ISSN 1028-334X, Doklady Earth Sciences, 2010, Vol. 434, Part 2, pp. 1377–1380. © Pleiades Publishing, Ltd., 2010.
Original Russian Text © B.N. Filyushkin, M.A. Sokolovskiy, N.G. Kozhelupova, I. M. Vagina, 2010, published in Doklady Akademii Nauk, 2010, Vol. 434, No. 5, pp. 688–691.

Dynamics of Intrathermocline Lenses

B. N. Filyushkin[a], M. A. Sokolovskiy[b], N. G. Kozhelupova[a], and I. M. Vagina[c]

Presented by Academician R.I. Nigmatulin April 15, 2010

Received April 21, 2010

DOI: 10.1134/S1028334X1010020X

The Mediterranean water outflowing with the bottom current from the Strait of Gibraltar occupies intermediate depths in the eastern part of the North Atlantic at depths from 800 to 1500 m [1]. Anticyclonic intra-thermocline eddies (lenses) are regularly found in the water column of this water mass over the entire region of its spread. They are also filled with the Mediterranean water and are clearly distinguished by their high values of temperature and salinity. This distinguishing property from the surrounding waters in the core of the lens can vary from 1 to 4°C by the temperature and from 0.3 to 1.0 psu by the salinity depending on the distance of the lens from the region of its formation [1]. At the same time, the influence of lenses on the density field is strongly mutually compensated, and the lens core is characterized by homogeneous water density. The absolute values of water density σ_0 in the cores of the lenses vary from 27.5 to 28.2, while the cores can be located at depths from 800 to 1400 m [2].

The available catalogue of the main characteristics of lenses in the Atlantic Ocean over the period 1970–2000 allowed us to demonstrate the character of their spatial spreading with respect to their volume [3]. For example, according to the estimate of Armi and Zenk [4], the lenses cover from 4 to 8% of the Canary Basin area. According to our estimates, under the condition that the lifetime of lenses is not less than three years, a total of 150–200 lenses can be located at any moment of time within a radius of 1800 km from the center of the Portimao Canyon [2]. The only experimental test of the lens lifetime is given in [5]. Lens “Sharon” (M1) was traced using acoustic floats for two years from October 1984 to October 1986. Lens M1 was found south of the Azores frontal zone. It drifted for almost two years to the south. If we assume that the lens existed for approximately 2–3 years before the beginning of the monitoring, we admit that lens Sharon (M1) was approximately 4–5 years old at the moment of its complete destruction.

During the analysis of the spatial distribution of lenses with respect to their volume, their highest concentration was found in the region of the Cadiz Gulf, Cape St. Vincent, and in the region north of the Azores frontal zone. Lenses of anomalously high volumes were observed in these regions [5]. The appearance of large lenses in the open ocean at distances up to 2000 km from the region of their formation makes their life significantly longer and provides possibilities of their drift over distances up to 7000 km. These long-living lenses located southwest of the Azores frontal zone allow us to confirm indirectly the fact of merging of anticyclonic eddies. It is possible to give examples, first of all, of a lens with a diameter of about 100 km found in 1976 in the southwestern part of the Sargasso Sea (25° N, 69° W) at depths from 600 to 1300 m. The anomalies of temperature and salinity in the core of this lens were as high as 2°C and 0.4 psu relative to the surrounding waters [7]. The second example is a lens in the tropical Atlantic (20° N, 37° W) at the depths of 800–1200 m with a diameter of about 70 km and temperature anomaly up to 4°C and salinity anomaly up to 1 psu [6].

These facts give grounds to apply a three-layer quasi-geostrophic hydrodynamic model of an ideal fluid with constant values of density in the layers. Owing to the geostrophic balance, anticyclonic (cyclonic) eddies of the middle layer have the form of double-convex (double-concave) lenses. In this work, we study the process of merging of anticyclonic lenses within such a model taking into account the realistic distribution of density [8] and the mean values of spatial scales of eddies [6].

