The Black Sea Undercurrents: Observations and Numerical Simulation Results

N. V. Markova and O. A. Dymova

Abstract The aim of the presented study is to investigate one remarkable feature of the Black Sea deep-water circulation. These are unsteady narrow anticyclonic currents that propagate under the main pycnocline in the direction opposite to the surface circulation and are called undercurrents. According to observation data, undercurrents were discovered in several field expeditions, and were also revealed in some results of the Black Sea dynamic modeling. However, due to the lack of regular observations, it was not entirely clear whether they were a real feature of the Black Sea current field or an artifact of the experiments carried out. In this work, to assess the spatial variability of the Black Sea current field and identify undercurrents, the results of modeling the Black Sea circulation for several periods were analyzed. Simulations were carried out using the MHI model, and the results were validated based on deep-water field observation data on temperature and salinity. As well, in the northeastern part of the sea the simulated currents were compared with the data of ADCP deep-water velocity measurements (with Aqualog profiler). It is shown that undercurrents are more often formed in the spring–summer period and their lifetime is from one to several weeks. And although the length of undercurrents along the continental slope can reach several hundred kilometers, their width is only 8–12 km. Such characteristics of undercurrents explain the difficulty of their detection and identification in previous works.

Keywords Black Sea · Deep-water circulation · Undercurrents · Observations · Numerical experiment · Simulation

1 Introduction

In contrast to the current structure of the Black Sea upper 200–300-m layer, circulation below the permanent pycnocline has been studied rather poorly. In the upper layer the circulation scheme was drawn up in the middle of the 20th century according to the

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data of field observations, and later it was only refined. Its general pattern is presented in [1, 2] and continues to be detailed. In the dynamics of the upper Black Sea layer, it is well-known some basic elements, such as the cyclonic Main Black Sea Current (the Rim Current), periodically forming sub-basin cyclonic gyres in the western and eastern parts of the sea, the Batumi and Sevastopol anticyclones, and the series of mesoscale and submesoscale eddies between the Rim Current and the coast. At the same time, there is still no current scheme of the seawater layer below the permanent pycnocline. Moreover, before the beginning of some large-scale expeditions in the Black Sea at the end of 20th century [3], deep-water currents were considered negligible. The results of the research vessel expeditions carried out showed that there are specific current systems with interannual variability at great depths, as well. At the end of the 20th and the beginning of 21st centuries, ARGO floats were started to deploy. ARGO floats drifting on deep horizons could be used as Lagrangian tracers to estimate the current velocity at the float parking depths [4]. Thus, it was confirmed that basin-wide circulation is generally cyclonic and deep currents have seasonal variability, as well. The few data of velocity measurements, indicating the presence of deep-water anticyclonic dynamic structures (eddies, currents) [5–7], have not found a convincing explanation yet. The main reason for the lack of detailed studies is the persistent deficit of field data at depths of more than 300 m. The greatest shortage is evident in the observational velocity data collected over the entire history of observations in the Black Sea. So, the anticyclonic circulation elements observed in deep seawater layers can be interpreted as undercurrents (opposite to the cyclonic currents on the sea surface), or as short parts of deep-water eddies, the evolution of which has not yet been studied.

Nowadays, it is know that in deep layers the average velocities are an order of magnitude lower than on the surface, and a single basin-scale gyre, similar to the Rim Current in the upper layer, is not observed. As already mentioned, a more detailed study of the structure of currents using only observational data is difficult due to the lack of the required amount of data, and a solution to this problem is not expected in the near future. Therefore, in this work, numerical modeling is used as the most effective and least resource-intensive method for reconstructing the three-dimensional structure of the velocity field and studying deep-water currents. But since the results of any modeling still need to be compared with observation data, additional processing of the available data is also carried out. Based on the processing of observation data and comparison with the simulation results, some features of deep-water circulation in the Black Sea, including anticyclonic undercurrents, have been discovered.

