Use and Performance of Several Mesoscale Models for Convective Forecasting During IHOP

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Abstract

During the International H_2O Project (IHOP) the NOAA Forecast Systems Laboratory (FSL) in Boulder played a significant role in the planning and implementation of forecasting and nowcasting support. In part to aid the nowcasting and short-range forecasting efforts, FSL ran several configurations of the Rapid Update Cycle (RUC) model, the Mesoscale Model version 5 (MM5), and the Weather Research and Forecast (WRF) model over various domains at a 3-h frequency. The forecasting and nowcasting support during IHOP are detailed, including the role the special model runs played in making the real-time forecasting decisions.

A subjective evaluation of model performance is given, with emphasis on prediction of convective initiation (CI) along dryline boundaries. A significant part of the evaluation is based on a questionnaire the forecasters completed in the field, plus additional notes made during the experiment. Post-IHOP analysis of the model forecasts is also used in the evaluation of CI along drylines, allowing for inclusion of the WRF model, which was rerun after the exercise, as well as an improved version of the MM5.

Generally, the models did well at forecasting major low-level mesoscale features that preceded convection and provided useful guidance for the location and timing of initial convection. There were, however, wide variations in day-to-day model performance, as well as for different runs on a single day, and often an ensemble approach had some merit. Certain systematic model biases were also evident. Two cases are examined in detail to better illustrate the model performance and forecast issues.

1. Introduction

The International H_2O Project (IHOP) was an extensive field project involving scientists from around the world that took place 13 May to 25 June of 2002 in the Southern Plains of the United States, with the purpose of better characterizing the four-dimensional distribution of water vapor through the use of special detailed observations and applying this characterization to improve the understanding and prediction of convection (Weckwerth et al. 2004). Successful execution of IHOP required very specific forecasts. Numerous aircraft, as well as ground crews with instrumented vehicles, all needed to be timely positioned within a relatively small area. In this paper we will give an overview of the forecast and nowcast requirements and implementation during IHOP, as well as discuss how several mesoscale models run specifically for IHOP were used and evaluated in real-time. Post-IHOP evaluation of these model runs, as well as reruns made after IHOP, is discussed with a focus on convective initiation (CI) along drylines.

The forecasting requirements for a significant field program can be extensive, as discussed for the Stormscale Operational and Research Meteorology-Fronts Experimental Systems Test (STORM-FEST) held in 1992 by Szoke et al. (1994). The requirements usually include requests for forecasts ranging from 1 h to a week in advance, and with a hope of both high specificity and accuracy. After lengthy pre-exercise planning, a specific forecast schedule was designed to meet the IHOP longer-range planning needs, and a nowcasting effort designed to address the shorter term needs. This resulted in a close cooperative effort between the NOAA Research Forecast Systems Laboratory (FSL) in Boulder, Colorado, and the NOAA Storm Prediction Center (SPC) in Norman, Oklahoma.

Motivated by a desire to contribute to the IHOP forecasting and nowcasting requirements, and by the opportunity to examine in real time the performance of models at resolutions and configurations that would not be realizable operationally for a few years in an environment often propitious for convection, FSL ran special versions of three models. These included the Rapid Update Cycle (RUC) model (Benjamin et al. 2004) at a 10-km horizontal grid resolution, the NCAR/Penn State Mesoscale Model version 5 (MM5) initialized using the Local Analysis and Prediction System (LAPS-Albers et al. 1996) at a horizontal grid resolution of 12 km with a smaller interior domain at 4 km, and a then current version of the Weather Research and Forecast (WRF) model (homepage at http://www.wrf-model.org).

In the spirit of the forecast exercises held in recent years at the SPC (Kain et al 2003), we took advantage of the special model runs and the forecasting requirements for IHOP to assess the forecaster's impression of model utility during real time using an online questionnaire. The input from these questionnaires is used for the discussion in Section 3, we then examine model performance for CI dryline cases in Sections 4 and 5. While the forecasters and nowcasters had access to and used the operational models, including the National Center for Environmental Prediction (NCEP) Eta, and the RUC, with operational horizontal grid resolutions of 12 and 20 km respectively, we concentrated on evaluating the special model runs during IHOP, and that is also the focus of this paper.

2. FSL special model runs and forecast activities during IHOP

a. Special model runs

The special models run by FSL for IHOP are listed in Table 1, and their domains shown in Fig. 1. The RUC is a hybrid isentropic-sigma coordinate model, typically run on a domain covering the coterminous United States, that was developed to fill a void in shorter-term (out to 12 h) frequently updated prediction (Benjamin et al. 2004). The RUC ingests many types of asynoptic data, and just before IHOP was upgraded to 20 km horizontal grid resolution for the operational runs at the National Center for Environmental Prediction (NCEP) (Benjamin et al. 2002). The special IHOP runs were spawned from a developmental cycle of the 20-km RUC running at FSL using a three-dimensional variational (3dVAR) analysis, described in Benjamin et al (2004), by directly interpolating the 20 km fields to the special IHOP 10 km grid.

Development of LAPS also began at FSL during the 1980s. In contrast to the RUC, LAPS has been viewed as an analysis system that could be run site-specific at a local forecast office, such as a National Weather Service (NWS) Weather Forecast Office (WFO) (Albers et al. 1996). As such, it is configured to ingest additional data that may not be available to national scale models but is available at a local office, such as detailed surface observations from non-conventional reporting stations, and to provide flexibility in configuration by a WFO. LAPS can be run just as an analysis package, as is currently the case at most NWS WFOs in the continental United States as a part of the Advanced Weather Interactive Processing System (AWIPS, Wakefield 1998). The "P" in LAPS represents the idea that a high-quality local analysis would be an ideal input to a local scale model that could also be run at a WFO. FSL has tested various models with LAPS, early on with the Colorado State University Regional Atmospheric Modeling System model (RAMS, Snook et al. 1995), more recently the MM5 model (Grell et al. 1995), and even more recently the WRF model. Currently, FSL runs LAPS with MM5 four times a day at a 10-km horizontal grid resolution and sends the output, a 24-h forecast at hourly intervals, in real-time to the AWIPS system at the collocated Boulder WFO, which allows for ongoing subjective model evaluation for a variety of weather events (Szoke et al. 2000, Szoke and Shaw 2001). Another application of LAPS with a local model is a pilot program at the WFO in Jacksonville, Florida, where LAPS is coupled with the WRF and run at 5 km horizontal grid spacing (Bogenschutz et al., 2004; Koch et al., 2004).

One goal of short-range numerical weather prediction (NWP) is to provide better prediction of precipitation by eliminating the model "spin-up" period, while maintaining computational efficiency. To aid in this goal a diabatic initialization (or "Hot Start") scheme was developed. This scheme relies on the ability of LAPS to ingest a wide variety of meteorological data, including WSR-88D radar and GOES satellite data, to produce a detailed three-dimensional analysis of the atmospheric state variables as well as all phases of condensate (Schultz 1995). The detailed cloud analysis is used to prescribe a vertical velocity profile within sufficiently deep clouds present at the initial time (Schultz and Albers 2001). Using the inferred in-cloud vertical velocity, a three-dimensional variational technique is used to dynamically balance the mass and momentum fields (McGinley and Smart 2001). The Hot Start scheme has been tested for several years in our daily runs at the Boulder WFO, and is used in other configurations of LAPS for models being run for specific applications at various locations (Shaw et al. 2001, Shieh et al. 2003). During IHOP, a 12-

km horizontal resolution MM5 Hot Start initialized with LAPS was run, with a nested 4-km version covering the IHOP experimental domain (Figure 1). LAPS was also used to initialize a similar 12-km setup for the WRF model, but the model was not able to be displayed in real-time during IHOP. The RUC model run during IHOP employed a 3dVAR analysis for the mass fields. For the initial hydrometeor fields, the 1-h forecast background is modified by comparison to satellite infrared cloud coverage and top, and to low-resolution base-scan reflectivity (Benjamin et al 2002). By contrast to the LAPS Hot Start procedure, there is no modification of the initial vertical velocity field for the RUC.

To display the output of the models for the forecasters and nowcasters in a timely manner, a workstation developed at FSL called FX-Net (Madine and Wang 1999) was employed. FX-Net emulates many of the capabilities of AWIPS in a PC environment, but with very flexible data transfer rates. During IHOP an FX-Net PC was available as a real-time meteorological workstation at various sites supporting the operations, including the Science Support Area (SSA), the Operations Center, and one of the main radar sites (S-Pol, in the Oklahoma Panhandle). FX-Net not only displayed all the conventional data, imagery and models found on AWIPS, but also the experimental model runs and some special IHOP data.

The FSL RUC 10 km, MM5 and WRF models were run on Linux clusters. Complete model cycles were made every 3 h, out to 12 h for MM5 and WRF, and varying from 12 h to one run out to 24 h for the RUC. Selected output from the experimental model runs were archived by the University Corporation for Atmospheric Research's (UCAR) Joint Office for Science Support (JOSS, at http://www.joss.ucar.edu/ihop).

b. Forecasting and nowcasting activities during IHOP

There were four research components of IHOP ranging from interest in CI to quantitative precipitation forecasting (QPF), and from convective systems to boundary layer studies using downward pointing lidars on research aircraft. This meant that operations could occur under a wide range of conditions, encompassing both fair weather days and days with convective potential. As a result, there were very few “down” days, and a forecast of clear conditions and a lack of any thunderstorms might be as critical for one IHOP operation as the forecast of CI for another.

After considerable interaction with IHOP scientists and the SPC, the forecasting and nowcasting activities were divided as follows. The SPC was responsible for issuing the main forecast products. These consisted of detailed forecasts (maps and text discussions) concentrating on the potential for CI over the IHOP area, as well as indicating where possible mesoscale convective systems might form and the position of the low-level jet, if present. An example of a forecast product for IHOP is shown in Fig. 2. These forecasts were issued each day, with a preliminary forecast due at 9:00 A.M. local time (CDT, 1400 UTC) and the main forecasts due by 1:00 P.M (1800 UTC), with the detailed forecasts covering the next 6 h period (through 0000 UTC), and one forecast covering the next day. The forecasts were discussed in detail by a forecaster at the daily 1:00 P.M. IHOP briefing. Generally SPC forecasters, or visiting forecasters and scientists, coordinated to produce the IHOP forecast products.

Shorter-range forecasting and nowcasting efforts were coordinated by FSL, and although FSL scientists largely staffed the nowcasting positions, others that took part included scientists from the

NOAA's National Environmental Satellite, Data, and Information Service (NESDIS), the National Severe Storms Laboratory (NSSL), and the SPC. In addition, the nowcasting staff worked very closely with the forecasters early in the day, and there was close interaction between the two activities. Generally, there were two nowcasters present at any one time, which helped to provide support for operations as well as allow for real-time evaluation activities to take place. Usually one nowcaster would be stationed at the IHOP Operations Center and the other remained at the SSA to work alongside IHOP forecasters, or to coordinate as necessary with forecasters who were working operational shifts at the SPC. Many forecast and nowcast decisions arose from both groups working closely together, especially for early operations when a forecaster from the SPC was specifically assigned to IHOP related forecasting.

The nowcasters did not issue specific products, but instead provided guidance tailored to the different needs of the IHOP operations. Nowcasting was, overall, a more variable activity than the formal forecasting for IHOP, differing in the types of short-range forecasts that were required and also the hours of operations. During the extent of IHOP, nowcasting activities occurred as early as 3:00 A.M. and went to as late as 8:00 P.M CST, though most of the nowcasting, especially for CI, tended to occur from the afternoon into the early evening hours.

3. Subjective real-time evaluation

a. Real-time evaluation efforts during IHOP

The design of the online form used by the SPC in their springtime experimental programs prior to IHOP (Kain et al. 2003) was followed for our real-time evaluation during IHOP. It became clear after designing the IHOP nowcasting and evaluation activities that it would take a multi-person effort to effectively accomplish everything. Since the subjective evaluation alone could be a full-time job, given that there were three different special model runs available to look at (RUC-10, MM5 12- and 4-km) every 3 h, at any given time there were almost always two nowcasters on duty. Although at times it was simply not possible to keep up with all the model output in terms of completing the evaluations, most of the models were examined carefully each day, forecaster impressions noted, and initial impressions of forecast verification recorded.

