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MARINE PHYSICS

Modeling Processes of the Protrusion of Near-Coastal Anticyclonic Eddies through the Rim Current in the Black Sea

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The eddy-resolving (1/30)° version of the low-dissipative DieCAST [7] ocean circulation model is used for modeling processes of the protrusion of near-coastal anticyclonic eddies (NAEs) through the Rim Current (RC). Under mean climatic forcing, the model realistically reproduces the evolution of the Caucasian NAE (CNAE) from its generation, formation of an attached anticyclonic meander, protrusion through the RC, and, finally, to the formation of an isolated anticyclonic eddy and its dissipation within the Eastern Cyclonic Gyre of the Black Sea. The process of double protrusion of the CNAE and the Kizil-Yirmak NAE into the RC, their passages through the RC, and merging in the eastern part of the Black Sea is also considered. The modeled space-time parameters of NAE evolution agree well with satellite observations [15, 23].

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1. INTRODUCTION

The mesoscale circulation structures of the Black Sea play an important role in exchange processes of the near-coastal zone and the open basin (Fig. 1). The main role here is played by near-coastal eddies (NAEs), which can accumulate pollutants entering, e.g., with river runoff and retain them in the near-coastal zone for a long time [5], thereby significantly degrading the ecology of local regions between the shore and the Rim Current (RC). NAEs are usually formed as a result of different types of RC instabilities and caught between the RC and the coast. However, under certain conditions, NAEs can protrude through the RC and hence carry pollutants from the near-coastal zone to the open sea.

A classic example is the Caucasian NAE (CNAE), which is periodically generated in the area between Sukhumi and Sochi [15, 23]. With increasing growth and advancement to the northwest along the Caucasian coast, under certain conditions, the CNAE can push the RC toward the open sea, facilitating the development of a wide anticyclonic meander that encompasses the CNAE. Gradually, in the process of protrusion, the CNAE ends up inside the meander. Such a meander–CNAE system under external, e.g., wind action becomes unstable and, as a consequence, when breaking up, leads to detachment of the CNAE from the outer side of the meander and its departure into the open sea. After this, the RC renews its initial position, located closer to the coast. Such a process occurs quite regularly; however, certain variations in the behavior of the detaching eddy, its trajectory, and dissipation within the Eastern Cyclonic Gyre are well known, as well as protrusions of NAEs into the RC from the Anatolian Coast. One of such phenomena that took place in January–March 1998 is described in [15].

It is possible to observe an even rarer phenomenon in the Black Sea: when anticyclonic eddies protrude simultaneously from the Caucasian and Anatolian coasts. In this case, the joined anticyclonic eddies disrupt the RC to their west, while in the eastern part of the sea (in the absence of Batumi NAEs [9]), the remnants of the RC self-organize into a giant cyclonic eddy/gyre.

Examples of the evolution of a "spring" and "winter" CNAE for which the processes of their protrusion into the anticyclonic meander of the RC and their subsequent detachment from the meanders are described in detail in [15, 23]. In these studies, the space-time scales of the evolution processes are determined from satellite observation data, from which it is possible to estimate the corresponding parameters obtained in model calculations.

The aim of this work is to reproduce the above-described processes, compare them to satellite observations, and obtain additional information on the three-dimensional structure and evolution of the CNAE.

2. STUDY REGION

We consider an area of the Black Sea east of the Kerch Strait (Fig. 1), although for modeling the circulation, we use a numerical model for the entire sea. The diagram in Fig. 1 generalizes the nonuniform