2   Simulation and Numerical Analysis

To calculate the seawater circulation in the basin, the Black Sea dynamics numerical model developed at the Marine Hydrophysical Institute (MHI) [8] is used. The complete system of equations of ocean thermo-hydrodynamics in the Boussinesq and

hydrostatic approximations is integrated in numerical experiments. The MHI-model includes the momentum, continuity, hydrostatics, heat and salt advection–diffusion equations, and the state equation [8, 9]. Horizontal resolution of the MHI-model is 1.6 km for the entire basin, with a time step of 1.5 min. The assimilation of observation data is not used in that version of the model, so the simulations are prognostic. The MHI-model takes into account the rivers runoff and exchange through the straits. The boundary conditions are: free slip for solid boundaries, the Dirichlet condition for liquid ones, and the linear kinematic condition at the sea surface. The full model formulation and numerical implementation are presented in [9]. The model is driven by wind and thermohaline forcing of the atmospheric models ALADIN (for 2006), ERA-Interim (for 2010 and 2013), and SKIRON (for 2011).

The structure of the calculated current fields at different horizons is analyzed in detail. Numerical analysis of three-dimensional daily fields of the Black Sea currents for several periods (2006, 2011, autumn–winter 2010, summer 2013) is carried out. Validation of the simulation results is performed on the basis of data from drifter observations [10], ARGO temperature and salinity profiling [11], and research vessel observations [12]. It is shown that all well-known features of the upper layer circulation are reconstructed in numerical experiments. The Rim Current, the seasonal evolution of the Cold Intermediate Layer, and the salinity field features (more saline seawater in the Bosporus region and in the centers of cyclonic eddies, and less saline waters in anticyclones) are reproduced. A similar structure of hydrophysical fields persists down to depth of about 300 m (lower boundary of permanent pycnocline). Some traces of the upper circulation are still found at depths of 300–500 m, such as the lower parts of the western branch of the Rim Current and largest mesoscale eddies.

The velocity field at depths of more than 500 m is characterized by the presence of numerous mesoscale eddies and currents. Mean current velocities are 2–5 cm/s, and background velocities do not exceed 1–2 cm/s. Maximum velocities of 15–20 cm/s are reached in eddy structures. Despite the great depth, a seasonal increase of currents is observed in winter and autumn, as well as in the upper layers. In the abyssal part of the sea some deep-water eddies are revealed. They are not clearly distinguished near the surface, but their structure is clearly traced below a depth of 150–300 m. In the central abyssal part of the sea that eddies retain their structure down to the bottom. The relief of the continental slope bottom can lead to deformation of deep-water eddies and their transformation into eddies of a smaller scale and dissipation.

The presence of deep-water undercurrents is found out. These are relatively narrow, irregular currents propagating in an anticyclonic direction along separate parts of the continental slope, opposite to the direction of currents at the surface. They are found according to the data of all the presented numerical experiments at horizons of 1,000 m and deeper. Undercurrent's wide is up to 10–12 km and it can propagate along the continental slope with mean velocity of 3–5 cm/s and maximum one up to 15–20 cm/s. Their generation is observed in all seasons but more often in the spring–summer period. The lifetime of undercurrents is from one to several weeks. Undercurrents are most often formed at the northeastern part of continental slope in the spring–summer period at horizons of 1,000 m and more (Fig. 1). Note
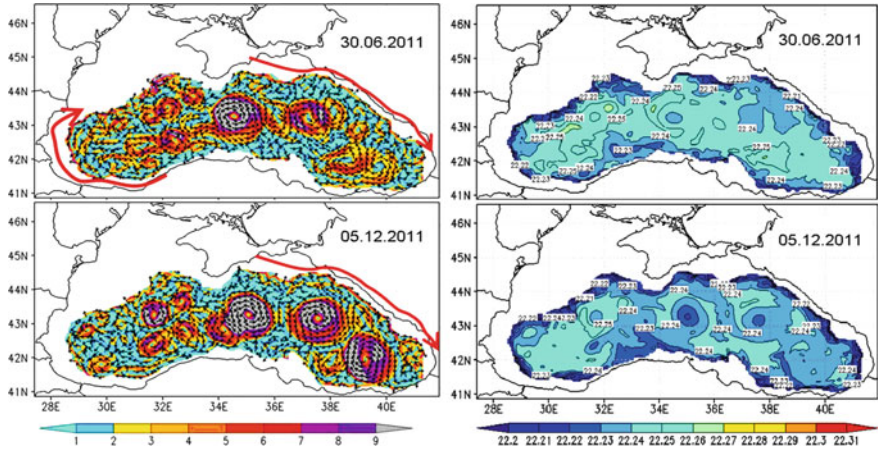
Fig. 1 Modeled fields of currents, cm/s (left panel) and salinity, ‰ (right panel) at 1,100 m horizon according to the simulation results for 2011

also the presence of mesoscale deep-water eddies of different vorticity signs (Fig. 1a) and the corresponding anomalies in salinity fields (Fig. 1b).

