8.2 BAROTROPIC AND SUPER-ROTATING JET FORMATION IN THE EVOLUTION OF VERY SHORT MIXED ROSSBY-GRAVITY WAVES

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1 INTRODUCTION

High resolution numerical simulations in a zonally periodic equatorial β-plane channel have shown that persistent, low vertical mode eastward jets can emerge at the equator from the destabilization of a short westward propagating mixed Rossby-gravity (MRG) wave. An eastward jet at the equator is an example of *super-rotation*, meaning that the zonally averaged zonal angular momentum is greater there than it was anywhere in the initial state. It cannot come about through a simple rearrangement of zonal mean angular momentum, nor can it be achieved if the effect of eddies on the zonal mean flow is to diffuse angular momentum down its gradient (Hide, 1969). Indeed, while the instability of the MRG wave can in principle lead to either eastward or westward flow at the equator, westward (sub-rotating) flow predominates in nearly all cases, presumably due to the dissipative effect of small zonal scale eddies on the zonal mean flow. The assumption of local down-gradient transfer of zonal mean angular momentum does not apply in all cases, however. Wave radiation and dissipation can transfer angular momentum non-locally, up or down gradient.

Super-rotation occurs in the atmospheres of certain planets, notably Venus (Gierasch, 1975), and in the eastward phase of the QBO in the Earth's stratosphere. Although such a state is not observed in reality, several studies have been able to generate super-rotating states in GCM's of the troposphere using zonally asymmetric heating at the equator (Suarez and Duffy, 1992; Saravanan, 1993; Kraucunas and Hartmann, 2005) or by shifting the midlatitude westerly jet equatorward of its typical Earth position (Williams, 2003), with super-rotation being linked to barotropic instability on the equatorward flank of the jet.

Extending the work of Gill (1974) on the instability of barotropic Rossby waves, the destabilization of MRG waves has been studied by Hua et al. (2007). The nature of the unstable linear modes depends on the wavelength of the initial wave. Short inital waves destabilize due to their strong horizontal shear and give rise to zonally symmetric zonal jets, including the low vertical mode eastward jets considered here.

Through the current work in progress, we hope to determine the mechanism behind the development of the super-rotating state in this simple system, whether it is due to equatorward or vertical angular momentum transport, whether it is part of the linear instability of the initial MRG wave or due to a secondary instability of an unstable mode of the initial perturbation, and why once established, the amplitude of the eastward jet does not strongly depend on the wavelength and amplitude of the initial wave beyond their threshold values. We also hope to understand the effect of including the nontraditional Coriolis force terms, due to the northward component of the planetary rotation vector, in the problem.

2 NUMERICAL SIMULATIONS

All simulations were performed with the Regional Ocean Modeling System (Shchepetkin and McWilliams, 2005) with 0.1° horizontal resolution and 200 vertical levels. Figure 1 shows depth-latitude cross-sections of the initial and long-time equilibrated zonal and meridional velocities of a destabilized MRG wave initialized in a 10° long equatorial β-plane channel with periodic east-west boundary conditions. The initial wave has amplitude $0.11c_1$, where c_1 is the phase speed of the Kelvin wave of the same depth, and zonal wavenumber $-8.5k_R$, where k_R^{-1} is the deformation scale for the gravest vertical mode. For large time, the zonal velocity is dominated by its zonal mean, so the lower figures are representative of the entire flow. Our focus is on the two eastward jets over the equator straddling mid-depth. Figure 2 shows the amplitudes of the lowest vertical modes of zonal velocity as functions of time for the simulations with $k = -6.3k_R$ and $k = -8.5k_R$, the eastward equatorial jets being absent from the former. The east-

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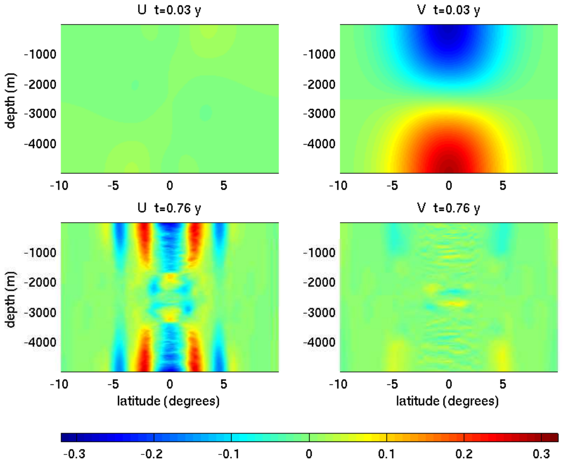

