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OCEANOLOGY

Evolution of Intrathermocline Eddies Moving over a Submarine Hill

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Abstract—Anticyclonic and cyclonic mediterranean eddies are formed on continental slopes of the Iberian Peninsula. Cyclonic eddies commonly live for 0.5–1 year at most. Anticyclonic eddies (meddies) live for 4–5 years, on average, but there are eddies of 7–8 years in age drifting at the distance of up to 6000 km from the region of its formation. According to the results of observations, in some regions of the Atlantic Ocean, the meddies are destructed partially or completely after contact with submarine mountains. However, it is impossible to trace evolution of the lens moving over the submarine obstacle by the field data. We studied the modeled influence of variable-height submarine hills on movement of cyclonic and anticyclonic intrathermocline eddies by the contour dynamics method. The evolution of lenses appeared to be quite sensitive to variations in hill height. Cyclonic and anticyclonic lenses interact with the hill in different ways. The data of unique field observations of Mediterranean lenses in the North Atlantic are confirmed by the results of our model experiments. Hence, it is possible to predict basic, similar to real, scenarios of interaction of intrathermocline eddies under conditions of complex bottom relief in the context of the three-layered ocean model.

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Anticyclonic and cyclonic Mediterranean eddies are formed on continental slopes of the Iberian Peninsula due to dynamic instability of the bottom flow of Mediterranean waters (MW). The MW jet moves along the southern and western slopes, and crossing of canyons and hills of the bottom is accompanied by both water running off over canyons [1] and jet separation towards the open sea [2]. Such eddies are distinguished by high temperature and salinity values relative to the surrounding waters and form a special class of Mediterranean eddies (lenses). This provides a way to identify the position in the ocean of geometric dimensions of fluid volumes with elevated contents of heat and salt and also to investigate their evolution at all stages of life up to destruction. All these eddies are commonly localized in the layer of 500–1500 m. When performing modeling, it is convenient to show lenses as eddy spots in the three-layered model with constant density values and the following thickness: upper layer is 0–500 m, middle layer is 500–1500 m, and bottom layer is 1500–5000 m [3, 4].

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The dipole system of two eddies is formed at the initial moment of water separation from the MW jet. Cyclonic eddies commonly live for 0.5–1 year at most, while anticyclonic eddies (meddies [3]) live for 4–5 years on average, but there are eddies of 7–8 years in age. Nevertheless, in the formation area adjacent to the Iberian Peninsular, there is an ocean region where eddies are characterized by reverse rotation signs [5]. A high concentration of eddies is noted precisely in this region. About 19 lenses were found and traced in the period from May of 1993 to February of 1994 under the AMUSE project [6]. Thus, when studying the evolution of meddies in this region, it is necessary to take into account their interaction with both each other and cyclonic rotation eddies. Both meddies and cyclonic rotation eddies are subject to the influence of bottom relief. Identical situations were discovered in the course of the SEMANE 99 and 2000 experiments in the south of the Gulf of Cadiz: two closely spaced meddies of different size interacted with each other and with a smaller cyclonic eddy also filled by warm and saline waters of the Mediterranean Sea [5, 7]. The meddies were characterized by a pronounced two core structure by vertical distribution of temperature and salinity. Maximum values of characteristics were noted at the depths of 270–800 m and 1100–1300 m. In the experiment of 2000 [7], the trajectories of floats showed that all of them were crowded in the strongest eddy, which confirmed their fast and intensive interaction. The attempt to trace the interaction stages of two meddies failed. Available satellite maps of tidal bulges