Figure 1 shows the general scheme of such a model. The solid line denotes long-term mean vertical distribution of density in the Atlantic [8]. This profile is approximated by a two-step piecewise constant function with density jumps at the boundaries between lay-

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[a] *Shirshov Institute of Oceanology,*
Russian Academy of Sciences,
Nakhimovskii pr. 36, Moscow, 117997 Russia

[b] *Water Problems Institute, Russian Academy*
of Sciences, ul. Gubkina 3, Moscow, 119991 Russia

[c] *Geographical Faculty, Moscow State University,*
Moscow, 119899 Russia
e-mail: borfil@ioran.ru

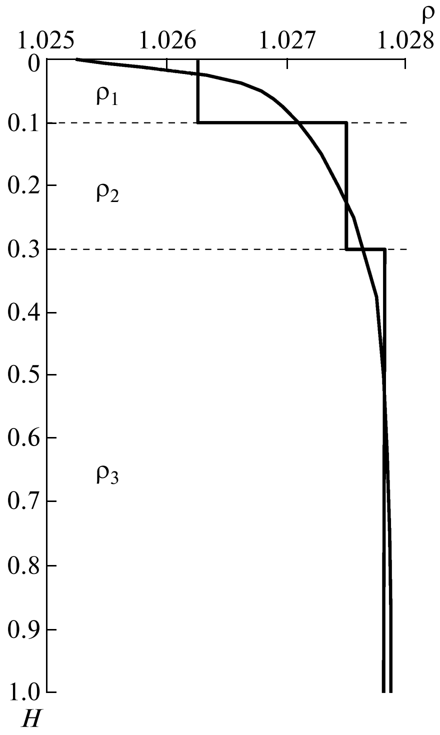

Fig. 1. General scheme of a three-layer model: smooth continuous vertical density distribution (ρ) in the Atlantic Ocean and piecewise-constant distribution in the selected layers (ρ_1, ρ_2, ρ_3).

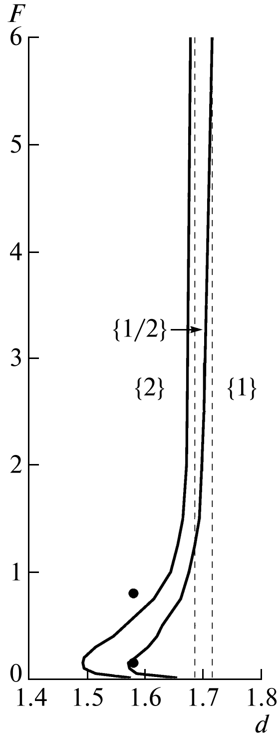

Fig. 2. Diagrams of different states of two circular eddy spots on the parameter plane (*d, F*) in a barotropic fluid (dashed lines) and in the middle layer of a three-layer fluid (solid lines): domain {1} no merging; domain {2} eddies merge, {1/2} intermediate domain with merging and further separation of eddies. The dots correspond to the coordinates of the plane with the given parameters, at which the numerical experiments shown in Fig. 3 were performed.

ers $\Delta\rho_1 = \rho_2 - \rho_1$ and $\Delta\rho_2 = \rho_3 - \rho_2$ so that $\Delta\rho_1/\Delta\rho_2 = 4$ and the dimensionless thickness of the layers are $h_1 = 0.1$, $h_2 = 0.2$, and $h_3 = 0.7$. At such a ratio between the thicknesses of the layers and the ocean depth of 5000 m, the middle layer would occupy levels from 500 to 1500 m. Two Froude numbers are necessarily associated with two density jumps $F_n = (fL)^2/g\Delta\rho_n H$, where f is the Coriolis parameter, which we assume constant, L and H are the horizontal and vertical length scales, and g is acceleration due to gravity. Let us select the parameter $F \equiv F_1$ as the determining parameter so that by virtue of the above assumption $F_2 = 4F$. The evolution of eddy spots in the middle layer is studied in this work on the basis of calculations within a three-layer version of the contour dynamics method (CDM) [9] that applies procedures of contour surgery [10]. The numerical experiments allow us to distinguish the criteria of merging of two initially circular lenses.

