The 4 June 1999 Derecho Event: A Particularly Difficult Challenge for Numerical Weather Prediction

WILLIAM A. GALLUS JR.

Department of Geological and Atmospheric Science, Iowa State University, Ames, Iowa

JAMES CORREIA JR.

Department of Agronomy, Iowa State University, Ames, Iowa

ISIDORA JANKOV

Department of Geological and Atmospheric Science, Iowa State University, Ames, Iowa

(Manuscript received 2 December 2004, in final form 16 March 2005)

ABSTRACT

Warm season convective system rainfall forecasts remain a particularly difficult forecast challenge. For these events, it is possible that ensemble forecasts would provide helpful information unavailable in a single deterministic forecast. In this study, an intense derecho event accompanied by a well-organized band of heavy rainfall is used to show that for some situations, the predictability of rainfall even within a 12–24-h period is so low that a wide range of simulations using different models, different physical parameterizations, and different initial conditions all fail to provide even a small signal that the event will occur. The failure of a wide range of models and parameterizations to depict the event might suggest inadequate representation of the initial conditions. However, a range of different initial conditions also failed to lead to a well-simulated event, suggesting that some events are unlikely to be predictable with the current observational network, and ensemble guidance for such cases may provide limited additional information useful to a forecaster.

1. Introduction

Skill scores for quantitative precipitation forecasts (QPFs) have improved over the years as models have used finer resolution and parameterizations, but warm season convective system events overall continue to be poorly forecasted (e.g., Olson et al. 1995; Stensrud et al. 2000). Many of the problems with these forecasts are related to the small scales of the convective systems and the processes that force them, which at best may be resolved only marginally by both observational networks and the models (e.g., Stensrud and Fritsch 1994). It also has been shown that convective parameterizations can introduce large errors, and the rainfall forecasts are very sensitive to the specific parameterization used (e.g., Wang and Seaman 1997; Gallus 1999).

Because of the lack of skill in these forecasts and the large sensitivity of a single deterministic forecast to physical parameterizations, an increasing body of research has been investigating the use of ensemble approaches for precipitation forecasting (e.g., Mullen and Buizza 2001; Wandishin et al. 2001). Ensemble forecasting approaches have long been used for medium-range forecasting, where the ensembles have usually been created through methods that perturb initial conditions (e.g., Tracton and Kalnay 1993). Such an ensemble will reveal useful information about the most likely state of the atmosphere to occur and the uncertainty in the forecast if initialization and observation errors dominate over model errors. However, for short-range warm season rainfall prediction, it appears model errors may be much larger than other errors. Alhamed et al. (2002), for instance, found that in a mixed model–mixed initial condition ensemble, the members clustered strongly by model. Gallus and Segal (2001) found that modifications in the initial conditions to better rep-

Corresponding author address: William A. Gallus Jr., Dept. of Geological and Atmospheric Science, Iowa State University, 3025 Agronomy Hall, Ames, IA 50011.
E-mail: wgallus@iastate.edu

resent mesoscale features did not systematically improve warm season convective system rainfall forecasts in the upper Midwest, and spread among the runs with adjusted initial conditions was much less than that occurring when the convective scheme was varied. Some studies have found little correlation between ensemble spread and forecast skill for short-range forecasts (Hamill and Colucci 1998; Stensrud et al. 1999a; Hou et al. 2001). Although it appears forecast skill of ensembles may be increased through the construction of a mixed physics–mixed model ensemble that increases dispersion (Stensrud et al. 2000), questions remain about the interpretation of results from such ensembles. Biases in the models may skew the ensemble prediction, and it is difficult to know if the dispersion present is an accurate reflection of the uncertainty in the forecast.

One possible advantage of using an ensemble approach for warm season convective system rainfall forecasting is that the actual event should end up somewhere within the umbrella of model solutions if the ensemble is constructed well, making an operational forecaster aware of the possibility, albeit small, for the event to occur. As shown in Jankov and Gallus (2004a), it is not uncommon to have warm season events where one or two model configurations exhibit almost no skill. Not only are objective measures of skill poor [which might reflect problems in applying traditional grid point–to–grid point verification methods to mesoscale model output; see Mass et al. (2002)], these forecasts, subjectively, look nothing like what actually occurs. Reliance upon any deterministic forecast would be foolish in such events. However, an important question becomes, will an ensemble always improve forecastability of the most challenging events? Is it possible that no existing model, observational dataset for initialization, or configuration of physical parameterizations may be able to accurately simulate some events?

In the present study, three commonly used operational and research models, the National Centers for Environmental Prediction (NCEP) Eta Model (Janjić 1994), the Weather Research and Forecasting (WRF) model (Skamarock et al. 2001), and the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5; Dudhia 1993) are used to simulate an intense derecho event that was accompanied by an organized area of substantial rainfall on 4 June 1999. Although the derecho winds and tornadoes caused widespread damage, our emphasis will be on its rainfall. Two different initialization datasets, NCEP's Eta and Global analyses, are used in the runs, along with variations in the depiction of mesoscale features within the initializations (see Gallus and Segal 2001 for details). Despite the use of different models, different initializations, and a range of different physical parameterizations, 12–24-h simulations suggest that ensemble guidance may be of little value in a case like this where the event may be unpredictable with the current observational network. A brief overview of the event is provided in section 2. Data used and the methodology are discussed in section 3. Results of the model integrations are found in section 4. The final section provides a summary and short discussion.

2. Overview of the 4 June 1999 derecho

Substantial convective activity occurred in the midwestern United States during the night of 3–4 June 1999. As is often the case during the warm season, the convection occurred 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 (not shown). These cells remained isolated as they moved northeast toward the central South Dakota–Nebraska border as other cells began growing into a convective system shortly after sunset (~0300 UTC on 4 June) in central Nebraska to the north of a warm front extending from southwest Nebraska southeastward into southwest Missouri. This system moved into western Iowa around 0700 UTC (denoted A2 in Fig. 1a). At about this time, additional convection developed along a NNW–SSE axis in central Iowa (denoted A1 in Fig. 1a).

To better depict mesoscale structures in Fig. 1, surface data were analyzed following the time to space conversion technique of Fujita (1955) and were gridded using the Barnes scheme according to Correia and Arritt (2004). Time to space conversion (TSC) of surface data was facilitated in this case by the availability of 1-min surface observations from Automated Weather Observing System (AWOS) sites in Iowa, which supplemented Automated Surface Observing System (ASOS) special and hourly observations. The TSC technique allows for feature continuity and for more information to be represented than is available at one time alone. An advection vector is used to relocate "off-time" observations relative to the station location. In the TSC analysis, the advection vector plays a substantial role in determining the separation of the off-time observations ("on-time" observations are assigned at the station location), with a station's off-time report influencing grid points at a distance of $|\mathbf{V}| \times \Delta T$. In Fig. 1, the advection vector used for all four times was based on the speed and direction of the bow echo (15 m s^{-1}

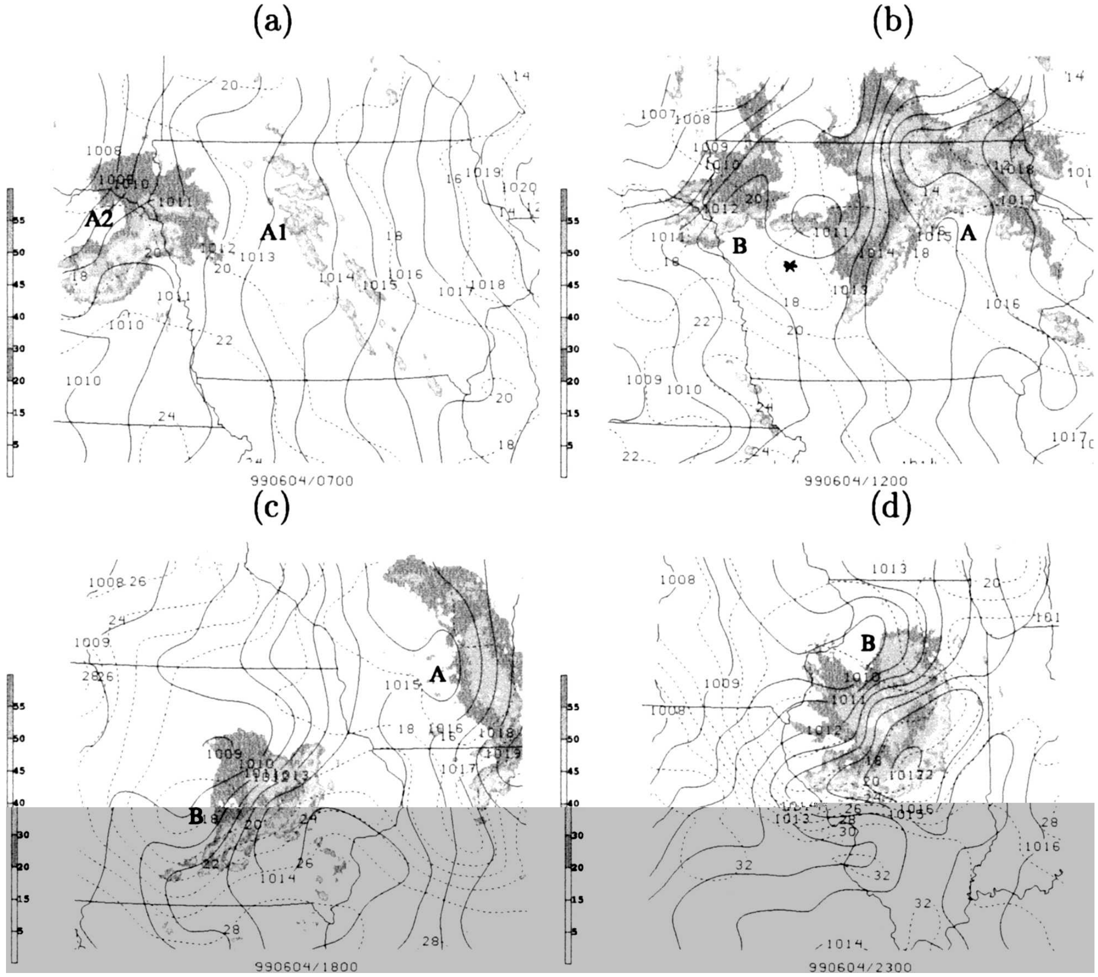

FIG. 1. Surface observations with radar data overlaid at (a) 0700, (b) 1200, (c) 1800, and (d) 2300 UTC 4 Jun 1999. Pressure is contoured (solid) every mb, temperature (dashed) every 2°C, and radar reflectivity following grayscale. Convective systems discussed in the text are denoted by A1, A2, A, and B. Site of sounding shown in Fig. 4 indicated with an asterisk (*) in Fig. 1b.

from 290°) rather than the mean wind from 700 to 400 hPa, which is often used (in this case the mean wind differed from the bow echo movement by nearly 90°). The 15 m s^{-1} advection vector applied to an observation 1 h old results in data being applied 54 km away from the station location. A time interval of ±1 h was used in this case in order to enhance the spatial resolution of the data using a grid with 40-km resolution. Tests using a shorter time interval showed little impact due to the use of the Barnes two-pass objective analysis scheme. The radar data were composited using the lowest-level maximum reflectivity from all available radar sites within the domain. A time window of 15 min was used to account for varying radar image times to allow for maximum coverage. The radar data were then interpolated onto a 500 × 700 point grid and overlaid with the TSC surface analysis.

System A2 (Fig. 1a) continued to move primarily eastward at a faster rate of speed than the Iowa convection (A1), so that by around 1200 UTC, the two systems had merged into one broader system (denoted A) over much of the northeastern quarter of Iowa (Fig. 1b). Meanwhile, the isolated cells that had been near the central South Dakota–Nebraska border at 0700 UTC (west of the domain in Fig. 1a) had continued to move eastward behind the larger system, reaching northwestern Iowa around 1200 UTC (system B). 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 (A) to its northeast generally dissipated around 1800 UTC (Fig. 1c). These trends would be consistent with a veering low-level jet during the late night and early morning, and subsequent interception by the bowing system of moisture transported in the jet, facilitating the demise of the more northeasterly system.

Severe weather reports in west-central Iowa were common by 1300 UTC [according to *Storm Data* (NCDC 1999)], with large hail (up to 50 mm in diameter) and wind gusts exceeding 30 m s^{-1}. The largest hail and strongest winds occurred along the south edge of the system, in south-central Iowa, around 1700 UTC. By 1900 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 2000 and 2300 UTC, when the system exhibited a classic bowing shape (Fig. 1d). The system exited far southern Illinois around 0100 UTC 5 June, but continued to produce severe wind gusts (greater than 25 m s^{-1}) through 0800 UTC as far south as central Alabama. It finally dissipated in southern Alabama shortly after 1200 UTC.

At 850 mb at 0000 UTC 4 June, a 15–20 m s^{-1} low-level jet was already present extending from central Texas northward through the Dakotas. This low-level jet veered and by 1200 UTC extended from western Texas into Minnesota (Fig. 2). Peak speeds were approaching 25 m s^{-1} in parts of Kansas and northwestern Oklahoma and Texas. At 500 mb, a closed low off the California coast moved eastward to near Las Vegas by 1200 UTC (Fig. 3). The low was unusually intense for early June, with temperatures around −24°C, and broad southwesterly flow of 12–20 m s^{-1} covered much of the upper Midwest. Jet stream winds at 300 mb (not shown) of nearly 50 m s^{-1} were associated with the low, and west-southwesterly flow in the Great Plains ranged from around 15 m s^{-1} in southeastern Iowa at 1200 UTC to around 35 m s^{-1} in southern Minnesota and the Dakotas.