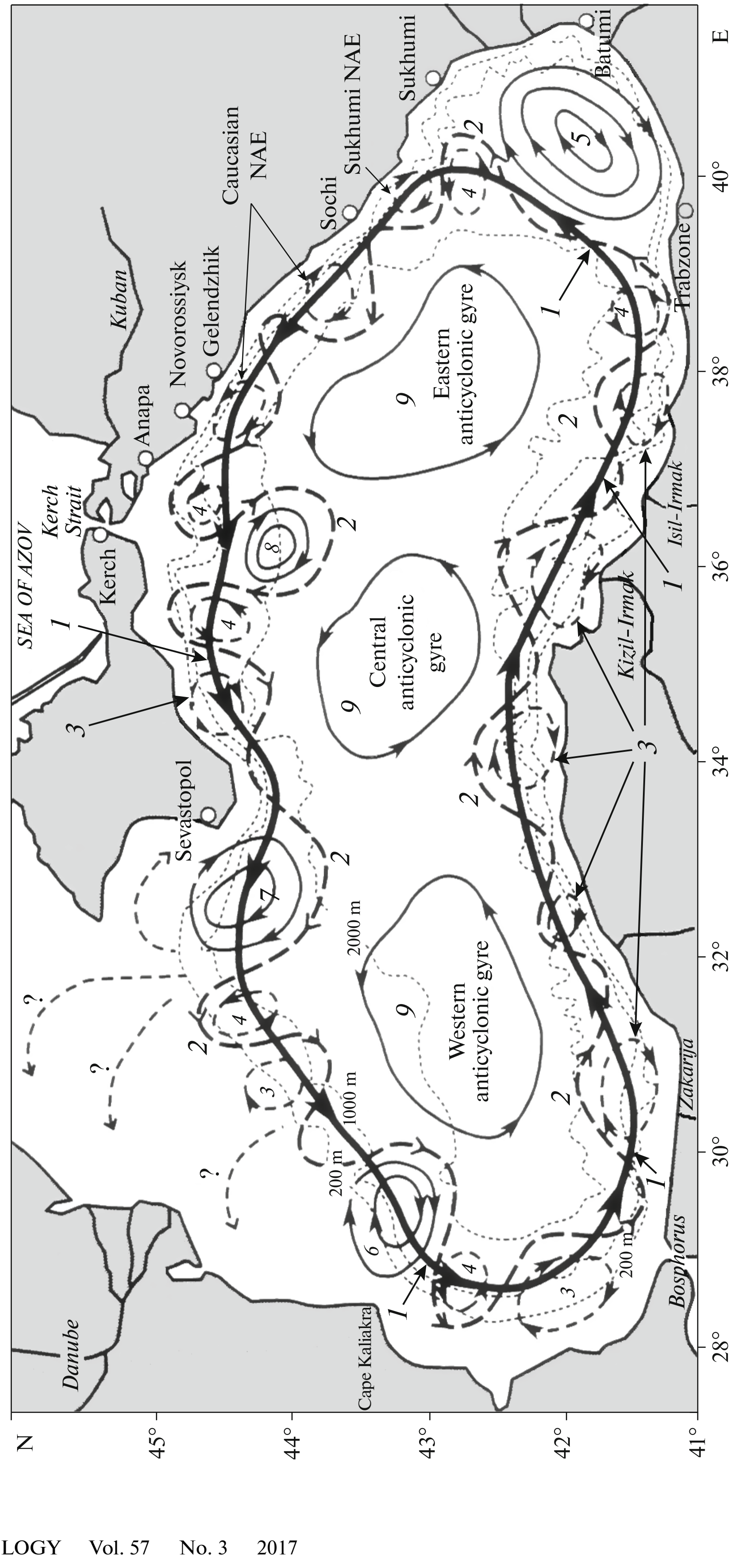

Fig. 1. Combined diagram of Black Sea circulation. (*1*) RC; (*2*) RC meanders; (*3*) NAE; (*4*) cyclonic eddies; (*5*) Batumi NAE; (*6*) Kaliakra NAE; (*7*) Sevastopol NAE; (*8*) Yalta NAE; (*9*) quasi-stationary cyclonic gyres [1, 8].

scale of the Black Sea's water circulation structure, compiled from multiannual instrumental and satellite observations (see [7]). The main element of this diagram is the RC, a ring-shaped longshore cyclonic current, the deep stream of which is located above the 500 m isobath and the width is 20–50 km. As field studies have shown, the RC has distinct seasonal difference: it weakens in the summer period and intensifies in the winter period. Along the periphery, the RC is surrounded by numerous predominantly near-coastal anticyclonic eddies with dimensions on the order of 40–60 km, which are wedged between the RC and the continental shelf.

