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EVOLUTION AND MAINTENANCE OF SIMULATED EXTREME-RAIN-PRODUCING MESOSCALE CONVECTIVE SYSTEMS

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1. INTRODUCTION

When mesoscale convective systems (MCSs) are organized such that new convection develops upstream of the existing convection and the system as a whole becomes nearly stationary, the potential often exists for large accumulations of rainfall and flash flooding. Schumacher and Johnson (2005a, 2006) examined MCSs of this type, which they termed "backbuilding/quasi-stationary" (BB, Fig. 1) in a radar-based study of extreme rain events in the United States.

In some BB MCS events, storm-generated outflow boundaries interacting with low-level wind shear provided the lifting for repeated cell development. However, in other cases it was difficult to identify any boundaries or other prominent mesoscale features, yet the convection was still able to persist and the systems remained quasi-stationary. The processes supporting the development and maintenance of one of these events will be explored in this study using the Advanced Research version of the Weather Research and Forecasting model (ARW; see www.wrf-model.org for details). In particular, we will address some of the issues involved with predicting this type of MCS and will discuss how a long-lived, high-impact mesoscale convective system of this type can be maintained in the absence of a strong surface cold pool.

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 very high relative humidity in east-central Missouri as well as a 40-kt low-level jet from the southwest that advected in moist air throughout the event. However, in contrast to other observed extreme rainfall environments, there were no apparent surface boundaries present prior to the onset of deep convection (not shown). A mesoscale convective vortex (MCV), which was generated two days prior and reintensified as a result of deep convection the previous day in Oklahoma, was in part responsible for initiating the convection around 0300 UTC. The convection became more organized with time and formed into an MCS that remained nearly stationary through 1200 UTC (Fig. 3). This overnight convection also reinvigorated the MCV, which then continued on its path toward the east through the next day.

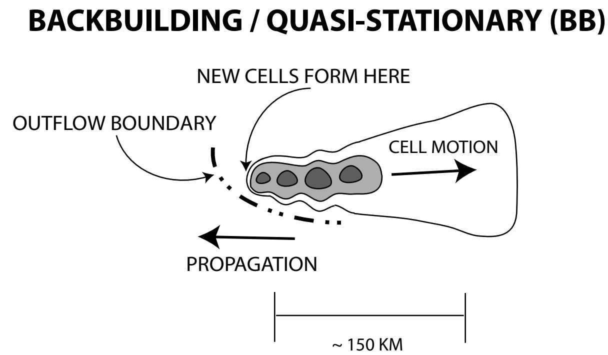

Figure 1: Schematic diagram of the radar-observed features of the BB pattern of extreme-rain-producing MCSs. Contours (and shading) represent approximate radar reflectivity values of 20, 40, and 50 dBZ. The dash–dot line represents an outflow boundary; such boundaries were observed in many of the BB 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 (2005a).

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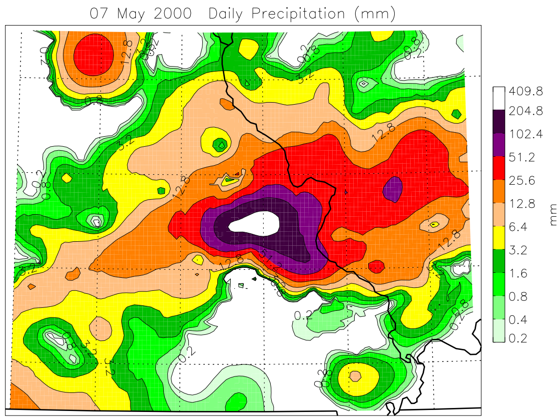

Figure 2: Objective analysis of rain gauge observations (mm) for the period 1200 UTC 6 May–1200 UTC 7 May 2000. The Missouri–Illinois border is shown with a bold line.

