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OCEANOLOGY

Reflection of Intrathermocline Eddies on the Ocean Surface

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Abstract—In the northeastern portion of the Atlantic Ocean, at depths of 500–1500 m, there are regular intrathermocline eddies that are characterized by high temperature and salinity. As these eddies interact with the ambient medium, they can transmit a dynamic signal to the ocean surface. These eddies are clearly identifiable on altimetric maps showing variations in the ocean's surface level obtained by satellites. Such observations allow recording not only the complex interaction pattern of surface cyclonic and anticyclonic eddies, but also the processes of merging and separation of intrathermocline eddies.

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This study considers the pattern of the dynamic effect of intermediate depth eddies on the entire mass of the ocean, in particular, on the surface layer using the contour dynamics method taking a three layer density quasi-geostrophic model as an example. It has been demonstrated that the pattern of the current lines of the velocity field induced by an intrathermocline eddy is qualitatively reproduced in the upper and lower layers. Numerical modeling clearly demonstrates the defining role of the processes of multiple merging and separation of eddies for mixing of water masses and the formation of hydrophysical fields of the ocean.

In the northeastern part of the Atlantic Ocean, at depths of 500–1500 m, there are regular intrathermocline eddies that are characterized by high temperature and salinity, with their different life cycle stages [1, 2]. The main source of eddy energy is hydrodynamic instability of the underflow of Mediterranean waters that discharges into the Atlantic Ocean through the Strait of Gibraltar. As it spreads westwards along the continental slope of the Iberian Peninsula [3], this flow forms complex systems of cyclonic and anticyclonic eddies in interaction with the bottom topography (canyons and seamounts) [4, 5]. Anticyclonic eddies (commonly called Meddies, i.e., Mediterranean eddies) are stable long-lived bodies having an ellipsoid shape with horizontal axes of 40 to 100 km and a vertical axis of up to 1 km; anticyclonic eddies spread over large distances (up to 6000 km) from the region of generation [1].

As these eddies interact with the ambient medium, they can transmit a dynamic signal to the ocean surface. These eddies are clearly identifiable on altimetric maps showing variations of the ocean's surface level obtained by satellites. Although the signal-to-noise ratio of the altimeter data for this part of the Atlantic Ocean was low, it was determined that the value of the altimeter signal corresponded satisfactorily to the data of the hydrophysical measurements [6, 7]. Such eddies are also distinguished by changes in the temperature of the ocean surface. The positions of the eddies determined from satellite observations are much worse compared with hydrological measurements [8]. However, satellite observations allow recording not only the complex interaction pattern of surface cyclonic and anticyclonic eddies, but also the processes of merging and separation of intrathermocline lenses, as well as their interaction with different topographic features.

This study considers the pattern of the dynamic effect of intermediate depth eddies on the entire mass of the ocean, in particular, on the surface layer using the contour dynamics method [9] taking a three layer density quasi-geostrophic model as an example.

It was demonstrated in our article [10], which dealt with the interaction pattern of lenses being middle layer eddy patches of the three layer model ocean, that the critical distance at which two originally circular eddies merge is a nonmonotonic function of the Froude number. Just like in paper [10], in this study we assume that the nondimensional thicknesses of the layers are 0.1, 0.2, and 0.7. Thus, if the average depth of the ocean is 5000 m, then the middle layer will be at the depths of 500–1500 m, which is in line with the

