On the Black Sea deepwater circulation features derived from numerical modeling and measurement data

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Abstract. The Black Sea deepwater currents below the main pycnocline at the depths more than 350 m are considered. Current velocities derived from different datasets are compared. Results of two numerical experiments with MHI non-linear z-coordinate ocean model, estimates of deep Argo float velocities, and in-situ data accumulated in MHI Database are analyzed. It is shown that sub-pycnocline velocities obtained by simulation with MHI model and SKIRON atmospheric forcing generally correlate with Lagrangian deep Argo velocity estimations and MHI Database mean velocities. Existence of deepwater cyclonic and anticyclonic vortexes is drawn from the datasets under consideration. The qualitative difference between modeling results and measurements is the narrow quasi-periodic currents along the northeast continental slope which are not succeeded to verify by available data of Argo and MHI Database collected so far.

1. Introduction
Main structure peculiarities, variability, and dynamic characteristics of the Black Sea surface circulation are generally quite well investigated. A number of large-scale and mesoscale circulation features in the top layers of the sea, such as Rim Current propagating above the continental slope, synoptic-scale cyclonic gyres in the western and east parts of the sea, mesoscale eddies between Rim Current and the coastline, quasi-stationary vortexes such as Sevastopol and Batumi anticyclones, etc are found out. This result was reached as by lots of measurements including surveys and satellite observations, as by hydrodynamical modeling. At the same time, there is a lack of works focused on studying currents in deep Black Sea including numerical simulations. Often the deepwater circulation study is a rather small part of more general research.

Some early publications on the Black Sea dynamics concerned the availability of anticyclonic circulation opposite to Rim Current ("counter-currents", "reverse circulation") in deepwater layers. A number of theoretical researches and calculations using field data proved the possibility of the existence of reverse circulation. For example, arguments for the counter-currents presence inside the main pycnocline are given in [1, 2]. At the same time, in research [3, 4] based on trajectories of 3 and 7 profiling floats no counter-currents were detected.

Although the discussion about the existence of such currents has a long history, opinions differ widely. Recently in publications concerning the Black Sea dynamics simulations with different numerical models some mentions about anticyclonic currents in deep layers have appeared. Existence of such counter-currents was established, for example, in modern modeling results [5-7]. So it seems to important to revise and compare new modeling results and other available datasets to make more
clear the character of the deep Black Sea circulation. Our study starts with four available datasets, we use the results of two different numerical experiments, Argo floats data, and MHI Database current velocity measurements.

2. Experiment 1 (modeling climatic currents)

In the first numerical experiment, the Black Sea climatic fields were simulated with three-dimensional nonlinear z-coordinate MHI model [8] which is one of the most well-established models of the Black Sea dynamics. It was included into the number of international projects and used as a part of operating marine prognosis system till now [9, 10]. The model allows us to reconstruct the full structure of main hydrophysical fields as temperature, salinity, horizontal currents, vertical velocity, and sea level in the basin. The climatic experiment successfully was carried out as part of our mostly methodological study [11], but the results of these computations were not compared with the data of numerical modeling and field measurements in such way we are going to use now. Moreover, it is climatic experiment that allows us to obtain the most general characteristics of hydrophysical fields. So we decided to look at the data calculated before from another side and to use the data for nowadays purposes.

We give a brief description of some particularities of the Experiment 1 running. The procedure of assimilation of mean in-situ temperature and salinity [12] interpolated to the model grid was applied. That technique was developed in [13]. Climatic boundary condition including atmospheric ones were used on the sea surface, and in the straits and river mouths. An annual cycle of the climatic hydrophysical fields on 45 levels vertically (2.5-2100 m) was obtained; the step by both horizontal axes was equal 5 km. The calculated fields were recorded daily.

To analyze the deepwater circulation, we select several standard hydrological horizons below 350 m. Generally the cyclonic type of basin-size deep circulation is presented but there are some structure features found out. There is a number of deepwater mesoscale eddies of different sign in which the maximum velocities at the horizons (5-8 cm s\(^{-1}\)) are established.

