and the Southern Caspian water exchange intensity

The flow rate above the Apsheron Sill for both directions (north, south), as well as the total flow rate depending on depth and time, are given in Fig. 4. It can be seen that, in general, the transport of water masses occurs in a southerly direction which is due to the inflow of river waters in the north of the sea, while the Southern Caspian has the largest total evaporation flux among the three basins. The greatest transport of the Southern Caspian waters to the Middle Caspian is associated with the above-mentioned northern current along 10–60 m isobaths of the eastern shelf and begins in late July with a higher incidence of eastern winds. At the same time, the transport of the Middle Caspian waters to the south is distributed more or less evenly throughout the year.



F i g. 4. Longitude-integral flow rate of the northward (*a*) and southward currents (*b*) as well as their sum (*c*) above the Apsheron Sill in 2003 as a function of depth and time (in mSv/m, i. e. 10^3 m^3/s per 1 m of depth)

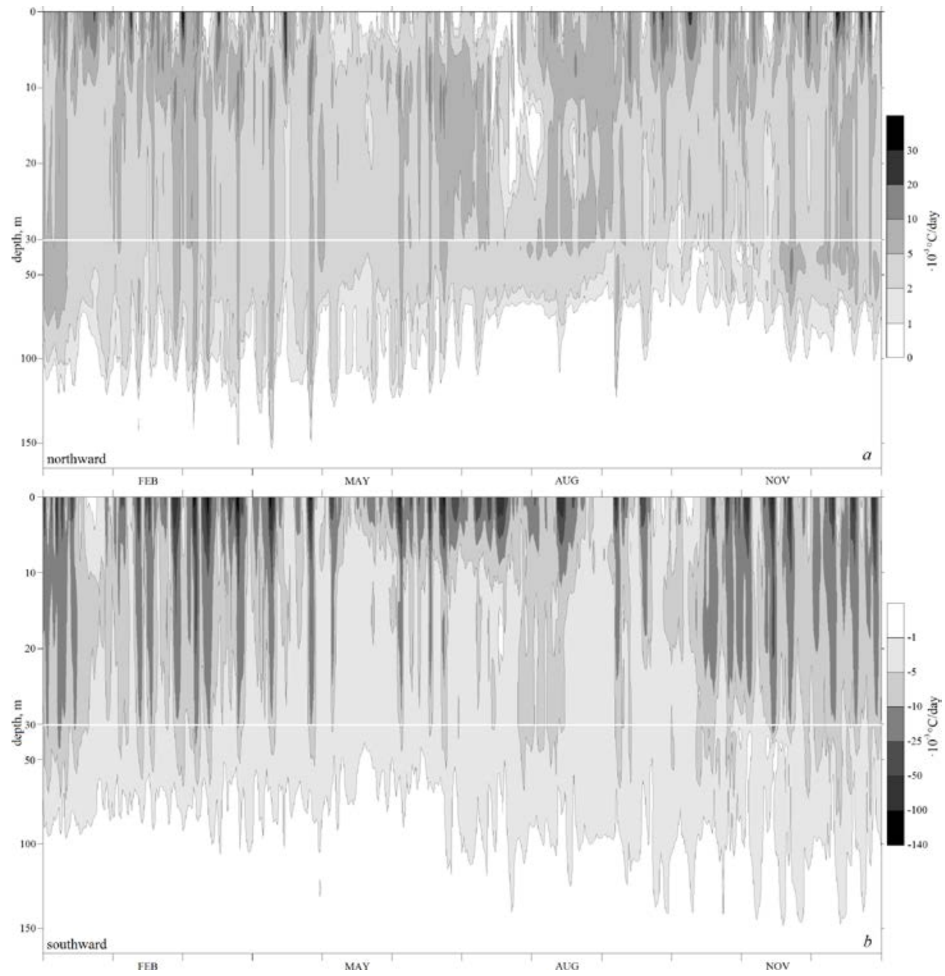
Water exchange effect on the sea thermohaline structure

For studying the effect of currents on the thermohaline structure of the Caspian Sea basins in the considered region, it is necessary to trace the trajectories of the waters they carry and the processes of their mixing with the surrounding waters, which is a separate complex problem. However, the significance of these currents for the Middle and Southern Caspian thermohaline regime can be assessed in a simpler way, by calculating the flows between them and somehow correlating them with the amount of heat and salt contained in these basins. To do this, we calculate the value (with °C/s dimension)

$$DT^{\pm}(z) = \frac{1}{S^{bas}(z)} \int \frac{|v(x,z)| \pm v(x,z)}{2} \left(T_{flow}(x,z) - \overline{T}^{bas}(z) \right) dx,$$

