

# The Black Sea Deep-Water Circulation: Recent Findings and Prospects for Research



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## 1 Introduction

In recent years, fundamental studies of the structure of the seawater of the Black Sea and the physical mechanisms of its circulation are constantly supplemented by works on the observation and modeling of processes occurring in its upper layer (0–300 m). These include, in particular, studies on the processing of data from remote sensing of the sea surface, numerical and laboratory modeling, field observations. The main particularities of the upper layer of the Black Sea waters are well known [1, 2]. Thus, the around-basin cyclonic Rim Current with average velocities in the mainstream of 30–50 cm/s is the dominant feature of the upper layer circulation. In the vertical hydrological structure, it is worth highlighting the permanent (main) pycnocline as one of the most significant features that affect the deep-water circulation. The core of the pycnocline lies at depths of 50–100 m. This layer of the maximum vertical density gradient (0.02–0.04 kg/m<sup>2</sup>) is typical for all seasons [2]. Density is determined mainly by salinity. The permanent pycnocline prevents vertical mixing, mass and momentum flows from the surface to the deep layers. The horizon of 300 m is often taken as its lower boundary. Deeper, the circulation acquires characteristics different from the surface one. There, temperature and salinity slowly increase with depth, and the currents are about an order of magnitude weaker than in the upper layer. So, to simplify the description of vertical density stratification, in some Black Sea dynamics models a two-layer approximation is used [3].

The Black Sea waters at depths of more than 200 m contain hydrogen sulfide, and they do not have the oxygen which necessary for the existence of most living organisms. As a result, deep waters—except for anaerobic bacteria—are uninhabited and are of no interest for economic activity, which, in turn, does not stimulate applied research. Based on non-regular deep-water observations of temperature and salinity,

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the dynamical (“the reference level”) method [4] calculations showed current velocities up to 1–2 cm/s, and approximately the same average values were determined with even more rare measurements of current velocities. Thus, the old problem of changing the direction of circulation from surface cyclonic to anticyclonic deeper than 300 m (the presence of a Countercurrent under the Rim Current), posed by Neumann in the 1940s [5], could not be solved on the basis of these irregular data alone.

So, before the start of a series of Research Vessels expeditions in the late 1980s and obtaining new observation data, the Black Sea deep-water circulation was assumed not only to be extremely weak, but also to have no variability (the definition of “deep-water” will be applied to the dynamics at the horizons of more than 300 m, below the permanent pycnocline). Based on the results of the expeditions, a description of some discovered deep-water dynamic structures [6, 7] was made, and the presence of interannual variability was revealed. In the early 2000s, the deployment and the movement monitoring of the first profiling floats showed the presence of a basin system of deep-water currents and made it possible to calculate their average velocities at float parking depths [8]. The presence of seasonal variability of currents at different horizons was revealed, however, according to the data of 3 considered floats, no anticyclonic Countercurrent was found. Thus, profiling floats were first used as Lagrangian tracers to study the current field. Actually, a new stage was opened in the study of the Black Sea circulation.

Great hopes in the study of the three-dimensional dynamics of the Black Sea were also placed on high-resolution numerical modeling, which began to be actively developed in the early 2000s as well. But still little attention was paid to deep-water circulation, since the results of numerical simulations did not yet have enough field data for validation. At the same time, according to some available modeling results, a Countercurrent under the Rim Current or its elements could still exist [9–11].

## 2 Sources and Methodology

Nowadays, the number of publications that present the results of studies of the deep-water dynamics of the Black Sea is still small, and the structure of currents below the permanent pycnocline is still poorly understood. The key reason for this situation is the lack of data and the difficulty of field observations at great depths. The second reason is the disintegration of research results and the data obtained. The first reason seems to be hardly-resistible at the present time, but we can combine available model results and observation data in order to systematize knowledge about deep-water circulation.

