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FINAL REPORT: N00014-96-1-0065, Vortex Generation due to Coastal and Topographic Interactions

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ABSTRACT:

For this grant, we performed two studies. In the first, the interaction of vortices with coastlines and broad topographic slopes was examined. In the second, the deviation of a coastal current due to an escarpment was investigated. The work included analytical, numerical and laboratory investigations.

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vortex-rebound from a coast

In this vortex-coast interaction problem, we were interested in determining the relative importance of inviscid vortex generation mechanisms as compared to viscous boundary layer vorticity generation at a coast. Primarily this work involved numerical simulations. The typical simulation that we performed had a dipolar vortex collide with a straight coast. The dipole was chosen because it is a convenient structure that can be used as a model of eddies approaching a coast. Alternatively, we could have simply positioned a single eddy at the coast and watched the subsequent evolution. However, in that case there is no natural way of choosing how close to the coast the unperturbed eddies should be placed. At least with the dipole, the approach to the coast and the original deformation of the eddies is a natural result of advection and the influence of the coast. Through these numerical simulations we found that if β is relatively large, the β -effect causes a vortex approaching an eastern boundary to rebound from the coast and move away permanently. If β is relatively small, viscous rebound dominates with the primary vortex repeatedly returning to the wall after the first rebound until it dissipates.

We can formulate a simple relation that determines how strong β must be in order to dominate over viscous effects. We have found that the distance that a vortex moves along the coast before separation due to the β -effect scales like $(\Delta y)_\beta \sim \omega_0/\beta$. Then if we use the relation $\omega_0 \sim U/a$ where U is the maximum velocity in the co-moving frame of the vortex and a is the radius of the vortex, then we have $(\Delta y)_\beta \sim U/(a\beta)$. Furthermore, the distance the primary vortex travels along the wall for the pure viscous rebound problem is roughly independent of the magnitude of the viscosity and can be taken as $(\Delta y)_\nu \sim a$. Thus, if we say that the β -effect will dominate when the expected Δy is less than that due to viscous rebound, we have the following inequality when the β -effect dominates:

$$(\Delta y)_\beta < (\Delta y)_\nu \quad (1)$$

or

$$\frac{U}{a^2\beta} < 1 \quad (2)$$

We verified these results through a series of numerical simulations and laboratory experiments.

Another interesting point of this work is the difference in the flux of fluid away from the wall for the two rebound mechanisms. In the viscous rebound case, the vortices leave the wall on a curved trajectory that brings them back to the wall, there is no transfer of wall fluid far away from the wall. In contrast, in the β -induced rebound, wall fluid can be carried arbitrarily far from the wall.

To further examine the simultaneous effects of the viscous boundary layer and the β -effect, we performed a series of laboratory experiments. These experiments were carried out in a rotating cylindrical tank with a sloping bottom. A straight vertical wall was inserted on one side of the tank to act as the coastal boundary. The tank rotates at a fixed angular rotation rate. A bottom with uniform slope is used to mimic the β -effect. The dipole is created essentially by a jet of fluid into the tank. The artificial coast was a straight wall on one side of the tank. The slope of the bottom of the tank was varied over a wide range in order to see both viscously dominated rebound and nearly inviscid rebound. All of the results are reported in Carnevale, Fuentes, and Orlandi, 1997.

coastal current bifurcation due to topography

Our study of the bifurcation of coastal currents due to topography is reported in Carnevale et al. 1999a. In that work, we combined theoretical analysis and numerical simulations to make several predictions about how coastal currents interact with escarpments running perpendicular to the coast. We found that there were profound differences in the effect of the topography on the coastal flow depending on whether the geometry was 'right' or 'left' handed (as we called it) independent of the direction of the coastal flow. A right (left) handed geometry is that in which the coast is on the right (left) when one is looking along the coast across the escarpment from deep to shallow water.

One interesting prediction was that when a coastal current encounters an escarpment in left-handed geometry, it would produce dipoles that 'rebound' from the escarpment and move back in the upstream direction. Also, we predicted that there would be no out-flow along the topographic slope of the escarpment in the left-handed geometry. In fact, our results suggested that this geometry would favor an inflow along the escarpment. Flow in the right-handed geometry is predicted to be very different. In that case, all eddies are predicted to remain near the escarpment with an off-shore current along the escarpment.

To verify this and other predictions from our previous work, we designed a series of rotating tank experiments. These experiments were performed by Roberta Serravall (graduate student of Paolo Orlandi) and Luis Zavalla Sanson (graduate student of Gert-Jahn van Heijst) at Eindhoven University. Along with our analytical and numerical work, this work formed the core of Serravall's thesis (Serravall, 1999). We are currently preparing an article on the results of the laboratory experiments, and this continuing work is funded by a new ONR grant.

In the laboratory experiments, we were able to obtain an example of the generation of multiple dipoles in the left-handed geometry and induced on-shore flow.