A sounding taken from the NCEP Aviation Model (AVN) initialization dataset valid for Carroll, Iowa [marked with an asterisk (*) in Fig. 1b], at 1200 UTC and representative of conditions throughout west-central Iowa in the hours preceding the arrival of the developing derecho is shown in Fig. 4. (Temperature

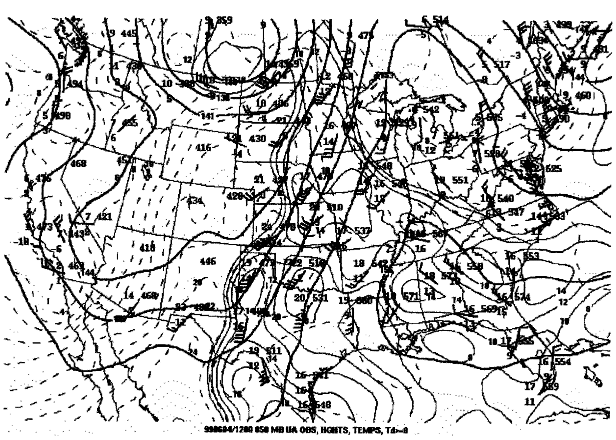

FIG. 2. The 850-mb analysis valid at 1200 UTC 4 Jun 1999. Heights contoured (thick solid lines) every 30 m, dewpoints above 8°C contoured (thin solid lines) every 2°C, and temperatures contoured (dashed) every 2°C. Standard station model used for plotting at rawinsonde sites, with winds in kt (where 1 kt = 0.514 m s^{-1}). Axis of low-level jet shown with arrow.

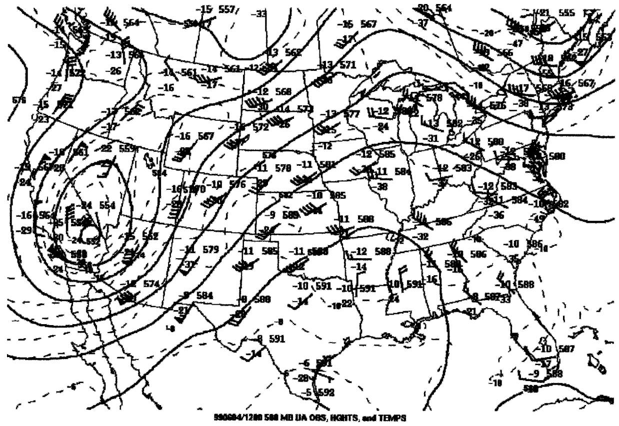

FIG. 3. As in Fig. 2 except for 500 mb, with heights contoured (solid) every 60 m and temperature (dashed) every 2°C.

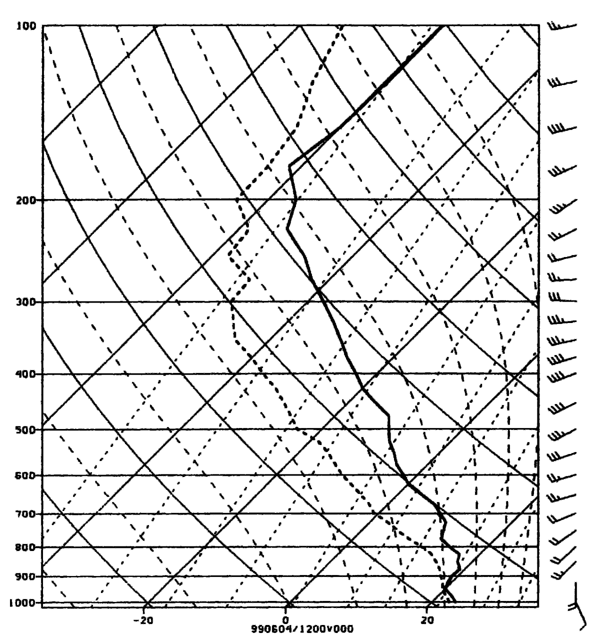

FIG. 4. Skew T–log$p$ diagram based on AVN analysis valid at 1200 UTC from a point near Carroll, IA [marked with an asterisk (*) in Fig. 1b].

and moisture profiles in this region in the Eta analyses were nearly identical, with only a few levels having any differences, and these were less than 0.5°C.) The sounding shows a substantial amount of convective available potential energy (CAPE) with only a small amount of convective inhibition (CIN) for parcels lifted from around 850 mb. This site was within the axis of maximum CAPE at this time (not shown) with values of 1500–3000 J kg^{-1} (using the lowest 180-mb layer) covering much of Missouri, the western 75% of Iowa, eastern Nebraska, and eastern South Dakota. Large values of CIN were advancing over much of this region from the west, but a narrow band oriented north-northwest–south-southeast at the east edge of the high CAPE region had values (computed for the lowest 180-mb layer) as low as 10–50 J kg^{-1}.

During the following 12 h, models showed high CAPE values (as large as 4000–5000 J kg^{-1}) developing over much of the area west of the Mississippi River with a tight gradient near the river. A tight thermal gradient with a nearby supply of extreme instability has been found to be common during derecho events (Johns and Hirt 1987). The strongly capped air mass to the west (high CIN) was also predicted to spread eastward, but CIN less than 10 J kg^{-1} was predicted to exist along the east edge of the high-CAPE region, near the Mississippi River. Thermodynamically, conditions looked favorable for the development of some intense convection. Winds at all levels, however, were predicted to be southwest or west and of generally modest strength ($\leq$20 m s^{-1}) during this time over eastern Iowa and Illinois, which would not be consistent with most derecho events. The southeastward track of the 4 June event was fairly typical for this region (Bentley and Mote 1998) but the derecho deviated more strongly to the right of the mean flow than usual, occurred with weaker than usual winds, and developed at an atypical time of day for this region.

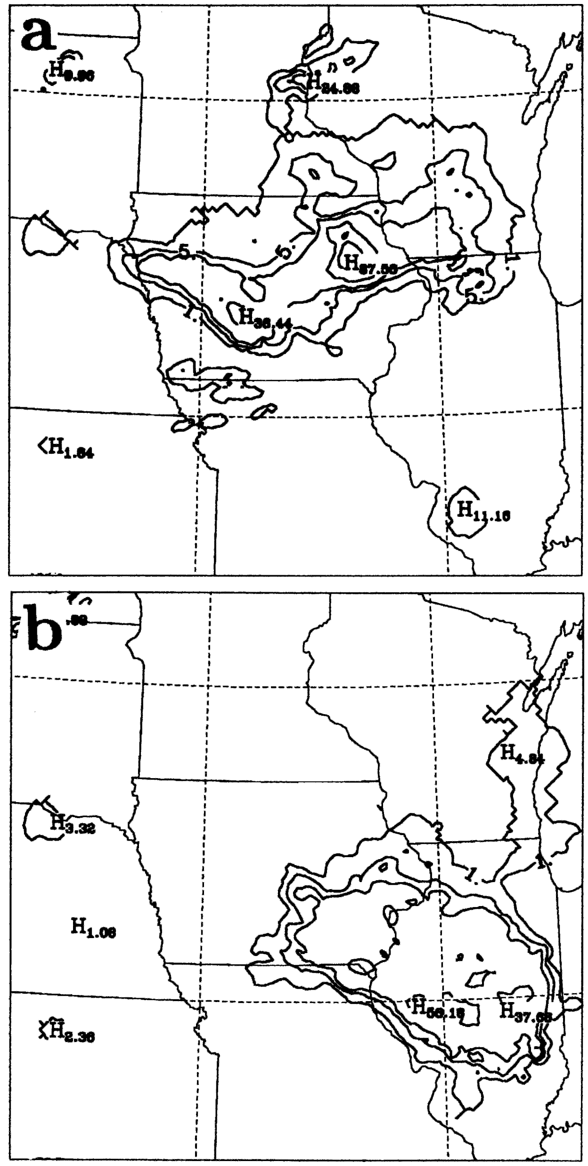

FIG. 5. Observed 6-hourly rainfall accumulations taken from stage IV 4-km gridded data averaged onto the Eta Model 10-km grid for the (a) 1200–1800 and (b) 1800–0000 UTC periods. Contours shown for 1, 5, 10, and 25 mm and every 25 mm above that.

3. Data and methodology

For the Eta, WRF, and MM5 simulations of the 4 June 1999 derecho event, a small domain of roughly 1000 km × 1000 km centered over Iowa was used (see Fig. 5 for domain region). A horizontal grid spacing of 10 km was used, and the three models were integrated to provide information over the period from 1200 UTC 4 June through 0000 UTC 5 June. Most of the simulations were initialized using 1200 UTC analyses from either the NCEP Eta or Global (AVN) models, but a few sensitivity tests were performed using an initialization at 0600 UTC based on the AVN analyses (to minimize any spinup effects that might influence the 1200 UTC runs). It should be noted that Gallus and Segal (2001) found little evidence of spinup problems in the 0–6-h precipitation forecasts from Eta runs using the modified Betts–Miller–Janjić (BMJ) convective scheme in a sample of 20 Midwest convective events, likely a result of NCEP's use of the BMJ scheme in its Eta data assimilation system. Spinup was more evident in the first few hours in Eta runs using the Kain–Fritsch (KF) scheme.

An examination of data availability for the 1200 UTC initializations showed no missing radiosonde winds at any sites in or near the model domain. The Eta three-dimensional variational data assimilation (3DVAR) scheme toss list for that time showed that no wind information was removed over the continental United States. It appears that these potential sources of error in the 1200 UTC analyses did not play a role for this case.

It should be noted that convection was ongoing at both the 0600 and 1200 UTC times used for initialization. Ongoing convection often causes problems in initialization datasets; poor initialization of the ongoing systems in this event may explain, at least partially, problems in the ensuing forecasts. The same limitations are routinely faced by operational models. For some runs, mesoscale initialization adjustments (Gallus and Segal 2001) were made to better depict small-scale features likely associated with ongoing convection at initialization time. These adjustments included (i) the use of a cold pool initialization scheme (Stensrud et al. 1999b), (ii) inclusion of mesonetwork surface observations using the model's own vertical diffusion formulation to allow the surface data to be assimilated into a deeper layer through a simulated initialization period, and (iii) addition of water vapor at points covered by radar echo to ensure relative humidities greater than 80% in the lower and middle troposphere. A summary of all model runs performed for the event is contained in Table 1.

For most runs, lateral boundary conditions were updated every 6 h. Tests of the sensitivity of rainfall forecasts to lateral boundary update frequency were performed with both the MM5 and Eta models using AVN output. Simulations were found to be generally unaffected by changes in the frequency from 6 to 12 or 6 to 3 h.

As discussed above, the derecho event of interest developed rapidly around 1200 UTC and exited the model domain by 0000 UTC. The short-range nature of the forecast and relatively weak synoptic forcing should help to minimize problems associated with the small domain size (Warner et al. 1997). A sensitivity test using the Eta Model with 10-km grid spacing on a much larger domain covering most of the United States showed almost no differences in the simulated rainfall compared to that valid for the smaller domain. In addition, operational Eta Model output (on a 40-km grid) for this case showed the same patterns of precipitation, further suggesting that lateral boundaries did not adversely affect the small domain forecasts.

Although three different models were used to simulate the event, 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). That version was run with 32 vertical layers. The second version of the Eta Model included upgrades present in NCEP's operational version in 2003. Perhaps the most important upgrade affecting the 4 June simulations was the replacement of the Zhao et al. (1991) explicit cloud water parameterization with the more sophisticated "Ferrier" microphysics (Ferrier et al. 2002). This version of the Eta Model was run with 38 vertical layers, although additional tests were performed using 60 layers. Both versions of the Eta Model included a modified Oregon State University (OSU) land surface parameterization (e.g., Pan and Mahrt 1987; Holtslag and Ek 1996; Chen et al. 1996). The moist physics in the model included options for either the modified BMJ convective parameterization (Betts 1986; Betts and Miller 1986; Janjić 1994) with both shallow and deep convection, or a version of the Kain–Fritsch (1993) parameterization that also accounts for shallow convection

TABLE 1. Summary of various model runs performed for the 4 Jun 1999 event. For initialization–boundary conditions, "rh" represents relative humidity adjustment, "mo" represents the vertical assimilation of mesoscale surface observations, and "cp" the use of the cold pool initialization procedure. All Eta and MM5 runs used the Eta PBL scheme; WRF runs used the MRF PBL with the exception of those listed as Eta-PBL in the column marked "other."

Model	Convective scheme	Initialization–BCs	Initialization time (UTC)	Other
Eta	BMJ	Eta	1200	
EtaNEW	BMJ	Eta	1200	
Eta	BMJ	Eta-rh	1200	
Eta	BMJ	Eta-cp	1200	
Eta	BMJ	Eta-mo	1200	
EtaNEW	BMJ	AVN	1200	
EtaNEW	BMJ	AVN-rh	1200	
Eta	KF	Eta	1200	
EtaNEW	KF	Eta	1200	
Eta	KF	Eta-rh	1200	
Eta	KF	Eta-cp	1200	
Eta	KF	Eta-mo	1200	
EtaNEW	KF	AVN	1200	
EtaNEW	KF	AVN-rh	1200	
WRF	BMJ	Eta	1200	
WRF	BMJ	AVN	1200	
WRF	BMJ	AVN	1200	Eta-PBL
WRF	KF	Eta	1200	
WRF	KF	AVN	1200	
WRF	KF	AVN	1200	Eta-PBL
MM5	BMJ	Eta	1200	
MM5	BMJ	AVN	1200	
MM5	KF2	AVN	1200	
WRF	BMJ	AVN	0600	
WRF	KF	AVN	0600	

(Kain 2004). A discussion of the basic differences between the two schemes is found in Gallus (1999) and Jankov and Gallus (2004a). Vertical turbulent exchange in the Eta analyses is calculated based on the Mellor–Yamada level 2.5 model (Mellor and Yamada 1974, 1982) with some recent modifications (Łobocki 1993; Gerrity et al. 1994).

