Study of the formation of the Black Sea haline stratification from the numerical simulations

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Abstract. The excess of river runoff and precipitation over evaporation (positive freshwater balance) and the supply of the Marmara Sea highly saline waters through the Bosphorus is the cause of the sharp halocline in the 100-300 m layer and low vertical mixing in the permanent pycnocline layer, where the contribution salinity to the seawater density prevails compared to temperature. Such features of the Black Sea waters make the description of the process of formation of the haline stratification an actual and inexhausted problem. Investigating the patterns of the formation of the haline stratification in the Black Sea, a laboratory model of a rotating cylindrical cavity and a numerical model are proposed. Laboratory studies have shown that in a simple configuration, the buoyancy flux across the basin boundaries leads to the formation of a sharp pycnocline and the formation of a three-layer vertical structure of horizontal currents. Numerical experiments demonstrate that halocline is formed at a depth of 10-40 m. The haline stratification has been established with a pronounced halocline for about hundred years which later slowly evolved.

1. Introduction
The description of the process of formation the Black Sea haline stratification is an actual and inexhausted problem. The vertical structure of the Black Sea waters has a number of distinctive features, among which we note the existence of a sharp halocline in a layer of 100-300 m where the seawater salinity affects density more than temperature. Such a stratification is caused by significant river runoff the domination of evaporation over precipitation and the inflow of Marmara Sea waters through the Bosphorus strait.

To study patterns of formation of the Black Sea haline stratification in works [1, 2] it was proposed to consider the motion in a rotating cylindrical cavity caused by the inflow of salt and fresh water on its boundaries. The conceptual model simplified in such way allows one to carry out laboratory studies of the generation of water circulation and stratification driven by buoyancy fluxes. The laboratory experiments described in [2] show that inflows of fresh and saline waters through the boundaries of a rotating cylindrical cavity lead to the formation of a sharp pycnocline and a three-layer vertical structure of horizontal currents. In the upper cavity layer a cyclonic circulation was developed and pressed towards the boundary as observed in the Black Sea. Thus laboratory studies have shown that the general large-scale features of circulation and stratification specific to the Black Sea basin are well reproduced within a simple axisymmetric configuration.
A more detailed study of the stratification and circulation in a rotating cylindrical cavity driven by buoyancy fluxes was performed in [3]. In this paper the results of laboratory studies were compared to numerical simulations. It was shown that the nonlinear terms in the equations of motion are rather small and significant nonlinear effects during the generation of the basin circulation and stratification are manifested from the equations of transport-diffusion of heat or salt.

Further analysis of the effect of buoyancy fluxes through the boundaries of a rotating cavity was performed in [4]. The aim of the work was to study the climatic changes of the Black Sea at scales of several thousand years. In the work the formation of vertical haline stratification was numerically simulated due to river runoff and inflow of highly saline Marmara Sea waters considering the real geometry of the Black Sea at various phases of its evolution from an unstratified lake to the current state. Numerical experiments were performed with different initial uniform salinities. Under all initial conditions a vertical stratification is established for about a hundred years which slowly changes further and has a pronounced halocline. Thus from the performed numerical experiments it follows that at climate scales the Black Sea basin is in nearstationary equilibrium. However based on the results of work [4] it is impossible to match any near stationary state to the absolute time scale.

Based on the concepts obtained in [4] an analytical model [5] was developed for the rotating cylindrical cavity, showing that there is a power law relationship between the difference of surface and bottom salinity and the salinity flux through the halocline. Such a relation allows one to describe the process of slow evolution of the salinity stratification. In addition, on its basis it is possible to estimate the characteristic time for reaching the near stationary regime. If the depth and volume of the cylindrical cavity corresponds to the Black Sea basin the typical time scale for reaching the quasi-stationary regime is close to the estimate from [4].

In the present work the relationship between the surface to bottom salinity gradient and salinity flux through halocline for the actual Black Sea geometry is investigated by means of numerical modeling. In the first chapter a brief description of the numerical model is used and its features are presented. The following section describes numerical experiments carried out. The last chapter shows the results obtained in this study.

2. Model Description
Studies of the climate variability of the stratification and circulation of the Black Sea based on numerical modeling is quite a challenge. The main problem is that potential changes in climate processes occur due to very different scales at least for mesoscale. Therefore direct numerical simulation should be carried out using a model with an extremely high spatial resolution which is not yet realistic. In addition it is not quite clear what is the effect of parametrization of different subgrid processes and its inaccuracy can lead to the accumulation of large errors with a considerable period of integration. Because of that the approach based on the physical knowing of the contribution of individual factors to the formation of long-term climate change fields of the Black Sea seems to be more promising.

