MULTIPLE JET FORMATION IN A CONVECTIVELY DRIVEN FLOW ON A BETA-PLANE

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<u>Summary</u>   We present results from laboratory experiments carried out on the Coriolis rotating platform in Grenoble, France, to investigate the influence of a topographic beta-plane (obtained via a sloping bottom) on convectively-driven geostrophic turbulence. Dense, salty water is sprayed continuously onto the surface of the tank, which leads to the formation of a field of convective vortices. In the presence of a sloping bottom, the vortices interact nonlinearly, leading to the formation of a series of quasi-steady, parallel azimuthal jets on a scale comparable with the so-called Rhines scale $L_R = \pi\sqrt{2U/\beta}$. Such jets are not found with a flat bottom. Implications will be discussed in the context of various geophysical problems, including the atmospheres of the outer planets and the Earth's oceans.

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 against latitude[1]. A similar pattern of zonation also occurs in the Earth's oceans. 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[2]. Until recently, quantitative understanding of this process has been based principally on numerical simulations of two-dimensional or geostrophic turbulence in stirred rotating fluids[3], 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 previous investigations[4] have been unable to access regimes at sufficiently high Reynolds number to convincingly demonstrate nonlinear zonation effects. Here we report the results of new experiments, conducted on the world's largest rotating platform, which confirm that multiple zonal jets may indeed be generated and maintained by this mechanism.

Methods

Our experiments were performed on the 14 m diameter "Coriolis" turntable in Grenoble, France. The schematic layout of our configuration is illustrated in Fig. 1. A circular cylindrical container was set on the turntable, and convective forcing was applied by gently spraying dense water from above the main fluid layer. An equivalent topographic β-effect was obtained by imposing a conical slope at the bottom of the circular container. The slope was implemented with a plastic-coated stretched fabric sheet, which could be removed for additional experiments with a flat bottom in order to compare the flow structure both with and without a topographic β-effect (apart from a weak centrifugal deformation of the free upper surface). The rotation period for most experiments was set to 40 seconds for the results to be presented herein.
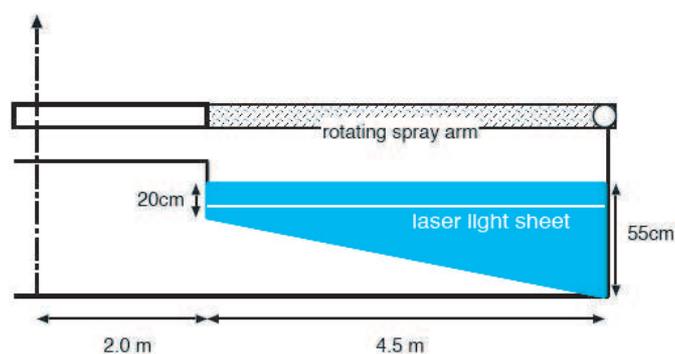

Figure 1: Schematic cross-section of the circular container, showing the rotating spray arm used to provide continuous convective forcing. The entire apparatus is set on a circular turntable.

Results

The horizontal velocity fields were obtained from plan view CCD images by a Correlation Imaging Velocimetry method. In order to diagnose the anisotropy of the evolving flow, the velocity fields were decomposed into radial and zonal (*i.e.,* azimuthal) components and mapped into $(r, r\theta)$ coordinates, where r is the radius and θ the azimuthal angle. The well-developed horizontal flow is dominated by eddies of various sizes, but there is also a clear indication of banded structure along the zonal direction. The temporal fluctuation of the radial profile of mean zonal flow is shown in Fig. 2a, well after the initial growth of the kinetic energy has saturated. The formation of sustained alternating jets is now evident

