5.1 IMPACT OF HEAT SOURCES IN THE TROPICAL AMERICAS: ROLE OF THE NON-LINEAR INTERACTION BETWEEN KELVIN AND ROSSBY WAVES

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1. INTRODUCTION

Apart from the well defined annual cycle, higher frequency variability is also detected in the convection in Amazon region up to the very prominent diurnal variation of convection. Theoretical studies have explored the role of the heat source of tropical S. America in the generation of Rossby (RW), Mixed Rossby-Gravity (MRGW), Kelvin (KW) and Gravity waves (GW) for the maintenance of the observed circulation patterns, such as the upper tropospheric anticyclonic circulation known as the Bolivian High. MRGW and KW are also generated by the stationary heat source. However, observational studies of the equatorial waves, based on satellite information and global reanalysis, have indicated a significant correlation between the classical equatorial waves and convective activity and organization. In particular, a significant signal of the MRGW with period of the order of a few days was identified. This paper explores a possible explanation for the relatively high magnitude of the MRGW detected in the tropical Atlantic sector, based on the non-linear interaction between Rossby and Kelvin waves. A spectral non-linear shallow water model is used to explore the role of the interaction among the tropical waves and a possible instability of the zonal flow which favors the amplification of the MRGW.

2. METHODOLOGY

The NCEP reanalysis is used to study the periodicities in the meridional flow in the S. American (Kistler et al., 2001) and Equatorial Atlantic sectors. The modeling component of this work is based on the solution of the vector form of the forced non-linear shallow water model

$$\frac{\partial \xi}{\partial t} + \Omega\xi = F + N - \kappa_0 \xi - \kappa \nabla^4 \xi \qquad (1)$$

where $\xi = [u(x,y,t), v(x,y,t), \phi(x,y,t)]^T$, Ω is the linear operator, N is the non-linear term, κ_0 is the linear damping (order of 10 days for internal mode with equivalent depth of 250m) and κ is the bi-harmonic diffusion coefficient (of the order of hours for the shortest waves) and F is a forcing term. Zonal periodicity and bounded solution as y goes to infinity provide a basis for the eigensolutions of Ω which are used in the expansion of ξ and all other terms in (1) as in

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$$G(x,y,t) = \sum_{k=-\infty}^{+\infty} \sum_{n=-1}^{\infty} \sum_{r=1}^{3} g_{k,n,r}(t) \xi_{k,n,r}(y) e^{ikx} \qquad (2)$$

where $G(x,y,t) = [g_1(x,y,t), g_2(x,y,t), g_3(x,y,t)]^T$ is a generic vector function, k is the zonal wavenumber, n is the meridional mode and r=1 for Rossby, r=2 for WGW, r=3 for EGW. The MRGW is included in the r=1 and n=0 mode. The Kelvin wave is represented by n=-1 and r=3. Substitution of (2) in (1), multiplication by the conjugate of the eigenfunctions and global integration lead to:

$$\frac{dc_{k,n,r}(t)}{dt} - i\omega_{k,n,r} c_{k,n,r}(t) = f_{k,n,r}(t) + \eta_{k,n,r}(t) - \left(\kappa_0 + k^4 \kappa\right) c_{k,n,r}(t) - \kappa d_{k,n,r}(t) \qquad (3)$$

for all modes. In this paper r is restricted to 1 in (2) and the Kelvin waves are considered only for small k. The forcing function is given by $F = [0,0, F\phi]^T$ where

$$F_\phi = F_0 e^{-\left(\frac{x-x_0}{r_e}\right)^2 - \left(\frac{y-y_0}{r_e}\right)^2} \qquad (4)$$

with y_0 and x_0 corresponding to approximately 11ºS and 65ºW, respectively, and r_e = 800km as in Silva Dias et. al. (1983) to simulate the effect of heat sources in the Amazon and Central Brazil. The analysis performed in this paper assumes that the equivalent depth of the shallow water equation model (1) is of the order of 250m, which is representative of the equatorial response to the tropical heat source (DeMaria 1985).

