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MARINE PHYSICS

Modeling Mesoscale Circulation of the Black Sea

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Abstract—An eddy-resolving (1/30)° version of the DieCAST low-dissipative model, adapted to the Black Sea circulation, is presented. Under mean climatological forcing, the model realistically reproduces major dominant large-scale and mesoscale structures of seasonal sea circulation, including the Rim Current, coastal anticyclonic eddies, mushroom currents, etc. Due to its extremely low dissipation and high resolution, the model makes it possible to trace the development of the baroclinic instability along the Turkish and Caucasian coasts, reproduce mesoscale structures generated by this mechanism, and assess the scales of these structures. The model also realistically reproduces short-term effects of bora winds on the evolution of subsurface layer structures.

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1. INTRODUCTION

Researchers focus on mesoscale structures of sea circulation since these structures are important in the exchange between open water and coastal areas. Each element of circulation plays a part in these transport processes. Thus, the stability and instability of currents promote contamination accumulation in the coastal area as well as contamination dispersal and coastal water self-purification, respectively. Coastal anticyclonic eddies (CAEs), which often accumulate contaminations that come, e.g., with a river runoff and ventilate ambient water, are important in this case. Eddy dipoles and mushroom currents also encourage exchange between coastal areas and open sea. Upwelling zones, which result in coastal water purification and/or saturation with nutrients, are also of paramount importance in the exchange processes. Figure 1 presents a SeaWiFS satellite color scanner image illustrating various mesoscale structures in the surface layer of the Black Sea.

Mesoscale structures of Black Sea circulation have been under study for many years [1, 2, 6, 9, 10, 14, 17–19]. The scheme shown in Fig. 2 generalizes different scale structures of Black Sea water circulation compiled based on long-term instrumental and satellite observations [9]. The Rim Current (RC), i.e., the alongshore annular current with a core above the 500 m isobath and a width of 20–50 km, is the main element of this scheme. Field studies indicate that the RC has distinct seasonal differences: it attenuates in the summer season and intensifies in winter. The peripheral RC is surrounded by numerous mostly coastal anticyclonic eddies, which are wedged between RC and the continental shelf. In addition, small CAEs sporadically appear along the Turkish and Caucasian coasts and trap contaminations and carry them over large distances from contamination origination areas along a coast according to the satellite observations.

We should note that not all CAEs shown in Fig. 2 originate simultaneously. Observations indicate that CAEs are formed more intensely during warm seasons, when RC substantially meanders and becomes unstable. Thus, CAEs are formed over 16–18 days in spring—summer and over 9–10 days in summer—autumn. The CAE lifetime is 6–14 days in summer and decreases to 3–6 days in winter [9]. Cyclonic mesoscale eddies, with a lifetime much shorter than that of CAEs, are generated offshore left of the RC in addition to CAEs that more frequently appear in the coastal zone (see Fig. 2).

Note that long-lived offshore eddies with a diameter of 80–100 km are observed in the layer from the surface to a depth of 300–400 m; at the same time, short-lived eddies are registered in the 0–50 m layer. The numerical calculations indicate that the largest anticyclonic eddies can increase to 100–150 km in diameter, and their thickness can reach 100–200 m [8, 17]. The so-called Batumi anticyclonic eddy (BAE) can increase and fill the entire eastern corner of the Black Sea, remaining in this area for several months. Another major Sevastopol anticyclonic eddy (SAE) is periodically (at an interval about three weeks) generated over a very steep continental slope south of the Crimea. In contrast to BAE, which dissipates in the eastern sea area, SAE detaches from the Crimea and moves southwestward along the continental slope at the RC periphery as a closed eddy structure [14].

