P15.1 THE 4 JUNE 1999 DERECHO EVENT: THE ULTIMATE CHALLENGE FOR NUMERICAL WEATHER PREDICTION?

William A. Gallus, Jr.,[1], Jimmy Correia[2], and Isidora Jankov[1]

[1] *Department of Geological and Atmospheric Science, Iowa State University, Ames, Iowa*

[2] *Department of Agronomy, Iowa State University, Ames, Iowa*

1 Introduction

Although increasing computational power has allowed numerical weather prediction models to be run at increasingly fine grid resolution such that small-scale weather features should be better simulated, warm season rainfall forecasts are still rather poor, remaining much worse than those for the cold season. Studies like Gallus and Segal (2001) have shown that even when many different methods are used to better depict mesoscale features in the initialization, little improvement typically occurs for many warm season convective system cases.

Because deterministic forecasts are often very poor for warm season rainfall, ensemble approaches are being increasingly explored as a possible method to obtain better guidance. It has been shown (e.g., Alhamed et al. 2002) that the use of mixed model and mixed physics ensembles can increase ensemble spread over that achieved by mixed initial conditions. Thus, one would assume that observed rainfall patterns will be represented adequately by at least one member in a well-designed mixed model/mixed physics ensemble. In the present study, however, three commonly used operational and research models, the Eta, the Weather Research and Forecasting (WRF) model, and the Penn State/NCAR Mesoscale Model 5 (MM5) were used to simulate an intense derecho event accompanied by an organized area of substantial rainfall on 4 June 1999. Despite the use of these three different models with various combinations of physical schemes, and the use of two different initialization and boundary condition datasets (Eta and Global) at two different times (06 and 12 UTC) with mesoscale adjustments tested in some initializations, none of the 12-24 hour simulations was able to simulate the derecho event of interest. This result suggests that ensemble guidance also may be of little value in some cases where the event appears to be unpredictable with the current observational network.

Corresponding author address: William Gallus, 3025 Agronomy, Iowa State Univ., Ames, IA, 50011, email: wgallus@iastate.edu

2 Overview of the 4 June 1999 derecho

As is typical in the Midwestern United States, nocturnal convective activity was common during the night of 3-4 June 1999 to the north of a surface warm front in an area of strong convergence at the northern end of a low-level jet. The evolution of the convection during the night was complex. A few convective cells had developed in northwestern Nebraska late in the afternoon on 3 June and had moved northeast toward the South Dakota/Nebraska border as other cells began growing into a convective system shortly after sunset ($\sim$ 03 UTC on 4 June) in central Nebraska to the north of a warm front extending from southwest Nebraska southeastward into southwest Missouri.

The central NE system moved into western Iowa around 07 UTC. At about this time, additional convection developed along a NNW-SSE axis in central Iowa. The NE system continued to move primarily eastward at a faster rate of speed than the Iowa convection, so that by around 12 UTC, the two systems had merged into one broader system over much of the northeastern quarter of Iowa (Fig. 1). Meanwhile, the more isolated cell that had been near the South Dakota - Nebraska border at 07 UTC had continued to move eastward behind the larger system, reaching northwestern Iowa around 12 UTC (Fig. 1). At that time, it began developing upscale, taking on bow echo characteristics and propagating with a slightly more southward component. In fact, after having been the much smaller system during the night, it became the more impressive system during the day as the larger system to its northeast generally dissipated by 18 UTC (Fig. 2). These trends would be consistent with a veering low-level jet during the late night and early morning, and the subsequent interception by the bowing system of moisture transported in the jet, facilitating the demise of the more northeasterly system.

