TRACK AND INTENSITY PREDICTION OF TROPICAL CYCLONE DIANA (1984): SENSITIVITY TO MM5 PHYSICAL PARAMETERIZATIONS

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1. BACKGROUND

As discussed by Bosart and Bartlo (1991, hereafter BB), tropical cyclone Diana (1984) formed to the east of Florida, and slightly poleward of a decaying stationary front that had moved unusually far south for early September. Poleward of this front, strong easterly flow drove large latent heat fluxes approaching 1000 W m^{-2}. The incipient cyclone was diagnosed by BB to grow in response to mesoscale ascent and vortex stretching caused by a cold-core upper tropospheric trough centered over Florida at 1200 UTC 7 September 1984. While many tropical cyclones developing in the northern Caribbean are influenced by extratropical, upper-tropospheric trough-ridge systems (Bracken and Bosart 2000), Diana was notable for the amplitude of the baroclinic precursor.

The present paper utilizes numerical simulations with the Fifth-Generation PSU/NCAR mesoscale model (MM5)(Grell et al. 1994) in order to quantify genesis of Diana better than could be done with observations alone. The unique aspect of our study is that no bogussing of an initial mesoscale vortex is performed. Our simulation captures the entire evolution of the storm from weak baroclinic cyclone to a tropical storm (Davis and Bosart 2001). This study primarily examines sensitivities to model physics and horizontal grid spacing. In particular, we use minimum grid spacings of 9 km, 3 km and a separate large-domain simulation with a grid spacing of 1.2 km. In Fig. 1 are shown the domains of the model integrations.

2. SIMULATIONS

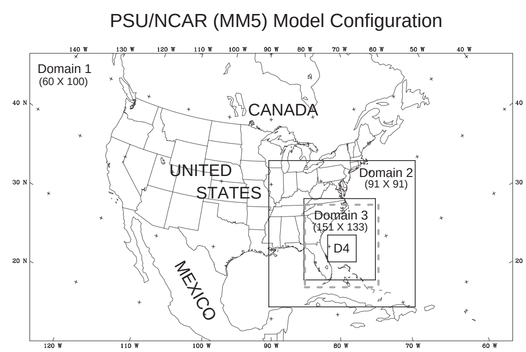

Figure 1. Domain configuration, including stationary location of Domain 4 (3 km grid spacing, 151 $\times$ 151 points). The dashed gray box defines the domain of the single domain simulation with 1.2-km grid spacing.

The control simulation (CTRL) is initialized at 1200 UTC 7 September and is integrated for 60 h. We use the NCEP/NCAR reanalysis as a first guess and enhance this with surface and upper air observations. The Kain-Fritsch cumulus scheme (Kain and Fritsch 1993), MRF PBL scheme (Hong and Pan, 1996) and NWP Explicit Microphysics (Schultz 1995) schemes are adopted in CTRL.

Many permutations to the model configuration in CTRL are considered, including variations in cumulus, boundary-layer and microphysics as well as model grid spacing. The primary variant discussed herein is the Betts-Miller-Janjic (Betts and Miller, 1993). In addition, several permutations of horizontal grid spacing are considered. All simulations contain 37 terrain following layers, stretched vertically from about 40 m spacing in the PBL to about 1 km spacing above the tropopause. Horizontal grid spacings of 27 km, 9 km and 3 km are considered separately by nesting within a larger domain of 81 km grid spacing (Fig. 1). On the domain with

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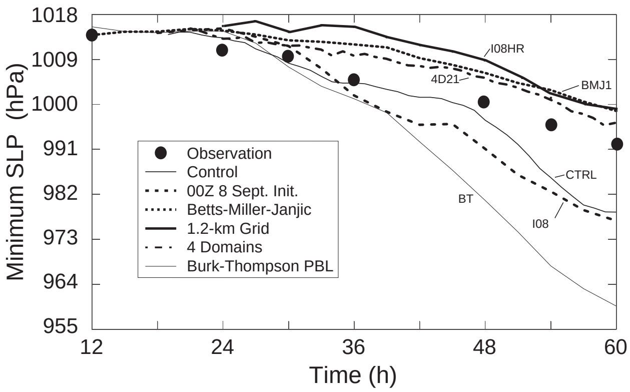

Figure 2. Minimum sea-level pressure time series for simulation CTRL and 7 sensitivity simulations. Observations are indicated with filled circles.

