WRF MODEL SIMULATIONS OF A QUASI-STATIONARY, EXTREME-RAIN-PRODUCING MESOSCALE CONVECTIVE SYSTEM

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1. INTRODUCTION

Extreme rainfall is responsible for a variety of societal impacts, including flash flooding that can lead to damage, injury, and death. Despite the great need for accurate forecasts and warnings of extreme rainfall that can produce flash flooding, the prediction of warm-season heavy precipitation continues to be one of the most difficult challenges in operational forecasting (Fritsch and Carbone 2004).

Schumacher and Johnson (2005, 2006) examined radar data and other observations for 184 extreme rain events in the eastern two-thirds of the United States over a three-year period. Among the types of mesoscale convective systems (MCSs) that commonly produce extreme rainfall, they identified one that may present significant forecast challenges, which they termed the "backbuilding/quasi-stationary" type (BB, Fig. 1). BB MCSs occur when convective cells repeatedly form upstream of their predecessors and pass over a particular area, leading to large local rainfall totals. They were found to occur in environments characterized by weak synoptic forcing, with storm-generated outflow boundaries often providing the lifting for repeated cell development.

In this study, one of the BB MCSs identified by Schumacher and Johnson (2005) will be examined in further detail using the Weather Research and Forecasting (WRF) model. The purpose of this study will be twofold: to determine the utility of the WRF model for simulating prolonged heavy-rain-producing convection, and to better understand the processes that are responsible for initiating, organizing, and maintaining such convection. Both of these purposes are focused on the goal of improving forecasts of extreme-rain-producing convective systems.

2. DESCRIPTION OF THE EVENT

During the evening and overnight hours of 6–7 May 2000 a small area of quasi-stationary convection produced a remarkable amount of rain over several counties just to the southwest of the St. Louis, Missouri metropolitan area (Fig. 2). The highest rainfall total reported at a National Weather Service rain gauge was 309 mm (12.15 in) at Union, MO, with unofficial reports of 406 mm (16 in) nearby (Glass et al. 2001). Consistent with past analyses of heavy rain environments (e.g., Maddox et al. 1979), there was high relative humidity in east-central Missouri as well as a 40-kt low-level jet from the southwest. However, in contrast to other observed extreme rainfall environments, there was relatively little instability and there were no apparent surface boundaries present prior to the onset of deep convection (not shown). A mesoscale convective vortex (MCV), evident in both the 500-hPa analysis and infrared satellite data, may have played a role in initiating and maintaining the convection in this event. Convection developed around 0200 UTC and formed into a mesoscale area of deep convection that remained nearly stationary through 1200 UTC (Fig. 3). Only a very weak cold pool and outflow boundary developed as a result of the convection.

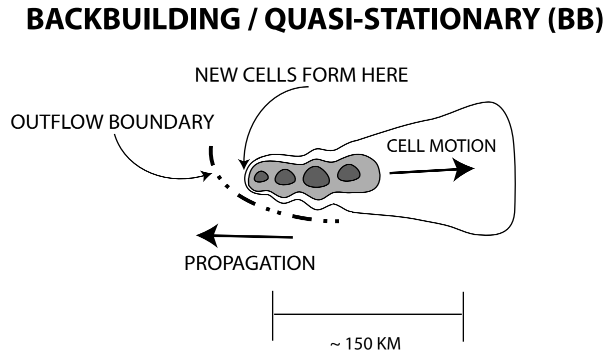

Figure 1: Schematic diagram of the radar-observed features of the BB pattern of extreme-rain-producing MCSs. Contours (and shading) represent approximate radar reflectivity values of 20, 40, and 50 dBZ. The dash–dot line represents an outflow boundary; such boundaries were observed in many of the BB MCS cases. The length scale at the bottom is approximate and can vary substantially for BB systems depending on the number of mature convective cells present at a given time. From Schumacher and Johnson (2005).

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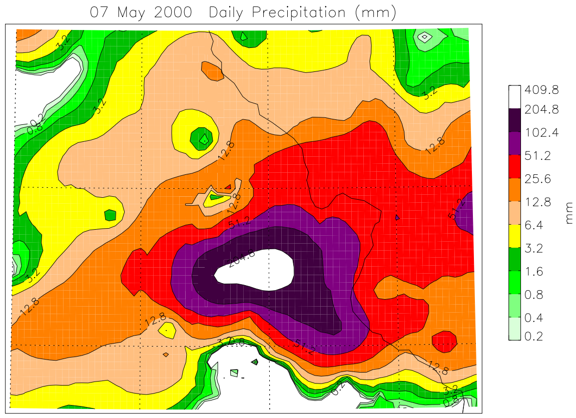

Figure 2: Objective analysis of rain gauge observations (mm) for the period 1200 UTC 6 May–1200 UTC 7 May 2000.