Author of [4] made an effort to clarify the contribution of river runoff, precipitation, evaporation and the inflow of Marmara Sea waters through the Bosphorus to the formation of the haline stratification of the basin. In this work the near stationary nature of the long-term evolution of the haline stratification was revealed. This allows with a fairly high accuracy to find correspondence between total amount of salt in the Black Sea basin and structures of circulation and stratification. However such an approach prevents from connecting each of the quasistationary states to the time scale. Fundamentally such possibility could be provided by the connection of the flow of salt through halocline with the difference between salinity in the surface and bottom layers of the sea similar to that found in [5]. In this paper a numerical model was prepared to perform the corresponding analysis in the real physico-geographical configuration of the Black Sea basin.
The numerical model is based on the NEMO model complex [6]. A configuration with a coarse spatial resolution (20 km) for the basins of the Black Azov and Marmara seas was used. The system of primitive equations of model has the form:

\[
\frac{\partial U_h}{\partial t} = -[(\nabla \times U) \times U + \frac{1}{2} \nabla \times (U^2)] + f \times U_h - \frac{1}{\rho_0} \nabla \cdot p + D^U + F^U, \tag{1}
\]

\[
\frac{\partial p}{\partial z} = -\rho g, \tag{2}
\]

\[
\nabla \cdot U = 0, \tag{3}
\]

\[
\frac{\partial P}{\partial t} = -(\nabla \cdot (TU)) + D^P, \tag{4}
\]

\[
\frac{\partial S}{\partial t} = -(\nabla \cdot (SU)) + D^S, \tag{5}
\]

\[
\rho = \rho(T,S,p), \tag{6}
\]

\[
w = \frac{\partial q}{\partial t} + U_{hz=\eta} \cdot \nabla_h(\eta) + P + R - E, \tag{7}
\]

where \( \eta \) is the sea level,

\( P \) – precipitation

\( R \) – river runoff,

\( E \) – evaporation;

\( F^U \) – surface forcing terms;

\( D^U, D^P, D^S \) are the parameterisations of small-scale physics for momentum, temperature and salinity;

\( U = U_h + w_k \) is the current velocity vector; the subscript \( h \) denotes the local horizontal vector, i.e. over the \((i,j)\) plane \( U_h \) is the horizontal speed;

\( f = 2 \Omega k \) is the Coriolis acceleration;

\( \Omega \) is the Earth’s angular velocity vector.

The subgrid processes in equations (1, 4, 5) are parameterized as follows. The vertical turbulent viscosity and diffusion were equal to \( 3 \cdot 10^{-6} \) m²/s. The horizontal turbulent viscosity and diffusion were parametrized by a bilaplacian with coefficients of \(-2 \cdot 10^{-10} \) m⁴/s and \(-1 \cdot 10^{-10} \) m⁴/s, respectively. The equation of state (6) is the UNESCO formula. The remaining designations in the system of equations (1) – (7) are as generally accepted.

The discretization of the system of equations was performed using Arakawa’s “C” grid [7]. The momentum equation (1) has the vector invariant form. The MUSCL scheme [8] is used for discretization of nonlinear terms in the transport – diffusion equations (4, 5). In z-coordinate partial step, the depths of the model levels are defined by the reference analytical function as described in the previous section. We used 35 z-horizons. The kinematic surface condition plus the mass flux of fresh water PRE (the precipitation plus river runoff minus evaporation budget) can be expressed as (7) [9]. The time splitting scheme used ensures splitting into barotropic (fast) and baroclinic (slow) mode. Time discretization is carried out by means of a modified leapfrog scheme [10].
3. Numerical experiments.

Previously numerical experiments were performed with different initial values of salinity that were uniformly vertical. These simulations allowed approximately estimating the time for establishing the vertical haline stratification which was about a hundred years. In the future there will be a slow evolution of halocline. The main factors influencing the formation of the vertical haline structure of the Black Sea are river runoff, precipitation and evaporation as well as water exchange through the Bosphorus Strait. In [11] it was shown that the use of the climatic river runoff, precipitation and evaporation gives the ratio of upper to Lower Bosphorus flows close to 2.

As a continuation of these studies five numerical experiments were carried out using the model described above. Simulations used a configuration with a coarse spatial resolution (20 km) for the basins of the Black, Azov and Marmara seas similar to that described in [4]. In this configuration water exchange through the Bosphorus is calculated in the model explicitly. The selected spatial resolution is much larger than the geographical parameters of the strait. Therefore in this paper as in [4] the zonal cell size was artificially reduced. Such a technique proposed by the authors of the model [6] is called a “partially open cell”. With its help the zonal cell size in the Bosphorus was reduced to 2 km. With the same parameters the exchange flow of the Upper Bosphorus and Lower Bosphorus currents is as close as possible to the climatic values [4,12].

Uniform vertical and horizontal salinity and zero flow rate were used as the initial conditions in all simulations. An initial salinity of 8, 12, 16, 18, and 22 ‰ was used in different simulations. The experiments also took into account the negative mass flux on the sea surface which corresponds to the predominance of evaporation over precipitation. In accordance with the results of [4] each simulation was carried out for 65 model years. The state of the basin achieved in the final year of calculation was used for further analysis.