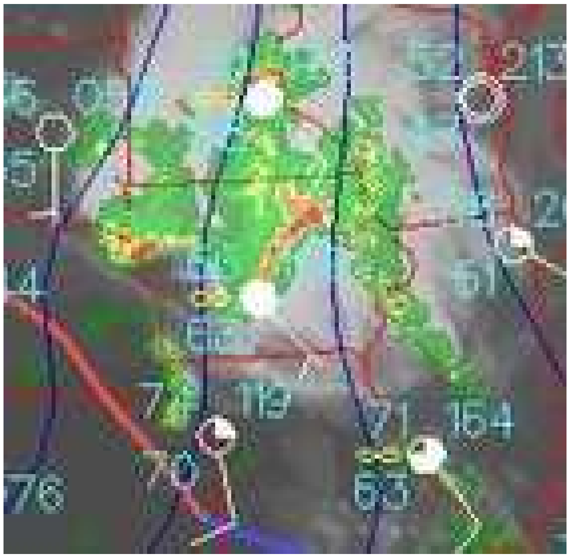


Figure 1: Satellite/Radar/Surface image valid at 1200 UTC June 4

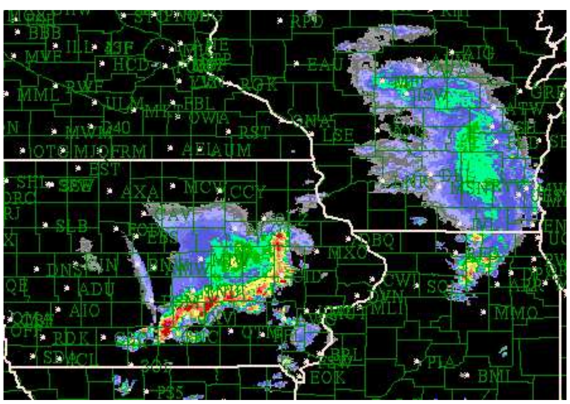


Figure 2: Radar image valid at 1730 UTC June 4 showing derecho system in IA and dying MCS in WI

Severe weather reports in west-central Iowa were common by 13 UTC (NCDC Storm Data Publication), with large hail (up to 50 mm in diameter) and wind gusts exceeding 30 m s^{-1}. The largest hail and strongest winds occurred at the south edge of the system, in south-central Iowa, around 17 UTC. By 19 UTC, the bow echo had crossed the Mississippi River and the severity of the damage reports increased in Illinois. Wind gusts reached to nearly 35 m s^{-1}, and over 20 F0 and F1 tornadoes were reported in central Illinois between 20 and 23 UTC. The system exited far southern Illinois around 1 UTC 5 June, but continued to produce severe wind gusts (greater than 25 m s^{-1} through 8 UTC as far south as central Alabama. It finally dissipated in southern Alabama shortly after 12 UTC 5 June.

At 850 mb, a 30-40 knot low-level jet was already present at 00 UTC extending from central Texas northward through the Dakotas. This low-level jet veered and by 12 UTC extended from western Texas into Minnesota with peak speeds approaching 50 knots to the southwest of Iowa. At 500 mb, a closed low off the California coast moved eastward to near Las Vegas by 12 UTC with broad southwesterly flow of 25-40 knots covering much of the Upper Midwest. Jet stream winds at 300 mb of nearly 100 knots were associated with the low, and west-southwesterly flow in the Plains ranged from around 30 knots in southeastern Iowa at 12 UTC to around 70 knots in southern Minnesota and the Dakotas.

3 Data and Methodology

For the Eta, WRF and MM5 simulations of the 4 June 1999 derecho event, a small domain of roughly 1000×1000 km centered over Iowa was used with horizontal grid spacing of 10 km. The three models were integrated to provide information over the period from 12 UTC 4 June through 00 UTC 5 June. Most simulations were initialized using 12 UTC analyses from either the NCEP Eta or Global (AVN) models, but a few sensitivity tests were performed using 06 UTC AVN analyses for initialization (in case model spin-up in the 12 UTC runs caused major problems). An examination of data availability for the 12 UTC initializations showed no missing radiosonde winds at any sites in or near the model domain. The Eta 3DVAR toss list for that time (E. Rogers, NCEP, 2004, personal communication) showed that no wind information was removed over the continental United States). It appears that these potential sources of error in the 12 UTC analyses did not play a role for this case.

Although three different models were used, the majority of the simulations examined in this study came from two slightly different versions of the NCEP Eta model. One version was similar to that used operationally at NCEP in 1999, and it had been used previously to study over 20 warm season convective cases (Gallus and Segal 2001). The second version of the Eta model included upgrades present in NCEP's operational version in 2003, the most important of which may have been the replacement of the Zhao et al. (1991) explicit cloud water parameterization with the more sophisticated "Ferrier" microphysics (Ferrier et al. 2002). The moist physics in the model included options for either the modified BMJ convective parameterization (Janjic 1994) with both shallow and deep convection, or a version of the Kain-Fritsch (1993) parameterization that also accounts for shallow convection.