Therefore, the methodology of this study was chosen as follows. At the beginning, we analyzed our own results of modeling the Black Sea currents [12, 13] carried out with MHI model [14], climatic atmosphere forcing and assimilation of climatic data of temperature and salinity calculated from long-term observations for each day of

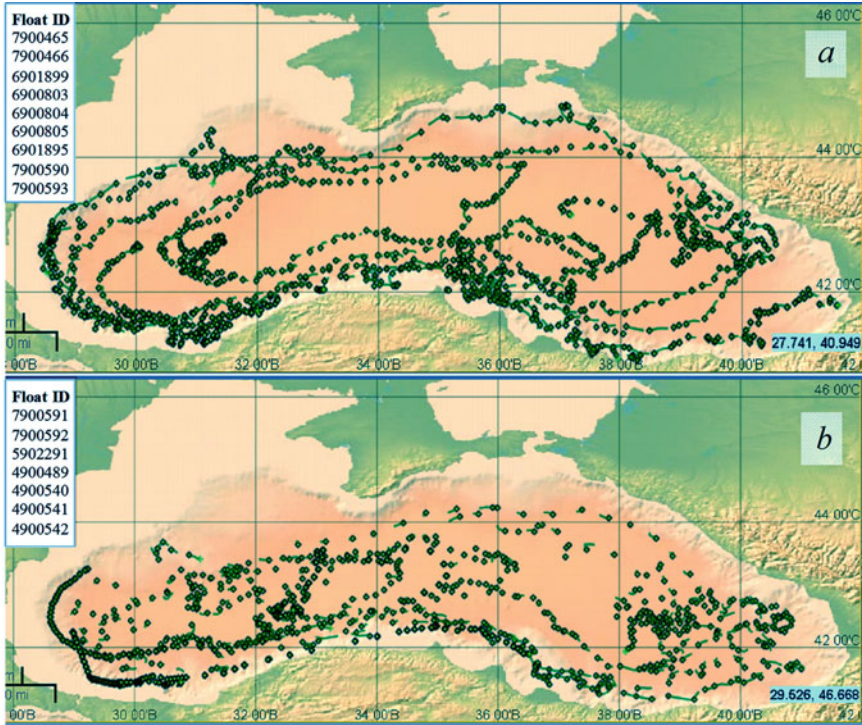
the year [15]. Then the most important features of the simulated (climatic) three-dimensional velocity field calculated for each day of the year were determined. These calculations were compared with estimates of the velocities of deep-water currents in certain areas of the Black Sea, which we also performed on the basis of the available field observation data. Also, we analyzed publications in the scientific literature containing any information about the studies of the Black Sea circulation, and tried to complete the picture of the features of deep-water circulation. Thus, thanks to collaboration with the authors of some publications not focused on the study of deep-water currents [16–19], it was possible to obtain the output data of other simulations with MHI model, process and use these data for a more detailed comparison and study of the characteristics of deep-water currents. Also, the results of a recent research project comparing the results of multi-model simulations of the hydrophysical fields of the Black Sea, carried out at MHI [20], were taken into account. Thus, based on the synthesis of information from various sources, the most complete picture of the deep-water currents of the Black Sea was obtained. All references to the papers and data archives used will be given below in the text of the article.

### 3 Analysis of Observation Data

This section presents the results of the revision and generalization of the currently available field observation data, which was necessary, both for comparison with the modeling results and for assessing the currents in certain areas of the Black Sea. We were able to compare current velocity measurements from the Bank of Oceanographic Data of Marine Hydrophysical Institute (MHI BOD) [21], data of regional observations in the northeastern part of the Black Sea (Gelendzhik test site) [22, 23] and freely available data of ARGO profiling floats [24, 25]. Based on the observation data only, it was possible to reveal some characteristics of the currents in the regions of the measurements.

Thus, the statistical characteristics of the currents at the horizons of 500, 750, and 1000 m were determined from measurements of the current velocities from 25 multi-day deep-water stations of various locations stored in the MHI BOD [26]. Despite the different location of the stations, it is shown that the velocity may be higher than previously assumed. The median velocity at deep-water horizons was varied from 2 to 12 cm/s and exceeded 5 cm/s at 50% of the stations at a depth of 500 m, at 45% of the stations at a depth of 750 m, and at 42% of the stations at a depth of 1000 m.

To study the average velocities of deep-water currents, the data from a 10-year array of observations of ARGO profiling floats (2005–2015) were processed [24, 25]. These data were collected and made freely available by the Coriolis project and programs that contribute to it [24]. ARGO floats carry out regular measurements throughout the Black Sea basin and transmit the data by satellites every 5 days. In Fig. 1 the satellite positioning points for the floats with a parking depth of more than 300 m are showed.



