High-Resolution Simulation of Hurricane Danny (1997): Comparison with radar observations

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1. Introduction

Over the past ten years, considerable progress has been made in the numerical simulation of hurricanes. Mesoscale numerical models with a grid resolution of less than 10 km have simulated these tropical storms with considerably success. For example, Liu et al. (1997) simulated the inner-core of Hurricane Andrew (1992) using a triply nested MM5, at a grid resolution of 6 km, with an explicit microphysics package. The model reproduced the track, the explosive deepening, the minimum central pressure of 919 mb, the strong surface wind, the eyewall, and the spiral rainbands. Liu et al. (1997) concluded that it might be possible to predict the track, intensity and inner-core structures of hurricanes if high grid-resolution, realistic model physics, and proper vortices are incorporated into the model. Using MM5, Davis and Bosart (2001) successfully simulated the genesis of Diana (1984) at 3 km resolution. They found that the simulated cyclone deepening rate, in the pre-hurricane stage, depended principally on choices of cumulus parameterization, boundary layer treatment, sea surface temperature, and grid spacing. They showed that simulations with cumulus schemes which allowed more grid-scale precipitation on the 9-km grid exhibited unrealistic grid-scale overturning, and slower intensification. Use of an innermost nest with 3-km spacing, and with explicit cloud microphysics (no cumulus parameterization), produced an intensification that agreed more accurately with observations. Although the results from these high-resolution simulations are very encouraging, a careful verification of model simulation at cloud-resolving resolution (~1 km) with radar observations has been rare in the literature. Such study would provide critical assessment of the realism of model simulations, and offer additional insights on the interaction between the cloud-scale circulation with the hurricane vortex.

Danny (1997) was a slow-moving, category one hurricane that made landfall on the coast of Louisiana and Alabama on 18-19 July 1997. It produced extreme precipitation over Southern Alabama. Radar rainfall estimates for total storm precipitation were 43 inches near Dauphin Island (Pasch 1997). Due to the slow movement of the storm, Danny's center remained within 100 km of WSR-88D radars at Slidell and Mobile for more than 48 hours. Radar observations of Danny showed interesting structural evolutions coinciding with its landfall. This includes the development of concentric eyewalls, a complete eyewall replacement cycle, and the development of a convective mesoscale vortex in the western eyewall (Blackwell 2000). Because nearly continuous radar observations were recorded for an extended period, this case provides a unique opportunity for a detailed mesoscale verification of high-resolution model simulation of a hurricane at landfall. The purpose of this paper is to perform a cloud-resolving (1 km) simulation of Hurricane Danny, and to perform a comparison with available radar observations.

2. Model and experiment design

In this paper, we carried out a series of numerical simulations on Hurricane Danny over a four-day period, from its genesis stage to its landfall, using the MM5 model. Our study began at 0000 UTC 16 July 1997, when only a weak surface low was present over the northern Gulf of Mexico. In the first experiment (control), the MM5, with triply nested (81/27/9 km) grids, was initialized at 0000 UTC 16 July 1997, using the ECMWF TOGA analysis without further enhancements. This version of MM5 used the following physics options: Betts-Miller cumulus parameterization, Reisner-I mixed phase microphysics, Blackadar planetary boundary layer (PBL) scheme, and Dudhia radiation scheme. The second experiment was started at 0000 UTC 17 July, when a 3-km mesh was initialized with the 24-h forecast of the 9-km grid. The 3-km model used the same physics options as those of the 9-km model, with the exception that the subgrid-scale cumulus parameterization was turned off. The 3-km experiment was integrated to 0600 UTC 19 July, and was driven by the 9-km model forecasts in a one-way mode. The third experiment used 1-km MM5, and was initialized at 0900 ITC 18 July, using the 33 h forecast from the 3-km model. The 1-km MM5 using the same physics options as those of the 3-km model, was integrated through 0000 UTC 19 July. The lateral boundary condition was provided by the hourly output from the 3-km model. The computational domains for the five grid meshes mentioned above are shown in Fig. 1. For comparison, we also performed a two-domain (81/27 km) MM5 experiment, with model configuration and physics similar to that of the control three-domain experiment (81/27/9 km).