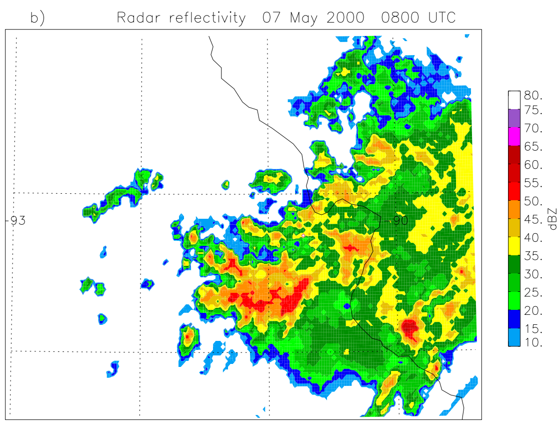

Figure 3: Observed composite radar reflectivity (dBZ) at 0800 UTC 7 May 2000.

3. MODEL CONFIGURATION

The simulations presented herein were produced using version 2.1.1 of the advanced research WRF model (details available online at wrf-model.org). Simulations were carried out for the 24-h period 0000 UTC 7 May to 0000 UTC 8 May 2000 with a nested grid as shown in Fig. 4. The horizontal grid spacing was 9 km on the outer grid, 3 km on the middle grid, and 1 km on the inner grid, with 39 levels in the vertical. Cumulus convection was parameterized using the Kain-Fritsch scheme on domain 1, while convection was explicitly resolved on domains 2 and 3. Other details of the model configuration are shown in Table 1. This model configuration is similar those that have demonstrated some success in near-real-time applications at NCAR. However, given that the model initialization time is only a few hours before the onjset of convection in this study, the results presented herein should be considered a "simulation" rather than a "forecast" that could have been utilized in real-time.

Table 1: Design of WRF ARW version 2.1.1 numerical model experiment. Multiple entries indicate different configurations for domains 1, 2, and 3. See Fig. 4 for domain locations. Technical descriptions of these parameterizations are available online at wrf-model.org.

Horizontal grid spacing	9.0 km, 3.0 km, 1.0 km
Vertical levels	39, 39, 39
Initial conditions	40-km Eta
Boundary conditions	40-km Eta
Cumulus convection	KF, explicit, explicit
Boundary layer	Yonsei University
Surface layer	Monin-Obukhov
Microphysics	Purdue Lin
Land surface	Noah
Turbulence	2D Smagorinsky
Shortwave radiation	Dudhia
Longwave radiation	Rapid radiative transfer

4. RESULTS

4.1 *Overall structure of convection and precipitation*

The model successfully produces a backbuilding/quasi-stationary MCS which replicates many of the features of the observed system (Fig. 5). The model also succeds in producing a region of extreme rainfall amounts, the location and distribution of which is also remarkably similar to the observed rainfall (Fig. 6). The model underestimates the maximum rainfall amount: the maximum simulated rainfall is 256 mm, which is somewhat less than the observed maximum of 309 mm. However, given the challenges of predicting ground-accumulated rainfall when using microphysical parameterizations (e.g., Gilmore et al. 2004) and the large amount of rain that fell in this event, this can probably be considered a successful result. Though the convective region of the MCS is well represented in the simulation, the model does not create the region of stratiform rain (with embedded convection) that extends eastward into Illinois in the observations.

4.2 *Mesoscale convective vortex and moist absolute instability*

As mentioned above, at the time of model initialization an MCV existed over central Missouri, near the region where the heavy rain would later

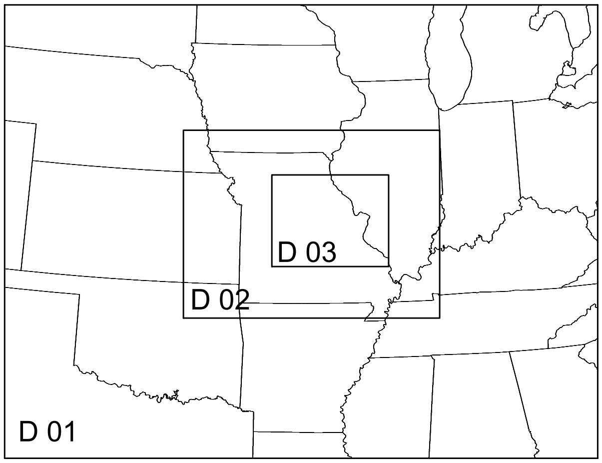

Figure 4: Location of model domains 1, 2, and 3.

fall. This vortex was captured in the initial model analysis on domain 3 (not shown). As illustrated by Raymond and Jiang (1990) and others, balanced motions that result from the presence of an MCV in vertical wind shear can lead to persistent convection directly beneath or just downshear of the vortex center. Additionally, Trier et al. (2000) show that the upward displacements that occur from this effect can destabilize the atmosphere by lifting initially moist and conditionally unstable layers to saturation. This can result in moist absolutely unstable layers (MAULs, Bryan and Fritsch 2000).