Objective QPF verification was also performed at FSL, using conventional scoring methods and attempting some experimental methods that try to account for displacement errors in the pattern of precipitation (Grams et al., 2004). Results for IHOP are available on FSL's Real-Time Verification Forecast System's (RTVS) homepage (http://www-ad.fsl.noaa.gov/fvb/index.html), but in this paper we concentrate only on the subjective evaluation.

The online questionnaire for real-time evaluation of the models in IHOP consisted of seven questions:

1) Initial boundary analysis - identify any boundaries in the model's initial analysis and compare to observations.
2) Boundaries involved in the forecast - identify the various boundaries that were forecast.

3) Boundary/precipitation relationship - document whether any precipitation forecast by the model was associated with a particular boundary.
4) Rainfall potential - document the maximum rainfall forecast by the model, and whether the forecast is deemed to be an overforecast, underforecast, or about right.
5) Timing of convective initiation - record when CI was forecast by the model.
6) Dominant convective mode - for the LAPS initialized models the model reflectivity field was used, whereas for RUC this was implied from the precipitation and cloud top fields where possible. A checklist was provided for the categories of non-supercell, supercell, MCS/MCC, and line.
7) Parameter assessment - evaluate the forecast values of Convective Available Potential Energy (CAPE), Convective Inhibition (CIN), surface mass convergence, and, where applicable, model sounding structure.

The focus was usually the main IHOP domain, roughly equivalent to the MM5/4-km domain in Fig. 1, unless IHOP operations extended outside this area. During IHOP all the models except the WRF were evaluated. For all but questions 1 and 7, the 12-h total forecast period was evaluated separately for the time periods of 0-3 h, 3-6 h, and 6-12 h. Additionally, except for question 1, the evaluators recorded their confidence in the model forecasts on a scale from 1 (lowest) to 10 (highest) by checking an appropriate box. There was also ample area to record free-form comments.

b. Analysis of the questionnaires

The somewhat imposing length of the online questionnaire meant that some of the questions towards the end of the form (such as the precipitation characteristics of the model forecasts, or the evaluation of pre-convective parameters) were typically not answered. The free-form commentary section provided a means to address some of the questions the forecaster may not have had time to complete, as well as to record insight of other features of the model forecasts. Although we carefully considered the questionnaire prior to IHOP, our experience from IHOP suggests that with actual forecast responsibility added to the duty of the participant, the more succinct the form the better. In addition to the full questionnaire, we had available a simple text editor where the forecaster could quickly enter a few notes, and this proved to be extremely useful for gathering information. The SPC may have had somewhat better success in addressing more questions in the online forms for their spring exercises because there was less of a requirement for specific forecasts, so more time was allotted to the evaluation efforts. The above problems not withstanding, we nonetheless consider real-time evaluation efforts to be very worthwhile, and an important method of gaining insight into model performance over a wide variety of weather types.

A summary of the comments from the real-time evaluation by each question follows.

1) Initial boundary analysis: Drylines were captured well in the initial analysis for all the models, but weaker boundaries, such as smaller-scale outflow boundaries, were often missed, although the 4-km LAPS analysis had better success at the smaller scale features.

2) Forecast boundaries: The forecaster's confidence in boundaries predicted by all the special models for the 1-3 h period was a 7, and this relatively high confidence only lowered to 6 for

the 6-12 h period. In the first 6 h the highest confidence was given to the MM5/12 km run, with a value up to a point higher than the other models. This reversed, however, for the 6-12 h period, with the RUC/10 km run having a slim (0.2) edge over the MM5/12 km run, likely a result of suspect convection influencing boundaries in the MM5 forecast. When separated into dryline days only, scores overall were about a point higher for all periods and for all the models, with the only exception a lower overall score of 5.9 in the 6-12 h period for the MM5/4 km run, which occasionally tended to erroneously drift the dryline westward with time. Although the MM5/12 km run still had higher scores for the dryline days in the first 3 h (8.0 or close to a point higher), scores were nearly identical (~7.25) for the 3-6 h period, and the RUC/10 km was slightly better than the MM5/12 km run for the 6-12 h period (7.3 vs. 7.0), similar to the trend when all types of boundaries were considered. Our interpretation of these scores is that the LAPS analysis (which provided the initialization for the MM5 models) was able to capture more of the smaller scale boundaries than the RUC, leading to higher scores for the first few hours of the forecast, but after about 6 h the forecasters doubted some of the convective development and associated outflow boundaries in the MM5 forecasts that were much less prevalent in the RUC model forecasts. The RUC forecasts were typically drier, but also much less prone to exhibit outflow boundaries even when appreciable convective rainfall was produced (also noted by Wilson and Roberts 2005).

3) Boundary/precipitation relationship: One would anticipate that forecaster confidence should drop for this question, since it considers both the forecast of boundaries and whether or not convection forms along the boundaries. Indeed this is the case, with confidence values for all the models lower by 2 points for the 1-3 h forecasts (5 vs. 7 for question 2). Interestingly, this

gap is less than 1 by the 3-6 h period, and then nonexistent by the 6-12 h period. Although the sample size is limited for the dryline only cases, the same trend occurs. Considering all types of boundaries, forecasters tended to have higher confidence in the RUC/10 km run than the MM5 runs (from 0.7 higher in the 1-3 h period to ~0.9 higher by 6-12 h), for the reasons noted with question 2. One source of the lower confidence for some of the 1-3 h forecasts was a loss of ongoing convection within the first 1-2 h of the forecast for the MM5 models, which negated the successful initialization of ongoing storms by the Hot Start method. Another issue was a perceived premature forecast of CI, equally spread among the models, for some cases.

4) Maximum rainfall forecast: The most notable characteristic of the forecaster responses for this question was the large variability in the confidence of the forecasts, covering the full spectrum for each model, from 1 or very low confidence, to 10 or very high confidence in the forecast. In the first 6 h of the forecast, both underforecasting and overforecasting of the rainfall were about evenly distributed as reasons for the lower confidence numbers. Some of the concerns expressed about underforecasting in the case of the MM5 models arose from a loss of the initial echoes in the first part of the forecast after being initialized successfully by the Hot Start, as noted above. For the 6-12 h forecast period, the pattern was closer to what has been noted by forecasters using the operational RUC and experimental versions of the MM5, that is a dry bias for the RUC and a wet bias for the MM5, although far more so for the 4 km run, which produced some very heavy rainfall totals at times. Interestingly, while the forecasters rightfully doubted the coverage of these forecast heavy rains, later verification often revealed that the rainfall forecast by the MM5 was a reasonable upper bound to the maximum point rainfall observed by a gage measurement or radar estimate. A similar observation has been noted for

the experimental MM5 model being run routinely at 10 km horizontal grid resolution at the Boulder WFO. Overall, confidence was lower than for forecasts of boundaries, and did not vary much over the 12-h forecast period, ranging from an average score for all the models of 5.6 for the 1-3 h period, to 5.3 for 3-6 h and 5.2 for 6-12 h. Sample size for only the dryline cases was too limited to make any comparison to these overall results.

5) Timing of CI: The average value of confidence for all forecasts was a modest 5.5, both for all the days and for the subset of dryline days. The confidence values for each model ranged from 5.1 for the MM5/12-km run, 5.4 for the RUC, but a notably higher 6.0 for the MM5/4-km run, which tended to develop initial cells sooner than the other models.

6) Dominant convective mode: Forecasters had fairly high confidence in the ability of the models to forecast the convective mode of the day, with scores for all models ranging from 7.4 for the 1-3 h period to 6.8 for the 3-6 and 6-12 h periods. Confidence was highest for the RUC, inferred by noting whether parameterized convection was isolated or in lines or clusters, and MM5/4-km runs, with a high confidence of ~8 for the 1-3 h period, ranging down to 7.4 for the 6-12 h period, while there was considerably less confidence for the MM5/12-km forecasts of storm type (scores ranging from 6.1 to 4.7). The storm types identified were heavily weighted towards supercells for the MM5/4-km model, which managed to more often produce long-lived individual storms, but split evenly between lines and supercells for the MM5/12-km and RUC models.

7) Parameter assessment: As noted earlier, forecasters often did not have time to complete the evaluation, and this rather involved question was often not addressed. Model forecasts of CAPE and CIN were the most frequently used parameters, with forecasters typically watching their trends for indications of when CI might occur. Generally forecasters had confidence in the predictions of these parameters, although it was noted that CAPE values in the RUC were occasionally excessive.

The were many other comments regarding model performance that were not directly related to the seven specific questions on the evaluation form, and some of these are summarized below.

- The MM5 models using LAPS for the initial state were successful at initializing ongoing convection as a result of the Hot Start method, but often this convection was lost in the first hour of simulation, effectively canceling the benefits of the Hot Start procedure. (Adjustments were made to the Hot Start scheme for the post-IHOP reruns of both MM5 and the WRF model.) The most easily "lost" convection was “elevated”, or not “surface-based”, i.e. updrafts having roots above the surface-based mixed layer.

- For the RUC, which, as noted earlier, initialized reflectivity-derived hydrometeors in regions of stable precipitation, and eased the CIN constraint on parameterized convection where indications from lightning or the satellite estimated cloud amount indicated the presence of convection, the impacts of the initialization procedure were much more conservative than for MM5. Absence of dramatically unrealistic behavior (large loss of precipitation in the first part of the forecast) often gave the RUC10 an edge in the forecasters' judgment, even though the RUC short-term convection forecasts were hardly consistently skillful.

- Elevated convection with surface precipitation was seldom forecast successfully, although in the case of MM5 there were often midlevel echoes forecast. Typically, elevated convection formed in the pre-sunrise hours, and could persist for six or more hours after sunrise. This type of convection is among the most challenging for operational forecasters, as it can occur without any obvious surface forcing feature present. Though seldom producing severe manifestations (at least during IHOP), elevated convective events were often of the "surprise" category for forecasters. Forecasting convection, often elevated, on the cool side of the warm front, was another area where the models were deficient.

4. Post-IHOP subjective model evaluation

In this section we examine model performance for the set of IHOP days shown in Table 2. After the completion of IHOP, it was determined that the MM5 and WRF forecasts could be improved by some changes to the Hot Start scheme. The main focus of these changes was to reduce systematic overforecasting of precipitation, and to improve the ability of the model to keep storms that were initialized correctly by the Hot Start procedure, but lost in the first hour of the simulation. The 12 km horizontal grid resolution MM5 and WRF models were rerun for the entire experiment with the Hot Start procedure adjustments (Shaw et al. 2004), and with the additional major change of turning off the convective parameterization scheme. Objective verification using a combination of gage and radar estimated rainfall for all the MM5 12-km forecasts made during and after IHOP by the Real-Time Verification System (RTVS) at FSL is shown in Fig. 3 for the 0 to 6 h forecasts. While the Equitable Skill Score (ESS) is better for all the ranges of precipitation through two inches in this 6 h period for the MM5 reruns with the changes noted above, the most striking difference occurs at lower rainfall amounts. The large decrease in the overprediction of amounts under 0.5 inch (12.7 mm) is a result of the removal of the convective parameterization scheme for the reruns. That the bias actually reverses to an underforecast of these lower amounts suggests the potential need for some type of parameterization, at least at the 12-km grid scale, to capture the lower amounts. This issue is addressed further in the case studies.

In evaluating the models subjectively using the cases listed in Table 2, we examined CI by comparing the model forecast surface reflectivity field, available at hourly intervals for all the models except for the RUC. For the RUC, output was available only at 3 h intervals, and precipitation and forecast cloud top were substituted for reflectivity. The most fundamental issue is whether the model correctly forecast the presence or lack of CI, and this is summarized in Table 3, for the runs initialized at 1200 and 1800 UTC. For the null case (no CI observed) on 22 May, there are mixed results, with the MM5 IHOP models forecasting CI, and the post-IHOP models split, while the RUC correctly did not forecast CI. All the models correctly predicted CI for the relatively moist environment on 10 June, but the 17, 18 and 19 June cases had some runs that did not forecast CI. These runs were for the most part the runs that did not have a parameterization scheme, suggesting that in these environments where the moisture was more shallow, and especially at grid resolutions of 12 km, such a scheme may be necessary to initiate convection. An interesting exception, though, is the 2 June case, discussed in the next section.