For the simulations discussed in the present study, the Eulerian mass-coordinate version 1.2.1 of WRF also was run with both the BMJ and KF convective schemes. Only small differences are present in these schemes compared to the versions used in the Eta model. The NCEP-3 class (vapor, cloud/ice and rain/snow) microphysics (generally similar to what was used in the Eta) was used. The MRF PBL scheme was used for most simulations, but sensitivity tests were done with the Ferrier and Lin et al. (1983) microphysics schemes, and the Eta PBL scheme.

The MM5 model (Dudhia 1993) was configured with 48 vertical levels, and used Reisner 1 mixed phase microphysics with the Eta PBL scheme. Again, both the BMJ and KF2 convective schemes were used. The KF2 scheme is different than the KF scheme used in the ETA model because the relative humidity based parcel perturbation is not used in KF2.

Model rainfall forecasts were compared to 4 km Stage IV multi-sensor observations which were areally averaged onto the Eta model's 10 km grid (using procedures similar to those used at NCEP; M. Baldwin, 2000, personal communication). To objectively evaluate the rainfall forecasts, traditional skill scores such as the equitable threat score (Schaefer 1990) and bias were computed for a range of precipitation thresholds. To better demonstrate the models' poor depictions of the derecho event, 6-hourly plots of simulated rainfall will be shown.

4 Results

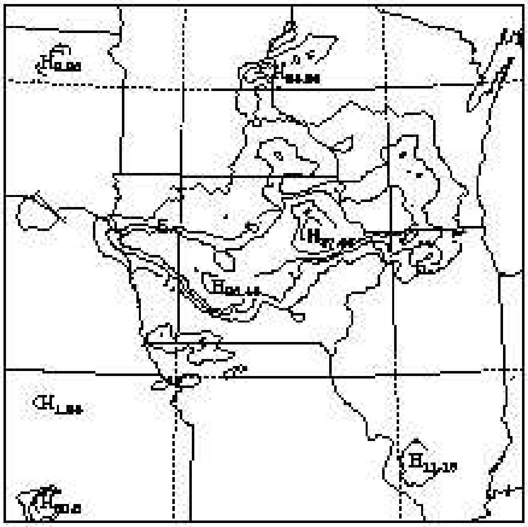
Despite the use of three different models, varied physical parameterizations, and different initial conditions, little evidence of a substantial precipitation event associated with the derecho could be found in any of the numerical output. Precipitation forecasts valid for 6 hour periods throughout the Midwest during the 12 UTC - 00 UTC period 4-5 June showed little skill as measured by ETS or bias scores (not shown). In the first 6 hours, only 4 of 22 simulations had an ETS above 0.10 for rainfall exceeding 0.05 inch, with generally worse performance for heavier amounts. During the 6-12 h forecast period when the derecho event was strongest, even for the lightest rainfall threshold evaluated (.01 inch) where skill is often highest for warm season precipitation, 17 of 22 simulations examined had ETSs below 0.10, and most were below 0.05. All runs using the BMJ scheme (Eta, WRF and MM5 models) had high biases (overprediction of areal coverage) for light rainfall amounts (2.54 mm or less) and low biases for heavier amounts. Runs using the KF scheme had biases close to the ideal 1.0 for light amounts, but very low biases for most heavier thresholds. As poor as these objective measures are, they do not truly reflect how much of a failure the forecasts were, because they are influenced by other areas of rainfall ongoing in the domain apart from the derecho. The failure of the models to forecast the primary derecho event is most evident in plots of rainfall.

Several rainfall systems were present at 12 UTC when most of the model versions were initialized. One dying MCS covered a rather large area in northeastern IA, southeastern MN and adjoining states to the east (Fig. 1). The derecho event was beginning at this time as a rather isolated cell was undergoing upscale growth in far western Iowa. The observed rainfall during the 12-18 UTC period can be seen in Fig. 3a. In this figure, rainfall from the large dissipating system overlaps some rainfall from the new derecho in central Iowa. The largest observed amounts were around 87 mm in northeastern Iowa, almost all from the dissipating MCS, and around 38 mm near central Iowa, mostly from the derecho event. In general, the stripe of amounts exceeding 10 mm that extends from far west-central Iowa into the center of the state came from the derecho system.