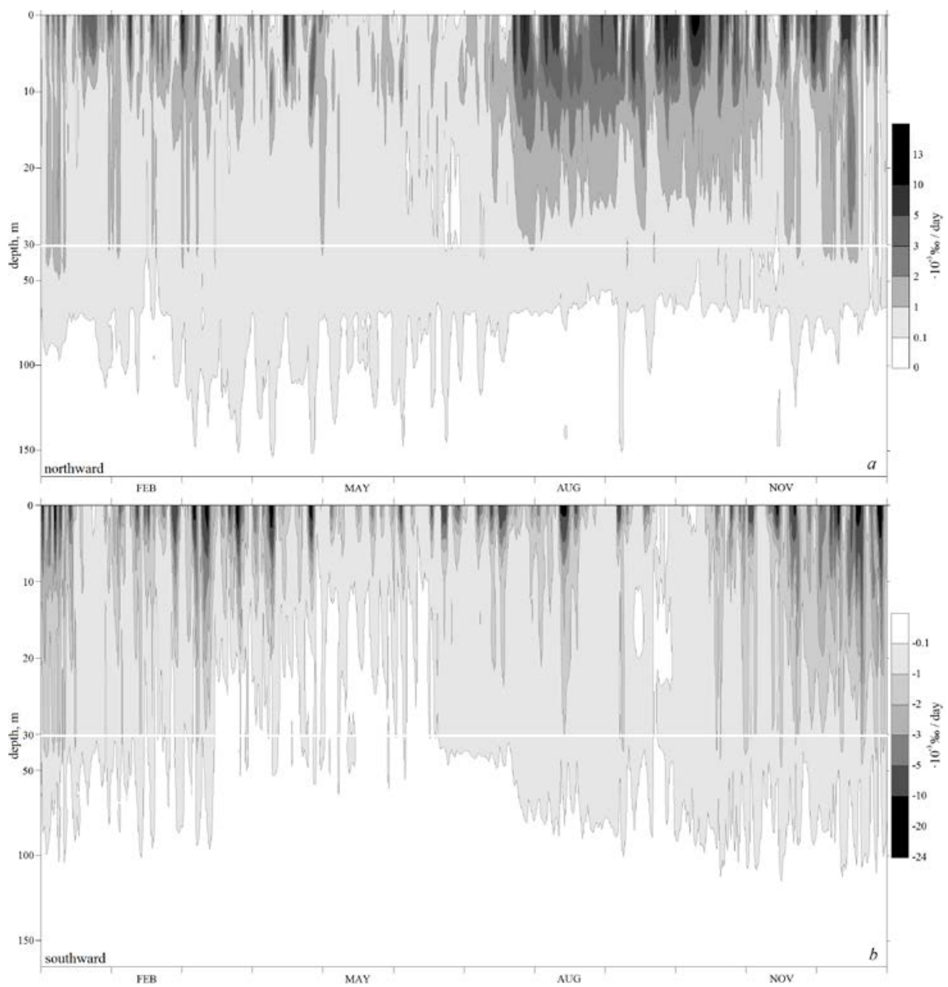
where v, T_{flow} is a meridional component of velocity and the temperature of current at the latitude of the section (40° 12′ N); $\overline{T}^{bas}$ is an average temperature at z depth in the basin into which this current flows in (the Middle or the South Caspian); S^{bas} is a section area of this basin by the horizon z. All the functions, except for S^{bas}, also depend on time. The integral is taken over the sill width. Correspondingly, DT^{+} characterizes the fluxes directed to the north, DT^{-} – to the south. Formally, this value is equal to the variation rate of the basin average temperature $\overline{T}^{bas}$ under effect of currents flowing into it at a depth z, under the assumption that the waters carried by them displace the waters of this basin with an average temperature $\overline{T}^{bas}$ for a given depth and remain at this depth. Since the intruding waters usually submerge to the neutral buoyancy depth, $DT^{\pm}$ value has no direct physical meaning. However, it can be considered as a quantitative measure of how contrasting is the temperature of the waters carried by the current relative to the waters of the basin into which they get, as well as how much water exchange between the Middle and the South Caspian can generally affect their thermal structure.

