17.2 The Promise and Challenge of Explicit Convective Forecasting with the WRF Model

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1. Introduction

Convective weather remains a significant challenge for numerical weather prediction systems, and is recognized as a major contributor to poor warm season quantitative precipitation forecasting (QPF). During the recent Bow Echo and MCV Experiment (BAMEX; Davis et al., 2004), and again, this past spring and summer (1 May through 31 July 2004), 36h realtime forecasts were conducted daily with the NCAR version 1.3 of WRF (WRF-EM), using a 4 km horizontal grid resolution over the central US (Fig. 1). A grid resolution of 4 km is nominally considered sufficient to represent mesoscale convective systems explicitly without the need for parameterization (e.g., Weisman et al. 1997), but is still insufficient for representing many cell-scale processes that are critical for severe weather forecasting (e.g., individual supercells are not properly represented; see also Bryan et al. 2003). Use of a 4 km grid over a single large domain, rather than using selective embedded high resolution windows, avoids the potential problems associated with mismatched model physics across windowed model boundaries (e.g., explicit convection on inner grid versus parameterized convection on outer grid; e.g. Warner et al. 1997).

The overall goal of these exercises was to determine if there is any increased skill in such convective-system-resolving forecasts during the warm season, measured objectively or subjectively, as compared to coarser resolution simulations using more standard convective parameterizations (e.g., operational ETA, 10 km WRF-EM, etc.). A more generic goal was simply to establish a better sense of the predictability of convective outbreaks over a 12-36 h period, and to better understand the factors that might be limiting this predictability within current numerical forecast models.

This effort should be distinguished from current nowcasting efforts which seek to improve very short term (1-6 h) convective forecasts, and which can rely heavily on the use of radar and computationally expensive assimilation techniques. In the present exercises, no assimilation was applied, and, thus, convection must develop purely in response to the local resolved forcings as specified in the initial state. We were actually quite surprised at how quickly this ``spin-up'' process occurred, with mature convective systems quite often being accurately reproduced within 3-5 h of model initialization (see also Skamarock 2004). This offered us confidence that our results for the 12 h + forecast periods were not unduly influenced by the simple cold-start procedure. Further discussion of this important issue, however, is beyond the scope of the current paper.

Other WRF-model specifics for these exercises included the use of 35 levels in the vertical, spaced roughly 250 m apart in the lowest km with monotonic stretching to about 1 km spacing near and above 14 km. The model top was set at 50 hPa. The basic physics packages included the Yonsai University (YSU) boundary layer scheme (Noh et al. 2001), the Oregon State University (OSU) land surface model (Chen and Dudhia 2001), and the Lin Microphysics scheme (derived from the original scheme described in Lin et al. 1983). The model was initialized at 00 UTC using the 40 km ETA analysis, with the boundary conditions updated on a 3 hourly interval using the ETA model forecasts. The

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lack of a convective trigger function for a 4 km grid resolution was initially a point of concern in designing these experiments. Our experiences, however, suggest that explicit convective triggering at such resolutions is sufficient in most cases, if not actually a bit overdone at times. These 4 km forecasts were also compared to equivalent 10 km WRF-EM forecasts as well as to the 12 km operational ETA model, which both employed convective parameterization. An updated version of the Kain-Fritsch convection scheme (Kain 2004) was included in the 10 km WRF runs. WRF output was generally available by 8:00 AM each morning.

2. Preliminary Results

Overall, we found that the 4km simulations did a surprisingly good job at forecasting the timing, location, and mode of convective system organization in the 12 to 36 h time period. Examples of some of the better forecasts are presented in Figs. 2 and 3, which depict the ability of WRF-EM to predict an intense bow echo system over Iowa and Nebraska 30 h in advance, as well as a line of strong, isolated cells over Illinois 23 h in advance (a line of tornadic supercells was observed). WRF was also quite adept at generating and maintaining observed MCVs (not shown). More generally, the 4 km WRF-EM simulations readily distinguished between organized and disorganized convective outbreaks (e.g., squall lines versus airmass convection).

The overall character of the results can be conveniently summarized via the use of Hovmoller diagrams (e.g., Carbone et al. 2002), which were produced here by interpolating hourly precipitation totals from the model and Stage IV plus radar rain estimates to a lat-lon grid, and then averaging them over the latitude band from 30 deg N to 48 deg N. Only the 12 to 36 h forecast period was used for the model precipitation data. The period from 28 May to 13 July 2003 is shown here (Fig. 4). From this perspective, WRF-EM did a surprisingly good job at replicating the frequency, longevity and propagational characteristics of the many precipitation episodes during this time period, but did have some problems triggering convection over the western high terrain, as is especially evident during the period from 9 June till 16 June. Also evident is a systematic overprediction of rainfall, a more specific example of which is presented in Fig. 5 for the 10 June 2003 bow echo depicted in Fig. 2. The cause of this overprediction is still under investigation, but is most likely related to deficiencies in the current microphysics scheme being employed, which has not yet been tuned for the present resolutions.