**Fig. 1** ARGO profiling floats trajectories used for the calculations of average velocities at deep-water horizons in 2005–2015: **a**—trajectories of floats with parking depths of 450; 500; 750 m; **b**—trajectories of floats with parking depths of 1000; 1300; 1500 m

It can be seen that the direction of movement of these ARGO floats generally corresponds to the cyclonic direction of deep-water circulation. The presence of mesoscale cyclonic and anticyclonic eddies is also determined. The location of some of them is consistent with the localization of well-known quasi-stationary eddies in the upper layer of the sea (Batumi, Sevastopol anticyclones, etc.). The average current velocities at the parking depths of the floats were calculated from the positioning data on the sea surface (which introduced some error into the calculations), as the ratio of the distance passed to the time of movement. As shown in [25], it is rather difficult to refine the calculation results for the Black Sea due to the almost two-layer structure of the currents in the basin.

The velocities of deep-water currents calculated in such way are maximum near the western part of the Anatolian coast, reach 15–20 cm/s, and are directed mostly along the continental slope. In general, the float trajectories follow isobaths, which was also noted in [8, 27].

The presence of seasonal variability of deep-water currents has been confirmed. Thus, the highest velocities were obtained for the period from January to March, and the lowest—from June to October. The 10-year average current velocities below

the main pycnocline were 3–4 cm/s, and even 6 cm/s in the 800–1200 m layer. A significant number of calculated mean velocity vectors had a value of more than 5 cm/s: 30% in the 350–600 m layer, 45% in the 800–1200 m layer, and more than 20% in the 600–800 and 1200–1600 m layers.

According to the positioning of the ARGO float ID6901833 with a parking depth of 200 m in the area of the IO RAS test site Gelendzhik (north-eastern part of the Black Sea), the movement of the float in the southeast direction was recorded. The lifetime of these currents (local undercurrents) detected was 40 days in autumn 2016 and 10 days in winter 2017 [20]. The presence of unsteady anticyclonic currents along the coast of the North Caucasus is consistent with other observation data obtained at the Gelendzhik test site. These are the shipborne CTD measurements to a horizon of 500 m taken between 1997 and 2008 [23], as well as observations of current profiles to a depth of 1000 m obtained by the Aqualog sounding complex in June 2011 [22]. Thus, according to Aqualog data, the sign of the velocity changed at depths of about 300–400 m, and the core of undercurrents about 3 cm/s was observed at horizons of 750–850 m [22]. According to the calculations using CTD data of temperature and salinity, the presence of undercurrents was also shown in the 0–500 m layer, but at depths of 200–250 m [23].

Thus, using of available observation data, it was possible to reveal some characteristics of currents in the areas of the measurements, but the full three-dimensional field of currents in the basin can be reconstructed only on the basis of modern numerical models.

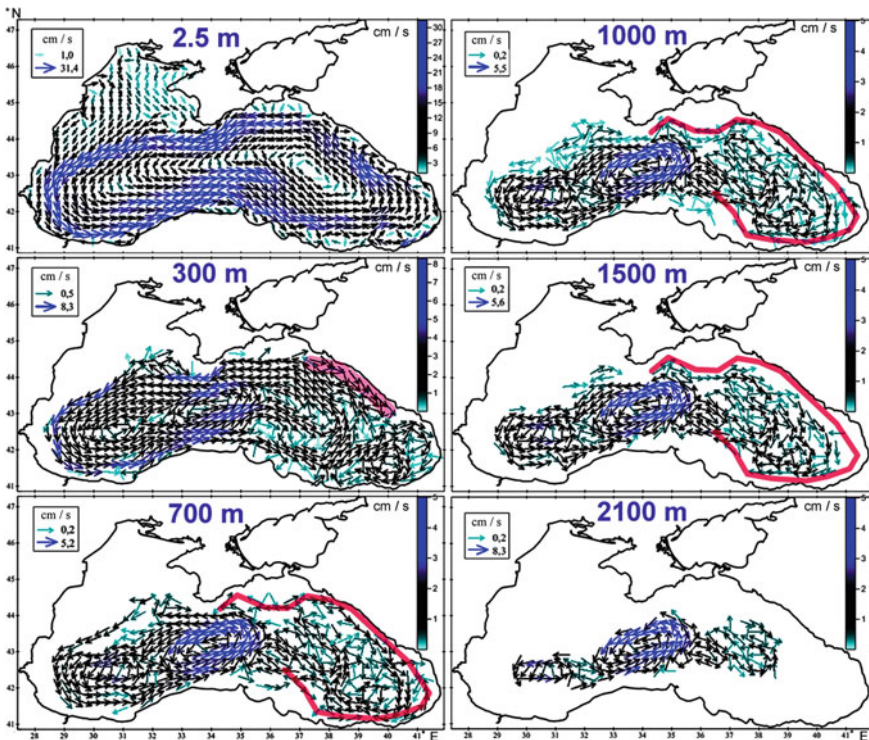
## 4 Comparison of Numerical Simulation Results

