BAROTROPIC INSTABILITY OF PLANETARY POLAR VORTICES: CONCEPT, EXPERIMENTAL SET-UP AND PARAMETER SPACE ANALYSIS

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We describe the concept and the experimental set-up for the laboratory experiments we carried out in the 5-m diameter rotating tank of the Norwegian University of Science and Technology in Trondheim (Norway), in June / July 2008. This set of experiments was conceived to study the barotropic instabilities that arise at the edge of the polar vortices in many planetary atmospheres. We report a few preliminary results from the analysis of the experiments.

1. INTRODUCTION

Polar vortices are a key element in the atmospheric dynamics of planets. These structures are observed in all planets with atmospheres, including the Earth, Mars, Venus, Jupiter and Saturn.

Earth's polar vortices in the stratosphere appear to have a fairly circular shape that is mostly stable, except during episodes of breaking that cause the "sudden stratospheric warming" phenomenon.

The polar vortices on Venus, on the other hand, show extremely rich dynamics, as recent observations by ESA's Venus Express spacecraft have revealed (Piccioni et al., 2007). They most often exhibit a double-lobed shape, as first observed by NASA's Pioneer Venus spacecraft in the late 1970s (Taylor et al., 1980), but have recently been found to vacillate rapidly among 1-, 2- and 3-lobed configurations. At the same time, observations of Saturn's north polar vortex by the NASA/ESA Cassini spacecraft have shown the complexity of an extraordinary six-sided geometric figure encircling the entire north pole (Fletcher et al., 2008).

There is not yet a fully comprehensive explanation for the variety of polar vortices in the atmospheres of the planets. Many factors have been invoked to set a theoretical framework that could describe their bizarre dynamics. Different kinds of instabilities could arise at the edge of the vortices, where the wind shear between the circumpolar jet and the vortex interior is strongest. In the case of Venus, the possibility of barotropic instabilities in the polar jets is supported by calculations made from radio occultation observations from Pioneer Venus (Newman et al., 1984), and by results of numerical models (Elson, 1982, Michelangeli et al., 1987, Limaye et al**.**, 2009). Furthermore, linear stability analysis suggests that the zonal wind profile on Saturn might be barotropically unstable at the latitudes of the North Polar Hexagon (Aguiar et al., 2009).

3. CONCEPT AND SET-UP OF THE LABORATORY EXPERIMENTS

We studied the barotropic instabilities at the edge of a polar vortex in laboratory experiments carried out in June/July 2008 at the Norwegian University of Science and Technology in Trondheim, using their 5-m diameter "Coriolis" rotating tank (Fig. 1).

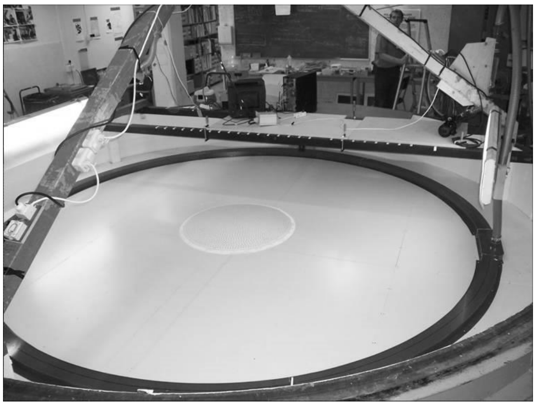

Figure 1: The 5-m diameter "Coriolis" tank of the University of Science and Technology in Trondheim (Norway), with our experimental set-up. The colander-like sink is visible in the centre of the tank. The ring of point sources is visible at the periphery.

In this experiment, we used a source-sink technique to create a central vortex in homogeneous water with fixed depth ($H = 0.4$ m). Water was pumped out of a source ring (radius = 2 m) at a given flux rate Q, and was sucked from a central, circular sink region (maximum radius = 0.45 m). See Fig. 2 (left panel) for a sketch of the experimental set-up. This colander-like sink region had a parabolic shape to account for the γ–effect at the pole of a planet, i.e. the quadratic term of the expansion of the Coriolis parameter $f = 2\Omega\sin\varphi$ near the pole. We were able to use different configurations of the sink region by covering selective portions with four specifically designed annular masks (Fig. 2, right panel), each of them 0.09 m across, and a central, circular mask of 0.18 m diameter.

