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A NUMERICAL STUDY OF THE EFFECTS OF SHALLOW CONVECTION ON TROPICAL-CYCLONE INTENSIFICATION

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1. INTRODUCTION

There is an increasing interest in trying to forecast tropical-cyclone intensity change using numerical models, but current operational models have only limited skill in this regard and debate continues as to what physical processes need to be represented in models to produce acceptable forecasts. In a recent paper Zhu and Smith (2002; here after ZS) investigated the importance of shallow convection on tropical-cyclone intensification using a minimal three-dimensional tropical cyclone model with three vertical levels including a shallow boundary layer. They found that shallow convection warms and dries the boundary layer, thereby lowering the equivalent potential temperature, θ_e, in the boundary layer. Further, it moistens and cools the lower troposphere, elevating θ_e in this layer. The former effect reduces the instability to deep convection, while the latter leads to earlier saturation on the grid-scale. In what seemed to be the more realistic parameter regime, the former effect was more important and led to a delay in the onset of rapid intensification of the model vortex by a day and a half. The results were suggestive, but the representation of shallow convection in such a simple model is necessarily crude and the object of the present work is to revisit this problem using the more sophisticated Pennsylvania State University-National Center for Atmospheric Research fifth-generation Mesoscale Model (MM5).

2. DESCRIPTION OF THE EXPERIMENTS

MM5 is a nonhydrostatic, three-dimensional model that can include both parameterized and explicitly resolved moist processes (Grell *et al*. 1994). Our configuration has an inner and outer domain: the outer domain is a 5400 km square with a 45 km mesh size and the inner domain is a 1800 km square with a 15 km mesh size. In some calculations, a third 600 km square domain with a 5 km mesh size was added in the central region. We chose 24 levels in the vertical. To simplify the problem as much as possible, only a few of the basic physics options available in MM5 were implemented. These include the bulk-aerodynamic boundary-layer parameterization and the simplest explicit moisture scheme. The shallow convection scheme used is based on the method proposed by Arakawa-Schubert (1974), but modified by Grell (1994).

The idealized model calculations are initialized with an axisymmetric vortex in a quiescent environment on an *f*-plane valid at 20°N with a constant underlying sea surface temperature of 28°C. The initial tangential wind profile has the same radial form as that used by Smith *et al.* (1990), but with a maximum speed at the surface of 15 m s^{-1} at a radius of 135 km and the speed decreases sinusoidally to zero at the top of the domain (50 mb). A balanced thermal field was obtained using a new method that solves the unapproximated form of the thermal wind equation as a first-order partial differential equation. As in ZS the far-field temperature, geopotential height, and humidity structure are based on the mean West Indies sounding. Table 1 lists the experiments that were carried out. The control experiments A1, B1 and B3 exclude shallow convection.

Table 1. List of numerical experiments.

Expt.	Description
A1	2 domains, control run
A2	Same as A1, but inclusion of shallow convection
B1	3 domains, control run
B2	Same as B1, but inclusion of shallow convection
B3	Same as B1, but V_m = 10 m s^{-1}
B4	Same as B3, but inclusion of shallow convection

3. RESULTS

3.1 Control run

The evolution of the maximum azimuthally-averaged tangential wind speed just above the boundary layer is shown in Fig. 1. The onset of rapid intensification occurred at about 9 h and the vortex reached an approximate steady state at about 54 h with the maximum tangential averaged winds of about 67 m s^{-1}.

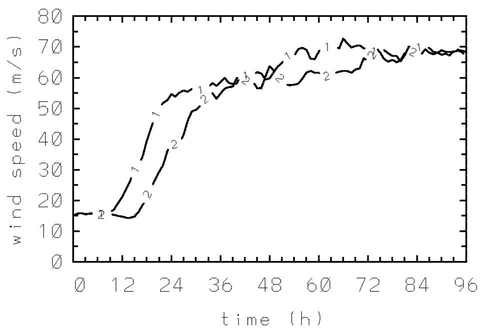

Fig. 1 Evolution of maximum tangential wind speed in m s^{-1}: (1) control calculation A1; (2) expt. A2.

