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EXAMINATION OF THE PERFORMANCE OF SEVERAL MESOSCALE MODELS FOR CONVECTIVE FORECASTING DURING IHOP

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1. INTRODUCTION

The International H_2O Project (IHOP) carried out an extensive field project in the Southern Plains from 13 May to 25 June of 2002. The main focus of IHOP is to improve the characterization of the four-dimensional distribution of water vapor and its application to improving the understanding and prediction of convection. The four main components of the program are quantitative precipitation forecast (QPF), convective initiation (CI), atmospheric boundary layer processes, and instrumentation. During IHOP, the Forecast Systems Laboratory (FSL) ran experimental versions of local and national scale models, both to assist with nowcasting and short-range forecasting for the project, and to determine whether such models could provide useful forecast and nowcast guidance for convective weather.

The FSL has been involved in model development through two main efforts, the Rapid Update Cycle (RUC; Benjamin et al. 2003) model, a national scale model, and with smaller scale models designed to run onsite at a National Weather Service Forecast Office (WFO) using local analyses that take advantage of locally-available data. Such local datasets can be used to initialize a model through analyses from FSL's Local Analysis and Prediction System (LAPS, McGinley et al., 1991; homepage at http://laps.fsl.noaa.gov). LAPS is currently running in AWIPS at WFOs on an hourly cycle with a 10-km grid spacing. During IHOP LAPS was run at a 12- and 4-km horizontal grid resolution and used to initialize some of the models that FSL ran. One goal of a short-range model is to provide better prediction of precipitation without a spin-up period. To aid in this goal a "hotstart" scheme was developed using the LAPS cloud analysis to prescribe a vertical velocity profile where sufficiently deep clouds are present at initialization time (Schultz 1995; Schultz and Albers 2001; Shaw et al. 2001). The three-dimensional dynamical relationship between mass and momentum is adjusted by the LAPS balance algorithm (McGinley and Smart 2001) to force consistency with the diagnosed cloud vertical motions and allow for a smooth model start.

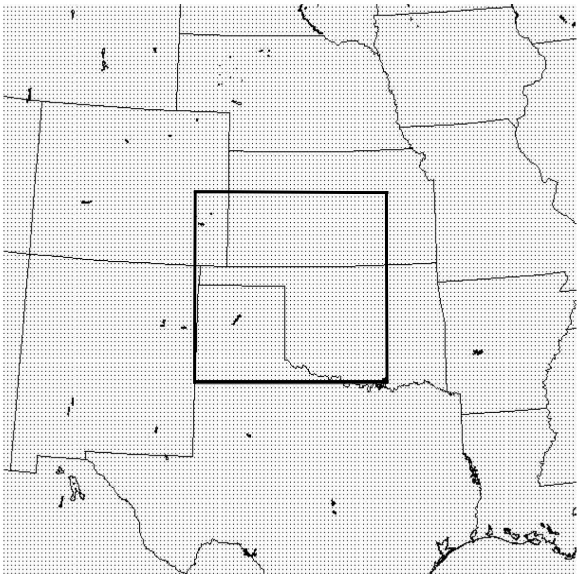

Figure. 1. The 12- and inner 4-km IHOP domains for the LAPS MM5 and WRF runs (points every 12 km).

During IHOP a 12-km horizontal resolution MM5 hotstart initialized with LAPS was run, with a nested 4-km version covering the IHOP experimental domain, (Fig. 1). LAPS also was used to initialize a similar 12-km setup for the Weather Research and Forecast (WRF) model. In addition to these models initialized with LAPS, FSL ran a 10-km version of the RUC model. The RUC model employs a 3DVar analysis for the mass fields, and initial RUC hydrometeor fields are adjusted to correspond to base scan reflectivity patterns at the initial time, but without any modification of the initial vertical velocity field (in contrast to the hotstart method). The experimental model runs for IHOP were archived by UCAR's Joint Office for Science Support at http://www.joss.ucar.edu/ihop. The models run by FSL for IHOP are summarized in Table 1.

2. EVALUATION OF MODEL PERFORMANCE

One of our goals during IHOP was to compile a fairly extensive subjective evaluation of the various models during real-time. Objective model evaluation was done within FSL and is discussed by Shaw et al. (2004). In order to perform subjective evaluation, an online evaluation form was designed that allowed the forecaster/nowcaster to document: 1) what the model was forecasting; 2) the relationship of various forcing features to the subsequent convection forecast by the-model; and 3) forecaster's confidence in the forecast.

There were many free-form comments also made

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Table 1: FSL real-time models in IHOP (*except LAPSWRF was only available after IHOP)

Model	delta x km	# vertical levels	Runs every x h	Forecast duration (h)	Convective scheme	Microphysics
MM5hot	4	34	3	12	None	Schultz
MM5hot	12	34	3	12	Kain-Fritsch	Schultz
LAPSWRF*	12	34	3	12	Kain-Fritsch	NCEP-5
RUC	20	34	3	6-24	Grell-Devenyi ensemble-closure	RUC/MM5 mixed phase
RUC	10	50	3	6-24	Grell-Devenyi ensemble-closure	RUC/MM5 mixed phase

The form that FSL developed (online at http://www-ad/~kay/ihop/evaluation.pl) for our evaluations was modeled after similar evaluation activities that the Storm Prediction Center (SPC) had used during the previous two spring seasons. The SPC activities were also intended to record real-time impressions of model forecasts, as well as to specifically evaluate various models daily in order to learn more about both the problems and the capabilities of the models.

The model fields that were addressed on our online form for each model run (if possible) are summarized below. For this form we concentrated on the main IHOP domain, roughly equivalent to the interior box shown in Fig. 1, and looked only at the first 12 h of the model forecast. During IHOP all the models except the WRF were evaluated regarding:

- Initial boundary analysis: Assessing how well the model resolved boundaries present in the actual data.
- Boundaries involved: Recording the various boundaries that were forecast.
- Boundary/precipitation relationship: Documenting whether any precipitation forecast by the model was associated with a particular boundary.
- Maximum rainfall forecast by the model.
- Timing of convective initiation compared to observations.
- Dominant convective mode. (For the LAPS initialized models we used the model reflectivity field, while for the RUC this was implied from the precipitation field where possible.)
- Parameter assessment: Summarizing the nowcaster's impression of the forecast values of CAPE, CIN, surface mass convergence, and boundary structure.

For most of these characteristics we broke the 12-h time frame into the 0-3 h, 3-6 h, and 6-12 h periods, and for applicable questions we had the evaluators record their confidence in the model forecast. There was also ample area to record free-form comments, which proved to be quite insightful in terms of documenting model behavior. The primary evaluators were from FSL, but several others took part from SPC, the National Severe Storms Laboratory (NSSL), and NESDIS.

- Initial boundary analysis: Overall the forecasters felt that the models were able to capture most boundaries quite well. Some of the more subtle/weaker boundaries, such as smaller-scale outflow boundaries, were missed, but drylines, even when somewhat complex, were usually well-initialized.
- Forecast boundaries: In general there was relatively high confidence in the boundaries forecast by the models; for example on a scale of 1 to 10 for the 1-3 h period forecasters gave a rating of 7, which dropped only to 6 for the 6-12 h period. Lowest confidence was given for boundaries that the models tended to have more trouble with, such as warm frontal boundaries, or with outflow boundaries. In the case of outflow boundaries, confidence was lower of course if the forecasters did not trust the prediction of model convection. At the upper end of the confidence level were forecasts of dryline position and timing.
- Boundary/precipitation relationship: Here the confidence in the model forecasts was generally lower than the previous question, since now the forecast boundary initiating storms was the issue. Still, forecasters overall agreed there was value in the model forecasts for convective initiation, especially along the more well-defined dryline type boundaries.
- Maximum rainfall forecast: Generally it was noted that the RUC tended to be at the low end of forecast precipitation while the MM5, particularly the 4 km resolution run, typically overforecast development. An adjustment was made to the hotstart procedure in late May during IHOP after early performance showed quite excessive precipitation rates, and thereafter the rates were more reasonable, though still often viewed as high. For some cases forecasters noted that the maximum rainfall forecast by the MM5hot-4 km run was a good estimate of the maximum potential precipitation on a given day, though not necessarily for the particular storm that was forecast.
- Timing of convective initiation: The models were used extensively for this purpose, since it was a critical forecast issue for deploying IHOP resources. Performance varied, but some of the dryline forecasts were quite good, in one case correctly initiating storms in the

by the forecasters that give insight into how the models performed with the various short-range forecast problems during IHOP. A summary of these comments that were not included above follows:

- The MM5 models using LAPS for the initial state did an excellent job of initializing ongoing convection, but often this convection was lost in the first hour of simulation. Adjustments were made to the hot-start scheme for a set of post-IHOP reruns of both MM5 and the WRF model, and our preliminary evaluation of some of these reruns indicates some improvement with this problem. The most easily "lost" convection were elevated storms (non surface-based convection), while very strong individual storms and lines were much better retained from the initialization.

- Outflows tended to be easily produced from convection in the MM5 model, especially so in the 4 km run, whereas the RUC tended to be more conservative in producing outflows but was able to do so.

- The most difficult storms to forecast were elevated convection, which usually formed in the very early morning (pre-sunrise) hours and could persist for up to 6 h hours after sunrise. Coincidently, this type of convection is also among the most challenging for forecasters, as it can occur without any obvious surface forcing feature present. Though seldom producing severe storms (at least during IHOP), elevated convective events were often of the "surprise" category. There were often indications in the model of possible activity, for example in the form of midlevel echo but without precipitation reaching the surface, so an underforecasting of the convection. Convection associated with a warm front (on the cool side of the warm front) also tended to be an area where the models were deficient. This type of convection often was not surface-based, sharing that characteristic with the elevated storms noted above.

- Some of the forecasts of convective initiation along drylines were quite good. For a few cases the model beat the forecasters, particularly when temperatures both at the surface and aloft were quite hot. In these cases, forecasters overestimated the time it would take to break the cap, while the model more correctly forecast convective initiation earlier.

- Other good forecasts occurred with well-defined surface-based forcing features, such as cold fronts.

