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BAROTROPIC INSTABILITY OF PLANETARY POLAR VORTICES: CIV ANALYSIS OF SPECIFIC MULTI-LOBED STRUCTURES

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We describe the laboratory experiments we carried out in the 13-m diameter rotating tank of the “Equipe Coriolis” of LEGI in Grenoble (France), March/April 2009. This set of experiments was conceived to investigate in the laboratory the evolution of the coherent structures at the edge of an atmospheric polar vortex, which are theorized to be produced by barotropic instability. This project was conceived to enlarge and strengthen our previous experimental results, which were collected at the 5-m diameter rotating tank facility in Trondheim (Norway). This time, we use advanced flow visualization techniques that are specifically designed for global Eulerian measurements (Correlation Imaging Velocimetry, CIV).

1. INTRODUCTION

In June/July 2008 we carried out laboratory experiments in the 5-m rotating tank of the Norwegian University of Science and Technology in Trondheim, to study the barotropic instabilities that arise at the edge of a polar vortex (Montabone et al., 2009). The goal of these experiments was to understand whether the barotropic instability could be a plausible physical mechanism for the formation of the multi-lobed coherent structures observed around the poles of several planetary atmospheres, including Venus and Saturn (Taylor et al., 1980, Piccioni et al., 2007, Fletcher et al., 2008).

These experiments showed that the presence of barotropic instabilities leads to the formation of coherent satellite eddies at the edge of the central “polar vortex”, which organize themselves in different multi-lobed structures (dipole, tripole, quadrupole and hexagon). Their stability, or conversely the transition between different modes, showed a dependence on the experimental parameters, namely the Rossby number and the volume flux.

The quantitative analysis of these experiments was limited by the lack of a suitable experimental technique in Trondheim that could provide high resolution Eulerian velocity fields throughout the experiments, starting from the initial conditions. For instance, we observed that slightly different initial conditions could lead to different dominating modes, after a transient period during which the instabilities grew. These bifurcations, although observed, could not be studied in detail.

The project described in this paper was therefore planned to improve and extend the set of polar vortex instability experiments described in Montabone et al. (2009), making extensive use of Correlation Image Velocimetry (CIV). This visualization technique, developed at the Coriolis/LEGI laboratory in Grenoble, allows one to perform high resolution Eulerian velocity measurements from the very beginning of each experimental run.

2. EXPERIMENTAL SET-UP

The experiments described here were carried out in the 13-m diameter rotating tank of the “Equipe Coriolis” / LEGI in Grenoble (France), March / April 2009. One of the goals was to directly compare with the results obtained in the 5-m diameter tank in Trondheim. Hence we decided to perform the new experiments in very similar conditions with respect to the previous ones. To do this, we used the same source-sink experimental set-up, although we made a few general improvements and necessary adaptations to the new, large-scale tank. Fig. 1 shows a detailed plan of the setup.

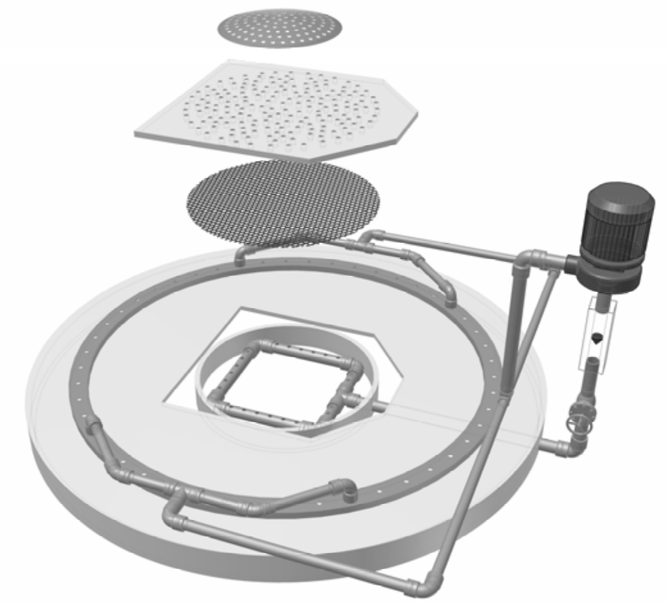


Figure 1: Plan of the experimental setup. The platform was positioned in the centre of the 13-m diameter tank. The diameter of the source ring was 4 m. The (maximum) diameter of the flat sink region was 1.6 m, and that of the parabolic-shaped sink region was 0.9 m.

