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MARINE PHYSICS

Interaction between Synoptic Gyres and Intrathermocline Lenses

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Abstract—In the northeastern Atlantic Ocean, intrathermocline lenses (ITL) occur at depths of 600–1600 m. These ITLs are localized vortex patches (anticyclonic and cyclonic), generally of an elliptical shape with horizontal axes from 40 to 100 km, vertical axes from 0.4 to 1 km, and volumes of 1000–3500 km^3. According to observations, the coexistence of several lenses is a rather common phenomenon in certain ocean areas. Thus, the problem of their interaction, and, in particular, the influence of lenses on larger vortices, is especially important. The aim of the present work is to study, using a three-layer quasi-geostrophic model, the interaction between intrathermocline lenses and synoptic gyres existing in few layers. Simulations show that synoptic gyres change significantly their shape under the effect of ITLs. The authors propose a tentative mechanism of ITLs' deceleration because of the interaction with synoptic gyres, located at different layers. It is obvious that turbulent exchanges at mid ocean depths intensify when vortices collapse.

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INTRODUCTION

In the NE Atlantic Ocean, intrathermocline lenses (ITL) occur at depths from 600 to 1600 m. They are localized vortex patches, both anticyclonic and cyclonic. As a rule, these patches are elliptically shaped. Their horizontal and vertical axes are 40–100 and 0.4–1 km long, respectively, and volumes measure from 1000 to 3500 km^3. These lenses, being filled with Mediterranean waters (MW), are easy to recognize in the ocean because their high values of temperature and salinity, which serve as natural tracers [11, 13, 22]. The difference of the characteristics in a lens core from those of surrounding waters varies within 1–4°C and 0.3–1.0 PSU in salinity, depending on the distance from their birthplace site. This allows us to determine both their location in the ocean and the dimensions of liquid volumes as well as to explore their evolution at any stage of their life up to the point of their disintegration [12].

Generally, dipole systems, composed of two vortices, form near canyons. The lifecycle of cyclonic vortices lasts from a half-year to a year. When disintegrating, they somewhat enhance the average salinity in the whole region of their stay. On average, anticyclonic vortices (the lenses) live as long as 4–5 years and play a key role in the transport of heat and salt at the intermediate ocean depths. Just these vortices determine the salinity of the MW tongue at large distances from their source. The MWs are traceable up to the Mid-Atlantic Ridge in the west, and propagate in the latitude diapason from 20° N (lenses "MESOPOLYGON" [3]) to 45° N (lens "Ulla" [21]). It should be kept in mind that about 75–100 lenses may coexist within this aquatic area [18]. Thus, it is possible to specify two regions: (1) The Gulf of Cadiz and the area adjacent to the Iberian Peninsula where the cyclonic and anticyclonic vortices coexist at intermediate depths, and (2) the open Atlantic Ocean where, as a rule, anticyclonic ITLs are observed at depths of 600–1600 m.

It should be noted that isolated ITLs bearing waters with abnormal properties occur in many regions of the World Ocean at depths from 200–500 to 3000 m. A detailed analysis of regional research [1] has revealed the importance of considering all the mechanisms of formation and propagation of the lenses, and their role in the formation of intermediate properties. However, in the present study, we primarily use observations on the dynamics and evolution of ITLs of a Mediterranean origin.

The observations show that the coexistence of several lenses within a limited area is a typical pattern. Thus, the problem of their interaction is quite important. However, most studies, including [14], consider only the external effects (steady flows, islands and submerged mountains) that determine the behavior of lenses, but they pay no attention to the impact of the lenses themselves upon external dynamical structures. The exceptions are [8, 15, 16, 17], which discuss the manifestations of the lenses on the ocean surface, and the recent publication [10], where the dynamics of neutral buoyancy floats (NBF) placed both inside and outside a lens is observed. However, the direct effect of the lenses upon the larger scale vortex structures has not been studied before now.

The goal of the present study is to investigate the mechanisms of the interaction of intrathermocline vortices and synoptic gyres in the framework of the three-layer ocean model. The lenses are located in the middle layer, while the mesoscale gyres are concentrated either in the upper layer or in the upper and lower layers. Although field observations of lenses reveal their substantial vertical variability, we suggest that the processes, discussed in the present study, are quite adequately described by the model of kinematically homogeneous vortex patches in each of the three layers.