3. RESULTS

Several observational studies of the structure of equatorial waves (Pires et al., 1997) have indicated a significant correlation between the classical equatorial tropospheric waves and convective activity. Symmetric westward propagating modes related to Rossby waves and highly asymmetric westward propagating structures, associated to the MRGW, have been detected in the reanalysis in the Pacific Ocean. Santos et. al. (2002) identified lower tropospheric structures representative of MRGW in the Atlantic Ocean and over tropical S. America. The time evolution of the meridional wind along the equator during the ABLEIIb experiment (April 13 to May 13, 1987) indicates the westward propagation of several disturbances throughout the Atlantic Ocean and entering the South American Continent. The dispersion relation of the perturbations observed in the meridional wind in the Atlantic Ocean and in the Amazon Basin has been estimated via Fourier analysis. Comparison between the dispersion of the equatorial waves analytically obtained with equivalent depth of the order of 250m with the observed dispersion relation indicates that the perturbations with period around 2.5 days or less are inertio-gravity waves, while the perturbations with period between 4 and 6 days fit the MRGW period. The perturbations with periods greater than 5 days are manifestations of pure RW. The maximum amplitude on the geopotencial is found at approximately 1 equatorial Rossby radius of deformation, thus fitting the theoretical structure of MRGW. The observed dispersion relation in Santos et. al. (2002) indicates that the preferred wavelength in the equatorial Atlantic is of the order of 10,000km with period of 4-5 days.

Several theoretical studies have discussed the origin of the MRGW. Lateral forcing (e.g., Magaña e Yanai 1995) by mid-latitude Rossby waves, wave-CISK mechanism (eg., Lau e Peng, 1987). This work proposes an alternative mechanism, associated with the instability of the basic state generated by the zonally symmetric Rossby and Kelvin modes which resonant to the stationary component of the heat source (4) in tropical S. America. A simple experiment with filtered gravity waves indicates that the quadratic energy associated with the MRGW increases

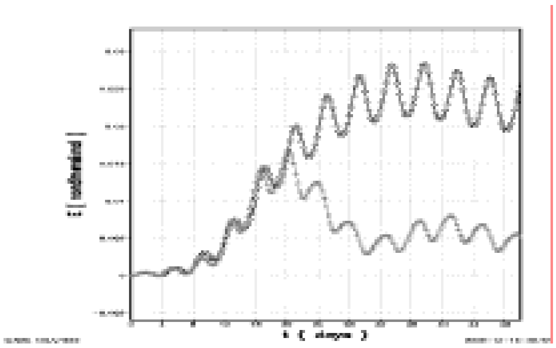

Figure 1 Quadratic component of the total energy associated with MRGW with k=4 (closed circles) and k=5 (open circles).

as a function of time during the first 30 days of the experiment, oscillating thereafter in view of the diurnal component of the forcing. At the beginning of the integration k=4 and 5 (about 10,000km) of the MRGW have similar magnitude but k=5 dominates as time increases. The approximately 4 day cycle associated with the energy oscillation in Fig.1 is quite close to the 3.75-4 day theoretical period of the MRGW with equivalent depth of 250m. When the maximum perturbation associated to these modes reaches the region near the heat source, there is a very intense energy non-linear exchange among these mixed modes, the RW and the KW locally excited by the source. The time and spatial scale of the model results are very similar to the long MRGW observed by Santos et al. (2002). The model results indicate that the MRGW has global structure in the integration after several days and although dominant over the tropical S. America and the equatorial Atlantic, significant amplitude is observed over the whole globe. A linear experiment does not indicate that growth of the MRGW. Thus, the large amplitude of the MRGW is associated to a dynamical instability of the zonal flow generated by the resonance of the k=0 RW and KW as shown in Fig.2

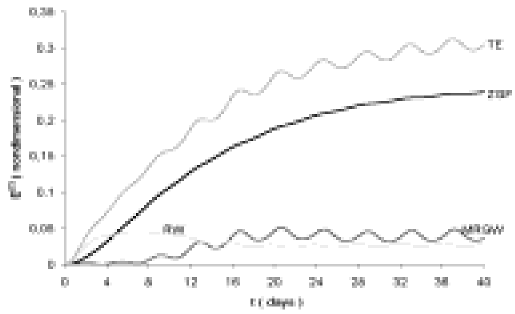

Figure 2 Quadratic energy of the zonally symmetric geostrophic waves (ZGF), MRGW, RW and Total Energy (TE).

The presence of Kelvin waves in this experiment is important to generate the correct zonally symmetric basic state and it also helps enhancing the inter-hemispheric response near the heat source (figures not shown). The larger response in the North Atlantic region is associated to the energy propagation through the westerly basic state generated in the equatorial region, which is significantly related to the Kelvin response. It is worth noticing that the Kelvin activity is greatly enhanced in the case of the diurnally oscillating heat source (figures not shown).

The experiments reported suggest a non-linear mechanism as the generating mechanism for MRGW. They also indicate that the inter-hemispheric response is significantly enhanced by the transience of the heat source in tropical S. America.

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