We should note that the scheme presented in Fig. 2 is incomplete. Intense recent studies [4] indicate that CAEs generated by RC can in turn promote the generation of submesoscale cyclonic eddies, the dimensions

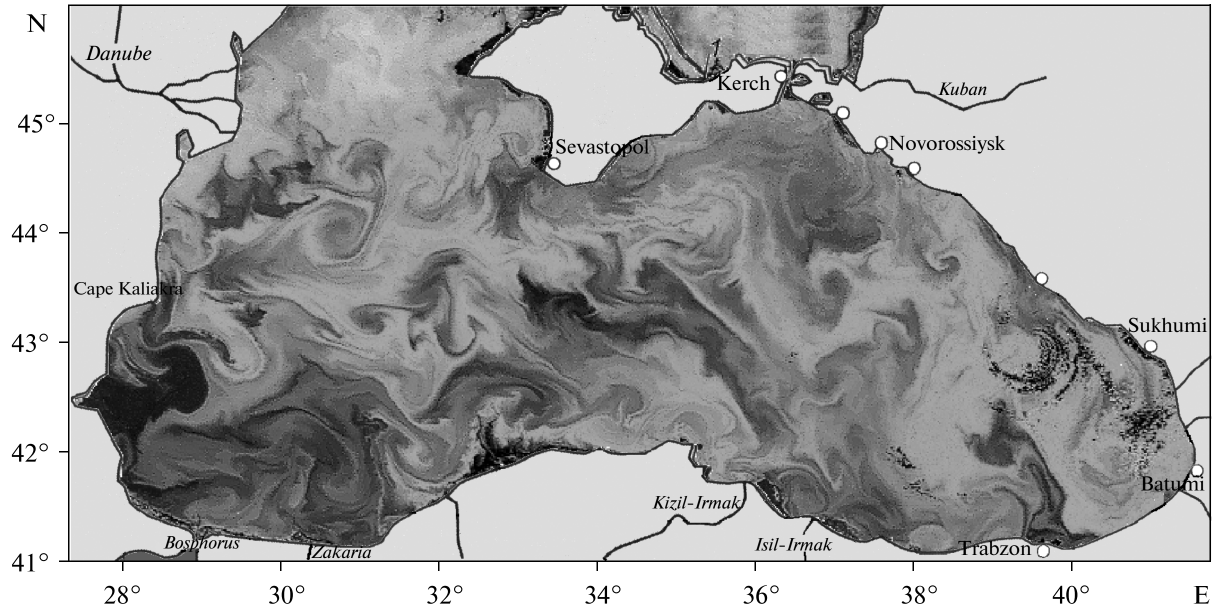

Fig. 1. Black Sea mesoscale structures. SeaWiFS satellite color scanner image (June 11, 2000).