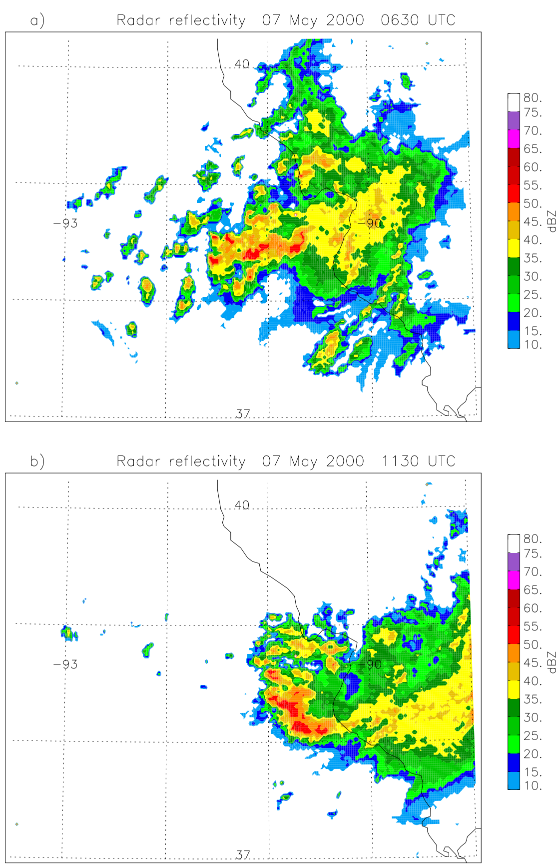

Figure 3: Observed composite radar reflectivity (dBZ) at (a) 0630 UTC and (b) 1100 UTC 7 May 2000.

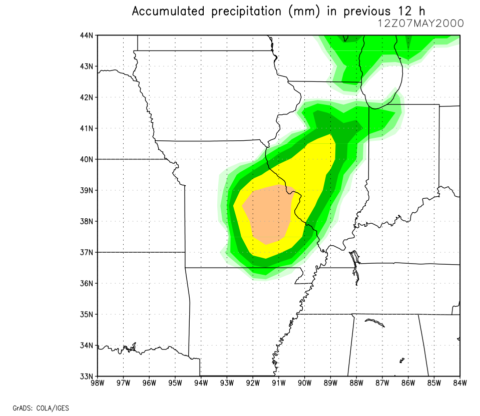

Figure 4: 12-h precipitation accumulation (mm) from the operational Eta model initialized at 0000 UTC 7 May 2000, for the period ending at 1200 UTC 7 May 2000. Color scale is the same as that used in Fig. 2

3. OPERATIONAL MODEL FORECASTS

As a point of reference, the rainfall forecast from the operational Eta model for the 12-h period encompassing the heavy rainfall is shown in Fig. 4. At this time in 2000, the Eta model had horizontal grid spacing of 22 km; however, the data shown here have been interpolated to 40-km grid. In the Eta forecast from 1200 UTC 6 May (not shown), a broad region of precipitation was predicted from Missouri northeastward into the Great Lakes. The forecast from 12 h later (i.e., shortly before the convection would begin) localized the region of heaviest rainfall over Missouri and Illinois, which was similar to the location of observed rainfall. However, in both instances, the maximum quantitative precipitation forecast amounts for the 12-h period were less than 12.8 mm (0.5 in). The operational model, with parameterized convection and relatively coarse resolution for a small-scale event such as this, severely underpredicted the observed precipitation in this event, though it did approximately identify the correct rainfall location.

4. MODEL CONFIGURATION

As mentioned above, the ARW model (version 2.2) was used to simulate this event. A series of simulations were carried out for the 24-h period 0000 UTC 7 May to 0000 UTC 8 May 2000. First, a few results will be shown for a run using 9-km horizontal grid spacing and parameterized cumulus convection. The rest of the simulations used a nested grid (shown in Fig. 5), with horizontal grid spacing of 9 km on the outer grid, 3 km on the inner grid, and

Table 1: Design of WRF ARW version 2.2 numerical model experiments. Multiple entries indicate different configurations for domains 1 and 2. See Fig. 5 for domain locations. Technical descriptions of these parameterizations are available online at wrf-model.org.

