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MECHANICS AND EFFICIENCY OF SYMMETRIC AND ASYMMETRIC INTENSIFICATION PROCESSES

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1. INTRODUCTION

Tropical cyclone develoment and intensification is driven in large part by the release of latent heat of condensation in cumulonimbus convection organized around the center of the storm. For developing storms, these areas of convection are highly asymmetric and often displaced from the center of the storm. In previous work, the author has developed a linear model of nonhydrostatic dynamics which simulates the evolution of either symmetric or asymmetric temperature perturbations or heat sources introduced into balanced, hurricane-like vortices (Nolan and Montgomery, 2002; Nolan and Grasso, 2003). It was found that heat energy released in asymmetric convection was converted into kinetic energy of the axisymmetric wind field through a series of asymmetric and then symmetric adjustment processes. The goal of this work is to quantify these energy transfers, and in particular, determine the “efficiency” of energy conversion. For a given heating structure and storm structure, how much of that energy ultimately ends up in the balanced flow of the symmetric vortex?

2. LINEARIZED, NONHYDROSTATIC MODEL

The starting point for the analysis is the anelastic equations of motion in cyindrcal coordinates, defined for a reference state which is an axisymmetric vortex in gradient and hydrostatic balance. These equations are then linearized for small perturbations. This formulation captures the rapid vertical motions and radiating gravity waves associated with adjustment processes, which are filtered from balance models like those of Schubert and Hack (1982) and Shapiro and Montgomery (1993). The dynamics are separated for harmonic functions around the azimuth, with separate equations for each azimuthal wavenumber n, n = 0 referring to symmetric perturbations. Damping regions are placed along the upper and outer boundaries to absorb outward-travelling gravity waves. To determine the interactions of the evolving asymmetries with the symmetric vortex, second-order heat and momentum fluxes associated with the asymmetric motions (e.g., $\overline{u'v'}$, $\overline{w'\theta'}$) can also be used as source terms for the symmetric equations.

3. SYMMETRIC VERSUS ASYMMETRIC DYNAMICS

Nolan and Grasso (2003) considered the net effect of a localized temperature perturbation displaced from the center of the vortex. In the linear model, such a perturbation can be decomposed into its projection onto purely symmetric and purely asymmetric motions. In particular, it was found that the net effect of the asymmetric dynamics was nearly negligible in comparison to the net effect of the symmetric dynamics. Thus, the intensification of the vortex can be accurately approximated by the projection of the heating onto purely symmetric motions.

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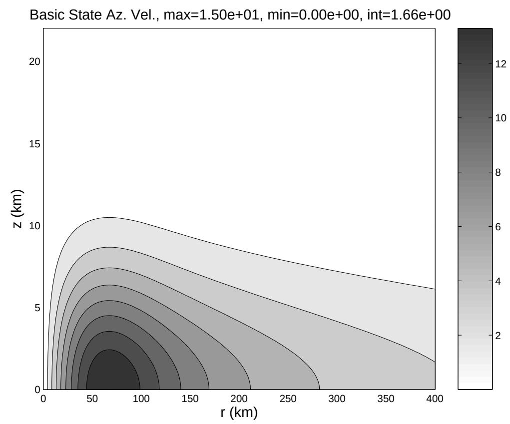

Figure 1: Velocity profile of a vortex modeled after a weak tropical cyclone. Units are ms^{-1}.

4. BASIC-STATE VORTICES

The vortices used in these studies are dry and reside on a frictionless f-plane. Their velocity fields $\bar{v}(r,z)$ are modeled after tropical cyclones, and the pressure and temperature fields are computed which satisfy the balance conditions. An example of a “weak” vortex with a maximum wind speed of 15 ms^{-1} and radius of maximum winds (RMW) 60 km is shown in Figure 1. The velocity field is generated from a Gaussian vorticity profile, with a Gaussian decay in the vertical direction. $f = 5.0 \times 10^{-5} s^{-1}$.

5. INTENSIFICATION BY SYMMETRIC HEATING

As an example, we show the response generated by a localized heating Q in the form of a Gaussian bubble localized at r = 100 km, z = 7 km, with radial and vertical half-widths of 10 km and 3 km respectively, and a maximum heating rate of 1 J m^{-3} that lasts for one hour. The heating generates unbalanced upward motions which lead to gravity waves, vortex stretching, and by t = 24 h, a balanced, positive symmetric velocity perturbation which represents a net change of the symmetric vortex, as shown in Figure 2.