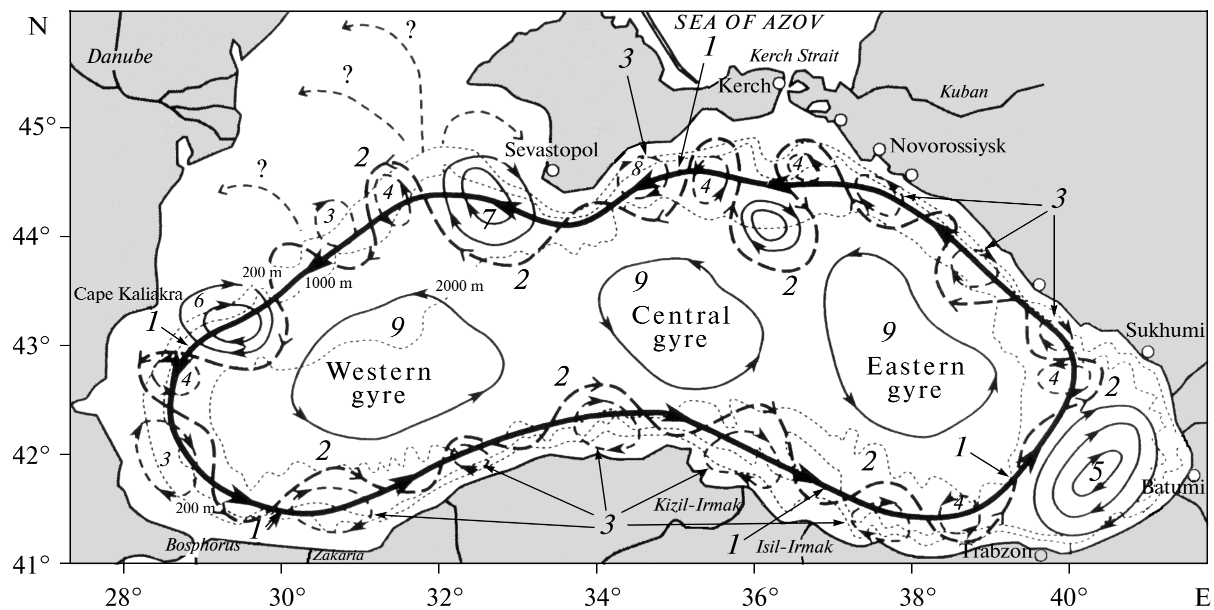

Fig. 2. Composite scheme of the Black Sea circulation. The denotations: (*1*) RC, (*2*) RC meanders, (*3*) CAEs, (*4*) cyclonic eddies, (*5*) BAE, (*6*) Kaliakra anticyclonic eddy, (*7*) SAE, (*8*) Yalta anticyclonic eddy, and (*9*) quasistationary cyclonic gyres (according to [9]).

of which are not larger than 2–4 km, pressed up against the coast. Such eddies appear in spring and summer, when RC meanders most intensely and CAEs are generated. Shear instability of alongshore current is a mechanism of CAE generation [4]. A numerical simulation of the Adriatic Sea circulation [12] indicates that a similar eddy system periodically originates behind Cape Gargano (Italy).

2. MODEL DESCRIPTION

To study the mesoscale circulation of the Black Sea, we chose a DieCAST *z*-coordinate low-dissipative model of the ocean circulation with "a rigid-lid" approximation. The model architecture is described in detail on the site http://efdl.as.ntu.edu.tw/research/diecast and in [13, 16, 17]. Therefore, we consider only the adaptation of the model to the Black Sea.

The computational grid of the model covers the entire Black Sea basin from 27.2° to 42° E and from 40.9° to 46.6° N, containing 426 × 238 cells in the horizontal direction and 30 unevenly spaced levels in the vertical. Longitudinal resolution was selected equal to 2 nautical minutes (unsmoothed bottom topography (ETOPO2) was used in the work), and latitude resolution varied so that the ratio of the horizontal cell dimensions ($\Delta X/\Delta Y$) would remain equal to unity. Thus, square cell dimensions varied only in latitude from 2.6 to 2.8 km.

The vertical step was uneven with the grid condensation near the sea surface in order to enhance the seasonal thermocline resolution. Thus, the cell interface position was selected at the 0, 3, 6, 10, 14, 18, 23, 29, ..., 1789, and 2221 m horizons. A vertical resolution of 2 m near the surface made it possible to adequately describe quasi-homogeneous layer dynamics. At a staggered representation of the bottom topography, bottom drag (its coefficient was taken as constant, equal to 0.0025) is applied only to horizontal surfaces. For vertical surfaces, the bottom drag was taken as equal to zero.

The coefficients of horizontal eddy viscosity and diffusion of heat and salinity (CHEVaDs) were specified as constant and equal to 3–10 $m^2 s^{-1}$, which is responsible for the low model dissipativity and made it possible to reproduce mesoscale CAEs. Note that we triggered a model with maximal CHEVaDs and subsequently performed the calculation with minimal CHEVaDs in order to make the model stable for the first five calculation years. The numerical scheme of the fourth-order-accuracy approximation provided stable calculation at the selected time step (10 min).