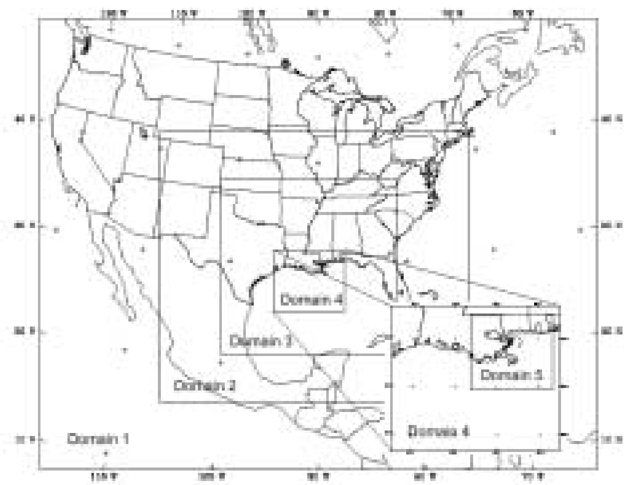


Fig. 1. The domains for the five MM5 grid meshes used in this study: Domain 1 (81 km), 2 (27 km), 3 (9 km), 4 (3 km), and 5 (1 km). The first three domains were integrated using two-way interactive mode. The 3 km and 1 km grids were integrated with one-way nesting.

3. Results

According to the Best Track analysis (which is only available at 6-h intervals), the minimum pressure of Danny reached 984 mb at 0000 UTC 19 July. The Best Track analysis also indicated that the storm was filled to 987 mb at 0600 UTC 19, and then deepened to 984 mb again at 1200 UTC 19, Afterwards, the storm moved into the southern U.S., and was considerably weakened. The storm was declared a hurricane during the period of 0600 UTC 18 through 1800 UTC 19 July 1997. Figure 2 shows the sea level pressure trace for 3 km, 9 km, and 27 km (two domain experiment) grids, as well as the observed central pressure from the Best Track analysis. The 27-km grid predicted only a weak storm, with a minimum central pressure of 995 mb, at 69-h forecast (valid at 2100 UTC 18 July). The 9-km grid (from the triply-nested control run) produced the most intense storm among all experiments, with a central pressure of 979 mb at 2200 UTC 18 July. The 3-km grid predicted a minimum pressure of 983 mb at 0300 UTC 19 July, and displayed a tendency of filling shortly after that. An interesting result from the 3-km model is the relatively slow deepening during the 24-h of integration (from 0000 UTC 17 to 0000 UTC 18). This was followed by a nearly 10 mb drop in central pressure in a two-hour period between 0200 UTC and 0400 UTC 18 July. This deepening was associated with the rapid development of a mesoscale convective system (with a size of ~45 km that produced precipitation exceeding 100 mm per hour) and its interacting with the vortex, although at this time, the realism of such deepening cannot be verified. Overall, the evolution of the storm was captured reasonably well by the 3-km grid.

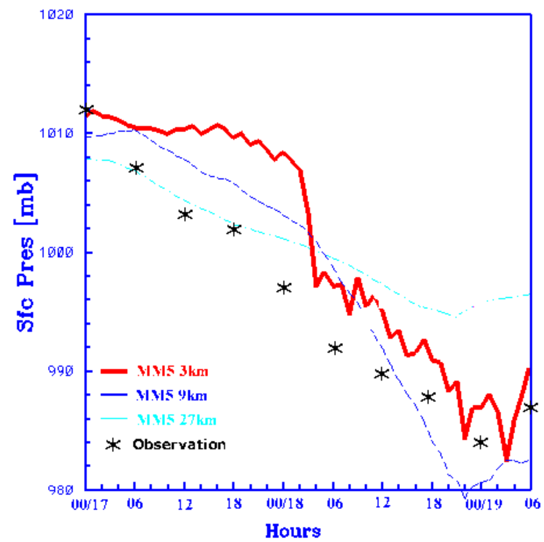


Fig. 2. The sea level pressure trace for four MM5 grids (27, 9, and 3 km), and the observed central pressure from the Best Track analysis from 0000 UTC 17 July to 0600 UTC 19 July, 1997.

Fig. 3 shows a comparison of storm position, as simulated by the 3-km grid, and estimated by KLIX radars. The model storm lagged the observed storm by about 130 km at 0000 UTC 18 July. However, by 1800 UTC 18 July, this distance was reduced to about 30 km.

The radar reflectivity and the derived GBVTD (Lee et al. 1999) tangential wind derived from the KLIX radar at 1358 UTC 18 July are shown in Fig. 4. The radar observation indicated a nearly closed eyewall except for a small gap in the northwestern quarter. There was a strong convective band with maximum reflectivity of 55 dBZ located on the eastern half of the storm. The GBVTD estimated maximum wind was located over the southeastern quarterly with a maximum speed of about 39 m/s.

