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A laboratory study of floating lenticular anticyclones

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ABSTRACT

Oceanic vortices play an important role in the redistribution of heat, salt and momentum in the oceans. Among these vortices, floating lenses or rings are often met in the meanders of warm currents. In order to better describe these vortices, we propose here a laboratory study of floating anticyclonic lenses. A small volume of fresh water is gently injected near the surface of a rotating layer of homogeneous salted water. Because of the opposite effects of rotation that tends to generate columnar structures and density stratification that spreads light water on the surface, the vortices take after a rapid transient, a quasi-stationary lenticular, finite-sized three dimensional typical shape given by the hydrostatic and geostrophic balances. Visualization and measurements of this equilibrium shape, aspect ratios and vorticity fields are performed. These measurements permit to compare our laboratory anticyclones to analytical predictions that use first a simple solid body rotation model and then a more realistic isolated Gaussian vorticity field. Finally, a comparison of our models with oceanographic lenses described in the literature is discussed.

1. Introduction: lenses in the oceans

Oceanic vortices contribute to the climate equilibrium on Earth as they transport heat and momentum inside the oceans or at their surfaces. For instance, the vortices that are generated by the retroflection of the North Brazil Current (NBC) are typical examples of these mesoscale oceanic structures that travel in the Atlantic Ocean for months or even years. These vortices are the subject of several studies [1,2] that show that they are generated through hydrodynamic instabilities of surface currents. Because of this generating process and in consequence because of their inherited geometrical characteristics, Fuglister [3] coined them as rings since their central cores have zero or very small relative vorticity. Then the vortex cores gain angular velocity through radial momentum diffusion and they transform into lenticular vortices or lenses [4]. They keep this lenticular form and coherence during a time much longer than their rotation period, thus transporting water with different physical, biological and chemical characteristics along distances much larger than the vortex diameters of several hundreds of kilometers. In the northern hemisphere, lenticular vortices are mostly superficial anticyclonic structures with warm cores. Unstable surface currents like the Gulf Stream [5], the Kuroshio [6], the Agulhas Current [5,7] or the North Brazil Current [2], show similar generation mechanisms of these vortices [8]. In this context, there is a growing interest in quantifying their main physical characteristics as well as their vertical and horizontal scale evolution. Determining the volume of lenticular vortices from surface observations is a difficult task for oceanographers and during the last decades there has been many hydrographic surveys in order to study their three dimensional structures. Olson [9] and Carton [8] carried out complete reviews about this subject. In particular, between 1998 and 2000, a detailed campaign was carried out on the NBC Rings [10–12] dedicated to the study of their structure and physical properties evolution. From these measurements, surface properties of such lenses, like the velocity and vorticity fields as well as the associated oceanic surface elevation, were reported by Castelão and Johns [13]. It was found in particular that these lenses have a vorticity field similar to that of isolated vortices, i.e. with a surrounding ring of opposite vorticity.

The main purpose of the present experimental study is to test analytical predictions of the aspect ratio of floating lenses against laboratory experiments. For this purpose we generate anticyclonic vortices by the gentle injection of a finite small volume of pure water at the surface of a salted water rotating layer in the same way that Griffiths and Linden [14] did. The

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injection of a fluid with different density has also been described in [15] to study the baroclinic instability. As we will see in the following, after a very fast adjustment, the vortices are dominated by the hydrostatic and geostrophic balances and a solid body rotation model is able to predict the main scaling trends of the vortices. However, this simple model is not sufficient to correctly predict the exact shape and sizes of our laboratory eddies. An isolated modified Gaussian model, as used by [16] greatly improves our theoretical predictions. The geostrophic and hydrostatic equilibrium equations will be integrated under the hypothesis of non viscous flows with non recirculating flows inside the vortices. We will show that a prefactor arising from the equations of motion is necessary to correctly predict the shape and dimensions of our floating anticyclonic lenses. Therefore, even if viscous terms can be incriminated for the slow and quasi-static damping of the vortex rotation through Ekman layers, its shape is controlled by the balance of the Coriolis term with the radial pressure gradient on one hand and by the balance of the buoyancy force with the vertical pressure gradient on the other hand. Lastly, a bibliographical study of oceanic anticyclones will be presented. We will show that the solid body rotation model predicts correctly the scaling of the shape of about one third of these vortices; the two other thirds needing prefactors in front of the scaling law that should be possible to calculate the same way we do in our experimental analysis if at least the vortices are not too far away from their quasi-geostrophic balance.