4. The main results of the simulations.

From the analysis of results of numerical simulation it can be noted that due to the influence of the river runoff there is a significant desalination of the upper 40 m layer. Slow salting of the basin goes deeper due to the inflow of high-saline Marmara Sea waters. Desalination of water in the surface layer and salinization in layers deeper than 40 m leads to the formation of halocline in a layer 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.

It should be noted that the experimentally achieved large-scale circulation has resulted solely from water exchange through the Bosphorus and river runoff. The cyclonic motion of water masses prevails in the sea surface layer. In this case the cyclonic circulation is expressed stronger when the initial salinity is higher. At depths below the halocline, anticyclonic vorticity prevails in all simulations.

Table 1 shows the difference between surface salinity and salinity at the bottom (Δ S) depending on the initial salinity. It may be concluded that the difference in salinity Δ S increases with increasing of initial salinity. With an increase in the salinity difference between the surface and bottom layers the salinity gradient in the halocline accordingly increases. With an increase in the initial salinity the thickness of the halocline also changes, therefore an increase in the salinity gradient is not proportional.

Let us now analyze the relationship between the average gradient in the halocline and the salinity difference between the near surface and near bottom layers. As a measure of the average gradient in the halocline we choose the difference Γ between the salinity at its lower and upper bounds taken equal to 40 m and 10 m, respectively. In accordance with the results of [5] we can expect a power-law relationship between the average gradient in the halocline and the salinity difference between the surface and bottom layers. For representativeness Figure 1 demonstrates natural logarithms of these quantities. The same figure also shows the linear approximation of the calculated values selected by the least squares method. The tangent of the slope of the approximation straight line turned out to be 1.27. Since the salt stream in the halocline is proportional to the average salinity gradient their analysis implies its...
exponentiation dependence on the salinity difference between the near-surface and near-bottom layers. The exponent of this dependence (1.27) is close to 4/3 - the same indicator found in [5].

Table 1. The dependence of the difference between surface salinity and salinity at the bottom of the initial salinity after 65 years

| Initial salinity | Δ S       |
|------------------|----------|
| 8 ‰             | -0.26638053918 |
| 12 ‰            | -0.340897897538 |
| 16 ‰            | -0.52433291767 |
| 18 ‰            | -0.606016722887 |
| 22 ‰            | -1.28198430151 |

Thus, as a result of the analysis of numerical simulations, a power dependence has been derived between the flow of salt in the halocline and the salinity difference between the surface and deeper layers of the basin. The index of power dependence is close to 4/3 which corresponds to the results of [5]. The regularity obtained in [5] which relates the salinity drop on the surface and at the bottom of a rotating cylindrical cavity with the flow of salt through halocline remains true for the configuration of the Black Sea. This result is extremely important since it allows reproducing the long-term evolution of the haline stratification of the Black Sea basin on climatic scales with an accurate reference in time.

Figure 1. The dependence of the mean salinity gradient in the halocline Γ on the salinity drop between the near-surface and near-bottom layer (Δρ). The points are the results of numerical simulations, the straight line is their least squares approximation.

5. Discussion
In the present work, on the basis of numerical modeling we investigated the near stationary states of the Black Sea basin with different total salt stock. The simulation results show the formation of halocline at a depth of 10-40 m. Its formation is associated with the desalinizing effect of river runoff on the surface layer of the sea and the influx of saline Marmara Sea waters through the Bosphorus into its deep layers. The depth of the halocline is determined by the intake of salt water at the bottom of the Bosphorus at a depth of about 40 m.

The basin large-scale circulation is formed due to the influence of river runoff, precipitation, evaporation and water exchange through the Bosphorus. In the carried out simulations cyclonic
circulation of water masses prevails above the halocline and anticyclonic circulation – below it. In this regard the results of this study are consistent with the conclusions of [2,5] obtained on the basis of laboratory and numerical studies of motion in a rotating cylindrical cavity.

Numerical simulation also show that in full accordance with the results of work [5] there is a relationship between the rate of salt through halocline and the salinity difference between the surface and deep layers of the basin. This relationship is represented by an exponentiation dependence with an exponent close to 4/3 predicted by theory. The presence of such a dependence allows one to construct a closed system of equations for average salinities in the layers above and below the halocline. The solution of this system of equations will provide an opportunity to tie each quasistationary state to a specific time scale describing various stages of the Black Sea evolution from a freshwater lake to the current state [4,11].

It should be borne in mind however that the real Black Sea basin is subject to both the effects of flooding flows and wind. The influence of the wind greatly enhances the cyclonic circulation in the basin at all depths and causes the development of mesoscale eddies. Seasonal changes in wind and transfrontal water transfer by synoptic eddies changed the salt balance in the upper layer of the sea which may affect climatic changes in the real Black Sea basin. The question of the influence of these processes on the formation of halocline requires further research.

Acknowledgments
This work was fulfilled in FSBIS Marine Hydrophysical Institute Russian Academy of Sciences with the support of the Russian Science Foundation, grant No. 17-77-30001

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