Figure 1: Depth-latitude cross-sections of early (top) and equilibrated (bottom) zonal (left) and meridional (right) velocity fields from ROMS simulation of the destabilization of an MRG wave of wavenumber $-8.5\ k_R$.

ward jets are evidently linked to a strong vertical mode 8 that strengthens as the lower modes peak and weaken. Simulations with a range of initial wave amplitudes and wavelengths indicate that the eastward jets develop and persist for $k \lesssim -8k_R$, but that the amplitude of the jet itself is apparently not sensitive to the wavelength of the initial wave. The threshold value of k becomes slightly less negative and the amplitudes of the eastward jets increase with increasing amplitude of the initial wave.

Simulations in a 150° long channel with a localized MRG wave initialized in the centre of the channel were done in order to observe the propagation characteristics of the different signals excited by the instability. Cross-sections along the equator of zonal velocity and its lowest four even vertical harmonics are shown in Figure 3. As can be seen in the uppermost panel, (weak) eastward equatorial jets develop in the western part of the region in which the wave was initialized, and the lowest vertical modes at the equator propagate westward. Notice also the correspondence between the longitudes of strong modes 6 and 8 weakened modes 2 and 4, which compares with the temporal correspondence between the same modes in Figure 2. Hua et al. (2007) and d'Orgeville et al. (2007) propose destabilization of MRG waves forced by low frequency variability in the western boundary of an ocean basin as an explanation for the observed vertical scale of deep equatorial jets, which they show propagate as a long, high vertical mode Kelvin wave. The fact that the low vertical mode signals propagate westward explains why the super-rotating jets are not seen in their basin simulations.

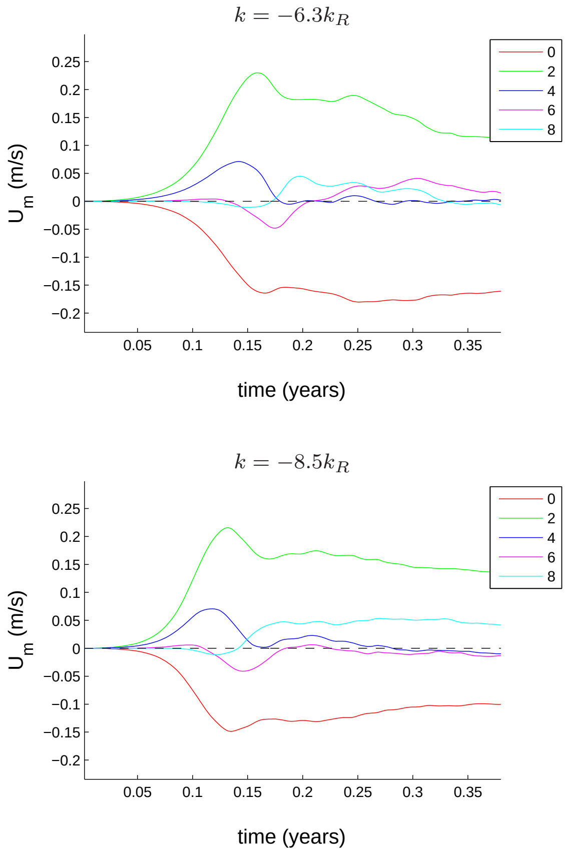

Figure 2: Signed amplitudes of lowest vertical modes in zonal mean zonal velocity as functions of time in case without ($k = -6.3k_R$, top) and with ($k = -8.5k_R$, bottom) super-rotating jets.