In Sevastopol anticyclone area, it is found that the sign of rotation of this vortex at the depth of about 400-450 m is changeable. Such behavior (change of the rotation direction) of deep vortexes was described, for example, in [14]. The complicated vertical structure of this vortex has been fixed repeatedly during expeditions [15, 16]. It was supposed that the rotation change was caused by the change of the direction of a barotropic component of a radial pressure gradient [14].

Along the northeastern continental slope at depths below the permanent pycnocline the circulation reverse Rim Current is shown. This feature is presented in the layer of 700-1500 m in spring and summer. The counter-current originates in the region of the Bulgarian coast and is directed anticyclonic towards the north-Caucasian coast. The absolute values of the mean climatic velocities are rather low (see table 1).

| Dataset                | Mean velocity (cm s\(^{-1}\)) |
|------------------------|-------------------------------|
|                        | \(z=500\) m  | \(z=750\) m  | \(z=1000\) m | \(z=1500\) m |
| Experiment 1 (climatic)| 1.1            | 0.9           | 0.8           | 0.8           |
| Experiment 2 (2011)   | 3.7            | 3.2           | 3.1           | 3.4           |
| Argo                  | 3.6            | 4.0           | 5.7           | 3.5           |
| MHI Database          | 4.6            | 2.8           | 6.2           | –             |

The maximum velocities of the counter-current do not exceeds 3-4 cm s\(^{-1}\), its average velocity is about 1.5-2 cm s\(^{-1}\). The background mean velocities hardly reach 0.5-1 cm s\(^{-1}\). In the area of the north-Caucasian coast which characterized by narrow continental slope, this current is found to start at higher horizons of about 350 m. So, the upper boundary of the climatic counter-current approximately corresponds to the main pycnocline bottom boundary in this region.
The comparison of the modeling results with the data of some non-assimilated hydrological surveys showed that the most differences between the model and in-situ temperature and salinity are in the shallow coastal zone. In this area the variability of the hydrophysical fields is typically most high due to a number of external factors. But the climatic fields are reconstructed under more smooth boundary conditions and do not assume such high-frequently response. In other circumstances, on more large temporal and spatial scales, the behavior of the climatic temperature and salinity is quite close to the measurement data. Corresponding climatic currents picture indicates well known hydrological features of the upper layers but characterized by low velocities. So, we can use climatic calculation data for the purpose of comparison with measurement data preferably averaged, but mostly qualitatively and offshore.

3. Experiment 2 (modeling for 2011)
Recently the second experiment was carried out with the same MHI model, but with some differ model parameters and atmosphere forcing (SKIRON reanalysis data for 2011 is used). The horizontal resolution of the model is improved up to 1.64 km. The experiment is conducted without assimilation of archive temperature and salinity.

It is shown that some mesoscale and sub-mesoscale structures of hydrophysical fields obtained for 2011, are absent in the previous experiment results. It is not unexpected, since the climatic experiment assumes the use of smooth atmospheric fields (wind field, heat and moisture flows) and its spatial resolution is three times worse. Actually, to reconstruct spatial sub-mesoscale features, a high model resolution are strongly required. And to get high-frequent temporal variability, the real forcing is needed.

In 2011 in deep layers the average velocities in relation to climatic ones are 3-4 times higher and equal 3.1-3.7 cm·s⁻¹ (see table 1). The maximum values of the velocity are 14-18 cm·s⁻¹ and achieved in mesoscale eddies.

Figure 1 shows the currents field at 1100 m horizon in spring, obtained in the climatic simulation (a) and in the modeling hydrophysical fields in 2011 (b). The climatic field is smoother and the velocities are lower. Apparently, the southeastern current along the continental slope of the Caucasus region (counter-current) is present on the both experiment pictures. The number of mesoscale eddies is also shown including ones in the regular area of Batumi anticyclone.