Diurnally averaged Hovmoller frequency diagrams for the entire BAMEX forecast period are presented in Fig. 6. These diagrams were created by counting the number of times for a given hour and given longitude that the average over latitude exceeded a specified threshold, here chosen to be .02 mm. This number of occurences is then plotted as a percentage of the total number of observations for a given hour and longitude. These diagrams clearly depict both a strong diurnal signal in precipitation frequency as well as a strong propagating component, for both the model and observations. This offers us further confidence that the WRF-EM model is properly representing the basic character of convection over the central US. However, as also noted above, WRF-EM does not completely capture the observed diurnal peak in convective frequency over the western mountains and High Plains.

The lack of a full diurnal signal over the western portion of the domain may partly have been due to having the western border of the WRF domain extending only to central Colorado during the BAMEX experiment in 2003, a decision that was based primarily on the availability of computational resources. During the 2004 exercise, the western border of the model domain was extended back to Nevada, and preliminary results suggest that the mountain convection is now more reasonably represented.

Fig. 7 presents a diurnally averaged Hovmoller diagram based on the 10 km WRF-EM simulations for the same time period used for Fig. 6. The 10 km forecasts actually did a better job of replicating the diurnal maximum over the mountains, due probably to the use of a larger domain, but the propagating component was significantly weaker. The weakness of the propagational component in these 10 km simulations seems most directly related to the lack of convectively generated cold pools in many of these cases. For example, as shown in Fig. 6 for the June 10 2004 bow echo case, cold pools are readily reproduced in the higher resolution explicit simulations, but are often nearly absent in the coarser resolution cases with parameterization. As has been shown in many studies, such cold pools are critical for properly representing convective system regeneration and propagation. Further discussion of the inability of coarser resolution simulations using convective parameterization to produce observed propagating precipitation episodes can be found in Davis et al. (2003).

3. Objective/ subjective verification:

In an attempt to further quantify the value of the 4 km WRF-EM forecasts, several objective approaches were tried, all of which suffered from the usual limitations associated with verifying small, intense, time- and location-specific events. For example, Done et al. (2004) applied an object-based approach for the 2003 BAMEX simulations, which measured the degree of correspondence between individually observed and simulated convective systems, based on a range of specified minimal distance and timing errors for the system centrioids during the MCS lifetime. This approach tended to verify our more subjective impressions that the 4 km WRF-EM simulations reasonably forecast the majority of significant convective systems during this time period.

For the purposes of the present paper, we take an even simpler approach, and focus on the 24-30 h forecast period, which generally represents the next period of maximum convective activity within the diurnal cycle. Correspondence was then defined by subjectively rating the forecast over the entire model domain as either very good (all significant observed convective systems were forecast within roughly half a state and 3 h; see Figs 2,3 for examples), good (the majority of significant convective systems were reasonably forecast), or poor (significant features were missed). From this perspective, out of a total of 113 cases from 2003 and 2004[2], about 33% of all of the forecasts were considered ``very good’’, 50% were considered ``good’’, and 17% were considered poor (subjective errorbars on these estimates were about 5%). Differences between 2003 and 2004 were not considered significant. All in all, these results matched the more objective approach of Done et al. (2004) quite well.

Since most of the significant convective outbreaks were associated with reasonably predictable larger-scale forcing features, a valid question to ask is whether similar guidance could have been acquired from careful inspection of the coarser resolution simulations. Indeed, we found that the operational 12 km ETA model did nearly as good a job as the finer resolution WRF-EM simulations at indicating the potential for significant convective outbreaks out to 36 h. For instance, using a similar rating system as for the 4 km WRF-EM simulations, except now using the 6 h total precipitation between 24 and 30 h from the ETA model as a surrogate for radar reflectivity (with all the appropriate caveats), 29% of the ETA forecasts were considered ``very good’’, 56% were considered good, and 15% were considered poor. However, more detailed information, such as convective mode, had to be inferred from the ouput (through experience and a good forecast of the pre-convective environment). The real value added of the higher resolution simulations, thus, was the additional information on convective mode and propagation characteristics.