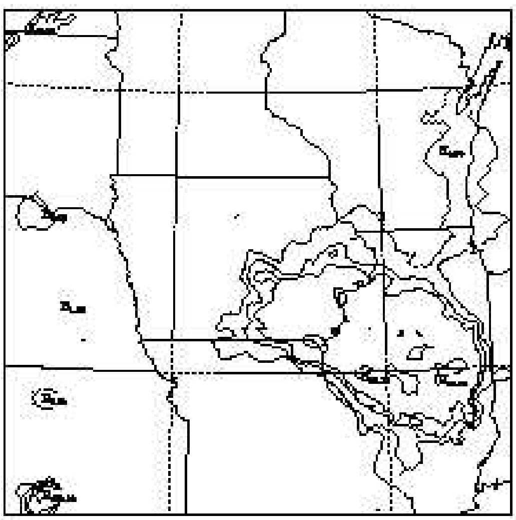
During the following 6 hours (18 - 00 UTC), the dissipating MCS stopped producing appreciable rainfall in the domain (Fig. 3b). Some light amounts in Wisconsin could be attributed to that system. Almost all of the other rainfall in the domain was caused by the derecho system which covered a wide area, roughly 200 km wide by 400 km long, with over 10 mm of rain. Peak amounts exceeded 30 mm in several areas.

1) ETA SIMULATIONS

Figure 4 shows the 6-hr accumulated rainfall in the Eta model using the BMJ convective scheme initialized with Eta output. The older version of the Eta model produces too large a region covered in very light rainfall in the first 6 hours (Fig. 4a). Most of the precipitation in Missouri was a false alarm. Where the heavy rainfall occurred in northeastern Iowa, the model showed no evidence of an organized system, with its heaviest amounts much farther to the north. With regard to the derecho event, the model only produced a small area of 1-2 mm rainfall in west-central Iowa that did propagate east.



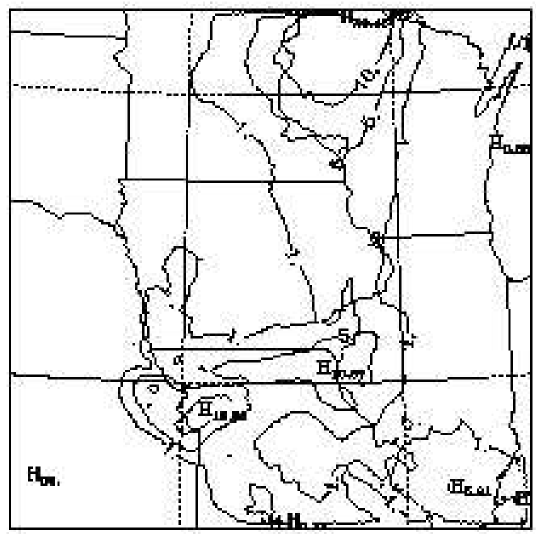
(a)



(b)

Figure 3: Stage IV rainfall observations for a) 12-18 UTC and b) 18-00 UTC 4 June 1999.

In the following 6 hours (18-00 UTC) the older Eta version produced a large area of rainfall in Minnesota where none was observed (Fig. 4b). The model continued to not have any derecho feature, such that no rainfall was predicted in all of eastern Iowa. The model did produce some rainfall in central Illinois where the derecho occurred, but this precipitation developed there after 18 UTC, roughly 100 km ahead of the location of the derecho at that time. Amounts were greatly underestimated.



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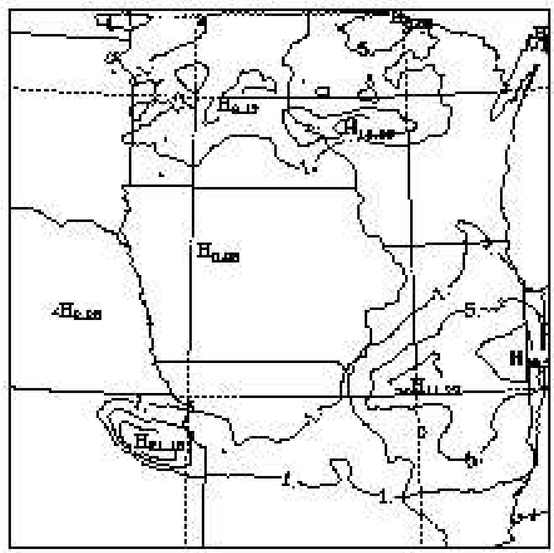
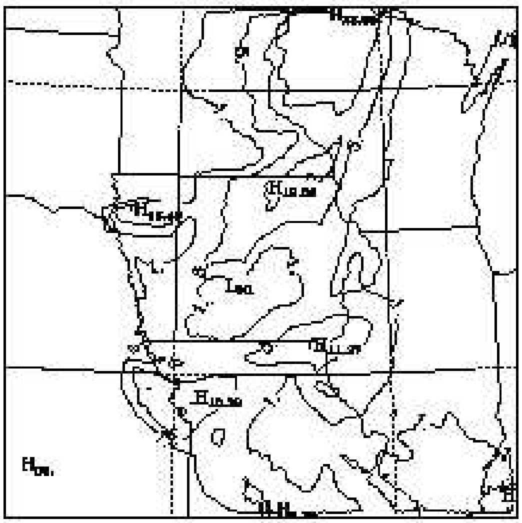