The WRF model was developed as a joint effort between the operational and research meteorological communities, and research quality versions were made available by the end of 2002. One valuable feature of the WRF model is its framework for allowing the testing and implementation of numerous different physical process schemes, including options for radiation, land surface, boundary layer, turbulence, convection, and explicit microphysical schemes. For the simulations discussed in the present study, the WRF 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. Version 1.2.1 of WRF was used in the simulations of the 4 June system with NCEP-3 class (vapor, cloud–ice, and rain–snow) microphysics [generally similar to what was used in the Eta; Hong et al. (2004)]. The Monin and Obukhov (1954) scheme was used for the surface layer. The OSU land surface model was used, with the Medium-Range Forecast model planetary boundary layer (MRF PBL) scheme for most simulations. Sensitivity tests were done with the Ferrier and Lin et al. (1983) microphysics scheme, and the Eta PBL scheme.

Numerics also differed between the Eta and WRF models. The Eulerian mass-coordinate version of the WRF was used, with third-order Runge–Kutta time integration. Turbulent mixing used second-order diffusion on the coordinate surfaces. Four soil layers were used, as in the Eta Model. The time step in the WRF model (60 s) was twice that used in the Eta (30 s).

The MM5 model (Dudhia 1993) is a nonhydrostatic sigma coordinate variable-resolution mesoscale model that, like the WRF, offers numerous options for physical parameterizations. The MM5 was configured with 48 vertical levels and a time step of 15 s. For the simulations in the present study, Reisner 1 mixed-phase microphysics (Reisner et al. 1998) were used with the Eta PBL scheme. Both the Betts–Miller (BM; Betts 1986) and KF2 convective schemes were used. The BM in the MM5 differs slightly in its computation of a reference profile from that used in the BMJ scheme in the Eta Model (Cohen 2002). The KF2 scheme is different than the KF scheme used in the Eta Model because the relative humidity based parcel perturbation (which assists in triggering convection in the Eta Model) is not used in KF2.

Model rainfall forecasts were compared to 4-km stage IV multisensor observations, which were areally averaged onto the Eta Model's 10-km grid using procedures similar to those used at NCEP. These data have been used in other studies of these convective events (Gallus and Segal 2001; Jankov and Gallus 2004a,b). For the WRF and MM5 model runs, the grid boxes closely matched those of the Eta Model, but a very small amount of bilinear interpolation was needed to create an exact match to allow straightforward computation and comparison of objective skill measures. A subjective comparison was made of the rainfall plotted directly onto the model grid, and on the interpolated grid, and differences were negligible.

To objectively evaluate the rainfall forecasts, traditional skill scores such as the equitable threat score (ETS; Schaefer 1990) and bias were computed for a range of precipitation thresholds. The ETS is defined as

$$\mathrm{ETS} = \frac{(\mathrm{CFA} - \mathrm{CHA})}{(F + O - \mathrm{CFA} - \mathrm{CHA})}, \qquad (1)$$

where CFA is the number of grid points where rainfall was correctly forecasted to exceed the specified threshold (a "hit"), F is the total number of grid points where rainfall was forecasted to exceed the threshold, O the number of observed grid points where rainfall exceeded the threshold, and CHA is a measure of the number of grid points where a correct forecast would occur by chance, where CHA is

$$\mathrm{CHA} = O\frac{F}{V} \qquad (2)$$

and V is the total number of grid points evaluated. The bias is the ratio of all grid points forecasted to have rainfall to the number of grid points where rainfall was observed:

$$\mathrm{bias} = \frac{F}{O}. \qquad (3)$$

These objective measures were applied to the entire model domain. To better demonstrate the model's depictions of the derecho event, 6-hourly plots of simulated rainfall also will be shown.

4. Results

Despite the fact that simulations of the 4 June 1999 derecho event were performed with 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 the numerical output. In the discussion

TABLE 2. ETSs for model runs discussed in the paper valid for 6-hourly rainfall accumulations in the 1200–1800 UTC 4 Jun 1999 period equal to or exceeding threshold values of 0.254, 1.27, 2.54, 6.35, 9.52, 12.7, and 25.4 mm. Naming convention for the model runs follows model-convective scheme-initialization-other adjustments.

Run	Precipitation threshold (mm)						
	0.254	1.27	2.54	6.35	9.52	12.7	25.4
Eta-BMJ-Etain	0.063	0.048	0.003	−0.027	−0.022	−0.012	0.000
EtaNEW-BMJ-Etain	0.053	0.005	−0.022	−0.028	−0.017	−0.004	0.000
Eta-BMJ-EtainRH	0.134	0.108	0.069	0.011	−0.024	−0.011	0.000
Eta-BMJ-EtainCP	0.026	−0.002	−0.037	−0.039	−0.026	−0.009	0.000
Eta-BMJ-EtainMO	0.039	0.023	−0.014	−0.035	−0.029	−0.016	0.000
EtaNEW-BMJ-AVNin	0.173	0.125	0.102	0.032	−0.003	0.000	0.000
EtaNEW-BMJ-AVNinRH	0.242	0.234	0.221	0.208	0.143	−0.003	0.000
Eta-KF-Etain	0.045	0.021	−0.008	−0.021	−0.015	−0.009	0.000
EtaNEW-KF-Etain	0.055	0.043	−0.008	−0.022	−0.019	−0.012	0.000
Eta-KF-EtainRH	0.124	0.068	0.032	−0.017	−0.014	−0.009	−0.001
Eta-KF-EtainCP	0.049	0.027	−0.001	−0.018	−0.014	−0.005	0.000
Eta-KF-EtainMO	0.043	0.015	−0.010	−0.019	−0.014	−0.009	0.000
EtaNEW-KF-AVNin	0.150	0.059	−0.002	0.020	0.000	0.000	0.000
EtaNEW-KF-AVNinRH	0.197	0.154	0.115	0.048	0.028	−0.007	0.000
WRF-BMJ-Etain-MRFPBL	0.173	0.057	−0.032	−0.024	−0.015	−0.004	0.000
WRF-BMJ-AVNin-MRFPBL	0.173	0.147	0.110	0.032	−0.002	0.000	0.000
WRF-BMJ-AVNin-EtaPBL	0.154	0.142	0.086	−0.020	−0.007	−0.001	0.000
WRF-KF-Etain-MRFPBL	0.034	0.030	−0.004	−0.017	−0.013	−0.008	0.000
WRF-KF-AVNin-MRFPBL	0.237	0.239	0.155	−0.002	−0.005	−0.002	0.000
WRF-KF-AVNin-EtaPBL	0.156	0.165	0.130	0.032	−0.003	−0.004	0.000
MM5-BM-Etain	0.201	0.158	0.070	−0.009	−0.006	−0.003	0.000
MM5-BM-AVNin	0.079	0.083	−0.010	−0.017	−0.009	−0.004	0.000
MM5-KF-AVNin	0.153	0.108	0.030	−0.004	−0.001	−0.000	0.000
WRF-BMJ-AVNIN-6Z	−0.25	−0.031	−0.030	−0.045	−0.029	−0.017	−0.001
WRF-BMJ-AVNIN-6Z	0.080	0.044	0.016	−0.014	−0.009	−0.006	0.000

below, the lack of skill will be shown both through objective measures that evaluate model performance over the entire domain and subjectively through the use of rainfall forecast maps that allow a closer evaluation of the derecho event alone.

a. *Objective measures*

1) 1200–1800 UTC 4 JUNE

Precipitation forecasts valid for 6-h periods throughout the Midwest during the 1200–0000 UTC period of 4–5 June showed little skill as measured by the equitable threat score (Tables 2 and 4). The Eta Model running with the BMJ convective scheme and initialized from NCEP's Eta analysis, for instance, had a peak ETS of only 0.063 for the lightest rainfall threshold evaluated for the 1200–1800 UTC period for the run initialized at 1200 UTC (Table 2). The updated Eta Model (with Ferrier microphysics) had even lower ETSs. Both of these versions of the model also exhibited high biases (overprediction of areal coverage) for light rainfall amounts (2.54 mm or less) and low biases for heavier amounts (Table 3).

The use of the KF scheme instead of the BMJ scheme did not improve results. ETSs (Table 2) were comparable to the BMJ runs in both the older and newer versions of the Eta Model. However, the bias scores (Table 3) were very different, with large underestimates of areal coverage for all thresholds in the older Eta and for all but the lightest amounts in the newer version of the Eta Model. As shown in Jankov and Gallus (2004b), these ETSs were much lower than the average values for 10-km Eta runs initialized at 1200 UTC for a sample of 10 warm season MCSs in the Midwest.

Gallus and Segal (2001) investigated the impacts of improved depiction of mesoscale features in the initialization of 10-km Eta runs on warm season rainfall forecasts and found that no initialization adjustment improved ETSs by a statistically significant amount over a range of all thresholds on a consistent basis, although an adjustment to remove low relative humidity values (by setting a minimum threshold of 80%) in areas of radar echo to try to force rapid activation of convective schemes did lead to statistically significant, albeit small, improvements to ETSs for lighter rainfall amounts. The 4 June case was not an exception, with no improvements from the use of a cold pool scheme (Stensrud et

TABLE 3. As in Table 2 except for bias scores.

Run	Precipitation threshold (mm)						
	0.254	1.27	2.54	6.35	9.52	12.7	25.4
Eta-BMJ-Etain	1.689	1.665	1.442	0.898	0.685	0.444	0.012
EtaNEW-BMJ-Etain	1.814	1.782	1.507	0.712	0.388	0.117	0.000
Eta-BMJ-EtainRH	1.824	1.809	1.628	1.285	0.962	0.427	0.000
Eta-BMJ-EtainCP	1.573	1.519	1.385	1.007	0.777	0.313	0.049
Eta-BMJ-EtainMO	1.662	1.813	1.658	1.171	1.011	0.737	0.000
EtaNEW-BMJ-AVNin	1.743	1.957	1.610	0.431	0.045	0.000	0.000
EtaNEW-BMJ-AVNinRH	1.664	1.852	1.679	1.129	0.643	0.089	0.000
Eta-KF-Etain	0.454	0.435	0.324	0.367	0.339	0.313	0.000
EtaNEW-KF-Etain	1.027	0.878	0.659	0.420	0.455	0.453	0.000
Eta-KF-EtainRH	0.583	0.572	0.458	0.436	0.388	0.318	0.098
Eta-KF-EtainCP	0.445	0.373	0.298	0.313	0.299	0.140	0.000
Eta-KF-EtainMO	0.436	0.375	0.311	0.347	0.317	0.246	0.000
EtaNEW-KF-AVNin	0.920	0.383	0.016	0.000	0.000	0.000	0.000
EtaNEW-KF-AVNinRH	1.121	1.080	0.893	0.462	0.431	0.405	0.000
WRF-BMJ-Etain-MRFPBL	1.462	1.074	0.802	0.478	0.330	0.123	0.000
WRF-BMJ-AVNin-MRFPBL	1.682	1.755	1.302	0.166	0.207	0.000	0.000
WRF-BMJ-AVNin-EtaPBL	1.694	1.750	1.454	0.343	0.139	0.017	0.000
WRF-KF-Etain-MRFPBL	1.073	0.950	0.524	0.297	0.288	0.263	0.000
WRF-KF-AVNin-MRFPBL	0.816	0.825	0.720	0.193	0.092	0.061	0.000
WRF-KF-AVNin-EtaPBL	0.954	0.972	0.905	0.372	0.154	0.109	0.000
MM5-BM-Etain	1.018	0.800	0.460	0.127	0.121	0.084	0.000
MM5-BM-AVNin	1.328	0.925	0.602	0.262	0.170	0.117	0.000
MM5-KF-AVNin	0.808	0.643	0.358	0.059	0.016	0.006	0.000
WRF-BMJ-AVNin-6Z	1.472	1.580	1.505	1.355	0.944	0.760	0.085
WRF-KF-AVNin-6Z	1.037	1.113	1.038	0.581	0.355	0.204	0.037

al. 1999b) or the inclusion of surface mesonetwork observations readily available in much of this region (Table 2). It should be noted that although a clear outflow boundary signal was present in the observations (Fig. 1b), none existed in either the Eta or the AVN analyses used for initialization. The failure of the initial data to contain this feature may have played some role in the poor forecasts since it is well known that outflow boundaries influence propagation and evolution, including upscale growth, of convective systems (e.g., Rotunno et al. 1988). However, the failure of both the cold pool scheme and the inclusion of mesoscale surface observations to improve the forecasts for this event suggest that the missing outflow boundary was not the primary cause of the forecast problems. The relative humidity adjustment did lead to improvements in the 1200–1800 UTC forecast period, although any skill was marginal and confined to only the 0.254- and 1.27-mm thresholds. The high bias at lighter thresholds in the BMJ runs worsened, however (Table 3).

The Eta simulations discussed above were rerun using AVN model output for initial and boundary conditions. It should be noted that AVN output was only available on a coarser 80-km grid, which could degrade the depiction of mesoscale details important to the forecast. As shown in Table 2, ETSs were higher in the Eta runs using the AVN initial and boundary condition data, although any skill was still confined to rainfall amounts of 2.54 mm or less in the Eta-BMJ run. The relative humidity adjustment, which led to improvement in the runs initialized with Eta input, again resulted in noticeable improvements to the AVN-initialized runs. In the BMJ run, ETSs were between 0.2 and 0.25 for thresholds of 6.35 mm or less, values near the averages found for ETSs by Jankov and Gallus (2004b). A high bias was present for the same thresholds, however (Table 3).

