High Resolution Numerical Simulations of Midwestern Quasi-Linear Mesoscale Convective Systems

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ABSTRACT

The Pennsylvania State University/National Centers for Atmospheric Research Mesoscale Model Version 5 (MM5) is employed to investigate the structure, evolution, and circulation of mid-western quasi-linear meso-scale convective systems (MCSs) during the cool and/or transitional seasons. The model employs three domains with 9, 3, 1 and 0.3-km grid spacing, respectively. A “standard" physical package was selected after running sensitivity tests.

Two cases were chosen for this study. The first case is a classic transitional-season event in which the model predicted very well. The kinematic and dynamic structure of the simulated system, however, provided very detailed information as to how the model maintained a linear MCS some time after model initialization. The low-level simulated reflectivity fields show a strong similarity to the observations. Cross-sectional views show the detailed evolution occurring at different locations of the bowing segment of the squall line. Plan views from low- and midlevels show the vertical structure of the dynamic interaction between the mass and momentum fields, which is further verified with selected cross sections. The low-level winds are also shown to create a reflectivity pattern similar to a line-echo-wave-pattern.

The second case involved simulation of a warm-season convective event. This simulation was not as accurate as the first as evidenced largely by the decreasing accuracy of the surface fields over time. This suggests a limit on the usefulness of the model's forecasts. The MM5 model is able to develop some linear, simulated reflectivity patterns, but they are not as organized as observations for this event. However, it is encouraging to note that the model attempts to develop some degree of organization given the relative success of the first case.

I. **Introduction**

To investigate the structure, evolution, and attendant circulations of mid-western quasi-linear mesoscale convective systems (QLCSs) numerical simulations of two QLCSs were simulated with MM5. In an attempt to gain a better understanding of the structure, evolution, and internal dynamics of linear MCSs that produce severe weather, the MM5 mesoscale model was employed to study this linear convective system. Specifically, the objectives of this research were to investigate the kinematics and dynamics of linear, bow-shaped MCSs, which primarily occur in *relatively* low-instability, moderate-to-strong dynamic environments, and to investigate the utility of a numerical mesoscale model in predicting the evolution of linear MCSs. The first case is a dynamically driven event that moved rapidly across the middle Mississippi Valley on 15 April 1994. This system developed and evolved within a moderately unstable strongly sheared environment. Convection initiated in eastern Kansas and extreme northwestern Missouri as an unorganized convective line. During the late evening and early morning hours, as the convection moved eastward, the line of broken storms became more organized. A solid convective line was first apparent just prior to 0700 UTC 15 April 1994 as the storm was near the Missouri–Kansas border. During the event, several bowing segments (Bow Echoes) were observed from the WSR–88D radar located in Saint Louis, Missouri (KLSX). These bowing structures were associated with a wide swath of damaging straight-line winds and several weak tornadoes (F0–F2).

The second case occurred during the late evening of 26 May and early morning of 27 May 2000, when a group of isolated convective cells was observed over western Missouri. Over the next several hours, the system intensified and organized into a QLCS that resulted in several areas of wind damage as the system progressed eastward into southeastern Missouri and west–central Illinois. Near the center of the line, a well-defined bowing segment was observed along with a prominent rear inflow notch. Several tornadoes were observed with this convective system. Through 0617 UTC, the QLCS continued to move eastward and expanded in size although the number of damaging wind reports decreased over the previous two hours. Overall, the results for the second case are not as accurate as the first. The model is never truly able to organize a system consistent with observations. The error is likely attributed to inadequate initialization of existing convection and subsequent poor surface forecasts.

II. Methodology

NCAR's MM5 (Dudhia et al. 2000) was chosen to simulate the QLCSs. Four domains were used in simulations, all of which allowed for two–way interactive processes to occur between adjacent grids. Results from the MM5 model are then compared to radar observations by "converting" the model output into reflectivity structures using software being developed at the University of Washington. Earlier sensitivity testing determined the various physics options that are chosen during the course of the research. One of the most important choices for this work is that of convective parameterization schemes (CPSs). Previous research (O'Sullivan 2001, Sheu 2000 etc.) revealed that the Grell scheme (Grell 1993) has performed well under similar conditions. Other parameterizations used in this research include the Blackadar radiation scheme (Blackadar 1976, 1979; Zhang and Anthes 1982) and a simple ice scheme for water physics (Dudhia 1989).

