Variability of the Black Sea deep-water circulation based on hydrophysical reanalysis results

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Abstract. Results of the Black Sea hydrophysical field reanalysis for the period of 1992-2012 are considered. The simulation was carried out using z-coordinate non-linear ocean model of the Marine Hydrophysical Institute. The hydrophysical fields were calculated with resolution of 4.8 km horizontally and by 38 vertical levels along the depth from the sea surface to the bottom. In contrast to a number of previous works, the focus now is on studying the variability of the Black Sea circulation below the main pycnocline (horizon of 300 m and deeper). Analysis of instantaneous and mean velocity fields is carried out, and main structural features are found in deep layers of the sea. It is shown that the most intensive dynamic structures are mainly the cyclonic mesoscale eddies moving from 33-38°E westward and passing through the abyssal central part of the sea. The problem of the existence of reverse (anticyclonic) deep currents opposite to the surface ones is also considered. It is shown that along the narrow north-eastern continental slope such currents exist occasionally. They are formed on the background of topography regional features mainly in summer and could be associated with the weakening of the overlying cyclonic Rim Current.

1. Introduction
Investigations of the variability of the Black Sea dynamics are conducted continuously. Some of them are based on the results of hydrophysical reanalysis. With the use of the MHI model [1], a large amount of such works was recently carried out to study the general circulation of the Black Sea and to analyze the hydrophysical fields in detail – but mostly in the sea upper layer [2-5]. In this paper the main attention is paid to the study of the general structure and variability of the deep-water circulation. Horizons below the Black Sea main pycnocline (300 m and deeper) are dominantly under consideration.

The problem of reliable description of the structure and variability of hydrophysical fields in the deep layers of the Black Sea has not been yet solved. The lack of measurement data, especially direct measurements of the currents velocity [6], forces the use of numerical experiment data as the most applicable basis for research.

So, structure elements of simulated velocity fields below the main pycnocline and their evolution are currently in the focus. In particular, the problem of the existence of reverse deep currents in the Black Sea is of interest. Nowadays it is believed that the general structure of the Black Sea deep circulation is cyclonic, in accordance with the direction of the Rim Current in the upper layer. But from time to time information appears about the detection of reverse (anticyclonic) currents in one or another part of the basin. The question of the presence of reverse circulation elements along the
continental slope of the Black Sea was recently touched upon in [7]. That study was performed using the results of 1.6-km horizontal resolution prognostic numerical experiments for certain periods of 2006, 2010 and 2013. The existence of such currents was found, mainly, at the region of the northeastern continental slope and this is presently confirmed by data of the only 3-day deep-water field experiment using “Aqualog” profiler [8]. Similar quasi-periodic (1-3 weeks) structures were also presented by results of the climatology experiment [9], obtained on a 5-km spatial grid. Thus, the additional motivation for present research is to solve the specific problem, whether the reverse currents are restored by results of the long-term (21 year) reanalysis involving assimilation of measurement data.

2. Data
The results of a retrospective analysis (reanalysis) of the hydrophysical fields of the Black Sea for the period of 1992-2012 are considered. This dataset is obtained by the numerical experiment using z-coordinate nonlinear ocean dynamics model of the Marine Hydrophysical Institute (MHI) [1]. Now the dataset is a part of the archive of the Experimental Center of Marine Forecasts MHI [10, 11]. It contains the simulation results of the sea level and distribution of temperature, salinity and horizontal velocities on 38 horizons from the sea surface to the bottom. The resolution in the horizontal directions is 4.8 km, the data are recorded daily. ERA-Interim atmosphere forcing [12] is used on the sea surface. Satellite data on sea surface temperature and sea level anomalies, as well as in-situ temperature and salinity profiles are assimilated. The data on currents velocity under consideration are the completely modeling result, which is originally agreed with the model output fields corrected by the assimilation of observational data. Other parameters of the model correspond to those described in detail in [10].

3. Analysis
When analyzing the instantaneous and statistically processed fields of currents, a number of plots and maps of their temporal and spatial distribution are drawn, and the most common features of the deep-water circulation of the Black Sea are revealed.