when the topographic β effect is imposed, although there is substantial meandering of these jets during this period and occasional splitting and mergers. Fig. 2b shows the evolution of the zonal mean flow observed in a corresponding flat bottom experiment. The domain-filling single-cell circulation, which is most evident in this case, is presumably due at least in part to differential wind stress effects. The characteristic scale-widths of the jets are closer to the Rhines scale L_R (on the order $L_R = \pi\sqrt{2U/\beta}$, where U is a typical horizontal velocity scale) of 0.63 to 1.4 m, rather than to the external radius of deformation ($L_D \sim \sqrt{gD}/f$, where f is the Coriolis parameter and D the fluid depth), which ranged from $L_D \sim 4.5$ m (along the inner wall) to 7.4 m (near the outer wall).
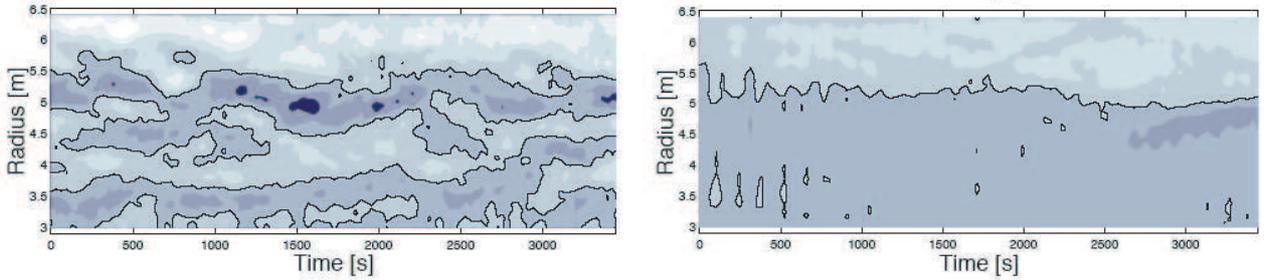

Figure 2: Horizontal velocity field. a, structure and fluctuation of the mean zonal velocity of the mature flow. The contour interval is 0.2 cm s^{-1} and the solid line denotes the contour of null velocity. b, initial development of the zonal mean flow in the flat bottom experiment.
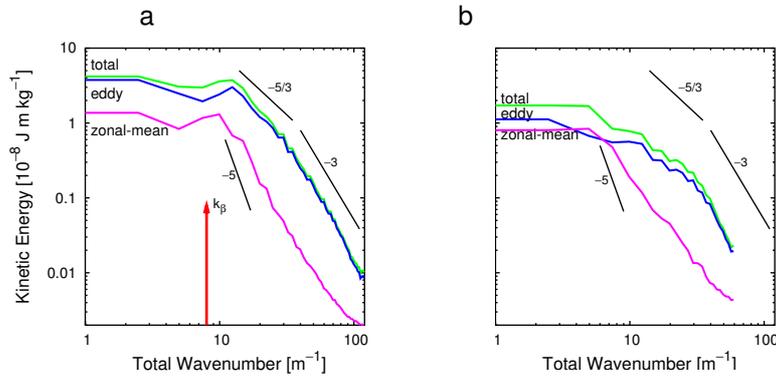

Figure 3: Spectra of total, zonal-mean and eddy components of kinetic energy versus total wavenumber (2π / wavelength) for (a) the sloping bottom experiment and (b) the flat bottom case. The straight lines are references for the $-5/3$, -3 and -5 slopes. The arrow in a indicates the wavenumber k_β associated with the Rhines scale.

Spectra

Fig. 3 shows spatial kinetic energy spectra for the two configurations. The spectra of the zonal-mean and eddy components of kinetic energy were calculated from velocity fields obtained by a high resolution camera as a function of the total wavenumber. In the sloping bottom case, there is a peak near the Rhines scale (indicated as k_β) for both the zonal and eddy components, with the peak wavenumber of the eddy energy being slightly higher than that of the zonal mean. The spectrum matches well with a $-5/3$ slope at large scales and -3 at small scales, which is predicted by the theory of geostrophic and two-dimensional turbulence[2]. Interestingly, the spectrum of the zonal mean kinetic energy at wavenumbers between 10 and 30 m^{-1} shows a significantly steeper decay with k, though does not quite reach the k^{-5} variation anticipated from the work of Huang et al.[3]. The apparent near-equilibration of the jets at a scale comparable to L_R would seem to indicate that we are in a regime for which bottom drag is relatively insignificant in the selection of jet scale.

References

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