Observations of lenses in the ocean. ITLs of Mediterranean origin were found in the data of hydrological surveys [11], as well as in the observation data of profilographs of the ARGO global project [2] due to their higher temperature and salinity. The most comprehensive observations on the MW propagation, formation of the dipole vortex structures, their motion, and the interaction of the cyclones and anticyclones in the areas of the Gulf of Cadiz and those located to the west of the Iberian Peninsula have been obtained in the experiments SEMANE, 1999–2001 [16, 17], MEDTOP [11, 19, 24], ARCANE [21], and POMME [20]. The first two projects resulted in cogent natural evidence for the substantial role of ITLs in the processes of mixing and exchange of properties at intermediate depths. The consideration of vortices of different signs as bodies of revolution in the middle layer (600–1600 m), and the capability of scanning their manifestations on the ocean surface by means of the satellite altimetry have been justified. Furthermore, intricate interactions have been observed, e.g., between three vortices of different signs [16] or between two dipole systems against the background of a cyclonic gyre in the middle layer [19]. No direct measurements of this gyre velocity have been conducted. Therefore, the influence of this gyre on the character of dipole structure interaction may be at least qualitatively evaluated in model experiments (Figs. 1–3).

The ITL "Ulla" was discovered in the course of the ARCANE experiment in April, 1997, to the NW of the Iberian Peninsula at 45° N, 11.5° W [21]. It was located at a depth of 600–1700 m and measured 50–60 km in diameter. The observation of the lens, using Lagrangian floats for tracing its travel, took 18 months. During 11 of the 18 months, the lens performed only small displacements above the underwater mountain Charcot at the level of 3500 m over its summit. After 360 days of its staying in the zone of influence of Charcot mountain, the lens begins to move southwestward. In 150 days, after drifting until the latitude of 42.5° N, the lens found itself in a local cyclonic gyre about 100 km in diameter. Next, the lens returned for 100 days, along a virtually parallel track up to 44° N (Fig. 12 in [21]). The analysis of the available observations and additional NBFs data from depths of 400–600 m and 1000–1500 m in a region adjacent to the lens, was unable to explain the specific features of this vortex behavior, in particular, its long-lasting stay over the Charcot mountain during the initial stage of observations. Investigations of averaged and mesoscale circulations in the 0–500 m layer west of Charcot mountain in the POMME project [20] demonstrated the existence of cyclonic and anticyclonic activity zones of synoptic scales. Taking into account that this region is subjected to the effect of passing Atlantic atmospheric cyclones during most of the year, it is possible to assume that relatively stable cyclonic vortices regularly emerged and existed in the upper layer above the Charcot mountain. This specific feature of water circulation in the upper layer allows us to explain the behavior of the lens above the bank by means of a model experiment (see Fig. 3).

Numerical simulation of the vortex interaction. The numerical calculations, whose results are given in the present section, have been carried out on the basis of a three-layer quasi-geostrophic model on the f-plane having the following parameters, characteristic to the conditions of the North Atlantic: the total depth is 4 km and the thicknesses of the upper, middle, and lower layers were $H_1 = 600$ m, $H_2 = 1000$ m, and $H_3 = 2400$ m, respectively; the first and the second deformation radii [4] take the values $Rd_1 = 32$ km and $Rd_2 = 15$ km [25].

The results of the calculations are represented as a sequence of contours of vortex patches in layers. We used the three-layer version of the Contour Dynamics Method (CDM) [6, 7]. This assumes that potential vorticities (PVs) $q_j (j = 1, 2, 3)$ in the layers are characterized by a piecewise constant distribution $q_j = \sum_{j=1}^{N_j} q_{ij}$, such that q_{ij} (the first index defines the number of a vortex patch while the second index is the number of the layer) are the constants inside certain compact domains having areas S_{ij} and are equal to zero outside the domains; i.e., they are vortex patches, and N_j represents the number of vortex patches in the jth layer.