For the 15 April 1994 simulation, MM5 was initialized at 0000 UTC 15 April 1994 utilizing initial conditions provided by the NCEP Global Tropospheric Analyses (NMC 1988). The simulation was run with 9, 3, 1 and 0.3 km grid spacing. The largest domain is placed to capture as much of the Mississippi Valley region as possible, while including the topographical influences of the state of Missouri. The 3 km domain captures the influences of the surface frontal zone as the system moves across Missouri. Finally, the smallest domains utilizing resolutions of 1 and 0.3 km capture the storm–scale structures of the simulated squall line. Convective clouds will be represented explicitly in the two finest grids (1, and 0.3 km) while at the larger grid spacing . The May 26, 2000 was initialized with 1200 UTC 26 May 2000 ETA model forecasts. This simulation used three domains. The largest domain has 27–km resolution. The second domain, with 9–km resolution, is placed to capture as much of the Mississippi Valley region as possible while including the topographical influences of the state of Missouri. Finally, the 3–km domain captured the structure and evolution of the simulated squall line.

III. Results

MM5 Simulation of the 15 April 1994 Linear Convective System.

Initial inspection of MM5 output for 15 April 1994 is highly encouraging. The model accurately simulates the occurrence, character, and relative strength of the linear mesoscale convective system; however, the simulated line trails observations by several hours. Model output will be shown during the lifetime of the simulated squall line, and selected plan–view and cross–sectional figures will be shown to describe the evolution and characteristics of the MM5–generated squall line. A comparison of the MM5 simulated reflectivity and winds at 1000UTC and the 0825 UTC KLSX reflectivity are shown in Figure 1. One hour later, the low–level wind fields clearly depict a simulated LEWP structure at the surface. The pressure perturbations at 2.5 km AGL for 1100 UTC are presented in Fig. 2 air ascending along the leading edge. This is evident by noting the positive buoyant anomaly along much of the leading edge of the system. The strong storm–scale horizontal pressure gradients in the lower level (below 2 km) are responsible for accelerating the low–level winds away from the high-pressure center (associated with the cold pool) toward the low pressure center in the direction of the squall line's leading edge. The most significant force to be considered is the horizontal pressure gradient force. Based on an estimate of the pressure gradient (per unit mass), which equates to 3.6 m s^{-1} per minute and 18 m s^{-1} over a 5 minute time interval (the interval of a WSR-88D volume scan). This is a very large change in wind speed over such a small horizontal distance in only six minutes. The acceleration at 0.5 km is just slightly higher, revealing that there is a substantial depth to this acceleration of the wind. Vertical velocities exceed 10 m s^{-1} (see Fig. 3). This circulation has a diameter of approximately 6 km and a velocity differential of approximately 30 m s^{-1}. This diameter falls within the accepted range of 5–7 grid points that are needed in order to resolve a meteorological wave. This clearly illustrates that the MM5 model is capable of simulating storm–scale features associated with QLCSs. In addition, to the southwest of the mesocyclone, a divergent flow characteristic of a downburst is evident (see Fig. 4). This is consistent with work done by Fujita (1978) attributing the bowing structures in QLCSs to downburst activity.

MM5 Simulation of the 27 May 2000 Linear Convective System.