![Figure 1. Deep currents in the Eastern Black Sea (April, 11; Depth 1100 m): (a) – Experiment 1 (climatic velocities), (b) – Experiment 2 (velocities in 2011).](image)

Results of the Experiment 2 allow us to detail some characteristics of counter-current of anticyclonic orientation. It is about 5-9 km in the transverse direction, and propagates at the depth of
about 1000 m along the steep and narrow continental slope. Unlike the climatic experiment, in 2011 the intensity of this counter-current is not seasonally depends, but quasi-periodically fluctuations of 1-2-3 weeks are present. It suggests an idea that such currents might be forced by low frequency waves.

4. Calculations with Argo floats data

Any simulation results require verification by in-situ measurement data. For this purpose, the data of the Argo floats, which are freely available (http://www.usgodae.org), can be used. However, the floats are not able to measure currents directly.

The average velocities of the floats underwater movement can be estimated only from the data of their positioning at the surface by the satellites. It seems that the average float velocity at the parking depth is easy calculated, but there is a problem on the assessment of a buoy velocity shift during its ascent and descent stage. The float velocity is ordinary calculated as the ratio of the drifted distance underwater to the time. This method does not take into account the peculiarities of the buoy duty cycle. Therefore, there are errors caused by effect of faster currents in upper layers, during the float ascent for communication with the satellite and its descent to the parking depth. This problem is discussed for example in [17]. Some sophisticated algorithms offered to solve the problem. But as far as we know, there are no published works on successful filter of such errors for the Black Sea floats to date. Further we plan to specify the calculations of Lagrangian velocities of Black sea deep Argo floats as an additional research. But now, as the first iteration, we use the same technique as in earlier works [3, 4] and recent [18] and so confined with a rather rough estimate the value of mean velocity derived from Argo.

Although we use the same calculation method, the most complete decadal Argo data array 2005-2015 is processed. The data of 16 Argo deepwater floats with parking depths of 450 m and lower are considered. Preliminary discussion and data statistical processing was reported in [19]. The selected floats drifted at the parking depth of 450, 500, 750, 1000, 1300 and 1500 dbar. Due to the peculiarities of the bottom relief the buoys sometimes moved above the programmed levels. Therefore, we have to check the information for each float and consider its possible grounding. Taking into account the actual depth of the drift, the found velocities are tied to layers of 350-600, 600-800, 800-1200, and 1200-1600 m. The highest values of the velocities are reached in January-March, and the lowest ones from June till October. The values of the obtained float mean velocities are given in the table 1 (in the rows of standard horizons included into the corresponding layers).

They can be traced by the trajectories of the Argo floats (figure 2). At the figure we coupled the trajectories into layers of 350-800 and 800-1600 m for easy perusal. Vortexes of predominantly synoptic scale are found in the central and western parts of the sea, and smaller ones in the eastern part. The presence of mesoscale structures in the Batumi, Sevastopol and Sakarya anticyclone zones is apparent. Along the Anatolian coast, a significant part of the trajectories of deepwater floats follow along the continental slope to the east. This behavior is consistent with the mechanism of the spread of heavy Mediterranean waters propagating from the Bosporus Strait.

5. In-situ deep currents measurements

We considered data of direct in-situ measurements of currents velocity in the Black Sea of different years. This massive is collected in Database of currents, which is the part of the MHIDatabank [20]. The data of 4000 soundings at 25 oceanographic deepwater stations (locations see at figure 2) are suitable for statistical estimation. We selected data at three standard horizons: 500, 750 and 1000 m. The 1500 m horizon is not taken into account due to lack of data. Statistical processing of the sample is performed. The average deep currents velocity is given in table 1. The mean value is of the order of some centimeters per second. The sample contains a number of extremely values as high as 80 cm·s⁻¹, which need to be filtered out. To exclude such non-realistically data, the third quartile of the velocity modules at each horizon is considered. Thus, 25% of the highest values are discarded. After the filtration, the maximums of instantaneous velocities are equal: at a depth of 500 m – 45 cm·s⁻¹, at
750 m – 13 cm·s\(^{-1}\), and at 1000 m – 15 cm·s\(^{-1}\). The median values are accordingly equal to 24 cm·s\(^{-1}\) at a depth of 500 m, 12 cm·s\(^{-1}\) – at 750 m, and 15 cm·s\(^{-1}\) – at 1000 m. But the contribution of small near-zero velocities is considerable and the mean values are got to be quite moderate.