According to modern laboratory and satellite observation data, the eddy dynamics of the Black Sea intensifies in the summer period. During this time, due to a decrease in the cyclonic wind vorticity and Ekman pumping of the water circulation, the RC weakens, breaks down into intense anticyclonic chains, and all but disappears, like a coherent stream [1, 17, 22]. In cold periods of the year, with an increase in Ekman pumping of the water circulation, the RC intensifies, whereas the eddy activity of the sea and, accordingly, the number of NAEs decrease.

It should be mentioned that NAEs aperiodically appearing along the coasts of Turkey, Bulgaria, and the Caucasus can play the role of pollution traps and deliver it to the coasts to places, as satellite observations show, far from their origin. In addition, the described phenomenon of the CNAE protrusion, along with other near-coastal processes, is of significant value for self-purification of near-coastal waters, pollution of which occurs due to the numerous rivers of the Caucasian coast [5]. Development of gas and oil deposits on the shelves of Turkey and Georgia [4, 12, 21] that has commenced in recent years also represents a serious pollution threat to the Black Sea.

2. NUMERICAL MODEL

To study the processes of NAE interaction with the RC, the DieCAST z coordinate low-dissipative ocean circulation model was used [11]. A detailed description of the model's architecture can be found at http://efdl.as.ntu.edu.tw/research/diecast and in [16, 19]. Therefore, we only dwell on certain details of its adaptation to the Black Sea [7, 16].

The calculation grid of the model encompasses the entire Black Sea basin from 27.2° E to 42° E. and from 40.9° N to 46.6° N and contains 426 × 238 cells along the horizontal and 30 unevenly spaced levels in the vertical. The longitudinal resolution was chosen as 2 nautical minutes (the study used the ETOPO2 unsmoothed bottom relief); the latitudinal resolution was varied such that the ratio of the horizontal cell sizes $\Delta X/\Delta Y$ remained equal to unity [6]. Thus, the dimensions of square cells changed only with latitude from 2.6 to 2.8 km. The step along the vertical was nonuniform, with thickening of the grid at the sea surface for the best resolution to the seasonal thermocline.

The coefficients for the horizontal turbulent viscosity, heat diffusion, and salinity diffusion were calculated with a use of the well-known Smagorinsky formula. To calculate the vertical heat and salinity diffusion, as well as the viscosity, the model used the k–ε–τ turbulence model with second-order closure for the diffusion terms describing the kinetic turbulence energy k and its dissipation ε. To estimate the Reynolds stresses τ in the turbulence model, algebraic Launder–Spalding expressions were used [6]. The mean monthly temperatures and salinity for January were used to initialize the model.

The model was launched from a resting state (i.e., everywhere the current velocity was equal to zero), and it was unwound with mean multiyear (monthly) data on wind stress, heat fluxes, evaporation, sediments, and river runoff [19]. Runoff from rivers—31 rivers along the perimeter of the Black Sea—were assigned from mean climate data [13], which were interpolated such that the annual cycle was continuous. This algorithm is described in detail in [7, 19].

At the open boundaries of the sea, two-layer water exchange through the Bosporus was set similarly to [19] and the mean annual water flow from the Sea of Azov through the Kerch Strait was taken equal to 15.5 $\text{km}^3\ \text{yr}^{-1}$ [7].

The unwinding time of the model to obtain a quasi-periodic circulation regime was 24 years, although the main features of Black Sea circulation appear already after five calculated years. A more detailed description of the model can be found in [7].

