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THE NOAA HAZARDOUS WEATHER TESTBED: COLLABORATIVE TESTING OF ENSEMBLE AND CONVECTION-ALLOWING WRF MODELS AND SUBSEQUENT TRANSFER TO OPERATIONS AT THE STORM PREDICTION CENTER

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1. INTRODUCTION

NOAA's Hazardous Weather Testbed (HWT) is a joint facility managed by the National Severe Storms Laboratory (NSSL), the Storm Prediction Center (SPC), and the NWS Oklahoma City/Norman Weather Forecast Office (OUN) within the National Weather Center building on the University of Oklahoma South Research Campus. The HWT is designed to accelerate the transition of promising new meteorological insights and technologies into advances in forecasting and warning for hazardous mesoscale weather events throughout the United States. The HWT facilities include a combined forecast and research area situated between the operations areas of the SPC and OUN and a development laboratory also located nearby on the second floor. The facilities support enhanced collaboration between research scientists and operational weather forecasters on specific topics that are of mutual interest.

The HWT organizational structure is composed of two primary overlapping program areas, the Experimental Forecast program (EFP) and the Experimental Warning Program (EWP) (Fig. 1). The EFP focuses on forecast-scale activities while the EWP concentrates on short-fused warnings of severe convective weather. A natural overlap exists between these two areas, particularly within emerging concepts such as Warn-on-Forecast, a key National Weather Service goal designed to extend warning lead times through the development and application of convection-allowing numerical models to extend short-term predictability of hazardous convective weather. Both programs reside beneath the overarching HWT organization and facility with a focus on national hazardous weather needs.

The EFP branch of the HWT is focused on predicting hazardous mesoscale weather events on time scales ranging from a few hours to a week in advance, and on spatial domains ranging from several counties to the CONUS. The EFP embodies the collaborative experiments and activities previously undertaken by the SPC/NSSL Spring Experiments. The EWP branch of the HWT is concerned with detecting and predicting mesoscale and smaller weather hazards on time scales of minutes to a few hours and on spatial domains from several counties to fractions of counties. The EWP embodies the collaborative warning-scale experiments and technology activities previously undertaken by the OUN and NSSL.

Rapid science and technology infusion for the advancement of operational forecasting requires direct, focused interactions between research scientists, numerical model developers, information technology specialists, and operational forecasters. The HWT provides a unique setting to facilitate such interactions and allows participants to better understand the scientific, technical, and operational challenges associated with the prediction and detection of hazardous weather events. The HWT allows participating organizations to:

- Refine and optimize emerging operational forecast and warning tools for rapid integration into operations.
- Educate forecasters on the scientifically correct use of newly emerging tools and to familiarize them with the latest research related to forecasting and warning operations.
- Educate research scientists on the operational needs and constraints that must be met by any new tools (e.g., robustness, timeliness, accuracy, and universality).
- Motivate other collaborative and individual research projects that are directly relevant to forecast and warning improvement.

For more information about the HWT, see www.nssl.noaa.gov/hwt.

2. SEVERE WEATHER FORECASTING AT THE SPC

Operational forecasting of severe convective weather at the SPC has traditionally focused on the observation-based diagnosis and prediction of the synoptic and mesoscale environments associated with severe storms (e.g., Johns and Doswell 1992, Thompson et al. 2003). The emphasis on the pre-convective and near-storm environments is necessary because severe thunderstorms and tornadoes occur on

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scales smaller than standard observational networks and operational numerical prediction models are capable of resolving. The prediction process is further complicated by the presence of mesoscale and stormscale variability in the environment (Davies-Jones 1993, Markowski et al. 1998a, 1998b) which may not be adequately sampled in real-time. This is particularly true when the four-dimensional distribution of water vapor is considered (e.g., Fritsch et al. 1998), which is a critical ingredient for the development and maintenance of thunderstorms. Thus, observational limitations remain an inherent part of forecasting thunderstorms and, when coupled with a more limited scientific understanding of smaller scale physical processes, result in considerable uncertainty in forecasting details of convection. For example, uncertainties exist in predicting the time and location of initiation and subsequent evolution of storms, maximum storm intensity, and potential to produce high impact weather events such as tornadoes, convective wind damage, large hail, and heavy rain. Furthermore, in recent years it has become increasingly evident that that the type of severe convective weather that occurs is often closely related to the convective mode, e.g., discrete cells, linear systems, or multicellular systems (Snook and Gallus 2004, Trapp et al. 2005, Thompson and Mead 2006). Thus, accurate forecasts of severe weather are dependent on forecasters being able to predict properly not only when and where severe thunderstorms will develop and how they evolve over time, but also the convective modes that are most likely to occur.

In addition to extensive use of observational datasets, numerical weather prediction model guidance has become increasingly important in recent years. For example, model guidance is used in the short term to supplement standard observational data by blending surface observations with 0-1 hour RUC model forecasts (Benjamin et al. 2004a, 2004b) to produce hourly three-dimensional mesoscale analyses (Bothwell et al. 2002). Model guidance becomes increasingly important beyond 6-12 hours and it forms the primary input for many of the SPC Convective Outlook products. However, modeling systems also reflect inherent errors and uncertainties in specifying the initial state of the atmosphere, and simplifications in physics and parameterization of sub-grid scale processes further contribute to errors in model forecasts. It is believed that physics errors become more important as model resolution increases (e.g., Stensrud et al. 2000, Wandishin et al. 2001), such that numerical prediction of precipitation and associated convective processes remain a key challenge. Despite these issues, the limits on predictability imposed by using observational data alone strongly suggest there may be important opportunities to improve severe weather forecasting through the application of newer modeling concepts.

3. SHORT-RANGE ENSEMBLE AND HIGH RESOLUTION MODELS

Large increases in computer power and communications capabilities in recent years have facilitated the development and operational testing of two key modeling initiatives: 1) short-range ensemble forecast (SREF) systems (e.g., Du et al. 2006) and 2) high resolution deterministic Weather Research and Forecasting (WRF) models (e.g., Done et al. 2004, Kain et al. 2006, 2007). The application of ensemble concepts to short-range prediction provides forecasters with systematic information about the possible range of solutions and measures of forecast uncertainty, which can then be used to better convey appropriate levels of forecaster confidence to the user community. The inclusion of uncertainty in weather forecasts is considered to be an important forecast element (National Research Council 2006), and recent approaches to generating probabilistic information have been based largely on ensemble systems. At the SPC, SREF output is created to provide basic synoptic and mesoscale guidance for a variety of products ranging from synoptic pattern evolution and the likelihood of precipitation to more specialized fields such as thermodynamic and kinematic parameters related to convective storm potential.

Additional research efforts have been focused on high resolution models that use explicit cloud and precipitation microphysics to generate precipitation (no parameterized convection is used in these models). The convection-allowing models are typically run with grid lengths of ~4 km or less, and have the capability to generate explicit convective systems such as Mesoscale Convective Systems (MCSs), as well as near-storm scale convective elements including model generated storms containing rotating updrafts. In addition, model precipitation fields include simulated radar reflectivity displays which allow forecasters to see predictions of precipitation systems in the same visual framework as observed radar images. Not only does this permit a more direct comparison between model forecasts and observational data, but the high resolution model output often contains detailed mesoscale and near-stormscale structures such as squall lines and bow echoes that resemble convective storm echoes observed in actual radar data (see Koch et al. 2005 for details about WRF model-derived reflectivity fields). Thus, high resolution models have potential to provide unique guidance to severe weather forecasters regarding key topics of convective initiation, evolution, mode, and intensity.