- As noted earlier, there was some skill in the model's ability to forecast storm type and evolution, with several events during IHOP that featured upscale growth into organized lines that often accelerated much faster than indicated in the precipitation fields from conventional models (for example, the Eta model).

3. SOME CASES FROM IHOP

Two cases are examined using both the runs during IHOP and the reruns that occurred after IHOP. The primary reason for doing the reruns was to have a series of model runs from the WRF model, which was actually run during IHOP but not able to be displayed in real-time. It was decided that improvements to the hotstart method as a result of the real-time experiences during IHOP should be applied to the reruns. A significant improvement was removal of a warm bias that existed in the LAPS initialization, and was likely responsible for overprediction of convective precipitation during IHOP from the MM5.

3.1 ***2 June 2002: Dryline case.***

On this day the western half of the IHOP domain (Fig. 1) was dominated by very hot temperatures reaching into the lower 100's (^{o}F) during the afternoon where conditions were drier, to the 90's in the more humid air to the east. Initially there was not a well-defined dryline, but as shown by the LAPS analysis of wind and dewpoint along with low level reflectivity in Fig. 2, the dryline sharpened during the early afternoon. This sharpening first appeared as a surge of westerly surface flow emerging out of eastern Colorado that then pushed into Kansas. The IHOP forecasters on this day predicted that a dryline would become better defined during the afternoon (somewhat later than what occurred) but felt convective initiation along it would be fairly late in the afternoon, waiting for the dryline to sharpen up as well as temperatures to break the significant cap that was in place. As it turned out, the presence of the very hot surface temperatures and a somewhat stronger and earlier

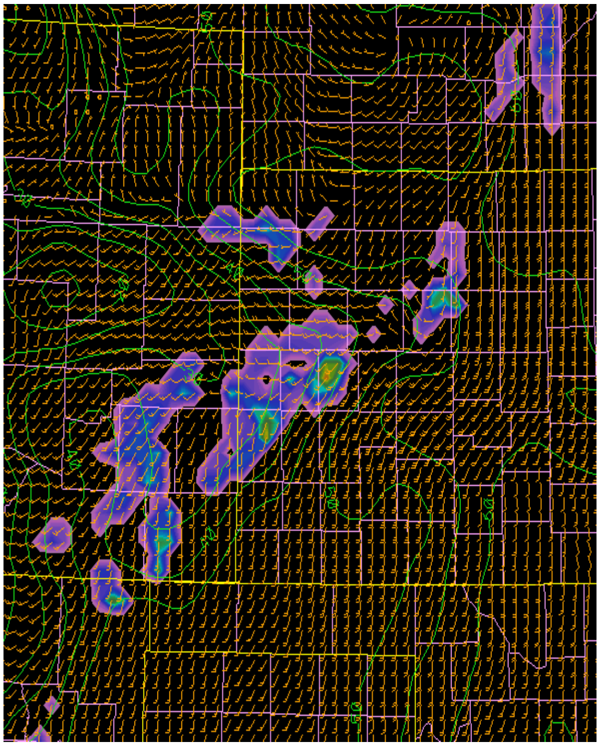


Figure 2. LAPS analysis at 2100 UTC on 2 June of surface wind, dewpoint, and low level reflectivity. The western portion of Kansas is centered in the figure.

dryline push then expected allowed the cap to be broken and convective initiation to occur over 2 h ahead of the forecast made by the IHOP forecasters. It was noted in IHOP that the MM5 model had done a good job of indicating this convection earlier than expected, particularly the run initialized at 1500 UTC. Here we examine some of the runs from that day and contrast the somewhat different forecasts for this relatively “tricky” case. With the expense of some of the resources in IHOP, in particular the aircraft, timing of convective initiation was a critical forecast issue. In this case it turned out that even a forecast error of 2 h for convective initiation from a mid-morning forecast was critical and resulted in an aborted mission as convection was well underway before the aircraft (leaving from Norman, Oklahoma) could reach the dryline target.

We will first examine some forecasts initialized at 1200 UTC since reruns of both MM5 and WRF are available at this time. A forecast from the MM5 run initialized at 1200 UTC and valid at 2100 UTC is shown in Fig. 3. In this and subsequent figures, when no contours are present, the model is forecasting reflectivity aloft with no precipitation reaching the surface. For the most part the reflectivity values for the image in Fig. 3 are 30 dBZ or less. There are some stronger cells forecast, and for these surface reflectivity contours are depicted (e.g., in extreme northeastern Nebraska and along the Iowa/Illinois border). The insert, which shows a composite low-level reflectivity image overlaid with a visible satellite image (white areas in the image) over a region centered on western Kansas, indicates that storms were in fact producing rain by 2100 UTC, with maximum reflectivities exceeding 50 dBZ. Thus, the MM5/12-km run was forecasting high-based convection that would not produce precipitation, so it correctly indicated that storms would be produced along the dryline but was underforecasting development. For comparison the post-IHOP rerun of the MM5/12-km model for the same time is shown in Fig. 4, and for the WRF/12-km model in Fig. 5. The MM5 rerun is very similar to the original MM5/12 km run during IHOP, and the WRF forecast from the 1200 UTC run valid at the same time is also very similar. All the runs indicate convective development with reasonable timing but only forecast virga-producing storms. The forecasts from these same runs valid 3 h later at 0000 UTC on 3 June (WRF is shown in Fig. 6) were very similar to the 2100 UTC forecasts in that there continued to be no indication of storms that would produce precipitation. In reality, the line of broken storms advanced slowly to the east and by 0000 UTC extended all the way from north-central Kansas south-southwest to the far western Texas Panhandle.

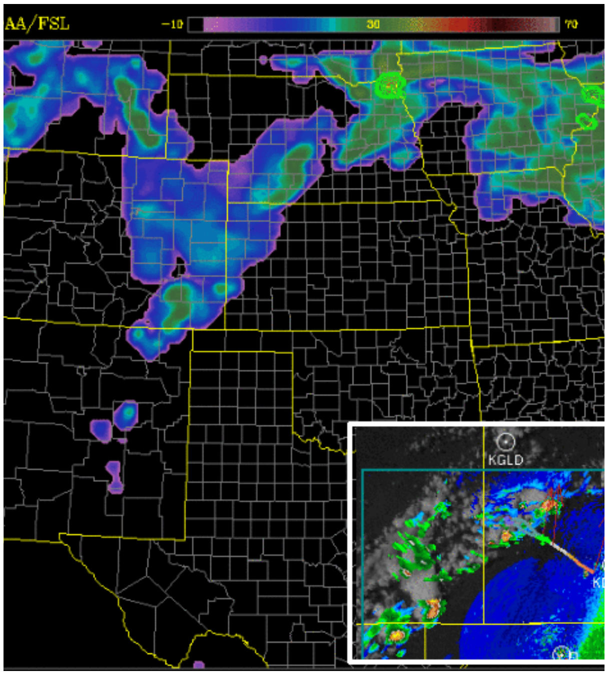


Figure 3. 9-h forecast from the MM5/12 km IHOP run valid at 2100 UTC on 2 June 2002. The image is composite reflectivity, with contours indicating model surface reflectivity. The inset shows a composite low-level radar image at this time over western Kansas.

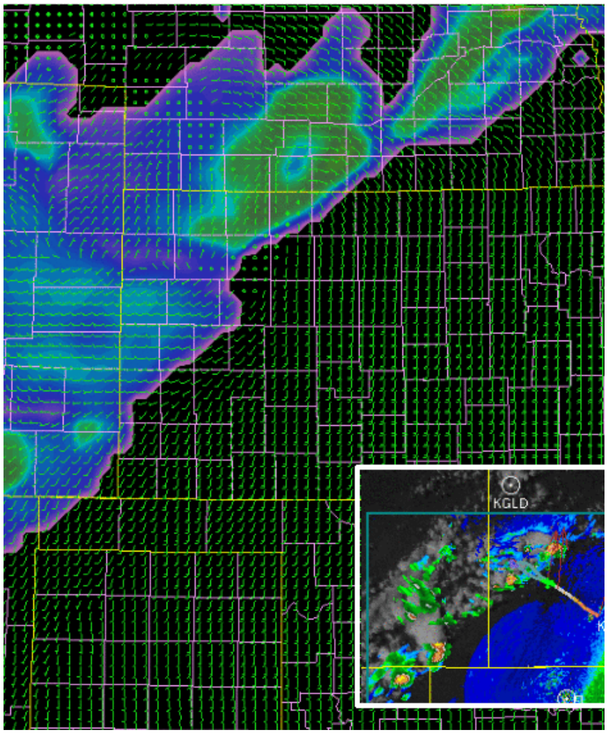


Figure 4. As in Figure 3 but a 9-h forecast from the MM5/12 km rerun valid at 2100 UTC.

The MM5/4 km run initialized at 1200 UTC produced higher values of composite reflectivity, but still no surface reflectivity (and therefore no precipitation reaching the ground. On the other hand, the MM5/4 km run initialized 3 h later at 1500 UTC did produce well-defined surface storms, although slower than what actually occurred

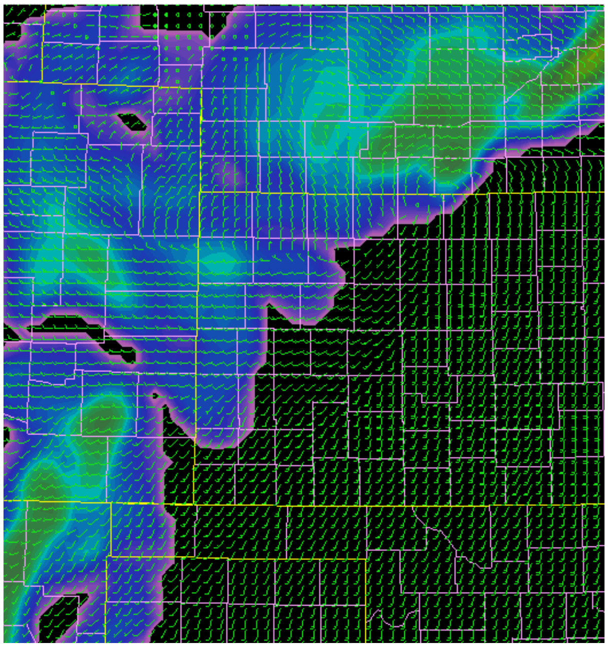


Figure 5. As in Figure 3 but a 9-h forecast from the WRF/12 km rerun valid at 2100 UTC.