The generation of deep-water anticyclonic currents in the western part of the Black Sea occurs less frequently than in the northeastern region. For example, the formation of undercurrents at horizons of more than 1,000 m is found near the Bulgarian coast, as well as along the northwestern part of the continental slope (Fig. 2). Here, the
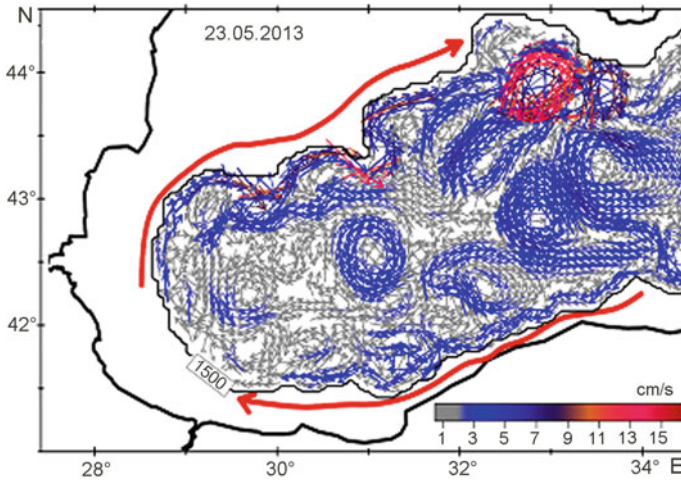

Fig. 2 Modeled currents in the western part of the Black Sea on May 23, 2013 at 1,500 m horizon. Anticyclonic currents are duplicated by additional red arrows

currents are also rather narrow (up to 8–12 km) and it is characterized by lifetime from several days to several weeks. Their mean velocities are 3–5 cm/s, while maximum velocities can reach 9–13 cm/s.

3   Comparison with Observations

The model results are consistent with the data obtained in other works. Thus, the values of the velocities of deep-water currents can be confirmed by information from 16 autonomous profiling ARGO floats with parking depth of more than 350 m. These velocities were calculated over a 10-year period in [13]. In that study it was also showed that the cyclonic direction prevails in the deep-water circulation, and the strongest currents were located above the continental slope. The range of calculated velocities of deep-water currents was from 1 to 20 cm/s, but no undercurrents were identified there. According to ARGO float ID6901833 data, undercurrents were discovered some later—in 2016–2017. The float was moved at a depth of 200 m along the northeastern part of the Black Sea continental slope (Fig. 3). Its trajectory was tracked using satellite positioning. Coordinates of the float were obtained when it ascended to the surface to transmit the data collected (every 120 h). The movement of the float to the southeast along the North Caucasus coast in September 2016 (for 40 days) and in February 2017 (10 days) indicates the presence of anticyclonic currents. The mean velocity of the float motion between stations #20 and #28 in the autumn of 2016 was 2.4 cm/s, and between stations #50 and #52 in the winter of 2017—8 cm/s. The characteristics of the undercurrents are generally consistent with our results of modeling the current velocities in this region and in other years.
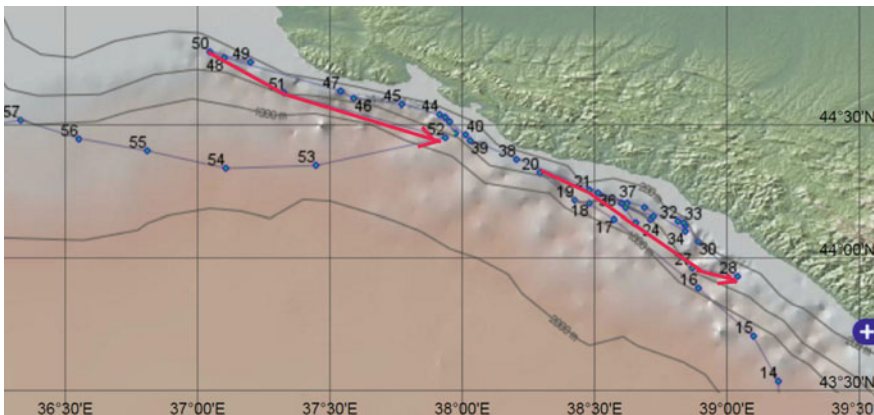