(b)

Figure 4: As in Fig. 3 but for Eta-BMJ run initialized with Eta output

The updated Eta model generally exhibited similar problems to the older version during the two time periods. Likewise, the cold pool and mesoscale observation runs discussed in Gallus and Segal (2001) did not noticeably change the bad forecast.

An adjustment to initialized relative humidity to remove dry layers (RH<80%) where radar echo was present did result in a prediction of some rainfall associated with the derecho (Fig. 5a) during the first 6 hours of the forecast. However, inspection of hourly rainfall plots (not shown) indicated that the system was not sustained in the model, with all rainfall gone by 15 UTC. By the following 6 hour time period, the effects of the relative humidity adjustment had nearly vanished (Fig. 5b) and the precipitation plot resembled that of the original Eta run (Fig. 4b).



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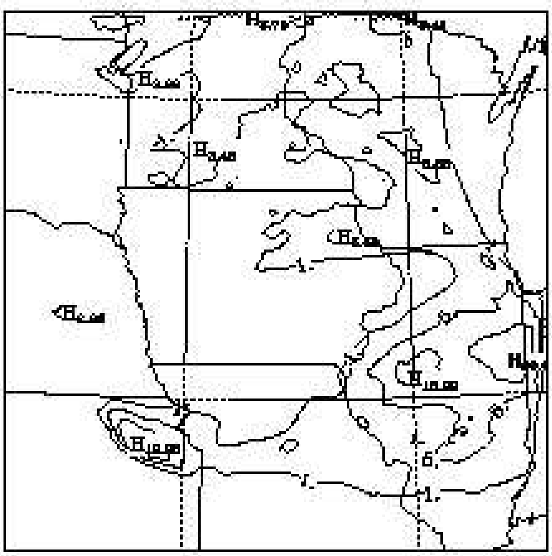
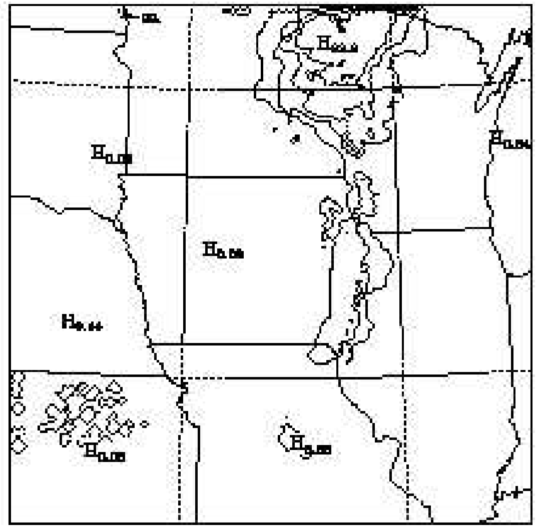


(b)

Figure 5: As in Fig. 4 but for Eta-BMJ run with relative humidity adjusted at initialization

The Eta model run with the KF scheme and Eta initial and boundary condition input likewise failed to produce the derecho system. The older Eta version in the first 6 hours (Fig. 6a) evidenced some of the same problems in its depiction of the northeastern IA system as the Eta with the BMJ scheme (Fig. 4a). However, the KF run had fewer problems with false alarm rainfall in Missouri.