Two other evaluated characteristics are the location of the first CI, summarized for the 1200 and 1800 UTC runs in Fig. 4, and the timing difference between the model forecast of first CI and when it was observed, in Fig. 5. There is quite a bit of variation in these characteristics both among the model runs on an individual day, and among the different days. In general, all the models tended to perform better on certain days (such as 2 June and 19 June), and worse on others (for example 18 June), although timing errors often behaved opposite to location errors. While overall the results indicate that the RUC made a better forecast of the location of the first CI, its timing errors were more often higher than for the other models (in part this is a result of having output only at 3 h intervals for the RUC). The variability in the performance of the models suggests that an ensemble of different model runs might provide a consistently better forecast than any single model.

There is also opposite behavior in terms of improvement between the 1200 and 1800 UTC runs; for CI location the 1800 UTC runs showed improvement, but the opposite is true for CI timing. For the most part the 1800 UTC model runs erred in being too slow to develop CI. A possibility for why the later runs were inferior is that the model initialization at 1800 UTC did not correctly capture the moisture gradient (horizontally and vertically) that may have been focused right along the dryline. Numerous studies of boundaries (for example, Szoke and Brady, 1989; Wilson et al., 1992) and drylines (Ziegler et al., 1998) have shown that the environment on small horizontal scales near a boundary can be considerably more moist than the surrounding environment, with moisture also extending higher above the surface. Short of having conventional observations fortuitously positioned along a boundary, only special observations, indeed like many of those that were tested as part of IHOP, can capture this structure. Coupling this dilemma with relatively coarse model resolution, it is not surprising that an analysis might be too dry in the vicinity of a boundary, which could explain the model's lateness in developing CI. The details of the moisture structure along a dryline would likely be more important for cases where the environment was more marginal for convection and the eventual CI highly dependent on the evolution of a more favorable local environment along the dryline. We speculate that the runs initialized earlier, at 1200 UTC, had smaller timing errors because moisture convergence over time along the model dryline, although constrained by model resolution, could lead to CI relatively close to when it was observed; i.e., the model could develop smaller scale convergence with time due to nonlinearity. Ironically then, at least for some of the dryline cases, with relatively coarse model resolution relative to potentially important moisture gradients across a dryline, there can be a penalty paid for a model run starting closer to the time of CI, as the model may well begin with an environment along the dryline less favorable for CI than the environment that had evolved along the model forecast dryline in an earlier model run. This is particularly true for MM5 and WRF runs, since there is no cycling from a previous model run to provide a background for the LAPS analysis. A consequence of this is the rendering ineffective of the “dprog/dt” technique for gaining confidence in a forecast, a result noted by Hamill et al. (2003) for longer time and larger area-scale forecasting.

5. Case studies

Two cases are examined in detail using both the model runs during IHOP and the reruns that occurred after IHOP. The first case is a stationary dryline event that was a successful IHOP mission late in the field program. The second case involves a moving dryline that presented some problems for the IHOP forecasters that led to an aborted mission.

a. 19 June 2002: Stationary Dryline Case

This event was late in the IHOP experiment, and with crews anxious for one more good dryline case the intense observation area was positioned over northwestern Kansas, outside the main IHOP experimental area (inner box in Fig. 1); therefore the 4-km MM5 is not applicable. A dryline extended from southeast Colorado north-northeast across western Kansas, just east of Goodland, and on into Nebraska (Fig. 6). There was also a cold front advancing southward that merged with the dryline in Nebraska, and also brought northerly flow into eastern Colorado. By mid-afternoon these northerly winds had mostly reached the dryline, increasing the low-level horizontal shear across the dryline, which set the stage for an outbreak of 11 nonsupercell tornadoes near Goodland, Kansas between 2310 and 0045 UTC. Initial convection along the dryline developed around 2000 UTC in southeastern Colorado, while over the Kansas area CI occurred at 2100 UTC (Fig. 6). After 2100 UTC convection developed rapidly along the line, with an extensive line extending from southeastern Colorado to western Nebraska by 2300 UTC (Fig. 7).

All the models resolved the dryline and correctly held it stationary during the afternoon, close to where it was observed. There was, however, a very wide variation in the CI forecasts, with substantial differences in the amount of convection forecast and the timing. A comparison of the 6-h forecasts from the 1800 UTC runs with the observed low-level reflectivity for 0000 UTC on 20 June is shown in Fig. 8. In this and subsequent figures showing results from MM5 and WRF, when no contours are present, the model is forecasting reflectivity aloft with no explicit precipitation (and resulting model surface reflectivity contours) reaching the surface. The main features determined by comparing the model runs with the observed reflectivity are:

- The RUC (Figs 8 a and b) was too slow to develop storms and too dry, for all the model cycles (1200 UTC through 2100 UTC). While still an underforecast, the 1800 UTC run did develop a small convective line along the dryline by 0000 UTC and was an improvement over the operational RUC forecast (at 20 km horizontal grid resolution), which did not produce any precipitation for the same period.

- The MM5/12 km IHOP real-time run initialized at 1800 UTC (Figs. 8 c and d) did a better job than the RUC forecast of producing a line of echoes with precipitation. Relative to the other initialization times, the 1500 UTC run was actually the best overall forecast, with the 1800 UTC run not far behind. All the precipitation, however, was from the convective parameterization scheme, with no formation of explicit echoes in Kansas. There were explicit echoes produced in Nebraska, where other models, including the RUC, also had more precipitation, in the area where the cold front had most strongly merged with the dryline. A dryline-front merger is often associated with rapid development of frontogenesis (Koch and McCarthy, 1982), which would have provided the stronger forcing and subsequent strong convection in Nebraska that the models were most successful at predicting.

- Based on the above observation, it is not surprising that the reruns, without convective parameterization, did not produce as good a forecast as the MM5 IHOP real-time run both for the MM5 (Figs. 8 e and f) and WRF (Figs. 8 g and h). Neither of the reruns for either the 1200 UTC or 1800 UTC initialization times produced any explicit echo in Kansas through 0000 UTC, and so produced no precipitation. Explicit convection did develop from the 1800 UTC runs in Kansas but not until close to 0300 UTC.

That all the models, in general, had more precipitation and stronger echoes (including extensive explicit echoes) along the portion of the dryline that extended into Nebraska rather than the portion in Kansas suggests that the forcing and environmental conditions in western Kansas came together on a scale that was not captured sufficiently with models at 10 and 12 km resolution. In particular, moisture may have been insufficient to support a broad enough moist updraft to produce explicit echoes at the 12-km scale. The vertical motion along the dryline was likely too weak in the forecast, and with the only means of producing clouds being grid-scale saturation, cloud initiation was delayed several hours (as discussed by Weisman et al., 1997). On the other hand, with the convective parameterization scheme in effect for the IHOP MM5 run at 12 km, there was precipitation produced and the timing and location of CI were quite good. As noted earlier, the RUC10 (with parameterization) also initiated convection, but a few hours later than observed.

b. 2 June 2002: Moving Dryline Case

On this day the western half of the IHOP domain was dominated by very hot temperatures, reaching around 40 °C during the afternoon. A well-defined dryline was not present during the morning, but became apparent and sharper in the early afternoon, as a surge of low-level westerly flow emerged out of eastern Colorado and pushed into western Kansas just after 1800 UTC, as depicted in the LAPS analysis in Fig. 9. Subsequently, the dryline surge initiated a line of storms exceeding 50 dBZ in western Kansas that eventually moved into central Kansas (Fig. 10). The IHOP forecasters predicted that a dryline would become better defined during the afternoon (somewhat later than what occurred), but they thought CI along it would hold off until late in the afternoon, not until the dryline sharpened and temperatures rose enough to break the significant cap that was in place. As it turned out, the presence of the very hot surface temperatures and the stronger and earlier dryline push, allowed the cap to be broken and CI to occur over 2 h ahead of the IHOP forecasters' prediction. This timing error resulted in an aborted mission, since convection was well underway before the aircraft (leaving from Oklahoma City, Oklahoma) could reach the dryline target.

Key forecasts from the IHOP runs and the runs made after IHOP are presented together in Figure 11. One set of forecasts are from the runs initialized at 1200 UTC and valid at 2100 UTC and 0000 UTC (except that the RUC forecast is from 1500 UTC as the 1200 UTC run was not made), and the other set 6 h forecasts from the 1800 UTC runs valid at 0000 UTC. The characteristic shared by all the model runs for this case is that the CI and eventual extent of convection was underforecast. For the MM5 and WRF 12 km reruns, there is never any prediction of surface reflectivity, which can only be produced explicitly, and consequently no surface precipitation. Since the IHOP MM5/12 km run had a convective parameterization scheme, precipitation is still produced, and corresponds to the area of reflectivity above the surface shown by the image. The post-IHOP MM5 12 km run forecasts more cellular-like echoes than the IHOP 12-km run or the WRF, and these echoes come close to producing precipitation by 0000 UTC. The RUC model (Figs. 11 m-o) also underforecast the convection, with the model predicting almost nothing at 2100 UTC in the 6 h forecast from the 1500 UTC run (Fig. 11 m), and limited development by 0000 UTC (though with very little precipitation). The RUC was consistent in predicting the strongest echo by 0000 UTC near the Nebraska/Kansas border, with the 1800 UTC run forecasting more precipitation with this storm, but very little (1 mm or less in 3 h) with any of the other cloud tops shown in Fig. 11o.

Only the MM5 4-km model forecast significant surface echo, and a side by side comparison with the MM5 12-km model for the 1500 UTC initialization, the best forecasts of all the initializations on this day, is shown in Fig. 12. The forecasts depicted in Fig. 12 were the ones available during IHOP, where the relative success of the model was noted in its prediction of CI earlier, and as it turned out more correctly, than the IHOP forecasters. The most obvious difference between the two runs in Fig. 12 is the ability of the 4 km run to create convective cells at more realistic scales, showing the advantage of the higher horizontal resolution. The other difference is that the 4-km run predicted far more surface echo, owing to the stronger cells produced. Both runs forecast precipitation, with the explicit 4-km run predicting amounts somewhat above those estimated by radar, while the amounts from the convective parameterization scheme of the 12-km run were generally too low. The position of the echoes is similar for both runs, and while initially rather accurate, in both cases the actual line of convection moved faster to the east than in the forecasts.

The lack of development of explicit echoes on the 12-km scale suggests, as noted also for the 19 June case, that under more marginal conditions it is likely difficult for the model to produce a strong enough updraft to bring the air to grid-scale saturation. Consequently, under such conditions it appears that a convective parameterization scheme has some value in terms of at least being able to forecast precipitation at a horizontal grid resolution of 12 km, while it may not be necessary at a resolution of 4 km.

6. Summary and Conclusions

Forecasting and nowcasting for IHOP was a challenge, requiring close cooperation between forecast groups from the SPC and FSL, and involvement of a number of visiting scientists. The availability of special model runs with output in most cases at hourly intervals, and at a frequent (3 h) update cycle, was of value to the short-range forecasting/nowcasting effort. It was important to have a user-friendly platform to examine the model forecasts, as well as to combine them with observations, and the PC-based FX-Net workstation proved indispensable. The real-time evaluation of the models proved to be a challenging undertaking, but we believe it resulted in valuable subjective evaluation and insight into model performance. We would recommend that a similar type of evaluation be part of future field exercises where forecasting may not be the primary motive of the experiment.

The overall subjective input from the nowcasters indicated the models were of value in a number of aspects, particularly in diagnosing and predicting drylines and the potential for CI, as well as other types of boundaries. One very useful aspect of the MM5 model (and WRF, though not available during IHOP in real-time) was a model output field of simulated reflectivity, available at hourly intervals. This gave the forecaster a chance to directly compare to radar observations in a timely manner, and also allowed one to get a much better feel for the type and organization of convection forecast by the model. Although the focus here is on CI, a review of the comments from the forecasters indicated that the models showed some ability to predict storm type, and to indicate organization of echoes and upscale growth into accelerating lines.

Model forecasts for the special model runs of the RUC, MM5 and WRF models were examined in detail for six IHOP dryline days that either produced CI or had the potential to do so. In agreement with the impression of the forecasters during IHOP, the models were usually able to capture the pre-convective structure and position of the dryline fairly well. There were some problems predicting echo development on the dryline days with a more marginal moisture environment for convection, especially for the 10-km and 12-km models. Given that the MM5 4-km run had better success for some of these cases, a probable cause of this problem was the inability of the coarser resolution models to forecast the concentrated low-level convergence along the boundary, and consequent failure to predict strong enough vertical motions to bring the grid scales to saturation. A convective parameterization scheme was usually necessary for the 10 and 12-km horizontal grid resolution models to produce precipitation for these more marginal cases, as shown by comparing the MM5 real-time 12-km runs with the post-IHOP runs.

