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THE COMPARATIVE EFFECTS OF FRICTIONAL CONVERGENCE AND VERTICAL WIND SHEAR ON THE ASYMMETRIES OF A HURRICANE

by
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1. INTRODUCTION

There has been much interest in the recent literature on the effects of vertical shear on hurricanes (e.g. Bender 1997; Frank and Ritchie 2001 and refs; Jones 2003 and refs; Reasor *et al.*, and refs). The first two of these papers focus on moist processes while the last two concentrate on dry processes. Here we use the minimal three-dimensional hurricane model of Zhu and Smith (2003; henceforth ZS), which includes a representation of moist processes, to investigate the asymmetries that develop when a model storm intensifies in ambient vertical wind shear. ZS showed that even for an initially-symmetric vortex on an *f*-plane, significant flow asymmetries develop when latent heat release occurs. The spurious development of asymmetries is not just a feature of the three-layer model, but occurs also, for example, in multi-level tropical-cyclone simulations using the MM5 model (S. Nguyen, personal communication). For this reason some of the asymmetries in previous numerical studies of tropical cyclones might be affected by the computational mode when moist processes are involved, even though the models have a higher vertical resolution than the ZS-model. ZS showed that the spurious asymmetries were very much weaker if a Charney-Phillips (CP-) grid is used for vertical differencing.

2. A FEW MODEL DETAILS

The model is based on the hydrostatic primitive equations formulated in σ-coordinates. It uses the CP-grid for the vertical differencing. The model equations and the advantages of CP-grid are discussed in ZS. The model is divided vertically into four layers of unequal depth in σ: the lowest layer has depth 0.1 and the three layers above have depths 0.3. The calculations are carried out on an *f*-plane. Newtonian cooling is used to represent the effect of radiative cooling. The turbulent flux of momentum to the sea surface and the fluxes of sensible heat and water vapour from the surface are represented by bulk aerodynamic formulae.

Explicit condensation occurs when the air becomes supersaturated at a grid point. At such points the excess water is assumed to precipitate out while the latent heat released increases the air temperature. The scheme involves an iterative procedure. The parameterization of deep cumulus convection is based on a mass flux approach suggested by Arakawa and detailed in ZSU. Implementation of the scheme in the CP-grid model is described in ZS.

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2. EXPERIMENTAL DESIGN

The initial vortex is axisymmetric and baroclinic. The tangential wind profile has maximum tangential wind speed of 20 m s^{-1} in the boundary layer at a radius of 180 km and its magnitude reduces to 14.5 m s^{-1} at the highest level. The initial mass and thermal fields are obtained by solving the inverse balance equation. The far-field temperature, geopotential height and humidity structure are based on the mean West Indies sounding. The horizontal grid spacing is 20 km and the integration time step is 12 s. The ocean surface temperature is 28^{o}C and the calculations are performed on an *f*-plane at 20^{o}N.

Three experiments are carried out. The first excludes moist processes and boundary-layer friction. A unidirectional linear easterly shear of 5 m s^{-1} is added above the boundary layer at the initial instant. The second experiment is a dry simulation also with the same shear as Expt. 1, but includes boundary-layer friction. Experiment 3 is like Expt. 2, but includes a cumulus parameterization scheme as well as an explicit scheme for latent heat release when saturation occurs at a grid point. The three experiments are designed to compare the role of the boundary-layer convergence and vertical shear on the inner core asymmetries of a hurricane in the dry and moist simulations. As the asymmetries of vortex in the dry simulation have been investigated by many previous workers, we focus attention here mainly on the vortex asymmetries in the moist simulations.

3. RESULTS

(a) Stages of evolution

Figure 1 shows a time series of the maximum boundary-layer wind speed during the 96 h integration period in Expt. 3. The heating of the vortex core by parameterized deep convection leads to a secondary circulation with low-level convergence and upper-level divergence. In contrast to Expts. 1 and 2, in which there is no latent heat release, the primary (tangential) circulation strengthens at

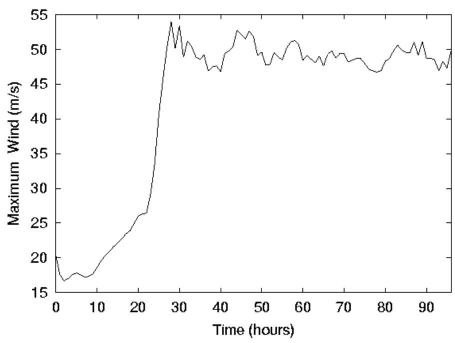

Fig. 1 Time evolution of the maximum surface wind speed in Expt. 3 in m s^{-1}.

