The Bosphorus exchange flow impact on the river runoff

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Abstract. The regional configuration with coarse spatial resolution for the basins of the Black, Azov and Marmara seas is developed for NEMO ocean circulation model. Long-term simulations are carried out to reconstruct the inflow of the Marmara Sea highly saline waters into the Black Sea freshwater basin. Effects on the haline stratification and the Bosphorus outflow of different values of river runoff are investigated.

1. Introduction

Being the only connection to Atlantic Ocean the Bosphorus is integrated to the Black Sea water formation process. Number of studies have been carried out to prove its importance [1,2,3].

The fact that the Bosphorus exchange flow has a two-layer structure is known for a long time [1,2,3]. It is formed due to the differences in level and density between the Black and Marmara seas. These two factors determine the presence of northward and southward streams, the runoff of which is the main factor in the water balance of the Black Sea.

The northward stream exists due to the pressure gradient, caused by the higher Marmara Sea water salinity (about 38 ‰) compared with the salinity of the Black Sea (about 18 ‰). The impact of river runoff, precipitation and evaporation leads to the level difference forming the southward stream. Positive freshwater balance (excess of river runoff and precipitation over evaporation) and the supply of Marmara Sea highly saline waters through the Bosphorus impact directly the results in a high pycnocline Black Sea stratification and reduce vertical mixing through it. Such water exchange form observed vertical salinity distribution in this basin [1].

There are several explanations of the Bosphorus origin. One of them is the Ryan – Pitman theory of the Black Sea Flood theory [4]. It claims that an earthquake in about 5600 BC caused the strait formation and start of supply of the Marmara Sea highly saline waters into the Black Sea basin with initial low salinity. Numerical simulation of the supply based on this theory [5]. As a result, it was obtained that, despite the initial Black Sea salinity, average southward flow discharge is twice higher as in the northward. This relation is (as much as possible) an approximate of the current state [6]. The modeling results allows us to conclude that the runoff strait determines the salinity of the whole basin.

The aim of this paper is to analyze relation between the southward and northward streams and the river runoff, as well as to investigate the formation of the Black Sea haline structure. The paper consists of 2 sections first of which provides brief description of the ocean circulation model use, notes the implementation features for experiments with coarse spatial resolution and contains task definition. The second section is devoted to the obtained results analysis.
2. Materials and methods
Numerical experiments were performed using regional configuration of NEMO modeling framework [7]. Its core is based on the ocean general circulation model OPA [7]. It uses system primitive equations with Boussinesq and hydrostatics approximations [7].

The system of equations is discretized using Arkawa’s "C" grid [8]. Equations of motion are represented in the vector form. Nonlinear terms are approximated using MUSCL scheme in the transport-diffusion equations [9]. Vertical turbulent mixing is calculated using k-ε closure model [10]. It is based on the following equations:

\[
\frac{\partial k}{\partial t} + U_i \frac{\partial k}{\partial x_i} = \frac{\partial}{\partial z} \left( \frac{K_m}{\sigma_k} \frac{\partial k}{\partial z} \right) + P + B + \varepsilon, \tag{1}
\]

\[
\frac{\partial \varepsilon}{\partial t} + U_i \frac{\partial \varepsilon}{\partial x_i} = \frac{\partial}{\partial z} \left( \frac{K_m}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial z} \right) + \frac{\varepsilon}{k} (c_{\varepsilon 1} P + c_{\varepsilon 2} B - c_{\varepsilon 3} \varepsilon) \tag{2}
\]

where: \( B = -K_m N^2 \), \( P = K_m M^2 \), \( M^2 = \left( \frac{\partial U}{\partial z} \right)^2 + \left( \frac{\partial V}{\partial z} \right)^2 \).

\( k \) – is the kinetic energy of turbulence,
\( \varepsilon \) – is the rate of dissipation,
\( U_i \) – is the averaged velocity component,
\( \sigma_k \) – is an empirical constant,
\( c_{\varepsilon 1}, c_{\varepsilon 2}, c_{\varepsilon 3} \) – are constants determined by the stability function.

Boundary conditions are as follows: on solid lateral boundaries, there is no slip condition for the velocities. At the bottom nonlinear friction is specified. No flux condition is used for equations of heat and salt transport – diffusion at the lateral boundaries and bottom. On the sea surface we use \( \partial \eta = w |_{z=0} + P + R − E \). The open boundary is set in the Marmara Sea (figure 1). The temperature and salinity profiles are prescribed on the boundary.

Simulations are started from homogeneous and zero sea level. In the configuration used, climatic runoffs for 11 rivers are taken into account. The following algorithm is applied: we consider rivers at their mouths as a water column mixing in all model boxes from the surface to the bottom. In all rivers we prescribe monthly climatic temperature values and the salinity is set to 2 ‰. Temperature, salinity and sea level are corrected at these points, in addition, enhanced vertical mixing is used in the 10 m layer. We put uniformly spaced freshwater flux obtained from the difference between evaporation and precipitation as the surface boundary condition. The Bosphorus and Kerch straits are resolved.