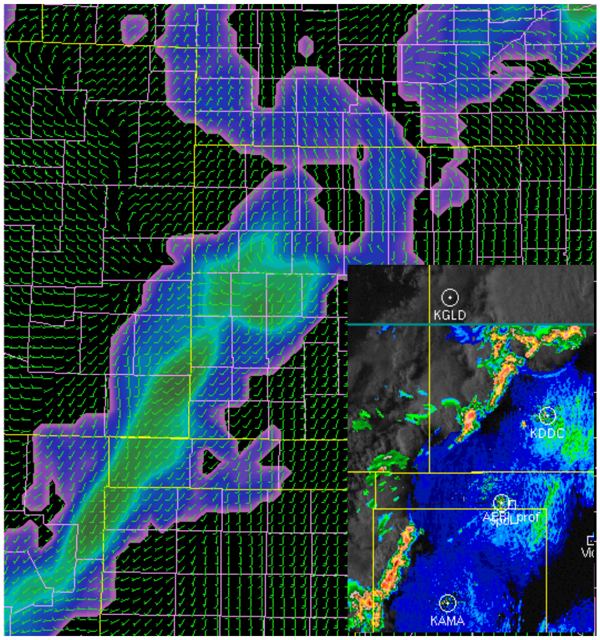


Figure 6. As in Figure 5 but a 12-h forecast from the WRF/12 km rerun valid at 0000 UTC on 3 June. The insert depicts the actual radar reflectivity at this time.

and ending up by 0000 UTC with a line of storms not far enough east (Fig. 7). The MM5/12 km run for this same time made during IHOP (Fig. 8) was not as bodacious with storm development as the 4 km run but it did indicate a surface echo in the Oklahoma Panhandle and another much farther north along the line. The actual reflectivity at 0000 UTC is shown in Fig. 9.

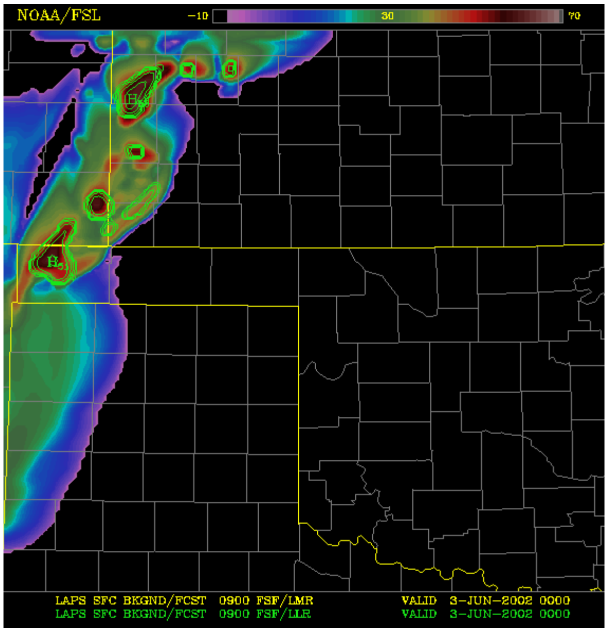


Figure 7. MM5/4 km 1500 UTC IHOP run 9 h reflectivity forecast (as in Fig. 3) valid at 0000 UTC on 3 June. The color scale runs from -10 to 70 dBZ (top) and is similar for all model figures of this type.

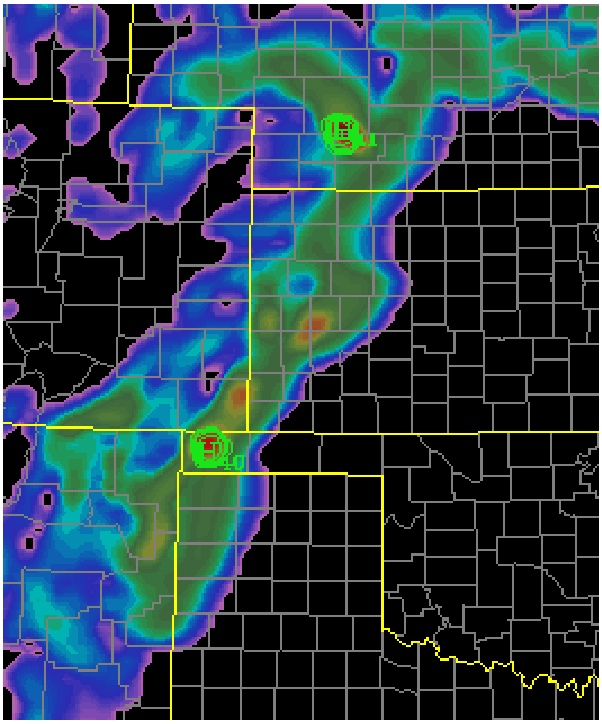


Figure 8. As in Fig. 7 but for the MM5/12 km 1500 UTC IHOP run 9 h reflectivity forecast valid at 0000 UTC on 3 June.

While the forecasts (especially the 4 km runs) initialized at 1500 UTC were better then the 1200 UTC ones, for some reason this improving trend did not continue

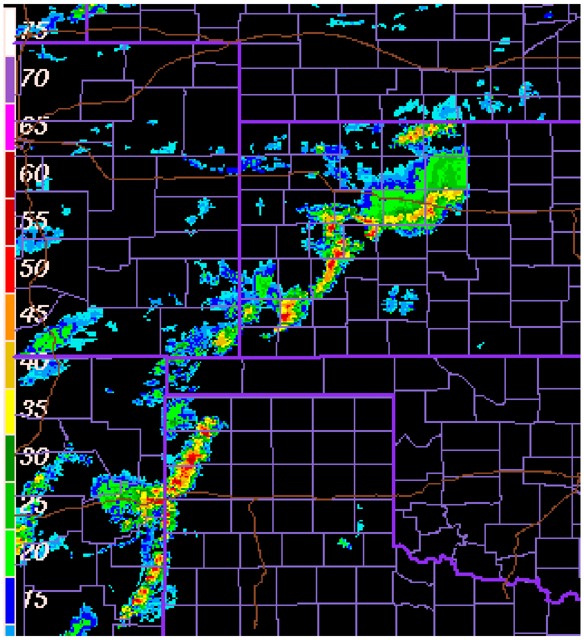


Figure 9. Observed low-level radar reflectivity at 0000 UTC on 3 June.

with the 1800 UTC runs. The 6 h forecasts from the various models (MM5/4 km, MM5/12 km IHOP run, MM5/12 km rerun, and WRF/12 km rerun) are shown in Figs. 10, a-d. While the MM5/4 km run still correctly produces surface echo, there is less echo than in the forecast from the 1500 UTC run, and the line of echoes is even further west. The MM5/12 km runs (Figs. 10b and 10c) are quite similar to each other and neither predicts any surface echo. Recall (Fig. 8) that the 1500 UTC 12 km IHOP run actually did predict an echo reaching the surface by 0000 UTC, so the forecast initialized 3 h later is not as good, similar to the behavior of the 4 km run. Note that the WRF/12 km rerun (Fig. 10d) is actually a little drier then the MM5/12 km rerun and similar to the WRF/12 km rerun from 1200 UTC.

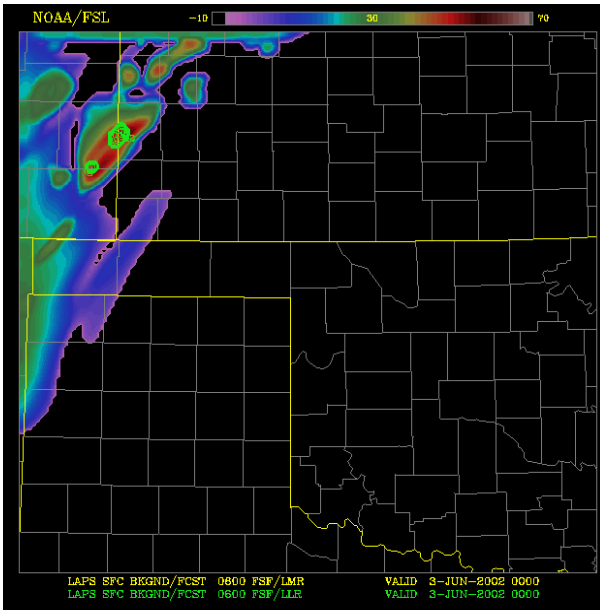


Figure 10a. MM5/4 km 1800 UTC IHOP run 6 h reflectivity forecast (as in Fig. 7) valid at 0000 UTC on 3 June.

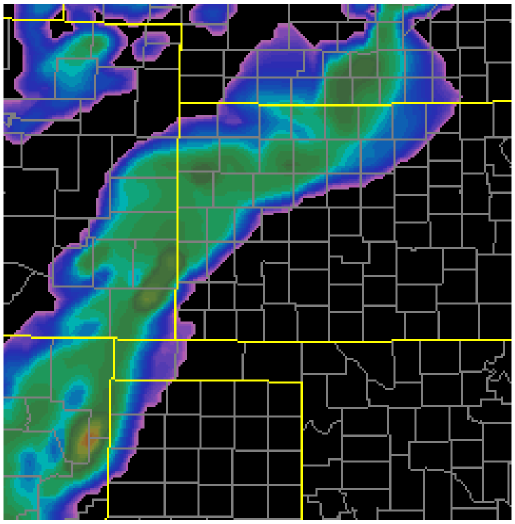


Figure 10b. As in Fig. 10a except for the MM5/12 km run.