Horizontal grid spacing	9.0 km, 3.0 km
Vertical levels	48, 48
Initial conditions	40-km Eta
Boundary conditions	40-km Eta
Cumulus convection	KF, 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

48 vertical levels. (Additional simulations have been carried out with a third grid at 1 km horizontal grid spacing to examine the storm-scale characteristics of the convection. The general results from the 1-km runs were similar to those at 3 km, and since this manuscript will focus on the mesoscale aspects of the storm the 3-km results will be used.) The primary run will be referred to as "CTRL,", and two sensitivity experiments will also be presented: "NOLATENT", where phase changes are allowed but no latent heat is released; and "NOEVAP", where evaporation of rain and cloud drops is not allowed in the model. Other details of the model configuration are shown in Table 1.

5. RESULTS

5.1 *Coarse-resolution simulation with parameterized convection*

In the run with 9-km horizontal grid spacing and using the Kain-Fritsch convective parameterization scheme, the model produces a broad region of moderate to heavy precipitation that is similar to the operational model forecasts (Fig. 6, cf. Fig. 4). The rainfall totals are somewhat higher than in the operational forecasts, but still well below the observed totals. Despite the underestimation of the rainfall amount, the parameterized convection in this run was apparently sufficient to re-intensify the MCV over eastern Missouri (not shown).

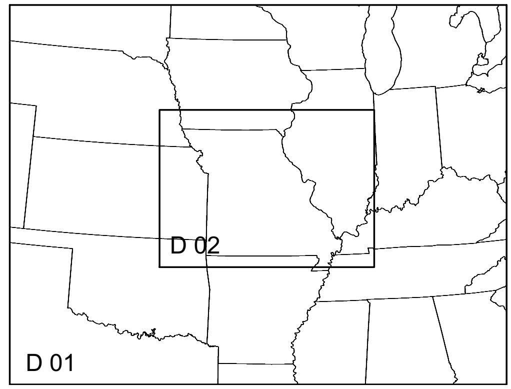

Figure 5: Location of model domains 1 and 2.

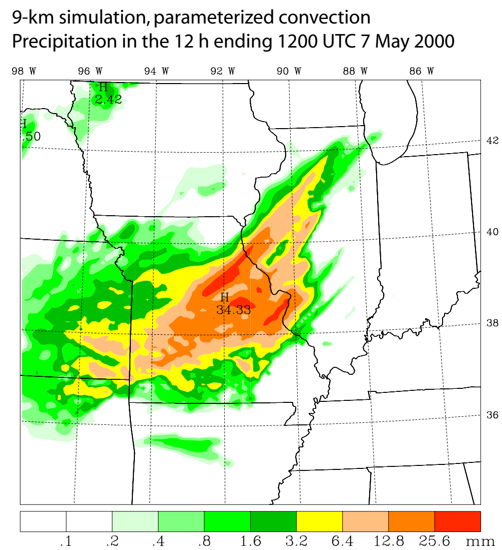

Figure 6: Model accumulated precipitation (mm) for the 12-h period ending at 1200 UTC 7 May 2000 from the run with 9-km grid spacing and Kain-Fritsch convection. Color scale is the same as that used in Fig. 2

5.2 *Overall structure of convection and precipitation in run with nested grid*

In the simulation using nested grids and explicit convection on the inner grid, the model successfully produces a backbuilding/quasi-stationary MCS which replicates many of the features of the observed system. The model also succeeds in producing a region of extreme rainfall amounts, the location and distribution of which is also remarkably similar to the observed rainfall (Fig. 7). Though the convective region of the MCS is well represented in the simulation, the model does not create the large region of stratiform rain (with embedded convection) that extends eastward into Illinois in the observations. Additional details of the convective structure