To calculate the vertical diffusion of heat and salinity as well as viscosity, we used the "k–ε–τ" eddy model with second-order closure for diffusion terms describing the kinetic energy of the eddy (k) and its dissipation (ε). We used the Launder—Spalding algebraic expressions [7] in the model in order to estimate the Reynolds stress (τ). We applied the "k–ε–τ" model instead of the Pakanowski–Philander model used in the original DieCAST version [13]. This made it possible to adequately describe the eddy energy generation and dissipation in the surface layer, which substantially affected the adequate reproduction of the annual heating–cooling cycle in the surface active sea layer and the action of anomalously strong bora winds.

A fourth-order of accuracy is used in the model in order to approximate all advection and horizontal pressure gradient terms except those at control volumes at the calculation domain boundaries. These terms are calculated here with second-order accuracy. In addition, a combination of the numerical grids is used in the model: grids "A" and "C" are such that DieCAST can be considered as an "A" grid model, where the continuity equation is solved on grid "C." Note that the space interpolation error is minimal on collocation grid "A" when calculating the Coriolis term substantially contributing to the current velocity value.

Monthly average January data on temperature and salinity were used in order to initialize the model. The model was triggered from the state of rest (i.e., the current velocity was zero everywhere), and the long-term average annual (monthly) data on the wind stress, heat fluxes, evaporation (E), precipitation (P), and river runoff [17] were used in the model spin-up. River runoff (31 rivers around the Black Sea perimeter) was specified based on the average climatic data [15], which were interpolated so that the annual cycle would be perpetual. The monthly average runoff was specified for the main 11 rivers (except for the Danube). The fresh water discharges were added to the P–E ratio through the regions of permeable sea surface near river mouths. The vertical velocity at the corresponding grid point was calculated with regard to the volume of each river runoff. This algorithm was described in detail in [17]. To specify the Danube runoff, the delta of this river was represented as four points on the grid.

Since the exchange through Bosphorus Strait plays a key role in the Black Sea water balance and circulation, we specified a two-layer flow (as in [17]) in order to maintain the water and salinity volumes. The Dirichlet boundary conditions were applied to the upper- and lower-Bosphorus currents. Water inflow from the Sea of Azov through Kerch Strait was taken to be similar to the river runoff and equal to the average annual volume (15.5 $km^3 yr^{-1}$).

The model "spin-up" time for reaching circulation quasiperiodic mode was 24 years, although the main features of the Black Sea circulation (such as RC and cyclonic gyres, Rossby waves and coastally trapped waves) appeared after five computation years. The model adequately reproduces RC intensification in winter and its attenuation and meandering in the warm season, as follows from field observations. The mode of quasi-periodicity was controlled based on the average kinetic energy in the volume and horizons. In this case, special attention was paid to the bottom layer, which will be studied in following works. Characteristic seasonal variations in the integral kinetic energy, reflecting a high wind intensity in winter and a lower intensity in summer, are distinguished in the surface layers.

Model verification consisted in a comparison with the known characteristics of the general circulation and mesoscale structures of the Black Sea obtained based on the satellite data [12, 14, 19], measurements [6, 9, 10], and experiments with drifting buoys [3, 19]. The results were also compared with data obtained using a more rough model with a resolution of (1/12)° [8, 17].

3. MODELING RESULTS AND DISCUSSION

Results of numerical simulation indicate that the model adequately reproduces the fundamental features of the dynamics of the Black Sea. We observe the