4. Summary:

The analyses of the 2003-2004 WRF-EM forecast exercises to date offer hope that significant improvements in convective forecast guidance out to 36 h can be achieved by increasing horizontal grid resolutions into the

[2] Only a subset of the 2004 forecasts are used here, due to an inadvertent error in implementing the horizontal diffusion in WRF-EM version 2.0, which was run from 1 May till 11 June. Only results from WRF-EM version 1.3, which was run from 12 June till 31 July, are used here, and we are in the process of rerunning the earlier forecasts with version 1.3 to maintain consistency.

convectively-explicit regime, thereby avoiding uncertainties inherent with convective parameterization schemes, as currently are used in coarser-resolution operational models. Herein, we used a 4 km grid resolution, which is nominally enough to explicitly resolve convective systems, and found at least as good a guidance as regards timing and location of significant convective outbreaks as the 12 km ETA model out to 36 h, and, additionally, achieved much improvement in representing convective system mode and propagation characteristics on a day-to-day basis. These improvements in convective forecast guidance were found to be extremely useful for BAMEX operations planning each day, and have also highly praised by NWS forecasters.

Many challenges remain, however, as there is still a systematic bias towards producing too much convective precipitation in these high resolution simulations. Yet, stratiform precipitation regions appear too small. This suggests that further refinements are needed to the microphysical representation for such resolutions. Another systematic bias noted from these simulations was that a significant number of the larger convective systems failed to decay as observed. This, again may be related to deficiencies in the current microphysical formulations, or, could also be related to current boundary layer formulations.

The relative success of forecasting a seemingly unpredictable phenomena such as convection out to 36 h seems most directly related to its strong connection to identifiable and more easily predictable synoptic or subsynoptic features, which serve as the primary triggering agents. The assumption implied by this is that, in most cases, the feedback of the convection on the larger-scales is not significantly impacting the predictability of the primary convective forcing features over a 1 to 2 day period. The diurnal cycle also helps in this regard, by providing a reasonably predictable cycle of convective enhancement and decay juxtaposed on the other forcing influences.

Future studies must also consider the potential value of increasing resolutions further, to, for example, begin to explicitly represent supercell processes. Past research has suggested that 2 km resolutions may be sufficient in this regard, but the cost of such a simulation over the large domains used here are still prohibitive for realtime use. Preliminary results suggest that the use of 2 km grids does indeed improve the structural features of convective systems,
and does begin to depict supercellular behaviors, but does not significantly improve the forecast of system timing and location. These latter attributes of the forecast may be more sensitive to improving the model initial state, via assimilation techniques, or by adjusting forecasts on the run via nudging techniques, etc. Looking further down the road, differentiating between tornadic and non-tornadic storms may require horizontal grid resolutions much finer than 1 km.

Through these forecast exercises, we have just begun to systematically look at the abilities and weaknesses of the present WRF-EM configuration for explicitly forecasting convection, and further refinements to such a young model will inevitably be necessary before it realizes its full capability. More generally, we have tried to offer support for moving operational models to explicit convective resolutions by offering some preliminary measures of the forecast value-added of such an advancement.

5. Further Information:

The 4 km and 10 km WRF-EM forecasts for the 2003 BAMEX experiment and 2004, along with radar images and ETA forecasts, can be found at

http://www.joss.ucar.edu/bamex/catalog/

and

http://www.joss.ucar.edu/wrf-2004/catalog/,

respectively. Results from an NWS forecaster's questionnaire for 2004 can also be viewed at the above JOSS site. Comparisons between the WRF-EM simulations, a CAPS WRF-EM simulation using an advanced data assimilation system (ADAS), and the NCEP WRF-NMM core are also available for 2004 from roughly

May 1 through June 4, and can be viewed at

http://www.nssl.noaa.gov/etakf/compare/wrf/

(see Weiss et al. 2004 for a discussion of these comparisons).