To identify and generalize the features of the Black Sea deep-water circulation, a large study was carried out on comparing the output data of several different numerical experiments. These were the results of numerical simulations under different atmospheric conditions, with or without assimilation of observational data, for time intervals from several months to several years, on different grids (from 1 to 5 km), and using different numerical models. Digital arrays of the Black Sea circulation model output data obtained in the works of the author, as well as kindly provided by other authors [16–19], were processed and used to study the characteristics of deep-water currents. Combining the data of the recent studies made it possible to estimate the interannual variability of the velocity field below the main pycnocline and to reveal the features of currents in the deep part of the Black Sea.

Thus, as a result of modeling the climatic fields of the Black Sea based on the MHI model with the assimilation of averaged long-term data on temperature and salinity [12, 13], three-dimensional climatic current fields were reconstructed on a grid with a horizontal resolution of 5 km for each day of the year. Based on the calculated field analysis, the main features of the deep-water circulation were shown. These include the absence of a single Rim Current at horizons below 300 m and the predominance of mesoscale dynamic structures—eddies and currents propagating

along the continental slope. The general character of deep-water climatic circulation is cyclonic. It was shown that below the main pycnocline the average velocities are an order of magnitude weaker than the surface ones. The background values of climatic velocities are less than 2 cm/s, and the highest velocities (up to 10–12 cm/s) are achieved in mesoscale, predominantly cyclonic eddies characteristic of the inner abyssal part of the sea. It has been established that the evolution of deep-water eddies at the depths slope leads to the formation of smaller eddy structures of different signs of vorticity. Below the main pycnocline, the positive temperature anomalies are formed in the centers of cyclonic eddies, and negative ones are formed in the centers of anticyclones. This feature distinguishes the Black Sea deep-water eddies from the deep-water eddies of the ocean and is explained by an increase in the temperature of the Black Sea waters towards the bottom. The calculations of climatic fields showed for the first time the presence of anticyclonic currents (undercurrents) along the North Caucasian coast most pronounced in the spring–summer period (Fig. 2).

In Fig. 2 the climatic field of currents is shown at different horizons on the date April 11. It can be seen that, starting from a horizon of 300 m, anticyclonic currents