After six hours of integration, the MM5 model was able to reproduce a large convective region extending from central Iowa south and west through much of Missouri, but several hundred kilometers west of its observed location (St. Louis was experiencing convection at this time). Figure 5 is the simulated reflectivity fields valid at approximately 0600 UTC 27 May 2000. At this time, the existing line was propagating through Missouri and into southern Illinois and Kentucky. These discrete cells would later grow into the severe QLCS, responsible for the wind damage and tornadoes over the St. Louis area. At this time, the simulated squall line has just reached the St. Louis area, still several hours behind observations. It is interesting to note that the large heavy–stratiform/light convective precipitation area over much of Illinois and northern Iowa is accurately simulated. At this time, the model does initiate convection over northwest Missouri (to the east and slightly north of where it was observed). By 0200 UTC, the system was evolving into a severe QLCS across west–central Missouri. The MM5–initiated convection fails to maintain itself and nearly completely dissipates. At this time, the only convection the model simulates is spuriously located over the Saint Louis region (see Fig. 6). Two hours later, a large, bowing QLCS is seen across central Missouri. MM5 has forecast a disorganized array of weaker echoes (20–30 dBz) extending southwest from the Saint Louis area in a linear fashion. The model has also developed several convective cells between Columbia and Kirksville, Missouri. These cells initiate along a narrow band of model–forecast instabilities, in which CAPE values near 1000 J kg. Over the next several hours, the main portion of the system propagated across central Illinois with weaker convection extending back through the Saint Louis area. MM5 model finally develops a weak linear system by 0600 UTC. The system is short lived, orientated too far east–west, and lags observations by several hours.

IV. Discussion

The 15 April 1994 model simulation reproduces the observed system to a high degree of accuracy. The model is able to capture the development and translation of the synoptic–scale features and associated forcing extremely well, however, the mesoscale conditions develop more slowly than what was observed. The MM5 forecast initiation, development, and propagation of the simulated squall line lag observations by 2–3 hours. In addition, the model solution is skewed slightly south of the observed location of the system. Furthermore, the simulated system is orientated slightly less north-south than observed. However, given the complexity inherent to these weather systems, the overall similarity shown between the model solution and the observed system should be regarded as excellent. Many of the features observed by the KLSX radar are simulated by the model, including LEWPs in the convective line, intense cells and a strong reflectivity gradient along the leading edge, and slower ground-relative winds along the trailing edge indicative of RINs.

The results from 26–27 May 2000 do not attain the same level of agreement with the observations as the 15 April 1994 case. Part of the difficulty in simulating this event lies in the timing of the squall line over the area of interest. The observed system traversed through eastern Missouri between 2300 UTC 26 May and 0500 UTC 27 May 2000. The model was initiated with the Eta model at 1200 UTC on the 26th. The 12-h upper-air model forecast fields do agree well with the observed analyses over much of the model domain. The locations of the upper-air troughs are in good agreement. Winds are forecast well also, as are low-level moisture patterns and amounts. As the model forecast duration approaches 12 hours, the surface fields start to deviate significantly from those observed. The model delays progression of existing convection out of the region. This leaves the boundary layer cooler and moister than what was observed. In addition, the northward progression of the warm frontal boundary was too fast. In effect, the forcing mechanism was several hundred kilometers north of its observed location and the air in its wake was nearly 10 cooler in places than observed. This caused the simulated atmosphere in central and eastern Missouri to be much more stable than was observed.

Despite the aforementioned errors, the model is able to initiate discrete convection reasonably accurate both temporally and spatially. However, the simulated environment is not able to sustain convective activity, much less develop a coherent QLCS. With time, the model-predicted system does eventually move into portions of eastern Missouri, where moisture and instability is sufficient to produce more of a coherent linear pattern of simulated reflectivities. Given the erratic and weak nature of the simulated convection, the usefulness of the model as an aid to forecasters simulated could be questioned for this event.

