15.5 NUMERICAL INVESTIGATION OF THE ROLE OF MID-LEVEL DRYNESS ON TROPICAL MINI-SUPERCELL BEHAVIOR

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1. INTRODUCTION

Tropical cyclones that approach land are known to bring with them many hazards, including high winds, torrential rainfall and destructive storm surge. Further, some systems are also accompanied by a tornadic threat from tropical cyclone mini-supercells. Tropical cyclone variants of the supercell are spatially smaller in extent than those commonly found on the Great Plains, yet are still capable of generating significant tornadoes (McCaul 1991).

Favorable vertical shear of the horizontal winds and buoyancy capable of supporting severe thunderstorms is often found in the right-front quadrant of the hurricane (e.g., Bogner 2000; McCaul 1991; Novlan and Gray 1974; Hill 1966). Despite this common feature, not all hurricane landfalls result in significant tornado outbreaks. Within the broad favorable region, numerous rainbands may be present and the threat associated with any particular rainband within this quadrant is uncertain.

A challenge for forecasters is the anticipation and identification of rainbands posing a public risk. These forecasters could better warn the public of potential hazards associated with rainband convection given a better understanding of the behavior and characteristics of outer rainband convective elements and the environment in which they occur.

Cloud-scale simulations of tropical cyclone mini-supercells by McCaul and Weisman (1996, 2001) significantly furthered the understanding of the behavior of these storms, yet left several issues to address. In this study, the impact of mid-tropospheric dry air on tropical cyclone mini-supercell convection is examined in closer detail.

The case examined for this study is Hurricane Opal (1995), which generated twenty-two tornadoes reported during the landfall. Mean tornado reports for a Gulf Coast landfall are only 5.7 (McCaul 1991), making the Opal case unique. Radar investigations revealed many of Opal's tornado events were associated with mini-supercell type convection embedded within outer hurricane rainbands.

A high resolution simulation of Hurricane Opal (1995) was conducted by Romine and Wilhelmson using the MM5 (Romine and Wilhelmson 2002). The simulation by Romine and Wilhelmson (2002) well captured the observed evolution of Opal, including the track, intensity and precipitation distribution. Within the simulation, a favorable convective environment existed in the right front quadrant of the hurricane supportive of tornadic supercell-type convection using the mesoscale model output criterion of Strensrud, Cortinas and Brooks (1997).

The innermost nested grid spacing of 1.1 km modestly resolved the convective elements within the simulated Opal outer rainbands. These convective elements displayed persistent, rotating updrafts, which is consistent with tropical cyclone mini-supercells observed during the actual event. Upon closer examination, it was evident that the simulation also replicated several dry air entrainment episodes along the eastern flank of the hurricane.

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Mid-tropospheric dry intrusions roughly coincided with the position and orientation of simulated outer hurricane rainbands, and hence may play a role in the convective evolution within these bands. Satellite observations also were indicative of a band of dry air entraining along the eastern flank of the hurricane several hours prior to landfall.

Storms forming within a moist environment have cold pools that are typically less intense than those that form in the presence of mid-tropospheric dry air. Entrainment of dry air into convective cells leads to evaporational cooling, which hastens the formation and strength of negatively buoyant air feeding the low-level cold pool. This in turn could lead to increased baroclinic generation of low-level vorticity that could subsequently influence tornado formation.

Gilmore and Wicker (1998) examined the significant influence which mid-tropospheric dryness plays in supercell evolution. Notably, they found a direct relationship between midtropospheric dryness and cold pool intensity. Idealized simulations of supercell structure performed by McCaul and Weisman (1996, 2001) used a thermodynamic environment with fixed high relative humidity (90%) above the LCL. McCaul and Weisman (2001) recognized the need for a deeper examination of the potential role of midtropospheric dry air, noting that the magnitude of low-level vorticity was related to the cold pool intensity in their mini-supercell simulations.

2. METHODOLOGY

The grid spacing for the MM5 simulation could not practically be reduced any further without violating model assumptions. As a result, the convective elements within the outer hurricane rainbands, which were spatially small, were not fully resolved. Therefore, to allow for a more detailed analysis of the mini-supercell convection, cloud model simulations are employed to further determine the convective structure. Soundings were extracted from the MM5 simulation, and used for inputs to the cloud model simulations. The soundings selected were in close temporal and spatial proximity to areas where convection within an outer hurricane rainband developed in the MM5 simulation. Recalling the questionable role that dry air intrusions may play, the soundings were extracted along the edge of a midtropospheric dryness band. To test the moist hypothesis, the same sounding was also modified by moistening the profile throughout the cloud bearing layer. Both soundings were then tested in the experimental WRF model at higher horizontal resolution.