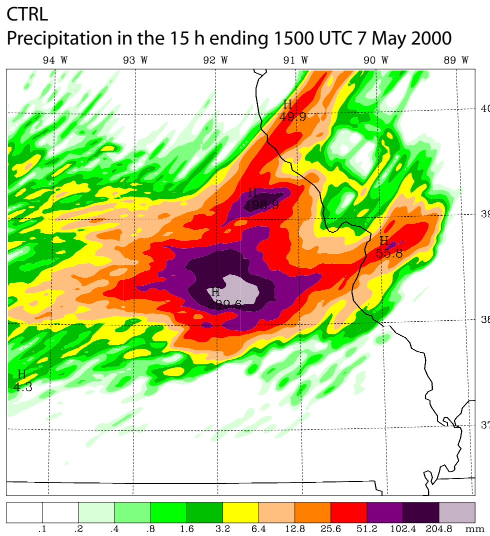

Figure 7: Model accumulated precipitation (mm) on domain 2 for the period 0000–1500 UTC 7 May 2000. Color scale is the same as that in Fig. 2.

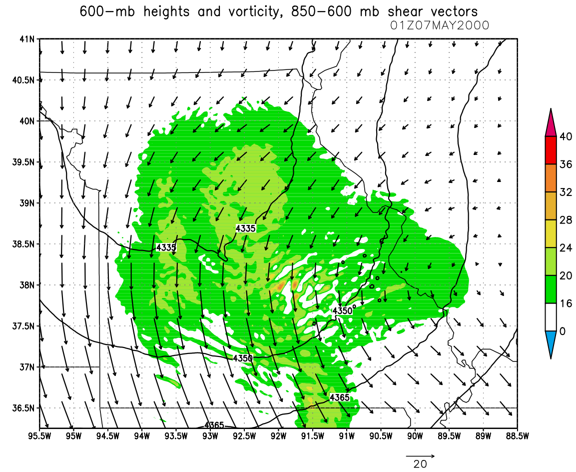

Figure 8: 600-hPa geopotential height (contoured every 15 m) and absolute vorticity (color contours every 4×10^{-5} s^{-1} for values greater than 16×10^{-5} s^{-1}), and 850–600 hPa shear vectors (20 m s^{-1} reference vector shown at bottom) on domain 2 at 0100 UTC 7 May 2000.

for a very similar simulation were reported in a previous extended abstract (Schumacher and Johnson 2005b).

5.3 *The mesoscale convective vortex*

In the early hours of the simulation, an MCV was located over central Missouri near the region where the heavy rain would later fall (Fig. 8). Past studies (e.g., Raymond and Jiang 1990, Trier and Davis 2002) have shown that layers of air are lifted on the downshear side of an MCV, and that this upward motion is supportive of persistent convective development. Owing to the presence of a strong southwesterly low-level jet and weak winds at upper levels, there was southerly shear near the surface (below the LLJ) which reversed to approximately northerly above the LLJ (Fig. 8). Lifting in the layer above the LLJ was important in this case; vertical motions in the region to the south and southwest of the MCV were on the order of a few cm s^{-1} (not shown). These vertical velocities are relatively weak, but over several hours air can be displaced upward by hundreds of meters.

An additional effect of the lifting on the downshear side of the MCV is that layers of air can be lifted to saturation, leading to moist absolutely unstable layers (MAULs, Bryan and Fritsch 2000). In a moist environment such as that in place on 7 May, very little lifting is required for saturation to occur; in fact, the observed Springfield, MO (KSGF) sounding from 0000 UTC 7 May exhibited a MAUL (Fig. 9). It was within this layer of moist instability (or near-neutrality) that scattered convection developed, both in the radar observations and the simulation. This convection eventually organized into the heavy-rain-producing MCS. Even after the MCS matured, scattered convective cells continued to form upstream and eventually merge with the larger system (some these cells can be seen in Fig. 3a). The duration of these scattered convective cells was unusual: one usually thinks of the life cycle of a single cell to be 30-60 minutes, but many of these persisted for over 2 hours and traveled 50–75 km before merging with the larger MCS. The nature of these cells is under ongoing investigation, but it appears that air is being lifted to moist absolute instability by the MCV in shear (as mentioned above), at which time any small perturbation can initiate a convective cell. However, the buoyancy (i.e., CAPE) in this area is relatively limited, so parcels do not accelerate rapidly upward; instead, they continue to be lifted and fed with saturated air so that evaporation does not take place and the updrafts can survive for extended periods of time. Eventually, they become more intense and merge with the convective system, a process which will be addressed in the next section.

