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The Role of Upper Tropospheric Inertial Stability in Hurricane Intensification

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1. Introduction

It is generally accepted that the maximum potential intensity (MPI) a hurricane can attain is controlled by the thermodynamics of the environment and sea surface temperatures (SST's) (Emanuel 1986; Holland 1997). In fact, idealized numerical simulations of tropical cyclones often reach this limit. However, in nature hurricanes rarely reach their climatologically defined MPI. Two possible explanations for this behavior are: the effects of the storm circulation on SST's which in turn modify the air-sea interaction, and the dynamical interactions of the hurricane with the storm environment which affect both peak intensity and the rate of intensification.

There has been considerable success using a coupled ocean-atmosphere model (Emanuel 1999) in predicting hurricane intensity changes. Upwelling below and mixing across the thermocline in response to the strong wind stress produces cooler sea surface temperatures and decreases the strength of the air-sea interaction. By including the feedback of the storm circulation on the sea surface temperatures Emanuel (1999) showed that a large number of storms can be successfully modeled in a simple framework that neglects dynamical interactions. It is also suggested that in some storms that undergo an external interaction that the key role played by the external system is to vary the storm speed and hence modify the storm circulation/air-sea interaction feedback.

Hurricanes not close to their MPI however can be significantly affected by hurricane-trough interactions (Bosart et al. 2000). The upper tropospheric environment can play a large role in determining intensity fluctuations. A vorticity source above a developing tropical cyclone will decrease the Rossby radius and the tropical cyclone will be forced to expend more energy to vent it's outflow from the storm core than otherwise. On the other hand, regions of weak inertial stability aloft provide a weaker resisting force so that the outflow expands more easily. It is the goal of this work to show that under the latter conditions, intensification is more rapid. The fact that the environments within idealized numerical simulations incorporate only one way interactions (that is, the environment is molded by the storm evolution and not vice versa), it is not surprising that the MPI is almost always obtained. Promotion of vertical shear by the hurricane-trough interaction will almost always subdue hurricane intensification.

2. Model and Results

The model used in this study is the aforementioned Emanuel model (a more detailed description can be found in Emanuel 1994) without the ocean coupling and modified to accommodate varying inertial stability at the tropopause level. Model variables are transformed to a potential radius coordinate, R, defined as

$$fR^2 = 2rV + fr^2$$

where f is the Coriolis parameter, r is the physical radius, and V is the tangential velocity. It is a two layer model with a boundary layer and a tropospheric layer. Treating R as a dependent variable, knowledge of where the physical radii intersect the top of the boundary layer and the tropopause is all that is needed to determine the azimuthal velocity at these locations. The model uses a convective parameterization based on equilibrium maintenance of the boundary layer entropy. Updraft mass fluxes are determined by an assumed equilibrium of surface latent heat fluxes and downdraft fluxes. The constraining balance condition of the model is a thermal wind balance which is obtained by assuming slantwise neutral ascent, hydrostatic, and gradient wind balance. This balance condition necessitates the use of a Sawyer-Eliassen type equation to diagnose the secondary circulation.

The model was modified so that the inertial stability of the tropopause level was set at zero for the entire time integration. This was accomplished by fixing the physical radii at tropopause level so that the relative vorticity had a value opposite the planetary vorticity. This was done only for the Sawyer-Eliassen type equation, the prognostic equation for the tropopause level physical radius was allowed to evolve unperturbed. The control run has no initial relative vorticity at the tropopause. As this model is axisymmetric, there is no way to incorporate the effects of vertical shear.