In the Eta-KF run, ETSs were not as high, but did exceed 0.1 for thresholds of 2.54 mm or less with biases close to 1.0. As will be shown later, however, the improvements in the forecast for all of the Eta runs initialized with AVN output were confined to the first few hours of the forecast, and the derecho itself was not simulated.

ETSs for the WRF runs showed some of the same trends as in the Eta runs (Table 2). For instance, the WRF initialized with AVN output and using the MRF PBL and BMJ convective schemes received generally higher ETSs than the same model configuration initialized with Eta output. Even so, ETSs were only above 0.10 for the lightest three thresholds in the AVN-initialized run. A high bias (Table 3) was present for

TABLE 4. As in Table 2 except for the 1800–0000 UTC 4–5 Jun 1999 period.

Run	Precipitation threshold (mm)						
	0.254	1.27	2.54	6.35	9.52	12.7	25.4
Eta-BMJ-Etain	0.021	0.107	0.173	0.186	0.074	0.005	0.000
EtaNEW-BMJ-Etain	0.028	0.059	0.099	0.072	0.027	0.000	0.000
Eta-BMJ-EtainRH	0.023	0.104	0.182	0.196	0.104	0.026	0.000
Eta-BMJ-EtainCP	0.068	0.122	0.172	0.246	0.111	0.012	0.000
Eta-BMJ-EtainMO	0.034	0.076	0.131	0.154	0.069	0.014	0.000
EtaNEW-BMJ-AVNin	0.066	0.011	−0.049	−0.010	−0.001	0.000	0.000
EtaNEW-BMJ-AVNinRH	0.277	0.266	0.187	−0.029	−0.008	0.000	0.000
Eta-KF-Etain	−0.021	−0.033	0.012	0.026	0.017	−0.005	−0.001
EtaNEW-KF-Etain	0.101	0.144	0.154	0.108	0.037	0.000	0.000
Eta-KF-EtainRH	−0.018	−0.002	0.007	0.015	0.010	−0.007	−0.001
Eta-KF-EtainCP	0.004	0.026	0.037	0.027	0.023	−0.003	0.000
Eta-KF-EtainMO	−0.017	0.015	0.034	0.026	0.022	−0.002	−0.001
EtaNEW-KF-AVNin	0.149	0.127	0.070	−0.023	−0.018	−0.011	0.000
EtaNEW-KF-AVNinRH	0.165	0.151	0.104	−0.020	−0.022	−0.014	−0.002
WRF-BMJ-Etain-MRFPBL	0.096	0.138	0.226	0.167	0.076	−0.004	0.000
WRF-BMJ-AVNin-MRFPBL	0.093	0.048	−0.020	−0.012	−0.007	−0.003	0.000
WRF-BMJ-AVNin-EtaPBL	0.152	0.079	0.015	−0.008	−0.005	−0.001	0.000
WRF-KF-Etain-MRFPBL	−0.029	−0.004	0.006	0.012	0.011	0.012	−0.002
WRF-KF-AVNin-MRFPBL	0.101	0.075	0.062	0.013	0.004	−0.005	−0.003
WRF-KF-AVNin-EtaPBL	0.125	0.083	0.062	0.015	−0.003	−0.012	−0.002
MM5-BM-Etain	−0.045	−0.030	−0.021	−0.001	−0.001	0.000	0.000
MM5-BM-AVNin	0.008	0.027	0.033	0.028	0.017	0.011	0.000
MM5-KF-AVNin	0.138	0.181	0.160	0.021	−0.004	−0.005	0.000
WRF-BMJ-AVNin-6Z	0.053	0.016	0.042	−0.012	−0.009	−0.006	0.000
WRF-KF-AVNin-6Z	0.063	0.028	0.010	0.025	0.015	0.000	−0.004

lighter thresholds and a low bias for heavier ones (generally 6.35 mm or more). A switch in the AVN-initialized WRF from the MRF PBL to the Eta PBL scheme did not improve the forecast at this time. For the WRF runs using the KF scheme (with MRF PBL), the difference in ETSs between the AVN and Eta initialized runs was more pronounced than in the WRF-BMJ runs. ETSs were much higher for the AVN-initialized run than in the WRF with BMJ, but were lower in the Eta-initialized run. The higher ETSs were restricted, however, to rainfall amounts of 2.54 mm or less, and as will be shown later, the better skill was due to a better depiction of the rain area associated with the original MCS in the northeastern part of the domain and not due to the depiction of the derecho event, which was completely missed. Finally, when the Eta PBL scheme was substituted in the AVN-initialized run, ETSs generally decreased.

In the MM5 run using the BM scheme with Eta initialization, ETSs for the lightest two thresholds were reasonably good in the 1200–1800 UTC period, peaking at 0.201 for 0.254 mm, but no skill was evident for amounts greater than 2.54 mm. The bias score (Table 3) was near 1.0 for the lightest threshold, but then exhibited a strong low bias at all other thresholds, similar to many of the KF runs with the Eta and WRF models. The switch to an AVN initialization resulted in worse ETSs at all thresholds (Table 2). Biases were generally higher than in the Eta-initialized run, but exhibited the same trends (Table 3). The MM5 run using the KF scheme with AVN initialization had ETSs roughly halfway between the other two MM5 runs, and the worst low bias problem of all MM5 runs.

2) 1800–0000 UTC 4–5 JUNE

In the following 6 h (1800–0000 UTC 4–5 June), ETSs continued to indicate little skill in the rainfall forecasts of all models examined (Table 4). The older version of the Eta Model and the newer one (both with the BMJ convective scheme) indicated little skill for the lightest threshold and most heavier ones. Skill peaked for amounts between 2.54 and 6.35 mm, but ETSs still never exceeded 0.186. ETSs for the newer Eta were noticeably lower for these thresholds. Biases (Table 5) showed the same trends present in the previous 6-h forecast period, with overestimates of areal coverage for light rain and huge underestimates for heavy rain. Mesoscale changes in the initialization did not appreciably change the ETSs, and as found by Gallus and Segal (2001), the relative humidity adjustment had less impact at this longer forecast range (not shown) than in the 0–6-h forecast period.

TABLE 5. As in Table 3 except for the 1800–0000 UTC 4–5 Jun 1999 period.

Run	Precipitation threshold (mm)						
	0.254	1.27	2.54	6.35	9.52	12.7	25.4
Eta-BMJ-Etain	1.611	1.624	1.441	0.542	0.263	0.099	0.000
EtaNEW-BMJ-Etain	1.894	1.846	1.338	0.107	0.036	0.000	0.000
Eta-BMJ-EtainRH	1.916	1.841	1.521	0.435	0.251	0.146	0.000
Eta-BMJ-EtainCP	1.364	1.558	1.539	0.505	0.240	0.094	0.000
Eta-BMJ-EtainMO	1.544	1.812	1.631	0.613	0.290	0.156	0.000
EtaNEW-BMJ-AVNin	1.228	1.122	0.776	0.111	0.006	0.000	0.000
EtaNEW-BMJ-AVNinRH	1.360	1.430	1.227	0.433	0.099	0.000	0.000
Eta-KF-Etain	1.040	0.853	0.541	0.203	0.135	0.090	0.228
EtaNEW-KF-Etain	1.681	1.694	1.325	0.475	0.211	0.104	0.000
Eta-KF-EtainRH	1.162	0.900	0.601	0.263	0.201	0.153	0.158
Eta-KF-EtainCP	1.069	0.674	0.319	0.135	0.080	0.031	0.000
Eta-KF-EtainMO	1.356	1.122	0.596	0.153	0.100	0.078	0.250
EtaNEW-KF-AVNin	1.671	1.391	0.806	0.280	0.240	0.214	0.000
EtaNEW-KF-AVNinRH	1.547	1.635	1.385	0.520	0.344	0.293	0.632
WRF-BMJ-Etain-MRFPBL	1.622	1.383	1.185	0.596	0.255	0.075	0.000
WRF-BMJ-AVNin-MRFPBL	1.485	1.221	0.657	0.126	0.078	0.054	0.000
WRF-BMJ-AVNin-EtaPBL	1.564	1.116	0.651	0.097	0.060	0.010	0.000
WRF-KF-Etain-MRFPBL	1.048	0.959	0.914	0.673	0.527	0.447	0.404
WRF-KF-AVNin-MRFPBL	1.459	1.495	1.343	0.594	0.303	0.207	0.754
WRF-KF-AVNin-EtaPBL	1.894	1.931	1.579	0.551	0.352	0.270	0.649
MM5-BM-Etain	0.253	0.211	0.162	0.012	0.013	0.008	0.000
MM5-BM-AVNin	0.274	0.196	0.154	0.045	0.026	0.019	0.000
MM5-KF-AVNin	1.278	1.382	1.228	0.498	0.266	0.112	0.000
WRF-BMJ-AVNin-6Z	1.194	1.036	0.627	0.132	0.101	0.102	0.000
WRF-KF-AVNin-6Z	1.286	1.400	1.362	0.945	0.732	0.612	1.842

When the KF scheme was used in the Eta Model, ETSs consistently showed no skill in the older version of the Eta. In the newer version, ETSs were noticeably higher with the peak ETS (still modest) at the 2.54-mm threshold. As with the BMJ runs, mesoscale initialization adjustments had almost no impact on the ETSs (not shown). Biases were generally too low in the older Eta (Table 5) but the newer version resulted in bias errors similar to those present in the BMJ runs.

Unlike in the first 6 h of the forecast, the Eta initialized with AVN output (using the MRF PBL scheme) received much lower ETSs than that initialized with Eta output. Almost no skill was apparent at any threshold. Of interest, when the relative humidity adjustment was made to the AVN initial data, the ETSs for thresholds of 2.54 mm or less did increase markedly, with the value of 0.277 for the lightest threshold being the highest ETS computed for any model run for this event. Unfortunately, no skill existed for amounts greater than 2.54 mm and, as will be shown later, little evidence of the derecho event existed. Although the same trend of a high bias for light amounts and a low bias for heavy amounts was present in the AVN-initialized runs, the positive bias errors were not as severe as in the Eta-initialized runs (Table 5).

When the AVN was used to initialize the Eta Model using the KF scheme, ETSs were generally lower than when the Eta was used for initialization, except at the first threshold. Thus, the AVN initial data seemed to have a negative impact on runs using both convective schemes during the 6–12-h forecast period.

The WRF runs using the BMJ scheme for this period earned ETSs roughly comparable to the Eta runs with the BMJ scheme. The WRF initialized with Eta output had its highest ETS for a threshold of 2.54 mm. The WRF initialized with AVN output had generally lower ETSs, with the peak value at the lightest threshold. A small improvement occurred in the peak ETS when the PBL scheme was switched from MRF to Eta. Similar to the Eta runs, a high bias was present for light rainfall with a very low bias for heavy rain. When the KF scheme was used, ETSs indicated no skill at any threshold for the rain using the MRF PBL and Eta initial conditions. Bias errors were generally small, though, for light rainfall, with the same large underestimate of heavy rain that was present in all other runs showing up for heavier thresholds. The use of AVN output for initial conditions improved ETSs by a small amount. A further small increase occurred when the PBL scheme was switched to the Eta. Bias errors for these runs were positive for light rainfall and negative for heavy amounts.

The MM5 run using the BM scheme and an Eta initialization during this time evidenced the worst ETSs with no skill for any threshold. These low ETSs were associated with extremely low biases, and as will be discussed later, this MM5 run produced almost no precipitation in the domain during the period, missing the derecho event entirely. The MM5-BM with AVN initialization likewise showed no skill in ETSs at all thresholds, with biases comparable to the Eta-initialized run. The MM5 run using the KF scheme with AVN initialization had higher ETSs with some marginal skill for rainfall amounts of 2.54 mm or less with no skill above that threshold. Its bias scores exhibited the same trend as most model runs examined, with high bias for light rain and low bias for heavy rain.

As noted earlier, in addition to the runs above, all initialized at 1200 UTC, the WRF model was run using 0600 UTC AVN output for initialization and boundary conditions to test whether or not some of the problems in the forecast were related to spinup and the fact the convective systems were already ongoing at 1200 UTC. The WRF was run with both the BMJ and KF convective schemes, and some tests were performed with differing microphysical schemes available in that model (Ferrier, NCEP-5 class). In Tables 2 and 4, it can be seen that the earlier initialization time did not improve the forecast from that using 1200 UTC data. In fact, during the 1200–1800 UTC period, the BMJ run had no skill at any threshold, and the KF run had only marginal skill for the lightest threshold. The bias trends were slightly different from the 1200 UTC runs, with a more gradual trend from high biases at light amounts to low biases at heavier amounts. In the 1800–0000 UTC period, both the BMJ and KF runs again had low ETSs at nearly all thresholds. The BMJ run demonstrated similar bias trends as the 1200 UTC WRF-BMJ initialized with AVN output. The KF run again had a more gradual decrease in bias from light to heavy rainfall amounts than the 1200 UTC initialized WRF-KF run. It thus appears from ETSs that problems in the forecast related to 1200 UTC initialization data are not corrected for by using a 0600 UTC initialization.

b. Precipitation plots

1) Observations

Although the objective measures discussed above show poor performance from every model at nearly all thresholds, the numbers do not provide many details about the model depiction of the derecho event alone. As discussed earlier, there were several observed rainfall systems present at 1200 UTC when most of the model versions were initialized. One dying MCS covered a rather large area in northeastern Iowa, southeastern Minnesota, and adjoining states to the east. The derecho event was beginning at this time as a rather isolated cell began upscale growth in far western Iowa. A few other scattered areas of rain were present in smaller regions to the south of these convective elements. The observed rainfall during the 1200–1800 UTC period can be seen in Fig. 5a. 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 extreme west-central Iowa into the center of the state came from the derecho system.