The model simulated radar reflectivity from the 1 km, 3 km, and 9 km experiments was shown in Fig. 5. The 9 km model (Fig. 5a) simulated one broad area of reflectivity with an arc shape. The radar echo extended from the southeast quarter to the western quarter of the storm. There was a large opening on the south side of the storm. The simulated model radar reflectivity is very smooth, with no small scale features. The maximum wind at 1 km elevation was located in the northeastern quarter of the storm, with a speed of 42 m/s. The radius of maximum wind was about 35 km, which is approximately four grid points away from the center of the storm.

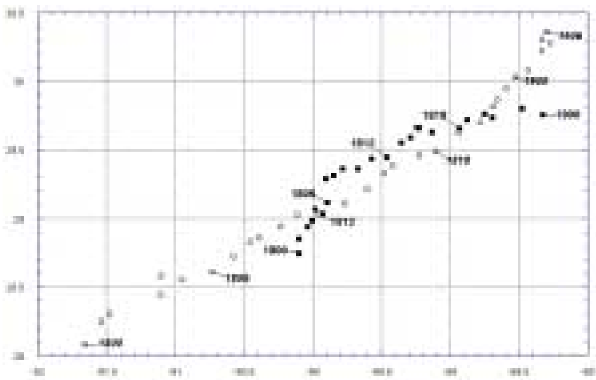


Fig. 3. The positions of model storm as simulated by the 3-km MM5 (open circles) and the positions of the observed storm as estimated by KLIX (black squares) radar.

The 3 km model simulated two wind speed maxima, one over the southeastern quarter, and the other on the northwestern quarter. The maximum speeds were 36 m/s and 32 m/s, respectively. With the use of the 3 km grid, the radius of maximum wind was reduced to about 15 km, and the model began to show small-scale details in the simulated radar echoes. A ring of strong radar reflectivity extended from the southeastern quarter to the southwestern quarter, forming a partial eyewall. There was an opening to the south of the storm, similar to that of the 9 km model. But, the eyewall was of considerably smaller size, and the radar reflectivity was considerably stronger. The 3-km model attempted to show a rainband approximately 60 km to the south of the center (this rainband was missing in the 9-km model). However, the radar echoes appeared cellular and patchy. It seems that at 3 km, the model was at the limit of adequately resolving the convection.

With the use of 1 km resolution, the model simulated a complete eyewall, and the multiple rainbands around the eyewall at 1400 UTC. The radius of maximum wind remained at 15 km, unchanged from the 3 km results. The maximum wind speed was 39 m/s, which was slightly stronger than the 3 km simulation, and a very good match with the radar observations. Additional analysis at other times indicated that the 1 km model was able to simulate the repeated initiation of convective systems around the eyewall and their subsequent outward propagation, resulting multiple rainbands around the storm and concentric eyewalls with structure similar to what was found in the radar analysis (not shown).

4. Summary and conclusions

In this paper, we performed a preliminary simulation of Hurricane Danny with MM5, with grid resolution that varied from 81 km to 1 km. The triple nested MM5 (81/27/9 km) was able to simulate the genesis of Danny from the smooth ECMWF global analysis at 0000 UTC 16 July. [It should be noted that the ETA model at 80 km resolution initialized at the same time failed to simulate the development of the storm.] Comparison with radar observations indicated that the 9-km model predicted a storm stronger than the observation. Also, the simulated radius of maximum wind was about twice as large. The 3-km model was able to correct this problem, and produced a radius of maximum wind at 15 km that was consistent with the radar observations. It appeared that for this small, category one storm, we need at least a grid resolution of 3 km to properly simulate the wind field structure. The results were further improved with the use of 1 km grid. Particularly in the simulation of eyewall convection and rainbands surrounding the storm. A comparison with radar observation suggests that 3-km may not be adequate for the detailed simulation of convection in this hurricane. The use of 1 km grid resolution (or higher) is desirable if we are to properly simulate the evolution of mesoscale convective systems and their interaction with a hurricane vortex.

