EDDY-DRIVEN JETS AND VORTICES IN CONVECTIVELY FORCED GEOSTROPHIC TURBULENCE ON A TOPOGRAPHIC BETA-PLANE

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We present here results from large-scale laboratory experiments on forced-dissipative geostrophic turbulence in a large rotating tank. Small-scale convection is driven either by a steady flux of dense salty water onto the top surface of a rotating water tank, or by direct heating of the lower boundary. The whole tank rotates at constant angular velocity Ω and dynamical effects equivalent to the spherical curvature of a planetary atmosphere are emulated by use of a radially-sloping bottom. The experiments were carried out on the 13 m diameter rotating Coriolis platform in Grenoble, France. Results demonstrate the formation of multiple, undulating, parallel, barotropic zonal jets, in which $\overline{u'v'}$ fluxes maintain the jets against viscous (Ekman) dissipation. Use of different rotation rates of the tank confirms the dual role of planetary vorticity gradients (β) and bottom friction in governing the jet separation scale, approximated by the well-known Rhines scale ($L_R = \pi(2U/\beta)^{1/2}$). The jets formed are also frequently found robustly to violate the Rayleigh-Kuo barotropic stability criterion, leading to formation of larger-scale waves and eddies and influencing the kinetic energy spectrum. These experiments serve to elucidate mechanisms for jet formation and saturation that may apply to gas giant planet atmospheres and, more controversially, the terrestrial oceans, and suggest a number of new diagnostics to be investigated in observations and models of both Jovian and terrestrial ocean circulations.

1. INTRODUCTION

The banded pattern of ammonia clouds is one of the most striking features of the atmospheres of Jupiter and Saturn. These bands are associated with multiple zonal jets of over 100 m $s^{-1}$with alternating sign versus latitude (e.g. see Limaye (1986). A similar pattern of zonation may also occur in the Earth's oceans (Maximenko et al. 2005). The dynamical origin of this banded structure remains poorly understood, but most approaches towards understanding the zonation have suggested that the pattern may originate from the anisotropy in a shallow turbulent layer of fluid due to the β effect, i.e., due to the latitudinal variation of the effective planetary vorticity (Rhines 1975). Until recently, quantitative understanding of this process has been based principally on numerical simulations of two-dimensional or geostrophic turbulence in stirred rotating fluids (e.g. Williams 1975), but such models are highly idealised and take little account of the vertical structure. Laboratory experiments provide an alternative means for studying these processes, though many previous investigations have been unable to access regimes at sufficiently high Reynolds number or low Ekman number to convincingly demonstrate nonlinear zonation effects.

In an initial series of experiments (Read et al. 2007), carried out on the world's largest rotating platform at the Coriolis Laboratory in Grenoble, France, we confirmed that multiple zonal jets may indeed be generated and maintained by this mechanism. In a new set of experiments, carried out in late 2007 also using the 14 m diameter "Coriolis" turntable, we have extended this study to explore the parametric dependence of jet formation in convectively driven geostrophic turbulence.

2. EXPERIMENTAL CONFIGURATION

A circular cylindrical container was set on the turntable, and convective forcing was applied by 11 kW of electrical heating, applied uniformly under a sloping base consisting of a series of curved, aluminium sheets over a wooden frame. The overall configuration is illustrated schematically in Fig. 1. The bottom surface was inclined at an angle ~5^{o} to produce a topographic beta-effect whose magnitude depended on both the slope angle and the rotation speed of the table. The rotation period used ranged from 40 – 320 s for the results to be presented herein. Horizontal flow was measured using PIV methods from images taken by two digital cameras mounted in the rotating frame at a height of ~4 m above the free surface of the tank. Vertical temperature profiles were measured at interval using thermistor probes moved vertically through the tank in two radial locations. A plastic curtain surrounded the tank to eliminate wind stress effects.