While there were certainly a number of successful model forecasts, the diversity in forecasts from the different models and configurations, without one particular model showing clear superiority, together with the difficulty of the convective forecast problem, suggests that an ensemble approach to convective forecasting would be useful. Indeed, forecasters usually gained more confidence when the different models showed better agreement, both for a given initialization time, and for different model runs.

Acknowledgments

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Table captions.

Table 1. FSL numerical models run for IHOP.

Table 2. CI dryline days examined in this study.

Table 3. CI along the dryline: observed vs. model forecast.

Table 1. FSL numerical models run for IHOP

Model	*Horizontal grid*	*Vertical levels*	*Run every x h*	*Forecast duration (h)*	*Convective scheme*	*Microphysics scheme*	*Uses hotstart?*
Models run in real-time during IHOP							
MM5	4	34	3	12	None	Schultz	yes
MM5	12	34	3	12	Kain-Fritsch	Schultz	yes
RUC	10	50	3	6 to 24	Grell-Devenyi Ensemble Closure		no
Models run after IHOP							
MM5	12	42	6	12	None	Schultz II	yes
WRF	12	42	6	12	None	NCEP 5-class	yes

Table 2. CI dryline days examined in this study

Date	*CI?*	*Weather summary*
22 May	no	Dryline close to S-Pole; tcu form but no storms
2 June	yes	Very hot, dryline surges out of Colorado into western Kansas causing CI
10 June	yes	Strongly capped well-defined dryline; CI and severe storm near DDC
17 June	yes	Dryline near S-Pole with rapid CI mid-afternoon
18 June	yes	Dryline in western KS with CI producing small cbs late afternoon
19 June	yes	Well-defined dryline western Kansas with widespread CI to strong storms

Table 3. CI along the dryline: observed vs. model forecast

Date:	*22 May*		*2 June*		*10 June*		*17 June*		*18 June*		*19 June*	
Observed CI?:	no		yes		yes		yes		yes		yes	
Initial time (UTC):	12	18	12	18	12	18	12	18	12	18	12	18
MM5/12 km IHOP	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
MM5/4 km IHOP	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y
RUC/10 km IHOP	N	N	Y*	Y	Y*	Y	Y	Y	Y	N	Y	Y
MM5/12 km post-IHOP	Y	N	Y	Y	Y	Y	N	N	Y	Y	Y	Y
WRF/12 km post-IHOP	Y	N	Y	Y	Y	Y	N	N	N	Y	N	Y

Y = yes, model forecasts CI, N = no, * = 1500 UTC run used instead of 1200 UTC run.

Figure captions

Fig.1. Model domains for the FSL IHOP model runs.

Fig. 2. Example of an IHOP forecast product. Shown is a Day 1 IHOP boundary and probability of precipitation forecast issued for the period 2100 to 2300 UTC on 2 June. Boundaries are depicted valid at 2200 UTC, along with outlines of precipitation chances over the 2h period.

Fig. 3. Scores for all the runs of the MM512-km model for 0-6 h QPF, comparing the runs made during IHOP with the post-IHOP (rerun) runs.

Fig. 4. CI location errors for the different cases in Table 2 and the various model runs, initialized at 1200 UTC and 1800 UTC.

Fig. 5. As in Fig. 4 but for CI timing errors, in hours, with positive values indicating the model forecast was later than the time of observed CI.

Fig. 6. Visible satellite image with METAR observations centered over the Kansas/Colorado border at 2100 UTC on 19 June 2002. Standard NWS station plot is shown in units of °C for temperature and dewpoint (left side of observation), with sea-level pressure (tenths of mb, minus 1000), and pressure tendency (tenths of mb) on the right. Long wind barb is 5 ms^{-1}, short barb 2.5 ms^{-1}, with gusts shown at the end of arrows, if present, in ms^{-1}. Dryline denoted by long dash-dot line, and cold front by solid line with barbs.

Fig. 7. Composite lowest elevation angle radar reflectivity image with station plot, centered over northwestern Kansas, for 2200 UTC (a), 2300 UTC (b), and 0000 UTC (c). Station plot as in Fig. 6.

Fig. 8. Comparison of 6 h forecasts from 1800 UTC runs valid at 0000 UTC on 20 June. In (a) and (b) RUC10, with 3-h precipitation (mm) and wind in (a) and cloud top height (kft) in (b); in (c) and (d) MM5/12 km IHOP run, 1-h precipitation (mm) and surface wind in (c), and composite reflectivity in dBZ (image, with scale shown) with surface reflectivity contours (maximum value indicated) in (d); same in (e) and (f) but for the MM5/12 km rerun (and without surface winds in (e)); in (g), same as in (e), and in (h) same as in (f), except for WRF/12 km rerun.

Fig. 9. LAPS 12-km 1800 UTC 2 June surface analysis of temperature (contours, °C), dewpoint (image, °C, with scale at bottom), and wind (long barb = 5 ms^{-1}, short barb = 2.5 ms^{-1}).

Fig. 10. Combined radar and visible satellite image using the low level reflectivity scans from the radars within the IHOP domain (the northern limit of the radar imagery is denoted by the horizontal gray line south of KGLD). Times are 1800 UTC (a), 2000 UTC (b), 2200 UTC (c), and 0000 UTC (d).

Fig. 11. Forecasts from 2 June special model runs. For a-l: left and middle columns, 1200 UTC runs valid at 2100 UTC (left column) and 0000 UTC (middle column); right column 1800 UTC runs valid at 0000 UTC. Model runs are from MM5/4 km (a-c), MM5/12 km IHOP run (d-f), MM5/12 km post-IHOP run (g-i), WRF/12 km post-IHOP run (j-l). Image is max column

reflectivity (scale in a-c), contours surface reflectivity (when present, with maximum value labeled (dBZ)). In m-o are RUC/10 km IHOP model runs showing forecast of cloud top height, in kft above ground (scale shown). Since the RUC 1200 UTC run was not available, forecasts from the 1500 UTC run are used, valid at 2100 UTC (m) and 0000 UTC (n).

Fig. 12. 1500 UTC runs for the 4-km (left column) and 12-km (right) MM5 IHOP models, with forecasts valid from 2100 through 0000 UTC. Reflectivity scale as in Fig. 11.

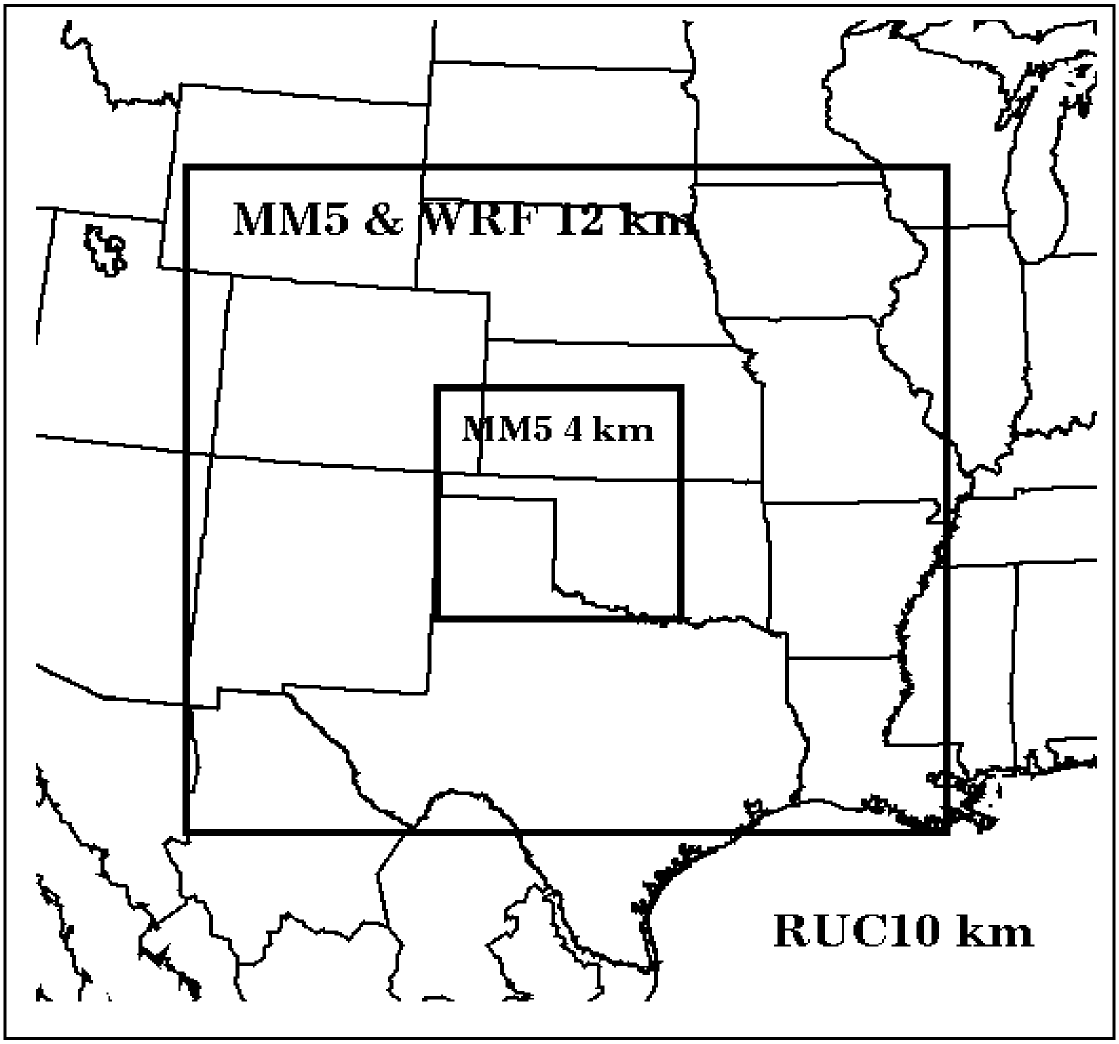
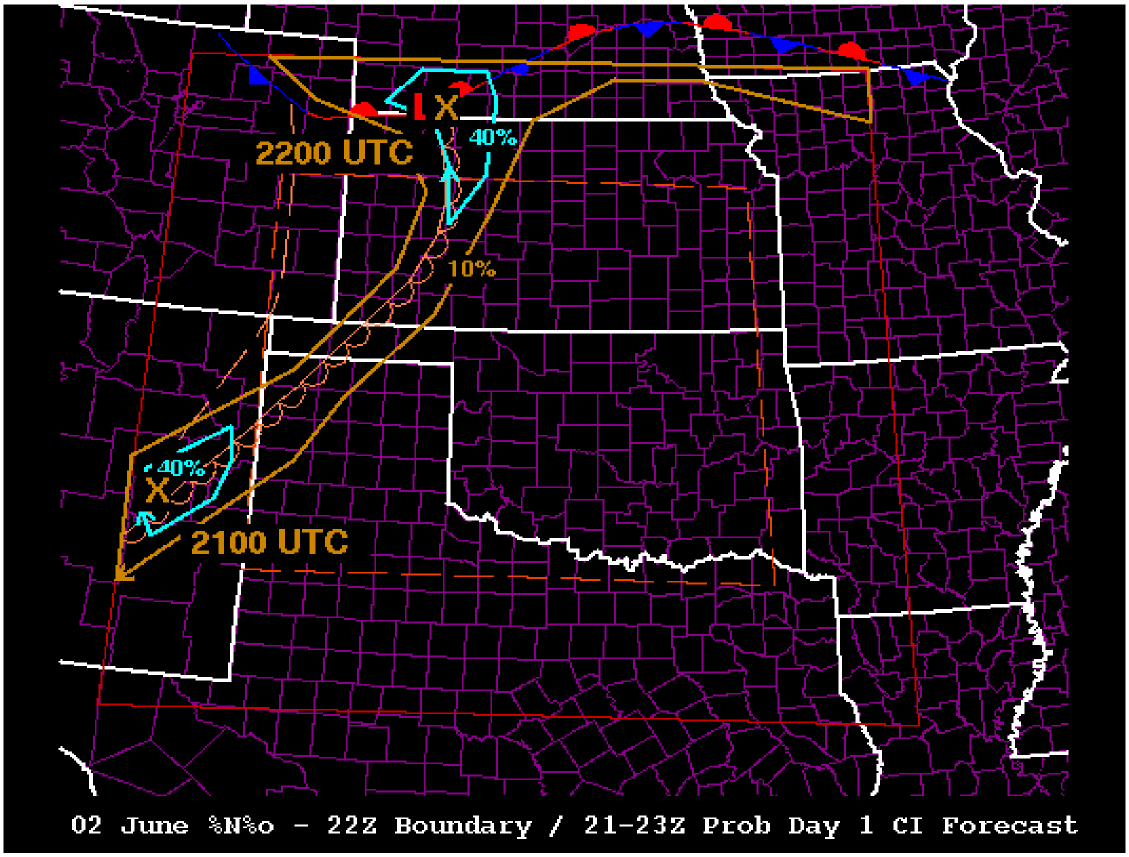


Fig.1. Model domains for the FSL IHOP model runs.



