The impact of surface boundary conditions on the formation of the Black Sea haline stratification from the numerical simulations

M V Senderov and A I Mizyuk

Federal State Budget Scientific Institution Federal Research Center “Marine Hydrophysical Institute of RAS”, 2 Kapitanskaya Street, Sevastopol, 299011, Russia

E-mail: senderovmaxim@gmail.com

Abstract. Following a series of studies of the formation of the Black Sea haline stratification by various initial and boundary conditions, three numerical experiments were performed. For this purpose, the previously performed experiment with a spatially uniform salinity of 12 ‰ was chosen (experiment 1). New simulations were carried out with heat fluxes on the surface (experiment 2) obtained in the department of VAO FSBSI FRC MHI. In addition to heat fluxes, a constant cyclonic tangential wind stress curl (experiment 3) and a tangential wind stress curl with a seasonal variation (experiment 4) were also set. The results of numerical simulations show that in all experiments where heat fluxes were set on the surface, the upper mixed layer appears. The depth of the halocline does not change and is at about 20 m. Also in all experiments the relation between the southward and northward currents are close. Water exchange through the southward current is almost two times greater than that through the northward.

1. Introduction

The works studying the formation of the Black Sea haline stratification and water exchange through the Bosphorus Strait [1]–[3] aim at long-term numerical simulation of the temperature and salinity fields with different initial and boundary conditions in the basins of the Black, Azov and Marmara seas.

At the first stage, the Ryan-Pitman theory (Black Sea Flood theory) was tested [4]. For this purpose, 5 numerical experiments were carried out with different initial salinity that is uniform in space (values of salinity 8, 12, 16, 18, and 22 ‰ were chosen). In these simulation the value of the basin-averaged difference between precipitation and evaporation (7.515 · 10^-6 m^3/s) and the climatic runoffs for 11 rivers was specified. As a result of numerical experiments it was possible to approximately estimate the salinization period of the Black Sea from a freshwater lake to its current state. One of important result of this work is the establishment of a two-layer structure in the Bosphorus Strait (the existence of the southward and northward currents). Regardless of the selected initial salinity such a relation between the southward and northward currents establishes that the flow of southward current exceeds the flow of northward current almost two times [1]. In all experiments the halocline is formed at a depth of 10 - 40 m. This arrangement of halocline is due to the fact that saline water penetrates through the Bosphorus at a depth of about 40 m. The results of numerical simulations have also shown that there is a relationship between the flow of salt through the halocline and the difference in salinity between the surface and deep layers pool. This relationship is represented...
by power dependence with the exponent close to 4/3. The presence of such dependence allows describe various stages of the Black Sea evolution from a freshwater lake to the current state [3], [5].

The next part of the work was devoted to studying the influence of changes in river runoff on the formation of the haline stratification of the Black Sea and the Bosphorus exchange flow [2]. In this work 4 numerical experiments were carried out with the climatic value of river runoff and multiplied by 2; 0.5; 1.5; 0.75. The results of numerical modeling show that the relation between the southward and northward currents linearly depends on changes in river runoff. The river runoff has a greater effect on the vertical haline structure in the upper 40 m layer. Salinity values on the surface range from 8 to 15.5 ‰, and at a depth of 40 m and below - from 16.2 to 16.9 ‰ depending on the specified river runoff [2].

Continuing the cycle of numerical experiments described above, in this paper we will study the effect of surface boundary conditions on the formation of vertical haline stratification of the Black Sea and water exchange through the Bosphorus Strait. The aim of this work is to analyze the results of long-term numerical simulation with various surface boundary conditions, to compare them with each other and with the results obtained in [1]. The second section of the paper describes the used numerical model and features of the numerical experiments. The third section is devoted to the analysis of the results. The last section provides the main results of the work.

2. Materials and methods
To achieve the goals set in this work we use the configuration of NEMO (Nucleus for European Modeling of the Ocean) modeling framework [6], which is described in [1]. Three numerical experiments were carried out with duration of 65 model years. The previously performed simulation with a spatially uniform salinity equal to 12 ‰ (experiment 1) was selected as their basis [1]. In these simulations the heat fluxes (obtained in the department of VAO FSBSI FRC MHI [7]) were taken into account as surface boundary conditions. NEMO model provides several methods for setting surface boundary conditions (SBC). Since it was not necessary to specify all the fields but to use the water-average difference between evaporation and precipitation (7.515 10^{-6} m^3/s) as in earlier works the SBC flux formulation was chosen. In experiment 2 the SBC fields were set: total heat flux, total short-wave radiation, and evaporation minus precipitation. In the third experiment in addition to the same fields as in the second experiment the constant cyclonic tangential wind stress curl in the zonal and meridional directions was taken into account. In the fourth experiment in addition to the fields from the second experiment the tangential wind stress curl with a seasonal variation in the zonal and meridional directions was set.