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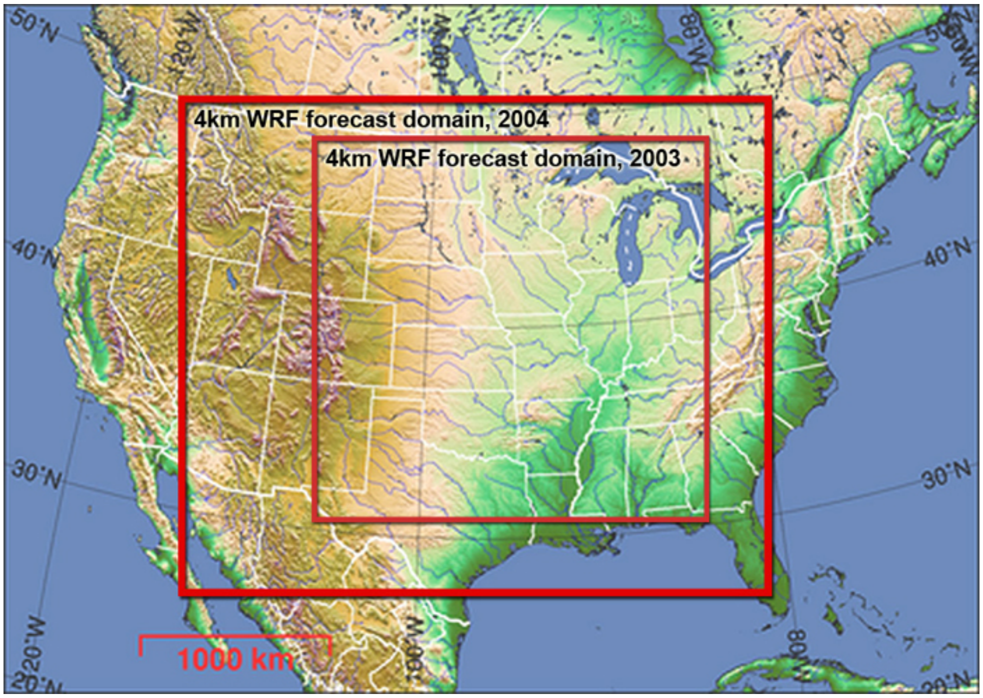

Figure 1: Forecast domains (red boxes) for the 4 km WRF-EM realtime forecast exercises.

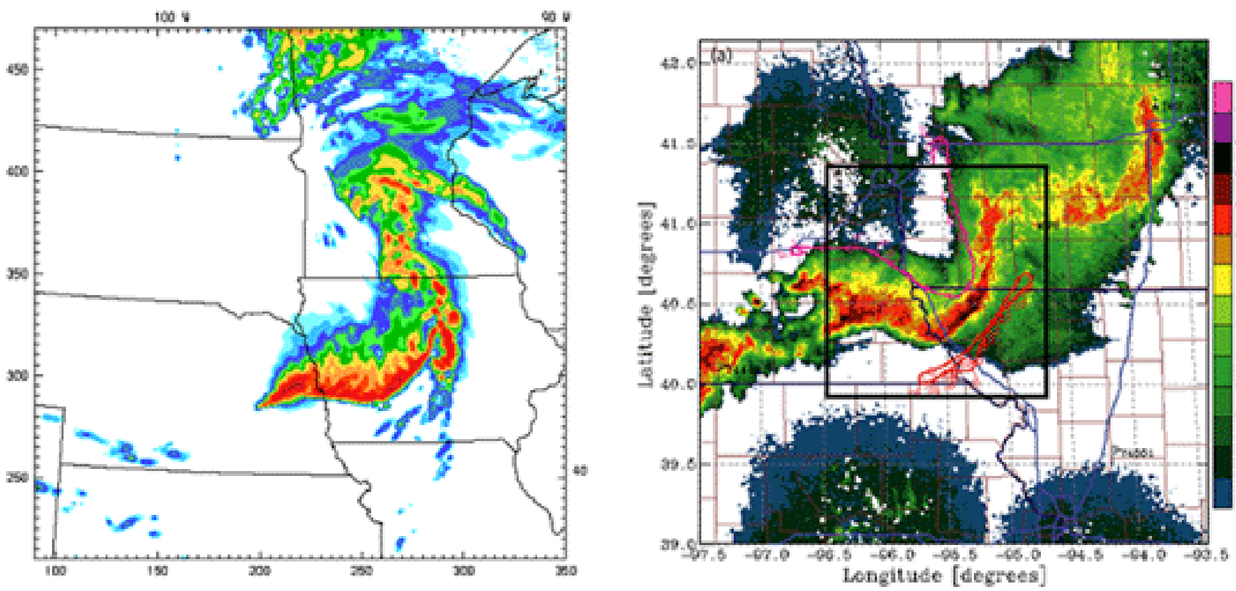

Fig. 2: 30h WRF forecast (left) and NEXRAD radar observations (right) of maximum reflectivity for June 10, 2003 at 06 UTC, during the BAMEX field program