Note that the interaction of vortex patches depends primarily on the "efficient" potential vorticity (PV), which is equal to the product $q_{ij} S_{ij} H_j$ and is designated as Π_{ij}, rather than on the local PV q_{ij}.

In this model, the intrathermocline vortex (cyclone or anticyclone) will be understood as an vortex patch concentrated in the middle layer and characterized by a constant positive or negative value of potential vorticity.

Let us take a linear spatial scale as Rd_1, and the rotational period of the revolution of an initially circular vortex patch around its center in the absence of external fields as a time scale T^*. So, if we assume that the maximum velocity achieved at the circular contour of a unit-radius vortex (remember that the dimensionless unit of length corresponds to 32 km) is 40 cm/s, we obtain $T^* \sim 9$ days.

The first two numerical experiments demonstrate the specific features of interaction of a synoptic gyre, belonging to the upper layer and having radius $R = 6$, with two pairs of ITLs of unit radii located in the middle layer. Thus, in this case $N_1 = 1$ and $N_2 = 4$. In

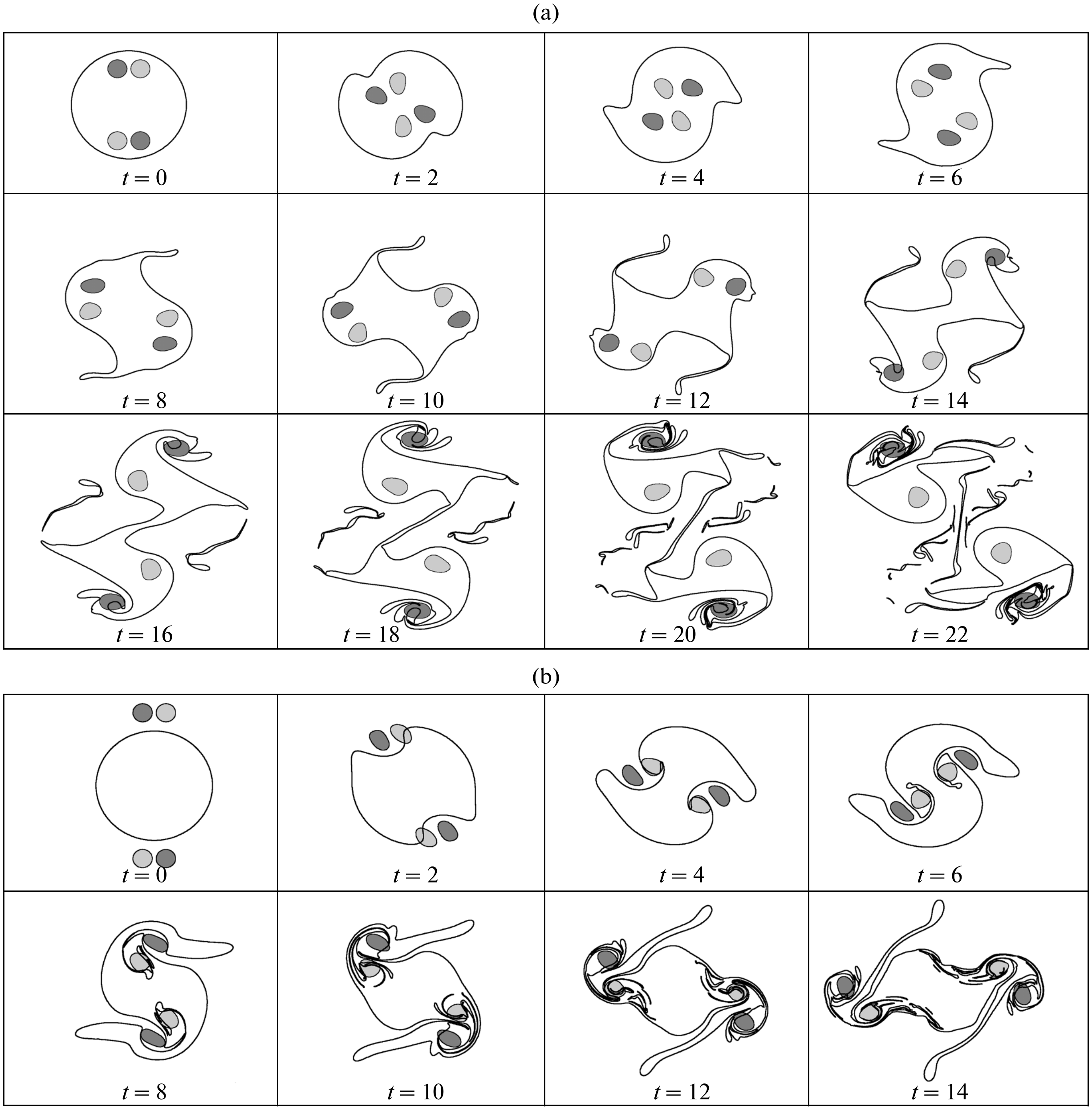

Fig. 1. Evolution of the vortex structure consisted of a synoptic cyclonic gyre of the upper layer (solid line contour) and two pairs of ITLs that belong to the middle layer and are located under the former (the patches of light and dark shades indicate cyclones and anticyclones, respectively). The values of t are dimensionless instants of time. At $t=0$, the center of the upper layer cyclone is located