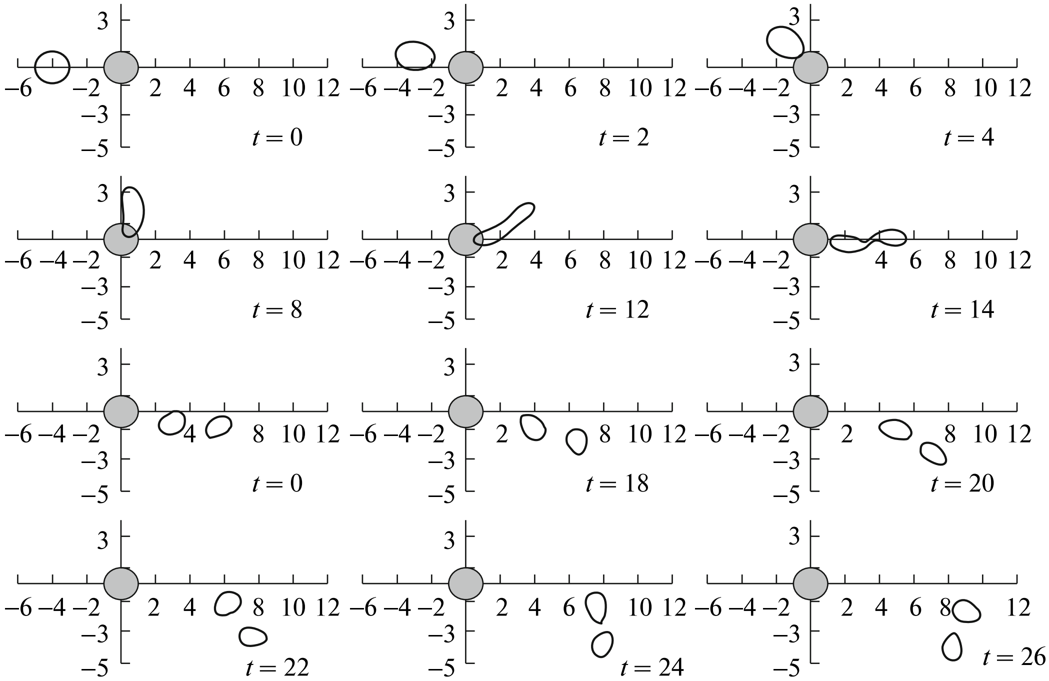

Fig. 1. Configurations of contours of the anticyclonic lens running on the submarine obstacle at $U = 2$ cm/s and $h = 1000$ m at the indicated moments of nondimensional time. The radii of the initial lens and model circular hill (filled everywhere) equal to 50 km.

occasionally provide a way to distinguish meddies on the ocean surface [4], but in the considered case the attempt to obtain the data on interaction and movement of eddies in time and space consistent with the results obtained in the course of hydrological observations failed [5, 7].

At distances of more than 200–400 km from the region of its formation, there are only anticyclonic eddies, which migrate at the rate of 1–3 cm/s at a distance of up to 6000 km. Meddies are commonly destroyed at a distance of 2000–2500 km from the region of its formation. According to the results of observations, in some regions of the Atlantic Ocean, the meddies are destroyed partially or completely after contact with submarine mountains. Work [8] contains the results of two hydrological surveys (February 1–3 and 9–12, 1989) of a large lens (with the diameter of about 100 km and volume of about 4600 km^3) when it approaches from the northeast the Cruiser and Irving Seamounts. In the period of survey, the lens got over 12 miles, lost 100 km^3 in volume, and approached the submarine strait between Irving and Hier islands. In January of 1990, a lens as a stable hydrodynamic formation of about 600 km^3 in volume was found west of that strait. It can be suggested that this is a fragment of the above-mentioned big lens [9]. Contacts of lenses and submarine mountains were studied by hydrogeological surveys [10] and deep float trajectories [6, 11].

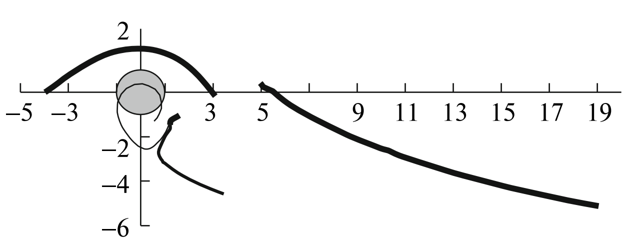

Fig. 2. Trajectories of eddies' centers at $U = 2$ cm/s and $h_1 = 1185.12$ m, and $h_2 = 1185.11$ m.