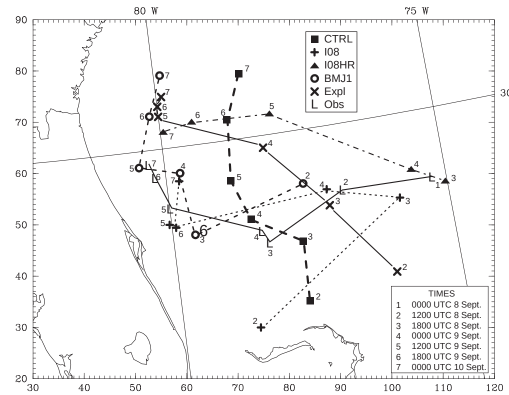

Figure 3. Tracks of cyclone center for simulations CTRL, BMJ1, GRELL, EXPL, and I08 along with the observed storm track (L's connected by a solid line).

3-km grid spacing, we forego a cumulus scheme. Two additional simulations are integrated beginning at 0000 UTC 8 September, denoted I08 and I08HR. The first tests the effect of initializing 12 h later, when initial conditions are better defined. Simulation I08HR is a large-domain simulation with uniform 1.2 km grid spacing designed to test the effect of explicitly resolving convection. Simulation I08 uses the same physics as CTRL. Simulation I08HR uses the Reisner et al. (1998) level 2 scheme instead of the NEM scheme.

3. SENSITIVITY TO PHYSICAL PARAMETERIZATIONS

As indicated by Fig. 2, there is considerable simulation sensitivity to the variation of physical processes in the model. We note that the most intense storm was produced using the Burk-Thompson PBL scheme (Burk and Thompson 1989). Using the Betts-Miller-Janjic cumulus scheme, simulation BMJ1 improves the intensity prediction (Fig. 2) and the track prediction relative to simulation CTRL (Fig. 3). Most sensitivity simulations shown produce a more westward track than CTRL. The more westward track occurs because either the upper-level cutoff low is better defined with a later initialization (as in I08), or because of the precipitation physics.

In the case of varying implicit precipitation schemes, simulations GRELL (using the Grell cumulus scheme), BMJ1 and EXPL (no cumulus scheme on the 9-km grid) all produce a relatively smaller fraction of sub-grid-scale precipitation than CTRL. In EXPL, this occurs by definition, but BMJ1 and GRELL produce grid-scale convection at many locations outside the core of the storm. In CTRL, most of the grid-scale condensation occurs near the radius of maximum wind and coincides with intensification periods. The grid-scale overturning in BMJ1 produces unrealistic rainfall rates (exceeding 100 mm h^{-1} on a 9-km grid) and numerous localized lower-tropospheric PV and relative vorticity anomalies 100-300 km from the storm center. As shown in Fig. 4, the effect of the localized vorticity anomalies on increasing the mean angular momentum of the vortex $(\int dt(\overline{ru'\zeta'}))$ is reduced in BMJ1 and confined mainly to $r > 150km$. Here, u is the radial wind and ζ is the relative vorticity, with overbars and primes denoting the azimuthal mean and deviations from it. The introduction of cyclonic vorticity anomalies at large radii is known to limit storm intensification (Montgomery and Enagonio, 1998).