low levels and weakens aloft. The intensification is slow at first characterizing a gestation period lasting about 24 h, but becomes rapid later when the inner core saturates on the grid scale. After about 6 h the tangential wind speed reaches a maximum of 54 m s^{-1}. Thereafter the vortex settles down to a quasi-steady state in which the intensity fluctuates about some mean value that is a little less than the earlier maximum. We refer to the period beyond 42 h as the mature stage.

Figure 2 shows successive positions of the relative vorticity centre in the boundary layer and in the upper troposphere in Expt. 3. These centres begin to separate during the gestation period with the boundary-layer centre moving slightly south of west and that in the upper troposphere moving north of west. This movement is different from that in the dry simulations and different to a corresponding calculation by Frank and Ritchie (1999), in which the early motion is similar to the dry calculation. During the period of rapid intensification, the two centres converge and subsequently track together, moving generally westwards in the mature stage.

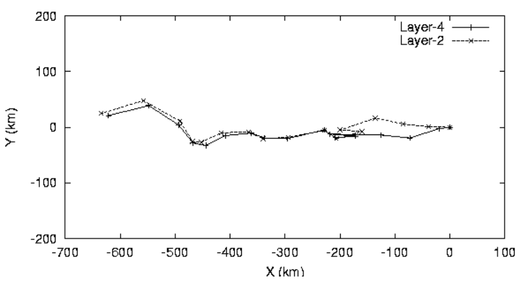

Fig. 2 The tracks of the vortex centres in the upper layer and boundary layer for Expt. 3. The vortex centres at 6 h intervals are indicated.

The differences in the vortex tracks during the gestation period compared with the dry simulations must arise from the implementation of a cumulus parameterization scheme in Expt. 3. First, the strengthening of the lower tangential circulation and the weakening of that aloft reduce the mutual advection of the upper and lower PV anomalies by the upward (downward) projection of the tangential circulation at lower (upper) levels as happens in the dry case. However, in the presence of vertical shear the parameterized heating is not symmetric and leads to asymmetries in the vortex circulation that have an important influence on the track. In the dry case, vertical shear leads initially to cooling on the downshear side and as the vortex tilts, the maximum cooling shifts downtilt, i.e. to the southwest. In Expt. 3, however, the initial downshear cooling together with the increased surface heat flux ahead of the storm increases the convective instability in that region. The result is to enhance subgrid-scale convection, which provides an additional source of positive (negative) PV at low-levels (high-levels) ahead of the storm. Compared to the dry simulation, the convective heating induces a positive relative vorticity at the front of the storm in the lower troposphere and a negative in the upper troposphere. The absolute value of relative vorticity in the lowest level is about three times more in Expt. 3 than in Expt. 1. We attribute the differences between our calculation and Frank and Ritchie's to the different parameterization schemes used.

Other aspects of the calculations will be presented during the talk. In particular we will discuss the relative contribution of boundary-layer friction and vertical shear to the asymmetries and will relate our findings to those of previous authors.

4. SUMMARY OF FINDINGS

The asymmetries that develop in the moist version of the model have a different structure to those that develop in a dry version. In the former case there are two competing factors that influence the asymmetric structure of the inner core: vertical wind shear and frictional convergence in the boundary layer. Moreover the asymmetries are different in the different stages of development, and also different in the core region compared with the outer region of the vortex. In the developing stage, the patterns of vertical velocity and temperature deviation above the boundary layer are primarily determined by the shear, but parameterized convective heating contributes to the temperature deviation also. When saturation occurs in the core region, rapid intensification takes place and the vortices in the upper layer and lower layers become strongly coupled so that there is little tilt of the core region. In the mature stage, ascent associated with frictional convergence in the core dominates the vertical motion field induced by the shear. Even though the inner core of the vortex becomes upright, the outer regions continue to have a significant tilt. The asymmetries in the pattern of vertical motion above the boundary layer and outside the core region are primarily associated with the vortex tilt in this region and are different from those in the core region, which are mainly determined by the boundary layer flow in the mature stage.

7. ACKNOWLEDGEMENT

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