$DT^{\pm}$ values are given in Fig. 5. Since the waters of the Middle Caspian are systematically colder than the ones of the South Caspian, these values correlate well with the flow rate (Fig. 4). The South Caspian waters regularly get into the Middle Caspian at up to 20 m depths, the heat content of which is sufficient to increase the average temperature of this basin at the corresponding depth by only 0.01–0.03 °C per day. The water exchange effect on the South Caspian is more significant: relatively cold waters regularly intruding it from the north lower its temperature at a rate of up to 0.17 °C/day on the surface and up to 0.1 °C/day in the upper 30-meter layer. In general, we can conclude that the effect of water exchange between the Middle and the Southern Caspian on the thermal regime of these basins is quite significant. In this case, cold intrusions to the south are 2–3 times more intense and also more frequent and regular than the reverse fluxes of warm waters.



F i g. 5. Sectional heat fluxes calculated by the model: *a* – DT^{+} (northward flux, 10^{-3} °C per day); *b* – DT^{-} (southward flux, 10^{-3} °C per day)

We analyze the salt fluxes between the Middle and the South Caspian in a similar way. In Fig. 6 $DS^{\pm}$ values calculated by the above-described formula with the temperature replacement by salinity are given. In the summer, after a flood of the Volga River, the Middle Caspian upper layer salinity is minimal, therefore, the northern currents carrying relatively salty waters of the Southern Caspian from the end of July to October, most significantly replenish the salt balance of the Middle Caspian: the salt transported by them is enough to increase the salinity of its surface waters by about 0.5 psu in 100 days (Fig. 6, *a*). The reverse (southern) currents almost always carry relatively fresh waters that lower the South Caspian salinity. They are most pronounced in late November – December, as well as in March – early April, when within a month the South Caspian surface salinity may decrease by 0.1–0.2 psu (Fig. 6, *b*).



F i g. 6. Sectional salt fluxes calculated by the model: *a* – DS^+ (northward flux, 10^{-3} psu per day); *b* – DS^- (southward flux, 10^{-3} psu per day)

Conclusion

The Middle and the Southern Caspian have a significantly different thermohaline structure. Therefore, the water exchange between them is associated with regular intrusion of waters with contrasting temperature and salinity from the neighboring basin. In the presented work, using the numerical model of the Caspian Sea three-dimensional circulation, a quantitative assessment of the effect of this water exchange on the heat and salt balances of the two Caspian basins is carried out. The southern currents are more intense and regular throughout the year and carry 2-3 times more water than the northern ones, the main flow rate of the latter falling on the second half of the year. A similar picture is observed in the heat fluxes: relatively cold mid-Caspian water fluxes are sufficient to lower the temperature of the South Caspian upper 30-meter layer at 0.1 °C/day rate, and at up to 0.17 °C/day rate on the surface. At the same time, reverse currents carrying warm waters to the north can provide an increase in the Middle Caspian temperature only by 0.01–0.03 °C per day. Salt exchange is even more significant: from the end of July to October, the northward fluxes extending along the eastern shelf carry a sufficient amount of relatively saline water to increase the salinity of the Middle Caspian upper layer by 0.5 psu in 100 days. Reverse fluxes of relatively fresh waters contribute to an even faster decrease in salinity of the Southern Caspian upper layer – up to 0.2 psu per month. However, such significant values are noted no longer than 1.5 months: in late November – December, and also in March – early April.

The structure of currents above the Apsheron Sill is primarily due to the wind distribution in the water area and the bottom topography. The northward currents are most often formed above the eastern shelf slope, the southern ones – above the slope of the western shelf, and the latter, as a rule, are more intense and regular since the winds of the northern directions prevail in this region. From mid-July to October, eastern winds regularly blow over the Caspian Sea, several times strengthening the northern currents that carry the relatively salty and warm waters of the South Caspian to the Middle Caspian along the eastern coast. Rather stable current of southward direction is located along the western shelf slope at 100–150 m depths and is formed by a density gradient between the cold Middle and warm South Caspian. In general, the water flux above the sill is directed from the north to the south. The southern fluxes are distributed relatively evenly throughout the year, while the highest flow rates of the northern currents are observed from the end of July to December.

During the calculations the resources of the Joint Supercomputer Center of the Russian Academy of Sciences and HPC computing resources at Lomonosov Moscow State University [22] were used.

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Contribution of the co-authors:

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Gleb S. Dyakonov – formulation and carrying out the computational experiments, their analysis, and the text preparation

All the authors have read and approved the final manuscript.

The authors declare that they have no conflict of interest.