It is known [11] that two point eddies of one sign and equal intensity always rotate along circular orbits with a constant angular velocity relative to the center of the segment connecting these eddies in the direction determined by the cyclonic property of the eddies. Two identical distributed circular eddies located at a distance behave similarly [12]. However, the latter have the property that they merge if located quite close to each other. The problem of merging of the eddies of one sign in a homogeneous fluid (plasma) is one of the fundamental problems of hydromechanics. Many papers are dedicated to this problem. The key question is the one about the critical distance between the centers of these eddies at which the merging starts. It was found with a high degree of reliability that two circular cylindrical eddies of a unit radius merge if condition $d < d^* \sim 1.6$–1.7 is satisfied for the value of d (half-distance between the centers of the eddies) [12]. We note that these results for the critical values of d^* were obtained for the eddy spots (eddies with constant distribution of vorticity) in a barotropic fluid. In the case we consider here, internal eddy spots are located between two “free” interface surfaces between the layers, which becomes principal according to the calculations.

The interval for $d^* \in [1.69, 1.71]$ in Fig. 2 based on the CDM calculations for barotropic case is shown with a dashed line. Eddy spots always merge left of this interval and do not merge right of this interval. Inside the interval, either short-time or periodical merging is observed with further separation. The behavior of the corresponding regimes of the interface boundaries is different for the anticyclonic lenses (solid line): at