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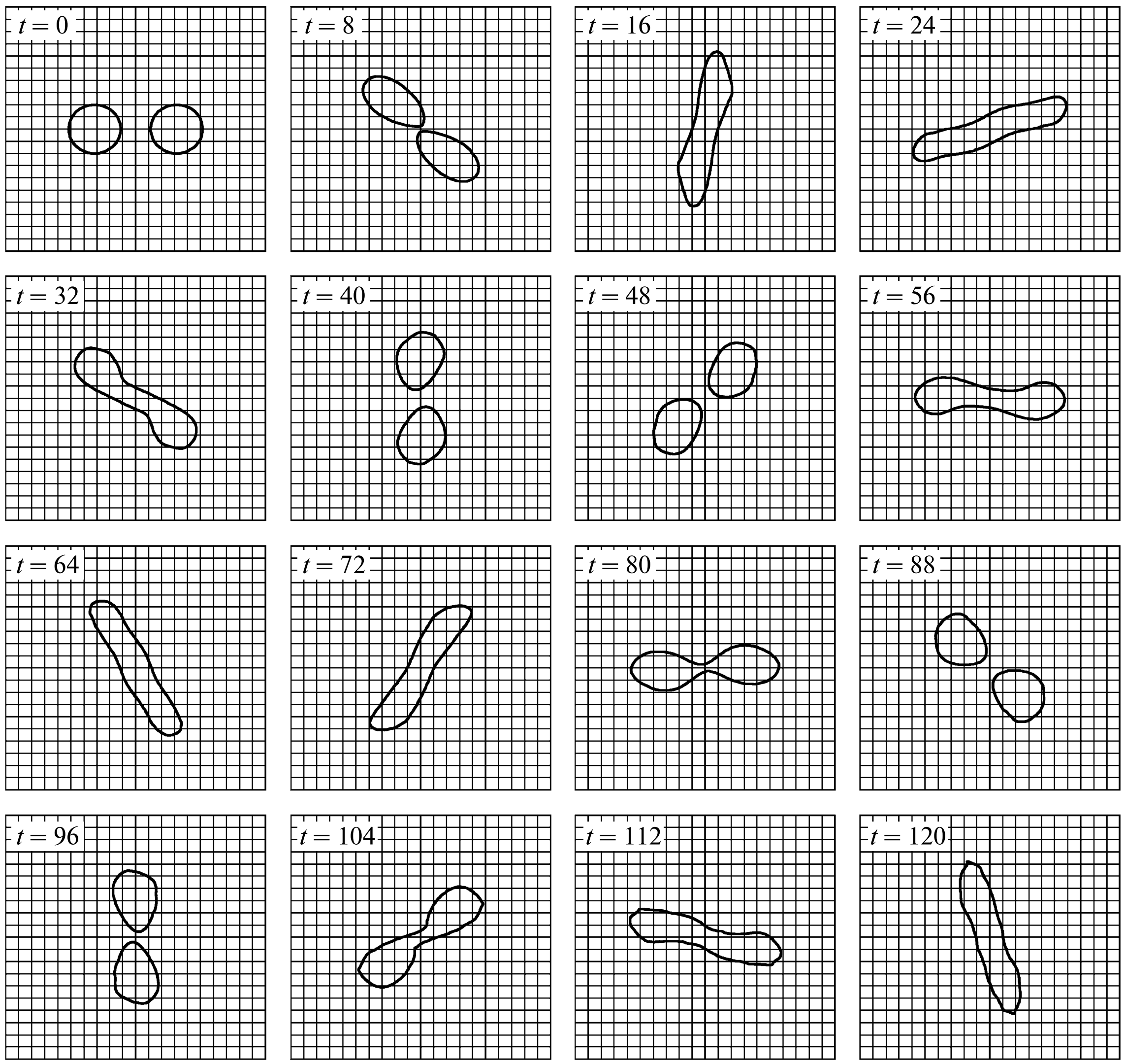

Fig. 1. Instantaneous images of originally circular middle layer eddies at the specified points in nondimensional time (t): periodical merging followed by separation.

statistical average data on the depths of lenses in the Atlantic Ocean [1].

In [10], it was discovered in particular that there is a distance range between the centers of eddy patches where the eddy patches partly merge. This is the behavior of eddies shown in Fig. 1 where the results of numerical calculations intended for determining the instantaneous evolving configurations of the outer boundaries of eddies are shown. Two originally circular anticyclonic eddies rotate clockwise around a common center of mass. At the same time, the contours of the eddies pulsate in such a manner that at some points in time the distance between them becomes less than the critical distance at which they merge. As a result of such an approach of eddies, linked quasi-elliptic structures are formed, which in this case are unstable (It should be noted that the presence of dynamic structures in the form of elongated eddies is very typical of most regions of the World Ocean [11].) Due to

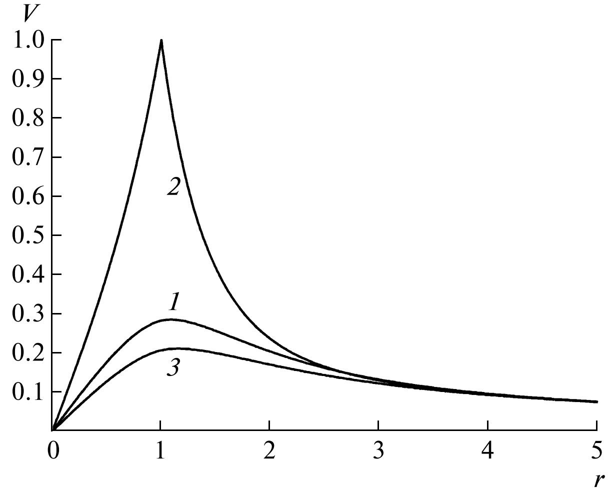

Fig. 2. Normalized profiles of azimuthal velocity $V(r)$ in the upper (*1*), middle (*2*), and lower (*3*) layers induced by a circular anticyclonic unit lens belonging to the middle layer.