Figure 1 shows intensification, as measured by maximum tangential wind speed, of both the control

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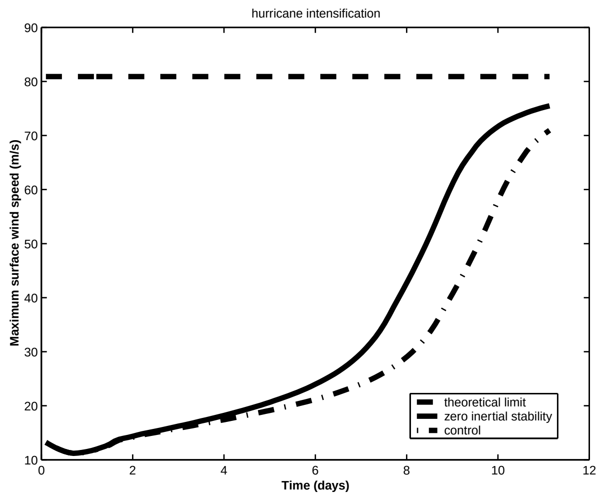

Figure 1. Hurricane intensity as measured by maximum wind speed in the control (dash dot) and modified experiments.

experiment and the modified experiment. As anticipated there is more rapid development when the outflow layer is predisposed to weak inertial stability. Figure 2 displays the time evolution of the radial extent of the anticyclonic outflow. There is a weaker resisting force in the modified experiment so that the outflow can grow stronger and extend to greater distances from the storm core before adjustment. When the modified experiment is run out to greater times, a series of eyewall replacement cycles occurs (not shown). It was suggested by Emanuel (personal communication) that these replacement cycles could be the result of perturbations introduced by the inertially weakened outflow. If integrated to long enough time periods the storm eventually collapses as the eyewall radius extends to greater and greater distances from the storm center. Perhaps the explanation lies in the significant strengthening of the anticyclonic outflow beyond that of the control run at later times (not shown).

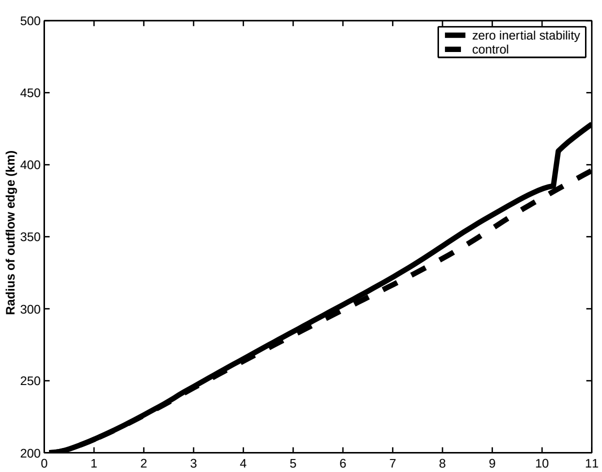

Figure 2. Radial extent of the anticyclonic outflow in the control (dashed) and modified experiments.

3. Future Work

This work was intended to provide a stepping stone to the more dynamically interesting problem of hurricane-trough interactions. This interaction may be considered as a cold core trough impinging upon a warm core hurricane. The enhanced tropopause height gradient that develops between the two will be associated with a strengthening jet. It is proposed here that idealized modeling of the hurricane-jet couplet will lead to a better understanding of rapid intensification changes in both incipient and mature vortices.

It is suggested here that early in the interaction strengthening will occur as a result of the coupling of the hurricane outflow with the right jet entrance region. Later in the interaction, weakening is expected in association with either a decrease in SST's or enhanced vertical shear (strong baroclinic zones are found in the midlatitudes). An excellent example of such a sequence of events occurred with Hurricane Opal (1995) in which prior to landfall rapid intensification occurred in response to both a warm core ocean eddy and a dynamical interaction with a extratropical system (Bosart et al. 2000) followed by very rapid decay.

To account for the significant effect of environmental asymmetries on hurricane evolution a three-dimensional primitive equation model will be developed. By modeling the convection explicitly it is hoped that knowledge will be gained of the role of environmental influences on storm core ascent. Particular attention will be given to the feedback between jet strength and momentum transport by cumulus clouds.

4. References

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