WRF model idealized simulations are carried out at 1 km and 500 m horizontal resolutions on a 91x91x60 xyz grid with a 17.5 km model top. Convection is initiated using standard thermal bubble techniques, following the methodology utilized by McCaul and Weisman (2001). While sensitivities between Lin ice and Kessler microphysics schemes appear negligible, Lin ice is hereafter employed for greater consistency with the Reisner mixed phase scheme within the MM5 simulation. Fig. 1 illustrates the sounding input to the WRF simulation described hereafter. 50 mb mixed surface layer CAPE was near 1000 JKg^{-1}, concentrated in the lower portion of the profile.

3. RESULTS

Idealized simulations were conducted using similar horizontal resolution to the MM5 finest grid for assessment. Qualitative comparisons between the convective elements generated within the MM5 simulation and those generated within the coarse WRF simulations were in good general agreement. In particular, vertical velocities were slightly more robust within the WRF simulations, but vertical and horizontal scales, precipitation patterns and low-level vorticity magnitudes were all quite uniform in scale and magnitude. Cells remained steady beyond two hours.

With horizontal resolution improved to 500 m, considerable increases in updraft vertical velocities and surface vorticity were noted, roughly doubling in magnitude. Convective behavior also seemed quite different, with increased tendency toward splitting cells, as demonstrated by the rainwater field shown in Fig. 2. Surface vorticity fields rapidly reached large values, exceeding .02 s^{-1} in under 25 minutes from storm initiation.

In contrast to the anticipated results, initial simulations at 500 m resolution suggest the magnitude of surface vertical vorticity was only weakly moderated by increased tropospheric humidity. These differences became greater as the simulations progressed, with the dry profile surface vertical vorticity 13% larger in magnitude, as shown in Fig. 3.

Much greater sensitivity was found in the choice of diffusion and microphysical parameterizations, which in turn appear to have some impact on the degree of sensitivity to the humidity profile. The microphysical parameterization sensitivity is negligible early, but substantial after the first hour of simulation for the Lin ice and Kessler microphysics options. While this option had little impact at 1 km resolution, Lin ice showed a 60% increase in surface vorticity magnitude by the end of the second hour.

A more complete vorticity budget calculation likely is needed to determine the attribution levels from individual generation terms for the tropical mini-supercell convective environment. Sensitivity to variations in the height and depth of the dry layer also requires further investigation. Further testing is also clearly needed to quantify the role of model physics options for this case.

Precipitation distributions of the cells generated in the higher resolution (500 m) WRF simulations appeared to have exaggerated hook-echo shaped protrusions. While the observed cells, shown in Fig. 4, did have more prominent hook-echo shaped features than was captured in the 1 km WRF and 1.1 km MM5 simulations, they generally were less extreme than that shown by Fig. 2. Differences in cell orientation are likely related to differences in azimuth between observed and simulated cell locations relative to the hurricane core.

Preliminary results from these and higher resolution simulations and how they relate to the MM5 simulated outer rainband convection will be presented.

4. REFERENCES

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5. ACKNOWLEGEMENTS

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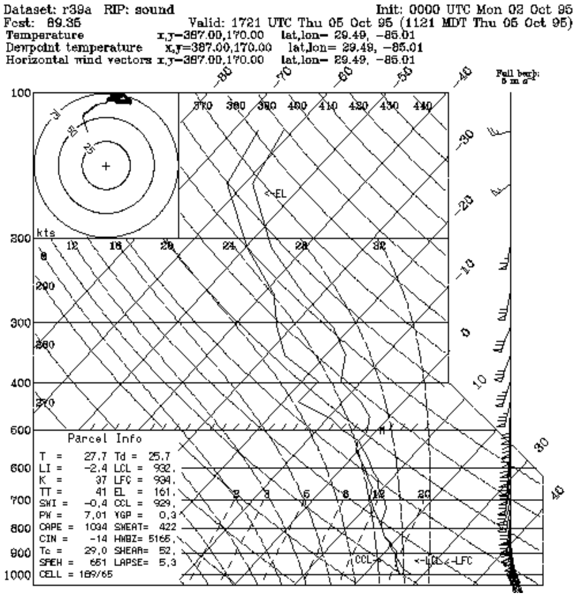

Fig.1. Extracted sounding from the MM5 simulation used to initialize the WRF model idealized simulations.