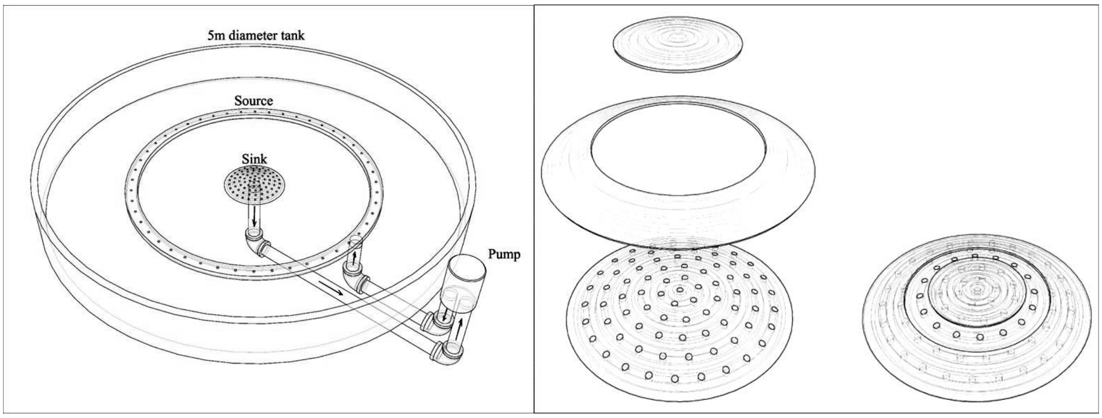

Figure 2: Sketch of the experimental set-up (left panel) and of the masks used to cover portions of the parabolic sink region (right panel)

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, 0.5, 1 and 2 l/s.
- ✓ The rotation period of the tank, T. We used 80, 30, 15 and 10 s.
- ✓ The configuration of the sink region, which determines the typical length scale of the flow. We mostly used a circular configuration with 0.54 m diameter, but we also carried out a few experiments with circular configurations of 0.18 and 0.90 m diameter, and annular configurations (0.09 m across) at 0.22 and 0.40 m distance from the centre.
- ✓ The configuration of the source region. We mostly used an axisymmetric distribution of point sources, but we also tested a non-axisymmetric distribution, with a “hemispheric” distribution of point sources.

We used three measurement techniques: 1) dye injection at the surface of the water to visualize the coherent structures at the edge of the central vortex, 2) a Doppler velocity probe to measure the three components of the velocity field at 25 radial locations, each separated by 0.05 m, starting from a distance of 0.09 m from the centre (The probe measured at depths of 0.05 and 0.17 m below the surface of water at rest), and 3) particle tracking with 1 cm diameter surface tracers. Particle tracking with such large tracers, unfortunately, did not provide sufficient resolution to resolve the dynamics of the coherent structures at the edge of the central vortex.

4. PRELIMINARY ANALYSIS OF RESULTS

We were able to establish the presence of a central (“polar”) vortex that formed by conservation of angular momentum associated with the poleward flux in a rotating frame. We observed barotropic instabilities forming at the edge of the central jet, which led to the formation of coherent satellite vortices. These vortices organized themselves into different minimum-energy configurations (including dipole, tripole, quadrupole and hexagon), which closely resembled those observed in the atmospheric polar vortices of different planets (see Fig. 3).

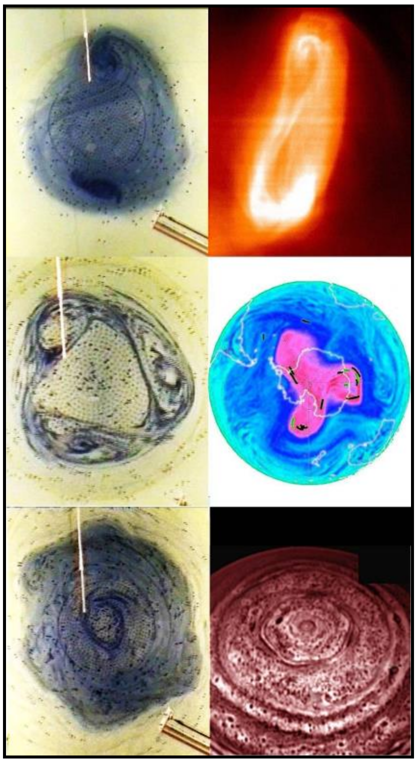

Figure 3: Left panels: mode-2 (dipole), mode-3 (tripole) and mode-6 (hexagon) patterns obtained in the laboratory analogue of a polar vortex. The diameter of the vortex is approximately 1 m. Right panels: the same configurations observed in Nature: mode-2 in Venus’ south polar vortex (ESA/Venus Express), mode-3 in the Earth’s south polar vortex (ECMWF and VORCORE), and mode-6 in Saturn’s north polar vortex (NASA- ESA/Cassini).