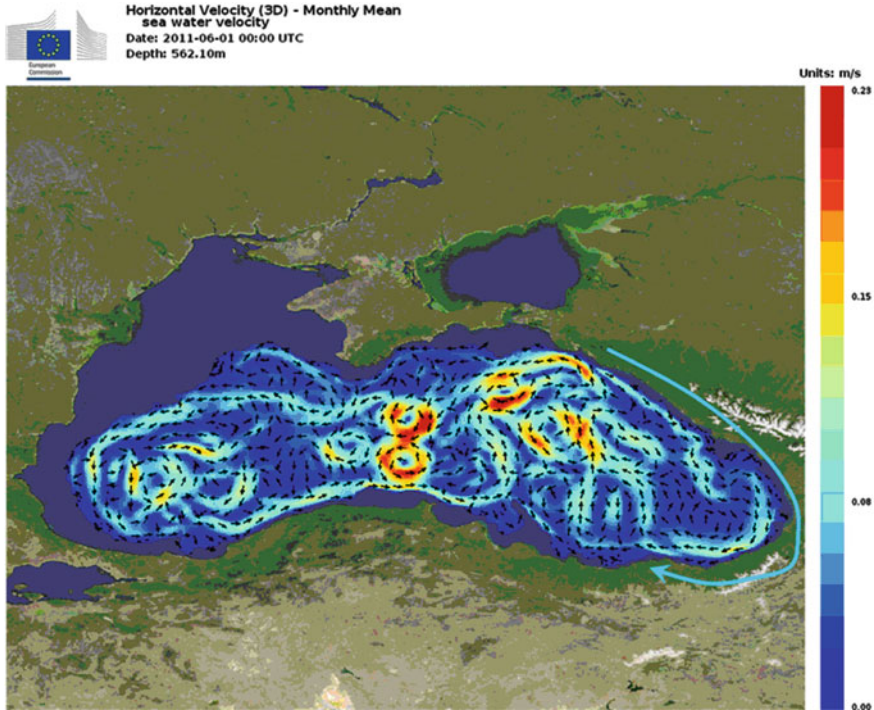


**Fig. 2** The Black Sea climatic currents on different horizons according to simulations with MHI model on April 11 (undercurrents are marked in red)

appear along the northeastern and eastern coasts of the Black Sea. The climatic velocities do not exceed 3 cm/s. A branch of the Rim Current is observed along the western coast, deepening approximately to the horizon of 700 m. In the central part of the sea the most intense dynamic structure is a cyclonic eddy that can be traced down to the bottom.

Processing of the output data of simulations carried out using MHI model but with realistic atmospheric forcing, such as prognostic calculations for 2006, 2010, 2011 and other periods [16, 17], as well as a long-term reanalysis of the Black Sea hydrophysical fields [18, 19], made it possible to refine the understanding of the structure of deep-water currents obtained from the climatic fields. Thus, from the analysis of average daily and average long-term current fields, it follows that the Rim Current as a single cyclonic basin-scale gyre is absent at depths of more than 300 m. However, its western branch in the winter season can even reach a horizon of 1200 m as a narrow current along the continental slope. At depths greater than 300–500 m all simulations showed the background velocities up to 1–2 cm/s, and the presence of mesoscale eddies and currents is revealed, in which the average velocities are from 5 to 8 cm/s, and the maximum velocities reach 15–20 cm/s. Mesoscale eddies in the central abyssal part of the sea are clearly identified from depths of 150–300 m down to the bottom without a significant change in their structure, while at the depths slope, bottom relief features can lead to the transformation of eddy structures and deep-water currents. According to the results of prognostic simulations, the formation of irregular narrow anticyclonic undercurrents in different seasons in the northeastern and other parts of the continental slope was established. The reanalysis data [18, 19] show the formation of undercurrents in the eastern half of the sea, mainly along the North Caucasian coast.

In the paper [20] on modeling and analysis of the Black Sea deep-water circulation in 2011, four numerical models of ocean dynamics (MHI, INMOM, INM-IO, NEMO) were used. The description of the models is given in the work cited. All of them are world-class models successfully reproduced the main well-known features of the Black Sea dynamics. Three of the models are implemented in z-coordinates, and INMOM is a sigma-coordinate model. The resolution of the models was ranged from 1 to 4 km. According to the simulations results, under the Rim Current, below the main pycnocline the anticyclonic undercurrents were also revealed in the northeastern part of the sea. The most intense undercurrents of 4–5 cm/s were reproduced by the MHI model, and the velocity sign changed at a depth of about 900 m. The weakest undercurrents of 1–2 cm/s were reproduced by the INMOM and NEMO models, at depths of more than 600–700 m. The results of this work showed the agreement between the results of all numerical simulations on the presence of undercurrents observed at least in the northeastern part of the Black Sea. The considered simulation results are also consistent with the observations of deep-water velocity profiles by the Aqualog sounding complex in June 2011 at the Gelendzhik test site [22]. Moreover, the available results of NEMO model reanalysis published at [28], confirm the presence of deep-water undercurrent in the northeastern part of the Black



**Fig. 3** Monthly mean velocities for June 2011 at the depth of 562.1 m obtained by NEMO model [28]

Sea in June 2011. As can be seen from the screenshot shown in Fig. 3, the undercurrent followed to the southeast along the coast of the North Caucasus and merged with the Batumi anticyclone (the undercurrent is additionally indicated by an arrow).

It has been established that such unsteady anticyclonic currents (undercurrents) below the permanent pycnocline can also form in the western part of the sea. In the prognostic simulation results considered above [16, 17, 23], they were found in different periods along the Bulgarian coast, as well as along the northwestern part of the continental slope. They were identified at horizons of more than 1000 m, their lifetime ranges from several days to several weeks, the average velocity was 5–7 cm/s, and the maximum was up to 15 cm/s.