However, it is virtually impossible to trace evolution of the lens moving over the submarine obstacle by the field data [12]. Satellite observations of manifestations of intrathermocline lenses on the ocean surface are still not always accurate and fail to yield precise data on interaction of eddies with both each other and submarine hills. The problem of distance observations is also complicated by the fact that, for instance, floats placed into lens body can move chaotically when they interact with another lens [4, 7].

We study the modeled influence of variable-height submarine hills on movement of cyclonic and anticyclonic intrathermocline eddies by the contour dynamics method.

We investigate the running of initially circular anticyclonic lens transported by the barotropic eastern flow with the velocity U (Figs. 1–3) on an axially symmetrical submarine hill (analogue of an individual seamount) with the mount height of 800–1400 m above the bottom, i.e., when its top is within the bottom layer. The evolution of lenses appeared to be quite sensitive to variations in hill height. For instance, at $h =$

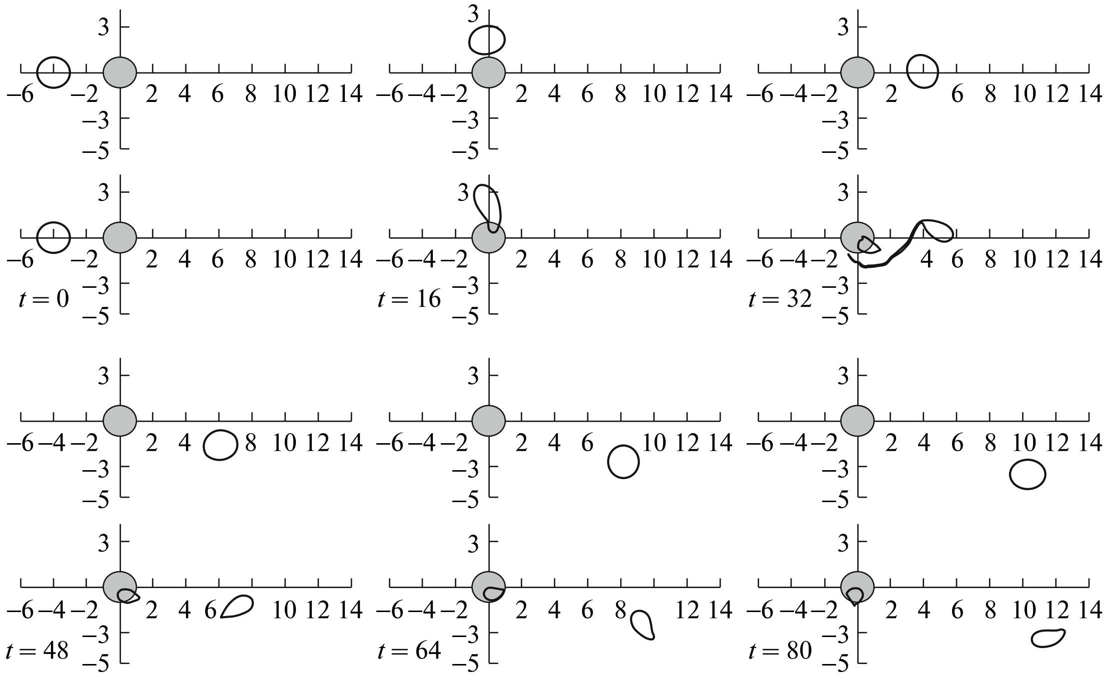

Fig. 3. Synchronous configurations of contours of cyclonic (above) and anticyclonic (below) lenses running on the submarine obstacle at $U = 2$ cm/s and $h = 1400$ m.