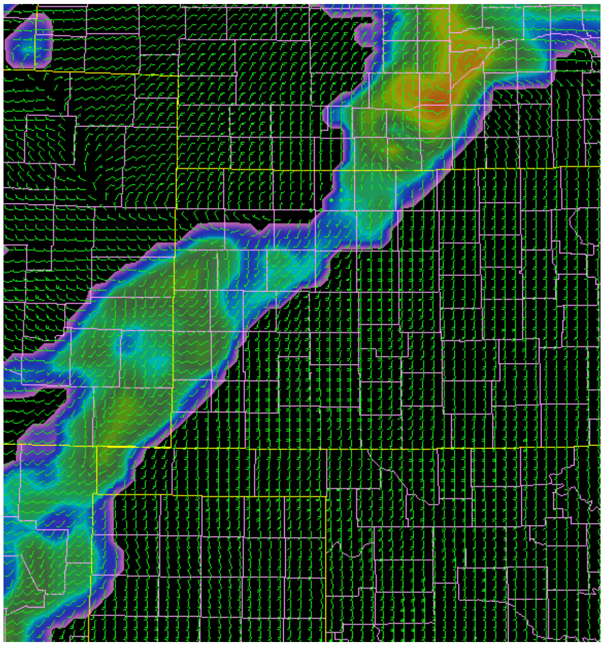


Figure 10c. As in Fig. 10a except for the MM5/12 km rerun.

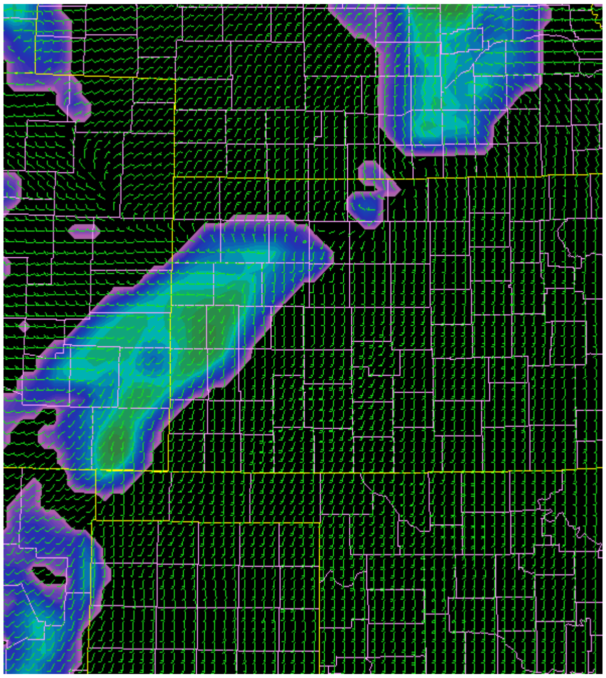


Figure 10d. As in Fig. 10a except for WRF/12 km rerun.

In summary, for this case the models showed a dryline moving into western Kansas more or less as occurred. The main message from the model runs was that convection would be initiated by the dryline but the storms would be weak, without any surface rain, typical of high-based mostly dry convection that might occur on such a hot day with marginal moisture. The 4 km MM5 runs accurately indicated that more substantial storms could occur that would produce surface precipitation, and in particular the run initialized at 1500 UTC was the closest to reality. In real-time during IHOP forecasters saw this run but doubted that such echoes could develop with the environment that appeared to be in place, opting for a forecast of later and weaker storm development than indicated by the model (or than actually occurred). At this time we are not certain why the runs initialized at 1800 UTC did not perform as well as those initialized 3 h earlier.

3.2 ***15 June 2002: Complex case.***

The 15 June IHOP case had almost all forms of convection in a single day, from early morning elevated storms to a supercell storm that eventually produced a tornado, to upscale growth of strong cells into an organized line that bowed and accelerated southward out of the domain. The actual focus of IHOP operations on this day was where convective initiation would occur along a dryline feature, which, like the rest of this case, was a fairly complex feature with a double structure. For the purposes of examining the performance of the various models, we will not discuss the specifics of the dryline part of the forecast, but instead will concentrate on the convective types that occurred.

Widespread development of elevated convection over the Texas Panhandle between 0800-0900 UTC was a forecast issue for an early IHOP flight to investigate a low-level jet. The storms eventually exceeded reflectivities of 50 dBZ at low levels, and persisted well into the daytime hours (until around 1600 UTC). Fortunately, as forecast by the SPC, the storms did dissipate, allowing for the rest of the day to become a very interesting IHOP case. However, the development of the storms was not anticipated by IHOP forecasters, and as is typical in cases of elevated nighttime convection, was a difficult forecast problem. A radar overview of the storms is presented in Fig. 11.

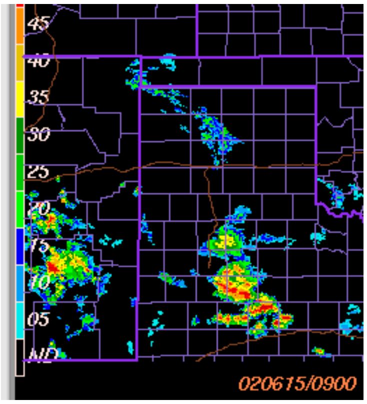


Fig. 11a, 0900 UTC.

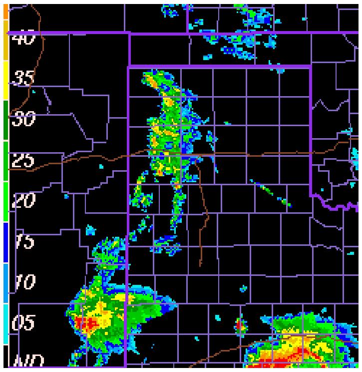


Fig. 11b, 1200 UTC.

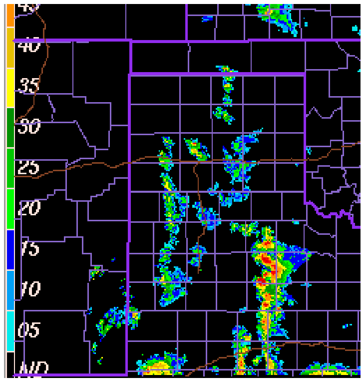


Fig. 11c, 1500 UTC.

Figure 11. Low-level reflectivity composites. A couple of strong surface-based storms are at the south end of the area, while elevated convection develops to its north over the Texas Panhandle.

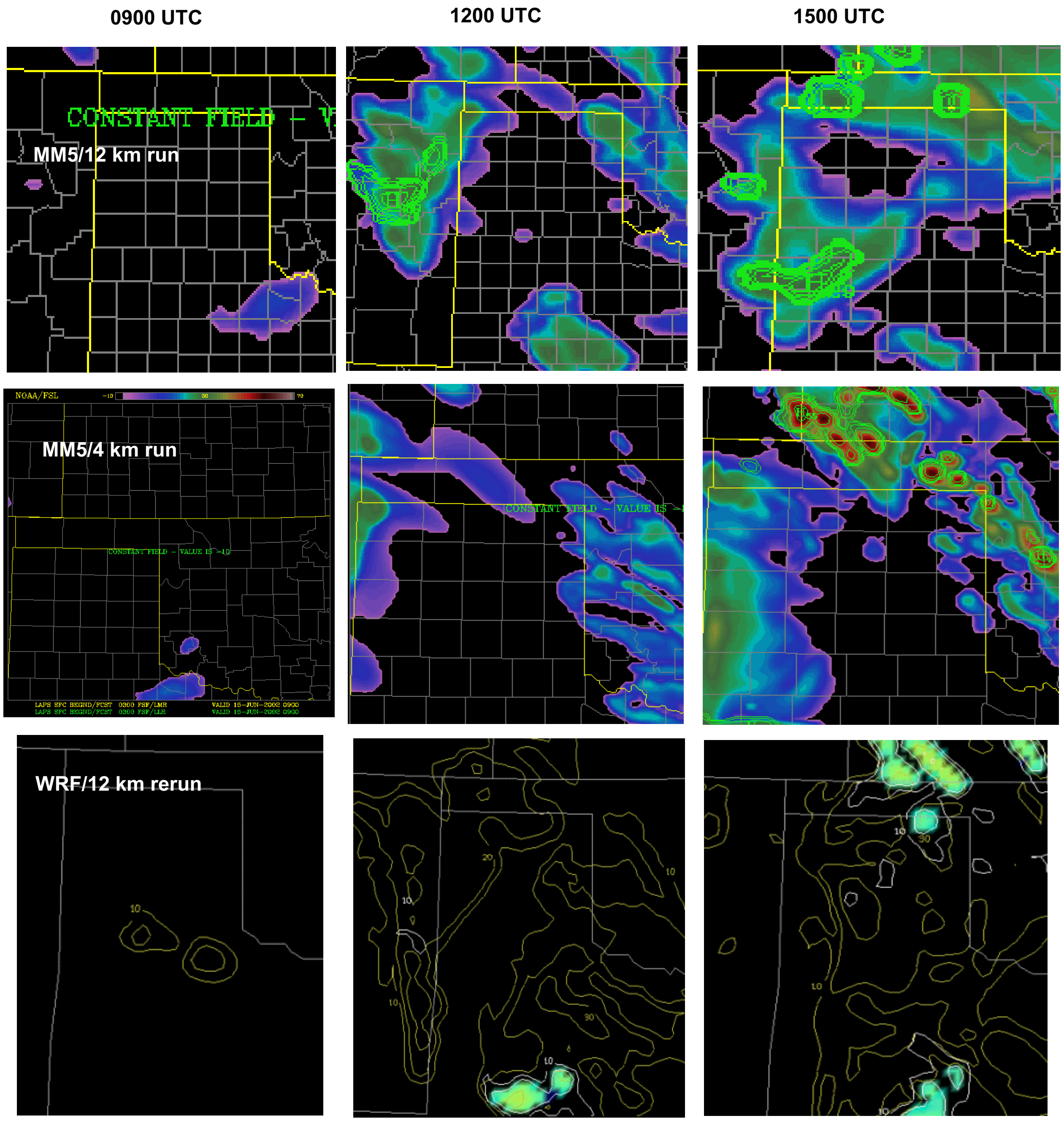


Figure 12. Model simulations from the 0600 UTC 15 June runs of the MM5/12 km (top row), MM5/4 km (middle), and WRF/12 km (bottom) models for the elevated convection in the Texas Panhandle. Reflectivity is displayed as before for the MM5 models, while for the WRF contours are composite and image surface reflectivity.

