8D.2 WAVE ACTIVITY DIAGNOSTICS IN A SIMULATED HURRICANE

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1. INTRODUCTION

The dynamics of vortex Rossby waves as a mechanism governing spiral rainbands in hurricanes has been studied extensively in recent years. In the absence of a well-defined timescale separation between "fast" and "slow" wave modes, vortex Rossby waves have only been isolated from gravity waves by the use of filtered models (e.g., Montgomery and Kallenbach 1997; Möller and Montgomery 2000; and others) or normal mode models (Guinn and Schubert 1993). Although observational analysis (Reasor et al. 2000) and numerical simulations using 3D primitive equation models (e.g., Chen and Yau 2001, Wang 2001) show that inner spiral rainbands exhibit characteristics of vortex Rossby waves , it is still desirable to isolate vortex Rossby waves from gravity waves and to ascertain their sole effect on the structure and intensity changes of hurricanes.

Conventional principal component analysis can be used to extract statistical significant modes which may not bear any dynamical meaning. In this study, we apply empirical normal mode (ENM) theory to decompose the wave modes. The ENM method, invented by Brunet (1994), takes the advantage of the conservation law for wave activity. It is capable of decomposing simultaneously wind and thermal fields into dynamically consistent and orthogonal modes. Wave activities and Eliassen-Palm (EP) flux associated with each ENM are also valuable to provide information on wave-mean-flow interactions.

2. WAVE ACTIVITIES AND ENM

The model equations used to construct the bilinear form of the wave activities are the primitive equations in storm-following cylindrical and isentropic coordinates (r, λ, θ). By assuming small amplitude disturbances and by linearizing the equations about a time-mean symmetric basic state, the generalized conservation law for two wave activities can be found: pseudo-momentum density J and pseudo-energy density A. The azimuthally averaged equation for J is

$$\frac{\partial \bar{J}}{\partial t} + \frac{\partial}{r\partial r}\left(-r^2\sigma_0\overline{u'v'}\right) + \frac{\partial}{\partial\theta}\left(\overline{\frac{p'}{g}\frac{\partial M'}{\partial\lambda}}\right) = \bar{S}, \quad (1)$$

where $J = -r\left(\sigma' v' + \frac{\sigma_0^2 q'^2}{2\gamma}\right)$, u is the radial wind, v the tangential wind, σ the isentropic density, q the potential vorticity (PV), p the pressure, M the Montgomery function, and S the forcing term. γ is the radial gradient of the basic state PV. A subscript zero signifies the basic state quantities, a prime the small amplitude disturbance, and an overbar the azimuthal average. J contains two terms. The second term includes the PV disturbance and the PV gradient. It is therefore the vortical component or the vortex Rossby wave component. The first term is associated with density perturbation and hence is the gravitational component or gravity wave component. The second and the third terms in (1) represent the divergence of the EP flux, which is related to the mean tangential wind change (e.g., Schubert 1985; Molinari et al. 1995). A positive EP flux divergence indicates that the eddies induce positive torque on the hurricane, and vice versa.

The basic approach of ENM is to find eigenvectors of a covariance matrix whose elements are in the form of a wave activity (pseudo-momentum in this study). An eigenvalue denotes how much wave activity an ENM carries and conserves. ENM method has been used to diagnose gravity waves (Charron and Brunet 1999) and Rossby waves (Zadra et al. 2002) in general circulation model output and global analysis dataset. In our case, the dataset is the output of a hurricane simulation using high-resolution PSU-NCAR nonhydrostatic mesoscale model (MM5) (see Chen and Yau 2001 for details).

3. RESULTS

The 24-hour time mean and azimuthal mean state is chosen as the basic state, which indicates a ring structure in the mean PV field. Wave activity spectra for azimuthal wavenumber one and two anomalies suggest the existence of both retrograde and prograde waves.

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The leading modes contribute 85% of the total pseudo-momentum which in turn is dominated by the vortical component. This explains why the wavenumber 1 and 2 inner spiral rainbands in hurricanes, both observed and simulated with full-physics models, exhibit vortex Rossby wave characteristics.

As an example of the wave modes diagnosed, we show in Fig. 1 the time series (principal components) of the first two leading modes for wavenumber 2 anomalies. The two series show the same time period (about 1 hour) but with a phase lag of 16 min. They contribute about equally (11% and 10.5%) to the total wave activity and form an azimuthally retrograde wavenumber 2 vortex Rossby wave.

The EP flux for this pair of ENMs (Fig. 2) show that this vortex Rossby wave is concentrated in the inner-core region where the radial gradient of the basic state PV is large and negative. In general, the EP flux indicates wave activities propagate outward in the lower troposphere and inward in the upper troposphere. Consequently, the wave transport eddy momentum radially inward and outward, respectively. The wave activities also propagate slowly upward inside the eyewall and downward outside. The associated eddy heat transport tends to warm the air in the eye region. The divergence of the EP flux indicates that the waves tend to accelerate the mean tangential wind in the lower and middle troposphere inside and outside the eyewall but cause a deceleration of the mean tangential wind aloft in the eyewall region.