The diabatic heating associated with the convection also serves to reintensify the MCV, a process which has been explored by many past studies (e.g., Fritsch et al. 1994). The "NOLATENT" sensitivity simulation demonstrates the role of the MCS

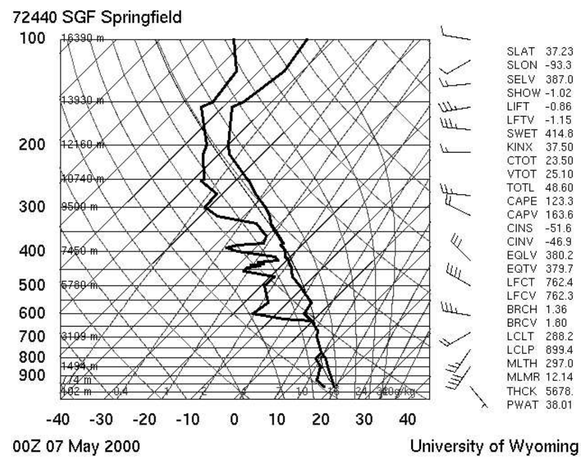

Figure 9: Skew–T log p diagram of the observed sounding from Springfield, MO (SGF) at 0000 UTC 7 May 2000.

in generating vorticity: when there is no diabatic heating, by 1200 UTC (12 h into the simulation) the MCV has moved eastward in time and gradually weakened (Fig. 10a). In CTRL, the convection has generated a strong vortex which is centered to the west of that in the NOLATENT run (Fig. 10b). The new MCV extends through a deep layer that reaches down near the surface, which creates a positive feedback process that helps to maintain the quasi-stationary MCS; this will be the subject of the next section. Note that the redeveloped MCV has been generated in the model despite the fact that the simulated stratiform rain region was much smaller than observed. The details of the MCV intensification are being investigated, but the process has many similarities to studies that have considered vortex intensification within convective regions of midlatitude and tropical MCSs (e.g., Rogers and Fritsch 2001, Tory et al. 2006).

5.4 *Maintenance of MCS*

In most midlatitude cases, MCSs that persist for a long period of time are maintained at least in part by either a preexisting boundary or a convectively-generated cold pool near the surface (e.g., Rotunno et al. 1988, Houze 2004). Even for MCV-associated heavy rain events, a surface cold pool is usually found to play some role (Fritsch et al. 1994, Davis and Trier 2002). In contrast, surface observations prior to the onset of the the 6–7 May 2000 MCS did not show any apparent surface boundaries, and both observations and simulations indicate that the nearly saturated environment did not allow for the