Fig. 3 Satellite positioning of ARGO float ID6901833 offshore North Caucasus coast in 07.08.2016–10.03.2017 (numbered blue dots indicate float stations, red arrows mark undercurrents). Drawn using service http://www.ifremer.fr/co-argoFloats/float?ptfCode=6901833

The presence of undercurrents along the northeastern part of the continental slope (Fig. 1) is also consistent with the results of current velocity profiling by the Aqualalog moored station. These measurements were carried out on June 17–19, 2011 at the test site of the Institute of Oceanology of the Russian Academy of Sciences in Gelendzhik [14]. According to the data of deep-water (to a depth of more than 1,000 m) profiling of the velocity, the anticyclonic current during this period was recorded at depths of 500–950 m. Its core with a velocity of about 3 cm/s was located in a layer of 700–850 m. At the nearest node of the model grid, the presence of undercurrent was also revealed (Fig. 4). Analysis of the results of simulations shows that it is quasi-periodically revealed at that region at the lower horizons throughout the year.

In the western part of the Black Sea, the presence of anticyclonic currents with characteristics similar to those calculated using the MHI model is consistent with the published results of long-term (more than a year) deep-water velocity observations using ADCP at a horizon of 1,700 m southwest of Cape Chersonesos [15], as well as with the results of a number of experiments using other numerical models, for example, simulations based on the Institute of Numerical Mathematics model [16] or recent experiments based on the modified ROMS model [17].

4 Discussion

It should be noted that the features of undercurrents established in this work correspond to the hypotheses of their formation available in the scientific literature. Thus, a number of authors point to the possibility of generating currents propagating along the continental slope in the anticyclonic direction as a result of low-frequency wave processes under the main Black Sea pycnocline. The formation of such currents at horizons over 300 m is indicated, for example, in [5–7]. The periodicity in the intensity of undercurrents found from the results of modeling on scales from several days to several weeks can be an argument for the wave hypothesis.

The formation of undercurrents can also be associated with the passage of mesoscale anticyclonic eddies over the continental slope (as in the situation in Fig. 2). The behavior of coastal mesoscale eddies was studied, for example, in [18, 19]. Eddies act as generators of jet flow between the periphery of the eddy and the bottom, and also change the slope of isopycnic surfaces, as a result of which internal waves and gradient flows can also form. Currents associated with the passage of mesoscale anticyclonic eddies near the shelf zone boundary were also noted in other regions of the World Ocean, for example, near the western coast of the Bay of Bengal [20].