A model sounding from a point just southwest of the active convection (i.e., in the region where new cells are forming) at 0600 UTC shows the presence of a MAUL from approximately 800 hPa to 700 hPa (Fig. 7). There is relatively little convective available potential energy (CAPE) in this sounding (246 J kg^{-1}). The center of the mid-level MCV is immediately northwest of the convection at this time, and the hodograph plotted in the upper left of Fig. 7 illustrates that the low-level shear vector points toward the southeast in this region. The model results from this case support the previous findings mentioned above, with the heaviest rainfall occurring just downshear of the midlevel vortex center.

4.3 *Surface features*

In contrast to most long-lived convective systems, this MCS was very slow in producing a low-level cold pool and outflow boundary. In the model's initialization, there was a dome of relatively cool air at the surface underneath the midlevel MCV. However, convection repeatedly developed in certain areas for several hours before a mesoscale storm-

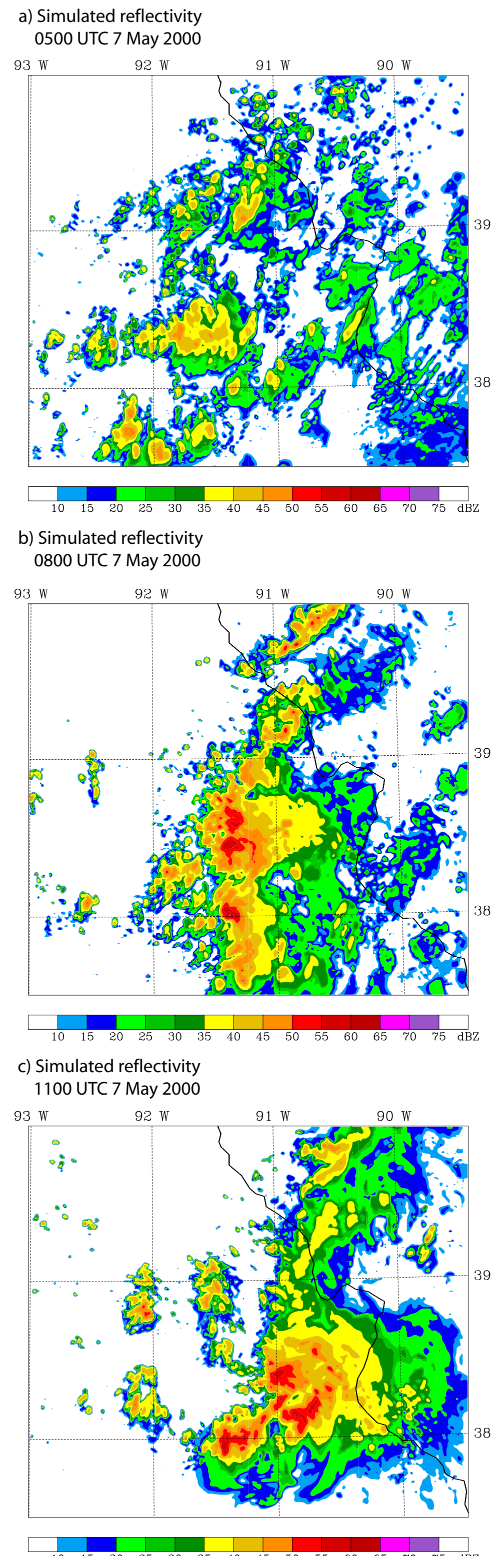

Figure 5: Simulated composite reflectivity (dBZ) on domain 3 at (a) 0500, (b) 0800, and (c) 1100 UTC 7 May 2000. The portion of the domain shown is the same as that shown in Fig. 3 for comparison.