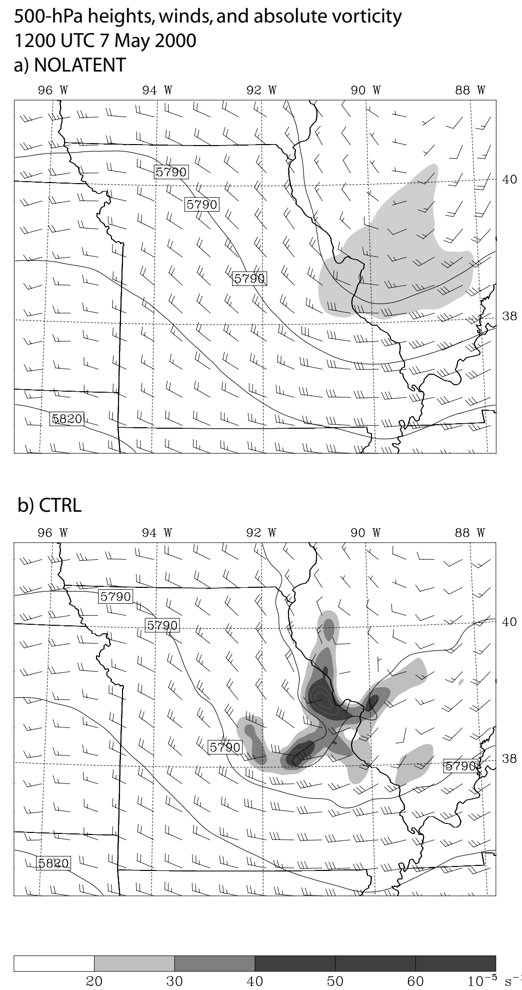

Figure 10: 500-hPa geopotential height (contoured every 15 m), winds (kt; conventional) and absolute vorticity (shading every 10 × 10^{-5} s^{-1} for values greater than 20 × 10^{-5} s^{-1}) at 1200 UTC 7 May 2000 for (a) NOLATENT and (b) CTRL. Winds are plotted every 15th grid point. Vorticity contours have been smoothed with a 10-point filter.

development of a cold pool at the surface even after the MCS had been producing heavy rain for many hours.

In a sensitivity simulation where evaporation was turned off (NOEVAP), the evolution of the MCS was nearly indistinguishable from the control run (Fig. 11). The location of the heaviest rainfall was also very similar, though rainfall rates were much higher in NOEVAP (because the precipitation efficiency was unity). As such, we can conclude that the MCS was not directly maintained by a cold pool resulting from evaporation (the possible effects of hydrometeor loading, which can also contribute to the strength of a cold pool, are currently being explored).

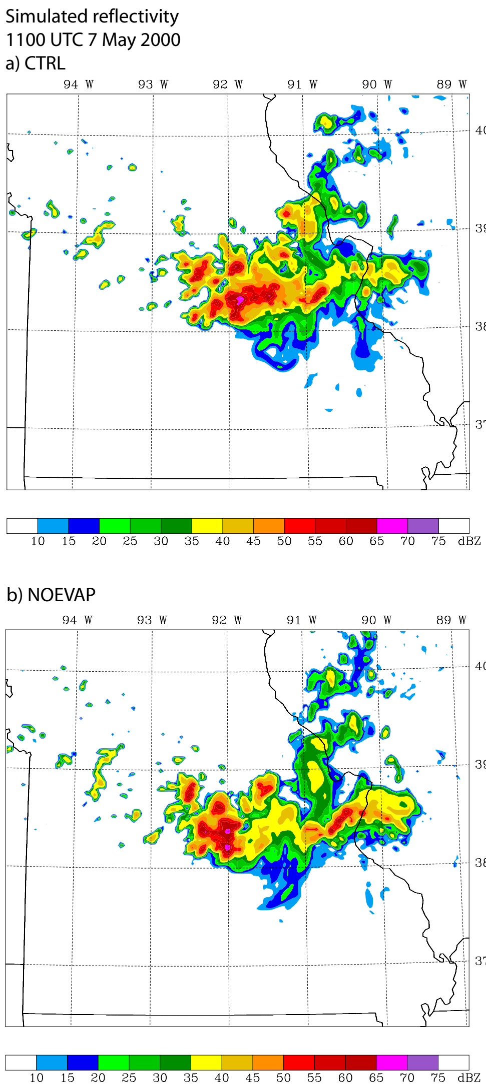

Figure 11: Simulated composite radar reflectivity on domain 2 at 1100 UTC for (a) CTRL and (b) NOEVAP.

The typical hydrostatic response to a cold pool at the surface is a mesoscale region of high pressure. However, in this case, a *mesolow* was apparent in both observations (Glass et al. 2001) and the simulations. As scattered convection develops in the first several hours of the control run, a surface pressure trough develops and then becomes stronger with time. It becomes oriented west to east with the mesolow located on the upstream side of the MCS, where new convective cells are developing (Fig. 12).