During the following 6 h (1800–0000 UTC), the dissipating MCS stopped producing appreciable rainfall in the domain (Fig. 5b), except for some light amounts in Wisconsin. 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.

2) Eta simulations

Figure 6 shows the 6-h accumulated rainfall in the Eta Model using the BMJ convective scheme initialized with Eta output. The older version of the Eta produces too large a region covered in very light rainfall in the first 6 h (Fig. 6a). Most of the precipitation in Missouri was not observed. 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 not propagate east. The updated Eta Model (primarily new microphysics) generally exhibited similar problems to the older version during this time (Fig. 6b).

As discussed in Jankov and Gallus (2004b), the relative humidity adjustment applied to the older Eta Model did result in the simulation of some rainfall associated with the derecho (Fig. 6c) during the first 6 h of the forecast. However, hourly rainfall plots (see Jankov and Gallus 2004b) indicated that the system was not sustained in the model, with all rainfall gone by 1500 UTC. This can be inferred by the lack of precipitation shown for a large portion of south-central Iowa downstream from the maximum farther northwest.

In the following 6 h (1800–0000 UTC) the older Eta version produced a large area of rainfall in Minnesota

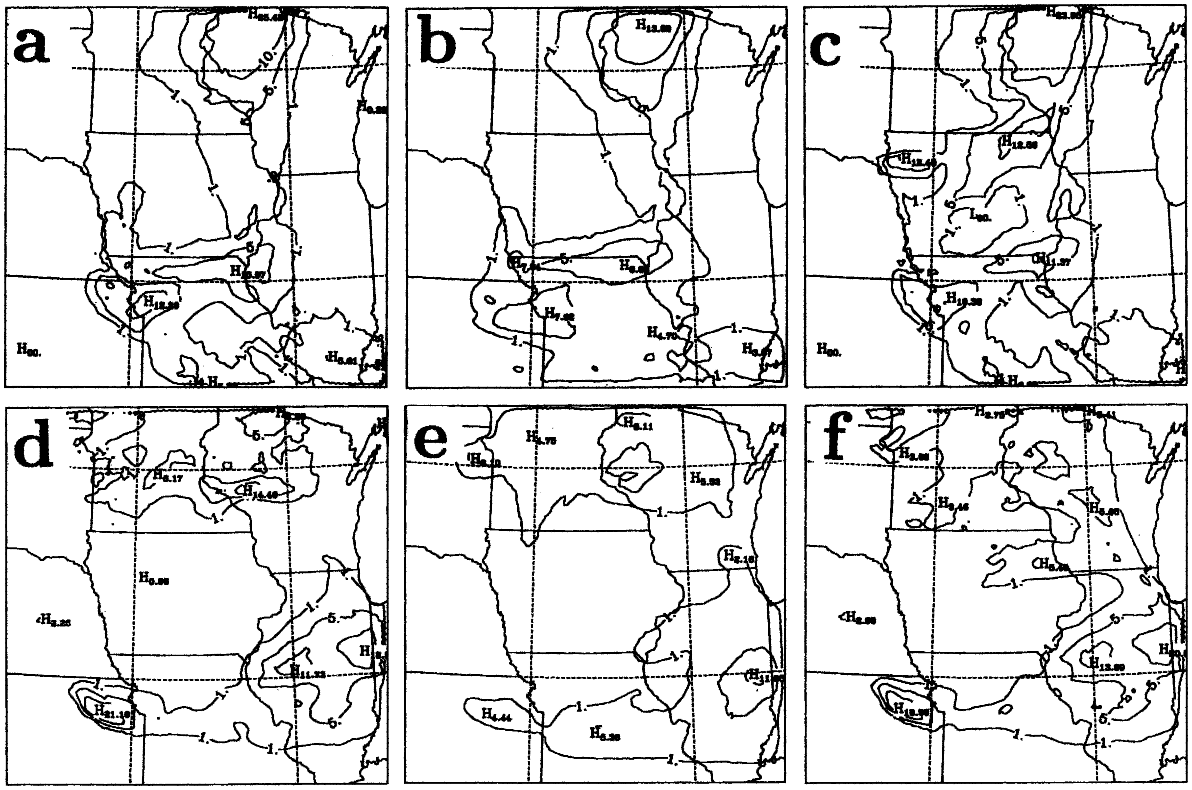

FIG. 6. The 6-hourly rainfall accumulations from the Eta Model using the BMJ convective scheme, initialized with Eta output for (a), (b), (c) 1200–1800 and (d), (e), (f) 1800–0000 UTC periods. (a), (d) Output from the older Eta version and (b), (e) from the newer version (different microphysics), and (c), (f) from the older version with relative humidity adjustment at initialization. Contours are the same as in Fig. 5.

where none was observed (Fig. 6d). The model continued to lack 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 1800 UTC, roughly 100 km ahead of the location of the derecho at that time. Amounts were greatly underestimated. The newer version of the Eta showed even less evidence of an organized precipitation system propagating southeast from Iowa across Illinois during this time (Fig. 6e), and produced generally lighter rainfall amounts. By this 6-h time period, the effects of the relative humidity adjustment had nearly vanished (Fig. 6f) and the precipitation plot resembled that of the original Eta run (Fig. 6d).

The Eta Model run with the KF scheme and the Eta initial and boundary condition input likewise failed to produce the derecho system. The older Eta version in the first 6 h (Fig. 7a) evidenced some of the same problems in its depiction of the northeastern Iowa system as the Eta with the BMJ scheme (Fig. 6a). However, the KF run had fewer problems with false alarm rainfall in Missouri. The updated Eta Model with the KF scheme (Fig. 7b) 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. 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 (Fig. 6c), the rainfall was confined to the first few hours of the forecast, and no noticeable improvements occurred to the forecast of the derecho itself.

During the following 6 h (Fig. 7c), the older Eta with the KF scheme 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 0000 UTC. Unfortunately this rainfall in the model occurred earlier in the simulation (primarily between 1800 and 2100 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 during this time had a somewhat larger areal coverage of rainfall (Fig. 7d), so that the Minne-

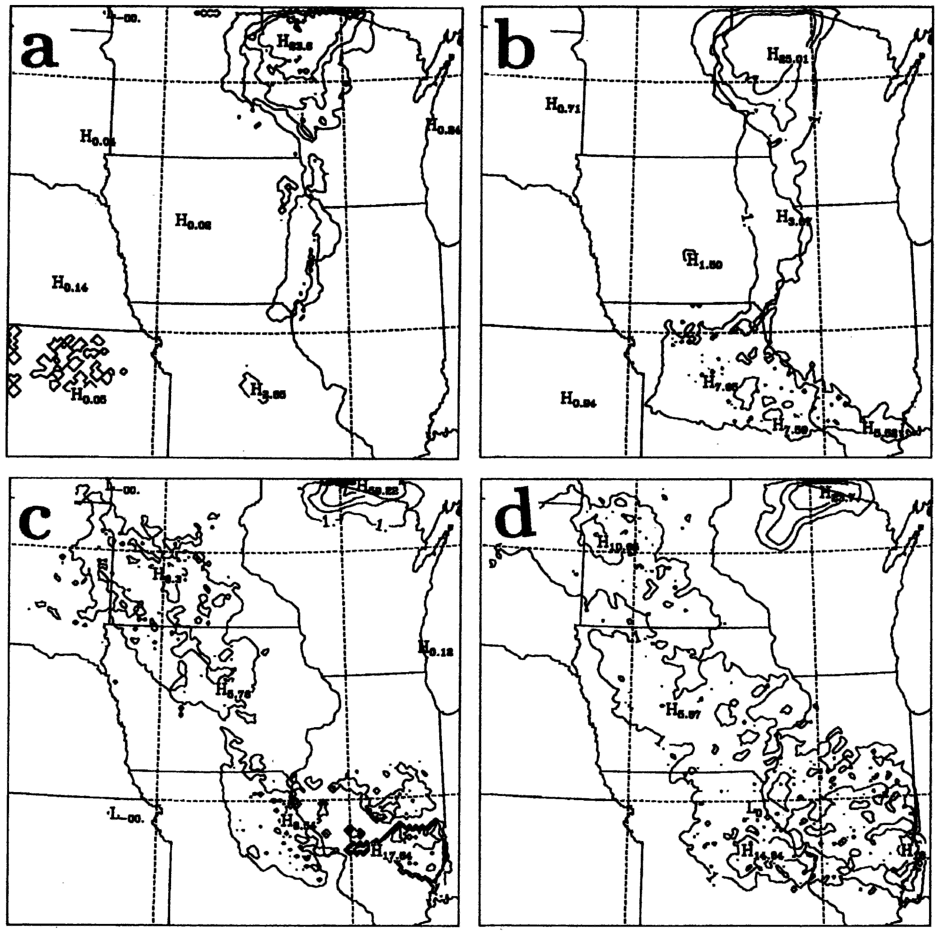

FIG. 7. Same as in Fig. 6, but using the KF convective scheme. (a), (c) Output from the older Eta version and (b), (d) from the newer version. Contours are the same as in Fig. 5.

sota 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 of no more than a few millimeters. It would be difficult to find any evidence from the rainfall forecast of a well-organized MCS.

The use of different initial and boundary condition input had a substantial, though not necessarily beneficial, impact on the rainfall forecast in the domain. When the AVN output was used instead of Eta output in the updated Eta runs using the BMJ scheme (Fig. 8), the model better depicted the system whose maximum rainfall in the 1200–1800 UTC period was over northeastern Iowa (Fig. 8a). 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.

Table 2 showed that some of the best ETSs for light rainfall amounts occurred in the updated Eta when the AVN output used for initialization was adjusted to remove dry layers in the relative humidity where radar echoes were present at initialization time. The improved forecast can be seen in Fig. 8b. The relative humidity adjustment can be shown here to increase the volume of water predicted in the system over northeastern Iowa, perhaps more effectively drawing the attention of forecasters to this region. Regarding the derecho, a small area of light rain was predicted in northwestern Iowa, and although it weakened over time, it could be tracked east-southeastward through much of the 12-h period along a path very similar to that taken by the derecho (Fig. 9).

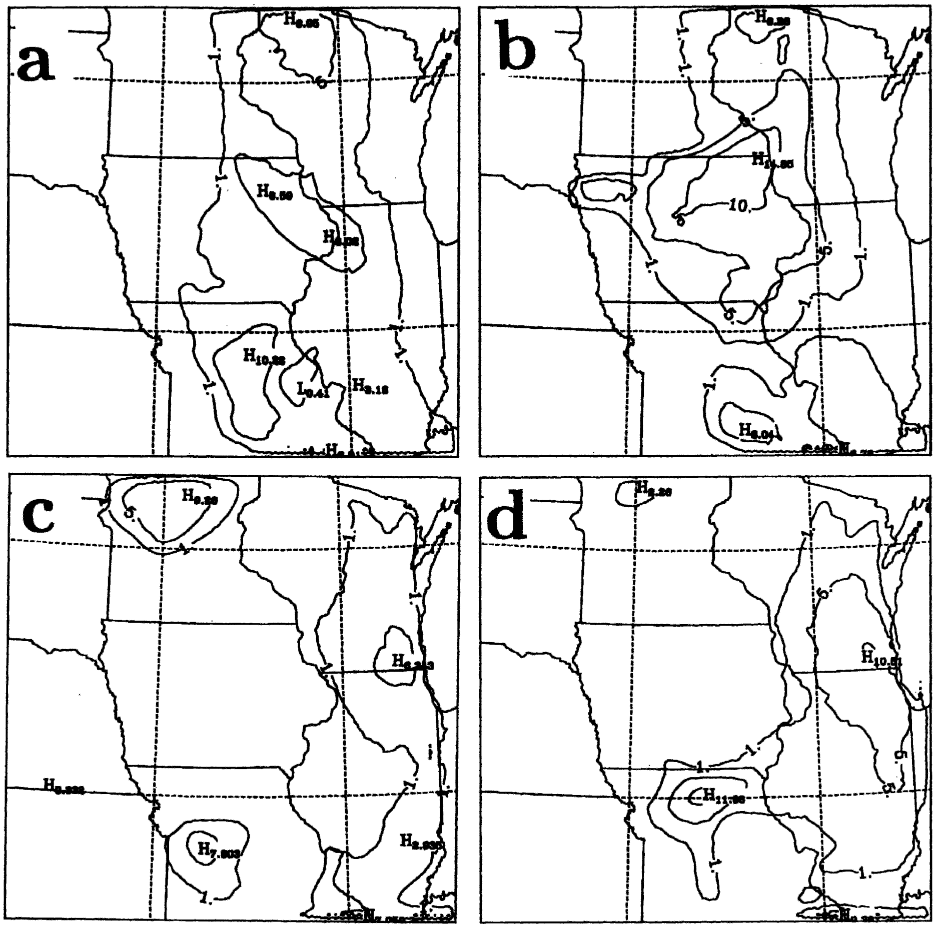

FIG. 8. Same as in Fig. 6, but using the BMJ convective scheme initialized with AVN output. (a), (c) Output from the newer Eta version and (b), (d) from the newer version with the relative humidity adjustment applied during initialization. Contours are the same as in Fig. 5.

During the 1800–0000 UTC period, the forecasts initialized from AVN output worsened appreciably compared to the already bad prediction of the Eta-initialized Eta. In the updated Eta version, 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. 8c), 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. The main impact of the relative humidity adjustment in this Eta run during the 1800–0000 UTC period (Fig. 8d) was to shift a bogus rainfall maximum from western Missouri to north-central Missouri, closer to an observed area but still outside of it. Very light rainfall (1–2 mm) covered the Illinois portion of the derecho path, but this rain appeared to be as much due to a weak extension of the main area of rain from the overpredicted dissipating MCS to the northeast as from the small system tracking southeastward from Iowa.