After test simulation of the second experiment, a significant overheating of water was discovered in the Azov Sea and on the northwestern shelf of the Black Sea in summer. Surface temperatures in these areas exceeded 40°C. In winter excessive cooling was observed when the surface temperature dropped below −40°C. To solve this problem, we used a special correction of the surface boundary conditions for the heat flux [8]. The lower limit was set at −0.06 °C, and the upper limit was set at 32°C. After using this correction, the values of the sea surface temperature became more physical.

3. Results
The haline stratification in the experiments with heat fluxes on the surface are similar to each other, but differ from the first experiment (Figure 1). Setting the SBC entailed the appearance of the upper mixed layer (UML) which was not in the first simulation. The presence of UML is visible after the first year of simulations. However, in simulations with SBC the rate of salinization of the Black Sea basin has changed. So, the difference salinity in the deep layers after 65 model years between the first experiment and the next three is about 2 ‰ (Figure 1). The rate of salinization was also affected by the presence of wind influence. If we compare the values of the average salinity at the bottom of the Black Sea basin from experiment 2 (wind forcing was not taken into account) and experiments 3 and 4, the difference between them will be 0.2%. At the same time, on the surface, the greatest value is observed in experiment 4 (with a value of 12.3 ‰) and the minimum value is observed in experiment 3 (with a
value of 12.0 ‰). In all the experiments studied, the depth of the halocline is approximately the same and is at a depth of about 20 m.

Figure 1. Salinity profiles averaged over the basin for the 65th year.

Analyzing the vertical distribution of the sea temperature it is worth noting the presence of a thermocline in the simulations taking into account SBC (Figure 2). In the first experiment it is not observed because the temperature in the Black Sea basin is affected only by warm Marmara water and the arrival of cold river runoff. In the second experiment the depth of the thermocline is about 50 m. In the two subsequent experiments (3 and 4) where the wind forcing was taken into account the thermocline drops to 100 m (Figure 2). The location of the thermocline in simulations 2, 3 and 4 corresponds to data from [5]. However, according to the results, no cold intermediate layer (CIL) appears in any of four numerical experiments. In the simulations taking into account the influence of SBC (experiments 2, 3 and 4) in the autumn - winter period a layer similar to the CIL is observed but with warmer water than on the surface and at a depth. At the same time the depth of such a layer corresponds to the depth of the CIL [5]. In the same period and in the same simulations we can observe the appearance of UML.

In experiments with the SBC task the upper mixed layer most likely appears due to the active heating of the upper sea layer [9]. Initially (experiment 1) the temperature in the Black Sea changes due to warm water inflow through the Bosphorus Strait and river runoff. In this simulation a thermocline was not formed (the difference between the temperature on the surface and in the deep layers is only half a degree). In the same experiments (2, 3 and 4) where the influence of heat fluxes on the sea surface was set, a thermocline was formed already after one simulation year (in these experiments, the temperature difference on the surface and in the deep layers is about 10°C). The presence of a difference between the surface temperature and the temperature at depth as well as the presence of halocline influenced the formation of the UML in experiments 2, 3 and 4. The thickness of the UML in these simulations is quite close to the data from [5] and [9] and is approximately 5 m. The UML is also affected by the presence of wind forcing in simulations 3 and 4. In these experiments, the UML is observed more often and is clearer in comparison with the data from the second experiment.
Another parameter of the study is water exchange through the Bosphorus Strait. The key factor in the cycle of these works is that the two-layer structure in the strait was formed only due to the difference in salinity in the Marmara and Black Seas (experiment 1). In subsequent simulations this structure is also formed. Analyzing the flow of highly salted Marmara waters into the Black Sea basin the ratio of the southward and northward currents is compared. The ratios of the southward and northward currents average over the entire simulation period are close in experiments 1 and 2 (being about 1.5) and in experiments 3 and 4 (of about 2). So it may be concluded that the influence of heat fluxes on the flow ratio in the strait did not affect it in any way, at the same time this ratio was influenced by the wind forcing in experiments 3 and 4. In this case the values of the flow rates of the southward and northward currents have changed. So in the first simulation, the southward flow rate is of the order of 40000 m³/s, and the northward flow rate is of the order of 30,000 m³/s. After taking into account the SBC (experiment 2) the flow rates of the southward and northward currents become 20000 m³/s and 12000 m³/s, respectively. Wind exposure setting also affected the flow rate in the Strait. The flow rate in the southward flow has not changed in comparison with the second experiment and the flow rate of the northward flow has decreased to 9000 m³/s. The change only in the northward current is associated with water locking due to the predominance of cyclonic vorticity over the Black Sea basin.

