EXPERIMENTS ON VERTICAL MOTIONS OF ROTATING FLOWS OVER VARIABLE TOPOGRAPHY

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The interaction of vortices with topographic features in a homogeneous rotating fluid is studied experimentally. The main goal is to examine the associated vertical motions generated during these processes and its potential to produce significant vertical transports. The topography used in this preliminary part of the study is an axisymmetric seamount. The vortices are monopolar cyclones initially generated near the mountain. For subsequent times, the vortices translate around the summit in anticyclonic direction due to the beta effect associated with the slope of the topography. The experiments are analysed for different vortex parameters and by their initial position with respect to the mountain. A fundamental subinertial oscillation of the vertical flow is consistently measured.

1. INTRODUCTION

The aim of this study is to gain a better understanding of vertical displacements generated during the interaction of a barotropic flow with bottom topography features. Although vertical motions in the oceans are usually one order of magnitude smaller than horizontal displacements, they play a fundamental role on a large number of oceanic processes by transporting physical, biological and chemical properties. In particular, aggregations of plankton are frequently observed over shelf breaks and seamounts, as well as fish and cetacean populations. These aggregations are produced by different mechanisms, some of which might be closely related with the dynamics of the flow-topography interaction. For instance, Zavala Sansón and Provenzale (2009) show that a cyclonic vortex over a seamount is able to induce upwelling motion, which eventually enhances the growth of phyto and zooplankton on top of the topographic feature.

The present project is aimed to provide a more detailed analysis of these processes from the experimental point of view. For this purpose, attention will be focused on the flow evolution of a cyclonic vortex in the presence of a pronounced, submerged mountain. In the context of barotropic flows, the relevant mechanism producing vertical displacements is the stretching and squeezing effects on fluid columns as they impinge over variable bottom topography. Laboratory experiments of these processes have been focused on the horizontal behaviour of the flow by using quasi 2D models (see e.g. van Heijst and Clercx, 2009). In this project, in contrast, the aim is to determine the structure of vertical motions during the flow-topography interaction.

2. EXPERIMENTAL SET-UP

In all experiments the tank is filled with fresh water with a maximum depth H=85 cm, and set in solid-body rotation with a Coriolis parameter f=0.42 s^{-1}, which gives a rotation period of T=30 s. Horizontal motions are observed with a camera mounted on top of the rotating platform. Vertical motions are recorded in a vertical plane across the mountain. The fluid velocities are measured by using PIV. The flow is set in motion by inducing a cyclonic vortex near the topographic feature. The characteristics of the vortices are measured from an additional set of experiments with no topography. The experiments have a duration of 20 min (about 40 periods of the system), which is the same order of the Ekman time scale T_E = 2H/√νf (with ν the kinematic viscosity of water). Thus, bottom friction effects are expected to play a secondary role on the flow dynamics, at least during several rotation periods.

Bottom topography: The seamount consists of a solid, axisymmetric structure, with maximum height of 30 cm. The radius of the mountain is 50 cm, so the mean slope is about s=0.6. The vortices are generated over an arbitrary radial line, such that the important parameter is the distance of the initial vortex to the edge of the seamount along this line.

Initial vortices: Circular vortices are generated by immersing a cylinder of radius R a depth h before the start of each experiment. At t=0 s, the cylinder is removed, and a cyclonic monopolar vortex is generated by conservation of potential vorticity. Four types of vortices are studied by using two values of R (30 and 60 cm) and depth h (25 and 50 cm). Wider cylinders generate larger vortices, and deeper h's give stronger vortices. Typical radial profiles of azimuthal velocities obtained with PIV measurements are shown in Figure 1. The experimental curves are fitted with the so-called "sink-vortex" profile, for which the azimuthal velocity decays as 1/r for large r and the vorticity profile is assumed to be Gaussian.

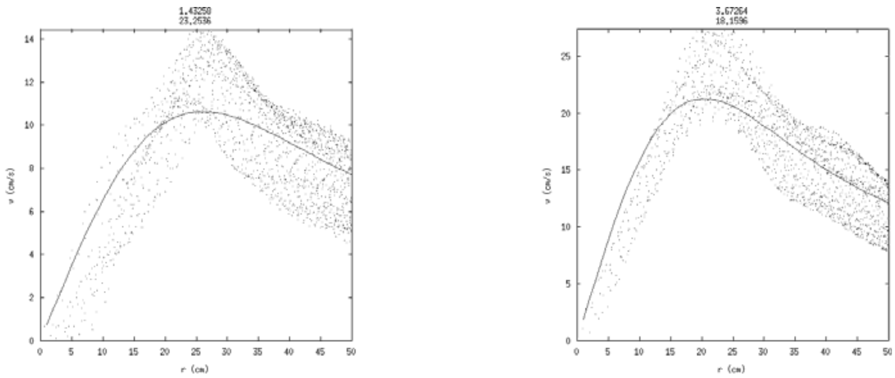

Figure 1. Azimuthal velocity profiles of two types of initial vortices used in the experiments. Experimental points are indicated with dots, and solid lines indicate the fitted profile.