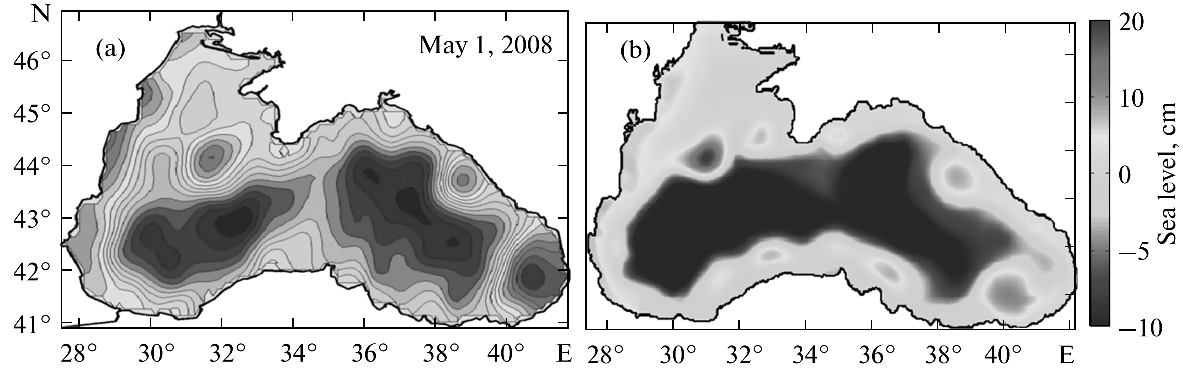

Fig. 3. Sea level anomalies (a) according to satellite observations on May 1, 2008, and (b) calculated by the model based on pressure at the sea surface.

seasonal variations of RC, cyclonic gyres in the deep sea, numerous anticyclonic RC meanders and eddies between RC and the coast, and other structures that are schematically shown in Fig. 2. Sea level elevations, obtained based on the satellite observations (http://www.aviso.oceanobs.com) for May 1, 2008, and calculations for climatically average May, are compared in Fig. 3. BAE, SAE, and small CAEs along the Caucasian, Turkish, and Crimean coasts (such as the Bosphorus, Sinop, Kizil-Irmak, Caucasian, Kerch, and other eddies) are adequately traced.

Note that the SAE quasi-stationarity, which is referred to in many field studies, should be interpreted conditionally so that a powerful anticyclonic eddy is periodically formed west of Sevastopol and is subsequently transported by RC to the Bulgarian coasts, where it dissipates. The SAE trajectory was previously reproduced in detail based on satellite sea surface temperature surveys. The trajectory of this eddy in June—August 1998 was analyzed in [14]. This analysis indicated that the travel time for eddies time from the origination to Cape Kaliakra (Bulgaria) is about three months. This is in good agreement with the SAE motion estimated in this work.

The model indicates that tripole structures composed of two successively formed anticyclones and a cyclone sometimes appear west of the Crimea. Such structures have been previously registered based on hydrographic surveys and satellite observations [6, 14].

The model calculations indicate that BAE formation and its subsequent decay are distinctly traced from April to September. Under certain conditions (usually in April to May), BAE is formed from CAE, which originates near the Turkish coast at 38° E. When this CAE, which is carried and replenished by RC, grows in summer in the eastern Black Sea on the Batumi beam, this results in that RC deviates westward. In September, BAE is replaced by two cyclonic eddies, as a result of which the tripole structure appears in the eastern Black Sea. BAE subsequently dissipates north of Sukhumi (Georgia), and is replaced by a powerful cyclonic whirl, which is observed up to January. Note that the previous (1/12)° model version [8, 17] did not allow revealing the above tripole structure during BAE dissipation.

In accordance with field observations, the model indicates that CAEs are intensely formed near the Turkish coasts from March to August. In this case, the formed eddies move along the coast, being trapped by RC.

CAEs are mainly generated when capes and submerged ridges are obstacles to flow, being due as well to the baroclinic instability of littoral currents. A high model resolution (cell size is much smaller than a deformation internal radius of ~5–15 km) makes it possible to reproduce this mechanism as was shown previously in [12]. This effect can be especially evident in river runoff regions along the Caucasian and Turkish coasts as well as on the northwestern shelf, where the influence of the Danube runoff is considerable. Figure 4 shows the model of the distribution of salinity, where the cascade of anticyclonic eddies along the Caucasian and Turkish coasts as well as BAE and SAE are observed. Figure 4 also shows other specific mesoscale circulation elements corresponding to Fig. 2. These structures are also clearly defined in the velocity field (see Fig. 5 in [16]).