3 EFFECT OF THE NONTRADITIONAL CORIOLIS FORCE TERMS

We also consider the effect of the nontraditional Coriolis force terms, due to the northward component of the planetary rotation vector. These terms, which couple the zonal and vertical velocity components and are proportional to the cosine of latitude, can be significant at the equator (Colin de Verdière and Schopp, 1994; White and Bromley, 1995). When they are incorporated into the simulations, there is a breaking of the symmetry in the vertical direction, with the upper branch of the super-rotating jet intensified and the lower weak-

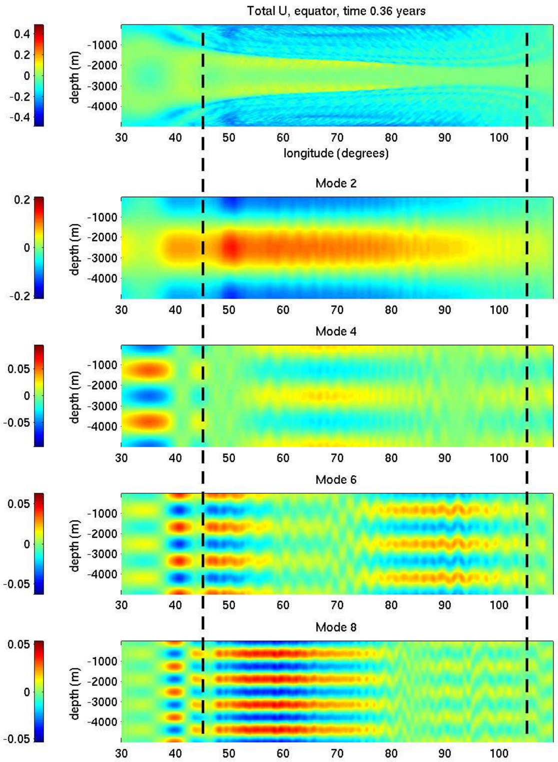

Figure 3: Depth-longitude sections along the equator for total zonal velocity and lowest four even vertical modes from simulations in 150° channel with MRG wave initialized between 45° and 105°.

ened or absent altogether (Figure 4).

In the linear equatorial wave solutions to the stratified Boussinesq equations, the fractional change in the velocity components due to the nontraditional Coriolis force terms is $\mathcal{O}(2\Omega/N)$. In our simulations $2\Omega/N \approx 0.07$, but the effect on the super-rotating jets is much greater. This is probably due to the coupling of u and w (which are out of phase by $\pi/2$ in the initial conditions), and the resultant interaction of the bottom boundary condition $w = 0$ with the zonal velocity.

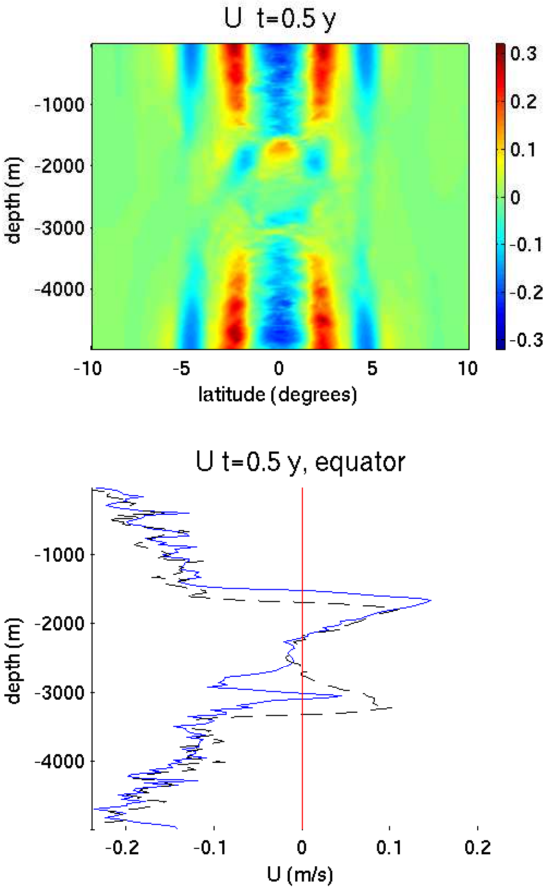

Figure 4: Depth-latitude cross-section of zonal velocity field with nontraditional Coriolis force terms (top) and vertical profile at the equator (bottom). Dashed line in bottom figure is from simulation without horizontal Coriolis force terms.

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