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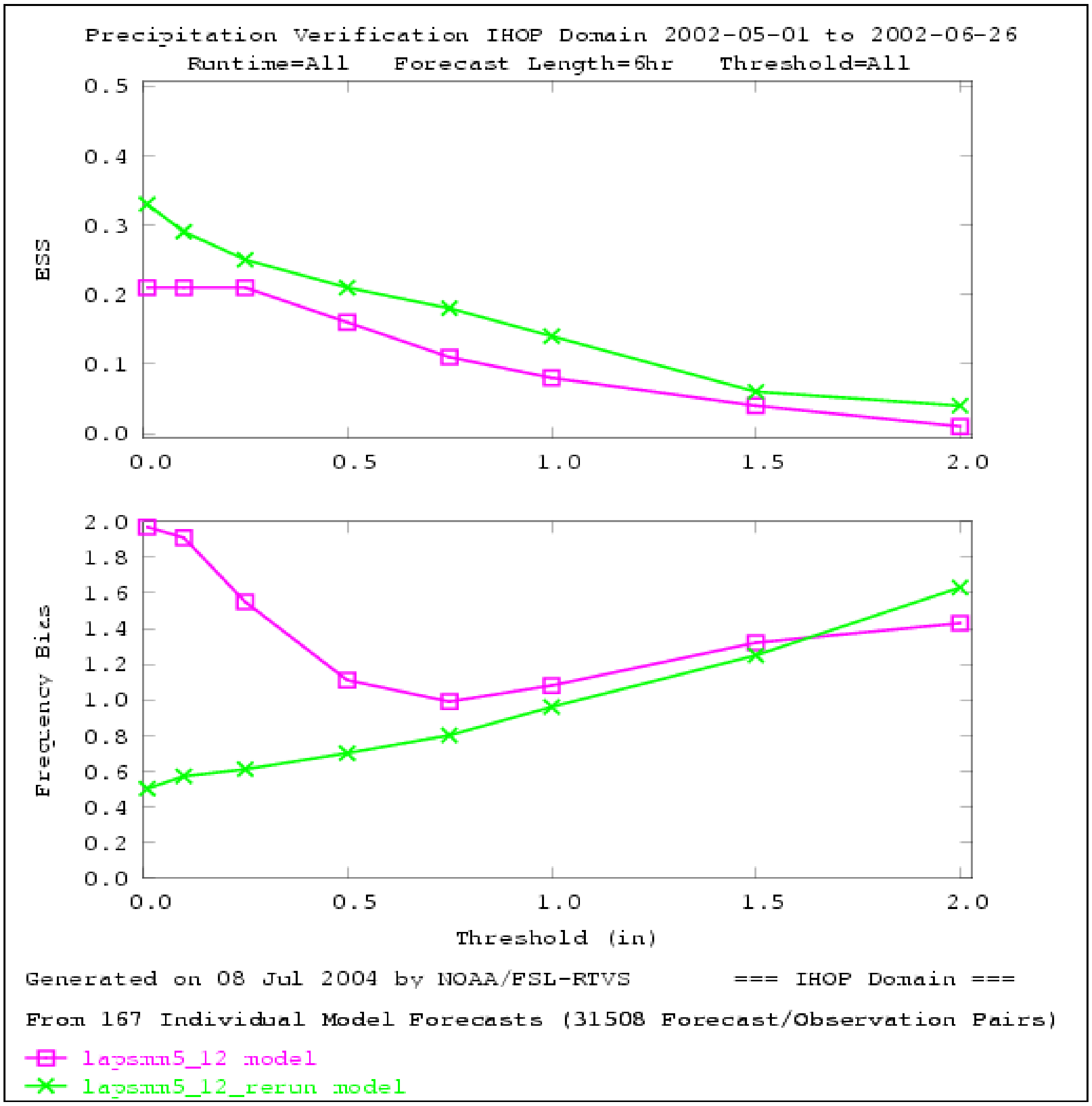
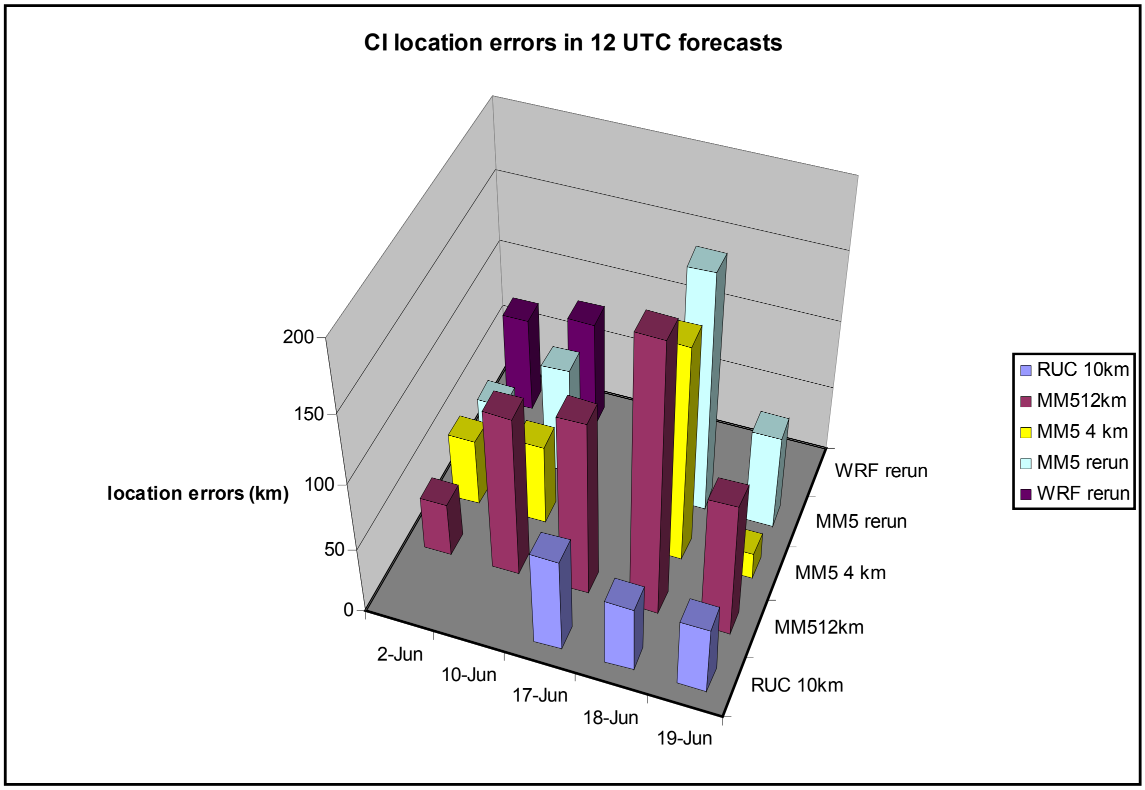
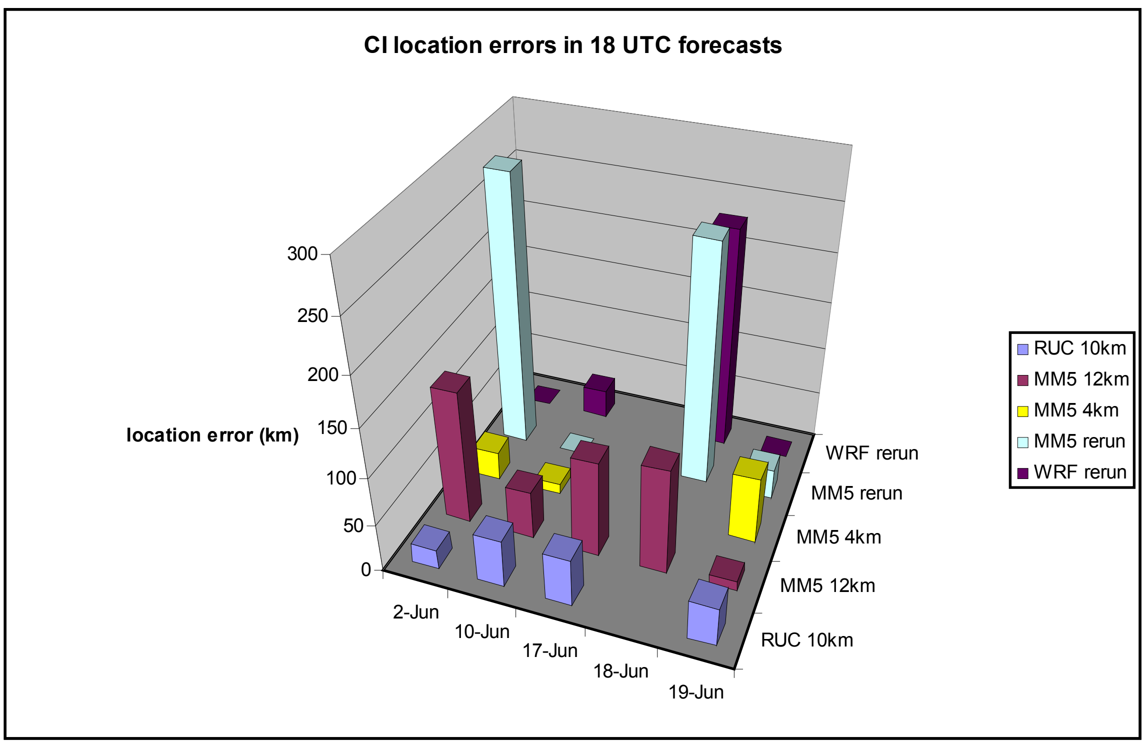


Fig. 3. Scores for all the runs of the MM512-km model for 0-6 h QPF, comparing the runs made during IHOP with the post-IHOP (rerun) runs.





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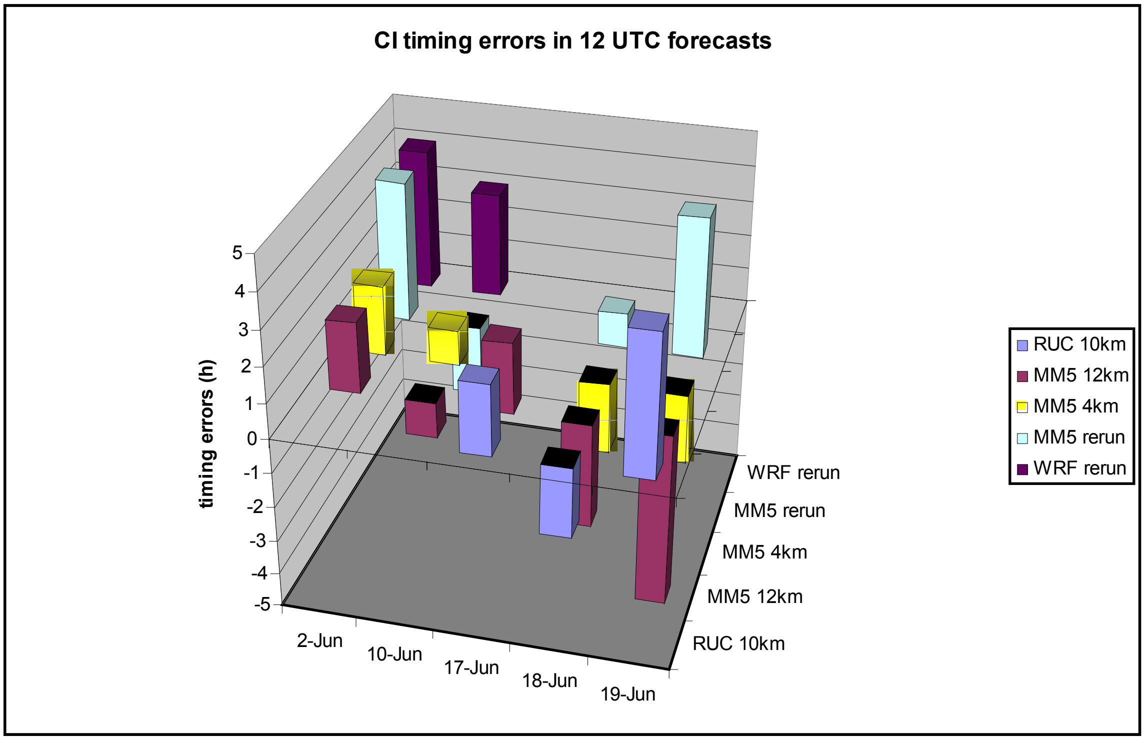