at coordinate origin (0, 0). The centers of four vortices of the middle layer have the following coordinates: (a) $(\pm 1.2; 4)$ and $(\mp 1.2; -4)$, (b) $(\pm 1.2; 8)$ and $(\mp 1.2; -8)$. The upper sign always relates to anticyclonic ITL while the lower sign marks cyclonic ITL.

dimensional variables, the radii of the surface cyclone and of every ITL are 192 and 32 km, respectively. Let the upper layer cyclone be a relatively powerful vortical structure, and the ITLs in the middle layer be such that their total efficient potential vorticity is less than the PV of the cyclone. Let us take, for instance, the following dimensionless quantities: $\Pi_1 \equiv \Pi_{11} = 5.4$ and $\Pi_{12} = -\Pi_{22} = \Pi_{32} = -\Pi_{42} = -1.25$.

Let, in the first case (Fig. 1a), all ITLs initially lie under a surface cyclone (top view) while in the second case (Fig. 1b) they are outside the same cyclone. The initial position of the ITLs, being 180° symmetrical, facilitates a head-on collision. Note, that in the absence of the upper-layer cyclone, the initial stage of the approach of a vortex pair would result in the exchange of partners, and new pairs would scatter in opposite directions orthogonal to the initial motion

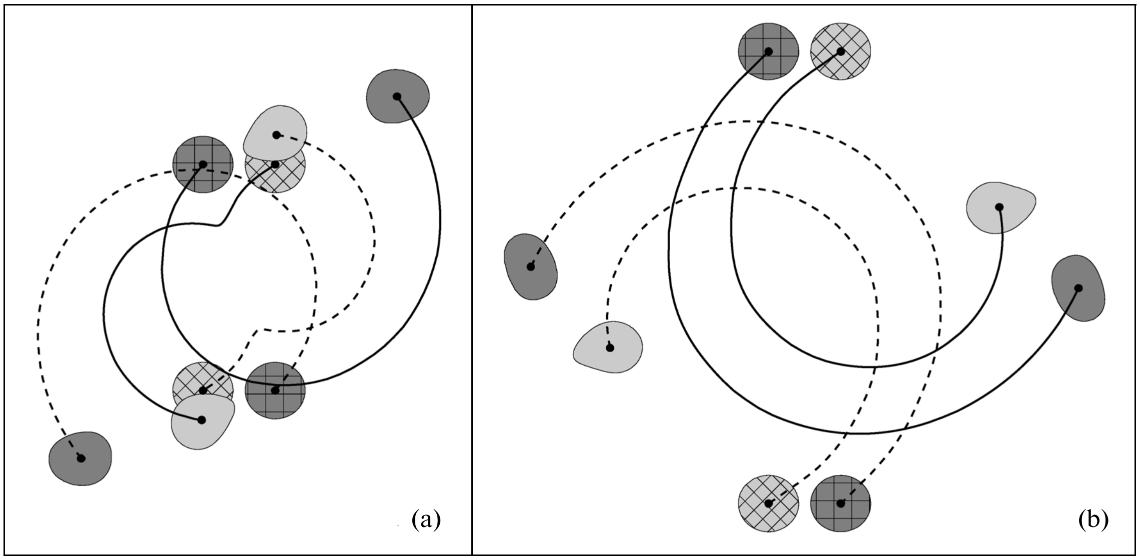

Fig. 2. Panels (a) and (b) show positions of the ITL pairs at $t = 0$ (the vortex patches are hatched) and at $t = 14$ for the cases represented in Figs. 1a and 1b respectively. The lines designate center trajectories of the vortices initially located in the upper (solid) and lower (dashed) parts of the plot.

