Equatorial zonal Jets formation

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Abtract :

After a brief review of oceanic mid - latitude zonal jets observations and of their currently proposed formation mechanisms, the characteristics of oceanic equatorial zonal jets are presented. A new mechanism for zonal jets formation is proposed based on the destabilization of short Mixed Rossby Gravity waves, providing a rationale for the difference of scales observed in the Pacific and in the Atlantic deep equatorial jets. Results of numerical simulations performed on the Earth Simulator are presented to validate the analytical theory.

Key- words :

Zonal jets, Floquet, Mixed Rossby Gravity wave

1 Introduction

Flows exhibiting multiple zonal jets are ubiquitous in observations of the atmospheres of giant planets and in the oceans, as well as in laboratory experiments. Such systems share in common east- west velocity directions that alternate either with latitude or with depth and present a marked asymmetry, with the eastward jets being narrower and faster than the westward jets.

Besides involving a considerable portion of the total kinetic energy, the existence of multiple zonal jets has profound implications for the transport and mixing of tracers by setting up barriers to meridional transport. Such barriers, which can be intermittent in space and time, partition the flow into well- mixed regions of distinct properties.

Zonal jets (ZJ) can be viewed as coherent structures that spontaneously arise when, in a differentially rotating medium, the well- known inverse cascade of two- dimensional turbulence is halted by wave dispersion effects or by friction: jets represent a spatial organization of a turbulent flow. One possible ZJ formation mechanism occurs through the destabilization by batropic shear instability of short meridional velocity fluctuations on a β-plane: the kinetic energy of the short waves is transferred through a negative viscosity effect to zonal jets of very long zonal scale, typical of the inverse energy cascade [Sivashinsky (1985) , Gill (1974), Legras et al. (1999), Manfroi & Young (1999)] .

While oceanic observations (Maximenko et al. (2006)) as well as most recent high-resolution ocean circulation models (Richards et al. (2006)) confirm that mid-latitude zonal jets tend to be barotropic, i.e. correspond to the largest vertical scale of motions, equatorial observations show that, in contrast, equatorial zonal jets present very small vertical scales, typically a vertical baroclinic mode 15-20 for the Atlantic and 30-40 for the Pacific (Gouriou et al. (2001), Firing (1988)). The formation mechanism of these depth-alternating zonal jets -- the so-called Equatorial Deep Jets -- have puzzled oceanographers for decades.

2 Short Rossby and Mixed Rossby-Gravity waves destabilization

For a rotating planet, the rotation rate about the local vertical axis varies with latitude: this is the β-effect, where β is the northward gradient of the Coriolis parameter due to the planet's rotation . This effect triggers the most important class of wave motions for large-scale meteorological and oceanic processes, namely the Rossby waves. The β-effect sets the elasticity of the wave for north-south displacements of a chain of fluid parcels about an equilibrium latitude (meridional motions are inherently necessary for the Rossby shear wave to propagate westward).

Lorenz (1972) and Gill (1974) have studied the stability of barotropic Rossby waves and shown that they are prone to destabilization by shear instability. For a mid–latitude β–plane, Gill (1974) demonstrated that a short Rossby wave can be unstable and generate low–frequency zonal flows, the mechanism being dependent on the stability of the meridional component of velocity (cf. Manfroi and Young (1999), Lee and Smith (2002) for an in-depth discussion). Gill's study was based on a Floquet analysis of a small-scale sinusoidal flow field dominated by meridional velocities that are characteristic of zonally-short Rossby waves.

At low latitudes, for an equatorial β-plane, the free wave whose characterisitics are the closest to those of the mid-latitude barotropic Rossby wave is the so-called Mixed Rossby Gravity (MRG) wave . A short westward–propagating mixed Rossby–gravity wave, like a mid–latitude Rossby wave with a similar zonal wavenumber, has predominantly meridional motions. Moreover, its group velocity is eastward like that of a short mid–latitude Rossby wave.

Following Gill (1974), a Floquet analysis of the flow field of a zonally-short MRG wave has been performed. The analysis establishes the characterisitics of the production of zonally coherent flows with low zonal wavenumber.