The model simulations from the 0600 UTC runs are depicted in Fig. 12. At 0600 UTC (not shown) a couple of surface-based storms were found at the southern end of the Texas Panhandle, having developed earlier in New Mexico and moved east. These storms are seen in Fig. 11 continuing to move southward with time. It is interesting that the hotstart method nicely initialized the LAPS runs (MM5 and WRF) correctly with echo at 0600 UTC, but the echo was mostly lost within the first hour. Although loss of initial echo was a problem for other cases during IHOP and is the subject of ongoing work with the hotstart procedure, it appears particularly acute in situations like this where nighttime surface conditions would not support surface-based storms.

The area of elevated storms developed north of the longer-lived echoes, and remained more or less in the same area, peaking around 1200 UTC and diminishing rapidly after 1600 UTC. All three of the model simulations shown in Fig. 12 initialized at 0600 UTC do develop some midlevel echo but for the most part it is not in the

Texas Panhandle specifically and is certainly slow to develop (for example, note the lack of any echo at 0900 UTC). There are contrasting forecasts among the three models, though, and apparent attempts at forecasting the elevated storms. The MM5/12 km run shows some significant surface echo, though the southernmost storm moved out of New Mexico apparently in the same manner as the earlier strong storms. The more northern cells develop in southeast Colorado and may well be the models forecast of elevated type storms. The MM5/4 km run also shows these more northern storms extending in a broken line from northwest to southeast. It is not certain what forced this line but it could be more of a development along a warm frontal type boundary that was actually positioned somewhat farther east and north. The WRF/12 km model appears to come closest to positioning the midlevel echo correctly in the Texas Panhandle, although it underpredicts the strength of the storms with only limited surface reflectivity (for the WRF model the image shows surface reflectivity of 20 dBZ and above, with the white contours showing values below 20 dBZ).

The next feature of interest is whether the models could predict a long-lived echo that formed from a group of small cells east of Denver (near Limon) at 1500 UTC that gradually grew as they moved east, with more or less one main storm by 1800 UTC that then turned to the right as it moved into western Kansas (see the reflectivity images in Fig. 13). This storm became supercellular but did not produce a tornado until 2100 UTC after it intersected a pre-existing north-south dryline (the one that IHOP was focusing on) and then moved southward along it. Although the resolution of the model runs at 12 km (and to a lesser extent 4 km) would appear to be too coarse to successfully forecast an individual storm, some surprisingly excellent forecasts have been made with a 10 km version of the MM5 (Szoke and Marroquin, 2000), so we were interested to examine the models for this event.

For this case the storm formed beyond the domain of the MM5/4 km model, and shown in Fig. 13 are forecasts from the 12 km MM5 and WRF models rerun after IHOP using some improvements to the hotstart method. The runs are both initialized at 0600 UTC so the forecasts shown begin 15 h into the run. Both runs seem to develop storms by 1500 UTC in the correct location in

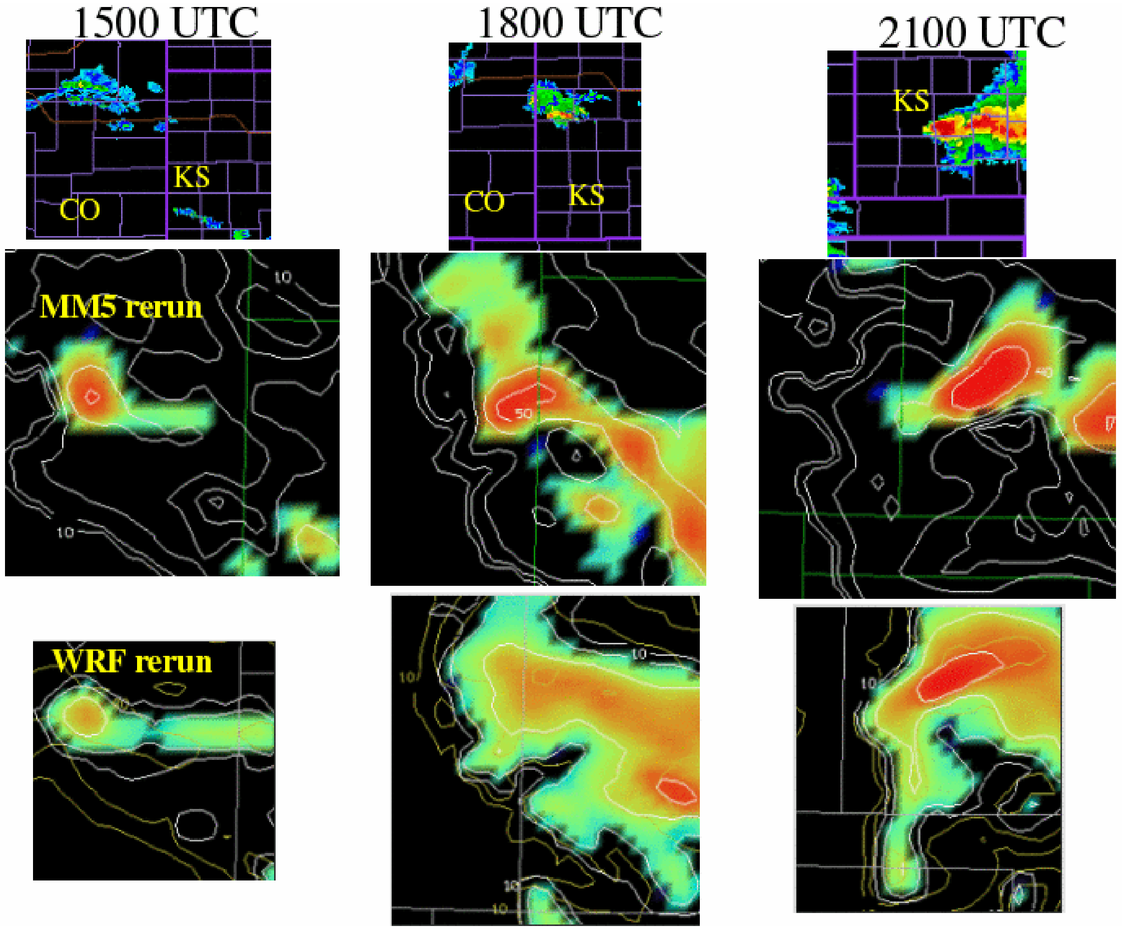
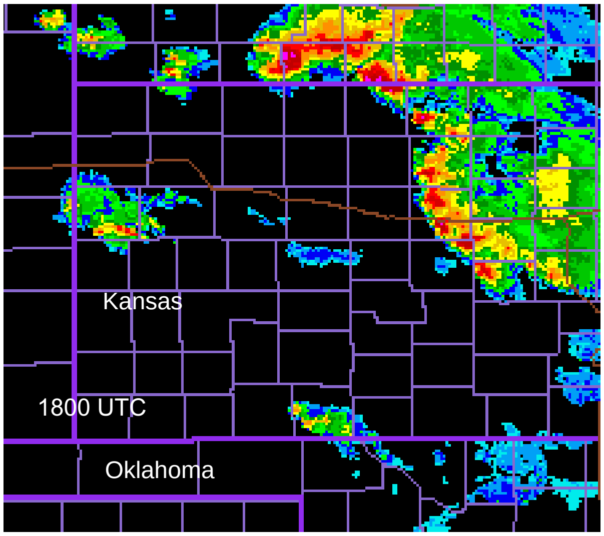


Figure 13. Comparison of the 12-km resolution MM5 and WRF model reruns initialized at 0600 UTC on 15 June with composite low-level reflectivity (top row). Model images and white contours are surface reflectivity (image is 20 dBZ and greater), with dimmer contours composite reflectivity.

eastern Colorado, strengthening the storm and moving it at about the right speed to near the Colorado/Kansas border by 1800 UTC. The model then continues to strengthen the echo and turns it to the right, in pretty good agreement with the actual behavior. The MM5 rerun tends to have a more concentrated and stronger surface echo then the WRF, but both have fairly impressive forecasts considering the one valid at 2100 UTC is a 21 h forecast. The IHOP MM5/12 km run (which extended to 12 h) from 0600 UTC was not as successful as the MM5 rerun, but had a weaker echo in about the same location. For unknown reasons, the forecasts from the IHOP runs initialized for 0900, 1200, and 1500 UTC were not very good in forecasting this long-lived system. Even the IHOP MM5/12 km 1800 UTC run, with the storm already in progress, did not have a good forecast as it tended to lose the initialized storm for the most part by 1 h into the forecast.

In summary, results are mixed for this aspect of 15 June; on one hand the 0600 UTC runs indicate some fairly impressive predictability, but inability to repeat this predictability for the IHOP runs closer to the event is curious. We hope to have MM5 and WRF reruns from 1200 UTC to compare to the 0600 UTC reruns to see if the storm was still forecast for these later model runs.

The final portion of the 15 June case that is examined involves the organization of three areas of convection into a squall line by 0000 UTC on 16 June that then accelerates southward out of the IHOP domain by 0600 UTC. A radar overview of this evolution is shown in Fig. 14. At 1800 UTC the organized storm discussed earlier is just crossing into western Kansas and at 2100 UTC is at the western end of the line segment located in southwestern Kansas. By 0000 UTC a line extends from northern Oklahoma west-southwest into the Texas Panhandle, with the eastern portion having developed from the area of cells that moved south out of Nebraska. After