V. Bibliography

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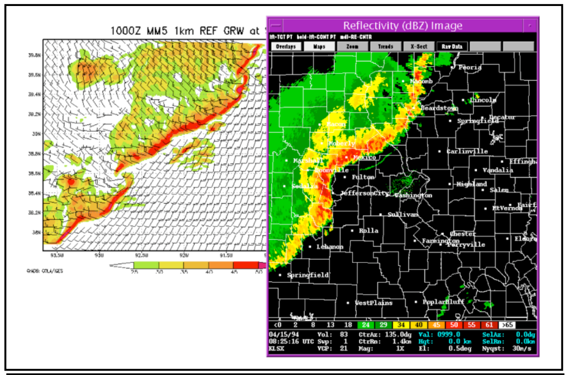

Figure 1
Comparison of simulated reflectivities and winds at 1000 UTC (left panel)to KLSX reflectivities at 0825 UTC (right panel). KLSX reflectivity (dBZ) key is located at the bottom of the image

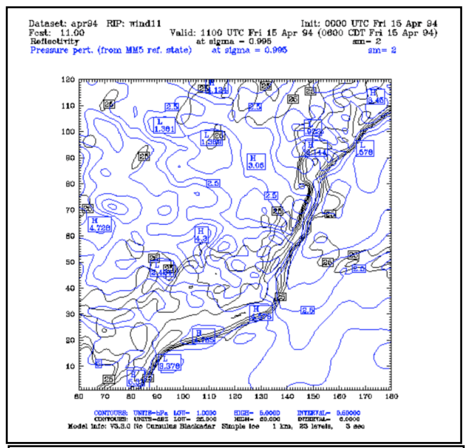

Figure 2
1100 UTC horizontal distributions of pressure perturbations at 2.67 km. Contour interval is 0.4 mb

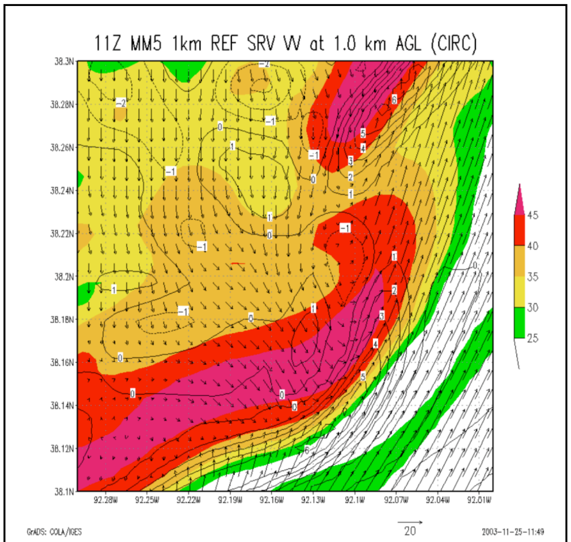

Figure 3
1100 UTC plan view presentation of reflectivity and vertical velocity at 2.67 km AGL. Vertical velocity is presented in m s^{-1}.

