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Eddy Splitting along Boundaries

Abstract

This paper addresses the question of what happens to an eddy that is forced "violently" against a boundary by an advective current or another vortex. The detailed temporal evolution of such a collision on an f-plane is examined using a barotropic model, a one-and-a-half-layer contour dynamics model and an isopycnic, primitive equation model. Our calculations show that an eddy splits into two along the wall: a cyclone to the right and an anticyclone to the left (looking offshore).

Introduction

Collision of eddies with boundaries is inevitable mainly because of two processes. First, the variation of the Coriolis parameter with latitude forces eddies toward the western boundaries of the ocean. Second, advection by main currents or propulsion induced by neighboring eddies also force eddies toward the ocean walls. The former process causes a "soft" and "gentle" impact with the western wall because of the β-induced westward speed is relatively small [$O(1 \text{ km day}^{-1})$] so that it takes many days [$O(\beta R_d)^{-1}$, where R_d is the Rossby radius] for a significant fraction of the eddy (i.e., a distance comparable to the eddy diameter) to be pushed into the wall. The latter processes, on the other hand, can be of a more "explosive" and "violent" nature as advection [$O(10\text{–}100 \text{ km day}^{-1})$] can push an eddy into the wall so rapidly that gross distortions in the eddy shape (and structure) can occur in a matter of days. The "gentle" eddy-wall interaction process has been studied extensively in Shi and Nof (1993) and the present article focuses on the more "explosive" and "violent" collision. Shi and Nof (1993) have shown that a soft collision is typically associated with (1) a small leakage from the eddy rim which forms a thin jet along the wall, and (2) a transformation of the eddy into a half-circular structure that migrates steadily along the wall (a wodon). We shall show in the present study that a violent collision causes more drastic effects. In particular, the eddy will not only migrate along the wall but will also split into *two* eddies with an opposing sense of rotation.

In this study, an eddy is conceptually cut by a wall at $t = 0$ (as if the advection forced violently the eddy into the wall). Our aim is to explain the subsequent development of the eddy-wall collision. We shall first use the so-called contour dynamics method, which will be applied to an eddy on an f-plane. We shall then investigate this process using a constant potential vorticity eddy in an isopycnic model (noting that the contour dynamics method is a Langrangian approach, whereas the isopycnic model is a Eulerian method). We shall show that both of these studies point to a new counter-intuitive eddy splitting proces. We speak here about a counter-intuitive process because intuitively we would expect that an eddy that is cut by a wall would simply leak along the wall until its outer rim leaks out completely and its core is merely "kissing" the wall (Nof, 1988). It turns out, however, that such a benign state is never reached and that instead both the core and the leaked fluid are forced farther and farther into the wall.

A contour dynamics model

In the following discussion, we present the contour dynamics results of a barotropic model. Earlier studies have shown that, in an open ocean, a barotropic eddy with $b < 2$ is linearly unstable (Flierl, 1988). Therefore, for the barotropic model, we shall focus on the evolution of a linearly stable eddy ($b > 2$) colliding with a wall. Before presenting the detailed evolution of the eddy-wall collisions, it is recalled that the evolution of a barotropic cyclone is the mirror image of its anticyclone counterpart. Therefore, it is sufficient to present only a cyclonic (or anticyclonic) evolution.

For the case of the linearly stable eddy-wall collision in a barotropic model (Fig. 1), there are two stages in the evolution process. In the first stage ($t = 0$–120) the stable eddy leaks fluid along the wall and the eddy's outer radius decreases (and eventually reduces to less than 2). In the second stage ($t > 120$), the eddy is unstable. The annulus fluid is peeled quickly off the parent eddy because the interior fluid advects the annulus fluid toward the wall. For $t > 160$, a new, large anticyclonic eddy detaches from the parent eddy. This new, anticyclonic, eddy consists of all the original annulus fluid. Another important evolution process is that, during this eddy-wall collision, the interior of the eddy is forced toward the wall by the leaked vortex on the left (looking offshore). As the interior is continuously forced toward the wall, its shape changes from a circle to a near-semicircle. It moves to the right (whereas the offspring eddy moves to the left) due to the image effect. As time goes on, the mutual advection of an anticyclone on the left and a cyclone on the right leads both eddies farther toward the wall. Eventually, we see a new anticyclonic eddy on the far left and a cyclonic eddy on the far right. It is also worth pointing out that, during the splitting process, outside fluid slowly intrudes into the new eddy through a streamer. Our calculations show that, once detached from its parent eddy, the new anticyclonic eddy moves to the left at a constant speed, and that the remaining cyclonic core migrates to the right at a different constant speed.