Since 2003, the SPC has played a leading role in testing various configurations of SREF systems (e.g., Bright et al. 2004, Levit et al. 2004, Homar et al. 2006) and high resolution WRF models (e.g., Kain et al. 2006, 2007) for their operational utility. This testing has involved collaborations with the NCEP Environmental Modeling Center (EMC), National Center for Atmospheric Research (NCAR), and the University of Oklahoma Center for Analysis and Prediction of Storms (CAPS), occurring both within SPC operations and as part of organized annual SPC/NSSL Spring Experiment activities within the HWT. See Kain et al. (2003a, 2003b) for a recent history of organized interactions between research and operations involving SPC and NSSL.

3.1 *NCEP SREF System*

Currently, EMC is running a 21 member multi-model, multi-analysis mesoscale SREF system with enhanced physics diversity four times daily at 03, 09, 15, and 21 UTC, with output through 87 hours (Du et al. 2006). Prior to the summer of 2006, the SREF was run twice daily at 09 and 21 UTC. It is currently composed of 10 NAM-Eta members, 5 Regional Spectral Model (RSM) members, and 6 WRF members (Table 1). All SREF members use Ferrier microphysics except the RSM members, which use GFS Zhou microphysics.

SPC processes the grids from all SREF members and produces a large variety of products for severe weather forecasting, including standard spaghetti, mean and spread, probability, and max/min charts, as well as specialized multi-parameter convective fields and post-processed calibrated probabilities for the occurrence of thunderstorms, dry thunderstorms, and severe thunderstorms (e.g., Bright et al. 2004, 2005, Levit et al. 2004).

3.2 *4 KM NCEP WRF-NMM and NSSL WRF-ARW*

The EMC began running an experimental 4.5 km WRF-Non-hydrostatic Mesoscale Model (WRF-NMM4) for the SPC in April 2004. The model is currently run at 4 km grid length and 35 vertical levels over a domain covering approximately the eastern three-fourths of the United States. Beginning in September 2006, NSSL has been producing forecasts using a 4 km Advanced Research WRF (WRF-ARW4 developed at the National Center for Atmospheric Research) with 35 vertical levels over a similar three-fourths CONUS domain. There is no parameterized convection in either WRF model; instead, all precipitation is produced from the microphysics schemes. Both convection-allowing WRF models are initialized from a cold start once daily at 0000 UTC using initial and lateral boundary conditions from the operational North American Mesoscale (NAM-WRF) model, and provide forecasts through a 36 hour period. Current configurations of the WRF models are found in Table 2.

Several unique WRF-NMM4 products have been developed for use by SPC severe weather forecasters, including simulated reflectivity and measures of updraft rotation in model-generated storms.

4. INCORPORATION OF SREF AND HIGH RESOLUTION MODELS INTO SPC OPERATIONS

The incorporation of SREF and high resolution WRF-NMM4 guidance into an operational severe weather forecasting environment already dealing with increasingly high volumes of observational and model data requires careful assessment of the unique strengths of each modeling system and knowledge of the specific needs of SPC forecasters. Simply introducing more data sources into the decision-making process is not likely to result in improved forecasts. Rather, better use of data that are tailored to address specific forecast needs is required before improvements are typically seen (e.g., Heideman et al. 1993). To better manage the process of introducing new tools into operations, the HWT provides a unique setting where initial exploration of cutting edge science and technology for possible use in operational severe weather forecasting can be accomplished. A key element in the initial testing and evaluation process is the direct participation of operational forecasters in HWT Spring Experiments. They provide real-world insights on the challenges of convective forecasting, including the appropriate blending of observational and model data in the forecast decision-making process, dealing with "data overload" and the need to improve the mining of relevant information from the increasingly complex and diverse datasets available to forecasters, accounting for uncertainty and conveying varying levels of forecaster confidence when formulating forecast products under tight forecast deadlines, as well as identifying new and unique meteorological information that may prove useful to forecasters and helping to design new data visualization displays that foster assimilation of information by humans. These steps are an essential component of the research to operations path, because it must be demonstrated in

Model	Convective Parameterization	Dx/ Vertical Levels	Domain/Configuration	Members	ICs/LBCs
Eta	BMJ	32km/60	NOAM/Hydrostatic	1 ctl, 2 bred	NDAS
Eta	BMJ-SAT	32km/60	NOAM/Hydrostatic	2 bred	NDAS
Eta	KF	32km/60	NOAM/Hydrostatic	1 ctl, 2 bred	NDAS
Eta	KF-DET	32km/60	NOAM/Hydrostatic	2 bred	NDAS
RSM	SAS	45km/28	NOAM/Hydrostatic	1 ctl, 2 bred	GDAS
RSM	RAS	45km/28	NOAM/Hydrostatic	2 bred	GDAS
WRF-NMM	NCEP BMJ	40km/52	NOAM/Non-Hydrostatic	1 ctl, 2 bred	GDAS
WRF-ARW	NCAR KF	45km/36	NOAM/Non-Hydrostatic	1 ctl, 2 bred	GDAS

Table 1*. Configuration of the 21-member NCEP SREF system. BMJ=Betts-Miller-Janjic; BMJ-Sat=BMJ with saturated moisture profiles; KF=Kain-Fritsch; KF-DET=KF with full detrainment; SAS=Simplified Arakawa-Shubert; RAS=Relaxed Arakawa-Schubert; NOAM=North America; NDAS=NAM Data Assimilation System; GDAS=GFS Data Assimilation Svstem.*

	NCEP WRF-NMM4	NSSL WRF-ARW4
Horizontal Grid Length (km)	4.0	**4.0**
Vertical Levels	35	35
PBL/Turbulence Parameterization	MYJ	MYJ
Microphysical Parameterization	Ferrier	WSM6
Radiation (SW/LW)	GFDL/GFDL	Dudhia/RRTM
Initial Conditions	32 km NAM	40 km NAM

Table 2. *Configurations of NCEP WRF-NMM4 and NSSL WRF-ARW4 deterministic models.*

advance that new forecast techniques or tools have a operational value and credibility, and that they provide new and unique information that cannot be obtained from existing data sources.

Since the SPC severe weather forecast mission focuses on phenomena smaller than those predicted by mesoscale models, such as tornadoes and severe thunderstorms, the traditional forecast methodology has focused on first predicting the evolution of the mesoscale environment and then determining the spectrum of convective storms a particular environment may support. SREF output has been found to be particularly useful in quantifying the likelihood that the environment will occupy specific parts of convective parameter space, as well as the likelihood and timing for thunderstorms and severe thunderstorms to develop over Outlook-scale regions. While this can be extremely helpful to SPC forecasters, more detailed information about the intensity and mode of storms is also needed, since the type of severe weather (e.g., tornadoes, damaging wind) is often strongly related to convective mode. The value of the convection-allowing WRF models is most evident here, as they have the capability to resolve near storm-scale convective characteristics. These include the development of discrete cells ahead of a line of storms, and the generation of model storms with rotating updrafts using new parameters such as Updraft Helicity (UH - see Kain et al. 2007). The operational application of the SREF and WRF models for three recent significant severe weather episodes is discussed in the following section.