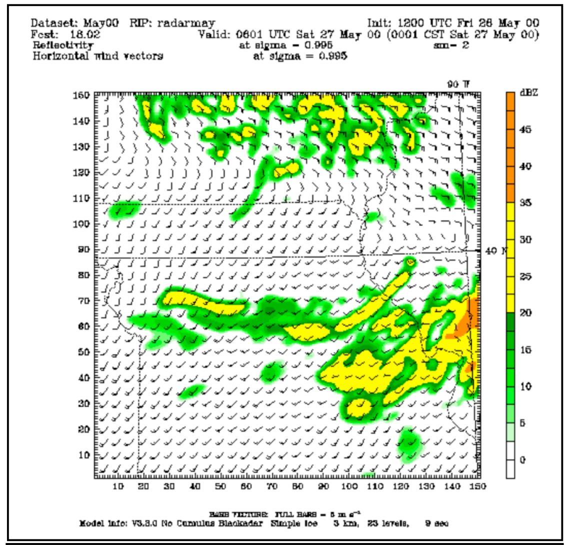

Figure 5a
MM5 simulated radar reflectivities for 0400 UTC 27 May 2000

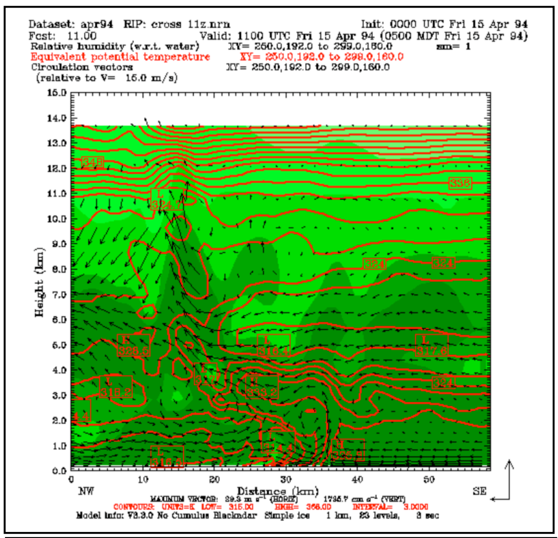

Figure 4
Cross sectional analysis along the blue line in Fig. 3. Values of relative humidity are shaded and equivalent potential temperature, θ_e (K) are contoured in red.

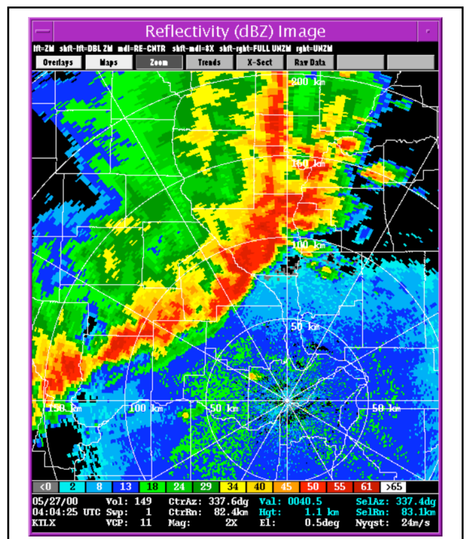

Figure 5b
0404 UTC 27 May 2000 KLSX reflectivity plan view display at the 0.5° elevation sweep.

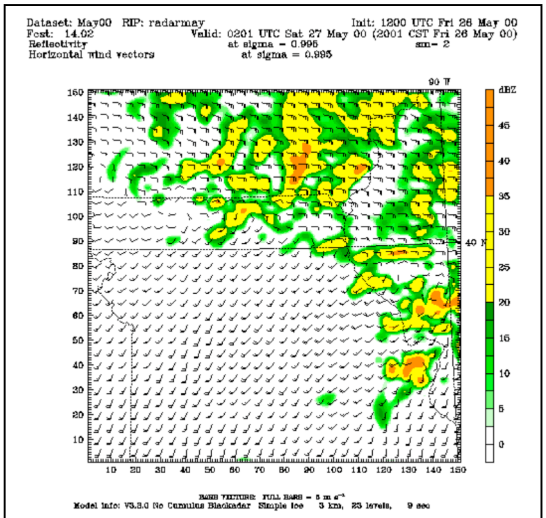

Figure 6a
0200 UTC 27 May 2000 simulated reflectivity display for the inner most domain.

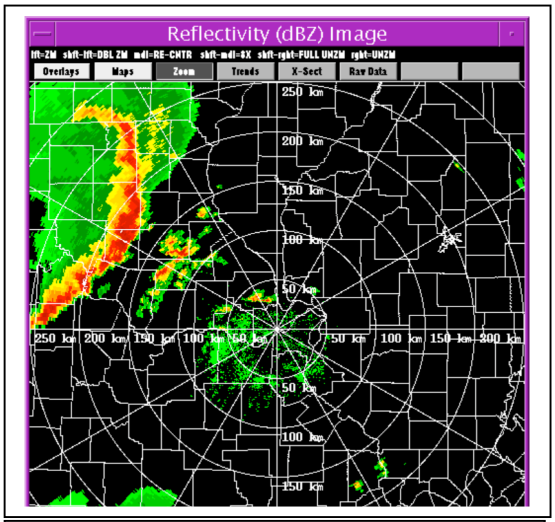

Figure 6b
0217 UTC 27 May 2000 KLSX reflectivity planview display at the 0.5° elevation sweep.