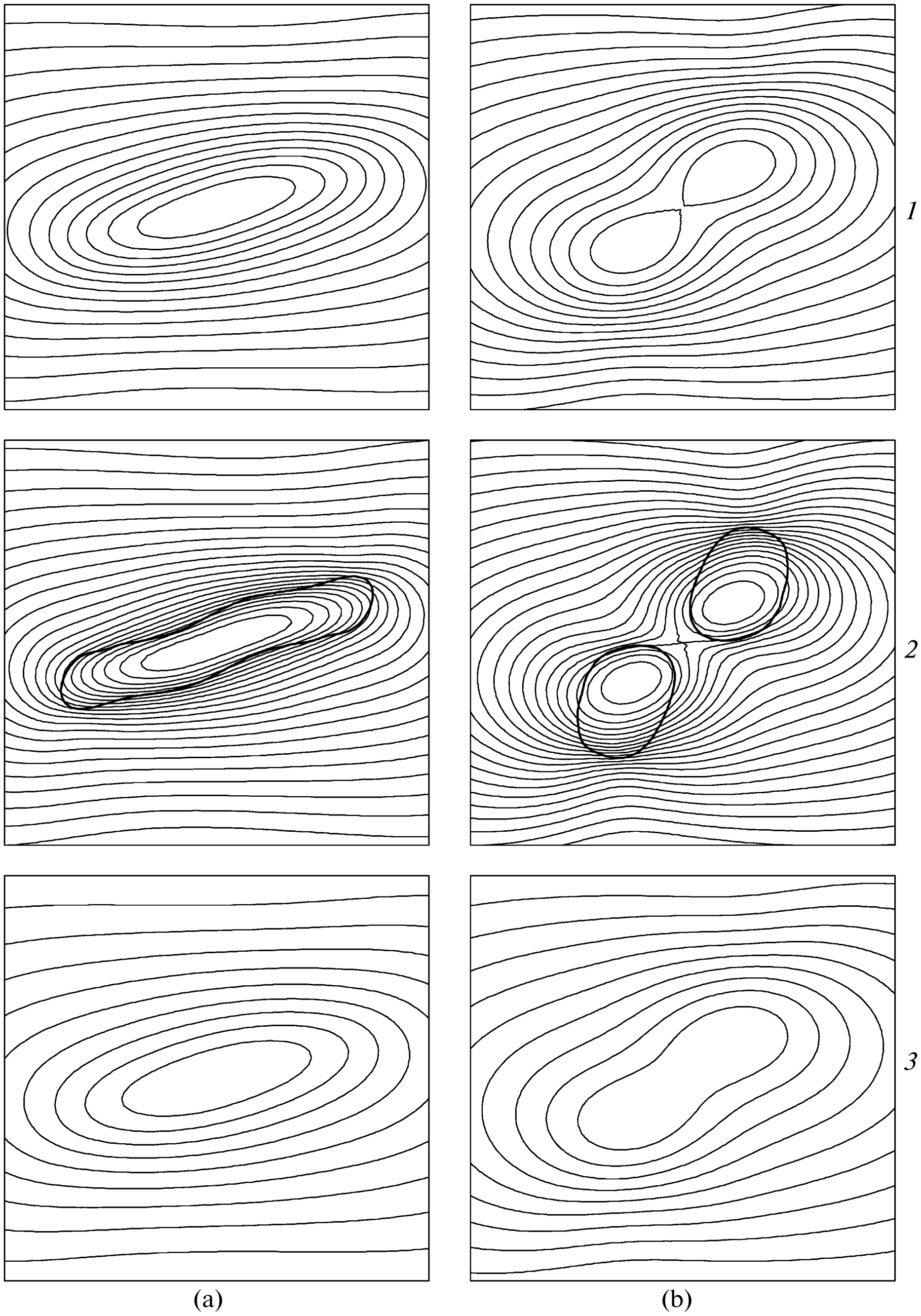

Fig. 3. Isolines of the horizontal motion current function in the upper (*1*), middle (*2*), and lower (*3*) layers for times $t = 24$ (a) and $t = 48$ (b) (Fig. 1). The contours of eddy patches in the middle layer are shown as heavy lines.

this, such eddies further separate to form two nearly circular eddies. Such a scenario can repeat periodically. In our case, we can observe three acts of eddy merging and two separations within the calculated time range. Taking this as an example, the reaction of the upper and lower layers to the dynamic structure of the intermediate horizons will be demonstrated below.

Due to the geostrophic balance, any middle layer anticyclonic (cyclonic) eddy induces local deformations of the boundaries of density contrasts between the layers in the form of a biconvex (biconcave) lens. Therefore, an upward directed hump will form at the lower boundary of the upper layer above the anticyclonic lens. Due to the invariant nature of the potential eddy, the hump, in turn, creates conditions for the formation of a negative relative vorticity (an analog of a topographic eddy above a supermerged hill). A similar situation arises in the lower layer. Thus, the middle layer anticyclonic eddy forms a clockwise circular motion of the liquid in the entire mass of the ocean.