3. RESULTS

Horizontal motions. The motion of the vortices strongly depends on their size and strength, as well as on the initial position with respect to the seamount. However, the general behaviour observed in all cases is that the vortices approach the mountain and rotate around the summit in anticyclonic direction. This behaviour was first described by Carnevale et al. (1991), who performed laboratory experiments with barotropic vortices over a conical bottom. Given the much larger horizontal scales, the present experiments have a much longer temporal scale, avoiding strong damping effects by bottom friction.

Figure 2 shows some snapshots of the horizontal velocity field in a typical experiment. Initially, the vortex is generated at the southeastern flank of the seamount (whose periphery is indicated with a black circle). After 560 s (about 19 rotation periods) the vortex has been displaced to the other side of the mountain along an anticyclonic trajectory (with shallow water to the right). This motion corresponds to the topographic beta effect associated with the slope of the mountain. Note the anticyclonic circulation induced over the tip of the mountain at t=560 s. The cyclone-anticyclone pair rotating around the mountain is one of the more remarkable features in most of the experiments. After 1100 s (almost 37 rotation periods), the predominant motion is the anticyclonic cell on the summit, whilst the signal of the vortex is only visible from the vorticity field as a patch of cyclonic vorticity at the periphery of the mountain (last panel).

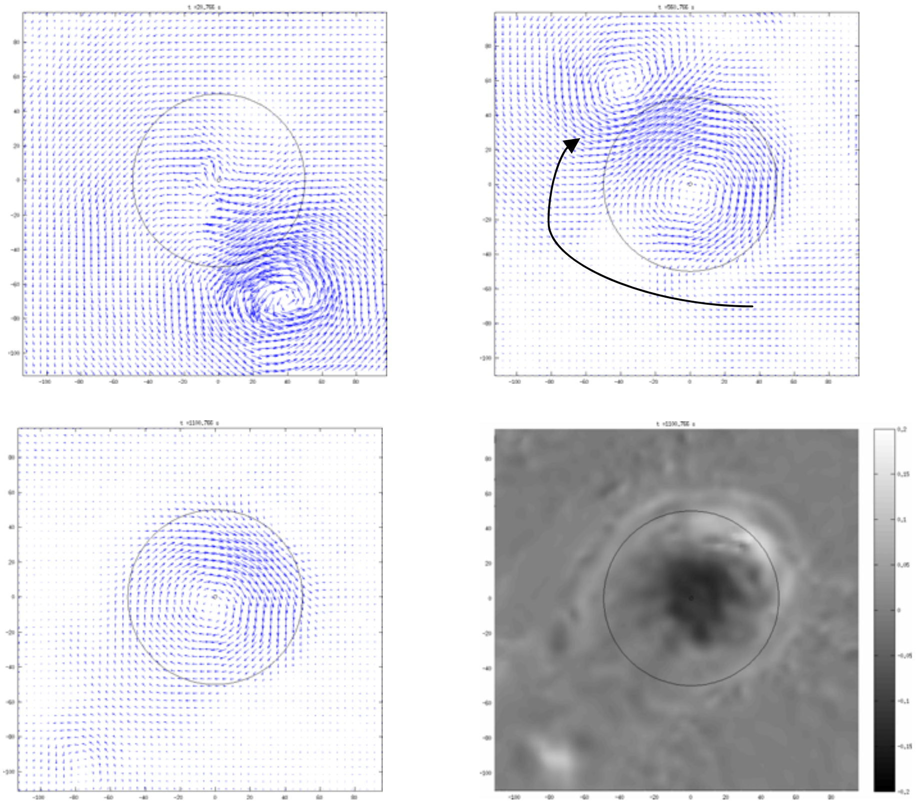

Figure 2. Velocity vectors from a typical experiment at times 20, 560 and 1100 s.
Last panel: vorticity field at time 1100 s.