In the Black Sea, the formation of mesoscale anticyclonic eddies is mainly caused by seasonal, spring–summer weakening and meandering of the Rim Current, in turn, caused by seasonal changes in wind vorticity over the sea. Features of stratification and bottom topography are also of great importance for deep-water processes. At present, given the current level of observation data availability, it is difficult to discuss about any specific reason for the formation of under currents in the Black Sea. In
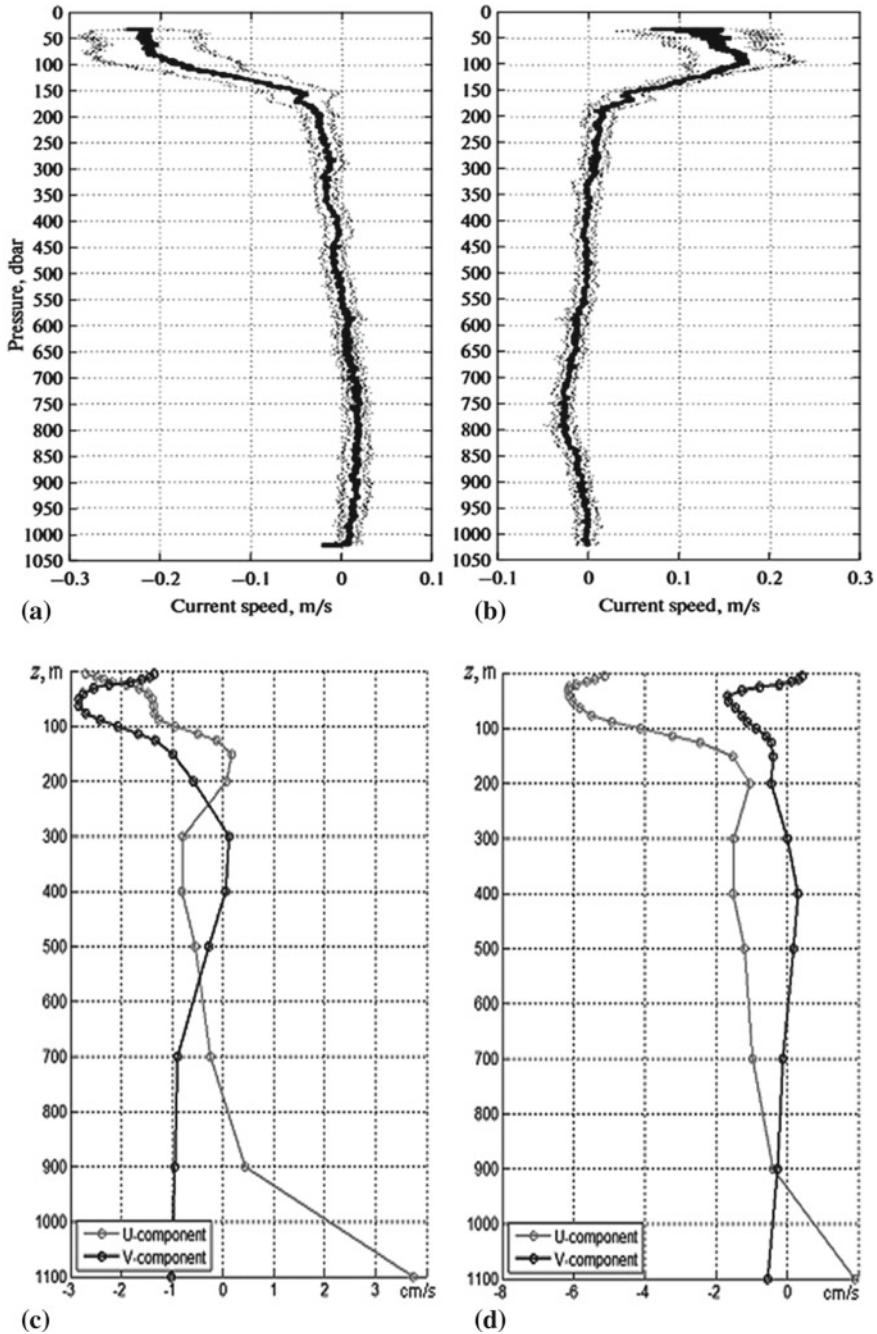
Fig. 4 Profiles of velocity components (u—zonal, v—meridional) at Gelendzhik region in June, 2011: **a**, **b**—u, v velocity components measured by Aqualog profiler at point (44°23′24″ N, 37°51′36″ E) [14], and modeled velocity components at nearest model grid node: **c**—on June 16, 2011, **d**—on June 20, 2011

a complicated system of interactions between the atmosphere and the ocean, much larger observation data and further research are required to clarify the prerequisites for the occurrence of undercurrents and to determine the dominant forcing factor.

Thus, the formation of anticyclonic currents in the deep layers of the Black Sea can be caused by various reasons: the movement of mesoscale eddies, wave processes, changes in density gradients, the combined effect of baroclinicity and bottom topography, and others. The final solution to the question of the mechanisms of the occurrence of undercurrents is the subject of further research.

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