The stability of a given configuration was dependent on two key experimental parameters: the Rossby number and the poleward volume flux Q. The Ekman number (i.e., bottom friction) also plays an important role, but in our experiments we didn’t vary the depth of the water (H = 0.4 m) and we mostly used only two rotation rates for the tank, so the dependence on the Ekman number was less clear. In general, previous studies spanning a large range in parameter space observed higher modes as the Rossby number decreased (our experiments confirmed this tendency), and lower modes as the Ekman number decreased, although the dependence of the flow on the Ekman number is less strong than on the Rossby number (see, e.g., Aguiar et al., 2009).

The analysis of the (time-averaged) azimuthal velocity profiles for different experimental conditions is ongoing (see Fig. 4 as an example). The qualitative results confirm that barotropic instability is 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. This strengthens the conclusions of previous laboratory experiments on shears induced by a solid rotating disk (Aguiar et al., 2009). Future analysis will include calculation of the (linear) barotropic flow instability for all cases using the Rayleigh-Kuo criterion and if possible an eigenvalue analysis. We also plan to perform a detailed intercomparison with the results from the later Grenoble experiment (see Montabone et al., 2009).

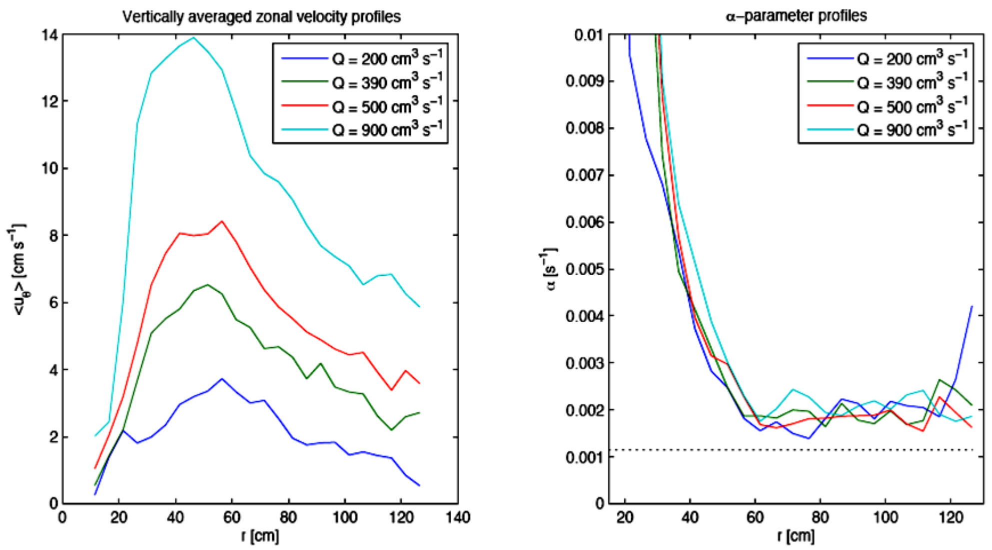

Figure 4: Left panel: the curves represent the (vertically and time averaged) profiles of zonal (azimuthal) velocity U_θ as a function of the distance from the centre of the tank. Different curves are for different values of the poleward flux Q. The velocity components (averaged over one minute time interval) were measured with a Doppler velocity probe, after the flow had reached a steady state. The rotation period of the tank was in this case T = 30 s, and the diameter of the circular sink region was 0.54 m. The jet formed at about r = 0.5 m (Ro = 0.67 - 0.19). Plots of the second derivative of the zonal velocity were quite noisy (not shown here), but they showed that the gradient of the total absolute vorticity changed sign several times. This is a necessary but not sufficient condition for barotropic instability, according to the Rayleigh-Kuo criterion. Right panels: We evaluated the eddy damping of angular momentum as the parameter α(r). This quantity is of fundamental interest, as it allows us to measure the efficiency of the eddies at removing energy from the zonal flow. The calculation was made assuming that the rate of change of angular momentum is given by the sum of the torques due to the Coriolis (spin-up) effect and the damping (Ekman+eddy), where the latter is simply given by $\tau_d = -\alpha L_z$ (L_z being the angular momentum vertical component). Therefore, an expression can be derived for the parameter α(r) as a function of known quantities (Q, U_θ and the angular velocity of the tank, Ω).

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