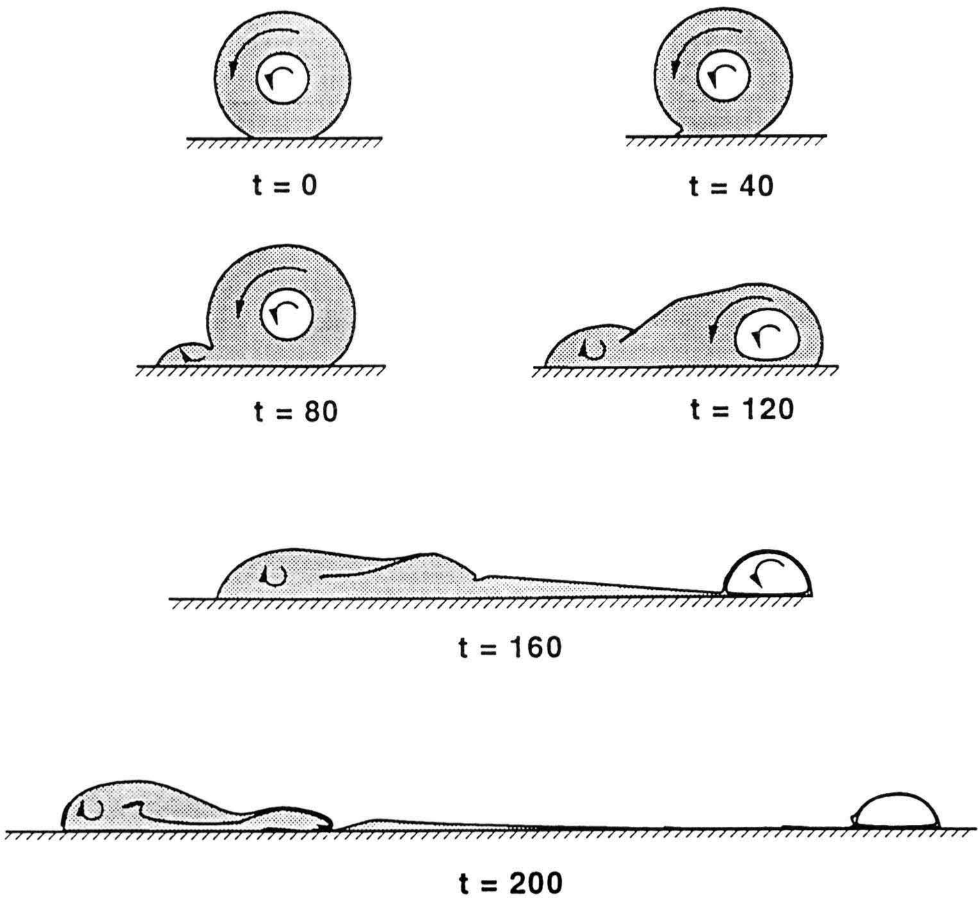

Fig. 1. The temporal evolution of the inner and outer fronts of an initially stable barotropic eddy from t = 0 to t = 200. The cyclonic eddy leaks its annulus fluid (shaded area) to the left and the leakage gradually forms an anticyclonic eddy moving to the left (looking offshore). The cyclonic interior of the parent eddy moves toward the wall and migrates steadily to the right.

An isopycnic, primitive equation model

To verify the new eddy splitting process presented earlier, we now use an isopycnic, primitive equation model described in Shi and Nof (1993). This Bleck and Boudra (1986) isopycnic model uses an Eulerian method, whereas the contour dynamics model uses a Langrangian method. Since the isopycnic model is a primitive equation model, it includes more dynamical processes than are contained in the contour dynamics model. For example, Kelvin waves are generated in an isopycnic model but such waves are not present in a contour dynamics model. Fig. 2 illustrates an anticyclonic eddy collision corresponding to such an