2. Theoretical modeling of anticyclones in rotating stratified flows

Theoretical studies about the vertical and horizontal structure of lenticular lenses are scarce. Nof [17] proposed a theoretical model to describe the horizontal structure, trajectory and evolution of a baroclinic eddy on the β-plane. His model was developed for anticyclonic lenticular vortices with rigid body rotation with density ρ_v immersed in a homogeneous rotating fluid of density ρ_f (with $\rho_v < \rho_f$). Goni and Johns [18] and Johns et al. [11] developed a theoretical model with a Gaussian vorticity profile to estimate the vertical and horizontal structures for the Agulhas and NBC rings. Their model showed a good fit for the vortex radius R at the air–water interface and for $\zeta_{\max}$ the maximum vortex sea elevation. Taking advantage of this model, Castelão and Johns [13] inferred the vertical and horizontal structure of the NBC rings but their results did not agree with observations. Likely, the cause was the radial structure of the vortices, which consists of two different regions for the angular velocity. A central core with angular velocity equal to a solid body rotation, and an external region whose velocity decreases exponentially. They conclude that generalized Gaussian models of isolated vortices (see [19]) should be able to provide a good approximation of the sea level elevation in the vortex cores but cannot represent the velocity structure because of the abrupt transition between inner and outer regions.

Recently, Cruz-Gómez and Salcedo-Castro [20] developed a model to determine the geometric properties of an homogeneous floating lenticular vortex, including its angular velocity ω, maximum surface elevation height $\zeta_{\max}$ (see also [13]), vertical depth $\eta_{\max}$ and radius R at sea surface. The reader can refer to figure 1 of [20] which gives an illustration of a floating lens with the definition of its geometrical characteristics. Their study is based on a simple reduced gravity model of the surface lens-like structure with solid body rotation. They found that the upper and lower surfaces are described by parabolic curves which depend upon the reduced gravity. Moreover, they found that the maximum depth was directly related to the vortex angular velocity. Their results were compared to drifting buoys records and sea level anomalies. They found that the geometrical values $\eta_{\max}$, $\zeta_{\max}$ and R were consistent with those found by other authors for a given particular vortex. However, their estimations for the velocity and vorticity fields were not reliable. They concluded that this discrepancy was caused by the too simple nature of the model and proposed an adjustment using isolated Gaussian vortices modeling initially proposed by Kloosterziel and van Heijst [16] for barotropic vortices.

Despite this weakness, it is possible to predict from the theory of Cruz-Gómez and Salcedo-Castro [20], the depth $\eta_{\max}$ of this kind of floating vortex and then to calculate its full height $H = \zeta_{\max} - \eta_{\max}$ taking into account the different parameters of the vortex in its surrounding fluid:

$$H = \frac{f\omega R^2}{2g'} = \frac{f^2 Ro R^2}{2g'} \tag{1}$$

with $g' = g(\rho_v - \rho_f)/\rho_f$, where ρ_v is the fluid density inside the vortex, ρ_f the fluid density outside the vortex, and Ro the negative Rossby number of the vortex defined by $Ro = \omega/f$, with the usual definition of the Coriolis parameter f. Note that g' is not the classical reduced gravity (see [14]) and is negative in our calculation so that H is a positive number.

In order to study experimentally the shape of these floating anticyclones, we can calculate their aspect ratio $\alpha = \frac{H}{2R}$ whose square can be cast under the form:

$$\alpha^2 = -\frac{f^2 Ro}{N^2}, \tag{2}$$

where we use the notation $N^2 = -8g'/H$, a pseudo Brunt-Väisälä frequency calculated on the density contrast between the vortex and the surrounding fluid and $H/8$ a typical vertical length. The law given by Eq. (2) is fully consistent with the result of the recent theoretical works of [21,22] which predict the aspect ratio of eddies in linearly stratified rotating fluids that depends upon the Rossby number of the vortices and the Brunt-Väisälä frequencies inside and outside the vortices. This theoretical prediction was confirmed by laboratory experiments, by oceanic meddies and Jovian vortices measurements [22], and by numerical simulations [21]. It is then worth mentioning that, as was done by these last authors, the centrifugal acceleration can be easily incorporated in the equations of motions and the right hand term of Eq. (2) should be simply multiplied by $(1 + Ro)$. This term will be ignored in the present study because of the small values of the Rossby numbers considered here.

Note that in the present case, it may be more convenient for oceanographic applications (R being more easily measurable than H) to express the aspect ratio of the floating lenses as a function of a pseudo Brunt-Väisälä frequency N' based on R defined as: $N'2 = -4\,g'/R$. In this case we obtain the following formula equivalent to Eq. (2):

$$\alpha = -\frac{f^2 Ro}{N'2}. \tag{3}$$

Laboratory experiments about floating lenticular vortices have been essentially developed with emphasis on their stability [15,14]. It was shown that most of the laboratory vortices are unstable to baroclinic or barotropic instabilities depending on their aspect ratio. Dipoles, tripoles or quadripoles are then formed after the transient growth of a perturbation. We will see hereafter that our anticyclones were also unstable but the small growth rate of the instability does not prevent the study of their aspect ratio.

3. Experimental set-up and measurement techniques

All the experiments were performed in the Geophysical Fluid Dynamics Laboratory of Guadalajara University, Mexico. As