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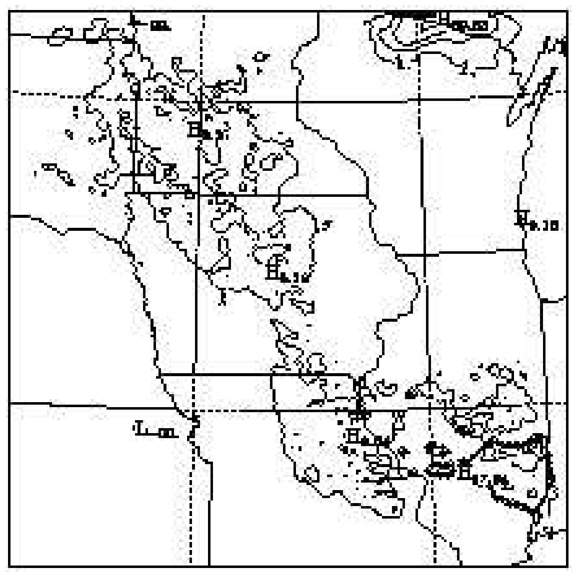


(b)

Figure 6: As in Fig. 4 but for Eta-KF run

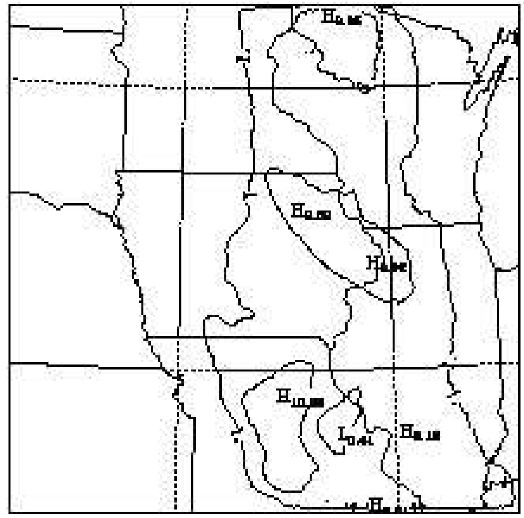
During the following 6 hours (Fig. 6b), this run produced a fictitious system in southwestern Minnesota and northern Iowa, displaced a little southward from the one in the Eta-BMJ. The Eta-KF did produce some rainfall in southeastern Illinois in the region affected by the derecho just before 00 UTC. Unfortunately this rainfall in the model occurred earlier in the simulation (primarily between 18-21 UTC) in a narrow east-west band that slowly moved toward the east, unlike the observed event. Most of the derecho path experienced no rain in the model.

The updated Eta model with the KF scheme differed little in this time period from the older Eta, with the exception of a large area of false alarm rainfall in Missouri in the newer version (not shown). In the 18-00 UTC period, the updated Eta had a somewhat larger areal coverage of rainfall, so that the Minnesota system was connected to the rainfall extending into the southeast corner of the domain. One could argue that this model did show some rainfall over much of the path of the derecho, but the rainfall was not organized, and generally occurred in tiny regions with amounts no more than a few mm. It would be difficult to find any evidence from the rainfall forecast of a well-organized MCS.

When the relative humidity adjustment was made to the Eta-KF run, the model did indicate a small area of heavy rainfall in northwestern Iowa with a peak amount of 40 mm (not shown), but as in the BMJ run, the rainfall was confined to the first few hours of the forecast, and no noticeable improvements occurred to the forecast of the derecho itself.

The use of different initial and boundary condition input had some impact on the rainfall forecast in the domain. When AVN output were used instead of Eta output in the Eta runs using the BMJ scheme (Fig. 7), the updated Eta better depicted the system whose maximum rainfall in the 12-18 UTC period was over northeastern Iowa (Fig. 7a). Its main band of rainfall, however, running north-south through a wide region in the eastern part of the domain, bore little resemblance to the observed field. Peak rainfall in northeastern Iowa was only around 10 mm, far less than the 80 mm or more amounts observed. False alarm rainfall was still common in Missouri in the AVN-initialized run, and once again, no evidence of the derecho existed.

During the 18-00 UTC period, the forecasts initialized from AVN output worsened appreciably compared to the already bad prediction of the Eta-initialized Eta. In the AVN-initialized run, except for a small region of light rain in eastern Wisconsin, almost all of the simulated rainfall fell in regions where none was observed (Fig. 7b), and the path of the derecho was devoid of rainfall. Thus, although the AVN initial data did improve slightly the depiction of the dissipating system in northeastern Iowa, it worsened the already poor forecast of the derecho.