5. APPLICATION OF SREF AND WRF GUIDANCE FOR SEVERAL SEVERE WEATHER CASES

5.1 *1 March 2007 Southeastern States Tornado Outbreak*

A widespread severe storm outbreak occurred during the afternoon and evening of 1 March 2007 resulting in reports of numerous tornadoes, damaging winds, and large hail from the middle Mississippi and Tennessee Valleys across the Southeastern States into the Carolinas (Fig. 2). These included six killer tornadoes that produced 20 fatalities, most of which occurred over southern parts of Alabama and Georgia during the afternoon and evening.

The synoptic pattern (not shown) was characterized by an intense middle- and upper-level trough moving northeastward across the Central Plains toward the Upper Mississippi Valley. A very strong upper level jet stream surged eastward across the southern plains toward the Lower Mississippi Valley with pronounced diffluence aloft from the Ohio Valley across the Southeastern States. A deep occluded surface low lifted northeastward into the Upper Mississippi Valley as a cold front arcing southward from the low accelerated eastward across the Southeastern States. The warm sector was limited by a slow moving warm front that extended across Alabama and Georgia into the eastern Carolinas. Surface dew points in the mid-upper 60s (^{o}F) were limited to the southern parts of Alabama and Georgia where maximum 100 mb Mean Layer CAPE (MLCAPE) values were around 1000 J/kg. Elsewhere over the region, MLCAPE ranged from 250-750 J/kg, which is typical for many cool season severe weather environments over the Southeast (Schneider et al. 2006). While the synoptic setup was well evident as being favorable for potentially significant severe storms and a High Risk Outlook was in effect, details of the convective evolution were complicated by the presence of morning severe thunderstorms and extensive cloud cover across much of the area.

5.1.1 *SREF Guidance*

Numerous specialized SREF products have been created to support the SPC severe weather forecasting program (Bright et al. 2004), and among the most useful are probabilistic products computed from the number of members exceeding various threshold values of fields such as dew point, wind speed, vertical shear, instability, and accumulated precipitation. One advantage of ensemble systems is that it is possible to apply ingredients-based concepts of severe weather forecasting (e.g., Johns and Doswell 1992) to SREF output to identify regions where favorable severe weather parameters coexist. This output can be used to identify where and when severe weather is more likely to occur. In most basic terms, thunderstorms are more likely to be severe if they develop within an environment characterized by large amounts of instability and vertical shear. This combination of ingredients can be approximated by examining SREF-based probabilities of CAPE, deep layer shear, and convective precipitation (as a proxy for thunderstorm development) exceeding specific threshold values for each field. Since there is a wide range of CAPE/shear environments supportive of severe weather (e.g., Thompson et al. 2003, Schneider et al. 2006), varying combinations of threshold values may be needed (for example, minimum CAPE of 2000 Jkg^{-1} in the warm season but lowered to 500 Jkg^{-1} in the winter). Further, the region of overlapping ingredients can be computed as the product of the three probabilities (a "combination product") by treating them as independent events. An example of the 18 hour forecast product valid 21 UTC 1 March for combined probabilities of CAPE $\geq$ 500 Jkg^{-1}, effective layer bulk shear (Thompson et al. 2007) $\geq$ 40 kt, and 3-hour convective precipitation $\geq$ 0.01 inch during 18-21 UTC is shown in Fig. 3, which approximates the time period of the EF4 killer tornadoes that struck Millers Ferry, AL, and Enterprise, AL. The axis of highest combined probability is located over the warm sector, with values diminishing northward into the lower Ohio Valley. Probability products for derived parameters such as the Significant Tornado Parameter values $\geq$ 3 (STP – Thompson et al. 2003) and the combined ingredients for STP=1 are shown in Figs. 4 and 5. These products focus attention on the potential for significant tornadoes (EF2+) and correspond reasonably well to the locations of observed EF2-4 tornadoes.

Nearly all SREF output products currently produced at SPC are computed from the raw ensemble member output. Although these uncalibrated products often exhibit reasonable skill, they also reflect inherent biases and errors in the ensemble system. Improvements to the skill and reliability of ensemble systems can be statistically developed using, for example, post-processed bias correction and calibration techniques. Bright et al. (2005) and Bright and Wandishin (2006) describe methods to develop calibrated SREF forecasts of CG lightning and severe thunderstorms, respectively. In both approaches, the resultant probability values are more reliable and skillful than uncalibrated SREF output. For this case, examples of the calibrated SREF probability of any severe storm (large hail, damaging wind, or tornado) valid for the 3 hour period from 18-21 UTC 1 March (Fig. 6) and the calibrated SREF severe thunderstorm probability for the 24 hour convective day starting 12 UTC 1 March (Fig. 7) are shown. The calibrated products indicated relatively high probability values across much of the area affected by severe weather on this day, although the 24 hour guidance places the axis of highest calibrated probability over the Atlantic coastal waters. This was co-located with the axis of maximum CAPE predicted by the SREF over the adjacent Gulf Stream waters.

5.1.2 *WRF Guidance*

Availability of forecast output from the convection-allowing WRF models is more limited compared to the number of products available from the SREF system. This is related to the very large number of grid points within the large WRF domains, the resultant high data volume produced by the WRF models, and the perception that the uniquely valuable component of convection-allowing models at this time is their ability to provide near storm-scale details of model predicted convective systems. Accordingly, development efforts have focused on creating output fields displaying simulated single level reflectivity at 1 km AGL and 4km AGL to observe low- and mid-level model storm structure, respectively, and composite reflectivity that shows the maximum value in the vertical column. In addition, the model resolution marginally permits the identification of storms with rotating updrafts by examining fields such as the relationship between vertical velocity and vertical vorticity in the low and mid levels (Kain et al. 2007), providing direct indication of supercell thunderstorm potential from the output.

The WRF-NMM4 and WRF-ARW4 18 hr forecasts of simulated reflectivity at 1 km AGL (Figs. 8 and 9) and the NEXRAD mosaic of 0.5 degree base reflectivity (Fig. 10) valid at 18 UTC 1 March allow comparison of the high resolution forecasts with observed radar. While there are differences in details of storm placement and character between the models and radar, the WRF models predicted multiple bands of NNE-SSW oriented convection moving across the region. Most importantly, the cellular nature of the model storms provided unique information to SPC forecasters about potential storm mode and associated severe weather types, which is not evident from mesoscale NAM model output of accumulated precipitation (Fig. 11). However, in this case and others that occurred during the 2006-2007 cool season, the WRF models have shown a tendency to underforecast the intensity and coverage of deep convection, which may be related to the more limited instability that is common this time of year.

5.2 *28 March 2007 High Plains Severe Weather Case*

Numerous severe storms occurred during the late afternoon over the High Plains from South Dakota into west Texas, producing reports of significant tornadoes, very large hail the size of baseballs and softballs, and wind gusts to 90 mph (Fig. 12). Three killer tornadoes occurred over parts of the Texas and Oklahoma Panhandles and near the Colorado/Kansas state line resulting in five fatalities. The synoptic pattern (not shown) was associated with a slowly moving upper low near the Four Corners region and strong deep layer meridional flow over the High Plains region. A surface low persisted over parts of eastern Colorado and convective development was limited to areas along and immediately east of a north-south dryline over the High Plains, as a capping inversion over much of the Central and Southern Plains precluded deep convection from developing. Predicting the location of the dryline was a key forecast challenge, as convergence along this boundary focused thunderstorm initiation within a very unstable environment where MLCAPE ranged from 2000-3000 J/kg.