Vertical motions. The essential character of vertical motions is given by a radial inward and outward flow as the vortex rotates around the seamount. This is shown in Figure 3, where two snapshots of the velocity field in a vertical section are presented. Consider the right flank of the mountain starting from the origin. Evidently, the flow is uphill at time t=105 s and turns downhill at time t=253 s. This oscillation was systematically observed, despite the high noise of the velocity measurements due to severe technical difficulties, as discussed below. The opposite motion occurs at the left flank of the mountain.

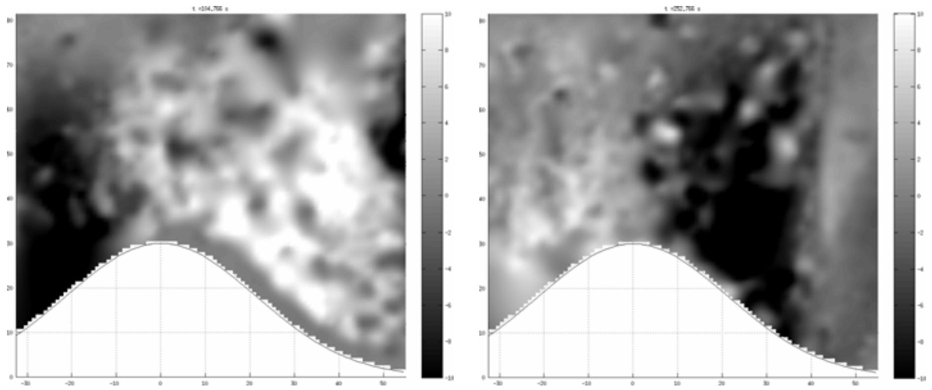

Figure 3. Surfaces of vertical velocities in an arbitrary vertical plane across the mountain at times 105 and 253 s. Bright (dark) colors indicate upwelling (downwelling).

Figure 4 shows the vertical velocity component integrated over the whole vertical section at the right flank of the seamount as a function of time. This plot clearly demonstrates the oscillatory character of the vertical motion as the vortex interacts with the seamount: the flow moves up and down every 200 s (7 rotation periods approximately). In addition, this oscillation decays in time as the flow is damped by bottom friction effects. The solid line indicates an Ekman decay proportional to $\exp(-t/T_E)$.

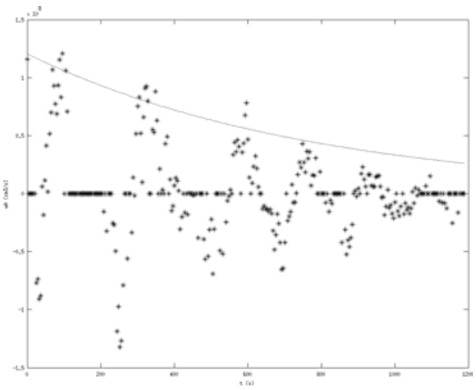

Figure 4. Vertical velocity component integrated over the right side of the vertical plane in the previous figure. The solid line is the exponential decaying function with the Ekman rate $1/T_E$.

4. DISCUSSION

The motion of a barotropic vortex in a rotating tank with a submarine topographic feature at the bottom was examined by means of laboratory experiments. The experiments were originally designed to observe vertical velocities over the mountain. The vertical component of the velocity field was directly measured by using PIV in a vertical laser sheet across the mountain. The oscillatory character of the flow during the vortex-topography interaction was clearly identified from these observations. Furthermore, this oscillation and the temporal decay of its amplitude were more clearly registered by calculating the vertical velocity component integrated in the vertical section.

Some difficulties to perform these measurements were found, however, due to two main factors: (1) the smallness of the vertical velocity component and (2) the strong light dispersion produced by particles located outside the vertical measurement plane. The magnitude of the vertical velocities is estimated to be around 10% of the horizontal velocities. Thus, vertical motions have a magnitude of about 0.5 cm/s at the beginning of the experiments and about 0.1 cm/s or less at the end (after 40 rotation periods). On the other hand, the excess of light dispersion was a more serious problem. This was due to the fact that the particles used for PIV measurements were randomly crossing between the vertical sheet of interest and the camera recording the experiments. The unavoidable presence of the particles in front of the camera produced artificial motions, since the camera images do not distinguish between particles in the vertical plane of interest, and the space between that plane and the camera. The solution consisted of seeding the flow with much less particles, with the cost of missing information at some times due to the lack of particles for PIV.

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