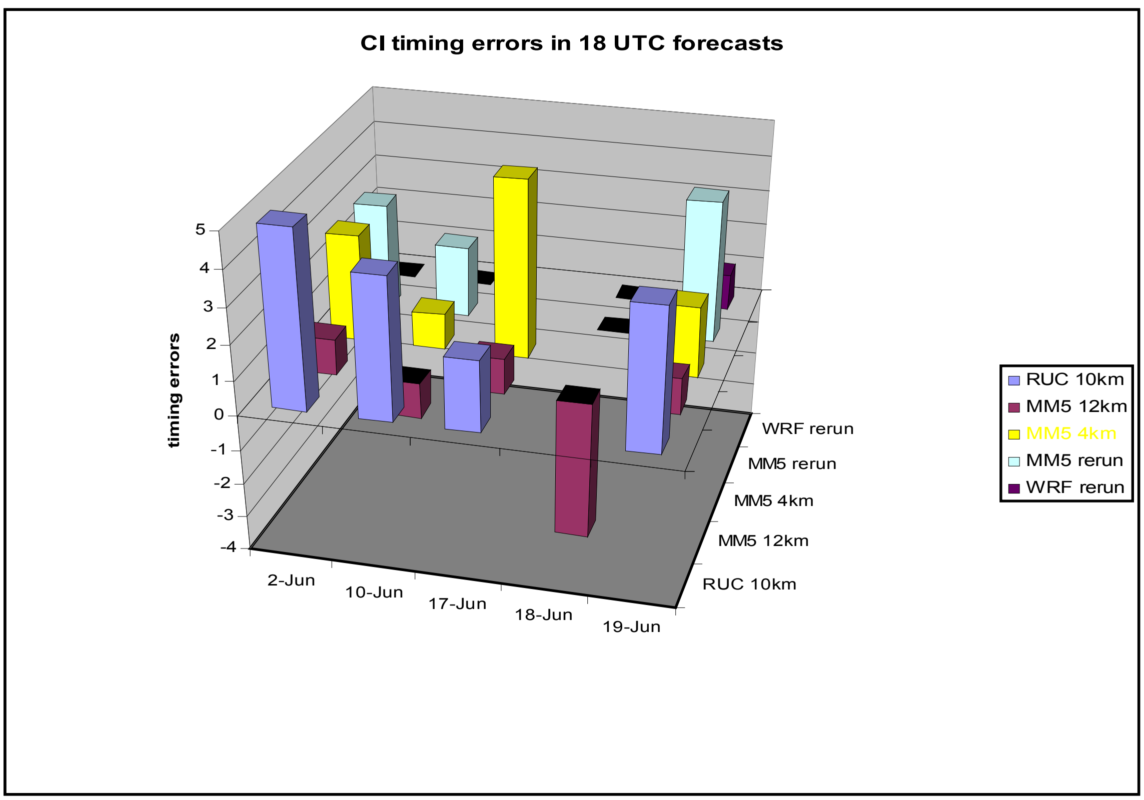

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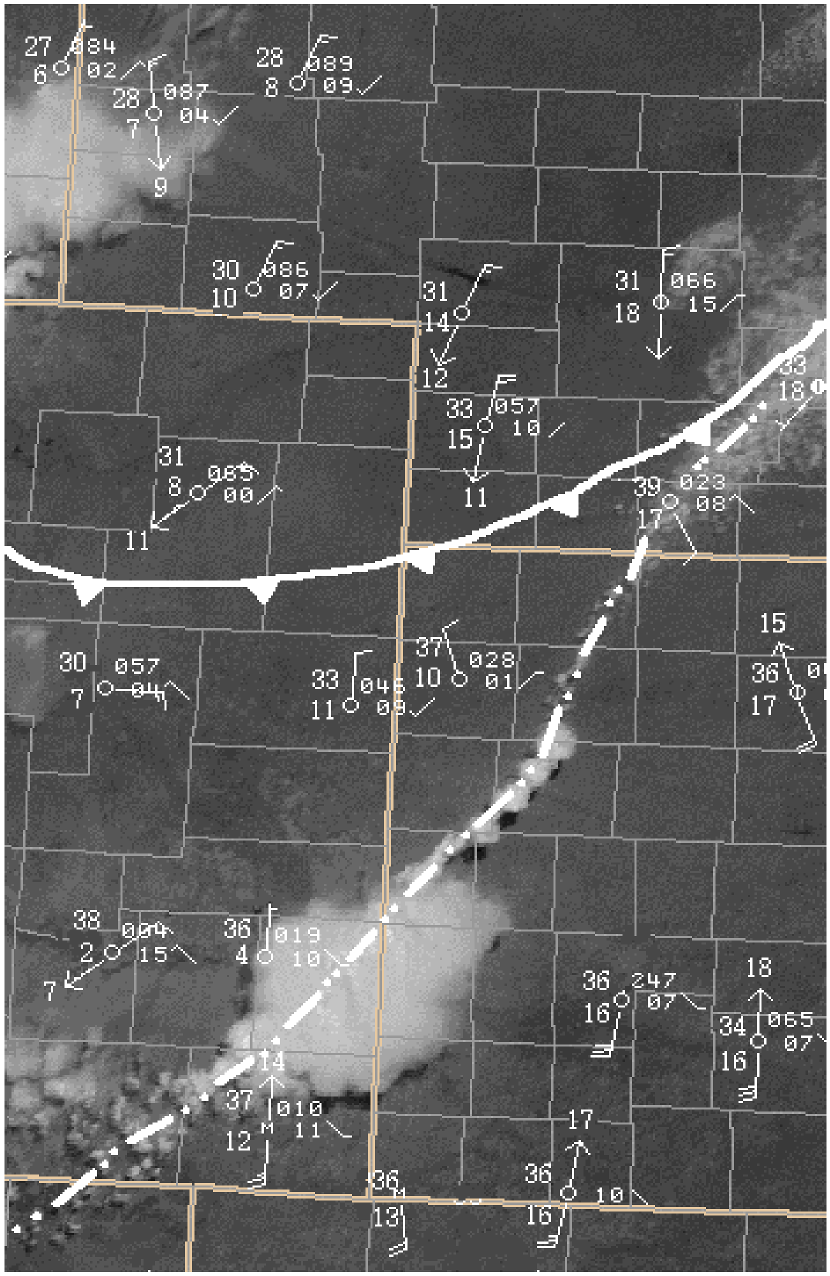

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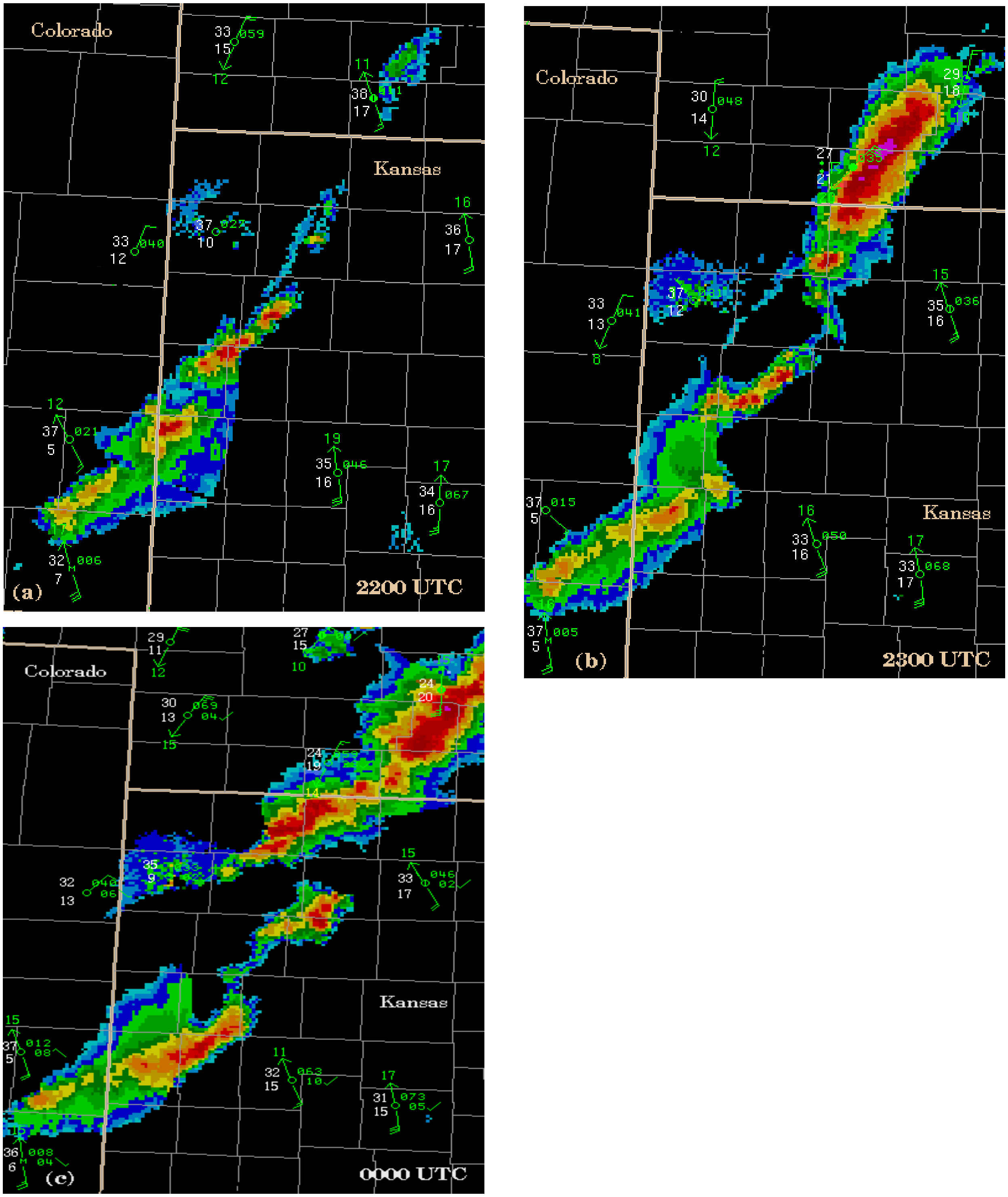