Water is pumped out of a ring of point sources of radius 2 m at a given flux rate Q, and is sucked from a circular central sink region. The sink is a random distribution of many holes of nominal diameter 5 mm. The maximum extension of the sink region is 3.2 m diameter. On the top of this flat sink region we could fix the colander-like, parabolic-shaped topography that we used in Trondheim to account for the γ–effect at the pole of the planet, i.e., the quadratic term of the expansion of the Coriolis parameter $f = 2\Omega\sin\varphi$ near the pole. As in Trondheim, a set of masks (parabolic-shaped or flat) allowed us to use different configurations of the sink region, by covering selective portions (see Fig. 2, right panel, in Montabone et al., 2009). We used a fiberglass cloth and a fine mesh to reduce the turbulence below the sink region surface.

The experiments were carried out in homogeneous water with fixed depth ($H = 0.4$ m). The free parameters of our experiments are:

- ✓ The flux rate Q, measured with an analogue flow meter. We used values of 0.2, 0.4, 0.8 and 1.1 l/s.
- ✓ The rotation period of the tank, T. We used 60 and 30 s.
- ✓ The configuration of the sink region, which determines the typical length scale of the flow. We only used circular configurations, no annular ones. We carried out experiments with both flat and parabolic-shaped configurations, with 0.54 and 0.90 m diameter. In the flat configuration, we also carried out experiments with 1.6 m diameter.

Two cameras were positioned to look at slightly different portions of the fluid, from above: one observed the central region, including the sink, and one observed a sector (specifically, one quarter) of the source-sink platform. The former was meant to capture the dynamics of the instability; the latter was used to provide zonal averages of the azimuthal velocity profiles over a quarter of the domain, at all radii. The flow was seeded with reflective particles and high quality CIV images were obtained and processed using the software specifically designed by the “Equipe Coriolis” of LEGI.

3. PRELIMINARY ANALYSIS OF RESULTS

Processing of the large number of images that we acquired during the set of experiment is currently underway. Each experiment with a particular configuration (Q, T and sink configuration) has been recorded from the setting of the initial conditions, using three burst of CIV acquisition. Each burst is 10 minutes long, and the time separation between two consecutive bursts is 30 minutes. So far, we have processed (at least at low resolution) most of the “second bursts”, i.e., those showing the evolution of the flow between 40 and 50 minutes after the setting of the initial conditions.

Figs. 2 and 3 show examples of the results we obtained for the case with T = 60 s, Q = 0.8 l/s, and a parabolic-shaped sink region with 0.9 m diameter. Fig. 2 is a plot of the vorticity of the central region of the flow, showing a tripolar structure that is *not* stable. During the 10 minutes burst, the configuration of the eddies about the centre vacillates between a tripole and a quadrupole. Future analysis will be focused on understanding whether, for example, this parameter configuration is intrinsically unstable, or whether the central vortex had not yet reached a stationary regime after 50 minutes from the setting of the initial conditions.