A preliminary analysis of the three-dimensional instantaneous velocity fields during 7672 days (21 years), which we are considering, allows us to note their most common characteristics on horizons below the main pycnocline. Thus, on the horizon of 300 m (which is considered the lower boundary of the pycnocline) some structures more characteristic of the upper layer of the sea are still traced. At the western boundary of the basin in the cold season, the lower part of the Rim Current is observed, but with much low velocity (up to 10 cm·s⁻¹) than on the sea surface. The Sevastopol, Batumi, Caucasus, Sakarya and other quasi-stationary mesoscale anticyclones can also be traced on the 300 m horizon, dominantly when they are of a quite developed stage on the sea surface. At lower horizons the field of currents is obviously characterized by considerable variability. The general orientation of the deep circulation is cyclonic as well, but unlike the surface one, there is no uniform current around the basin. The main structures are eddies with a diameter of up to 1-2° and short-lived (up to several days) narrow currents, mainly generated by eddies near the solid boundaries of the basin.

To perform a more complete analysis, statistical processing of the velocity components over the 21-year period is carried out. Thus, the monthly mean values of the velocity components are calculated. On the average, the absolute values of the velocities in the sub- pycnocline layer are of an order of magnitude lower than in the upper layer of the sea and rarely exceed 5 cm·s⁻¹.

A study of the monthly mean velocities on horizons below the main pycnocline has allowed us to reveal the following features of the annual cycle of deep-water circulation.

3.1. Horizon 300 m
Horizon of 300 m is accepted to be the upper boundary of the sub- pycnocline. During the winter, the highest values (5 cm·s⁻¹) are reached in a stream moving eastward from the Bosporus along the western part of the Black Sea Anatolian coast. Around 34° E this stream turns north towards the center
of the basin and generates a vortex dipole. In spring (March-April), the formation of quasi-stationary Sevastopol and Batumi anticyclones begins and by May they have already formed. Their size and velocities are several times smaller than near the surface. Since March, the presence of an anticyclonic current along the Caucasian continental slope (between Gelendzhik and Sochi) has been detected (figure 1, a). It is formed in the warm period between a group of anticyclones and a quite narrow continental slope. In other parts of the basin the currents along the continental slope are cyclonic. As a rule, at the periphery of the basin, the average current velocities are less than 2 cm·s⁻¹. At this depth the lifetime of the Sevastopol anticyclone is limited to July, and the Batumi anticyclone dissipates by the second half of September. The velocities in both eddies do not exceed 3 cm·s⁻¹. In July we also note the emergence of two anticyclones in the region of the Caucasus coast. In August, the eastern and western parts of the sea are covered with cyclonic gyres, which are more typical of the upper layer, and an anticyclone is formed near the southeastern coast of the Crimea. There are no stable eddies on the horizon during the cold season from October to March. It is primarily attributed to the strengthening of the overlying Rim Current due to seasonal intensification of the wind stress. So, the circulation structure at the horizon of 300 m is close enough to the upper layer one.

3.2. Horizon 500 m
At the depth of 500 m, mainly cyclonic eddies begin appearing in the abyssal central part of the sea, moving then to the west. In January, such an eddy forms between 33° E and 38° E, and by February it grows in size, stretches and shifts westward. The maximum of velocities of up to 5 cm·s⁻¹ is achieved in these eddies, against a background of velocities lower then 2 cm·s⁻¹. Such a behavior of the velocity field in the abyssal part of the sea can be traced at greater depths as well. On the horizon of 500 m, the appearance of the Sevastopol and Batumi anticyclones is delayed approximately for a month from a 300 m horizon one (April – Batumi, June – Sevastopol). In June, the reverse anticyclonic current in the Gelendzhik (Caucasus) area is revealed. Similarly to the horizon of 300 m, in May the stream along the western Anatolian coast turns to the center of the sea and forms 2 mesoscale eddies of different sign. By July, the anticyclonic one retains its size and speed of up to 3 cm·s⁻¹ and the cyclone is weakened. The Sevastopol anticyclone dissipates by August and the Batumi one in the second half of September. In autumn and winter there are practically no eddies on the periphery along the continental slope, cyclonic circulation with typical velocities of about 2 cm·s⁻¹ is observed here.

3.3. Horizon 1000 m
At the horizon of 1000 m in autumn and winter the situation is quite similar. There are no eddies at the periphery of the basin, but cyclones migrating west are formed in the central part. However, there are some differences. In the spring there is no Sevastopol anticyclone on the horizon, but at the same time, in the area of its characteristic presence, several relatively small (15-30 km in diameter) cyclones with rather low velocities (1 cm·s⁻¹) are revealed. From April to July, there is a reverse current along the Caucasian coast from Gelendzhik to the southeast, its velocity is comparable with the average one on the horizon (1.5-2 cm·s⁻¹). The maximum velocities are reached in the above-mentioned cyclonic eddies in the center of the sea. In May, at the center of the abyssal part, between 34° E and 35° E, an anticyclonic eddy is generated. Its velocity is not high (about 2 cm·s⁻¹), and by August a cyclonic eddy has already formed in this place. All the formed eddies move to the west.

