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FROM ASYMMETRIC HEATING TO AXISYMMETRIC INTENSIFICATION

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1. INTRODUCTION

While mature hurricanes exhibit remarkably axisymmetric structure, developing tropical cyclones are often highly asymmetric, particularly in regards to their convection and precipitation fields. Nonetheless, it is the convective heating that is ultimately responsible for intensification, despite the fact that the convection may not be localized near the center of the developing vortex. In this work we investigate the dynamical mechanisms by which asymmetric convective heating leads to intensification of the symmetric vortex.

In a series of related investigations, it has been shown that asymmetric vorticity perturbations introduced in the vicinity of a stable vortex may ultimately lead to the intensification of that vortex (e.g., Carr and Williams, 1989; Montgomery and Kallenbach, 1997; Montgomery and Enagonio, 1998; Nolan and Farrell, 1999; Möller and Montgomery, 2000). If vorticity perturbations are deformed by the shear of the basic-state flow, they cause upgradient momentum transport, leading to an increase in the kinetic energy of the symmetric flow, while suffering a decline in their own. This process is often referred to as *axisymmetrization*.

It has usually been assumed that asymmetries in the convection field of a developing tropical storm will generate localized vorticity anomalies. While this might be a very inefficient vorticity generation mechanism in the undisturbed tropics, it has been shown for symmetric perturbations that the efficiency of this process is greatly enhanced by the vorticity already present in the local flow, associated with a reduction in the local Rossby deformation radius (Schubert et al., 1980; Hack and Schubert, 1986). Here, we extend these ideas to nonhydrostatic, three dimensional, asymmetric perturbations to three-dimensional, balanced vortices which are modeled after tropical cyclones.

2. THREE-DIMENSIONAL, NONHYDROSTATIC, ASYMMETRIC DYNAMICS

The authors have developed a methodology for analyzing the linearized evolution of three-dimensional perturbations to axisymmetric vortices with arbitrary structure. The dynamics are nonhydrostatic, based on linearizations of the anelastic equations in cylindrical coordinates, such that the full fields are separated into a basic-state and perturbations of the forms

$$V(r, \lambda, z, t) = \overline{V}(r, z) + v_n(r, z, t)e^{in\lambda} \qquad (1)$$

as shown here for a single azimuthal wavenumber n. Details are available in Nolan and Montgomery (2002).

3. AN IDEALIZED, BALANCED, TROPICAL STORM-LIKE VORTEX

The basic-state vortex is modeled after a weak tropical storm. The surface wind field as a function of radius was constructed from a Gaussian vorticity distribution, such that the maximum wind speed is 21.5 ms^{-1} at a radius of maximum winds of 49 km. The surface wind field was then extended into the vertical using analytic functions, as illustrated in Fig. 1. The pressure and temperature fields which hold this wind field in gradient and hydrostatic balance were computed using an iterative procedure. The Coriolis parameter $f = 5.0 \times 10^{-5}$ s^{-1}.

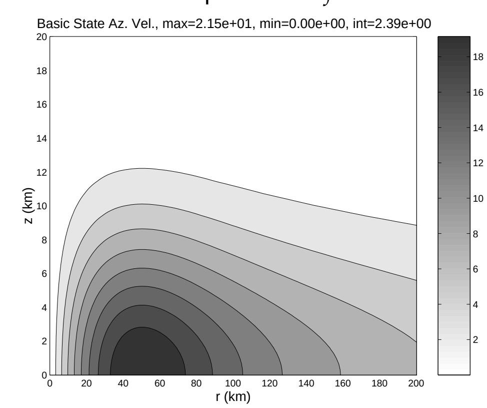

Fig 1. Azimuthal wind profile of the tropical storm-like vortex.

4. LINEARIZED EVOLUTION

As space here permits, we present only one particular case, that of a wavenumber three perturbation to the potential temperature field, in the shape of a Gaussian bubble localized at r=40 km, z=5 km, with horizontal and vertical half-widths of 20 and 2 km, respectively, as shown in Fig 2a. At early times, the bubbles of warm and cool air generate updrafts, downdrafts, and rapidly propagating gravity waves, as shown by a meridional cross-

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section of the complex magnitude of the vertical velocity field at t = 30 min (Fig. 2b). The motions interact with the basic-state vorticity fields to produce vorticity anomalies, which over about two hours adjust into quasi-balanced vorticity perturbations. These perturbations are then axisymmetrized by the shear of the basic-state wind, as shown at t = 4 h in Fig 2c.

5. **INTERACTION WITH THE BASIC STATE**

The asymmetric motions feed back onto the symmetric fields via eddy fluxes of heat and momentum. As expected from the results of two-dimensional studies, axisymmetrization leads to a positive tendency on the wind in the core of the vortex. However, since the vortex is balanced and axisymmetric, we expect axisymmetric circulations to develop in response to these tendencies, similar to the circulations predicted for purely balanced dynamics by Eliassen (1951) and others. To compute the full, time-dependent response of the symmetric vortex, the eddy flux tendencies are added to equations for symmetric perturbations (n=0). We find that these tendencies induce transient secondary circulations, symmetric gravity wave radiation, and a symmetric flow adjustment process similar to that demonstrated by Schubert et al. (1980). For the case presented here, we find that the asymmetric eddy fluxes and symmetric adjustment process leads to an increase in the inner core azimuthal winds, an amplification of the warm core, and lower surface pressures (not shown).

6. **CONCLUSIONS**

We have elucidated the dynamics by which impulsive asymmetric heating (caused by asymmetric convection) can lead to tropical cyclone intensification. Asymmetric heating leads to the generation of quasi-balanced vorticity anomalies via a gradient adjustment process. These anomalies are then axisymmetrized, causing inward transports of heat and momentum. Transient meridional circulations develop in response to these forcings, leading to a modified balanced vortex with higher wind speeds and a warmer core.

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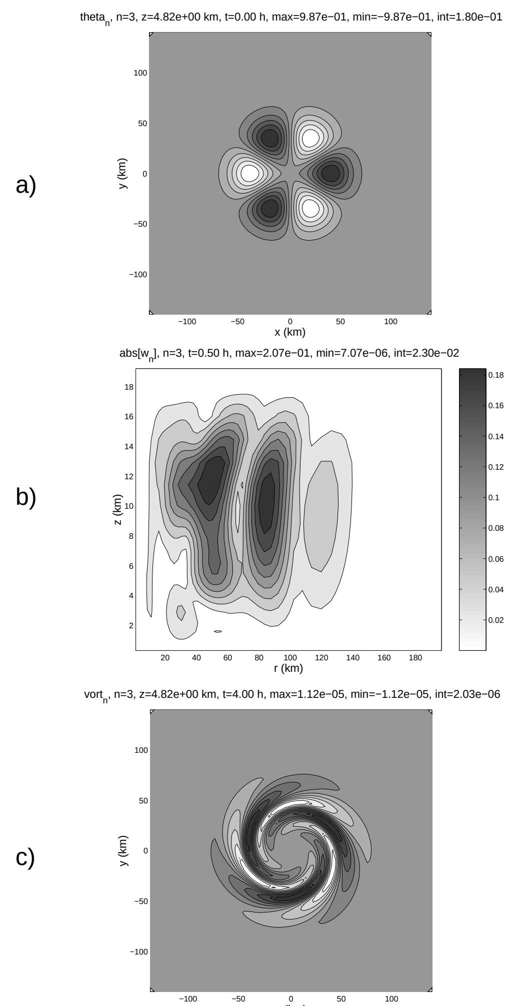

Fig. 2: Evolution of an asymmetry introduced into the potential temperature field. See text for comments.