5.2.1 *SREF Guidance*

A number of specialized SREF guidance products valid at 00 UTC 29 March highlighted a north-south axis from central Nebraska across western parts of Kansas and Oklahoma into West Texas as the most likely regions for severe thunderstorms to occur. For example, the combination probability (MUCAPE $\geq$ 1000 J/kg, effective layer bulk shear $\geq$ 40 kt, and 3-hour convective precipitation $\geq$ 0.01 inch - Fig. 13), the calibrated 3-hour severe thunderstorm probability (Fig. 14), the probability of STP $\geq$ 3 (Fig. 15), and the STP ingredients probability (Fig. 16) all focused relatively large probability values over similar regions of the High Plains. Although the SREF guidance correctly indicated potential for an extensive corridor of severe storms including significant tornadoes to occur, the location of the SREF probability axes was displaced slightly to the east of the actual severe reports, especially those that occurred near the Kansas/Colorado border. It appears that the dryline location and coincident western edge of low-level moisture and instability predicted by most SREF members was too far to the east, as indicated by the 2 m dewpoint mean and spread chart shown in Fig. 17. This suggests that the SREF was underdispersive in its prediction of the dryline location and associated low-level moisture and CAPE fields, illustrating how relatively small displacements in low-level moisture discontinuities characterized by very strong gradients can have a large effect on the location of severe weather occurrence.

5.2.2 *WRF Guidance*

The 24 hour forecasts of simulated reflectivity at 1 km AGL from both WRF models valid at 00 UTC 29 March 2007 showed several bands of discrete rotating thunderstorms over parts of the High Plains (Figs. 18-19). More extensive meridional coverage of storms was predicted by the WRF-NMM4, which is similar to the observed radar mosaic seen in Fig. 20. When compared to the 24 hour NAM forecast of 3-hour accumulated precipitation valid at the same time (Fig. 21), it is apparent that the detailed convective structure and direct indications of model generated storms with rotating updrafts from the WRF models provide forecasters with unique information not available from traditional operational mesoscale models. However, as noted in the SREF guidance, the WRF models also generated storms too far to the east compared to actual storms. The location of WRF storms and NAM precipitation are quite similar (compare Figs. 18, 19, and 21), and this occurrence has been found to be fairly common, especially during strongly forced situations. This suggests that the use of NAM initial and lateral boundary conditions in WRF models may strongly influence the timing and location of storms in the convection-allowing models, particularly when well-resolved synoptic features are present in the NAM. This finding has been noted in other studies such as Done et al. (2004) and Weisman et al. (2007).

5.3 *4 May 2007 Greensburg, KS, Isolated Tornadic Supercell Case*

Isolated long-track supercell thunderstorms formed over the northeast Texas Panhandle and far northwest Oklahoma during the late afternoon of 4 May 2007 and moved northeast into parts of western and central Kansas during the evening hours. The most significant event occurred when an EF5 tornado struck Greenburg, KS, destroying much of the town and killing 10 people. Other severe storms also occurred over eastern Colorado and Nebraska but the primary tornadoes were associated with the supercells over Kansas (Fig. 22). The synoptic pattern (not shown) was dominated by a deep long wave trough over the western U.S., a surface low over eastern Colorado, and a quasi-stationary front extending from the low across northwest Kansas into northeast Nebraska. A dryline was located across western Kansas into West Texas. A very moist and unstable air mass was present east of the dryline with MLCAPE values of 2500-3500 J/kg. However, convergence along the dryline was minimal and with weak forcing aloft, a capping inversion was expected to limit convective development, especially over the southern Plains.

5.3.1 *SREF Guidance*

SREF severe weather products focused higher probabilities over western and central parts of Kansas and adjacent parts of Nebraska and Oklahoma. This is seen by the combination probability of MUCAPE $\geq$ 2000 J/kg, effective layer bulk shear $\geq$ 40 kt, and convective precipitation $\geq$ 0.01 inch (Fig. 23), calibrated probability of severe thunderstorms (Fig. 24), probability of STP $\geq$ 5 (Fig. 25), and probability of STP ingredients (Fig. 26), all valid at 03 UTC 5 March 2007. The decrease in probability values with southward extent into Oklahoma and Texas in the combination, calibrated severe, and STP ingredients probability charts reveal increasing uncertainty for storm development over these areas, since they incorporate the probability of thunderstorms (or convective precipitation) in their computation. Conversely, the STP $\geq$ 5 probability chart (Fig. 25) shows high values across Nebraska, Kansas, and Oklahoma. Since the STP incorporates only environmental information in its formulation, it should be interpreted as a conditional parameter given the occurrence of supercell thunderstorms, that is, it does not provide information about the likelihood of storms to develop.

5.3.2 *WRF Guidance*

The regional radar reflectivity at ~03 UTC 5 May 2007 (Fig. 27) shows tornadic storms over parts of southwest and north central Kansas, with other severe storms over eastern Colorado. Corresponding 27 hour forecasts from the WRF-NMM4 (Fig. 28) shows more widespread coverage of convective storms compared to the WRF-ARW4 forecast (Fig. 29), which has been a common characteristic noted by SPC forecasters. Although the WRF-ARW4 develops too few storms, it is instructive to more closely examine the forecasts near the location and time of the Greensburg tornado. Radar reflectivity around 03 UTC 5 May shows the tornadic storm over Greensburg (denoted by the star in Fig. 30), with the WRF-NMM4 and WRF-ARW4 forecasts in Figs. 31-32. Both WRF models generated supercell storms within one county of the actual tornadic storm, and the WRF-ARW4 simulated reflectivity exhibits a hook echo signature with the updraft helicity contours identifying cyclonic rotation adjacent to the low level inflow region. The WRF-NMM4 depicts multiple storms with rotating updrafts, and although the reflectivity signatures do not closely resemble those of classic supercells, the WRF-NMM4 clearly indicated potential for significant rotating storms to develop over the area. For this case, SPC forecasters were able to use the convection-allowing WRF models to confirm that although storm coverage may be limited on this day, any sustained updrafts that developed within the very unstable and favorably sheared environment would rapidly develop rotating updrafts with potential for long-lived supercells.

6. CONCLUSIONS

Annual Spring Experiments conducted by SPC and NSSL in the NOAA Hazardous Weather Testbed (HWT) have enabled the SPC to play a leading role in the development, testing, and incorporation of SREF and convection-allowing WRF model data into the operational severe weather forecasting process. These efforts are the result of productive collaborations established with a number of partners, especially EMC, CAPS and NCAR. This effort has fostered a unique environment where operational forecasters, research scientists, model developers, and academic faculty and students work together to further advance the science of severe weather forecasting. Over the last several years, the infusion of cutting edge modeling concepts into SPC operations has had a noticeable impact on severe weather forecasting procedures as forecasters and researchers learn more about the strengths, limitations, and appropriate use of SREF and convection-allowing WRF models for the prediction of severe weather. The recent move of the HWT to the new National Weather Center facility in Norman has enhanced the opportunities for innovative collaborative activities such as the 2007 Spring Experiment, which explored the potential utility of a 10-member convection-allowing WRF ensemble for severe weather forecasting purposes (Xue et al. 2007, Coniglio et al. 2007).