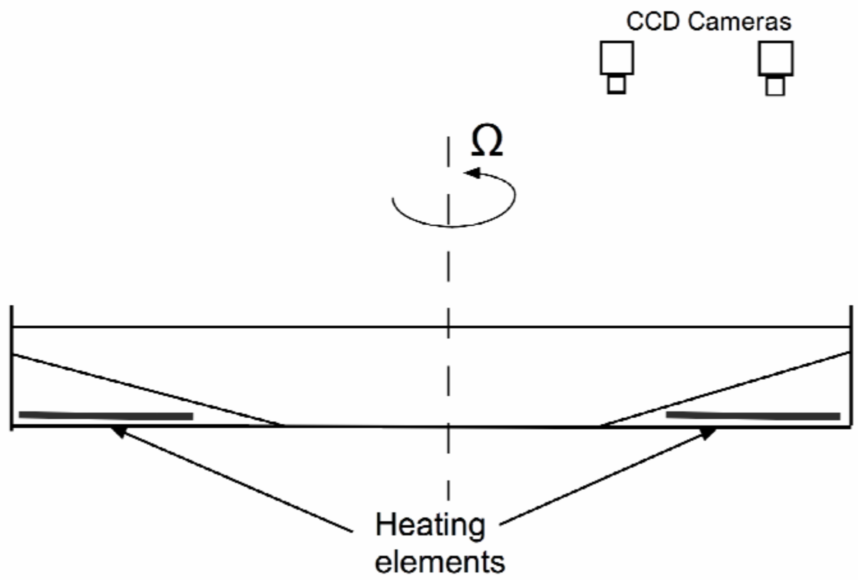

Figure 1: Schematic cross-section of tank, showing sloping bottom boundary and location of heating elements. The flow was viewed from above by two CCD cameras located along a radius.

3. RESULTS

A series of experiments were run for up to 3-4 days per run, in order to allow the flow to equilibrate fully. Convection and rotation led to the intermittent formation of intense cyclonic vortices that interacted eventually to form patterns of zonal jets. Fig. 2 shows some examples of the azimuthally averaged zonal flow, contoured as a function of time for four different rotation rates. Although individual jet structures clearly meander and vary in time, a clear scale emerges for the alternating jet patterns that scales approximately as the Rhines scale, L_R (shown to the right).

Diagnostics from these and the earlier series of experiments demonstrate that the pattern of jets is maintained principally by Reynolds stresses due to the (mainly barotropic) eddies in the flow. In the new series of experiments, at least some of the eddies present are formed as the direct result of convective heating. Dye visualization demonstrated the formation of highly intermittent, isolated convective vortices that would entrain dyed fluid into rising plumes and columns. An example is illustrated in Fig. 3. The formation of these vortices appears to be a key mechanism by which the large-scale flow is energized, on horizontal scales of a few 10s of cm. Kinetic energy then cascades to larger scales, ending up in large-scale jets and vortices as the topographic beta-effect causes the cascade to become anisotropic and non-local in character.

Further details of these experiments and diagnostics will be presented and discussed, together with their potential implications for jet formation and interactions in gas giant planets and the terrestrial oceans. Attention will be focused on kinetic energy exchanges between eddies and the zonal flow, and the flow of energy between different scales.