The existence of unsteady anticyclonic currents near the continental slope is also consistent with some of the recent results presented in the scientific literature. For example, it agreed with the single-station, but long-term (more than a year) deep-water observations of currents at a horizon of 1700 m southwest the Crimean peninsula [29], as well as the results of climatic current simulation with INM model [30], and the results of modelling using ROMS model published in [31].



## 5 Results and Discussion

The findings of recent studies were combined, that made it possible to assess and detail some features of currents in the deep part of the Black Sea. Based on generalization of numerical simulation results and field observation data, the following features of the Black Sea deep-water currents were found out. There is no single cyclonic Rim Current at depths of more than 300 m, but its most intense western branch is detected down to horizons of 700–1200 m in different years. Background velocities below the permanent pycnocline are less than 1–2 cm/s; however, in mesoscale eddies and currents, the velocity values up to 15–20 cm/s can be achieved. In winter, there is a general increase in current velocities. At depths greater than 300–500 m, mesoscale cyclonic eddies in the central abyssal part of the sea are the most intense dynamic structures characteristic of all seasons. Anticyclonic eddies are less intense and more often observed along the continental slope, and also prevail in the eastern part of the Black Sea in the spring–summer period. In all considered data of numerical simulations and field observations, unsteady narrow currents (undercurrents) were found that propagate in the anticyclonic direction along the continental slope.

The undercurrents were identified by processing and analysis of model output data obtained using different numerical models, with different atmospheric forcing and for different periods. They most often form in the spring–summer season from the lower boundary of the permanent pycnocline to a depth of about 1700 m. Their width reaches 10–12 km, length—from 100 to 700 km, and vertical size—from two to several hundred meters. The undercurrent velocities in the core is from 3 to 8 cm/s, the maximum instantaneous are up to 15–20 cm/s, and their lifetime is from one to several weeks. Near the North Caucasian coast, the presence of undercurrents is consistent with field observations at the Gelendzhik test site and data of ARGO float ID6901833.

The forming of anticyclonic undercurrents in certain parts of the Black Sea can be associated with various processes in the deep layers. Thus, it can be due to the influence of density anomalies, the movement of mesoscale eddies, waves, etc. Since the influence of density field features on the deep-water dynamics of the Black Sea is very strong [20, 32], it deserves close attention and requires more detailed study. The observed variability of velocity at great depths can also be associated with quasi-inertial waves [33], which intensify from September to February. As well, the passage of mesoscale anticyclones along the depths slope can lead to the formation of narrow unsteady undercurrents [34].

For further development of research on deep-water currents, in our opinion, it is necessary to work in several areas, including:

- increase in regular deep-water observations, primarily of the current velocity;
- improvement of the methodology for calculating the velocity of ARGO floats at their parking depths;
- refinement of numerical simulation results, primarily by improving the quality of boundary conditions used (especially bathymetry data and flows through the boundaries, which also requires field observations);

- identification of the causes for the formation of undercurrents and other features of deep-water circulation on the basis of numerical simulations and in comparison with observations.

The foregoing will make it possible to detail the characteristics of the already identified features of deep-water dynamics and to obtain new data. As well as, a more complete and thorough study of the causes of the forming and relationships of the main elements of deep-water circulation with each other, with the dynamics of the upper layer of the sea, and external influences at the boundaries of the basin, should be carried out.

## 6 Conclusion

The recent findings on the Black Sea current field structure below the permanent pycnocline are summarized. They are obtained on the basis of modern research data using advanced numerical models of ocean dynamics and field observations. Despite the still insufficient study of the spatial and temporal variability of the three-dimensional velocity field and the mechanisms that lead to a change in the structure of the currents at great depths, by now we can already talk about the presence of relatively intense, narrow unsteady deep-water currents of the anticyclonic direction, while cyclonic seawater circulation prevails in the Black Sea basin. A single basin-scale Countercurrent under the Rim Current was not found. In the central abyssal part of the sea, on the horizons below the main pycnocline, the presence of predominantly cyclonic mesoscale eddies, which retain their structure down to the bottom, was found out. The estimates of deep-water velocities based both on field observations and numerical simulations results show that the current velocities in the deep layers of the Black Sea can reach 15–20 cm/s.

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