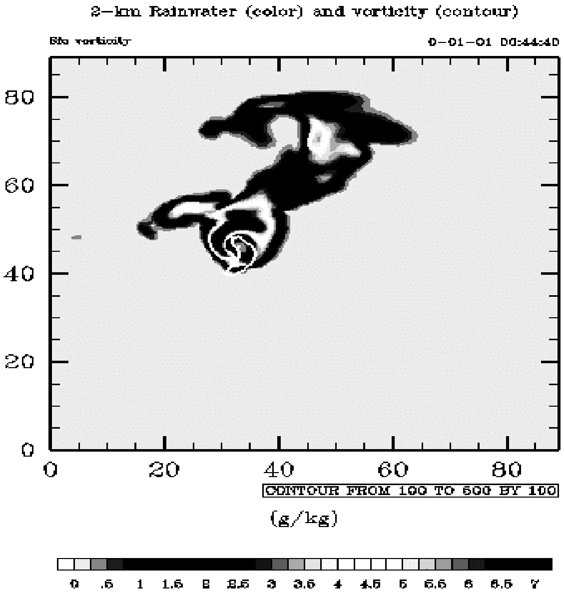

Fig. 2. Surface rainwater and .01s^{-1} vertical vorticity contour at 45 minutes from the 500 meter simulation. Primary convective cell is near the domain center.

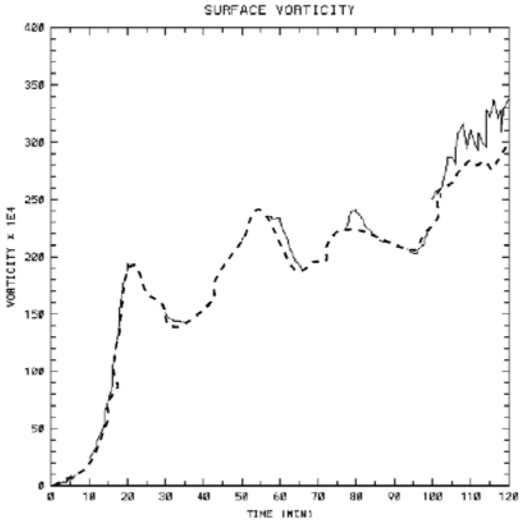

Fig. 3. Time trace of the surface vertical vorticity magnitude for the WRF 500 m resolution simulations, with the original (solid) and moistened (dashed) soundings.

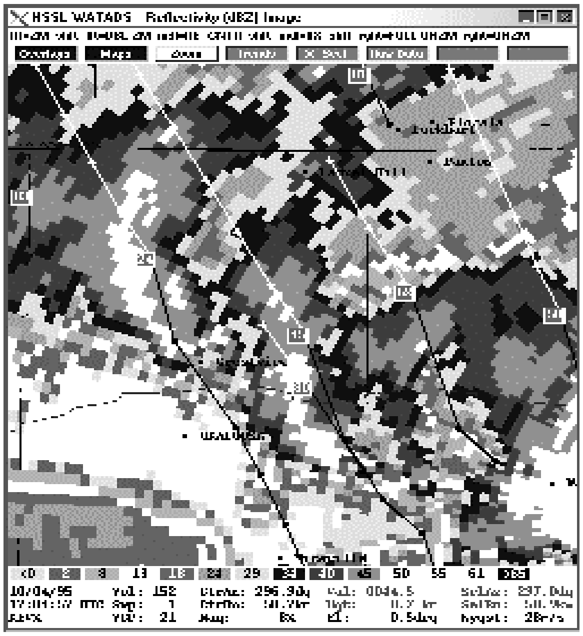

Fig. 4. Base reflectivity image of three mini-supercells within a rainband of Hurricane Opal. Precipitation footprints are roughly half-moon shaped, comparable with the shapes noted in the simulation (Fig. 2).