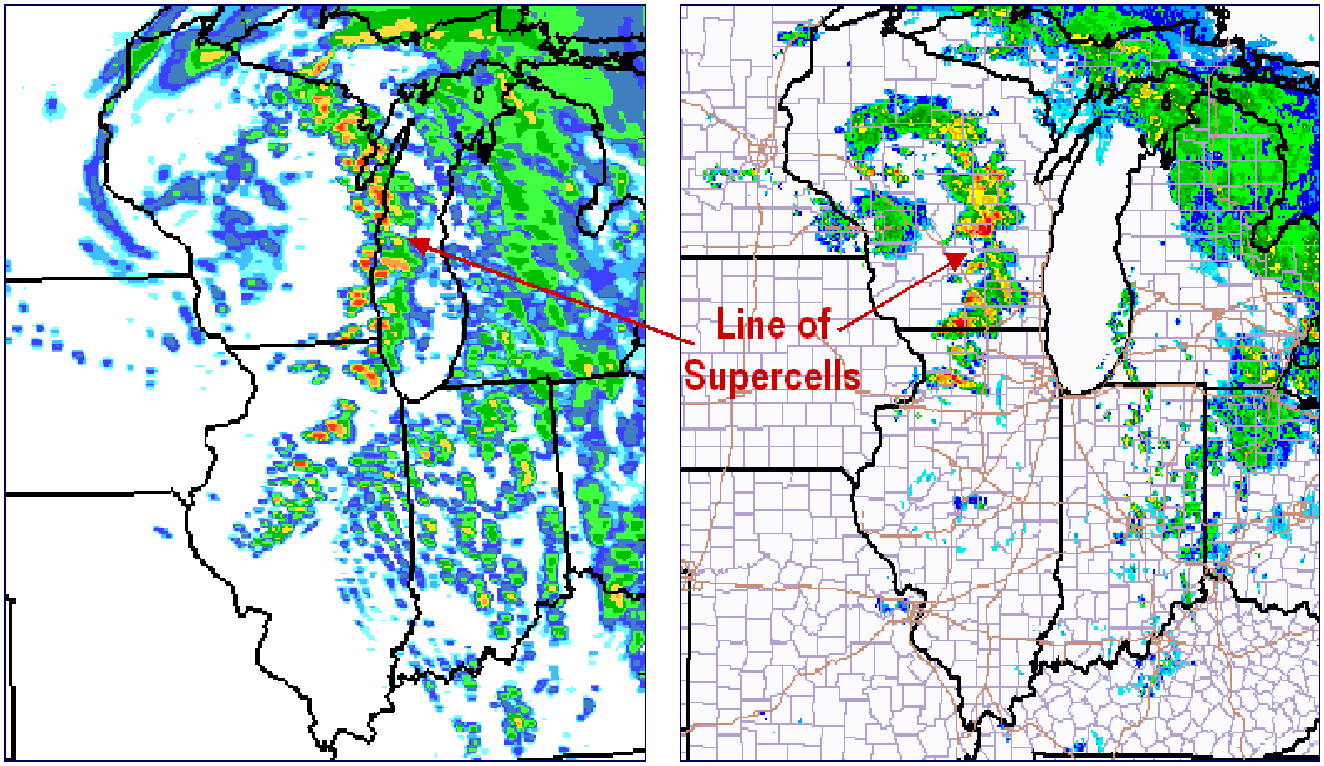

Fig. 3: 23h WRF forecast (left) and NEXRAD radar composite (right) of the maximum reflectivity for May 30, 2003 at 23 UTC, during the BAMEX field program