(the well-known Greenhill problem [5]). The effect of an upper-layer cyclonic gyre substantially changes this pattern, as shown in Figs. 1a and 1b. It is supposed in the figures that the upper layer of fluid is transparent and colored vortex patches in the middle layer can be seen from above. Each panel of these figures shows instantaneous contour configurations of all vortex patches at the indicated moments of dimensionless time. Thus, the time interval between neighboring images makes up 18 days in dimensional variables.

It is evident that the counter motion of vortex pairs is accompanied in both cases by the counterclockwise rotation of the whole vortical structure, what is induced by the rotation of the upper cyclone. In the first case, when vortex pairs lie under the cyclone, the exchange of partners between the pairs initially located in the upper and lower parts of the panel, takes place in the interval between $t = 2$ and $t = 4$. One of the new pairs joins those patches that initially belonged to the right-hand side of the panel, while the second new pair comprises patches from the left-hand side of the panel. At a later stage, they continue the common cyclonic rotation in course of running away along the spiral trajectories. In the second case, when the vortex pairs are beyond the boundary of the upper-layer cyclone, they remain indivisible vortex structures and continue to move away uniformly from each other along the spiral trajectories. Figure 2 demonstrates the differences of these scenarios for both cases where positions of ITLs are shown at initial instant and at $t = 14$ along with the continuous trajectories of centers of the vortices.

In our view, the most remarkable is the fact that the lenses affect the upper-layer cyclone. The ITL impact on the surface cyclone is substantial in spite of the fact that these vortex structures are separated in the vertical. In both cases the initially circular contour shapes of the cyclones become considerably deformed, intrusions and vortical filaments appear and take part in the common cyclonic rotation of the whole two-layer vortex structure. The compact parts of the cyclone are concentrated over the cyclonic ITLs, and the anticyclonic lenses build a "roof" above themselves of filaments of the surface cyclone. Note that in the first case, the upper layer cyclone has been virtually completely disintegrated during the calculation time (about 200 days) and divided into two large fractions and a multitude of smaller ones.

The next experiment, represented in Fig. 3, demonstrates the results of interaction of a single lens with synoptic and anticyclonic gyres placed into the upper and lower layers respectively. We think that this configuration is typical for the North Atlantic area in question. Indeed, on the one hand, the occurrence of a quasi-stationary cyclonic gyre in the upper layers has been corroborated by measurements, as was indicated above; on the other hand, the bottom relief of the area in question posseses a multitude of elevations, serving as a source of formation of anticyclonic vorticity in the lower layer. Just these circumstances prompted us to choose a model structure composed of a surface cyclone and a near-bottom anticyclone as companions of the ITL. For simplicity, the absolute values of the efficient PVs are equal, and the radii of these vortices are taken to be $R = 3$, which corresponds to 96 km. The lens of the middle layer has a unit radius and is located on one side of this structure. Under this positioning of the vortices and in the case of equality of density jumps at interfaces, the effects of synoptic gyres of opposite sign on the lens would be perfectly balanced, and the latter would remain motionless. In