As mentioned earlier, however, hourly rainfall accumulations ending at 1300, 1500, 1700, 1900, and 2100 UTC (Fig. 9) in this relative humidity adjustment run hint that some type of system was present (with very light rain) tracking southeastward following a path near the centroid of the derecho at most times. However, the model greatly underestimated the intensity of rainfall, showing hourly amounts of 3 mm or less, whereas observed amounts reached 8 mm by 1500 UTC, and 15–32 mm at all other times. Nonetheless, this particular model run offers the best hope that some set of initial conditions and model configuration might have been able to provide forecasters with useful guidance that a significant derecho and heavy rain event would track across Iowa and Illinois on this day. As such, further

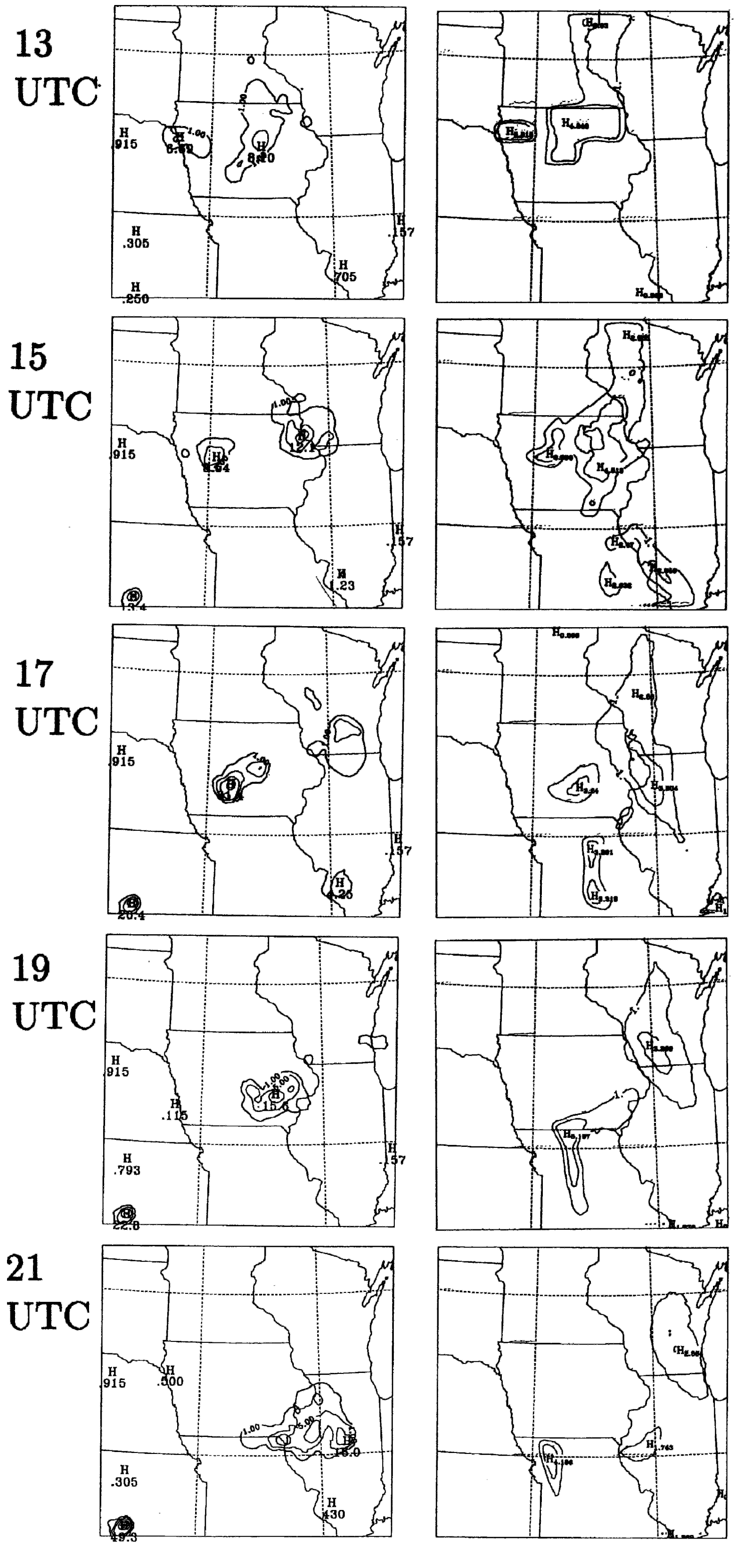

FIG. 9. Hourly rainfall totals from (left column) the stage IV observations and (right column) the updated Eta Model with BMJ scheme using AVN initialization and relative humidity adjustment for accumulations ending at 1300, 1500, 1700, 1900, and 2100 UTC. Contours are at 1, 5, 10, and 15 mm for observations (left column) and 1 and 2 mm for the simulation.

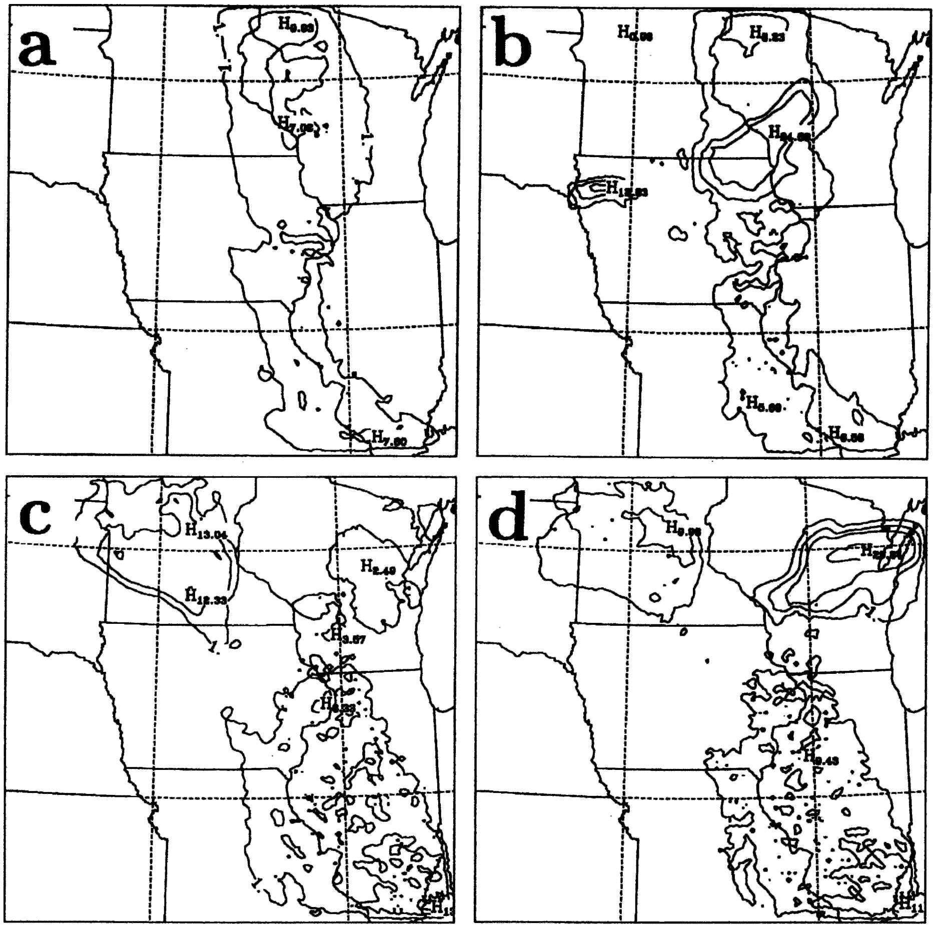

FIG. 10. Same as in Fig. 8 except using the KF convective scheme.

discussion of this simulation will follow in a later section.

The newer Eta with the KF scheme using the AVN output for initialization (Fig. 10) did not indicate as big an improvement over the Eta-initialized KF run (Fig. 7) as was apparent with the BMJ scheme (Figs. 6 and 8). In the first 6 h, the primary change in the standard AVN-initialized run was for less rainfall to be found in the large rain region over Wisconsin than in the Eta-initialized run (Fig. 10a). However, the rainfall was still displaced too far north from the observed MCS over northeastern Iowa. The relative humidity adjustment to the AVN-initialized KF run had resulted in relatively higher ETSs compared to many other runs in the 1200–1800 UTC period (Table 2) and the reason can be seen in its precipitation field (Fig. 10b). Much heavier rainfall amounts are produced in the northern MCS system, and the peak values are shifted southward so that the displacement error is much smaller (100–200 km) than that of the run without the adjustment. In addition, the adjustment does result in the model simulating some rainfall in northwestern Iowa, but unlike the BMJ run, the system dissipates quickly. In the following 6 h, the main change in the standard run (Fig. 10c) was a reduction in the peak rainfall amounts within the larger bands in the AVN-initialized run than in the Eta one (Fig. 7c). During this time, in the relative humidity adjustment run, the general forecast of the derecho system remains very poor (Fig. 10d).

3) WRF SIMULATIONS

The WRF simulations of this event differed in some ways from the Eta runs, but shared the unfortunate characteristic of not producing the derecho. The WRF run initialized with Eta output and using the BMJ scheme (Fig. 11a) showed a false alarm system with nearly stationary heavy rainfall over the Missouri River region of northeastern Kansas and northwestern Missouri during the 1200–1800 UTC period. The model did a poor job of showing both observed MCSs. When AVN output was substituted for the initial and boundary conditions in WRF-BMJ, the incorrect system near

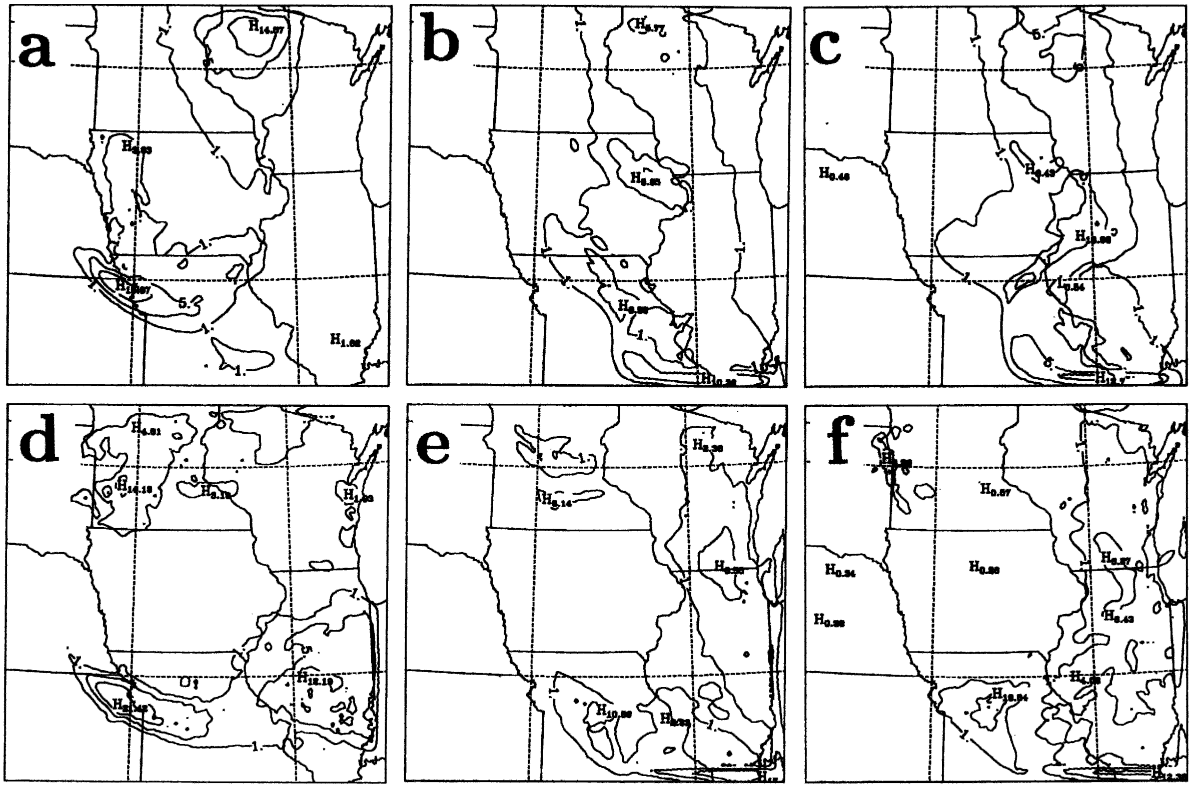

FIG. 11. Same as in Fig. 6, but with rainfall accumulations from the WRF model using the BMJ convective scheme. (a), (d) Output from the run initialized with Eta output, (b), (e) initialized from AVN output, and (c), (f) initialized from AVN output and using the Eta PBL scheme instead of the MRF. Contours the same as in Fig. 5.

the Kansas–Missouri border disappeared, but otherwise the forecast remained poor (Fig. 11b) with no sign of the derecho and large areas of false precipitation in eastern Missouri and Illinois. The northeastern Iowa MCS was better depicted than in the Eta-initialized WRF run, although as was common in all model runs, rainfall amounts were underestimated by a factor of 10 (Fig. 11b).

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 WRF-BMJ run with the AVN initialization was repeated using the Eta PBL scheme instead of the MRF scheme. In the first 6 h (Fig. 11c) the change in the PBL scheme generally led to only small changes in the rainfall forecast, 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 1800 UTC, the observed system was approximately 150 km northwest of here.