Note that the Black Sea mesoscale structures described above are in good agreement with similar structures obtained using the high-resolution model developed in [1, 2].

An important stage in model validation consists in the verification of sea-surface response to episodic strong wind forcing. This can be illustrated by the so-called Novorossiysk bora, the strong northeasterly wind originating when a cold atmospheric front approaches the coastal ridge from northeast. A cold front immediately crosses a low ridge. Under the action of gravity, cold air migrates down the ridge and accelerates. Owing to the nonuniform shielding action of mountains, the bora effect on the sea surface becomes spatially inhomogeneous [11]. Northeaster magnitudes are maximal in the Anapa–Tuapse region.

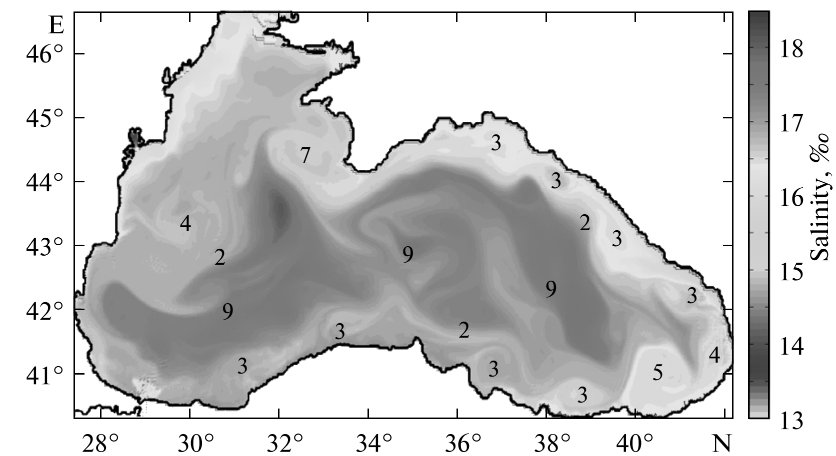

Fig. 4. Salinity distribution at the sea surface. The numbers of the mesoscale structures correspond to denotations in Fig. 2.