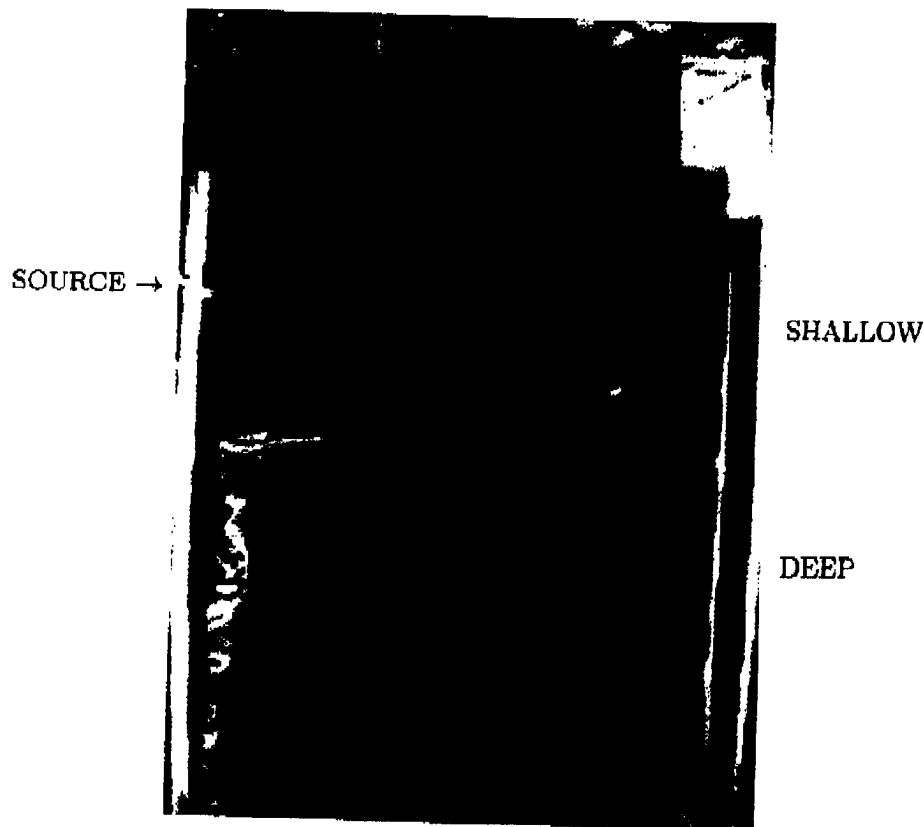


Figure 1: Photograph of dye concentration in rotating tank experiment viewed from above along the axis of rotation. The source of the boundary current is on the upper part of the left-hand wall. The current flows down along the left-hand wall until it hits the topographic slope (seen here as a horizontal line dividing the tank in two). There it bifurcates with part of the current following the wall and the other part repeatedly generates dipoles that leave the topography at an angle. At the same time an inshore current (i.e. a flow toward the left) is formed over the topographic slope.

An illustration of this is given in figure 1. The source of our boundary flow is a tube visible in the picture on the left-hand wall about one third of the way from the top of the picture (indicated by the arrow). The inflow from this tube results in a current that flows down in the picture along the left-hand wall. The lower half of the picture is deep fluid while the upper is shallow fluid. The depth change is from 17 to 23 cm. There is a smooth slope of width 4 cm connecting the two depths. The mean boundary current speed before reaching the escarpment is about 2 cm/s, and $f = 1/s$. The size of the area illustrated is about 30 cm by 20 cm. Before introducing the boundary current, dye lines were placed transverse to the line of the topographic gradient. As the 'coastal' current hit the 'escarpment', a flow toward the 'coast' was induced. It appears the this flow starts near the left boundary and then extends to cover the entire 'escarpment.' Eventually this topographic current becomes part of the long-term circulation pattern which involves cyclonic circulation over both shallow and deep basins. Furthermore, we examined flows in which the boundary

current was initially induced on the right-hand wall of the tank. In this case, the boundary geometry is right-handed, and, as predicted, a bifurcation of the current occurs in which a portion of the current leaves the boundary and follows the topographic gradient.

Other Results

In additions to the papers mentioned above, there were several others published or submitted in the past two years that we should mention. In Kloosterziel and Carnevale (1999) we presented a new model of vortex stability in which we were able to demonstrate the nonlinear saturation of the instability of circularly symmetric vortices in the form of multipole vortex structures. In Carnevale G.F., Briscolini M., Kloosterziel, R.C., and Vallis (1997) and Orlandi and Carnevale (1999a), we explored the stability of vortices with varied vorticity structure and also the effect of the bottom Ekman layer on vortex stability. In In Carnevale et al. (1999b), we presented an analytical criterion for the suitability of various kinds of boundary conditions in general circulation models. In particular we considered the super-slip boundary. This work grew in part out of our studies of vortex rebound from a coast in which we applied the super-slip boundary.

ONR Publications:

- Carnevale G.F., Briscolini M., Kloosterziel, R.C., and Vallis G.K., 1997, Three-dimensionally perturbed vortex tubes in a rotating flow, *J. Fluid Mech.* 341, 127-163.
- Carnevale G.F., Fuentes, O.V. and Orlandi, P., 1997, Inviscid dipole-vortex rebound from a wall or coast *J. Fluid Mech.* 351, 75-103.
- Carnevale, G.F., Llewellyn Smith, S.G., Crisciani, F., Purini, R. and Serravall, R. 1999a Bifurcation of a coastal current at an escarpment. *J. Physical Oceanography* 29, 969-985.
- Carnevale G.F., Cavallini, F. and Crisciani, F. 1999b, Dynamic Boundary Conditions Revisited. (submitted to *J. Physical Oceanography*)
- Kloosterziel, R.C. and Carnevale, G.F. 1999 On the evolution and saturation of instabilities of two-dimensional isolated circular vortices *J. Fluid Mech.* 388, 217-257.
- Orlandi, P. and Carnevale, G.F. 1999a, Evolution of isolated vortices in a rotating fluid of finite depth, *J. Fluid Mech.* 381, 239-269.
- Orlandi, P. and Carnevale, G.F. 1999b Large Eddy Simulation of Stratified Flows Proceedings of the ERCOFTAC meeting on 'Direct and Large-Eddy Simulation', Cambridge, UK May 1999. (in Press)