800 m the initially circular anticyclonic lens passed over the hill along its northern periphery, took a quasi-elliptic form, and revolving around its axis drifted away in the southeastern direction. At $h = 1000$ m, the lens evolution is different (Fig. 1): passing over the hill from the north, the lens is extended significantly. Two nucleuses with partition are formed; then partition is broken and two virtually equal-sized lenses are formed; then, they also drifted away revolving around a common center. At $h = 1200$ m the lens is divided into two unequal parts, one of which is drifted away by the flow, while the second one is captured firmly by the seamount.

The bifurcation behavior of trajectories of the anticyclonic lens eddy spots is demonstrated in Fig. 2 illustrating superimposed trajectories of the eddy spot centers at very similar height values: $h_1 = 1185.12$ m and $h_2 = 1185.11$ m. Coincident trajectories are indicated with a bold line, the course at $h = h_1$ is indicated with a thin line, and course at $h = h_2$ is indicated with a semi-bold line. Drifting away of both eddies corresponds to the first case, while capture of one of the eddies corresponds to the second case.

Analysis of the field of horizontal movement of current function isolines in the middle layer explains such bifurcation: the internal part of the separatrix loop forming above the southern part of the hill corresponds to the capture area.

Since, as was mentioned above, the ocean region adjacent to the Iberian Peninsular is characterized by the existence of both anticyclonic and cyclonic lenses, then it is essential to note differences in the interaction of eddies opposite in sign with the same hill. Figure 3 demonstrates synchronous configurations of evolving eddy spots for lenses with cyclonic (above) and anticyclonic (below) eddy motions at $h = 1400$ m. A cyclone passes over the hill along its northern periphery virtually not changing its form and is drifted away by the flow, while the anticyclone having passed over the mount is divided into two unequal parts, one of which is captured firmly by the seamount.

In the real ocean, the evolution and destruction of lenses create additional mechanisms of water mixing in the intermediate layer. Thus, a complex of multiscale lenticular eddies can appear in the ocean regions with complicated bottom orography upon lens drifting in a layer of 500–1500 m in thickness. This complicates the structure of temperature and salinity distribution in hydrological sections. For instance, according to the data of a detailed survey carried out by the R/V *Academik Ioffe* in August 1989, numerous eddies were identified in the layer of 550–1300 m in thickness on a small-scale site (100 × 110 km with center in 48°20′N and 21°10′S) [13]. The difference in temperatures between warm and cold waters attained 1.2°C, while the difference in salinity was 0.2 psu. An anticyclonic eddy substantially destructed by jet flows was found there as well. In fact, this is a fragment of the maternal eddy, which consists vertically of 5 lenses with the diameter of 10–20 km and thickness of 50–150 m. These lenses are characterized by an absolute temperature and salinity maximum at all the depths.

Moreover, as follows from the results of model experiments, the fragments of anticyclonic eddies can stay on above submarine hills for a quite long time (Fig. 2). The northernmost meddy "Ulla" was identified in April 1997 above the Sharko Seamount (45° N and 11°30′ W) with a depth of about 3500 m above the top [12]. That was an elliptic lens located in the layer of 600–1600 m with a maximum of temperature (2.5°C) and salinity (0.5 psu) anomalies at the depth of 1200 m. The azimuth rate of eddy rotation attained the maximum values of 15–20 cm/s at a radius length of 15 km. The lens was traced by Langrangian floats for 18 months, and the constancy of its characteristics was confirmed by hydrological probing. Meddy "Ulla" revolved clockwise exactly above the Sharko Seamount for 11 months (analogous behavior of the lens above the circular submarine obstacle is demonstrated in Fig. 3, where the characteristic time of calculation is about one year).

Hence, the data of unique field observations are adequately confirmed by the basic results of our model experiments. Such calculations make it possible to predict the main scenarios of hardly observable interaction between intrathermocline eddies under the complicated bottom relief conditions with the help of a simple hydrodynamic model. The obtained qualitative results may be used as a ground for planning the following field experiments.

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