The greater rainfall rates in BMJ1 are associated with a greater overall vertical mass flux and a related enhancement of the poleward outflow at the tropopause. The enhanced upward and poleward flow at this level in BMJ1 relative to CTRL deforms the tropopause, enhancing mesoscale ridging poleward of the storm. The effect of this process on the track of the storm can be quantified using PV attribution to calculate the difference in deep-layer steering flow that arises from

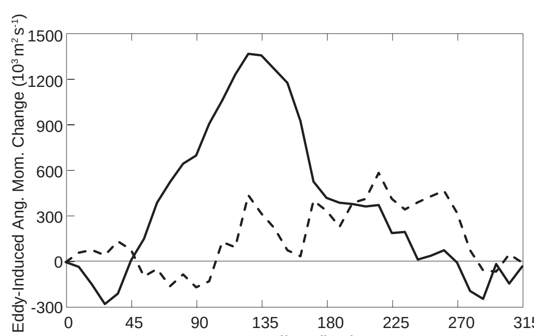

Figure 4. Radial profiles eddy-induced angular momemtum changes from CTRL (heavy solid) and BMJ1 (dashed). All quantities represent averages from 21 h to 36 h and from roughly 0 to 2 km MSL. All quantities represent averages between simulation hours 21 and 36 and over the lowest 2 km of the model domain.

the difference in upper-level PV (400 hPa and above) between CTRL and BMJ1. As shown in Fig. 5, the difference is enhanced easterly flow throughout the layer from 950 hPa to 400 hPa due to PV differences above 400 hPa. The difference in steering flow quantitatively corresponds to the difference in track, implying that the greater overall upward mass flux and more westward track are causally related.

4. RESOLUTION DEPENDENCE

We find generally better results when using higher resolution domains on which the issue of cumulus parameterization can be circumvented. We initialize domain 4 (3-km grid spacing) at 21 h or 0900 UTC 8 September (Simulation 4D21), prior to much of the development. The delay relative to the beginning of the simulation allows the mesoscale structure, especially mesoscale ascent within the weak frontal zone, to develop and thus condition the troposphere so that grid-resolved condensation can occur.

With a 3 km grid-spacing, many structures within the core of the storm can now be resolved. In Fig. 6 are compared the sea-level pressure and near-surface rain water mixing ratio fields. The obvious point, consistent with Fig. 2, is that the addition of a fourth domain produces a weaker storm than CTRL. The 4-domain simulation (Fig. 6b) also reveals numerous cyclonic circulation anomalies forming near and within the RMW. It turns out that the finer scale structures, especially in the vertical motion field, are related to the difference in intensity between CTRL and 4D21. Specifically, finer grid spacing allows better resolution of downdrafts and realistically incorporates non-hydrostatic effects, which limits the intensity of updrafts. The overall effect is to reduce the mean upward motion and vortex stretching in 4D21 and thus reduce the intensification rate.

Moving to still finer grid-spacing, simulation I08HR, beginning at 0000 UTC 8 September, runs on a

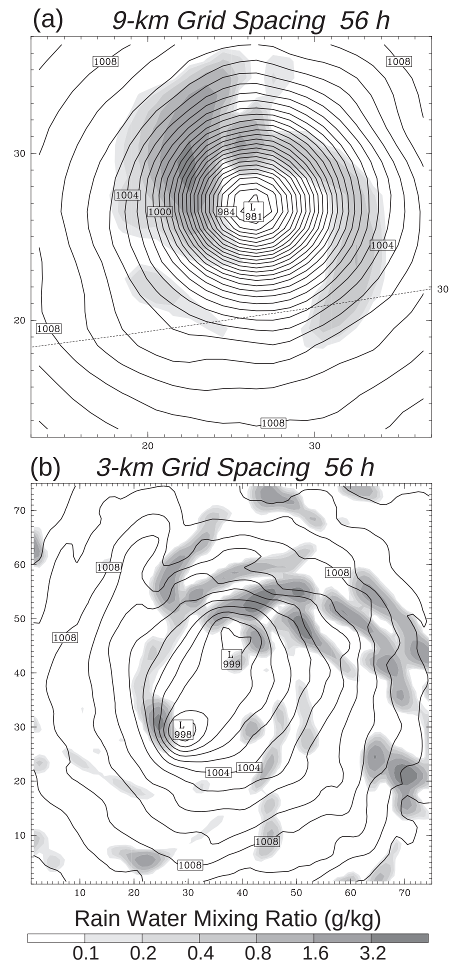

Figure 6. Comparison of sea-level pressure and rain water mixing ratio at lowest model level at 56 h (2000 UTC 9 September) for (a) CTRL and (b) 4D21.