The bottom topography (figure 1) for the Black Sea basin configuration was based on the data of the digital array from [11]. A regular geographic grid covering the basins of the Black, Azov and Marmara Seas is used with a horizontal resolution of about 20 km. Vertical discretization is performed using 34 irregularly spaced z-levels with increasing resolution at the surface. Time-step is 10 minutes.

Based on the theory of the Black Sea deluge a number of numerical experiments were conducted [5]. These experiments studied the influence of the initial conditions on water exchange across the Bosphorus Strait. To adapt NEMO model for the basins of the Black, Azov and Marmara Seas the numerical experiments were carried out. The initial conditions in the experiments were chosen as a uniformly distributed initial salinity values of 8 ‰, 12 ‰, 16 ‰, 18 ‰, 22 ‰ both vertically and horizontally. The temperature at the initial moment is uniform and equal to 6°C. In the Marmara Sea the initial temperature and salinity conditions are as close as possible to observed values.

Numerical experiments simulated the inflow of salty sea water into the Black Sea. These simulations showed that different initial salinity affects the relation between northward and southward streams. One of the most important results is the establishment of such relation. The upper stream is twice larger than the lower. From these simulations it can be revealed that the exchange flow determines the salinity of the whole basin.
Figure 1. Bottom topography of the configuration. The white line is the position of the original coastline of the Black Sea basin [4]. Black rectangle - the position of the open boundary in the Marmara Sea.

One of the major impacts on the exchange through the strait is the river runoff. It causes the question of how the exchange flow will change when river runoff changes? To answer the question, numerical experiments were carried out with the climatic value of river runoff and multiplied by 2; 0.5; 1.5; 0.75 (experiments 1, 2, 3, 4, 5, respectively). The better results were obtained with value close to the climatic ones with the initial salinity of 16 ‰ [5], that is why further experiments were performed using this value.

3. Results
Five numerical experiments were carried out. Experiments were carried out for 67 model years. Analyzing the kinetic energy of the velocities of the Black Sea basin currents, it can be concluded that all experiments go to the quasistationary level after the 20th calculation year.

Further analysis of the results suggested comparing the values of the southward to the northward current relation. In figure 2, the graphs of this relation for all experiments are shown. The flux of rivers increases, the southward to the northward current relation begins increasing if we decrease it, the relation begins decreasing. This is due to the fact that the change in river runoff affects the flux of the southward current, while the northward remains unchanged. The significance of the northward current is close to the climatic one and on average is 10,000 m³/s. According to the result obtained in [5], the southward current is 2 times higher than the northward currents. The climatic rivers runoff was obtained in the 20th century that gives the explanation for the above-mentioned fact.
Figure 2. The relation between the southward and northward current, the black line - the average value of the ratio: experiment 1 (a), experiment 2 (b), experiment 3 (c), experiment 4 (d), experiment 5 (e).

Average relation between southward and northward current values was calculated for 67 model years. The data obtained are uniquely correlated with the runoff of the rivers presented in figure 3. In this figure the abscissa axis shows the R / R₀ relation where R is the flux of rivers in the conducted experiment, R₀ is the climatic flux of rivers, and on the ordinate axis the relation of the southward current Qₛ to the northward Qₙ is presented. As can be seen from the figure, the discharge in the Bosphorus is linearly dependent on changes in river runoff.
Figure 3. The average relation of the southward current to the northward (black dots) for 67 years for experiments with different river runoff rates (where $R$ is the flow rate in the conducted experiment, $R_0$ is the climatic flow).

Figure 4. Salinity profiles averaged over the basin for the 67th year.

In connection with the change in river runoff, the haline stratification in the upper 50 m layer changes significantly. As can be seen from figure 4, an increase in the discharge value by a factor of 2 leads to a strong desalination of the surface layer, but with a 2-fold decrease, we do not observe such a high salinity values. It can also be noted that in experiments with increasing river runoff, freshening occurs to a greater extent than salting with a decrease in runoff. In this case, the change in salinity at the deep-water part is insignificant, for all experiments. Analysis of the results showed that in all carried out experiments, the vertical haline structure is qualitatively close to the observed one.

The maximum depth of halocline occurrence is observed in experiments where the runoff of rivers has been increased (calculation 2, 4). This fact is associated with large freshening of the surface layer in these experiments. In the results obtained, the halocline is located at a characteristic depth of occurrence for the Black Sea, which is 50-100 m.
4. Conclusions
Numerical experiments in the developed configuration of the model with a rough resolution made it possible to obtain - that in experiments with initial salinity of 16 ‰, the runoff of the southward and northward currents turned out to be close to the climate values. The results of numerical simulation showed that the relation between the southward and northward currents directly depends on the rivers flux. The main factors affecting the salinity of the Black Sea basin are water exchange through the strait and runoff of rivers. Also, the analysis of the results showed that the upper 50 m layer in experiments with an increased river runoff is decompressed much faster. In the same experiments, significant lowering of the halocline occurs. In all experiments in the deep-water part of the basin, the salinity values are slightly variable and fairly close to each other. The haline stratification of the Black Sea qualitatively coincides with the observed structure.

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