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9. FIGURES

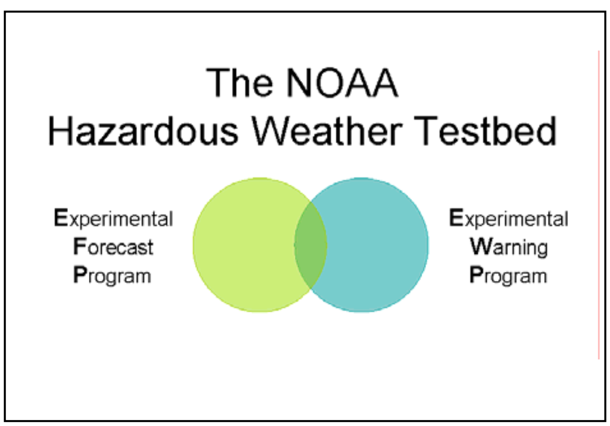

Figure 1: ***The umbrella of the NOAA Hazardous Weather Testbed (HWT) encompasses two program areas: the Experimental Forecast Program (EFP) and the Experimental Warning Program (EWP).***

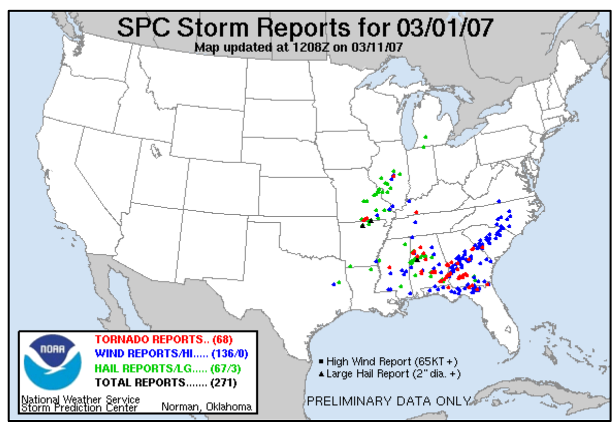

Figure 2: Severe storm reports (red = tornado, blue = wind, green = hail) for the period 12 UTC 1 March 2007- 12 UTC 2 March 2007.

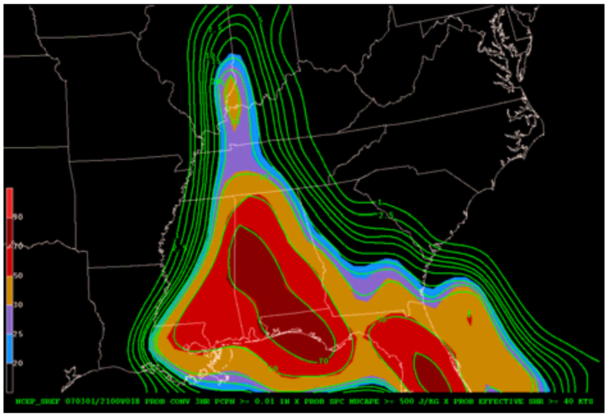

Figure 3: ***SREF 18 hr forecast of combined probability of MUCAPE ≥ 500 Jkg-1, effective bulk shear ≥ 40 kt, and 3-hr accumulated convective precipitation ≥ 0.01 inch valid 21 UTC 1 March 2007.***

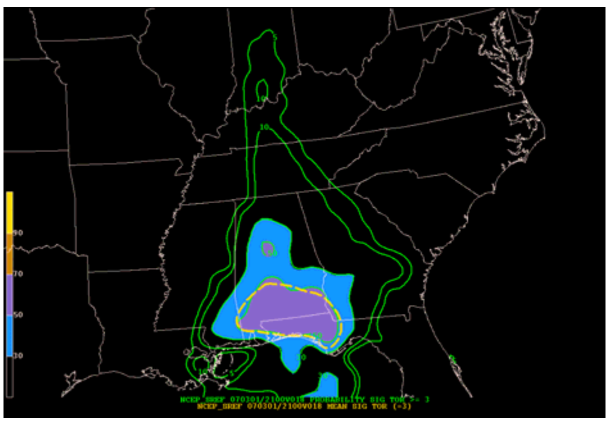

Figure 4: ***As in Fig. 3 except for probability of STP ≥ 3.***

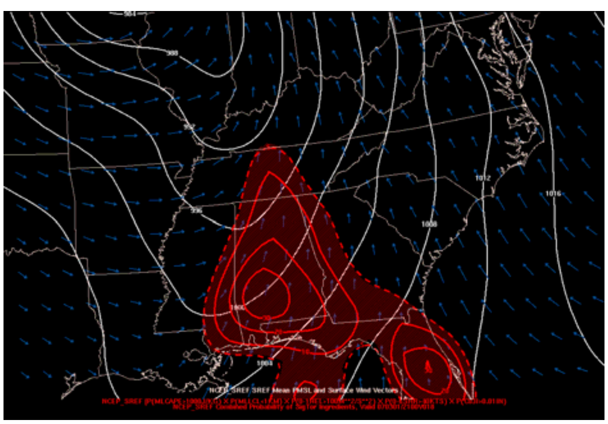

Figure 5: ***As in Fig. 3 except for combined probability of STP ingredients for MLCAPE ≥ 1000 Jkg^{-1}, 0-1 km SRH ≥ 100 m^{2}s^{-2}, 0-6 km shear ≥ 40 kt, MLLCL ≤ 1000 m, and 3-hr accumulated convective precipitation ≥ 0.01 inch.***

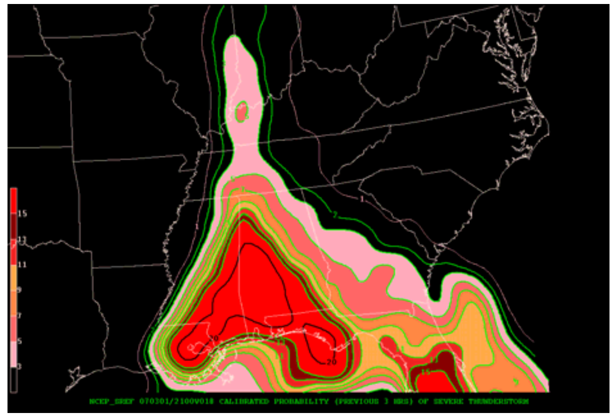

Figure 6: ***As in Fig. 3 except calibrated 3-hour probability of severe thunderstorms.***

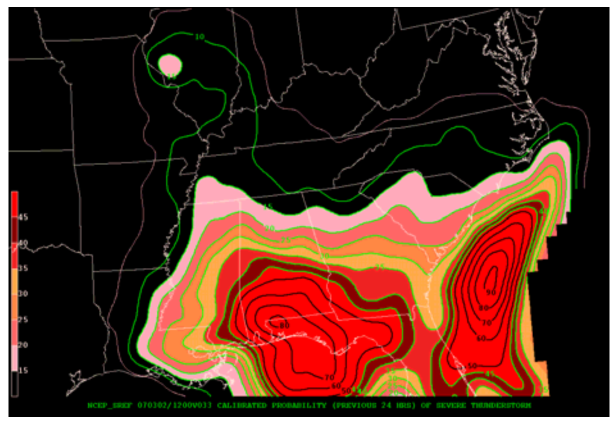

Figure 7: ***SREF calibrated 24-hr probability of severe thunderstorms valid 12 UTC 1 March 2007-12 UTC 2 March 2007.***