The zonal jet–like structures are formed through a barotropic instability associated with the zonal derivative of the meridional velocity field. This process enables an inverse cascade to zonally coherent low and high vertical modes, which is conjectured to correspond to the extra–tropical low vertical mode jets and the equatorial deep-jets, respectively.

The vertical scale is selected as follows: barotropically unstable meridional flow favors a certain meridional scale, which in turn determines the vertical scale through the equatorial radius of deformation relationship. This implies that the dominant vertical mode number scales like the square of the dimensional period of the short MRG wave (Hua et al. (2007)).

3 Numerical simulations

Numerical simulations using primitive equations for a continously stratfied fluid on an equatorial β-plane have been performed on the Earth Simulator (Japan) for several types of configurations, a re-entrant channel, a basin and an initially zonally-localized MRG wave in a very long channel, to sort out whenever possible the different signals that are excited through their eastward/westward propagation.

The basin simulations concerned a bihemispheric basin of idealized geometry, centered about the equator and of comparable width to either the Atlantic or Pacific. Typical resolutions vary between 1/12°and 1/24° in the horizontal and between 200 and 400 levels in the vertical.

We have analyzed the basin response to an oscillating forcing located in the western boundary layer. The symmetry of the forcing about the equator is such that mixed Rossby-gravity (MRG) waves are excited in the western part of the equatorial ocean. The forcing frequency for short MRG waves has typical intraseasonal periods of 40-80 days.

These short waves, as expected from theoretical considerations, will destabilize in the vicinity of the western boundary. This leads to the formation of finite amplitude, nonlinear jets in the entire equatorial basin. The space and time patterns of the jets correspond to low-frequency oscillating equatorial basin-modes, the period of which is set by the dominant vertical mode of the MRG wave instability. The vertical scale of the jets is a function mainly of the forcing period and is independent of the forcing vertical mode, as long as the excited MRG waves are in a sufficiently short regime to be unstable.

As a result, unlike a steady western boundary current, an oscillatory western boundary current leads to a permanent equatorial zonal circulation,. But most importantly, MRG waves destabilization appears to be a plausible formation mechanism for the observed Equatorial Deep Jets. The spatial and dynamical characteristics of the zonal circulation achieved with a 60 days forcing period are indeed compatible with the observations in the Atlantic Ocean (d'Orgeville et al. (2007)), while those with a 75 days forcing period agree with the Pacific ocean observations.

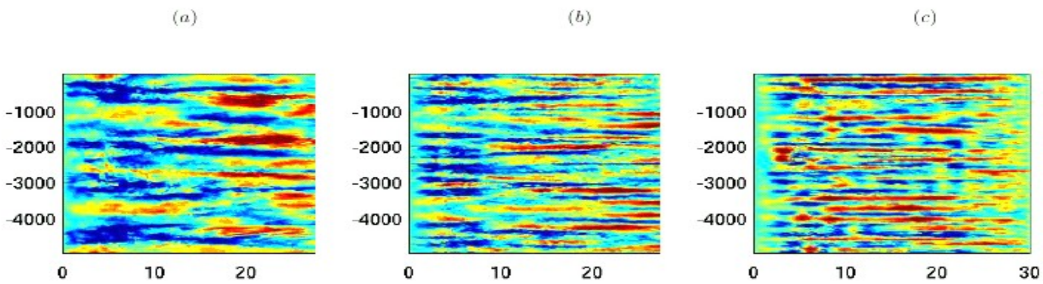

FIG. 1 – LONGITUDE-DEPTH SECTION ALONG THE EQUATOR OF THE ZONAL VELOCITY FIELD FOR A 40 DAYS (A), 60 DAYS (B) AND 75 DAYS FORCING FREQUENCY INSIDE THE WESTERN BOUNDARY LAYER.

4 Conclusions

A Floquet analysis predicts the destabilization of a westward-propagating Mixed Rossby Gravity wave producing zonally coherent jets, provided the wave is short enough. The main result concerning the vertical scale selection of high baroclinic mode zonal jets is that the dominant vertical mode scales like the square of the dimensional period of the short MRG wave.

Applying these theoretical considerations to the response of an equatorial basin to an oscillating forcing located in the western boundarylLayer, we show that intraseasonal variability can excite short MRG waves whose destabilization leads to the formation of Equatorial Deep Jets with east-west velocity directions that alternate with depth at vertical scales comparable to observations

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