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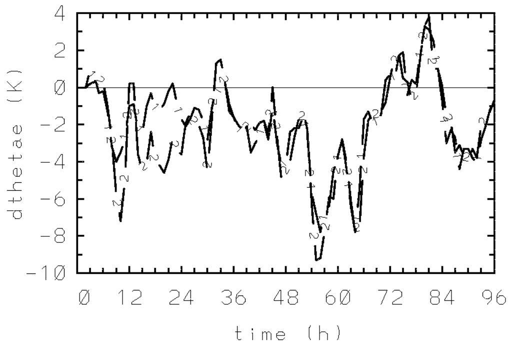

Fig. 2 Differences in the maximum azimuthally-averaged pseudo-equivalent potential temperature in K between the two calculations A1 and A2 at: σ = 0.945 (curve 1) and σ = 0.910 (curve 2).

3.2 Inclusion of shallow convection

Figure 1 shows also the evolution of vortex intensity in Expt. A2. With the inclusion of shallow convection, the onset of the rapid intensification is delayed by about 6 h. The mean intensity in the period from 12 h to 36 h is about 12 m s^{-1} more than in the control calculation. After 72 h, there is little difference in the intensity between the two cases. We attribute the delay in the onset of rapid intensification to the reduction in the low-level pseudo-equivalent potential temperature, θ_e. Support for this conclusion is provided by the time-series of the differences in the maximum azimuthally-averaged θ_e at two σ-levels (σ = 0.945 and σ = 0.91) shown in Fig. 2. At both these levels, θ_e is smaller by a few degrees except for short periods of time.

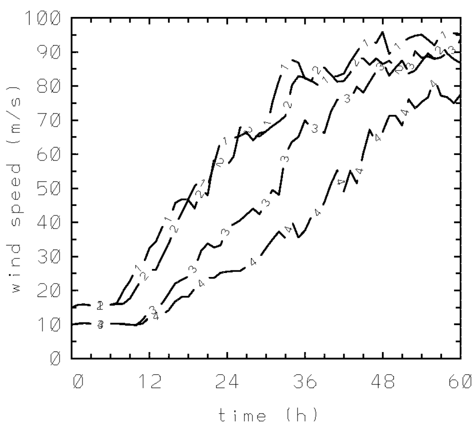

Fig. 3 Time-series of the maximum tangential wind speed in m s^{-1} in the control calculation B1 (curve 1), Expt. B2 (curve 2), Expt. B3 (curve 3), Expt. B4 (curve 4).

3.3 Sensitivity tests with higher resolution

It is of interest to know to what extent the foregoing results are dependent on the model resolution. For this reason we introduced the third nest with a 5 km grid size and performed the model runs B1 and B2 with the same physics options and initial conditions as in A1 and A2, respectively. The vortex evolution in these two cases is shown in Fig. 3. With the greater resolution, the onset of rapid intensification in the case with shallow convection is only slightly delayed by about 1 to 1.5 h.

Two more runs B3 and B4 were carried out to examine the dependence of the effects of shallow convection on the strength of the initial vortex. The physics options for B3 and B4 are the same as B1 and B2, respectively, but the maximum wind speed of the initial vortex is reduced to 10 m s^{-1}. The vortex evolution in these experiments is shown in Fig. 3 also. With the weaker initial vortex, rapid intensification is delayed by a further 3 h, but occurs at about the same time in both experiments, although the rate of intensification is lower in the case with shallow convection. Efforts are still underway to understand these sensitivities.

4. DISCUSSION AND CONCLUSION

Our results support the findings of ZS that the principal effects of shallow convection are to reduce the boundary-layer θ_e and to delay the onset time of rapid intensification. However the delay time is less than that estimated by ZS. The inclusion of shallow convection tends to reduce the vortex intensity in the mature stage also. These findings point to the need for a realistic representation of shallow convection in tropical-cyclone forecast models.

5. ACKNOWLEDGEMENT

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