Figure 8: ***WRF-NMM4 18 hr forecast of 1 km AGL simulated reflectivity valid 18 UTC 1 March 2007.***

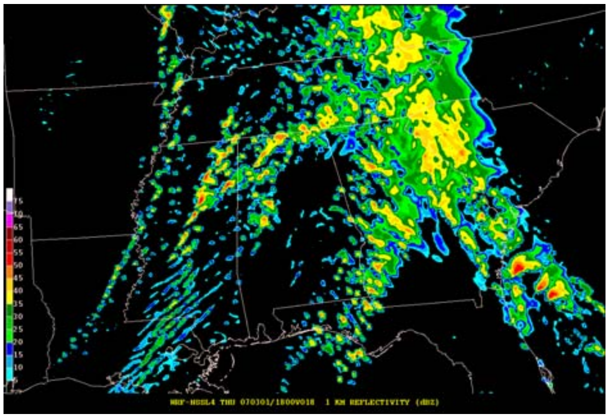

Figure 9: ***WRF-ARW4 18 hr forecast of 1 km AGL simulated reflectivity valid 18 UTC 1 March 2007.***

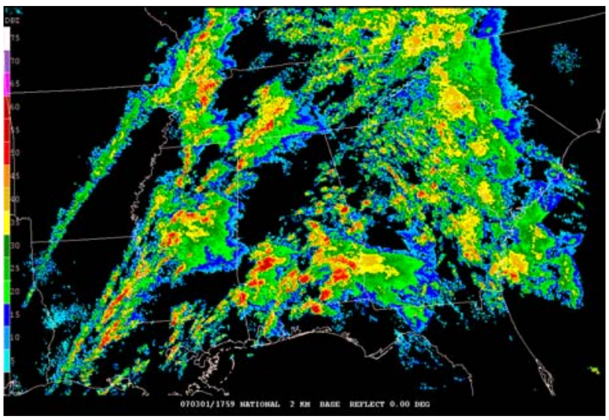

Figure 10: ***Mosaic of radar base reflectivity valid 1758 UTC 1 March 2007.***

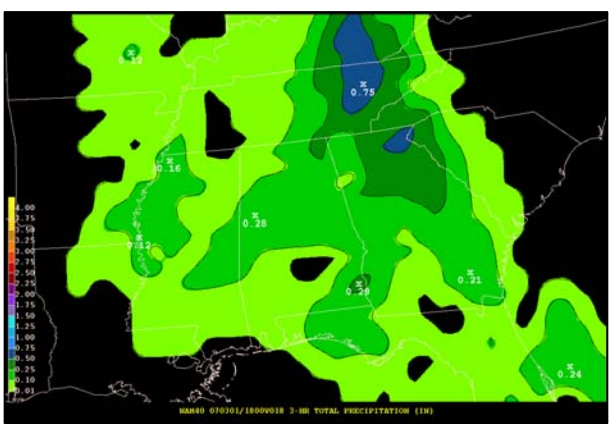

Figure 11: ***NAM-WRF 18 hr forecast of 3-hr accumulated precipitation valid 18 UTC 1 March 2007.***

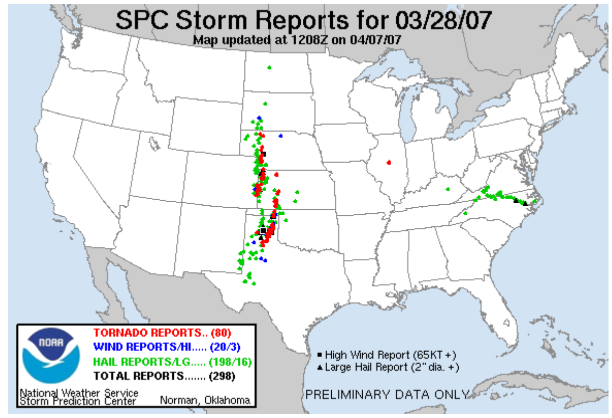

Figure 12: ***Severe storm reports (red = tornado, blue = wind, green = hail) for the period 12 UTC 28 March 2007-12 UTC 29 March 2007.***

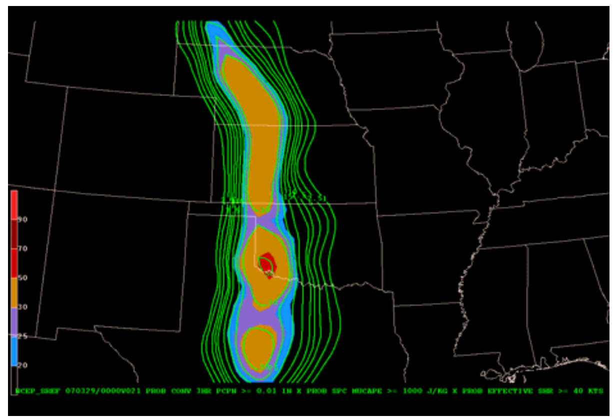

Figure 13: ***SREF 21 hr forecast of combined probability of MUCAPE $\geq$ 1000 Jkg-1, effective bulk shear $\geq$ 40 kt, And 3-hr accumulated convective precipitation $\geq$ 0.01 Inch valid 00 UTC 29 March 2007.***

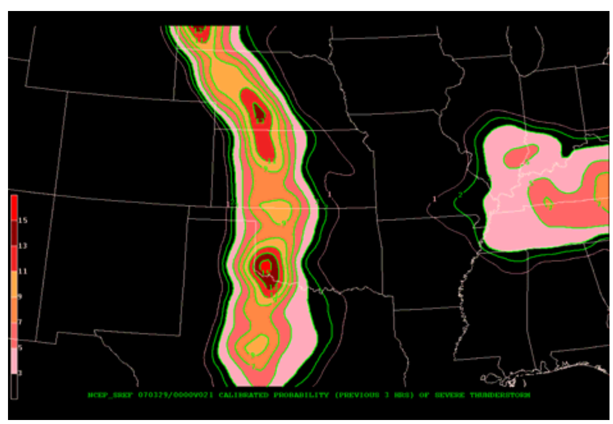

Figure 14: ***As in Fig. 13 except calibrated 3-hour probability of severe thunderstorms.***