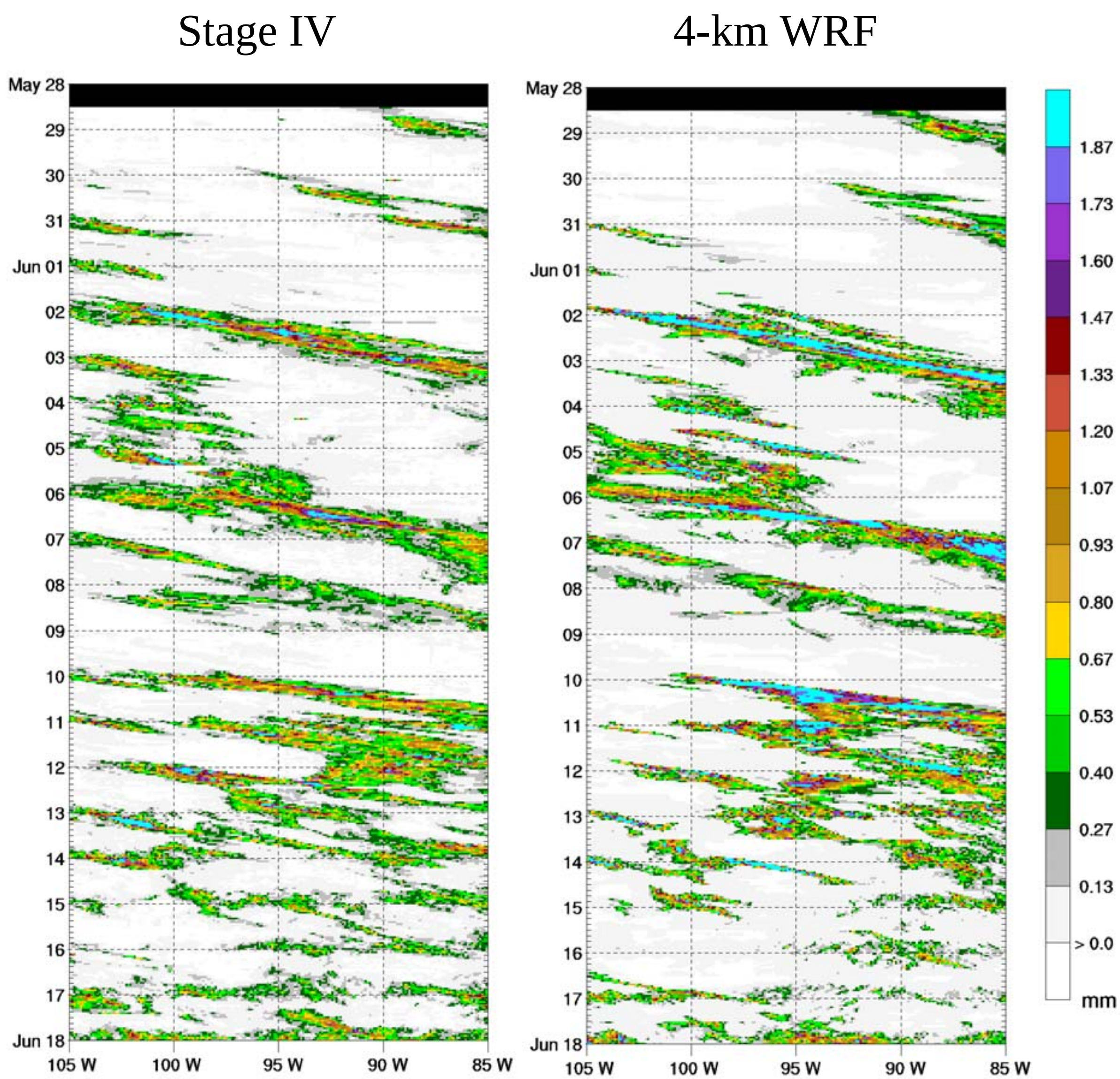

Fig 4: Hovmoller diagrams of observed (left) and simulated (right) precipitation as derived from the 4 km WRF forecasts, averaged from 30 N to 48 N from 28 May through 18 June 2003 during the BAMEX experiment.

