Numerical Simulations of the Black Sea Hydrophysical Fields Below the Main Pycnocline: Validation by ARGO Data

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Abstract. Modeling of hydrophysical fields of the Black Sea for the one year period (2011) is carried out using the MHI z-coordinate nonlinear model with a spatial resolution of 1.6 km. Comparison of the simulation results with ARGO floats data shows a quite satisfactory agreement between the model and the measured parameters below the main pycnocline up to the maximum profiling depth of the floats equal to 1500 m in 2011. The greatest differences for temperature and salinity are in the seasonal thermocline, which is reproduced by the model a few meters deeper in comparison with the data of measurements. In most cases the shift of the thermocline reconstructed is the main reason of the discrepancy between the model and in-situ data in the upper layer. It is shown, that in the layer below 300 m, the circulation features are simulated in a quite sufficient agreement with ARGO data and allow us to describe the field of the deep Black Sea currents.

Keywords: Black Sea · Modeling · Circulation · Deep currents · Temperature · Salinity · ARGO

1 Introduction

The number of recent publications focused on the Black Sea deep circulation [1–4] is rather limited. The most completely reconstruction of the three-dimensional hydrophysical field structure below the Black Sea main pycnocline is carried out by numerical modeling [2–4]. Modern numerical models successfully reproduce the dynamics of the upper sea layer, especially in experiments involving data assimilation of some measured hydrophysical parameters. The prevalent quantity of in-situ measurements is concentrated in the upper layer (depth from 0 to 200–300 m), and satellite remote sensing involves the operative obtaining of information only about the state of the ocean surface. So, as a rule, numerical models are well validated according to field measurements and remote sensing data mainly in the upper sea layer.

At the same time, the deep-water measurements are quite rare. To fill this data gap, in the Black Sea since the beginning of the 2000s such measurements are carried out by ARGO floats [5]. An ARGO float drifts at its parking depth and performs the profiling of the sea water parameters when it ascends to the surface for data transfer via satellite

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or descends back. For the Black Sea, in open access the ARGO data are available since 2005 [5].

In this paper, we compare results of the prognostic numerical experiment on modeling the Black Sea parameters in 2011 and data on the temperature and salinity obtained by ARGO floats during the same period.

2 Model and ARGO Data

The calculation is performed by using of nonlinear z-coordinate ocean hydrodynamics model of the Marine Hydrophysical Institute (MHI) [6]. The bathymetry from MHI Oceanography Database [7] is applied. The SKIRON [8] reanalysis products such as the wind stress, heat fluxes, precipitation and evaporation for 2011 are used as boundary conditions on the sea surface. The sea surface temperature is assimilated daily. The rivers runoff and water exchange through the straits are also taken into account. Sea level, temperature, salinity, and horizontal current velocity are set at the initial moment from MHI reanalysis [9].

The model is implemented on a C-grid, the horizontal resolution is 1.6 km, and 27 z-level is defined vertically. Modification of the MHI model with a spatial resolution of 5 km was early validated in the frame of the MyOcean project [10].

All boundary and initial fields are interpolated linearly into the grid nodes. Horizontal viscosity and diffusion are described by biharmonic operators with constant coefficients of 10^{16} $cm^4 \cdot s^{-1}$ and $5 \cdot 10^{16}$ $cm^4 \cdot s^{-1}$, respectively. The coefficients of vertical viscosity and diffusion are computed using the Mellor-Yamada turbulence close model [11]. The equations of the model [6] are integrated for the period from January 1 till December 31, 2011, and three-dimensional hydrophysical fields for each day of 2011 are obtained.

For comparison with the simulation results, the data from 6 floats drifted at different parking depths and programmed to vertical profiling from horizons of 500–1500 m up to the surface are taken. The ID numbers of the floats, operating periods under consideration and number of profiles are presented in Table 1.

Table 1. ARGO floats in the Black Sea in 2011: operating period under consideration and number of valid profiles.

Float ID	Time range	Profiling depth, db	Number of profiles
7900465	02.01.11–28.12.11	500	70
7900466	02.01.11–28.12.11	500	65
1901200	05.01.11–31.12.11	700/1500	72
6900803	19.03.11–29.12.11	700/1500	55
6900804	19.03.11–29.12.11	700/1500	58
6900805	19.03.11–29.12.11	700/1500	57

So, we considered 377 profiles of both temperature (T) and salinity (S) and processed several decade thousands measurements. Observations covered the abyssal part of the sea and are performed in all seasons.

3 Comparison Results

The deviations of the model temperature and salinity from those measured during profiling are calculated. The spatial resolution of the model is high enough to reduce the interpolation error when the model data are determined at the profiling point. All data are divided according to the character sea layers: subsurface (0–5 m), upper mix (5–30 m), cold intermediate (30–100 m), and main pycnocline (100–300 m). The subpycnocline layer is considered as divided in two parts: of 300–800 m and 800–1500 m depth. The horizon of 800 m is chosen due to the increase in the currents velocities detected at the depth of 800–1000 m [4], and the horizon of 1500 m is the maximum of the ARGO profiling depth in 2011 (see Table 1).