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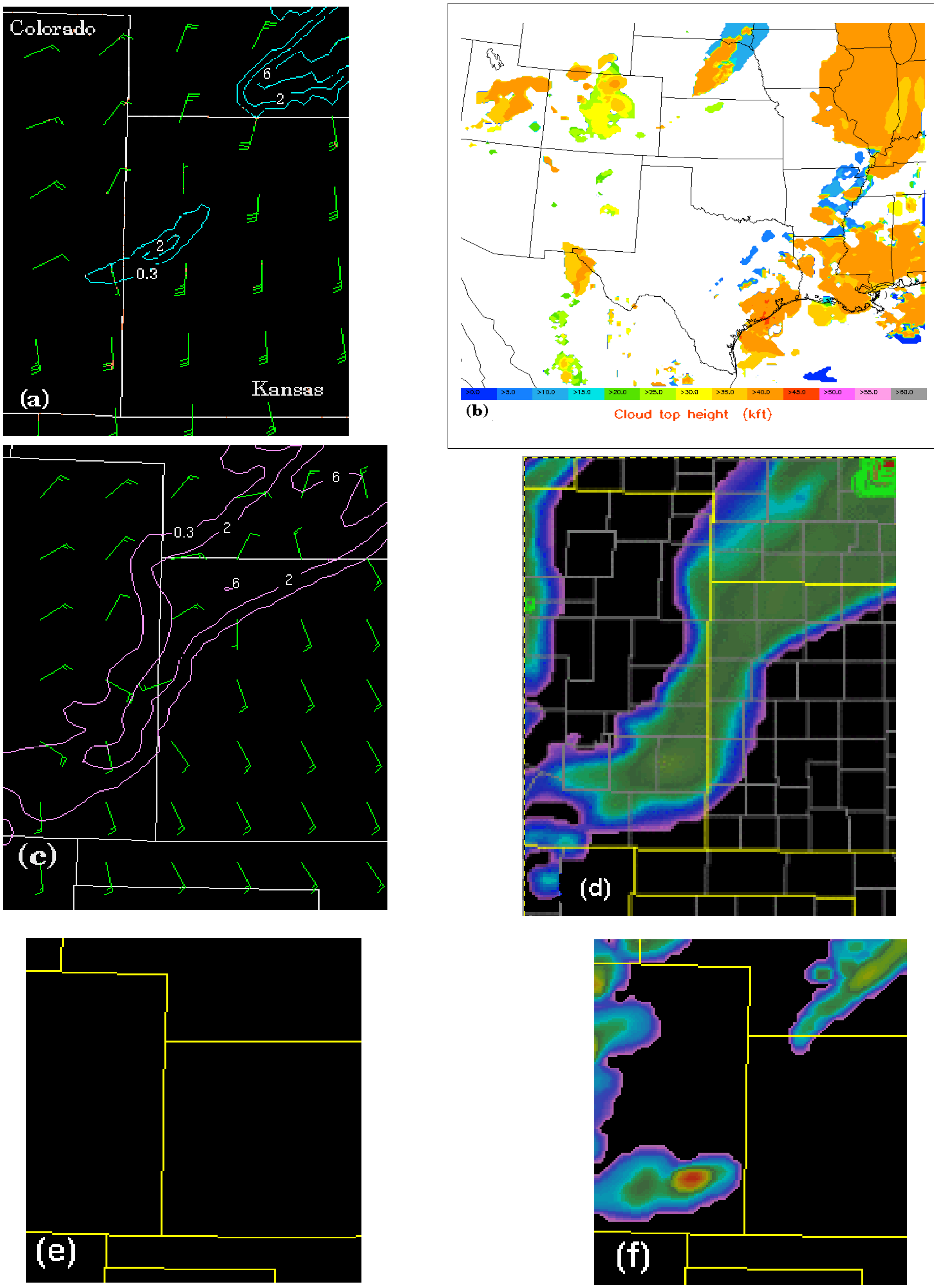

Colorado
6
2
2
0.3
Kansas
(a)
(b)
Cloud top height (kft)
6
0.3
2
6
2
(c)
(d)
(e)
(f)

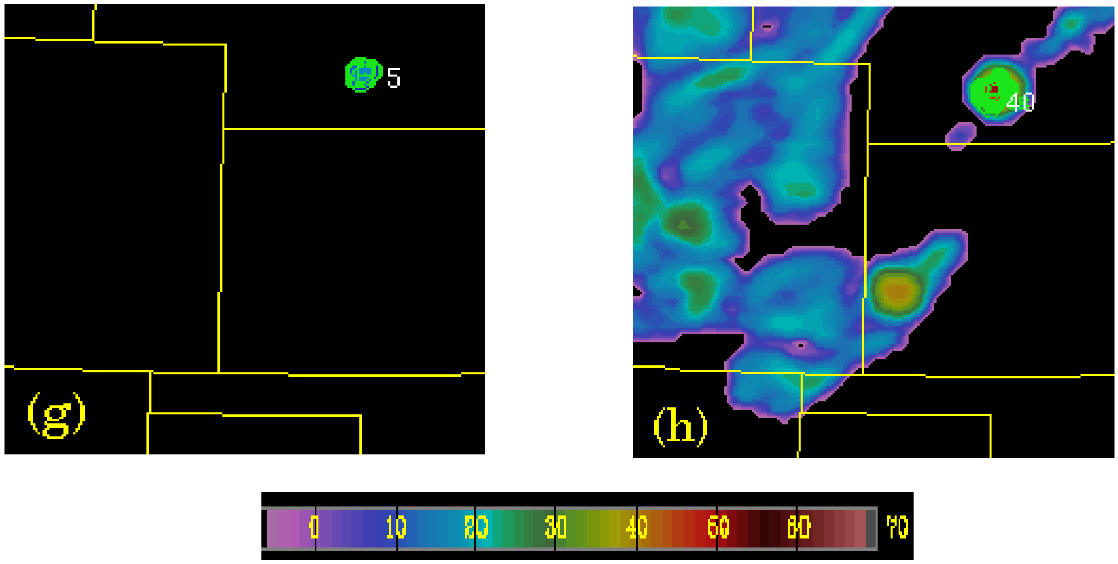


Fig. 8. Comparison of 6 h forecasts from 1800 UTC runs valid at 0000 UTC on 20 June. In (a) and (b) RUC10, with 3-h precipitation (mm) and wind in (a) and cloud top height (kft) in (b); in (c) and (d) MM5/12 km IHOP run, 1-h precipitation (mm) and surface wind in (c), and composite reflectivity in dBZ (image, with scale shown) with surface reflectivity contours (maximum value indicated) in (d); same in (e) and (f) but for the MM5/12 km rerun (and without surface winds in (e)); in (g), same as in (e), and in (h) same as in (f), except for WRF/12 km rerun.

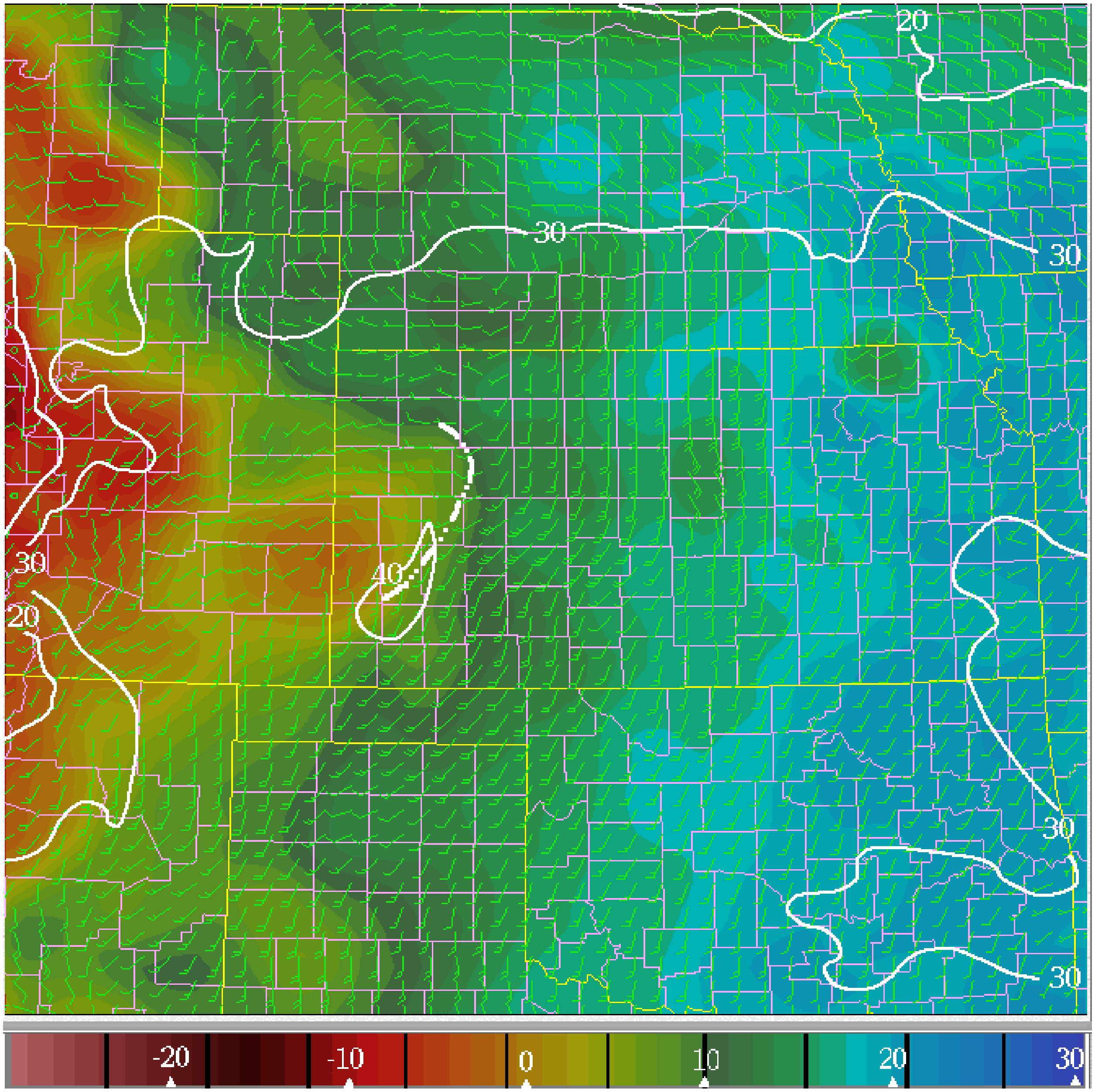


Fig. 9. LAPS 12-km 1800 UTC 2 June surface analysis of temperature (contours, ºC), dewpoint (image, ºC, with scale at bottom), and wind (long barb = 5 ms^{-1}, short barb = 2.5 ms^{-1}).