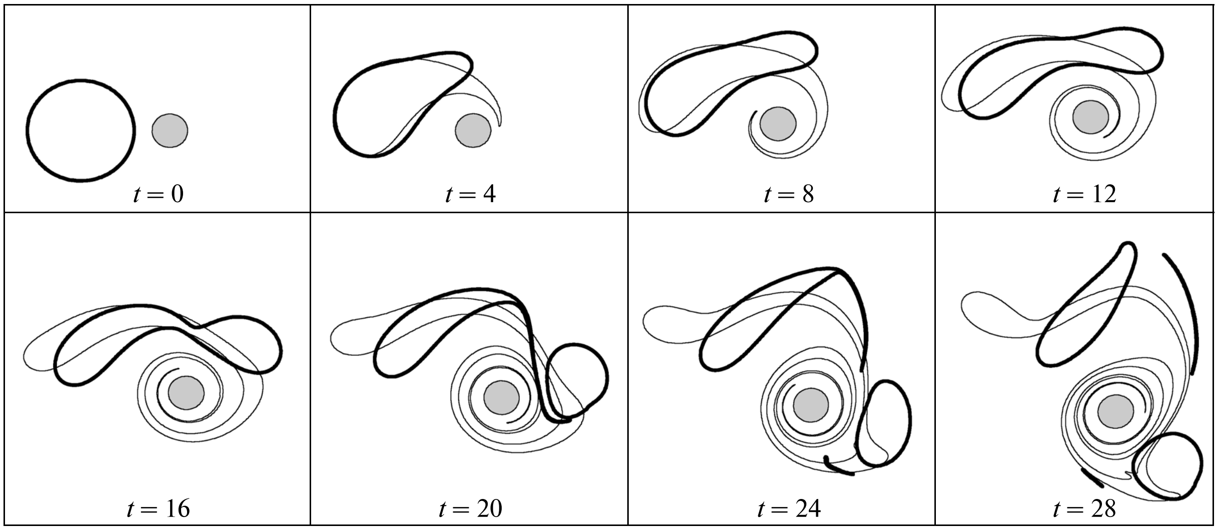

Fig. 3. Evolution of the vortex structure consisted of cyclonic vortex of the upper layer and anticyclonic vortex of the lower layer; both vortices have radii equal to 3. At time zero, the centers of synoptic vortices are located at sites $(x_{01}, y_{01}) = (x_{03}, y_{03}) = (0,0)$ (their contours are highlighted with thick and thin lines, respectively), while the center of a lens of unit radius (grey patch) is at $(x_{02}, y_{02}) = (5,0)$. The second lower index universally indicates the number of the layer.

the present case, the above equality is absent, but, as is shown in Fig. 3, the lens remains virtually motionless except for small deviations from the equilibrium position. At the same time, the vortex patches of synoptic structures are subjected to substantial deformations due to the impact of the lens: the synoptic gyre of the upper layer divides into two parts, each one participates in the rotation relative to the lens, and the lower layer anticyclone spins around a quasi-stationary area in the lower layer induced by the ITL.

Based on this experiment, we can formulate a hypothesis on the possible mechanism of origination of stagnation zones when lenses travel in the North Atlantic ocean (Figs. 4 and 7 in [19], Figs. 3, 12, 14, and 15 in [21]): *stagnation zones are defined as regions that occur in the vicinity of oppositely directed surface and bottom vortices*. The latter may be formed due to the effects of bottom topography, in particular, an anticyclonic deep-water vortex arises above an underwater mountain.

CONCLUSIONS

Detecting the lenses by means of remote monitoring of the ocean surface (which quite recently seemed unlikely [26]), is now a common practice in ocean science (see, among others, [16, 11, 17, 14, 8, 10, 18] and many other studies), since the interaction of vortex structures at different depth levels is an inherent property of vortices in a stratified medium. The general estimation of the spatial changes in kinetic energy of the intermediate layer vortices in the area of propagation of the MW demonstrated its significant decrease towards the open ocean where the frequency of the ITLs occurrence substantially drops [24].

In the present study, based on numerical simulation, we demonstrate that ITLs substantially influence the surface gyres of synoptic scales by by causing their deformations up to disintegration into smaller structures. Note that by instrumental methods, it is virtually impossible to trace the whole sequence of stages of the ITLs interactions in the ocean with surface cyclones and near-bottom anticyclones (Fig. 3) or of two submerged dipole structures with an upper-layer cyclone (Figs. 1 and 2) over a considerable period of time. We suggest that the synthesis of field measurements and model experiments is the only means to progressing in the understanding the mechanisms of interactions of different-scale vortices.

Our numerical experiments convince us that intrathermocline vortices are important elements forming the synoptic variability in the ocean.

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