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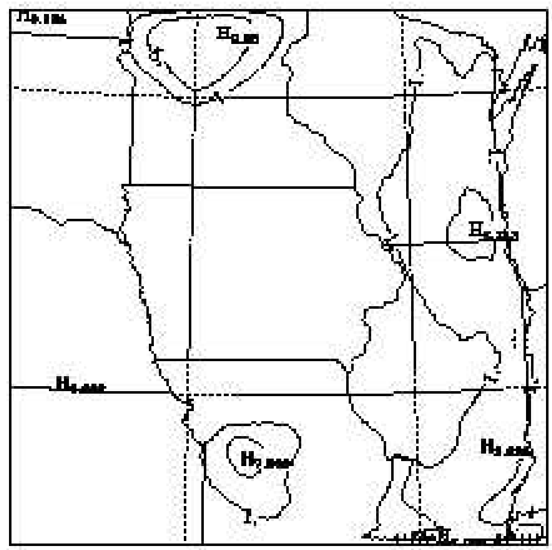

(b)

Figure 7: As in Fig. 4 but for Eta-BMJ run initialized with AVN output

When the AVN output used for initialization were adjusted to remove dry layers in the relative humidity where radar echoes were present at initialization time, some of the same improvements seen in the Eta-initialized runs were present but primarily again in only the first few hours (not shown). Regarding the derecho, a small area of light rain was predicted in northwestern Iowa, and it weakened over time. However, very small amounts could be tracked east-southeastward through much of the 12 hour period along a path very similar to that taken by the derecho, such that this run might be thought of as the best of all runs investigated. Nonetheless, the signal for any derecho was extremely weak at best.

The newer Eta with the KF scheme using the AVN output for initialization (not shown) did not indicate much of an improvement over the Eta initialized KF run (Fig. 6). The relative humidity adjustment to the AVN-initialized KF run resulted in much heavier rainfall amounts in the northern MCS system (not shown) with peak values shifted southward so that the displacement error was much smaller (100-200 km) than the run without the adjustment. The adjustment also resulted in simulation of some rainfall in northwestern Iowa, but the system dissipated even more quickly than in the BMJ run.

2) WRF SIMULATIONS

The WRF simulations of this event were generally very similar to the Eta runs, with both BMJ and KF runs failing to produce the derecho in runs using both Eta and AVN output for initialization and boundary conditions. The WRF model allows for a greater range of physical parameterizations than the Eta model, and to investigate the impact of the PBL scheme, the run with the AVN initialization was repeated using the Eta PBL scheme instead of the MRF scheme. In the first 6 hours the change in the PBL scheme generally led to only small changes in the rainfall forecast (not shown), except in the vicinity of southeastern Iowa and western Illinois where the Eta PBL scheme resulted in a band of rainfall oriented SW-NE that was not present in the run using the MRF PBL scheme. This orientation was similar to that of the observed derecho, but by 18 UTC, the observed system was approximately 150 km northwest of here. This enhanced area of precipitation lacked temporal continuity and the rainfall field in the following 6 hours was not much better than in the run using the MRF PBL scheme. No useful signal of the derecho existed. Additional tests were performed switching from the NCEP-3 class microphysics to Lin et al. (1983) and Ferrier, but for this event, the choice of microphysical scheme did not influence the precipitation forecast substantially, modifying amounts slightly but not locations of rainfall. Because none of the model runs starting at 12 UTC, whether initialized with Eta or with AVN output, were able to capture the derecho event and most did poorly with the northeastern IA MCS, one might suspect that the ongoing nature of the systems at 12 UTC was a problem (possibly through spin-up effects), and that an earlier initialization might result in a better forecast. To test this theory, the WRF runs using the BMJ and KF schemes were re-run with a 06 UTC initialization based on AVN output (Eta output were not available from NCEP at this time). Even worse problems occur in these simulations using the earlier initialization with a more northward displacement to the northeastern IA MCS, and no sign of the derecho event. Instead, the model produces a large MCS-like system in Missouri that was not observed. The forecast by 18-00 UTC (not shown) bears almost no resemblance to the observations. The WRF-KF run initialized at 06 UTC (not shown) looks surprisingly similar to the 12 UTC-initialized run with the same problems as the other KF runs.

3) MM5 SIMULATIONS

The MM5 model also failed to forecast either system well. The MM5 running with the BMJ scheme and Eta initialization had no evidence of the derecho event in the 12-18 UTC period and a broad band of light rain running north south across the domain instead of the concentrated MCS in northeastern IA (not shown). It had one of the driest solutions of all in the 18-00 UTC period and clearly would have provided no useful information to operational forecasters about the evolution of rainfall systems on this afternoon. A switch to an AVN initialization in this run resulted in almost no improvements (not shown) with the main changes being the production of an incorrect rainfall region near the KS/MO border area in the first 6 hours, and a shift of the small rainfall area in southern Illinois in the Eta-initialized run northward 100 km or so. The MM5 using the KF scheme with AVN initialization produced rainfall fields very similar to those in the newer Eta version using the KF scheme with AVN initialization (not shown).