3. RESULTS AND DISCUSSION

The model adequately reproduces virtually all elements of circulation, which are shown in Fig. 1. The model calculations confirm the trend of intensified formation of NAEs in the summer period, when the RC, losing stability, intensely meanders. Conversely, in the winter period with intensification of wind pumping, the RC is observed as a coherent jet pressed again the continental slope, and the intensity of NAE generation is sharply reduced [7]. Exceptions, however, are the CNAE, a number of NAEs of the Anatolian coast, and the Sevastopol anticyclonic eddy (SAE), the probability of the occurrence of which is great both for the summer and winter periods. However, for summer CNAEs, the protrusion process was not observed. Comparison of the wind situations for summer and winter has shown that the CNAE protrusion process developed in a period of prolonged intensification of northeast wind, which for the wind forcing chosen in our experiment fell in the fall–winter period. Note that NAE detachment from the anticyclonic meander in the period of wind intensification was revealed in [23] based on satellite and meteorological observations.

Here we do not consider the process of a "usual" passage of the CNAE along the Caucasian coast toward the Kerch Strait. This process has been described widely and in detail based on multiple observations [6, 15, 20] and numerical modeling [7, 21]. We only dwell on two, let us say, exotic cases: (1) when the developing CNAE protrudes through the RC and then dissipates in the eastern cyclonic gyre and (2) when the protrusion of two NAEs occurs simultaneously from the south (Anatolian coast) and the north (Caucasian coast). In this case, their evolution is determined by the size of both NAEs and the RC.

3.1. Protrusion of the CNAE into the RC

To model the protrusion of the NAE into the RC, for the initial temperature, salinity, and current velocity fields, we used those that formed by the 24th calculated year [7]. Calculations continued under the same forcing to obtain the two considered cases. The first case of protrusion of the CNAE into the RC was observed at the end of the 25th and the beginning of 26th calculated years.

Figure 2 shows the streamline function at the surface and an increase in sea level H (top panel), as well as the streamline function and the magnitude of the current velocity $|V|$ at a depth of 298 m (bottom panel). The phases of CNAE initiation, its protrusion into the RC, and dissipation in the eastern anticyclonic gyre are shown, respectively, for day 300, 350 (calculated year 25), 20 and 20 (calculated year 26) of the Julian calendar. The lower layer of 298 m (19th z layer) corresponds to the penetration depth of the CNAE. One can see that before protrusion of the CNAE into the RC, a wide meander develops in the latter (Fig. 2a), whereas the protrusion itself has the shape of a filament (Fig. 2b) that protrudes into the RC, as a result forming an isolated eddy (Fig. 2c), which gradually dissipates in the eastern anticyclonic gyre (Fig. 2d). According to estimates, the eddy dissipation process is quite prolonged: on the order of two to three months, depending on the anticyclonic activity along the Anatolian coast. Frequently the CNAE, having passed the RC, merges with the Sinop or Kyzyl-Yirmak NAE and does not have time to dissipate. Part of the CNAE–meander system that remained in the near-coastal zone develops and shifts toward the Kerch NAE (Fig. 2d). A similar CNAE protrusion process was described earlier in based on satellite altimetry [15, 23]. As well, the space-time parameters of the process coincide well with the modeling results. Note that, as shown in [10], the detected phenomenon of periodic filament protrusion (the so-called Rimini Squirt) into the West Adriatic Current is related to baroclinic instability. In our case, the protrusion process is apparently related to the total intensification of wind in the fall–winter period, since, despite the large number of rivers on the Caucasian coast, the influence of stratification as a result of freshening of sea water owing to river runoff on the CNAE dynamics is insignificant.

Also interesting is the variation in the three-dimensional structure of the CNAE and the anticyclonic meander in the protrusion process. Figure 2a shows the initial stage of CNAE protrusion, which, in relation to proximity to the coast and the slope of the bottom, introduces distortions into the RC at depths higher than 200 m. Therefore, at the initial stage in the area of the CNAE, the isolines of the streamline function at the surface are not closed; i.e., an eddy surrounded by the meander is observed. However, at a depth of 300 m, the isolines of the streamline function are closed; i.e., only an eddy is observed. Then (Fig. 2b), as the CNAE develops and shifts toward the center of the eastern anticyclonic gyre, the unclosed structure of the isolines of the streamline function at the surface and at 300 m testify to the formation of the eddy–meander system in the entire 0–300 m water layer. Figures 2c and 2d show the complete detachment of the eddy from the meander and its movement in the 0–300 m water column toward Cape Sinop. At these stages, one can also see the restoration of the RC and the formed CNAE moving along the North Caucasian coast toward the Kerch strait.