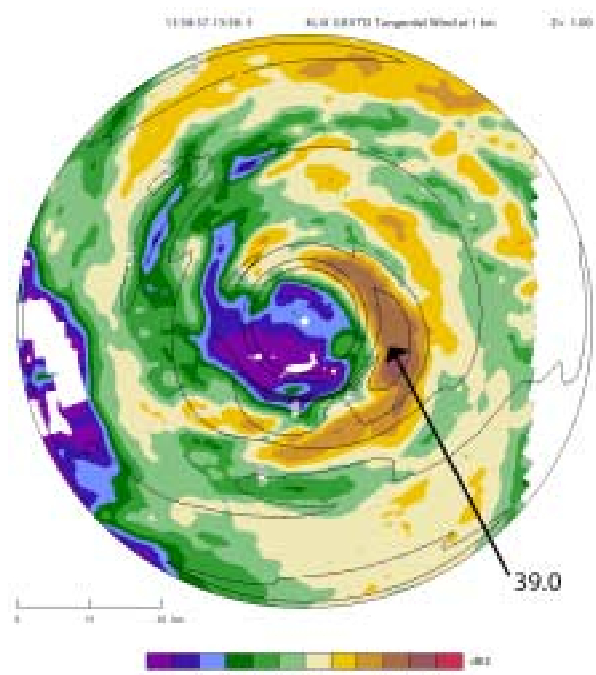
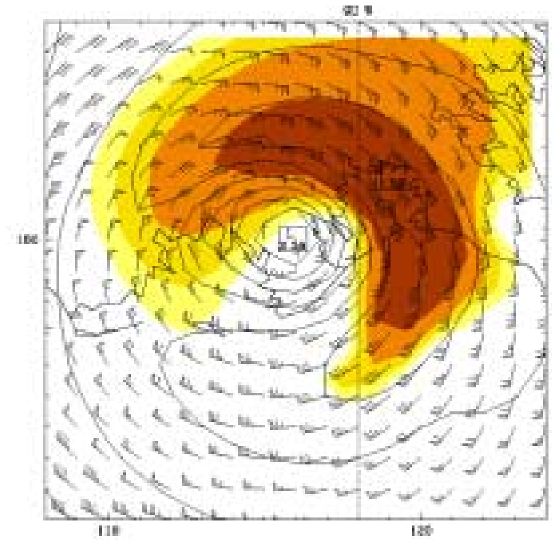
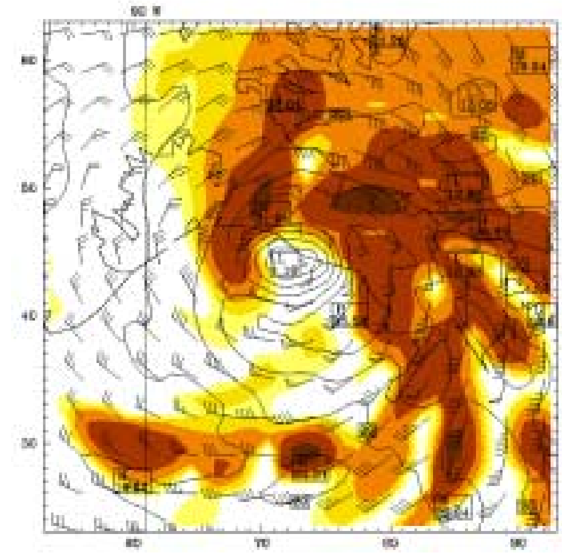


Fig. 4. Radar reflectivity and the GBVTD tangential wind obtained from the KLIX radar at 1358 UTC 18 July 1997.

(a)



(b)



(c)

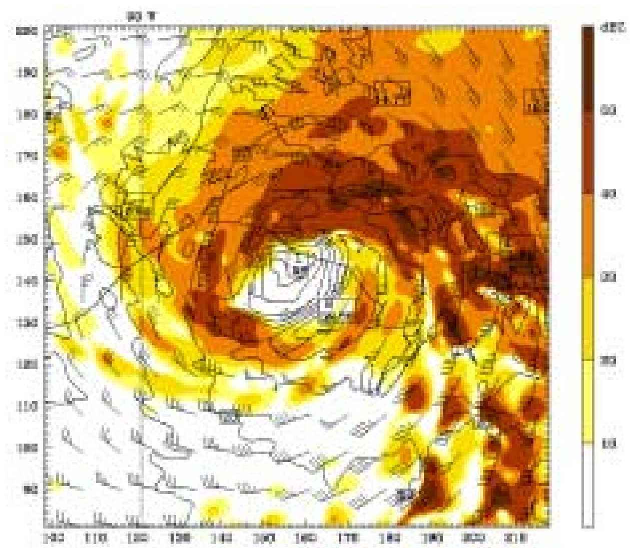


Fig. 5. *The simulated radar reflectivity and wind speed from (a) 9 km, (b) 3 km , and (c) 1 km MM5. A full barb represents 5 m/s, a half barb 2.5 m/s, and a flag for 25 m/s*

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