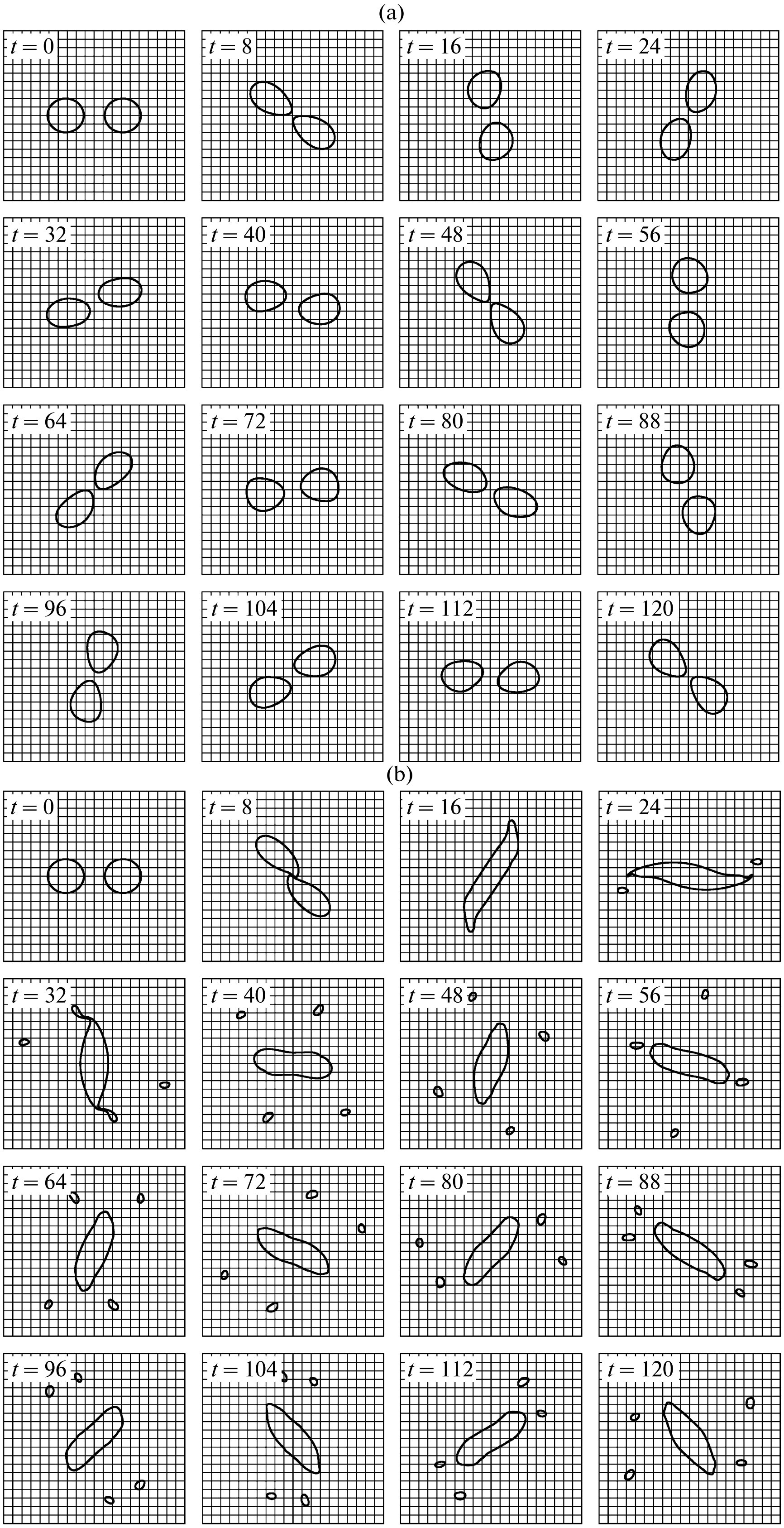

Fig. 3. Instantaneous configurations of initially circular eddies in the middle layer at the given time moments of dimensionless time (*t*): (a) at $F = 0.15$ and $d = 1.58$ (lower dot in Fig. 2); (b) at $F = 0.8$ (upper dot in Fig. 2).

large values of F we actually have a barotropic limit, and over the interval of variations of parameter F from 0 to approximately 1.5, the distribution is not monotonic with respect to parameter F with a minimum at $F \approx 0.15$. Assuming that $f = 10^{-4}$ s^{-1}, $g = 10^3$ g cm s^{-2}, $H = 5 \times 10^5$ cm, $\Delta\rho_1 = 4/5\Delta\rho = 2.4 \times 10^{-3}$ g cm^{-3}, and $F = 0.15$, we get that the eddies less subjected to merging have a characteristic radius $L = 4.24 \times 10^6$ cm = 42.4 km.

Figure 3a shows an example of the behavior of anomalously closely located lenses ($d = 1.58$) at $F = 0.15$ (the lower dot in Fig. 2) when eddy spots rotate relative to the common vorticity center without merging. The figure shows that eddy spots periodically approach and then move off from each other similarly to the behavior during the interaction of the Aska meddies B1 and B2 [13].

Figure 3b demonstrates the example of the scenario with eddy merging at the same external parameters excluding the changed Froude number (now $F = 0.8$ and correspondingly $L = 98.0$ km, the upper dot in Fig. 2). The eddy structure obtained after merging of the initially circular spots has the form of a pulsating quasi-elliptical lens rotating in the anticyclonic direction, which is surrounded by small-scale eddies that separated during the transition stage. After the separation of the eddy filaments and small eddies, the remaining core takes a compact form with the ratio of half-axes that does not exceed 3; thus, it is stable [14].

The configurations of eddy spots in both figures are shown at the given time moments of dimensionless time, and scaling was carried out under the condition that the velocity of fluid particles along the initially circular contour was 30 cm/s [6], then the unit of dimensionless time corresponds to approximately 10 days in the first case and to 24 days in the second case.

The regularity of the interaction between the eddy spots in the middle layer as a function of the Froude number was determined from the results of the numerical experiments within the model of a three-layered ocean with the distribution of density by depth close to the realistic one in the Atlantic and the observed eddy sizes. The criterion of critical distances between lenses for merging of lenses was determined. This result allows us to explain the observed fact of the existence of long-living lenses (up to 10 years) at large distances (more than 7000 km) from the source of their formation (the Gulf of Cadiz).

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research (project nos. 08-05-00061-a, 10-05-00144-a, 10-05-00432-a, and 10-05-00646-a), the RFBR/CRDF program (project no. 09-01-92504-IK_a/RUM1-2943-RO-09), the Ministry of Education of the Russian Federation (Analytical Departmental Purposeful Program “Development of the Scientific Potential of Higher Schools,” project no. 2.1.1/554).

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