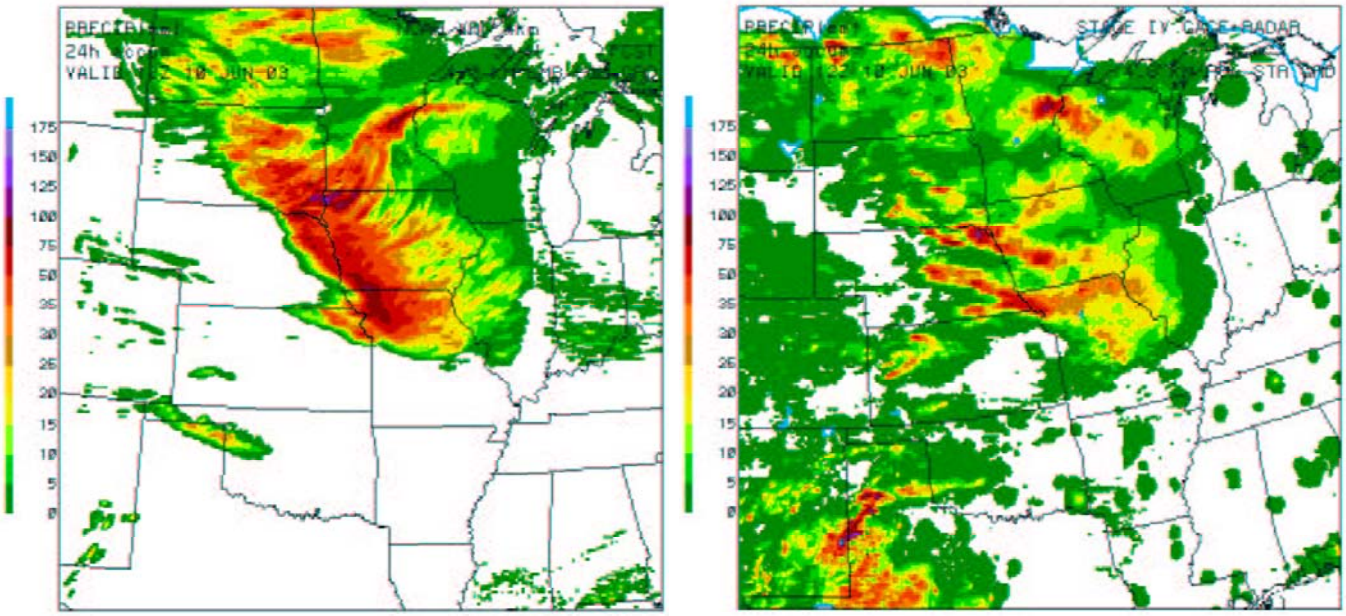

Figure 5: 24 h precipitation totals as derived from the 4 km WRF forecast (left) and Stage IV and radar rain estimates (right), valid at 12 UTC, 10 June 2003.

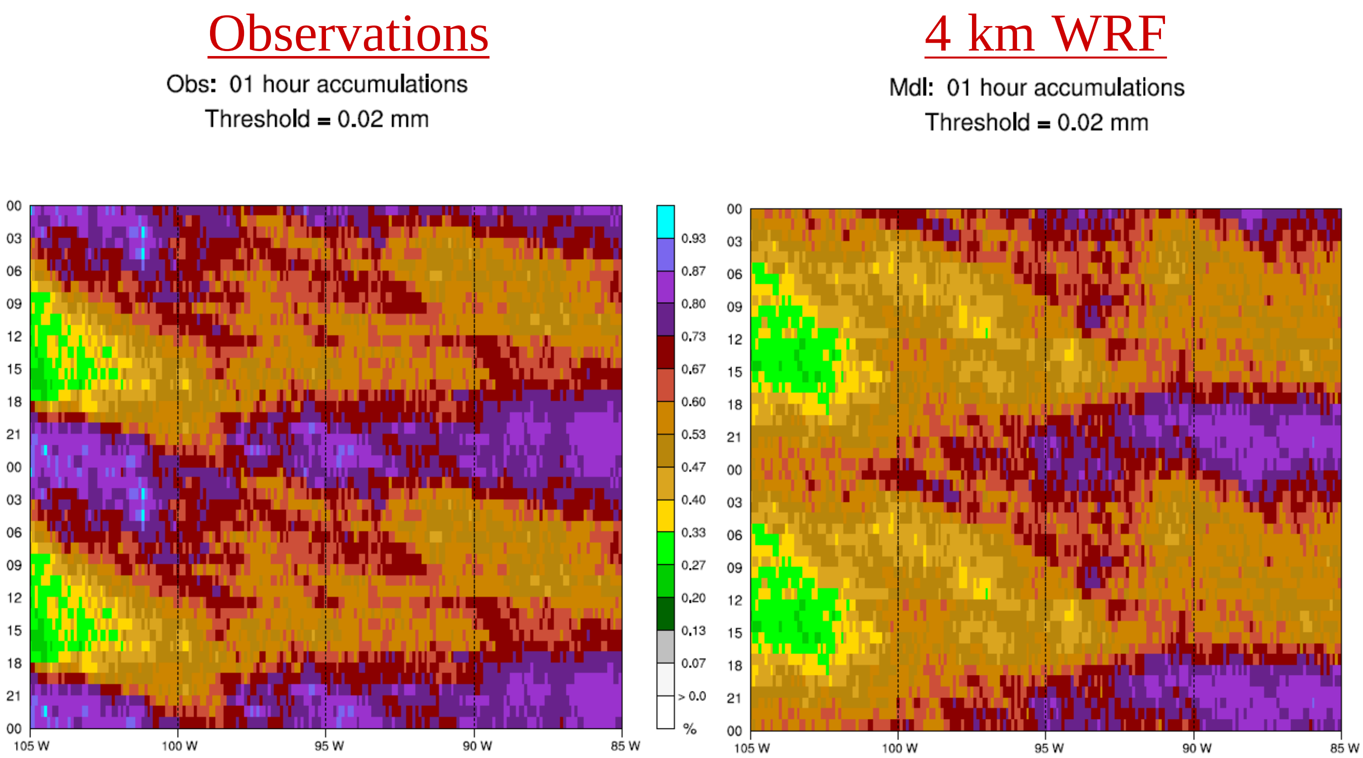

Figure 6: Diurnally averaged Hovmoller diagrams of 1 hr precipitation totals , as derived from Stage 4 and radar estimates (left) and from the 4 km WRF simulations (right) during the BAMEX experiment.