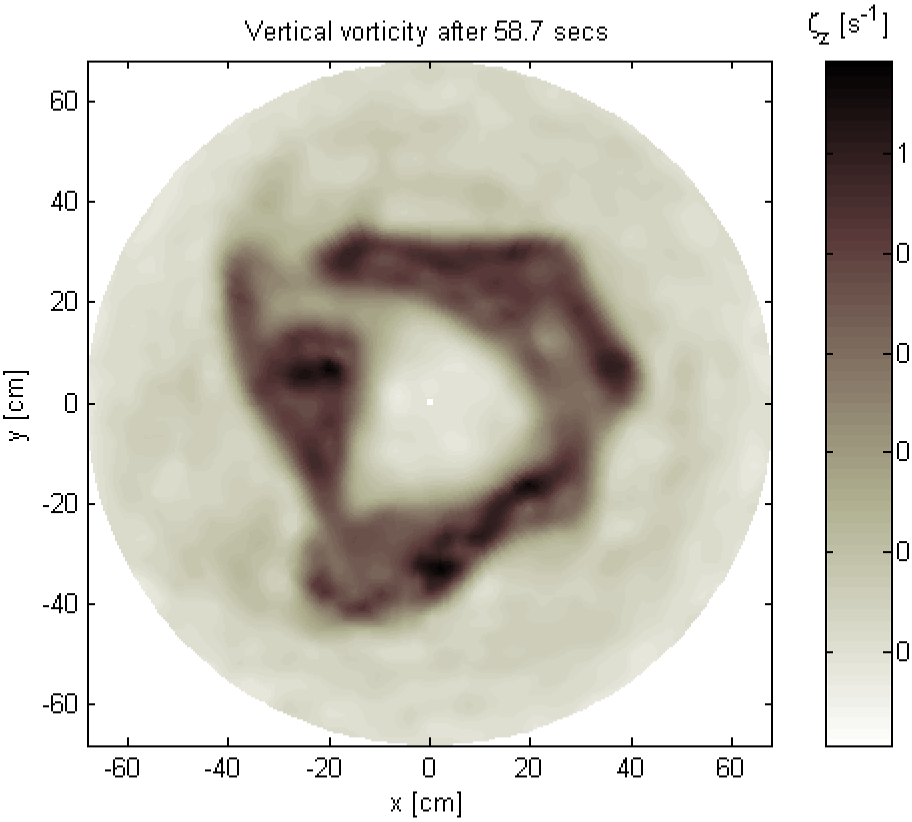
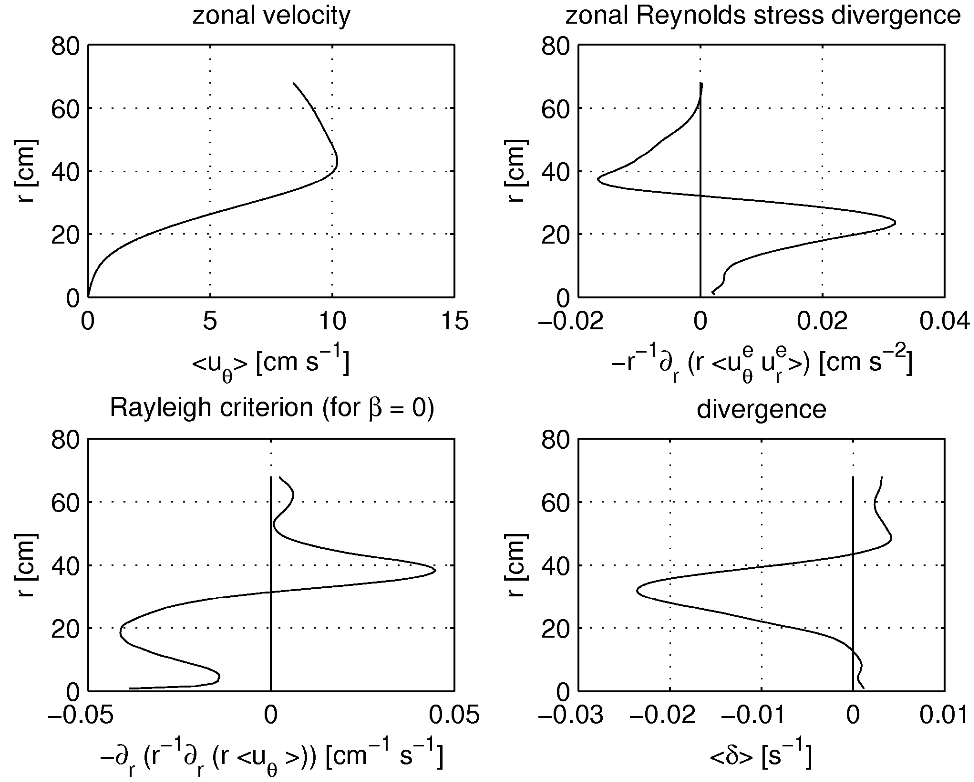


Figure 2: Vertical vorticity component at time t = 40+1 minutes after the setting of the initial conditions for the case of the experiment with T = 60 s, Q = 0.8 l/s and parabolic-shaped sink region with 0.9 m diameter.

Fig. 3 shows the zonal (azimuthal) velocity, the divergence of Reynolds stress, the vorticity gradient and the horizontal divergence for the same dataset. All quantities are time and zonally averaged, and they were calculated after projection onto polar coordinates.

The zonal flow is similar to the one recorded in Trondheim for the same experimental parameters. The zone of negative divergence where the fluid is sucked downwards (particularly at the edge of the sink region) is clearly apparent. The Reynolds stress divergence (RS) shows that the eddies are transporting zonal momentum towards smaller radii, and hence weakening the jet. Interestingly, the divergence peaks in almost exactly the same place as where the vorticity gradient and RS change sign, which deserves more detailed investigation. The fact that the divergence is positive at large radii could be either due to measurement error, or 3D effects (baroclinic or boundary-layer fluid transport).

Once all basic CIV processing of the experiments is complete, we will be able to build a more detailed picture of the dynamics and variations of the flow regime with basic parameters. In the final stage of the analysis, we will compare our results with the observations of planetary vortices.



zonal velocity

zonal Reynolds stress divergence

Rayleigh criterion (for β = 0)

divergence

Figure 3:
Zonal (azimuthal) velocity, divergence of Reynolds stress, vorticity gradient and horizontal divergence for the same dataset as in Fig. 2.

A necessary (but not sufficient) condition for barotropic instability is the *Rayleigh-Kuo criterion*, which states that the gradient of total absolute vorticity must change sign within the domain of interest, namely $\partial q/\partial y = df/dy - \partial^2 u/\partial y^2 \leq 0$, where y is the northward coordinate, u is the zonal wind, f is the Coriolis parameter, and $q = f - \partial u/\partial y$ is the total absolute vorticity. 'f' in our case is a quadratic function, which is neglected in the lower right panel, where only the relative vorticity is plotted.

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