During the 1800–0000 UTC period, the rainfall field in the WRF-BMJ run initialized with Eta output (Fig. 11d) strongly resembled that present in the older Eta-BMJ initialized with Eta output (Fig. 6d), with some rain over the path taken by the derecho in central Illinois from 2100 to 0000 UTC. Hourly output (not shown) indicated the simulated rainfall region remained roughly stationary during the 1800–0000 UTC period, and did not exhibit the correct rapid southeastward propagation of the derecho. When the initial and boundary conditions were switched to use the AVN analyses (Fig. 11e), the model did a particularly poor job with the derecho, showing a minimum in rainfall along the path of the observed event.

In the WRF-BMJ run that used the Eta PBL scheme instead of the MRF scheme, the enhanced area of precipitation present during 1200–1800 UTC (Fig. 11c) lacked temporal continuity, and the rainfall field in the following 6 h (Fig. 11f) was not much better than in the run using the MRF PBL scheme (Fig. 11e). No useful signal of the derecho existed. Additional tests were performed switching from the NCEP-3 class microphysics to that of 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.

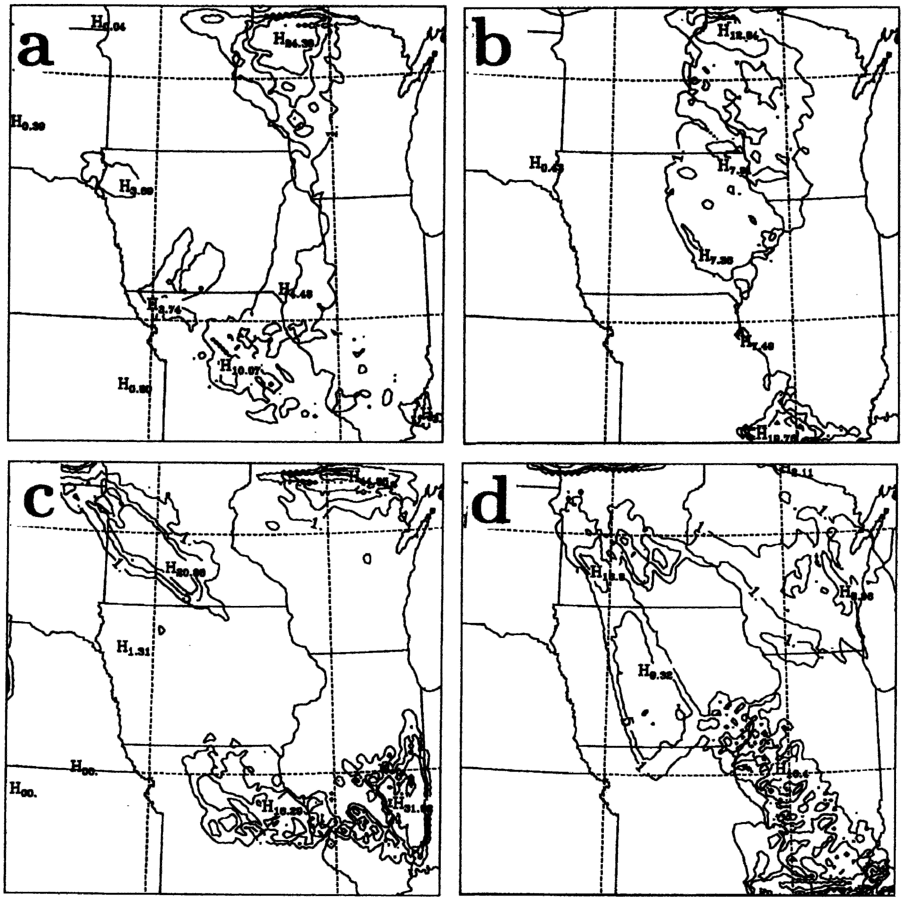

FIG. 12. Same as in Fig. 11, but using the KF convective scheme. (a), (c) Output from the run initialized with Eta output and (b), (d) initialized from AVN output. Contours are the same as in Fig. 5.

The WRF run using the KF scheme initialized with Eta output (Figs. 12a and 12c) resembled the Eta runs with the KF scheme initialized with Eta output (Fig. 7). The northeastern Iowa MCS was displaced far to the north. The derecho path was generally rain free in the model. The WRF-KF run did produce a small area of light rain in northwestern Iowa in the first 6 h (Fig. 12a) but this system was not sustained. It is worth noting that in only the WRF-BMJ and WRF-KF runs initialized with Eta output (Figs. 11a and 12a) did the model produce any rain in northwestern Iowa without an adjustment to the initialized relative humidity. The switch to AVN initial and boundary condition data weakened the incorrect precipitation maximum (compared to the Eta-initialized WRF run) in far northern Wisconsin from 1200 to 1800 UTC (Fig. 12b) and broadened slightly the area of light rain depicted near the observed MCS in northeastern Iowa. However, the different initial conditions eliminated the rainfall area that had appeared in northwestern Iowa.

As in the Eta-KF runs, heavy rainfall did occur in the WRF-KF run in the 1800–0000 UTC period (Fig. 12c) in southeastern Illinois around the area where the derecho arrived just prior to 0000 UTC. The incorrect rainfall depicted in Minnesota was more sharply focused in the WRF run than in the Eta runs. In the run where the initialization was provided by the AVN analyses instead of the Eta analyses, an area of rainfall could be seen in the model in west-central Iowa during this time (Fig. 12d) that was not present in the other model versions. No rain was observed over most of this region. Hourly output (not shown) showed that rainfall in northeastern Iowa during the first few hours of the simulation was followed by a band that slowly developed westward, possibly along the western edge of a cool pool. This band was located in central Iowa between 1800 and 2100 UTC and moved into western Iowa from 2100 to 0000 UTC. Farther southeast, this model version did depict a broad NNW–SSE band of rainfall in western Illinois, roughly occupying the southwestern half of the observed derecho track. However, hourly output (not shown) indicated the convection was not organized, and occurred in random spots over the full 6 h, thus not providing useful guidance that a sustained derecho event would be occurring. The replacement of the MRF PBL scheme with the Eta scheme in the WRF-KF run led to only minor changes in the rainfall forecast (not shown).

Because none of the model runs starting at 1200 UTC, whether initialized with Eta or with AVN output, were able to capture the derecho event and most did poorly with the northeastern Iowa MCS, one might suspect that the ongoing nature of the observed systems at 1200 UTC led to forecast problems because of model spinup 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 rerun with a 0600 UTC initialization based on AVN output (Eta output was not available from NCEP at this time). The BMJ run rainfall fields are shown in Fig. 13. It appears in this case that problems in the 1200–1800 UTC period (Fig. 13a) are just as bad with the earlier initialization, with almost no rain in northeastern Iowa and no sign of the derecho event. Instead, the model produces a large MCS-like system in Missouri that was not observed. In the following 6 h (Fig. 13b), the forecast bears almost no resemblance to the observations. The WRF-KF run initialized at 0600 UTC (not shown) looks surprisingly similar to the 1200 UTC initialized run with the same problems as that run (Figs. 12b and 12d).

4) MM5 SIMULATIONS

The MM5 also failed to forecast either system well. The MM5 running with the BM scheme and Eta initialization had no evidence of the derecho event in the 1200–1800 UTC period (not shown) and a broad band of light rain running north–south across the domain instead of the concentrated MCS in northeastern Iowa (with some evidence of boundary-induced enhanced rainfall near the north and south edges of the domain). It had one of the driest solutions of all in the 1800–0000 UTC period (not shown) 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 Kansas–Missouri border area in the first 6 h, and a shift of the small rainfall area in southern Illinois in the Eta-initialized run northward by 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). As such, it completely missed the derecho event in the first 6 h, and although it did indicate rainfall over much of the derecho path in the 1800–0000 UTC period, the rainfall was disorganized with random small elements of 5–14 mm of rainfall continuously developing throughout the 6-h period.

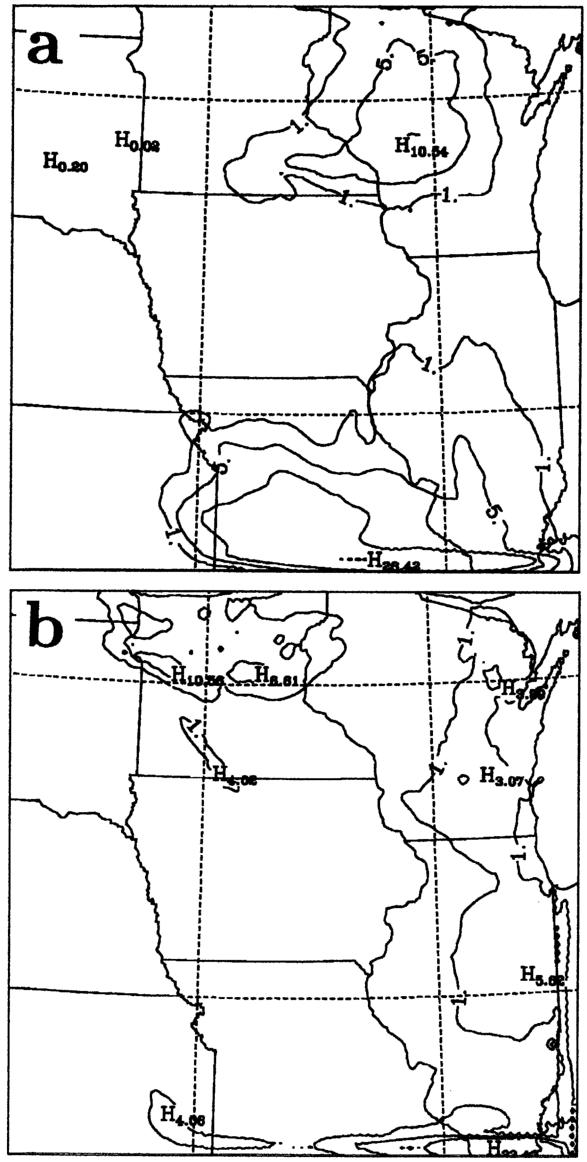

FIG. 13. The 6-hourly rainfall accumulations valid for (a) 1200–1800 and (b) 1800–0000 UTC 4–5 Jun 1999 from the WRF model with BMJ scheme using 0600 UTC AVN initialization data. Contours are the same as in Fig. 5.

5. Summary and discussion

A damaging derecho event accompanied by substantial rainfall occurred after 1200 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 1200 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 better represent mesoscale features and help initiate convection where radar echo was present at initialization time. Although the study emphasized runs initialized at 1200 UTC, some additional runs were performed using 0600 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 1200–1800 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.

WRF-BMJ runs initialized with Eta output did show a small region of light rain in northwestern Iowa near where the MCS began, but otherwise, only the runs that used a relative humidity adjustment in the initialized data to force the model to produce some precipitation showed any distinct enhancement in rainfall in that area, and even in these runs, the peak amounts only reached 12 mm. In the following 6 h (1800–0000 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 (but not occurring with a system persistent in space and time).

In addition to the general dry bias with respect to heavy rain in all models, the northeastern Iowa MCS was displaced far to the north in nearly all model versions except for a few initialized from AVN output. In particular, the WRF-BMJ with AVN initialization and the Eta-BMJ did shift the region of maximum rainfall farther south to near northeastern Iowa. The AVN output did not improve the large displacement error in all cases, however. The large errors remained in all runs using the KF scheme, except for one where the relative humidity adjustment was made to the initial conditions. In addition, the MM5 run with the BMJ scheme and AVN initialization still had the large displacement error.

For the derecho event, runs with initializations based on both the Eta and AVN output failed to depict the system. Most model runs did produce some rainfall over Illinois during the afternoon (1800–0000 UTC) but often only near the end of the derecho path, and with incorrect timing and propagation. The only runs to show any sustained precipitation in the first 6 h 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 h (Figs. 6c, 8b, 10b). 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 h after this time.

Only 1 of the 25 model runs examined suggested that any portion of the northwest Iowa system would remain active for more than 6 h. The newer Eta Model with the BMJ convective scheme and initialized with AVN output and the relative humidity adjustment (to eliminate dry low- and midtropospheric layers with relative humidity less than 80% in areas where radar echo was present at initialization time) did have a slightly enhanced area of rainfall that could be tracked into Illinois through 2100 UTC (Fig. 8). However, the peak rainfall in this system was only ~3 mm during the 1500–1800 UTC period, and 1–2 mm in the following hours before dissipation, around 2100 UTC.

A series of sensitivity tests were done to see if the forecasts could be improved further by adjusting two arbitrary parameters within the relative humidity adjustment scheme: the minimum relative humidity threshold (the lowest humidity allowed at levels warmer than $-10°C$ where radar echo was present) and the definition of locations of active convection at the 1200 UTC initialization time (based on radar echo coverage and intensity). It was found that a higher minimum relative humidity threshold [90% and 95% compared to the standard 80% used in Gallus and Segal (2001)] resulted in a slight enhancement of northwestern Iowa rainfall in the first 2 h (from ~5 mm in the 80% case to ~8 mm with higher humidity) but no increase at later times, and dissipation an hour earlier on its southeastward track. Finer definition of the existing radar echoes (including using only points with reflectivities above a higher threshold) led to only slight changes in the shape of the system.

The fact that such a large range of models and configurations all failed to simulate the derecho event suggests that model error (errors related to model design and not initial and boundary condition data) 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. It should also be noted that the problems likely cannot be attributed to the use of convective schemes alone. Tests performed with no convective parameterization at 10- and 4-km grid spacing resulted in almost no rainfall in the domain, and thus no improvement in the guidance (not shown). Additional tests with a modified form of the BMJ scheme designed to greatly limit deep convection (Ferrier 2004) in the Eta Model resulted in large changes in the rainfall forecast compared to standard BMJ runs, but still no derecho system. Likewise, tests with a few other convective schemes available in the MM5 [Grell (Grell 1993) and Kuo (Anthes 1977)] revealed some differences in the rainfall forecasts from the runs using BM and KF2, but forecasts remained poor with little or no rainfall simulated along the derecho path, and little evidence of any convective system behaving similarly to the observed derecho event. Although it is true that our study has investigated only a portion of the full parameter space (all known physical process parameterizations), the evidence clearly suggests that it is likely any model configuration running currently available parameterizations will have great difficulty simulating this event with grid spacings of 4 km or coarser.