Perturbation kinetic energy (KE) and available potential energy (APE), based on the equations presented by Chagnon and Bannon (2001), were computed for this simulation and are shown in Figure 3a. The heating generates APE, which is quickly converted to KE. Some of this KE is lost due to gravity wave radiation and

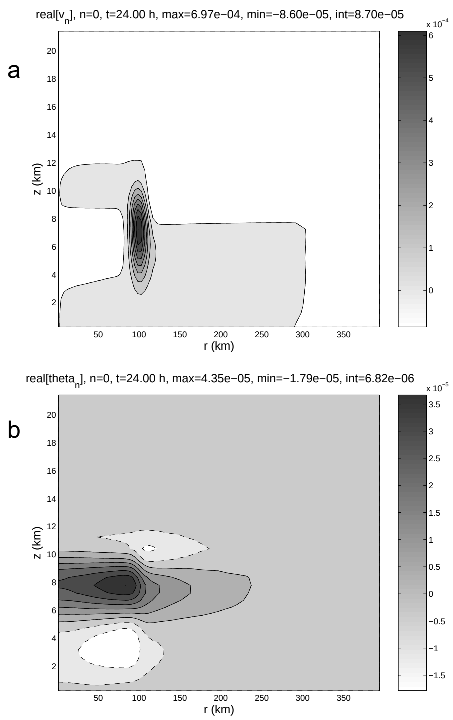

Figure 2: Net change to the symmetric vortex 23 h after a 1 h heating: a) azimuthal velocity; b) potential temperature.

diffusion, but most of it is retained in the balanced flow. The final state KE is, however, only a small percentage of the *heat* energy which was supplied.

Taking this type of analysis to the next step, we can compute the amount of energy retained in the balanced vortex as a fraction of a unit dose of heat energy supplied at each radius and height from the center of the storm, as shown for the 15 ms^{-1} vortex in Figure 3b. Maximum “efficiency” rates are around 1.5%, not surprisingly at the center axis and in the warm core. As the vortex increases in strength, the efficiency also increases. For a vortex with the same structure as in Figure 1, but with twice the wind speeds, the efficiency profile has a similar structure but maximum values over 5%. These results are quite similar to those found by Hack and Schubert (1986) using a balanced vortex model. It is interesting to note that the fraction of *available* energy, or APE, retained as KE can be close to 100%, as suggested by Figure 3a.

6. **CONCLUSIONS AND FUTURE WORK**

This work extends the results of Hack and Schubert (1986) to unbalanced motions generated by instantaneous or short-term heatings which might be generated by sporadic bursts of convection around the center of the storm. As a developing tropical cyclone increases in strength, the rate at which it asborbs energy released by cumulus convection increases dramatically. With some knowledge of storm structure and heating rates, it may be possible to identify storms ready to undergo rapid intensification.

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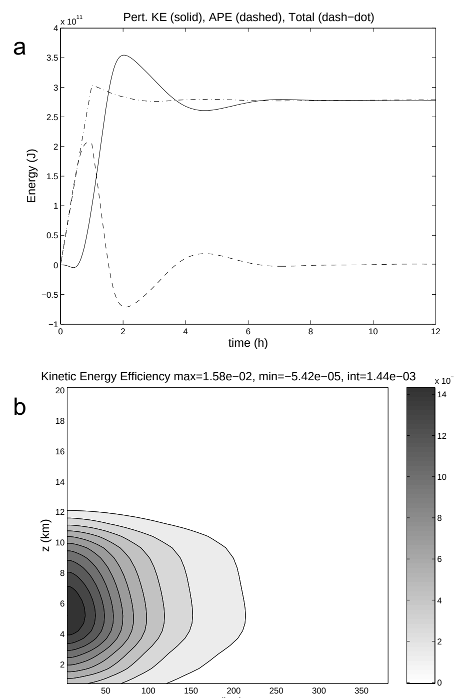

Figure 3: a) KE and APE in response to a localized heating for one hour; b) Efficiency diagram for conversion of heat energy to KE.