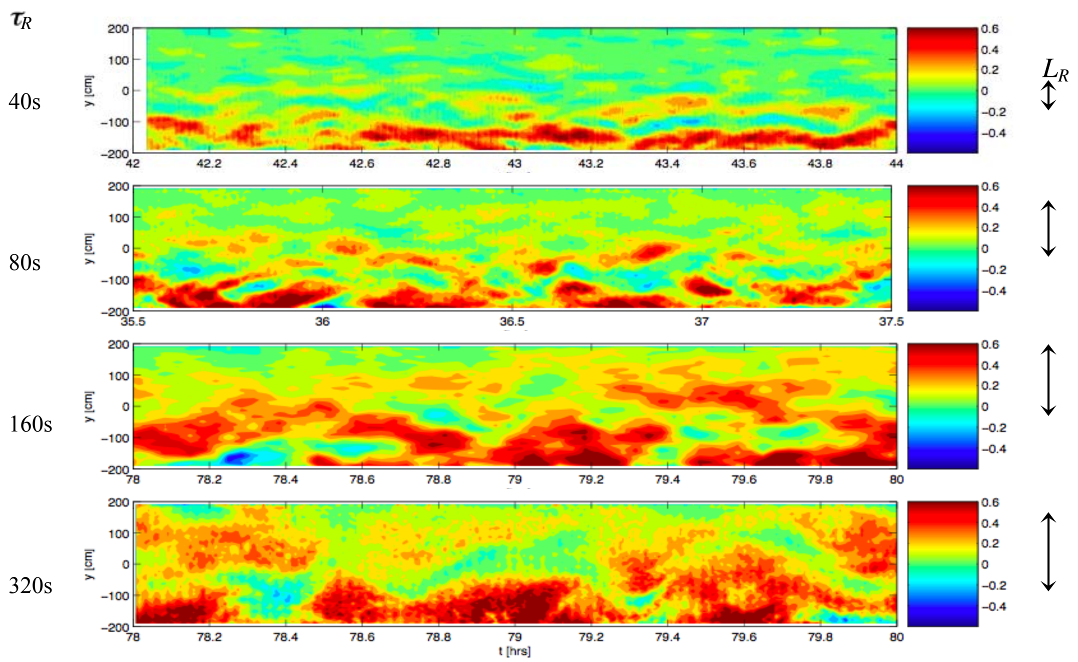

Figure 2 Azimuthal mean zonal (azimuthal) velocity (in cm s^{-1}) as a function of time within the field imaged by both cameras of the experiment, obtained at mid-depth of the tank. Four different rotation rates are shown, leading to values of $\beta L^2/U$ of 25 – 500. Jets scale roughly with the Rhines scale L_R, indicated by the arrows on the right.

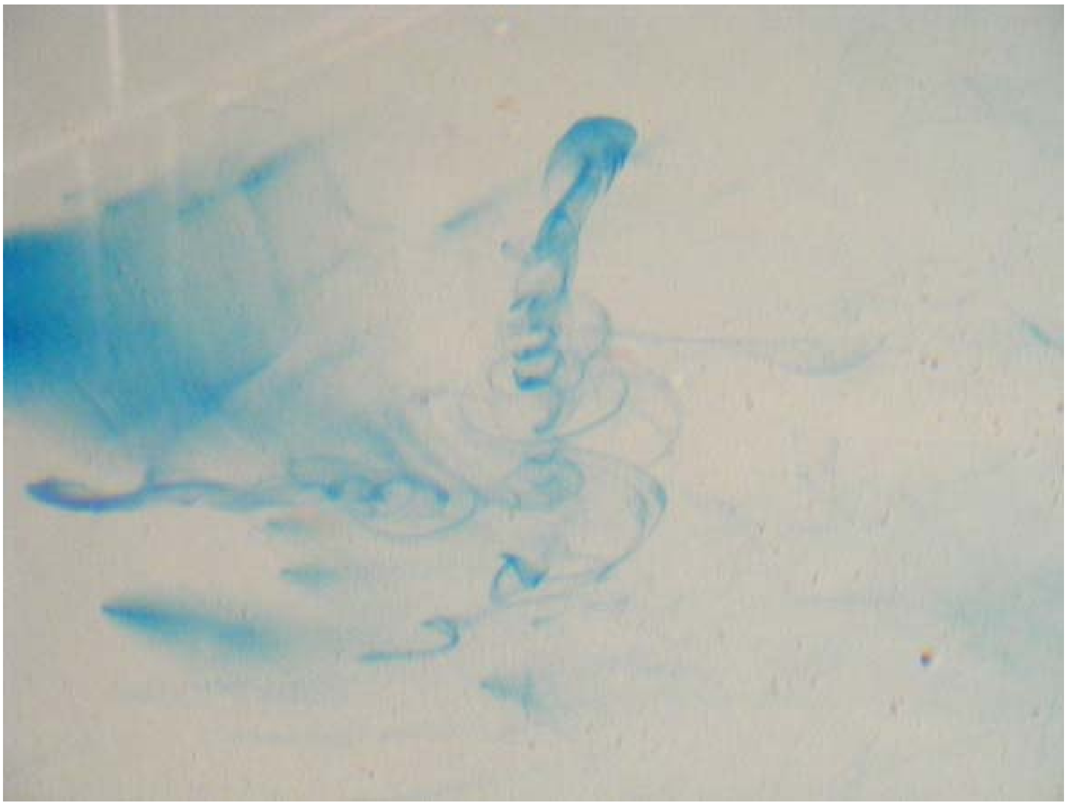

Figure 3: Photograph of a convective thermal plume rising from the bottom of the tank, visualized by blue dye. The plume is the core of a cyclonically circulating vortex of diameter ~10-20 cm and around 30 cm high.

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