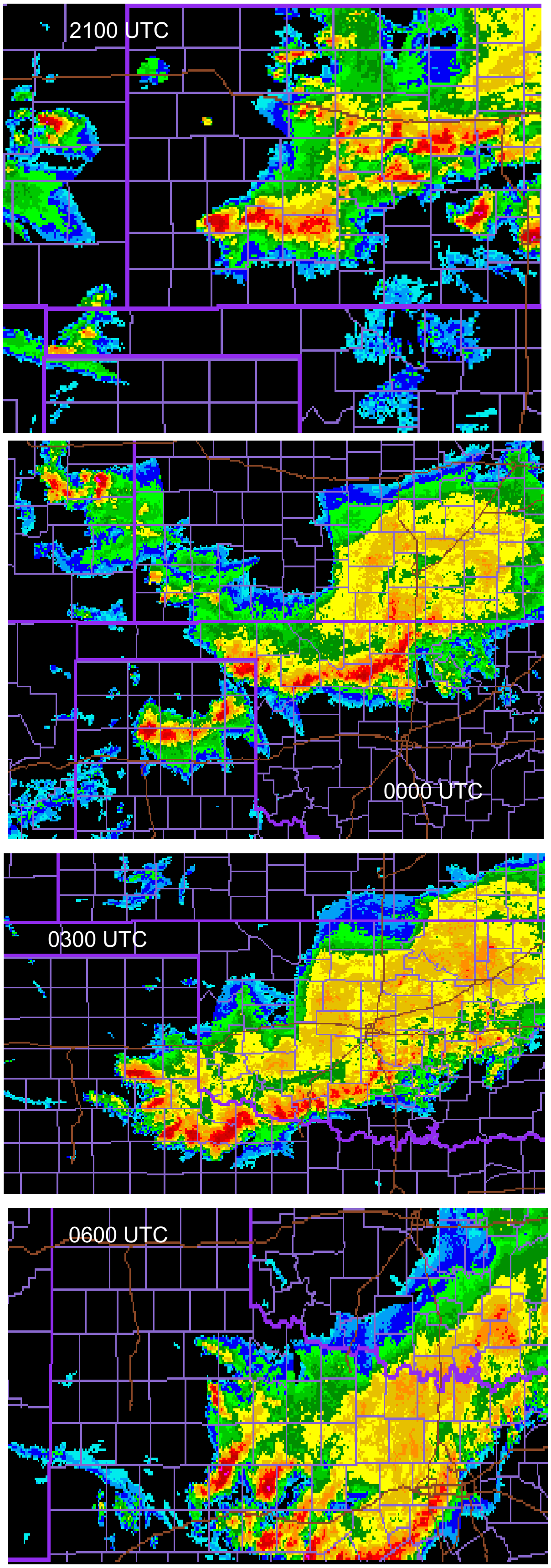
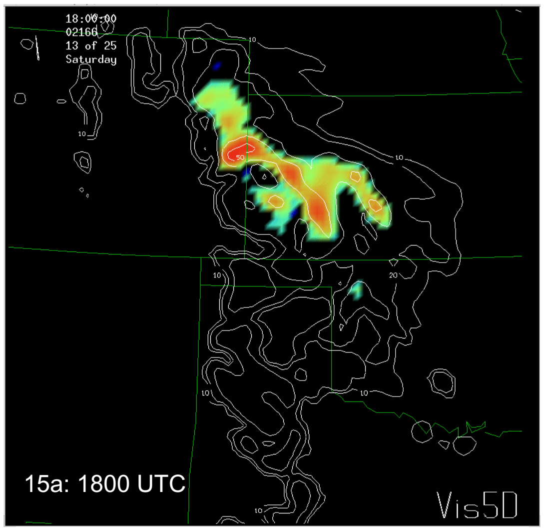
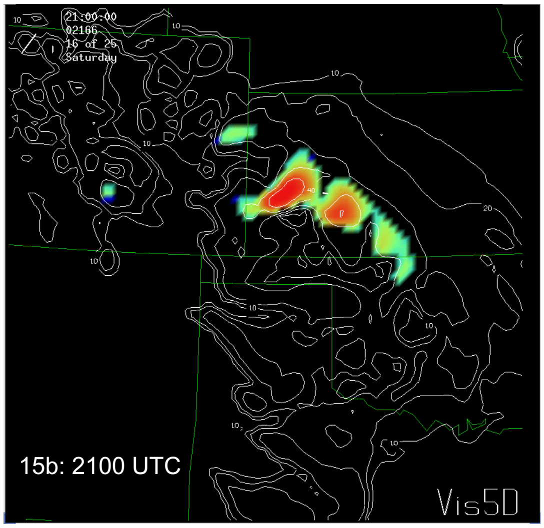
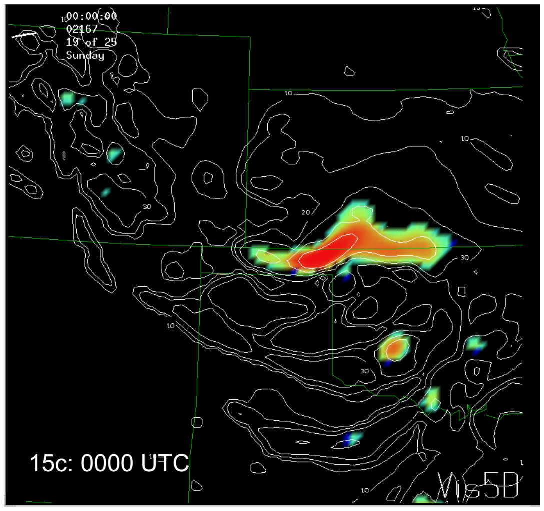


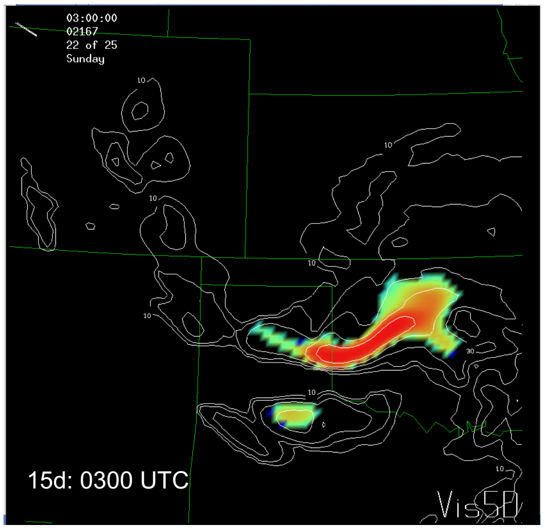
Figure 14. Series of composite low-level reflectivity images showing the organization of cells into a fast-moving squall line on 15 June.

0000 UTC the line organizes and accelerates as it bows over western to southcentral Oklahoma. The model forecasts from the 0600 UTC reruns of MM5/12 km are shown in Fig. 15 and the WRF/12 km in Fig. 16. The MM5 organizes a group of cells in Kansas at 2100 UTC into a line segment close to where it is actually found at 0000 UTC, then accelerates the line southward. Although the actual line moves faster than the forecast, the track is similar and the model forecast includes a bowing line as observed. Considering that the later period of this forecast is a 18-24 h forecast, it is fairly impressive, with the model doing a very good job of forecasting the organization into an accelerating, bowing line. This line forms in about the right place even though the MM5 essentially misses all of the storms that around 0900 UTC began to form in a NNW to SSE line from central Kansas to west-central Nebraska. These storms continued to expand in about the same place, and appear to have been, at least initially, somewhat ele-









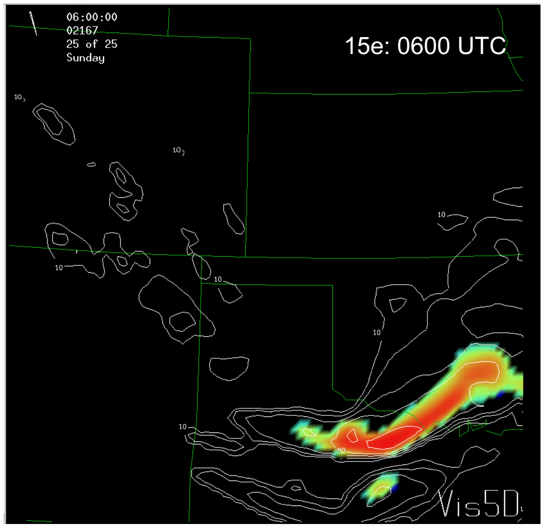
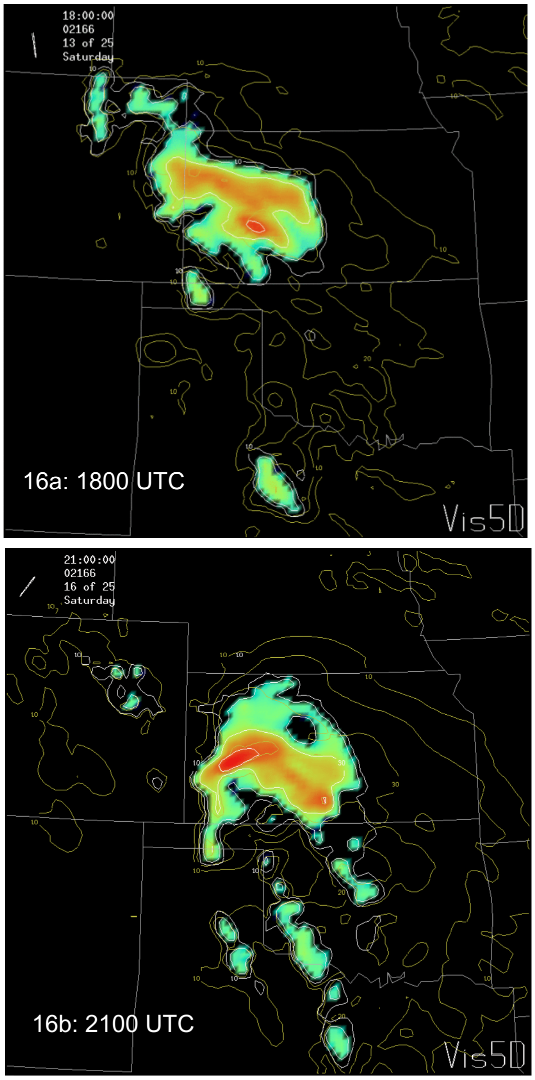


Figure 15 a-e. MM5/12 km rerun from 0600 UTC of low-level reflectivity (image, as in previous figures, beginning at 20 dBZ, red shows ~50 dBZ and higher) and composite reflectivity (contours, every 10 dBZ starting at 10 dBZ).

vated type storms that developed just ahead of a warm frontal boundary. The earlier times of this MM5 forecast never included anything but some mid-level reflectivity, and even then it was west of where the line actually occurred. The difficulty in handling convection that may not have been surface-based or forced by a distinct low-level boundary is similar to the problems the models all had with the elevated convection in the Texas Panhandle discussed earlier.