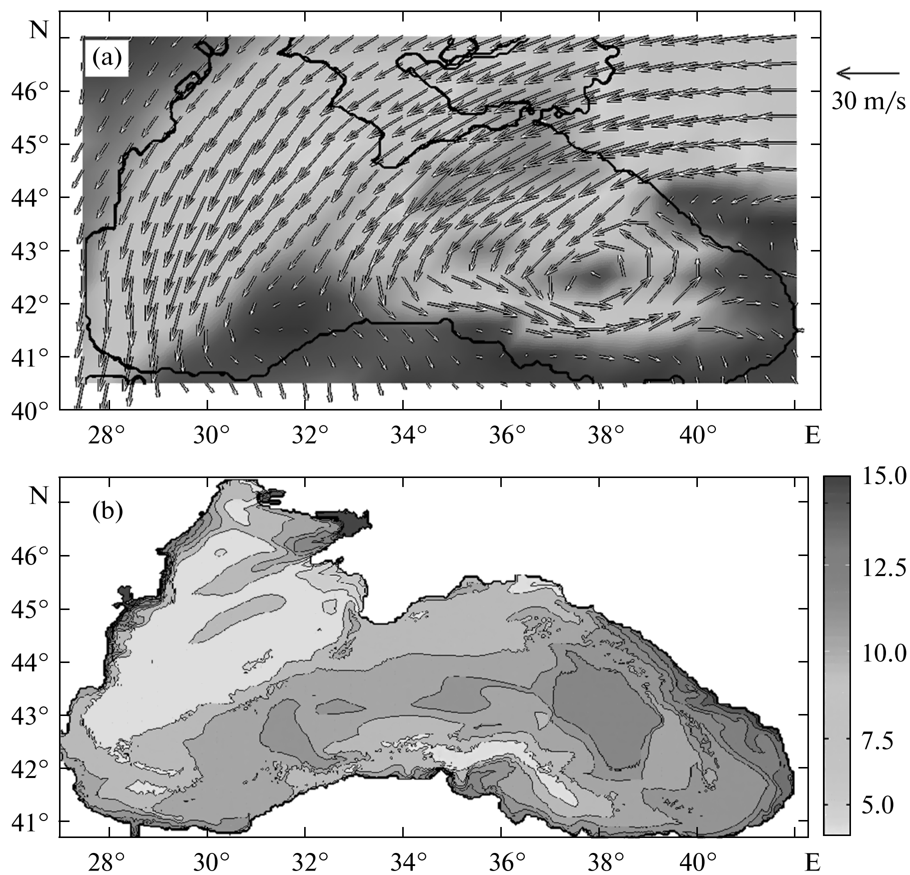

Fig. 5. (a) The northeasterly wind (bora) on April 17, 2013, and (b) the sea-surface model temperature.

South of Tuapse, the blocking effect of the high Caucasian mountains suppressed bora.

When we modeled the bora effect, we used the data from the web portal http://dvs.net.ru/mp/index.shtml for April 2013 instead of climatically average wind. During the bora period, the wind reached 35 m/s on April 17, 2009 in the Novorossiysk region (Fig. 5a). The modeling indicated that bora first promoted a short-term intensification of the RC coastal branch and the related heated water transport from the Black Sea Georgian sector into the northern water area. From April 17, 2009, a strong northeaster caused a negative surge in the Russian northern Black Sea sector. This phenomenon was followed by deep water upwelling in the coastal zone, as a result of which the sea surface temperature became lower than 10°C and lower than 5°C in the Kerch Strait region and on the northwestern shelf (Fig. 5b). The breaking of a warm alongshore jet propagating from the Georgian coastal area is an interesting manifestation of the bora effect. Figure 5b indicates that a warm RC jet with a temperature of ~15°C, which had previously reached the Crimea, breaks in the Novorossiysk region. This was also confirmed by the satellite observations. It is important to note that immediately after bora attenuation, warm water rapidly propagates northwestward along the coast as a narrow (about 20 km) jet. According to the results of modeling, the leading edge of this jet reached Kerch Strait within less than a week. A similar coastally trapped jet evolution in an intensification of the northeaster was previously instrumentally studied by Zatsepin with coauthors [5] under similar meteorological conditions, observed in June to July 2006. However, we should note that the northeasterly winds on April 15–19, 2013 covered almost the entire Black Sea; therefore, the decrease of water temperature was also observed in the northwestern Black Sea.

4. CONCLUSIONS

We proposed a (1/30)° version of the DieCAST eddy-resolving model for the Black Sea with the "k–ε–τ" turbulent closure. This model allows reproducing the main features of the large- and mesoscale circulation of the Black Sea. The application of the "k–ε–τ" model makes it possible to more adequately describe the annual cycle of heating and cooling of the sea surface layer and the layer response to the effect of strong winds such as Novorossiysk bora. The annual heating—cooling cycle indicated that good agreement between the predicted results and climatic data obtained by Belokopytov (see Fig. 6b in [17]).

Calculations indicated that the Sevastopol, Bosphorus, Sinop, Kizil-Irmak, Caucasian, and Kerch anticyclonic eddies are quasiperiodic structures. Mesoscale CAEs are generated and evolve between the coast and RC. Mesoscale CAEs are continuously formed along the Anatolian eastern coast as a result of the influence of an irregular bottom topography and river runoff. Being involved with RC, these eddies move along the coast, reach the southeastern Black Sea, and trigger the formation of BAE.

Since the model is extremely low-dissipative and has a high resolution (the cell size is much smaller than the internal deformation radius), it allows tracing the formation of eddy structures along the Black Sea coast generated by baroclinic instability.

The proposed model will form the basis of further study of mesoscale and submesoscale structures as well as bottom currents in the Black Sea.

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