Then the mean values of deviations for each float are averaged and reduced to the model horizons. The results of comparative analysis are shown in Table 2. It is obtained that the maximum of temperature deviations is reached in the layer of 5–30 m and equal to 0.39 °C, and salinity one – in the 30–100 m layer and equal to 0.33‰. Below the horizon of 300 m, the deviation of model values from measured ones does not exceed 0.03 °C and 0.09‰, for temperature and salinity, respectively. So, for the horizons under the main pycnocline, the model results and measured data are agreed enough.

Table 2. The mean and RMS deviations of model temperature and salinity from those measured with ARGO floats.

Depth, m	Temperature, °C		Salinity, ‰	
	Mean	RMS	Mean	RMS
0–5	0.167	0.182	–0.154	0.177
5–30	0.206	0.386	–0.164	0.172
30–100	0.200	0.242	0.007	0.326
100–300	0.107	0.112	0.239	0.231
300–800	–0.009	0.013	–0.072	0.091
800–1500	–0.026	0.027	0.001	0.007

The vertical profiles of T- and S-deviations for all floats trajectories are considered. It is shown that the maximal deviations are observed in summer period. The differences in temperature can reach several degrees in the upper mix layer. Figure 1 illustrates an example of mean and average T- and S-deviation profiles for the float 6900803. The data are used for the period March 19 – December 29, 2011 – from the float deployment till the last station before the end of 2011.

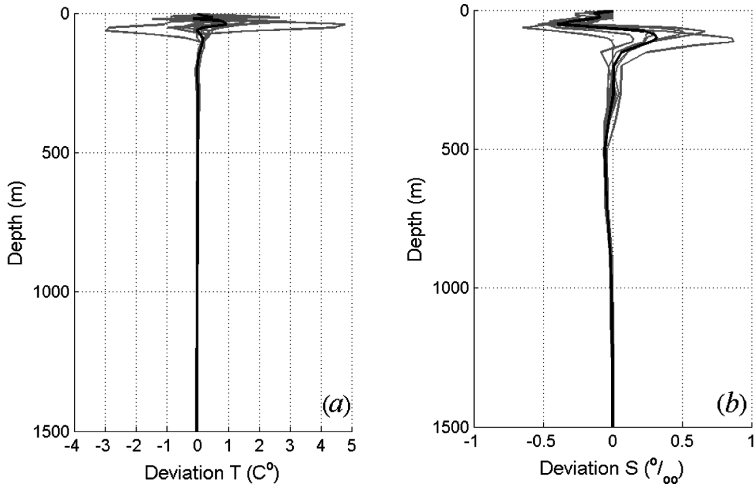

Fig. 1. Vertical profiles of the mean-track (black line) and deviations (grey lines) along the float 6900803 trajectory: a – temperature; b – salinity.

There are at least two possible reasons of these deviations in the upper layer. Firstly, the intensive mesoscale eddies causing an upwelling or downwelling are formed in summer [12], and it could lead to significant density variations. Such vortex structures could not be reconstructed by the model with the sufficient accuracy. Secondly, in the model results, the shift of the seasonal thermocline down several meters can be associated with an inaccurate description of the vertical redistribution of the heat flux, which leads to a deepening of the lower boundary of the upper mixed layer. These effects should certainly be eliminated, but also at the present time, the model shows quite satisfactory agreement in the subpycnocline layers under consideration. As seen in Fig. 1, the deviations are quite small on the horizons of more than 300 m. As an example, the deviations of T and S at lower horizons are shown in Fig. 2 for the same float 6900803 along its track in 2011. It is obvious that, for both temperature and salinity, the deviations are quite small and in some cases are comparable to the accuracy of the sensor measurements sated on Argo floats (0.002 °C and 0.005‰ correspondently).

In comparison to amount of temperature and salinity measurement data, the database of currents in the Black Sea is the most deficient [1, 13]. Moreover, the data of deep current soundings are in the greatest shortage. Measurements of currents by the ARGO floats are not carried out. Based on the displacement of the ARGO floats, the lagrangian velocities on their parking depth are just estimated from 2 to 6 $\mathrm{cm} \cdot \mathrm{s}^{-1}$ [14, 15]. So, numerical model output data are often used as the basic information on the state of the deep sea. The velocity field under the main pycnocline, obtained in accordance with the temperature and salinity verified, believed to be close enough to the actual picture of the currents.

The analysis of the subpycnocline currents derived from modeling results is carried out. The currents velocity maps for all model horizons are built. It is obtained that the