Conclusions
Three numerical experiments have been carried out to study the influence of surface boundary conditions on the formation of vertical haline stratification and water exchange through the Bosphorus Strait. Comparing the results obtained with each other and with the experiment conducted earlier (experiment 1) [1] the following can be noted. In all experiments the halocline is located at a depth of about 20 m. This depth of its occurrence is associated with the influx of highly saline marble-sea waters through the Bosphorus Strait, the depth of which in the created configuration is about 40 m, and with the influence of river runoff, which significantly desalinates the surface layer. The vertical haline stratification is also affected by the presence of wind forcing in the third and fourth experiments. The mean basin salinity values in these calculations are lower than in the second experiment. Wind forcing with seasonal stroke (experiment 4) influences the salinity difference on the surface and at depth: it is only 0.2‰, and in experiments 2 and 3 the difference is 0.8‰. Also the SBC task affects the rate of salinization of the entire basin. Compared to the first experiment where
after 65 model years the average salinity at a depth is of 15.3 ‰, in experiments 2, 3 and 4, this value is only 13 ‰.

Considering the vertical temperature distribution in the Black Sea basin it may be noted that setting the heat fluxes affects the formation of the thermocline. In the second experiment, its depth is about 50 m, and in experiments 3 and 4 due to the influence of the wind it deepens to 100 m. The thermocline depth in these three simulations corresponds to the data from [5] and [9].

The inclusion of heat fluxes in experiments 2, 3, and 4 affects the formation of the upper mixed layer which was absent in the first experiment. UML in these simulations is formed due to a significant heating of the upper layer, absent in the first experiment. In simulations with a wind effect (3 and 4), UML is formed more often and is more pronounced in relation to the data of the second experiment. The significant influence of the wind effect on the UML is confirmed in [9].

The task of wind exposure and heat fluxes on the surface also affected water exchange through the Bosphorus. The flow rates of the southward and northward currents in simulations taking into account the boundary conditions decreased almost two times in relation to the first experiment where there was no effect. In experiments 3 and 4 where the wind effect was taken into account the locking of high-saline waters of the Sea of Marmara occurred and the flow rate of the southward flow decreased. However, taking into account heat fluxes on the surface did not affect the value of the ratio of the southward to the northward flow, as in the first experiment, it is close to 1.5. And in simulations with the wind effect (experiments 3 and 4) the ratio of the southward to the northward current is close to 2.

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References
[1] Senderov M V and Mizyuk A I 2017 Vliyanie nachalnih uslovij na vodoobmen cherez Bosfor I formirovanie vertikalnoj halinnoj struktury chernogo morya (Sevastopol: Ecologicheskaya bezopasnost pribrejnoj i shelfovoj zon morya) chapter 2 82–9
[2] Senderov M V, Mizyuk A I and Korotaev G K 2018 Journal of Physics: Conference Series 1128(1) 012149
[3] Mizyuk A I, Senderov M V and Korotaev G K, 2019 Physical Oceanography 26(6) 569–83
[4] Ryan W B and Pitman W C 1999 Noah’s flood: the new scientific discoveries about the event that changed history (New York: Simon and Schuster) p 319
[5] Ivanov V A and Belokopytov V N 2011 Okeanologiya chernogo morya (Sevastopol) p 212
[6] Madec G 2008 NEMO reference manual, ocean dynamics component (France) 1288–619
[7] Shokurov M V 2017 Svidetelstvo o registracii baz dannych № 2017621287
[8] Mizyuk A I and Puzina O S 2019 Journal of Physics: Conference Series: Earth and Environmental Science 386 012023
[9] Kubryakov A A, Belokopytov V N, Zatsepin A G, Stanichny S V and Piotukh V B 2019 Physical Oceanography 26(5) 397–413