4. REFERENCES

Brunet, G., 1994: Empirical normal mode analysis of atmospheric data. *J. Atmos. Sci.*, **51**, 932-952.

Charron, M., and G. Brunet, 1999: Gravity wave diagnosis using empirical normal modes. *J. Atmos. Sci.*, **56**, 2706-2727.

Chen, Y., and M. K. Yau, 2001: Spiral bands in a simulated hurricane. Part I: Vortex Rossby wave verification. *J. Atmos. Sci.*, **58**, 2128-2145.

Guinn, T. A. and W. H. Schubert, 1993: Hurricane spiral bands. *J. Atmos. Sci.*, **50**, 3380-3403.

Molinari, J., S. Skubis, and D. Vollaro, 1995: External influences on hurricane intensity. Part III: Potential vorticity evolution. *J. Atmos. Sci.*, **52**, 3593-3606.

Möller, J. D., and M. T. Montgomery, 2000: Tropical cyclone evolution via potential vorticity anomalies in a three-dimensional balance model. *J. Atmos. Sci.*, **57**, 3366-3387.

Montgomery M. T., and R. J. Kallenbach, 1997: A theory for vortex Rossby-waves and its application to spiral bands and intensity changes in hurricanes. *Quart. J. Roy. Meteor. Soc.*, **123**, 435-465.

Reasor, P. D., M. T. Montgomery, F. D. Marks, Jr., and J. F. Gamache, 2000: Low-wavenumber structure and evolution of the hurricane inner core observed by airborne dual-Doppler radar. *Mon. Wea. Rev.*, **128**, 1653-1680.

Schubert, W. H., 1985: Wave, mean-flow interactions and hurricane development. *16th Conf. on Hurricanes and Tropical Meteorology,* Houston, Texas, Amer. Meteor. Soc., 140-141.

Wang, Y., 2001: An explicit simulation of tropical cyclones with a triply nested movable mesh primitive equation model-TCM3. Part I: Model description and control experiment. *Mon. Wea. Rev.*, **129**, 1370-1394.

Zadra, A., G. Brunet, and J. Derome, 2002: An empirical normal mode diagnostic algorithm applied to NCEP reanalysis. *J. Atmos. Sci.,* accepted.

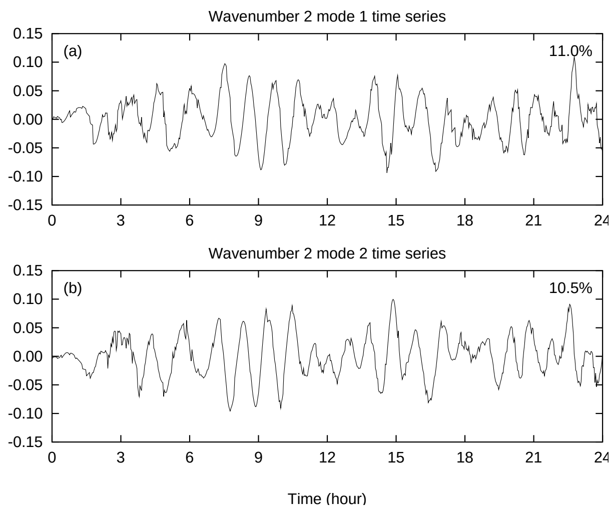

Figure 1: Time series of wavenumber 2 ENM 1 and 2.

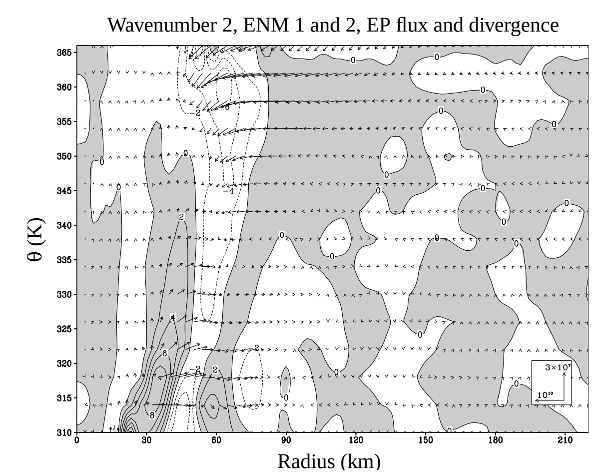

Figure 2: EP flux vectors (in unit of $\mathrm{m\ Kg\ K^{-1}\ s^{-2}}$ in horizontal direction and of $\mathrm{Kg\ s^{-2}}$ in vertical direction) and their divergence (in unit of $10^5\ \mathrm{Kg\ K^{-1}\ s^{-2}}$, contour intervals are 2) for wavenumber 2 ENM 1 and 2.