A similar set of forecasts from the WRF/12 km rerun is shown in Fig. 16. The WRF forecasts have a little more surface reflectivity then the MM5 forecasts, but like the MM5 run also misses the warm frontal convection discussed earlier. By 0000 UTC (compare Figs. 15c and 16c) the forecast for the developing line segment is similar to the MM5 and about in the same location, though the WRF continues to produce far more echo (and hence precipitation), with a large diffuse surface echo extending to the east-northeast of the line. This is a better forecast then the MM5 for the extent of echo if one compares to the observed echo at 0000 UTC that shows an extensive area of moderate-strength surface echo in about the same position as the WRF forecast. After 0000 UTC the



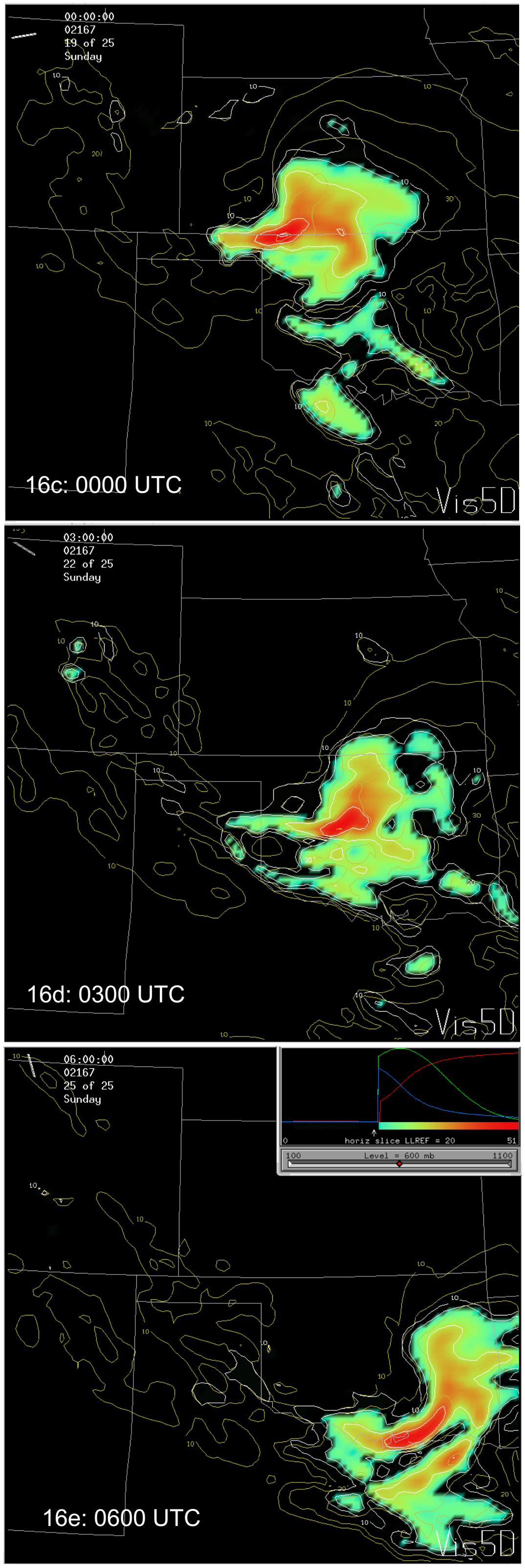
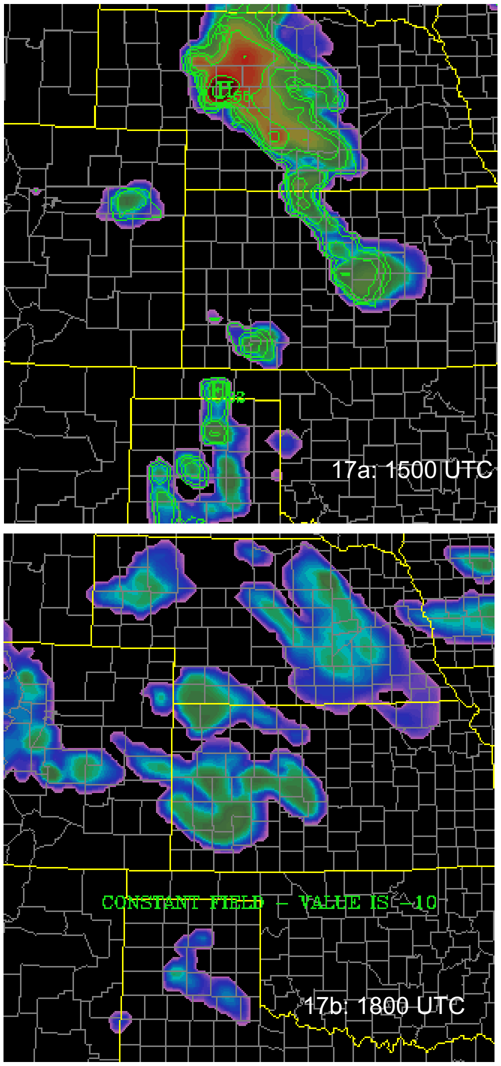


Figure 16 a-e. As in Figure 15 but for the WRF/12 km rerun initialized at 0600 UTC on 15 June.

forecast is not quite as good as the MM5 run with a smaller line that is located a bit too far east. However, like the MM5 rerun, it is impressive that the WRF model was able to predict the upscale growth to a bowing line in about the right place and about when it occurred.

The MM5 runs during IHOP extended out to 12 h, compared to 24 h for the reruns, so for comparison, runs beginning at 1500 UTC for the 12 km MM5 and at 1800 UTC for the 4 km MM5 will be shown. The 1500 UTC MM5/12 km IHOP run is shown in Fig. 17. Note how the initialization from LAPS nicely captures the ongoing convection at 1500 UTC (Fig. 17a), although the storms are quickly lost, mostly in the first hour. This occurred at times with MM5 during IHOP, as noted earlier, and for this case may have been exaggerated somewhat because much of this convection near an apparent warm front may not have been surface-based. Unfortunately there is such a loss of echo that by the 3 h forecast (valid at 1800 UTC), composite echo is forecast but none is predicted to reach the surface. Right after 1800 UTC, however, the midlevel echo shown entering northwest Kansas in the 1800 UTC forecast strengthens rapidly, then expands to form the line segment shown in the forecast valid at 2100 UTC. This line segment then moves southward and strengthens and expands, bowing some-



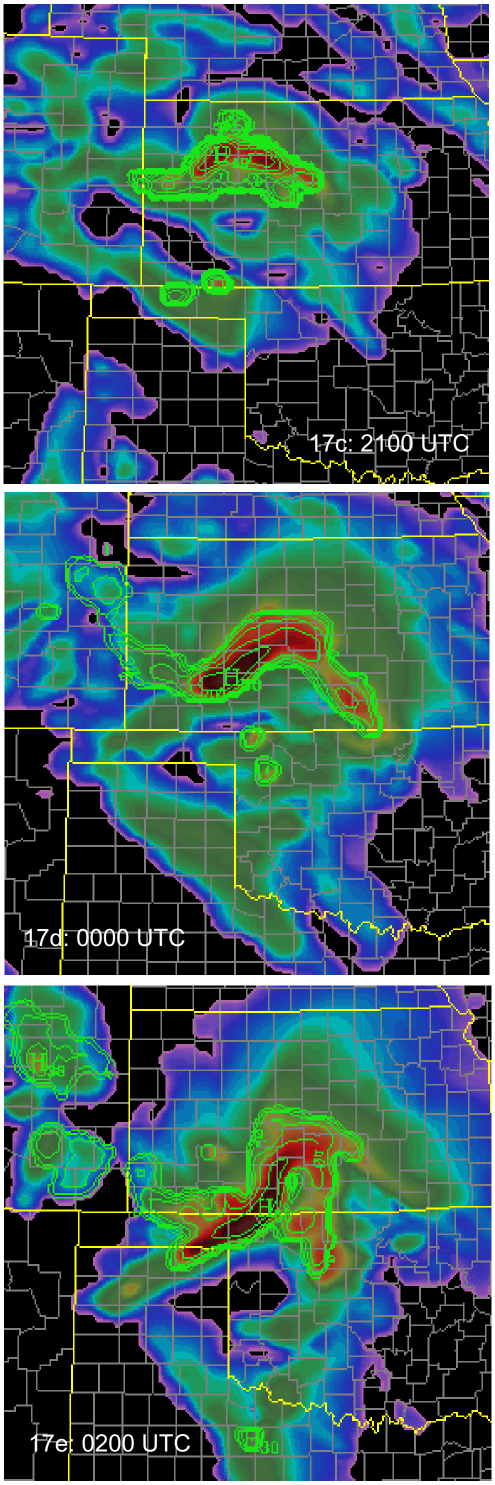


Figure 17 a-e. As in Figure 15 except for the MM5/12 km forecast made during IHOP and initialized at 1500 UTC. Note that the 12 h forecast was not available, so the 11 h forecast valid at 0200 UTC is in Fig. 17e.

what at 0000 UTC but then becoming more of a straight line by 0200 UTC. The line in this forecast does not accelerate as fast as in the 0600 UTC forecasts from the WRF and MM5 reruns shown earlier.