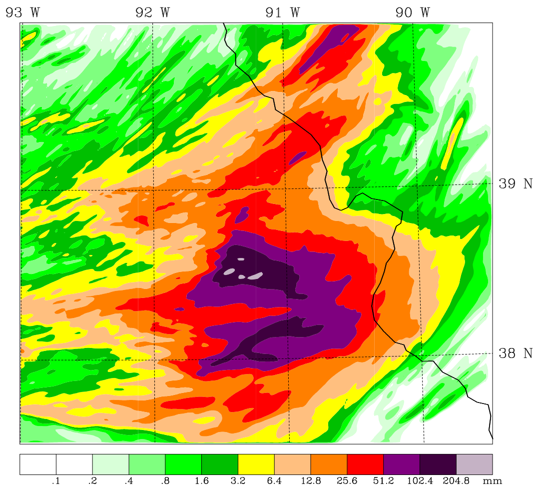

Figure 6: Model accumulated precipitation (mm) on domain 3 for the period 0000–1200 UTC 7 May 2000. Contour scale is the same as that in Fig. 2.

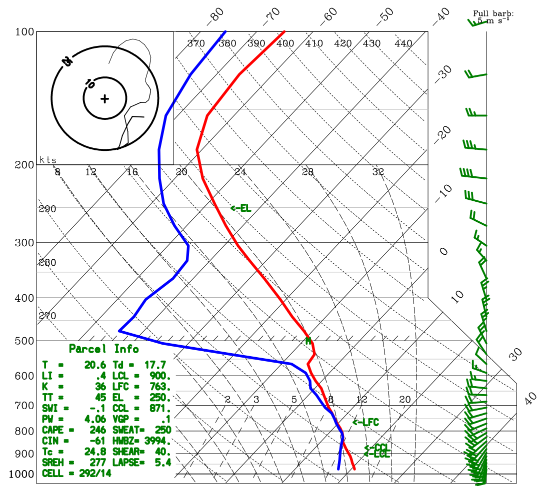

Figure 7: Model skew-T log p diagram from 0600 UTC 7 May 2000 at Kaiser, MO (KAIZ), which was just southwest of the active convection at this time.

generated outflow boundary was evident in the model output.

Instead of being forced by cold-pool lifting at the surface, it appears that much of the simulated backbuilding convection in this event originates from elevated convergence within the MAUL. Throughout much of the MCS's lifetime, regions of convergence centered at around 2 km AGL form upstream of the existing convection. As these pockets of convergence move downstream, they lead to upward motion and eventually deep convection with heavy rainfall (Fig. 8).At later times in the simulation, the convection does become surface based once a mesoscale outflow boundary forms.

5. CONCLUSIONS

Results from WRF model simulations of the extreme-rain-producing MCS on 7 May 2000 are presented herein. The primary findings are summarized as follows:

- The WRF model, with horizontal grid spacing of 1 km on the finest grid, is able to successfully replicate the backbuilding, quasi-stationary area of convection that occurred in this event.

- Despite the absence of a well-defined cold pool and outflow boundary, deep convection repeatedly develops and is maintained over east-central Missouri in the simulations. It appears that this convection originates within a moist absolutely unstable layer, which may have been created or enhanced by a mesoscale convective vortex.

Ongoing work is aimed at looking more closely at the mechanisms for initiating and maintaining backbuilding convection. In future efforts, it is hoped that long-lived quasi-stationary convection can be simulated in an idealized framework to further understand these difficult-to-predict systems that can produce extreme rainfall and have significant societal impacts.

6. ACKNOWLEDGEMENTS

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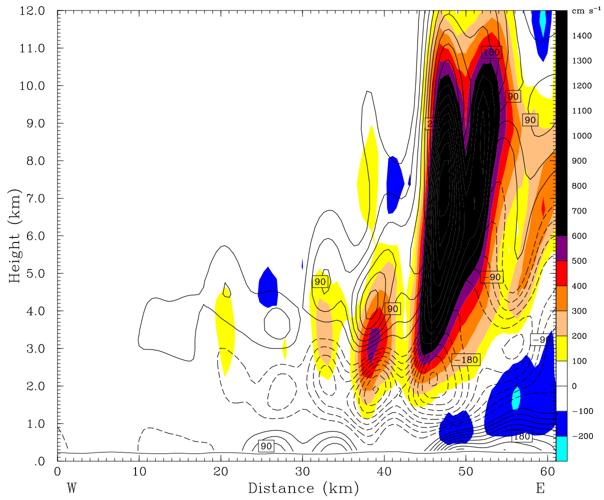

Figure 8: WSW-to-ENE cross section through active convection at 0709 UTC 7 May 2000. Fields shown are vertical motion (color contours every 1 m s^{-1}) and divergence (contours every 30 $\times 10^{-5}$ s^{-1}, negative contours dashed).

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