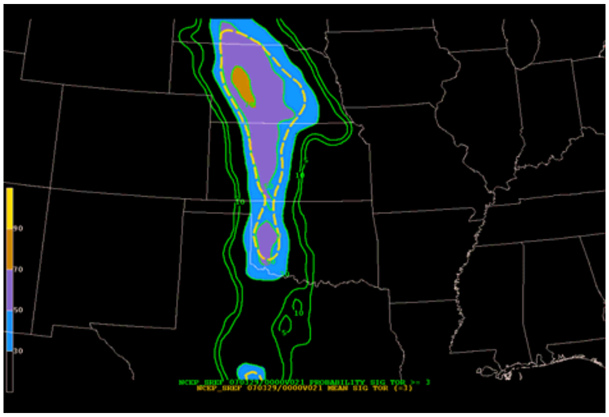

Figure 15: ***As in Fig. 13 except for probability of STP ≥ 3.***

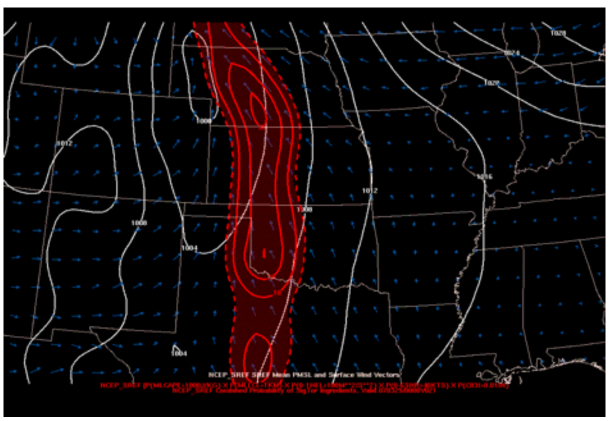

Figure 16: ***As in Fig. 13 except for combined probability of STP ingredients for MLCAPE ≥ 1000 Jkg^{-1}, 0-1 km SRH ≥ 100 m^2s^{-2}, 0-6 km shear ≥ 40 kt, MLLCL ≤ 1000 m and 3-hr accumulated convective precipitation ≥ 0.01inch.***

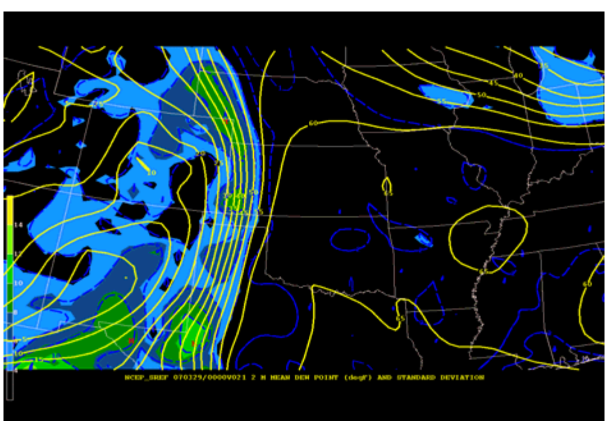

Figure 17: ***As in Fig. 13 except for SREF mean 2m dewpoint (yellow contours ^{o}F) and standard deviation (color fill).***

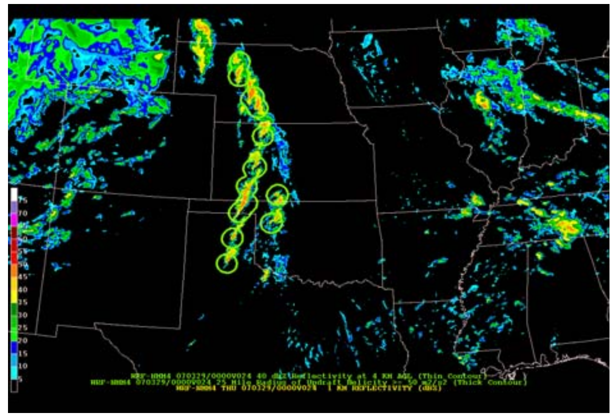

Figure 18: ***WRF-NMM4 24 hr forecast of 1 km AGL simulated reflectivity valid 00 UTC 29 March 2007. Circles denote locations of rotating updrafts where updraft helicity ≥ 50 m^2s^{-2}.***

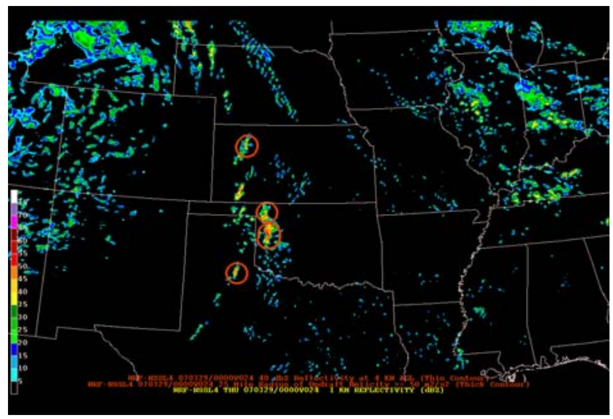

Figure 19: ***As in Fig. 18 except for WRF-ARW4.***

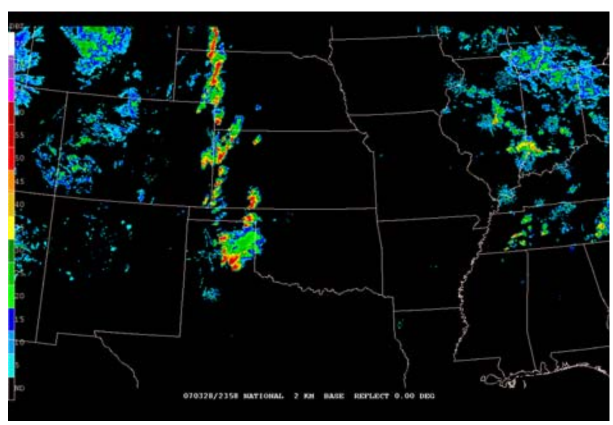

Figure 20: ***Mosaic of radar base reflectivity valid 2358 UTC 29 March 2007.***

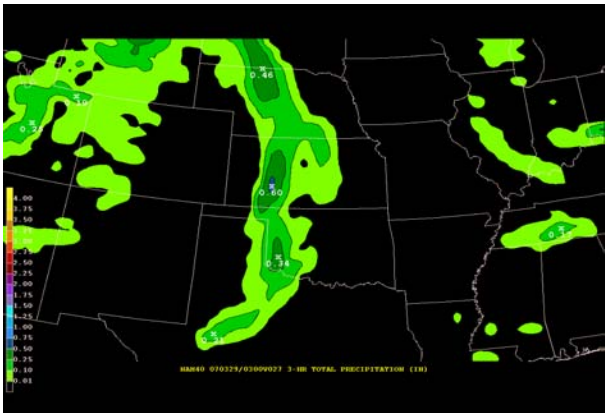

Figure 21: ***NAM-WRF 24 hr forecast of 3-hr accumulated precipitation valid 00 UTC 29 March 2007.***

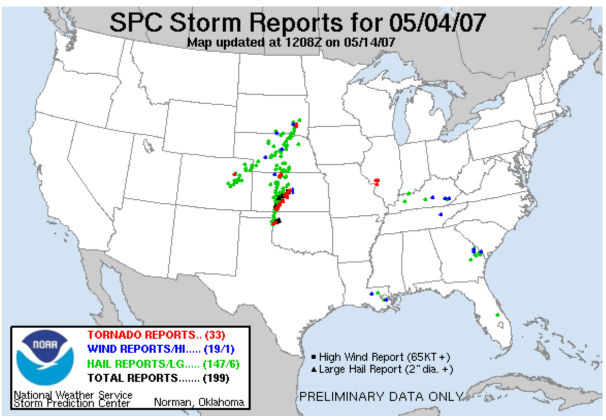

Figure 22: ***Severe storm reports (red = tornado, blue = wind, green = hail) for the period 12 UTC 4 May 2007-12 UTC 5 May 2007.***