3.2. Double Protrusion into the RC by NAEs from the Caucasian and Anatolian Coasts

In [15], based on satellite altimetry data, Korotaev et al. described the protrusion of the Caucasian meander and its interaction with the structures of the Anatolian coast in January–March 1998, which ultimately led to the formation of an isolated eddy in the eastern part of the Black Sea. A similar double protrusion process was observed in a numerical experiment in the course of the 27th calculated year.

Figure 3 shows the streamline functions at the surface and the increased sea level H (top panel) and the streamline function and magnitude of the current velocity $|V|$ at a depth of 298 m (bottom panel). One can see the phases of the generation of the Kyzyl-Yirmak NAE (K-INAE) and the CNAE (Fig. 3a), their protrusion into the RC (Fig. 3b), mergers of eddies, and breaking of the RC into branches to the west and east from the merger line (Fig. 3c). The system of associated eddies existed for only ten days, after which restoration of the RC and new intensification of the CNAE and K-INAE occurred (Fig. 3d). In contrast to observations [15], as one can see from Figs. 3a–3d, the protrusion process is not accompanied by complete detachment of the CNAE and K-INAE from their bases in the near-coastal zone, which would have led, just like in [15], to their merger and the formation of a single eddy dissipating in the open sea.

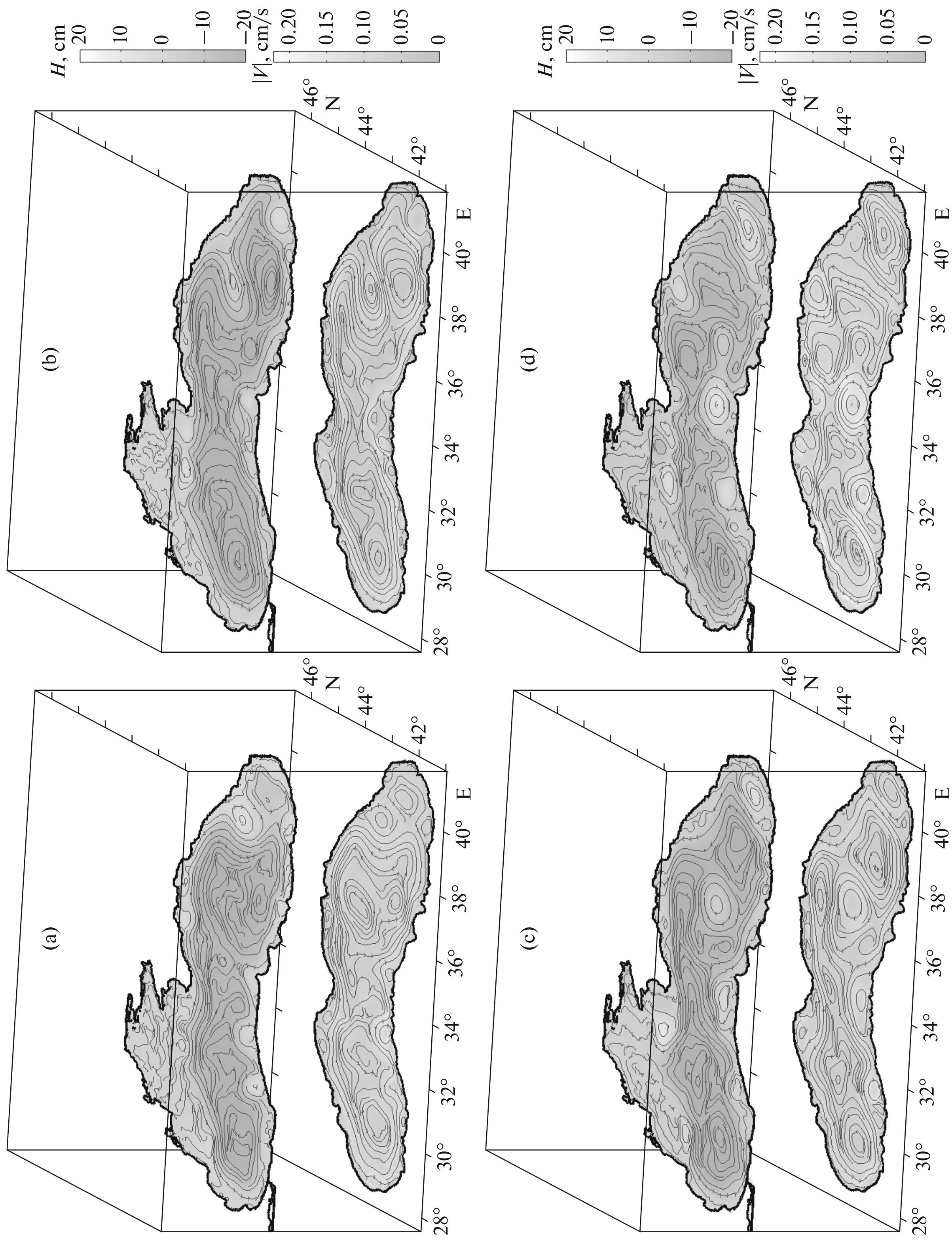

Fig. 2. Streamline function at surface and increase in sea level *H* (top panel); streamline function and magnitude of current velocity |*V*| at depth of 298 m (bottom panel). Phases of CNAE initiation process, its protrusion into RC, and dissipation in eastern anticyclonic gyre are shown, respectively, for day (a) 300, (b) 350 (simulated year 25), (c) 20, and (d) 90 (simulated year 26).