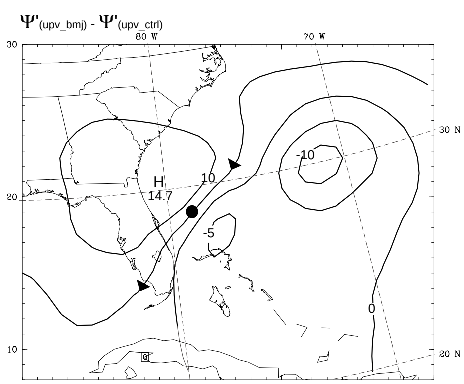

Figure 5. Deep-layer streamfunction difference field derived from inversion of PV differences between BMJ1 and CTRL at 1500 UTC 8 September (27 h). A variation of 5 m^2s^{-1} over 5° of latitude corresponds to a velocity of about 1 m s^{-1}. Black dot indicates location of storm center in CTRL at 27 h.

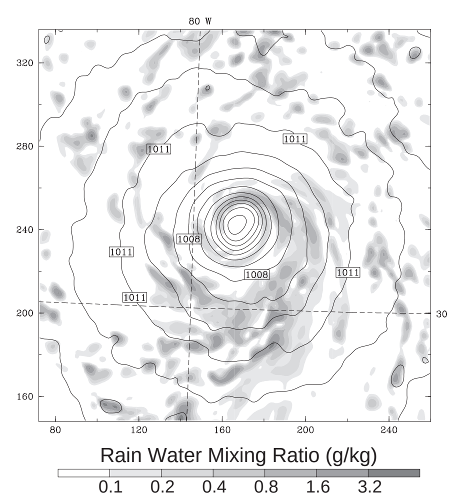

Figure 7. As in Fig. 5, but for simulation I08HR at 48 h (0000 UTC 10 September).

single domain of dimensions 1060 (E-W) x 1000 (N-S). It uses initial and hourly boundary conditions derived from output from the 27-km grid of I08. In Fig. 7, we show the sea-level pressure and near-surface rain water mixing ratio at 2000 UTC 9 September (as in Fig. 6). The storm in I08HR is developing an eye-wall-like feature in the precipitation field at a radius of only 20-25 km, compared with a scale of more nearly 50 km in all other simulations. The minimum central pressure is a few hPa higher than in 4D21 and about 20 hPa higher than in CTRL. However, the minimum pressure in I08HR is about the same as in a simulation integrated with a nest of 3-km grid spacing inserted at 12-h into simulation I08 (not shown).

5. CONCLUSIONS

We have conducted several sensitivity simulations of tropical cyclone Diana, enphasizing the transformation from weak baroclinic cyclone to tropical storm. Our general conclusions are:

(1) A storm of at least tropical storm strength was produced in all simulations.

(2) Intensity differences grew to be large by the end of the simulation. Most of these differences resulted from differences in the inner core dynamics. These are strongly affected by horizontal grid spacing, and the choice of cumulus and PBL parameterizations. Schemes in which a greater fraction of the precipitation was produced by the grid-scale scheme resulted in a storm of weaker intensity. The addition of finer grid-spacing generally improved the intensity prediction.

(3) Storm track was strongly affected by the choice of cumulus parameterization. In general, simulations with relatively more grid-scale precipitation produced stronger upward and poleward outflows at high levels. The outflow modified the tropopause structure, enhancing an anticyclone poleward of the storm and (perhaps counter-intuitively) allowed a more intense cold-core low to detach from the main westerlies. Initialization at a later time allowed the cutting-off process aloft to be better resolved and thus resulted in a more westward track as well.

The results of varying grid-spacing imply that tropical cyclogenesis can be simulated from synoptic-scale precursors with a model run at cloud-resolving scale. This is believed to be the first such instance where a fine grid (1.2-km spacing) is integrated over a domain that is large enough to capture motions ranging from cloud-scale to synoptic-scale. The variations in inner core structure differ markedly with grid spacing. The dynamics governing these differences, and the link with the treatment of precipitation, is the subject of ongoing study.

6. ACKNOWLEDGEMENT

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