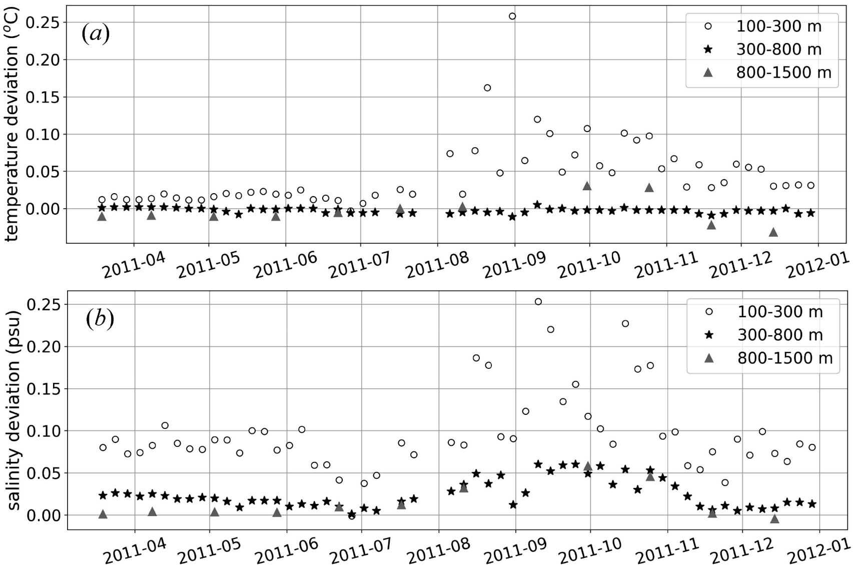

Fig. 2. Along-track temperature (a) and salinity (b) deviations between simulated and measured by the float 6900803.

basin-scale circulation is generally cyclonic. The qualitative structure of the circulation, corresponding to the surface one, is saved up to the depth of 500 m. The seasonal intensification of currents is observed in winter and autumn. The average velocities in the lower layers are in an order weaker than the surface ones. The mean values are about 2–5 cm • s^{-1}, and the instantaneous ones can reach 15 cm • s^{-1}. The structure of the velocity field in the layer of 500–900 m is unordered and consists of numerous eddies and currents. Several steady eddies with dimensions over 100 km and orbital velocity of about 10 cm • s^{-1} are located in the central and eastern parts of the basin throughout the year.

Some features of the currents field not typical for the general cyclonic circulation scheme are found at a depth of about 1000 m and more. Anticyclonic flows within the velocity of 3–10 cm • s^{-1} are detected in different parts of the Black Sea along the continental slope. These currents are about 10 km wide; their lifetime ranges from one up to several weeks, and they are found in all seasons. For areas characterized by the anticyclonic deep currents, normal to the shore sections of along-shore velocity are drawn. As an example, cross-sections normal to the shore near the Bulgarian (28°0′ E; 42°0′ N) and the Caucasian (39°12′ E; 43°54′ N) coasts in August 2011 are shown in Fig. 3. It is obvious that in these areas currents change their direction at horizons of 700–1100 m. Positive velocities correspond to the cyclonic currents, and negative values refer to the anticyclonic ones. Note that the velocity modules near continental slope at the depths of 300–500 m and 900–1100 m are close.

The modeling results are agreed with the data of numerical experiments on the reconstruction of climatic circulation of the Black Sea [16], field measurements [1] and prognostic numerical experiments [4].

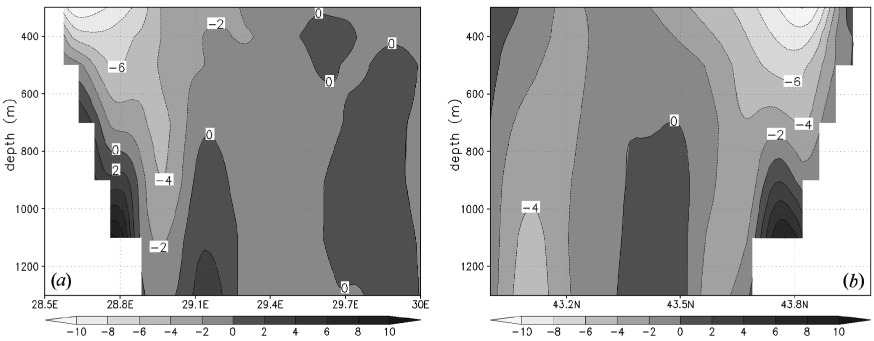

Fig. 3. The along-shore component of the velocity (cm · s^{-1}) on the normal to the shore sections: a – at point (28°0′ E; 42°0′ N) and b – at point (39°12′ E; 43°54′ N).

4 Discussion

We compare the model temperature and salinity of the Black Sea with ARGO measurements in 2011. It is shown that the greatest deviations are obtained in the upper layer of the sea. This is primarily due to the fact that the model reproduces the seasonal thermocline some deeper than the one obtained from the measurement data.

As well, it was found that in the deep layers, the differences between the model and the measured data are in order less. At the horizons below the main pycnocline, the deviations of the calculated temperature and salinity from the measured ones are quite small (of the order of 10^{-2} °C and 10^{-2}–10^{-3} ‰, respectively). So, we admit the temperature and salinity to be correct. The minimum errors are reached at depths of 500 m and more. This fact allow us to consider the model field of deep currents and to reveal its features such as eddies and narrow along-slope anticyclonic currents at horizons of 700–1100 m. In this regard, the present version of the model is seems to be suitable for investigation of the deep Black Sea. However, for the full realistic picture of the circulation, the parameterization refinement of the heat vertical redistribution in the upper sea layer is obviously required. We also hope for increase the number of measurements of the velocity of deep currents in order to be able to verify the velocity field as well.

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