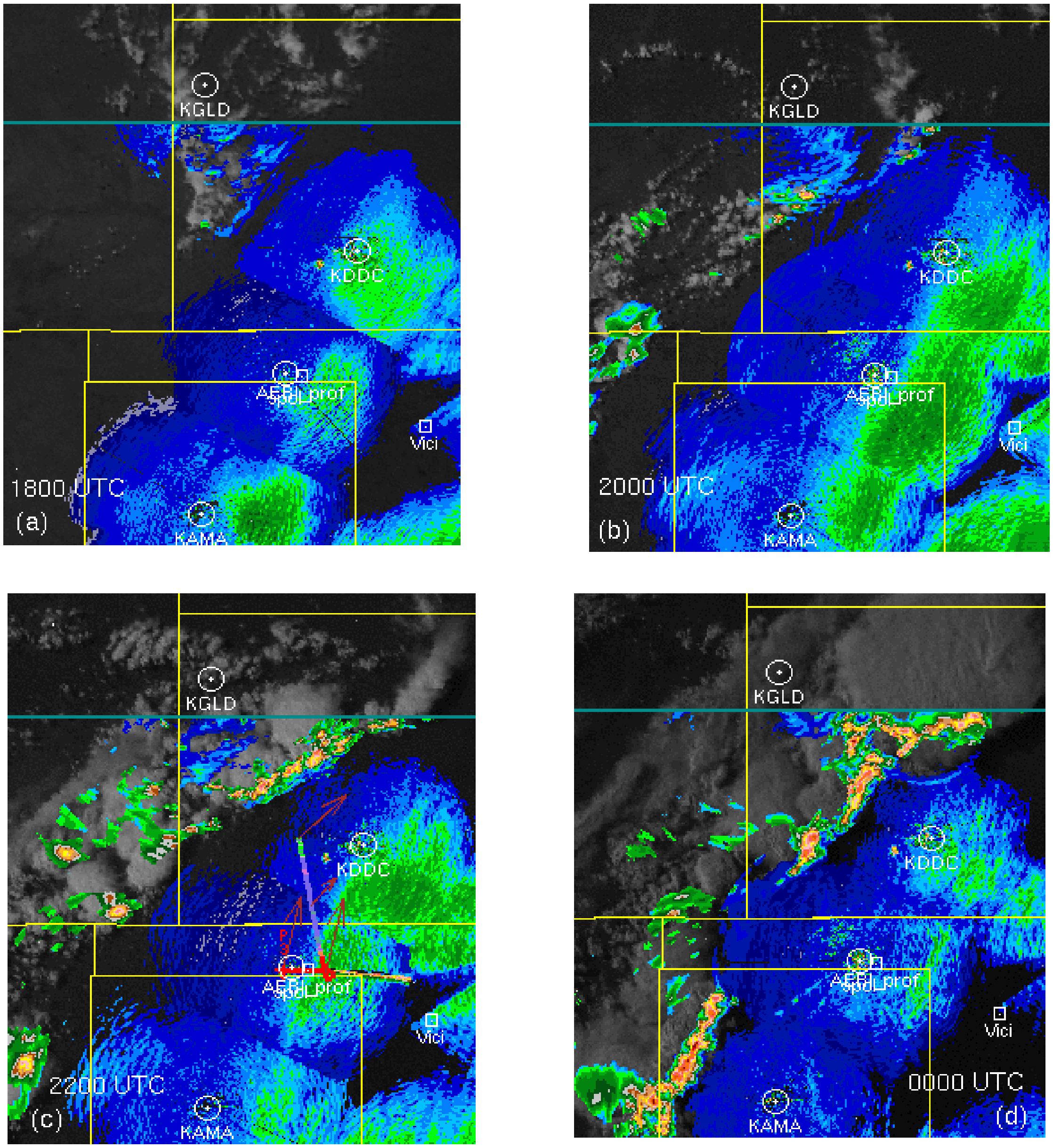
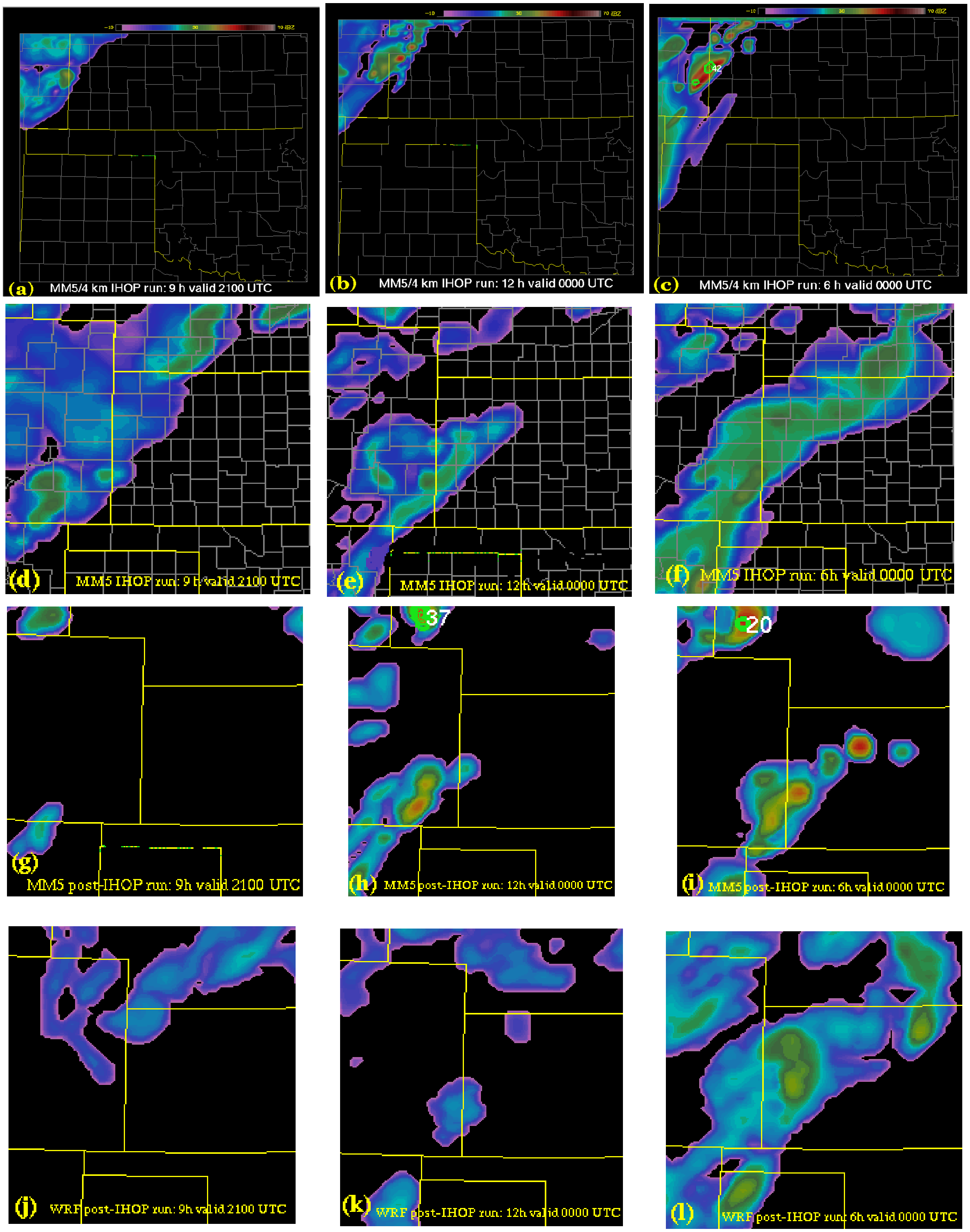


Fig. 10. Combined radar and visible satellite image using the low level reflectivity scans from the radars within the IHOP domain (the northern limit of the radar imagery is denoted by the horizontal gray line south of KGLD). Times are 1800 UTC (a), 2000 UTC (b), 2200 UTC (c), and 0000 UTC (d).


(a) MM5/4 km IHOP run: 9 h valid 2100 UTC
(b) MM5/4 km IHOP run: 12 h valid 0000 UTC
(c) MM5/4 km IHOP run: 6 h valid 0000 UTC
42
(d) MM5 IHOP run: 9 h valid 2100 UTC
(e) MM5 IHOP run: 12 h valid 0000 UTC
(f) MM5 IHOP run: 6h valid 0000 UTC
(g) MM5 post-IHOP run: 9h valid 2100 UTC
(h) MM5 post-IHOP run: 12h valid 0000 UTC
37
(i) MM5 post-IHOP run: 6h valid 0000 UTC
20
(j) WRF post-IHOP run: 9h valid 2100 UTC
(k) WRF post-IHOP run: 12h valid 0000 UTC
(l) WRF post-IHOP run: 6h valid 0000 UTC

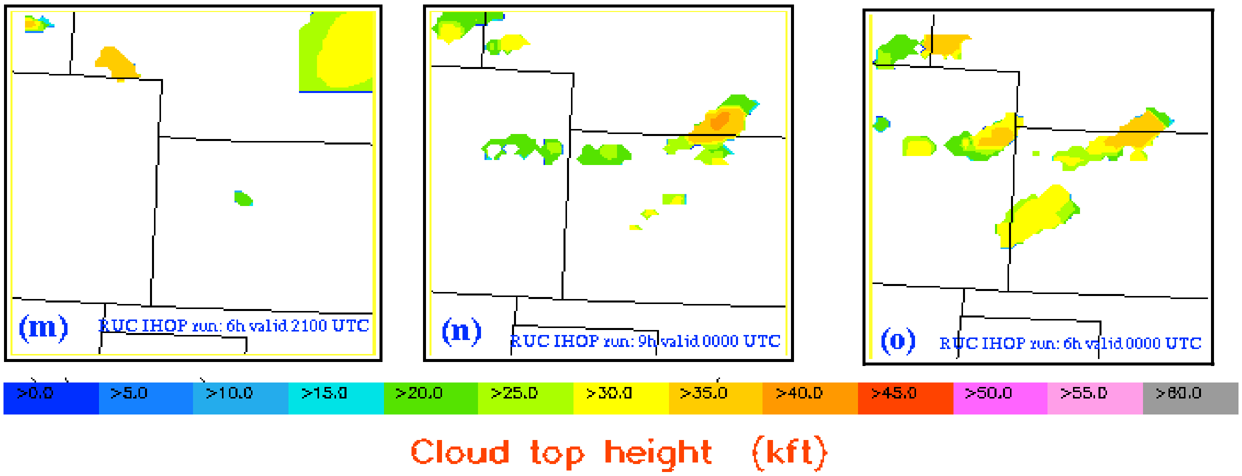


Fig. 11. Forecasts from 2 June special model runs. For a-l: left and middle columns, 1200 UTC runs valid at 2100 UTC (left column) and 0000 UTC (middle column); right column 1800 UTC runs valid at 0000 UTC. Model runs are from MM5/4 km (a-c), MM5/12 km IHOP run (d-f), MM5/12 km post-IHOP run (g-i), WRF/12 km post-IHOP run (j-l). Image is max column reflectivity (scale in a-c), contours surface reflectivity (when present, with maximum value labeled (dBZ)). In m-o are RUC/10 km IHOP model runs showing forecast of cloud top height, in kft above ground (scale shown). Since the RUC 1200 UTC run was not available, forecasts from the 1500 UTC run are used, valid at 2100 UTC (m) and 0000 UTC (n).

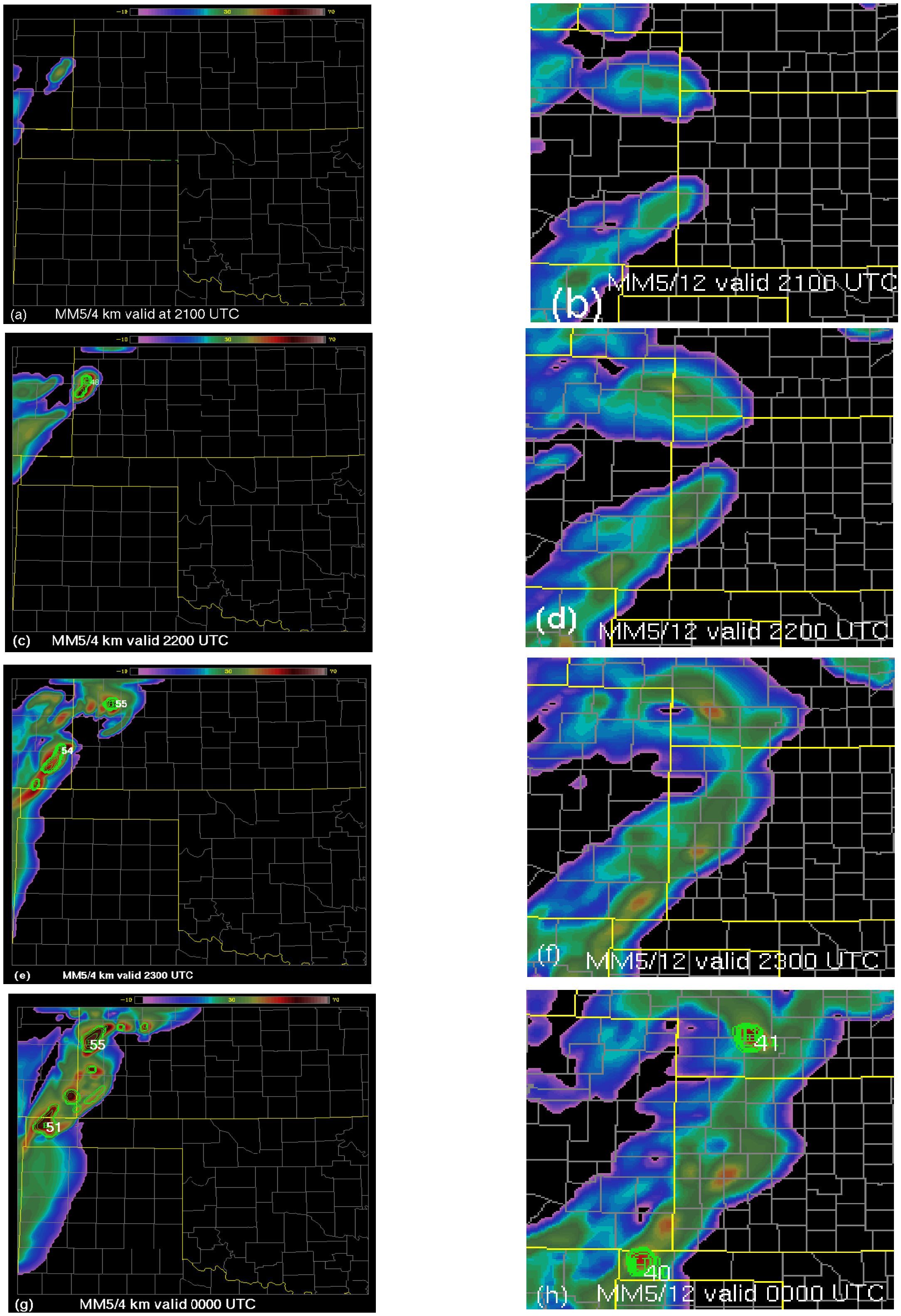


Fig. 12. MM5 runs as in Fig. 12, except only the 9 to 12 h forecasts from the 1500 UTC IHOP real-time MM5 runs.