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Eddy-driven jets and vortices in convectively forced geostrophic turbulence in the laboratory: implications for atmospheric circulations on giant planets?

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Abstract

We present here new results from large-scale laboratory experiments on forced-dissipative geostrophic turbulence in a large rotating tank. This provides an environment in which small-scale turbulence can interact with background rotation and other factors to produce rectified jets and a banded circulation, somewhat akin to what is observed on gas giant planets such as Jupiter and Saturn. We investigate the underlying dynamics and compare with observations of the cloud-level circulations on Jupiter and Saturn. In particular, the eddy-mean flow interaction is found to be strongly time-dependent, which may have important implications for understanding and measuring the kinetic energy conversion rates in the gas giants.

1. Introduction

We present here new results from large-scale laboratory experiments on forced-dissipative geostrophic turbulence in a large rotating tank (see Figure 1). In an earlier series of experiments, small-scale convection was driven by a steady flux of dense salty water onto the top surface of a rotating water tank. In the new work, convection was driven by continuous 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.

2. Results

Results demonstrate the formation of multiple,

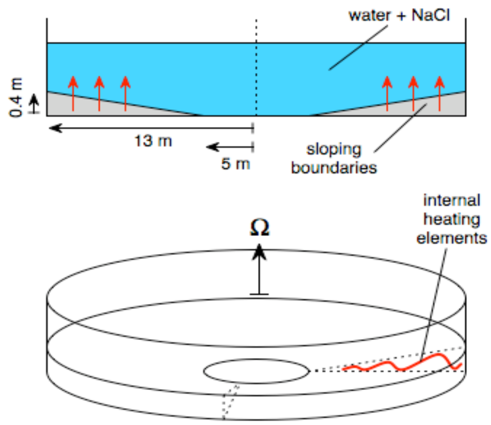

Figure 1: Experimental design for producing convection in a rotating fluid in the presence of a sloping bottom on the Coriolis Platform.

undulating, parallel, barotropic zonal jets (see Figure 2), in which $\overline{u'v'}$ fluxes maintain the jets against viscous (Ekman) dissipation. In the new experiments, use of widely 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 ($L_R = \pi(2U/\beta)^{1/2}$) under certain conditions. The jets formed are also frequently found robustly to appear to violate the Rayleigh-Kuo barotropic stability criterion, though not necessarily with respect to Arnol'd's second stability theorem. In some cases, this leads to formation of larger-scale waves and eddies and influences the kinetic energy spectrum.

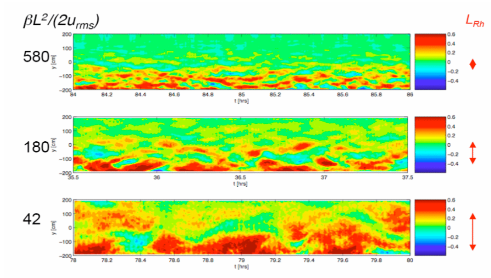

Figure 2: Time series of zonal mean velocity as a function of radius for three different rotation speeds, showing the variation in radial scale of the jets with Rhines lengthscale L_{Rh}.

Detailed analysis shows that the kinetic energy conversion rate from eddies into the zonal mean flow is not static, but fluctuates very substantially in time (see Figure 3), even though its mean value is close to the value expected from measurements of the frictional decay of kinetic energy when heating power is switched off.

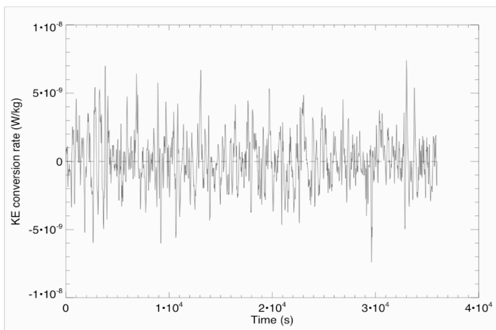

Figure 3: Time series of eddy-zonal flow kinetic energy conversion rate, showing large amplitude fluctuations in both magnitude and sign.

3. Implications for gas giant planets

These experiments serve to elucidate mechanisms for jet formation, eddy interactions and saturation that may apply to gas giant planet atmospheres and, more controversially, the terrestrial oceans. They suggest a number of new diagnostics to be investigated in observations and models of both Jovian and terrestrial ocean circulations, including KE spectra and time variations in the eddy-zonal flow energy transfer rate.

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