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. Some additional tests were done in the Eta Model alone using a third initial and boundary condition dataset, the Rapid Update Cycle (RUC; Benjamin et al. 1994, 1998). Unlike the runs that used Eta and AVN output, these RUC-based runs used analyses (instead of forecasts) for the lateral boundary conditions (RUC forecast output was not available to us). Despite the fact the RUC model is known for the quality of its analyses (e.g., Thompson et al. 2003), these RUC-based forecasts also failed to simulate the derecho event, with rainfall forecasts in the first 6 h resembling a mix of those that used Eta and AVN output. In the next 6 h, the forecasts looked like those using Eta output but with the incorrect rainfall in the northern part of the domain being much more intense and shifted south into northern Iowa.

It thus appears that useful forecasts of systems such as this one may require a much better observation network than what now exists, or better methods of including additional information from radar and satellites. These seemingly "unforecastable" systems will likely continue to be a problem for some time to come (e.g., a similar unpredicted system occurred in the same general region on 17 September 2004). It should be noted that Jankov and Gallus (2004b) 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 *some events may be unpredictable with currently existing models, observational datasets, and assimilation systems,* and *even ensemble systems may offer limited useful guidance for some events.* It must be acknowledged that our set of simulations would constitute a "poor man's" ensemble (Ebert 2001); a more sophisticated ensemble system might have the potential to provide a little better guidance. Finally, cases such as this one might serve as a good test for new parameterizations or models since so much room for improvement exists, although the apparent problems in the initialization datasets would argue against using this case to calibrate a model. Likewise, assuming all necessary data have 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 (Jian et al. 2003).

Acknowledgments. The authors thank Mike Baldwin for providing some of the codes necessary for verification of the simulations. Additional thanks are given to Dr. John Kain for assistance in implementing the Kain–Fritsch scheme in the Eta Model, and Brent Shaw of NOAA's Forecast Systems Laboratory and David Flory at Iowa State for help in performing some WRF runs. A few additional runs were performed by Aaron Todd and Elise Johnson at Iowa State University. This work was supported by the National Science Foundation Grant ATM-0226059.

REFERENCES

Alhamed, A., S. Lakshmivarahan, and D. J. Stensrud, 2002: Cluster analysis of multimodel ensemble data from SAMEX. *Mon. Wea. Rev.,* **130,** 226–256.

Anthes, R. A., 1977: A cumulus parameterization scheme utilizing a one-dimensional cloud model. *Mon. Wea. Rev.,* **105,** 270–286.

Benjamin, S. G., K. F. Brundage, P. A. Miller, T. L. Smith, G. A. Grell, D. Kim, J. M. Brown, and T. W. Schlatter, 1994: The Rapid Update Cycle at NMC. Preprints, *10th Conf. on Numerical Weather Prediction,* Portland, OR, Amer. Meteor. Soc., 566–568.

——, J. M. Brown, K. F. Brundage, B. E. Schwartz, T. G. Smirnova, and T. L. Smith, 1998: The operational RUC-2. Preprints, *16th Conf. on Weather Analysis and Forecasting,* Phoenix, AZ, Amer. Meteor. Soc., 249–252.

Bentley, M. L., and T. L. Mote, 1998: A climatology of derecho-producing mesoscale convective systems in the central and eastern United States, 1986–95. Part I: Temporal and spatial distribution. *Bull. Amer. Meteor. Soc.,* **79,** 2527–2540.

Betts, A. K., 1986: A new convective adjustment scheme. Part I: Observational and theoretical basis. *Quart. J. Roy. Meteor. Soc.,* **112,** 677–692.

——, and M. J. Miller, 1986: A new convective adjustment scheme. Part II: Single column tests using GATE wave, BOMEX, ATEX, and arctic air-mass data sets. *Quart. J. Roy. Meteor. Soc.,* **112,** 693–709.

Chen, F., and Coauthors, 1996: Modeling of land surface evaporation by four schemes and comparison with FIFE observations. *J. Geophys. Res.,* **101,** 7251–7277.

Cohen, C., 2002: A comparison of the cumulus parameterizations in idealized sea-breeze simulations. *Mon. Wea. Rev.,* **130,** 2554–2571.

Correia, J., Jr., and R. W. Arritt, 2004: Preliminary results from a real time, time to space conversion for surface analysis. Preprints, *16th Conf. on Numerical Weather Prediction,* Seattle, WA, Amer. Meteor. Soc., CD-ROM, P1.4.

Dudhia, J., 1993: A nonhydrostatic version of the Penn State–NCAR mesoscale model: Validation tests and simulation of an Atlantic cyclone and cold front. *Mon. Wea. Rev.,* **121,** 1493–1513.

Ebert, E. E., 2001: Ability of a poor man's ensemble to predict the probability and distribution of precipitation. *Mon. Wea. Rev.,* **129,** 2461–2480.

Ferrier, B. S., 2004: Modification of two convective schemes used in the NCEP Eta Model. Preprints, *16th Conf. on Numerical Weather Prediction,* Seattle, WA, Amer. Meteor. Soc., CD-ROM, J4.2.

——, Y. Jin, T. Black, E. Rogers, and G. DiMego, 2002: Implementation of a new grid-scale cloud and precipitation scheme in NCEP Eta Model. Preprints*, 15th Conf. on Numerical Weather Prediction,* San Antonio, TX, Amer. Meteor. Soc., 280–283.

Fujita, T., 1955: Results of detailed synoptic studies of squall lines. *Tellus,* **4,** 405–436.

Gallus, W. A., Jr., 1999: Eta simulations of three extreme precipitation events: Impact of resolution and choice of convective parameterization. *Wea. Forecasting,* **14,** 405–426.

——, and M. Segal, 2001: Impact of improved initialization of mesoscale features on convective system rainfall in 10-km Eta simulations. *Wea. Forecasting,* **16,** 680–696.

Gerrity, J. P., T. L. Black, and R. E. Treadon, 1994: On the numerical solution of the Mellor–Yamada level 2.5 turbulent kinetic energy equation in the Eta Model. *Mon. Wea. Rev.,* **122,** 1640–1646.

Grell, G. A., 1993: Prognostic evaluation of assumptions used by cumulus parameterizations. *Mon. Wea. Rev.,* **121,** 764–787.

Hamill, T. M., and S. J. Colucci, 1998: Evaluation of the Eta RSM ensemble probabilistic precipitation forecasts. *Mon. Wea. Rev.,* **126,** 711–724.

Holtslag, A. A., and M. Ek, 1996: Simulation of surface fluxes and boundary layer development over the pine forest in HAPEX-MOBILHY. *J. Appl. Meteor.,* **35,** 202–213.

Hong, S.-Y., J. Dudhia, and S.-H. Chen, 2004: A revised approach to ice microphysical processes for the bulk parameterization of clouds and precipitation. *Mon. Wea. Rev.,* **132,** 103–120.

Hou, D., E. Kalnay, and K. K. Droegemeier, 2001: Objective verification of the SAMEX '98 ensemble forecasts. *Mon. Wea. Rev.,* **129,** 73–91.

Janjić, Z. I., 1994: The step-mountain eta coordinate model: Further developments of the convection, viscous sublayer, and turbulence closure schemes. *Mon. Wea. Rev.,* **122,** 928–945.

Jankov, I., and W. A. Gallus Jr., 2004a: MCS rainfall forecast accuracy as a function of large-scale forcing. *Wea. Forecasting,* **19,** 428–439.

——, and ——, 2004b: Some contrasts between good and bad forecasts of warm season convective system rainfall. *J. Hydrol.,* **288,** 122–152.

Jian, G.-J., S.-L. Shieh, and J. McGinley, 2003: Precipitation simulation associated with Typhoon Sinlaku (2002) in Taiwan area using the LAPS diabatic initialization for MM5. *Terr. Atmos. Oceanic Sci.,* **14,** 1–28.

Johns, R. H., and W. D. Hirt, 1987: Derechos: Widespread convectively induced windstorms. *Wea. Forecasting,* **2,** 32–49.

Kain, J. S., 2004: The Kain–Fritsch convective parameterization: An update. *J. Appl. Meteor.,* **43,** 170–181.

——, and J. M. Fritsch, 1993: Convective parameterization for mesoscale models: The Kain–Fritsch scheme. *The Representation of Cumulus Convection in Numerical Models, Meteor. Monogr.,* No. 46, Amer. Meteor. Soc., 165–170.

Lin, Y.-L., R. D. Farley, and H. D. Orville, 1983: Bulk parameterization of the snow field in a cloud model. *J. Climate Appl. Meteor.,* **22,** 1065–1092.

Łobocki, L., 1993: A procedure for the derivation of surface-layer bulk relationships from simplified second-order closure models. *J. Appl. Meteor.,* **32,** 126–138.

Mass, C. F., D. Ovens, K. Westrick, and B. A. Colle, 2002: Does increasing horizontal resolution produce more skillful forecasts? The results of two years of real-time numerical weather prediction over the Pacific Northwest. *Bull. Amer. Meteor. Soc.,* **83,** 407–430.

Mellor, G. L., and T. Yamada, 1974: A hierarchy of turbulence closure models for planetary boundary layers. *J. Atmos. Sci.,* **31,** 1791–1806.

——, and ——, 1982: Development of a turbulence closure model for geophysical fluid problems. *Rev. Geophys. Space Phys.,* **20,** 851–875.

Monin, A. S., and A. M. Obukhov, 1954: Basic laws of turbulent mixing in the ground layer of the atmosphere. *Trans. Geophys. Inst. Akad. Nauk. USSR,* **151,** 163–187.

Mullen, S. L., and R. Buizza, 2001: Quantitative precipitation forecasts over the United States by the ECMWF Ensemble Prediction System. *Mon. Wea. Rev.,* **129,** 638–663.

NCDC, 1999: *Storm Data.* Vol. 41, No. 6, 324 pp.

Olson, D. A., N. W. Junker, and B. Korty, 1995: Evaluation of 33 years of quantitative precipitation forecasting at the NMC. *Wea. Forecasting,* **10,** 498–511.

Pan, H.-L., and L. Mahrt, 1987: Interaction between soil hydrology and boundary-layer development. *Bound.-Layer Meteor.,* **38,** 185–202.

Reisner, J., R. J. Rasmussen, and R. T. Bruitjes, 1998: Explicit forecasting of super-cooled liquid water in winter storms using the MM5 mesoscale model. *Quart. J. Roy. Meteor. Soc.,* **124,** 1071–1107.

Rotunno, R., J. B. Klemp, and M. L. Weisman, 1988: A theory for strong, long-lived squall lines. *J. Atmos. Sci.,* **45,** 463–485.

Schaefer, J. T., 1990: The critical success index as an indicator of warning skill. *Wea. Forecasting,* **5,** 570–575.

Skamarock, W. C., J. B. Klemp, and J. Dudhia, 2001: Prototypes for the WRF (Weather Research and Forecasting) model. Preprints, *Ninth Conf. on Mesoscale Processes,* Fort Lauderdale, FL, Amer. Meteor. Soc., J11–J15.

Stensrud, D. J., and J. M. Fritsch, 1994: Mesoscale convective systems in weakly forced large-scale environments. Part III: Numerical simulations and implications for operational forecasting. *Mon. Wea. Rev.,* **122,** 2084–2104.

——, H. E. Brooks, J. Du, M. S. Tracton, and E. Rogers, 1999a: Using ensembles for short-range forecasting. *Mon. Wea. Rev.,* **127,** 433–446.

——, G. S. Manikin, E. Rogers, and K. E. Mitchell, 1999b: Importance of cold pools to NCEP mesoscale Eta Model forecasts. *Wea. Forecasting,* **14,** 650–670.

——, J.-W. Bao, and T. T. Warner, 2000: Using initial condition and model physics perturbations in short-range ensemble simulations of mesoscale convective systems. *Mon. Wea. Rev.,* **128,** 2077–2107.

Thompson, R. L., R. Edwards, J. A. Hart, K. L. Elmore, and P. Markowski, 2003: Close proximity soundings within supercell environments obtained from the Rapid Update Cycle. *Wea. Forecasting,* **18,** 1243–1261.

Tracton, M. S., and E. Kalnay, 1993: Operational ensemble prediction at the National Meteorological Center: Practical aspects. *Wea. Forecasting,* **8,** 379–398.

Wandishin, M. S., S. L. Mullen, D. J. Stensrud, and H. E. Brooks, 2001: Evalution of a short-range multimodel ensemble system. *Mon. Wea. Rev.,* **129,** 729–747.

Wang, W., and N. L. Seaman, 1997: A comparison study of convective parameterization schemes in a mesoscale model. *Mon. Wea. Rev.,* **125,** 252–278.

Warner, T. T., R. A. Peterson, and R. E. Treadon, 1997: A tutorial on lateral boundary conditions as a basic and potentially serious limitation to numerical weather prediction. *Bull. Amer. Meteor. Soc.,* **78,** 2599–2617.

Zhao, Q., F. H. Carr, and G. B. Lesins, 1991: Improvement of precipitation forecasts by including cloud water in NMC's Eta Model. Preprints, *Ninth Conf. on Numerical Weather Prediction,* Denver, CO, Amer. Meteor. Soc., 50–53.