3.4. Horizons 1500 and 2000 m
The average velocities on the horizons of 1500 m and 2000 m do not exceed 1-2 cm·s⁻¹. There are cyclones moving to the west in the central part of the sea that already have been discovered on the upper horizons of 500 and 1000 m. The velocities in these cyclones reach 4 cm·s⁻¹. In May on the horizon of 1500 m and in the first half of June on the horizon of 2000 m an anticyclone in the central part of the basin begins to form and then dissipates by August. In summer (June, July) anticyclonic activity prevails in the eastern part of the sea (figure 1, b). At this time, the southeast reverse current
along the continental slope of the Caucasus are detected with average velocities of about 2 cm·s⁻¹. By the autumn, the eddy activity at the periphery of the basin subsides.

**Figure 1.** Monthly mean velocity (cm·s⁻¹) on the horizon of 300 m (a) and 1500 m (b) in June (the area of reverse currents is marked by arrows).

4. **Discussion**

Thus, below the Black Sea main pycnocline the long-term average velocities are rather low (up to 2-3 cm·s⁻¹), the general circulation scheme is cyclonic. In the eastern part of the basin in spring and summer, the deep circulation is characterized by a number of anticyclonic eddies. The most intensive mesoscale dynamic structures are the cyclonic eddies which are generated from the horizon of 500 m and more. They move westward from 33-38°E in the central abyssal part of the sea. In these eddies, the instantaneous velocities can reach 20 cm·s⁻¹ and their mean velocities are 2-5 times higher than the background ones.

Figure 2 shows the map of the standard deviation of the components of the current velocity on the horizon of 500 m. It is obvious that the maximum values (~2.5 cm·s⁻¹) are reached between 33-38°E in the central abyssal part of the basin, which is a zone of eddy generation. The time variation of the velocity components has a maximum in the same region. Thus, in the sub-pycnocline, the internal abyssal region is the most dynamic, in contrast to the surface layer, where the peripheral Rim Current dominates.

On the periphery of the basin, along the continental slope, vortex activity is realized as predominantly anticyclonic eddies, which form in spring and dissipate at the end of summer. The
location, sign and spatial structure of these eddies are not always in accordance with the structures of upper layer, they are largely affected by the topographic features of the bottom.

The analysis of the monthly mean and instantaneous velocities has allowed revealing the reverse (anticyclonic) current moving to the southeast along the quite narrow northeastern continental slope. It is determined on the horizon of 300 m and more and exists in spring and summer. Since March it is detected in the upper part of the sub- pycnocline (depth 300-500 m), since May – on the horizon of 1000 m, and in June - on 1500 m. It is formed between the chain of anticyclonic eddies and the abyssal slope. On the horizon of 2000 m the current is not detected.

![Figure 2. Standard deviation (cm·s⁻¹) of eastward (a) and northward (b) velocity components on the horizon of 500 m.](image)

Comparison of the reanalysis and prognostic simulation results [7] for the same periods shows the agreement as to presence of the reverse current at the northeastern continental slope. As well, reanalysis average fields are consistent with the results of climatic studies [9]. The reverse currents derived from the reanalysis, as well from prognostic experiment [7], are more rare and short-lived dynamic structures than climatic one [9]. The presence of such dynamic structures in the results of experiments of different types makes us more convinced of their existence in nature. Indeed, in some periods the anticyclonic current appears to really form, especially if we take into account the mentioned measurement results [8]. This current occurs mostly in spring and summer, during the overlying Rim Current mainstream weakening and meandering.

In the near future, we are to study the structure of a density field and other experimental results that should allow us not only to describe the variability of the deep-water hydrophysical fields, but also to confirm or reject the possible causes of specific vortex activity and reverse currents in the deep-water part of the Black Sea. As to current velocity data, a more detailed study of inter-annual variability, and a comparison with the data of other model outputs are planned as well.

Besides that, taking into account the low velocities in the deep Black Sea and the lack of in-situ data, long-term, high-precision measurements of deep currents are strongly required. It is clear that
this is difficult to carry out them for the entire sea, but it is realistic to implement these measurements locally in the course of planned regional projects in areas of the most interest.

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