A comparison of the MM5 IHOP 12 km and 4 km runs initialized at 1800 UTC is shown in Fig. 18. The two runs did capture the evolution to a line that accelerated and bowed with time. Organization into a stronger sys-

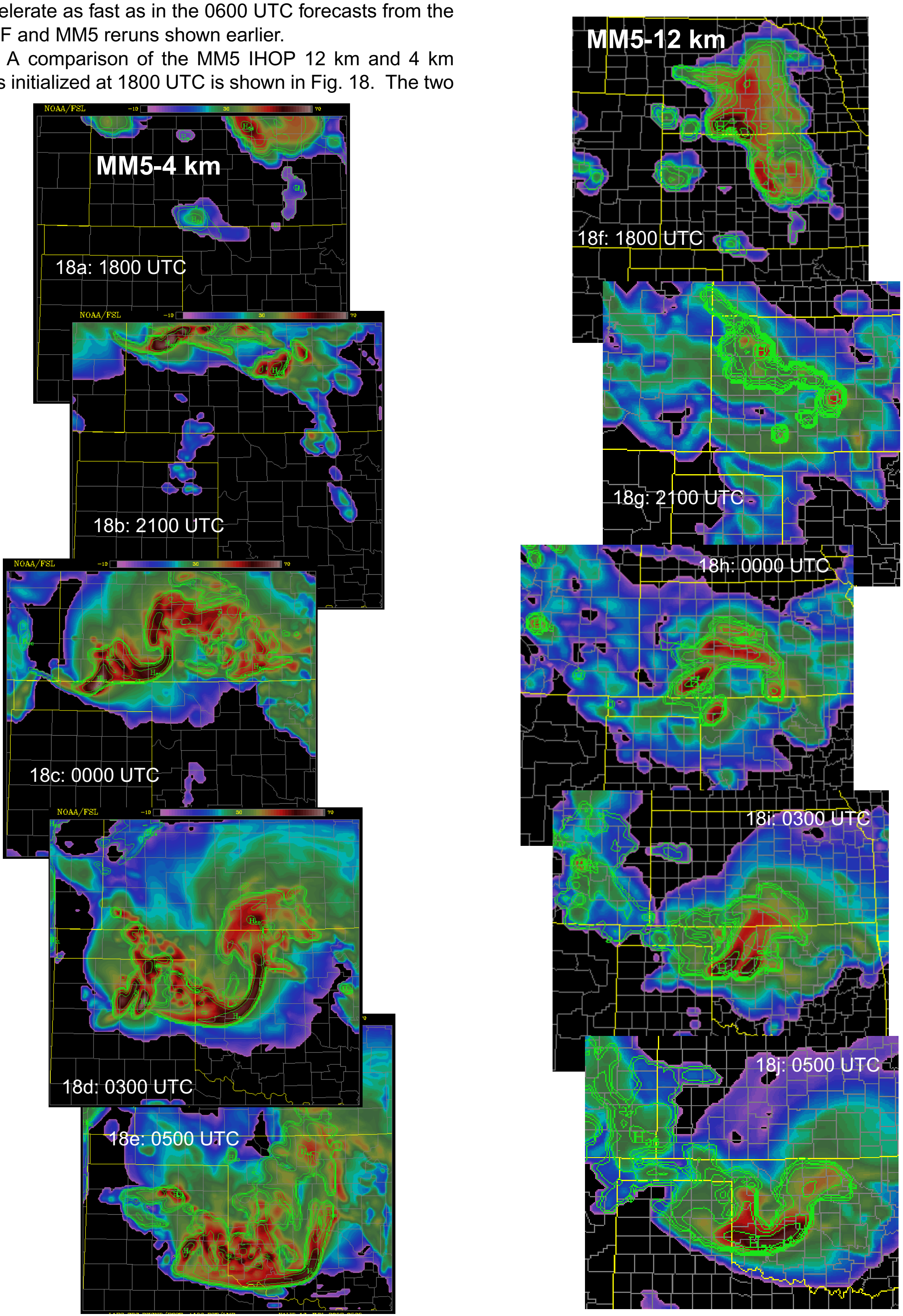


Figure 18 a-j. Comparison of MM5/4km (left column) and MM5/12 km (right) forecasts from the 1800 UTC runs. Reflectivity is shown, as in previous figures. Note that the 11 h forecast (not the 12 h) is shown in 18e and 18j.

tem with more bowing happens in the 4 km run ahead of the 12 km run, with the 4 km likely able to capture storm outflows better with its higher resolution. The 4 km run by 0500 UTC is still slower than reality with the position of the line but not by much. A similar set of model runs for the 2100 UTC initialization, when the convection was beginning to organize more, is shown in Fig. 19. Although there is some loss of the system in the first hour of the forecast after a good job of initialization (Figs. 19a and 19e), more is retained than in some of the other runs because of the presence of stronger echo at 2100 UTC. The MM5/12 km run is similar to the run initialized at 1800 UTC, although it develops a line sooner (by 0000 UTC) and ends up with a line position by 0600 UTC closer to reality and similar to the 0600 UTC MM5 rerun shown earlier (Fig. 15e). Interestingly the MM5/4 km run

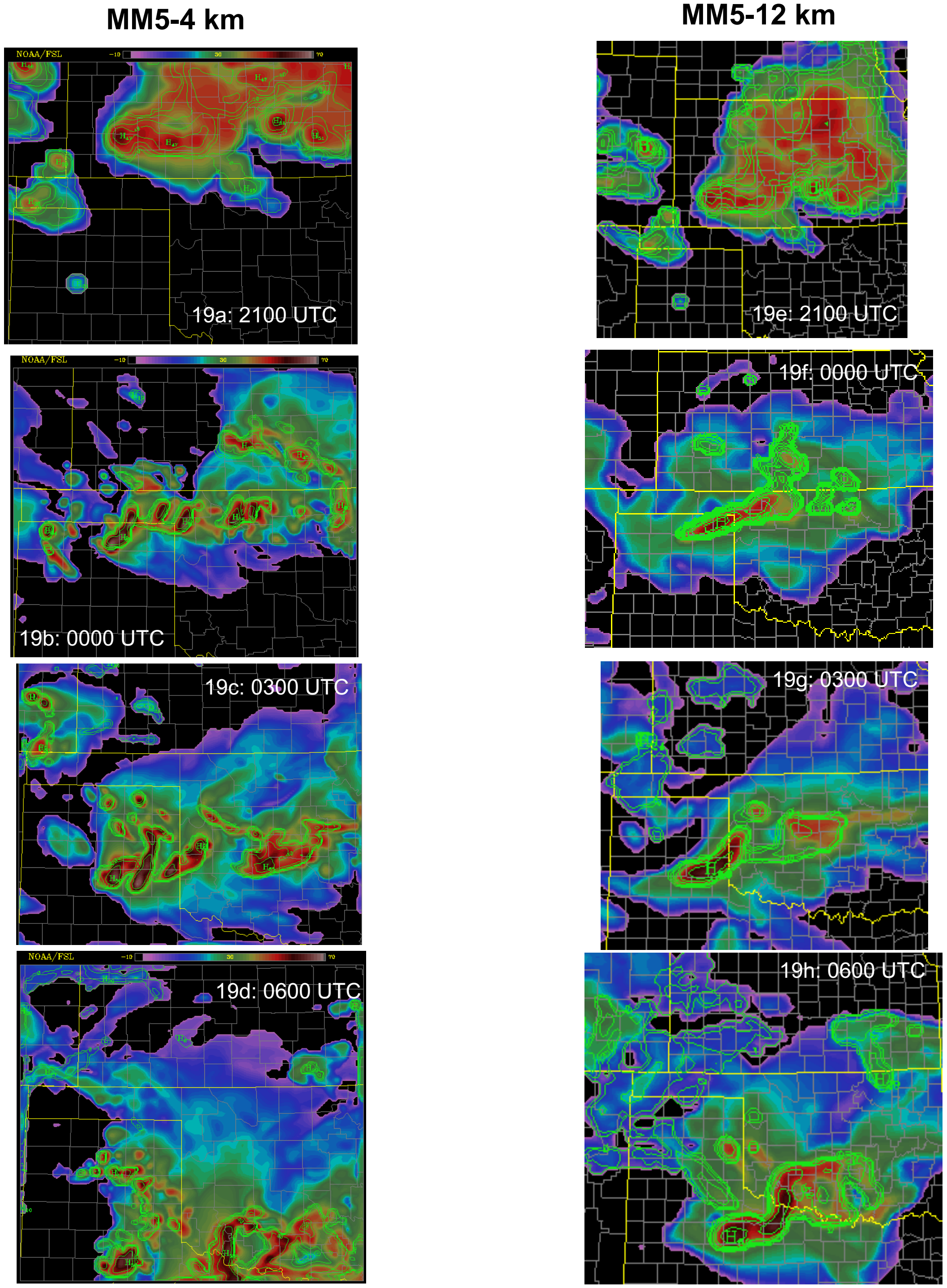


Figure 19 a-h. As in Fig. 18 except for the runs initialized at 2100 UTC on 15 June.

from 2100 UTC does not organize the convection into a line as fast it did with the 1800 UTC run, and even at 0300 UTC has more of a broken line that is not as good a forecast. By 0600 UTC it organizes the line more and accelerates it south of the 4 km domain, similar to the movement that was observed.

It is apparent that all the models were able to predict the upscale growth and organization of the convection into a line with good location and timing for the most part. There was good agreement between the different models and for the most part between the different initialization times. A consensus forecast from an ensemble viewpoint of the various runs would have been a good one. The dprog/dt method did not necessarily verify as well, however, especially for the MM5/4 km runs, for which the 2100 UTC run was not as good a forecast as earlier runs.

4. SUMMARY

Model forecasts were examined from two IHOP days that encompass a variety of forecast problems typically encountered, especially east of the Rocky Mountains, including convective initiation along a dryline, prediction of supercells, upscale growth and organization of storms into a squall line, and the very tricky forecast of overnight elevated convection. The forecasts presented are a good representation of the behavior of the models for the IHOP period, and indicate that there is potential for such models to offer forecast guidance that can be valuable to forecasters trying to predict convection. The model was most successful when the convective initiation was forced by a well-defined surface boundary, as in the 2 June case, and had the most difficult time with storms forced by more subtle boundaries (like the warm front on 15 June) or by no apparent surface boundary, like the elevated storms in the Texas Panhandle on 15 June. Some of the forecasts of supercell formation and movement, as well as upscale growth that occurred on 15 June were impressive, and there was even skill shown for such developments beyond the typical 6 to 12 h limit that one might suspect for convective forecasts.

During IHOP the RUC and MM5 special model runs by FSL were extensively used to help make short-range forecasts, with the models displayed on the FSL FX-Net workstation. Partial examination of an extensive real-time questionnaire completed by the forecasters for as many model runs as possible during IHOP has yielded good insight into various model issues that occurred, as well as how much the forecasters trusted some of the predictions. Often these predictions carried far more detail as well as forecast precipitation (convection) than would be indicated by the operational models (Eta, GFS), and in some cases a spin-up time was needed by some of the forecasters to understand whether the forecasts could be believed and how best to use them.

We continue to complete the analysis of the questionnaires. In addition, we hope to examine a broader spectrum of IHOP days for model performance, not in the detail as was done for 15 June, but more by phenomenon, such as the different convective types discussed for the 15 June case.

5. ACKNOWLEDGEMENTS

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