5 Summary and Discussion

A damaging derecho event accompanied by substantial rainfall occurred after 12 UTC on 4 June 1999 in the Midwestern United States. Despite the long-lived nature of the event, and the fact that the initial system was present at 12 UTC, numerical model simulations with 10 km grid spacing did an exceptionally poor job of depicting this convective system. Simulations were performed using the Eta, WRF and MM5 models with a range of physical parameterizations, and two different sources of initial and boundary condition data (from the NCEP Eta and AVN models). In addition, mesoscale adjustments were made in the initialization of some runs to help initiate convection where radar echo was present at initialization time.

Although the study emphasized runs initialized at 12 UTC, some additional runs were performed using 06 UTC AVN model output for initialization and boundary condition information.

Regarding general trends among all of the many different model runs, it appears that all model runs were far too dry with both MCS events. In the northeastern Iowa system, peak rainfall in the 12-18 UTC period exceeded 85 mm. In all model runs, the peak was between 6 and 25 mm. Most model runs completely missed the derecho MCS which produced up to 36 mm of rain in the same time period. Only the runs which used a relative humidity adjustment in the initialized data to force the model to produce some precipitation showed any distinct enhancement in rainfall in western Iowa, and even in these runs, the peak amounts only reached 12 mm. In the following 6 hours (18-00 UTC), most model versions incorrectly predicted large areas of rainfall in Minnesota and Missouri, while having no clear signal of an MCS moving from eastern Iowa southeastward through Illinois. Peak observed amounts in the derecho MCS exceeded 55 mm. Most model runs had less than 10 mm anywhere in Illinois, with the peak amount in any model being 32 mm in the WRF run using the KF scheme.

For the derecho event, success was elusive as initializations based on both the Eta and AVN output failed to depict the system. Most model runs did break out some rainfall over Illinois during the afternoon (18-00 UTC) but often only near the end of the derecho path, and in a manner showing no organized structure. The only runs to show any sustained precipitation in the first 6 hours were the ones that used an adjustment to relative humidity at initialization time that caused the convective scheme to activate within the first 1-2 hours (e.g., Fig. 5a). Unfortunately, in all cases, the rainfall intensity diminished rapidly with time so that even these model runs would have offered poor guidance that a long-lived derecho event would last for nearly 24 hours after this time.

The fact that such a large range of models and configurations all failed to simulate the derecho event suggests that model error alone was likely not the primary cause of the poor forecasts. Many earlier studies have shown that warm season rainfall forecasts are very sensitive to the convective schemes used (e.g. Wang and Seaman 1997, Gallus 1999), and thus it can be inferred that a wide range of models or different physical parameterizations within the same model ought to lead to at least one solution resembling the observations. With the 4 June system, evidence suggests inadequacies in the initial and boundary conditions probably harmed the simulations. Unfortunately, the use of two different sets of initialization/boundary condition data did not help the simulations. A simple mesoscale adjustment that forced the model to produce rain in the first hour or two near where it was observed at initialization time did not result in a system that was sustained in the model.

It thus appears that systems such as this one may require a much better observation network than what now exists, and these seemingly "unforecastable" systems will likely continue to be a problem for some time to come. It should be noted that Jankov and Gallus (2004) compared the Eta analyses used for initialization of the 4 June 1999 event to wind profiler data and found some discrepancies in direction over central Iowa, but even when these data were used to nudge the model initialization toward the profiler observations, no improvement resulted in the rainfall forecast. Thus, although the profiler network supplies somewhat finer resolution observations through the depth of the troposphere than the rawinsonde network, the spacing of the sites may not be sufficiently fine to detect mesoscale features important in the generation and sustenance of the derecho. The failure of all members of the vast array of models examined here to predict the system suggests that even ensemble systems may offer little useful guidance for some events. Finally, cases such as this one might serve as a good test for new parameterizations or models since so much room for improvement exists. Likewise, assuming all necessary data has been archived, these events would be excellent ones on which to test new data assimilation techniques such as the Local Analysis and Prediction System diabatic initialization procedure (Schultz et al. 2003).

6 Acknowledgements

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