Fields showing the difference between the control run and NOLATENT show that it is the MCS that is generating the low pressure rather than the larger-scale background flow (Fig. 13). A broad-scale circulation results (consistent with the development of the deep vortex discussed above), and

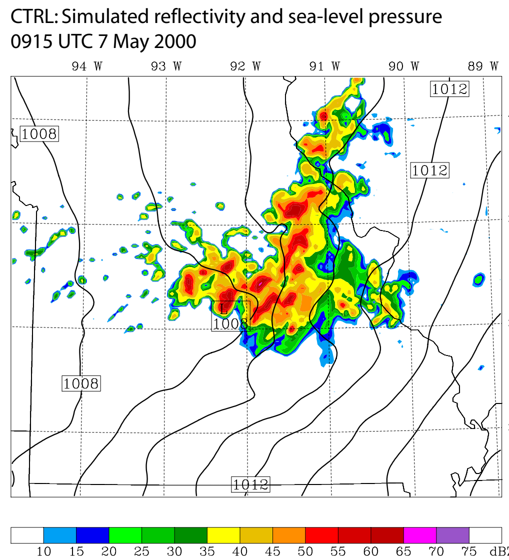

Figure 12: Simulated composite radar reflectivity and sea-level pressure (smoothed and contoured every 1 hPa) on domain 2 at 0915 UTC.

the pressure gradient between the mesolow and a weak mesohigh to the east creates a region of convergence on the upstream edge of the existing MCS. When the scattered shallow convective cells encounter this convergence line, they erupt into deep convection and merge with the mature system. Thus, rather than a traditional outflow boundary, this convectively-induced mesolow and pressure trough serve as the focusing mechanism for the quasi-stationary MCS. As more convection develops, it intensifies the circulation and associated low-level convergence, and the system is maintained without cold-pool lifting.

6. CONCLUSIONS

Results from 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 3 km (and also 1 km, not shown) and explicitly predicted convection is able to successfully simulate the organization and the extreme rainfall totals of this MCS. Operational models and coarser-resolution runs with parameterized convection did not provide any evidence of heavy rain in their output.

- A mesoscale convective vortex within strong low-level wind shear provided lifting to initiate scattered convection, which eventually or-

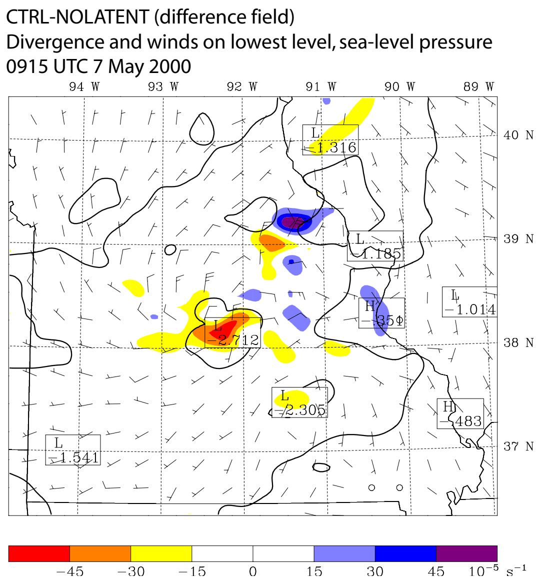

Figure 13: Differences between CTRL and NOLATENT, which represent the effect of the MCS: sea-level pressure (thick contours every 0.5 hPa), divergence (color contours every 15 $\times$ 10^{-5} s^{-1}) and winds (kt; conventional) on the lowest model level (approx. 50 m AGL). Winds are plotted every tenth model grid point. MSLP and divergence fields have been smoothed.

ganized into a quasi-stationary MCS. The diabatic heating associated with the MCS served to reintensify the MCV, which extended down to near the surface.

- The convective system is not maintained by a surface cold pool; instead, a mesolow and pressure trough form at the surface as a result of the convection and the developing MCV circulation. Low-level convergence is enhanced near this region of low pressure, which leads to the development of new convection upstream of the existing MCS. This allows the system to remain nearly stationary for several hours.

7. ACKNOWLEDGEMENTS

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