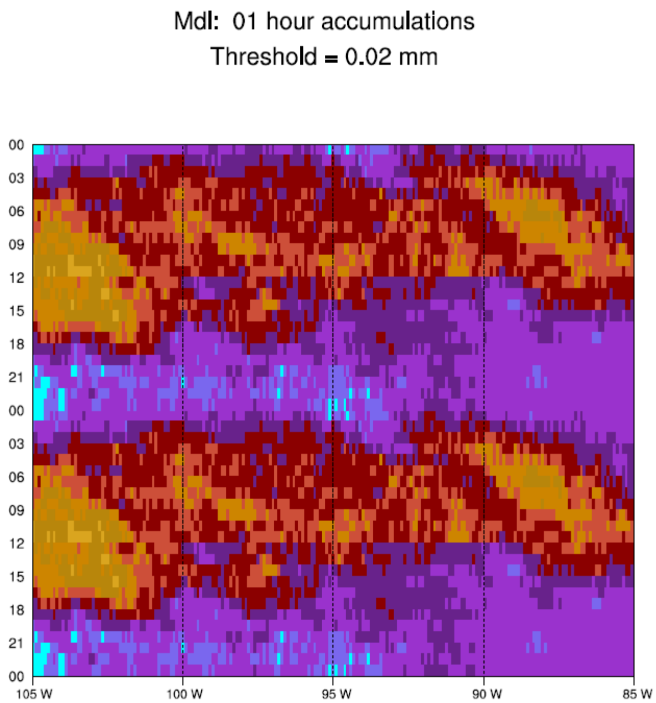

Figure 7: Diurnally averaged Hovmoller diagrams of 1 hr precipitation totals , as derived from the 10 km WRF simulations during the BAMEX experiment.

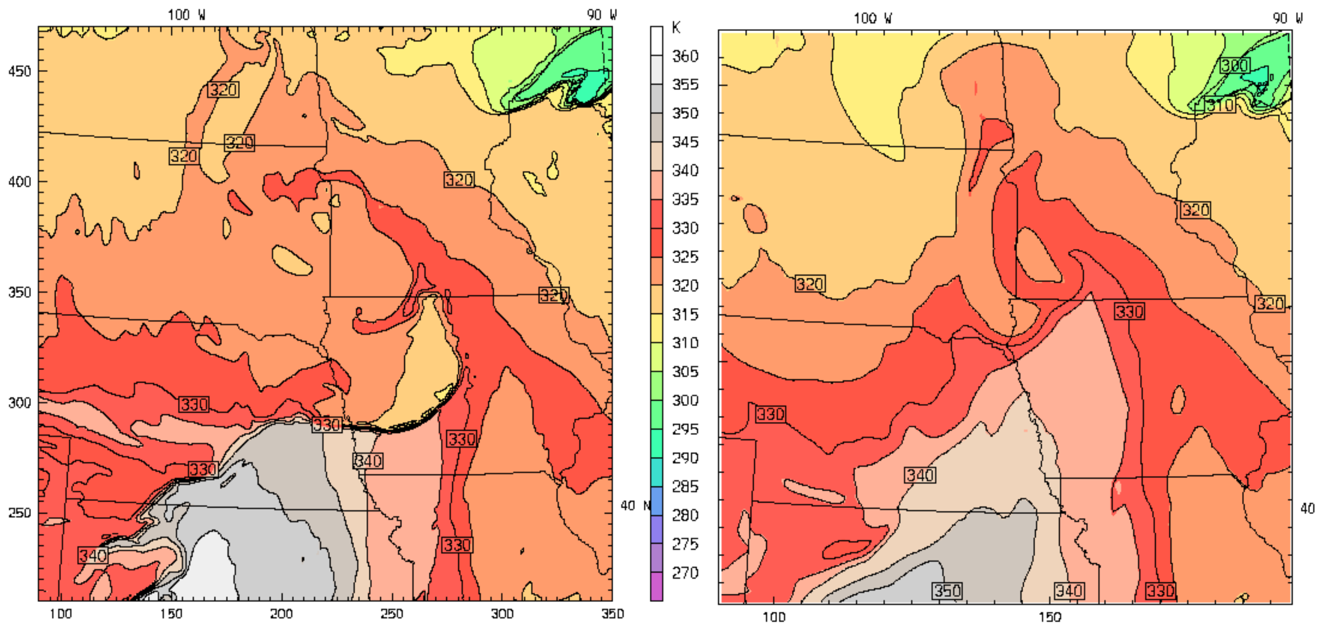

Figure 8: 30 h forecast of surface THETA-E for the 4 km (left) and 10 km (right) WRF simulations, valid at 06 UTC, 10 June 2003, during the BAMEX field program.