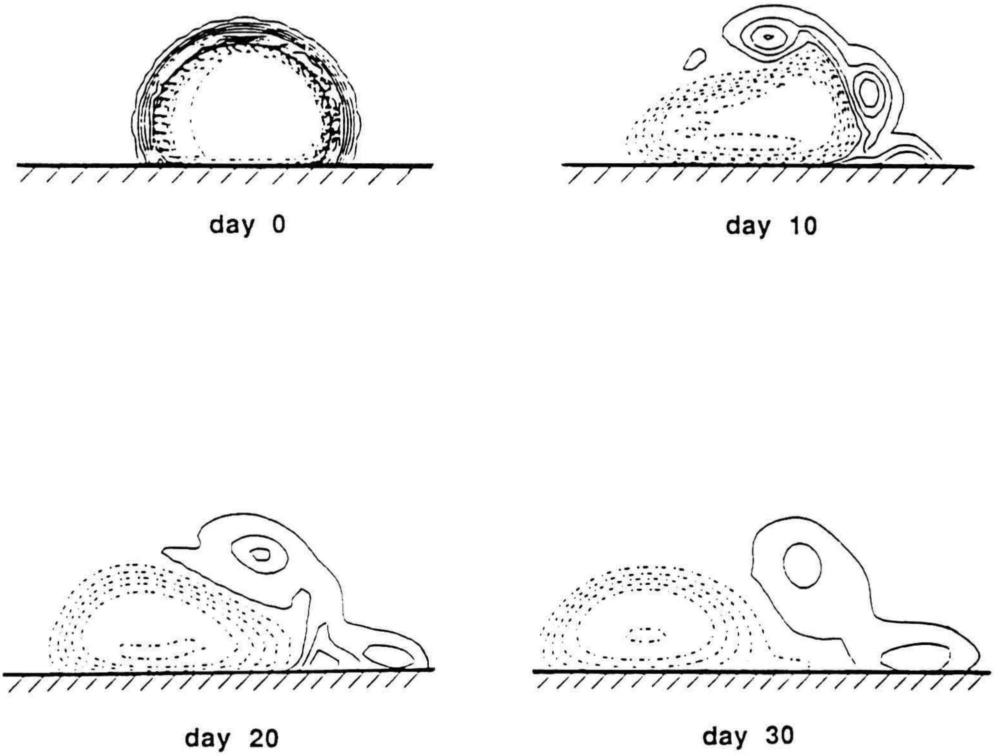

Fig. 2. Contours of the potential vorticity anomaly of an anticyclonic eddy colliding with a wall. The annulus fluid is advected anticyclonically to form a weak cyclonic eddy migrating to the right. The original eddy becomes half-circular and moves at a constant speed to the left.

eddy that is suddenly cut off by a vertical wall. From $t = 0$ day to $t = 20$ days, the interior anticyclonic fluid advects the annulus anticyclonic fluid to the right, and this process is compatible with that of Fig. 1. At $t = 10$ days, due to instability of the eddy, the shape of the interior is deformed. On day 20, the cyclonic annulus fluid is pushed farther to the right by both the interior and the image effect. At $t = 30$ days, this anticyclonic-wall collision produces a new cyclone to the right along the wall. Similar to the result of the contour dynamics study shown in Fig. 1, the newly formed cyclonic eddy is weak compared to its anticyclonic counterpart. This new, weak, cyclonic eddy moves slowly to the right. The area of the new eddy in Fig. 2 is approximately 100% of that of the initial annulus, which is identical to the final area of the new eddy in Fig. 1.

Interactions of the interior with the annulus force the interior to move farther into the wall. Then, the initial constant potential vorticity eddy is transformed into a half-circular wodon-like eddy (e.g., Shi and Nof 1993). In a fashion similar to the result shown Fig. 1, the present numerical calculation shows that the remaining parent eddy migrates to the left at a constant speed of

4.2 km day^{-1}. By using the wodon solution of Shi and Nof (1993), we obtain an analytical speed of 4.0 km day^{-1}, which agrees well with the numerical calculation. The isopycnic model also shows that eddy-wall collisions generate a Kelvin wave propagating along the wall. Such a wave was, of course, not present in the contour dynamics model because the contour dynamics technique filters these waves out.

Comparison with oceanic observations

One of the most comprehensive surveys of eddy-wall collisions is that of Vidal *et al.* (1992) who examined Loop Current rings. They identified the collision from temperature, salinity and dynamic topography distributions. As suggested by our models, they found that, when the anticyclonic eddy collided with the continental slope, the eddy translated to the left. During the collision process, the anticyclonic ring shed approximately one third of its volume to the right. They also found that a cyclonic ring was formed to the *right* of the parent ring as suggested by our model. Because of the relatively large amount of mass that was lost from the parent eddy, we speculate that the actual collision was similar to our collision processes, all of which have been termed "violent" collision.

While the above observations compare favorably with our model, the following data do not necessarily support our model predictions. Vukovich and Waddell (1991) used data from XBT/hydrographic cruises in the Gulf of Mexico and from satellite images to study collisions of a warm-core ring with the western slope. They indicated that the collisions of the anticyclonic ring with the continental slope induced a large-scale flow to the left in the upper layer near the slope. There was a cyclonic ring to the *left* of the Loop current warm-core ring along the slope. The line-up is the cyclone to the left and the anticyclone to the right, which is different from both our model results and the observations of Vidal *et al.* (1992). We speculate that the cyclonic ring of Vukovich and Waddell (1991) could have been generated by shelf water being pushed to deep regions by the anticyclonic ring. This process is, of course, absent from our analysis as our boundaries were taken to be vertical.

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