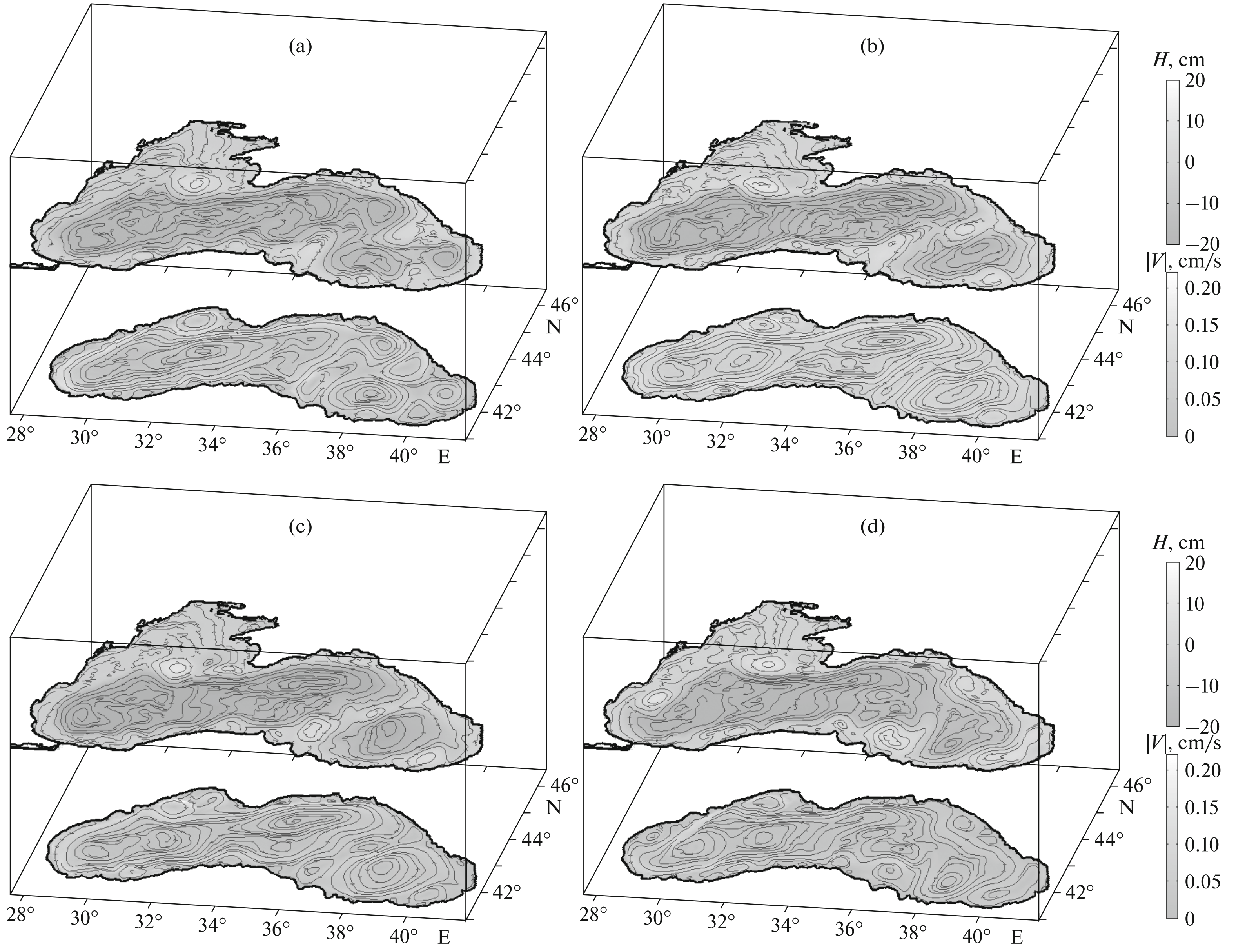

Fig. 3. Streamline at surface and increase in sea level H (top panel); flow function and magnitude of current velocity $|V|$ at depth of 298 m (bottom panel). Phases of CNAE and K-YNAE initiation process, their protrusion into RC, and merging and restoration of eddies are shown, respectively for day (a) 1, (b) 30, (c) 40, and (d) 80 for simulated year 27.

4. CONCLUSIONS

The eddy-resolving (1/30)° version of the low-dissipative DieCAST model was used to model the processes of NAE protrusion into the RC. As calculations and comparison with satellite observations have shown, the model sufficiently realistically reproduces the evolution processes of NAEs during their interaction with the Black Sea RC. The space-time parameters and character of NAE evolution agree well with the satellite observations described in [15, 13].

The evolution of a single CNAE goes through four main stages: initiation of the CNAE, its shift from the coast with simultaneous growth of the anticyclonic meander that surrounds it, protrusion of the CNAE through the RC, and dissipation of the free anticyclonic eddy into the eastern anticyclonic gyre. Thus, it takes about two months from the moment of CNAE initiation, its development, and advancement along the Caucasian coast with concomitant development of the anticyclonic meander to the onset of protrusion. Protrusion and detachment of the CNAE from the meander occurs approximately within the span of one month. Absorption of the NAE that passed through the meander within the eastern anticyclonic gyre is observed, as was mentioned above, over the course of two to three months. Close results were obtained in [15], which showed that after the protrusion of the CNAE and restoration of the anticyclonic meander, this eddy–meander system moves toward the Kerch Strait, also demonstrated by modeling. In [23], it was shown that the detachment of the eddy from the anticyclonic meander and its subsequent dissipation occurs approximately within three months, which is also close to the obtained estimates. As well, the detachment process is related to the total wind intensification in the observation period.

The initial three stages of the double protrusion process, based on the example of the K-INAE, occur similarly to those described above; however, at the final stages, the CNAE and the K-INAE merge, as a result of which, breaking of the RC occurs to the west and east of the eddy merging zone. After ten days, the CNAE and K-INAE separate and they are gradually restored, together with the RC, to a state close to the onset of protrusion.

In conclusion, it should be noted that the mechanism of pollutant transfer from the near-coastal zone to the open sea, related to NAE protrusion processes, should be considered on a level with other possible mechanisms. For example, in [1, 2, 18, 24], the transport of pollutants is explained mainly by their entrainment into the orbital motion of synoptic anticyclones that move in the stream of the RC and deliver pollutants along their periphery to the open sea.

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