At certain stations, a significant increase (2 or more times) in currents velocity from the surface to the maximum depth of soundings (500-1000 m) is obtained. The direction of circulation at some stations radically changes with depth, but at some it is practically constant. At third ones, it was not possible to allocate the prevailing direction of currents, because the probe has perhaps got to a vortex zone. We can assume then the existence of relatively powered dynamical structures on the weak background in the deep Black Sea.

Since the in-situ data belonged of different periods, and the distance between the stations is quite significant, we are not able to unambiguously reconstruct a map of deepwater currents only on their basis. However, the data of the MHI Database of currents allow us to evaluate the variability of the currents vertical structure.

![Figure 2. Argo profiling floats trajectories (at 350-800 m – dash lines, at 800-1600 m – solid lines) and MHI Database deepwater stations locations (black squares).](image)

6. Discussion

Numerical modeling seems to be the most informative method for studying the structure of the Black Sea currents. It provides full coverage of the entire basin with data. The use of the MHI climatic model allows us to obtain a four-dimensional structure of the current field, analyze its annual cycle and specify the deep currents features not identical with the surface ones.

As a result of the modeling, elements of reverse circulation are found in the form of anticyclonic counter-currents along the northeastern continental slope at depths of about 1000 m. They are present quasi-periodically in spring and summer as drawn from the climatic experiment, and in all seasons according by the results of experiment with real atmospheric forcing. The counter-current passes to the south of the Crimean Peninsula toward the North Caucasian coast and further to the southeast. In the climatic experiment the counter-current is obtained quite wide (8-20 km in transverse direction), and in Experiment 2 its width is 5-9 km.

By modeling, it is found a number of mesoscale (of the order of several tens kilometers) cyclonic and anticyclonic deepwater vortex structures. It is in these eddies that the highest velocities are attained. The trajectories of deep Argo floats confirm the presence of such features. The high current velocity and direction variability at some in-situ stations could be due to the probe getting into a vortex zone. Thus, in-situ measurements indirectly confirm the presence of vortex structures in deep
layers. That conclusion is agreed with results [21] inferred from the processing of survey temperature and salinity data.

The absolute values of climatic currents are low first of all due to the use of averaged atmospheric conditions. This values differ significantly both the results of Experiment 2 and the estimates of the average velocity with measurement data. For comparison, the mean values of the current velocities derived from different datasets are summarized in table 1. It is obvious that the most agreement between the mean velocities from all datasets excluding climatic is achieved at horizons of 500 m (velocity range 3.6-4.6 cm·s⁻¹), 750 m (2.8-4.0 cm·s⁻¹) and 1500 m (3.4-3.5 cm·s⁻¹). The mean velocities from Experiment 2 are most consistent with the estimates from Argo data. The most difference in the mean values is at the horizon of 1000 m, where the counter-currents are modeled and the highest Argo velocities and in-situ ones are reached.

The obtained results generalize the information from the considered datasets. It is clear that the basin circulation is generally cyclonic, but in deep layers it is not as strong and emphasized as in upper ones. There are some dynamic features (vortices, currents) with relatively high velocities that require an additional study to describe the Black sea deepwater circulation more definitely. At date there are some disagreements in important details. In particular, the presence of reverse circulation elements in model fields is not confirmed by data of Argo and in-situ currents measurements under consideration. Therefore, this research will be continued. For a better understanding of the deep Black Sea processes, in future research we assume to use measurement data from alternative sources, carry out additional simulations, improve calculation methods, etc.

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