The contours of the boundaries of eddy regions in the layers remain topologically similar.

Figure 2 shows normalized profiles of the absolute values of azimuthal velocities in the layers

$$V_j(r) = \Pi \sum_{n=1}^{3} q_{jn} \sum_{m=1}^{3} s_{nm} E_{m-1}(r), \quad j = 1, 2, 3,$$

where

$$E_0(r) = \begin{cases} r/2, & r \le 1 \\ 1/2r, & r > 1, \end{cases}$$

$$E_i(r) = \begin{cases} K_1(\gamma_i) I_1(\gamma_i r), & r \le 1 \\ K_1(\gamma_i r) I_1(\gamma_i), & r > 1, \end{cases} \quad i = 1, 2.$$

This axisymmetric velocity field is induced by the anticyclonic circular unit eddy patch with a potential vorticity Π located in the middle layer. Here, the index j denotes the number of the layer (from the top downward), r is the radial coordinate, the values q_{ij} and s_{ij} that depend on the external parameters of the task are elements of 3×3 square matrices diagonalizing the operator of the connection between the current function and the potential eddy, γ_1 and γ_2 are stratification parameters inversely proportional to the first and second Rossby radii, respectively, and K_1 and I_1 are modified Bessel functions.

It is obvious that the maximum movement rates of liquid particles take place at the contour of the middle layer eddy. In the upper and lower layers of the ocean, the velocities also reach the local maximum values at $r = 1$, but these values are approximately 4 and 5 times lower than in the middle layer, respectively.

This process explains the fact that middle layer eddies (just like submarine rises) form local anticyclonic circulation in the upper layer of the ocean.

In order to illustrate this effect, isolines of the current function are shown layerwise in Fig. 3 for two points in time when the eddy configuration of the middle layer has a simply connected structure (in the first case) and a doubly connected structure (in the second case). As is evident, the kinematic field of the middle layer of the ocean is reproduced well in the upper layer and partly in the lower layer. Although the calculations were made within the limits of a model assuming the presence of a “rigid lid” at the surface of the ocean, it is clear that in the field conditions anticyclonic eddy structures in the upper layer induce deformations of the ocean surface in the form of depressions above themselves. Thus, the locations and, to some extent, the configurations of intrathermocline lenses can be visualized using remote sensing altimetric methods.

It should be noted that there is another important phenomenon, which is demonstrated in Fig. 1, namely that merging and subsequent separation of eddy patches lead to intensification of the mixing of water masses. Indeed, the volumes of liquid originally contained in each of the eddy patches mix with each other after merging. If thereafter a repeated (or multiple) separation of the large eddy formed occurs, then liquid particles that previously did not belong to the eddies formed will necessarily be present inside these eddies. This fact can be one of the possible explanations of the frequently observed chaotic behavior of drifters.

As follows from the analysis presented, for mesoscale processes, the mass and heat exchange between eddies is the principal driver of efficient mixing of waters in the entire mass of the ocean and plays an important role in the formation of global hydrophysical fields and the Earth’s climate.

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REFERENCES

1. B. N. Filyushkin, D. L. Aleinik, N. G. Kozhelupova, and S. N. Moshonkin, Tr. GOIN **212**, 76 (2009).
2. L. Armi and W. Zenk, J. Phys. Oceanogr. **14** (10), 1560 (1984).
3. F. Madelain, Cah. Oceanogr. **22**, 43 (1970).
4. D. L. Aleinik, E. N. Plakhin, and B. N. Filyushkin, Okeanologiya **38** (5), 645 (1998).
5. X. Carton, L. Cherubin, J. Paillet, et al., J. Marine Syst. **32**, 13 (2002).
6. X. Carton, N. Daniault, J. Alves, et al., J. Geophys. Res. **115**, C06017 (2010).
7. D. Stammer, H.–H. Hinrichten, and R. H. Käse, J. Geophys. Res. **96** (C4), 7005 (1991).
8. R. Pingree, J. Mar. Biol. Assoc. UK **82**, 681 (2002).
9. M. A. Sokolovskiy, Izv. AN SSSR Fiz. Atm. **27** (5), 550 (1991).
10. B. N. Filyushkin, M. A. Sokolovskiy, N. G. Kozhelupova, and I. M. Vagina, Dokl. Akad. Nauk **34** (5), 688 (2010).
11. N. Maximenko, P. Niiler, M. H. Rio, et al., J. Atmos. Ocean. Tech. **26**, 1910 (2009).