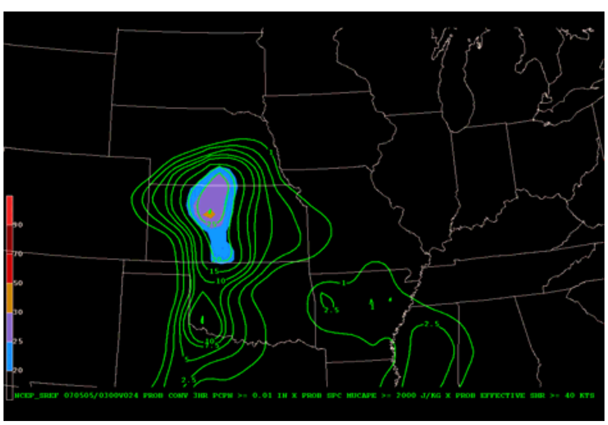

Figure 23: ***SREF 24 hr forecast of combined probability of MUCAPE $\geq$ 2000 Jkg-1, effective bulk shear $\geq$ 40 kt, and 3-hr accumulated convective precipitation $\geq$ 0.01 inch valid 03 UTC 5 May 2007.***

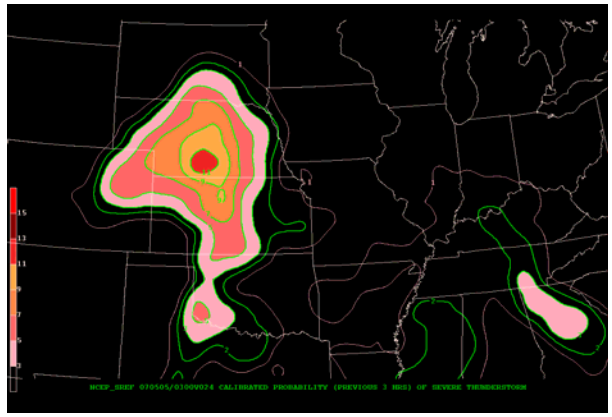

Figure 24: ***As in Fig. 23 except calibrated 3-hour probability of severe thunderstorms.***

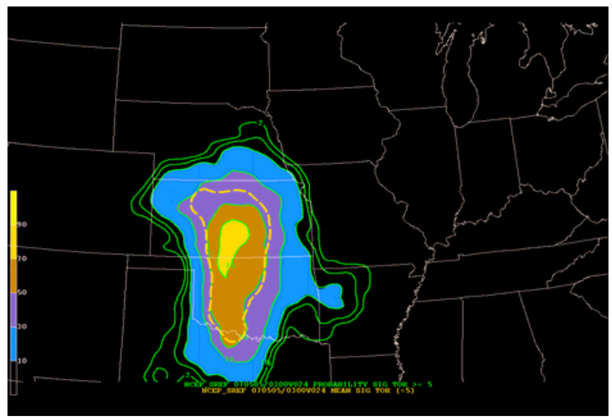

Figure 25: ***As in Fig. 23 except for probability of STP $\geq$ 5.***

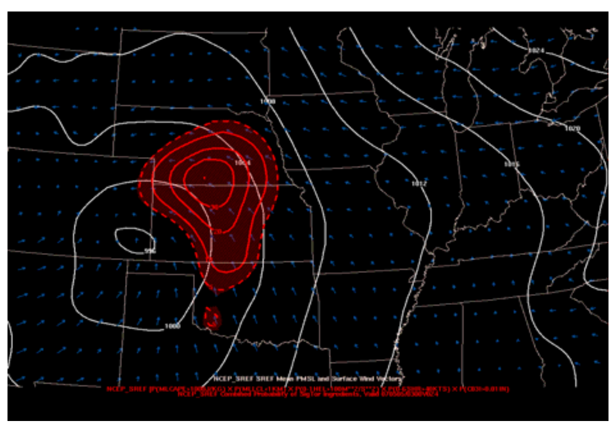

Figure 26: ***As in Fig. 23 except for combined probability of STP ingredients for MLCAPE $\geq$ 1000 Jkg^{-1}, 0-1 km SRH $\geq$ 100 m^{2}s^{-2}, 0-6 km shear $\geq$ 40 kt, MLLCL $\leq$ 1000 m, and 3-hr accumulated convective precipitation $\geq$ 0.01 inch.***

Figure 27: ***Mosaic of radar base reflectivity valid 0259 UTC 5 May 2007.***

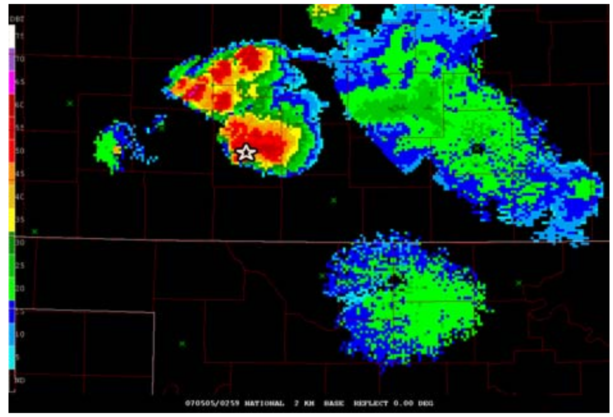

Figure 30: ***Zoom of radar base reflectivity valid 0259 UTC5 May 2007 over southern Kansas/ northern Oklahoma. Star denotes location of Greensburg, KS. Low reflectivity values over south central Kansas and north central Oklahoma are ground clutter around Vance AFB and Wichita RDAs.***

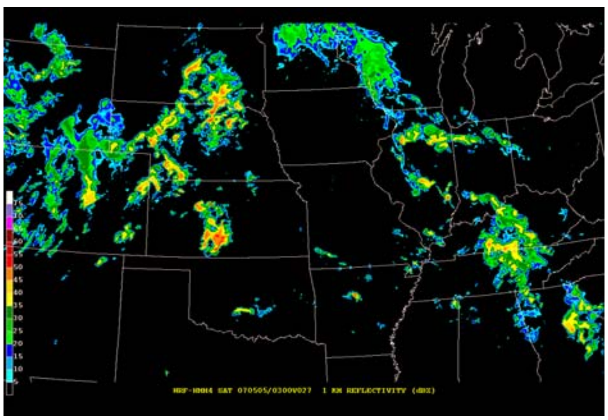

Figure 28: ***WRF-NMM4 27 hr forecast of 1 km AGL simulated reflectivity valid 03 UTC 5 May 2007.***

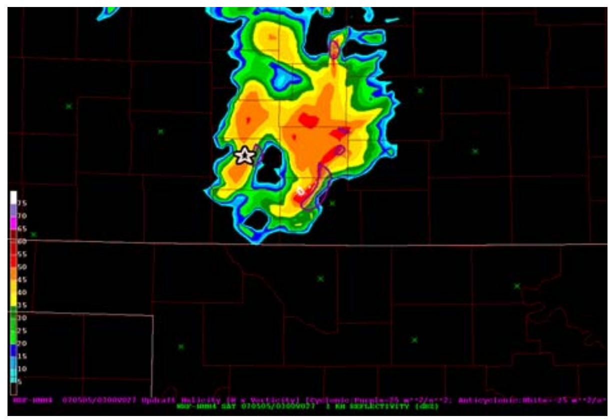

Figure 31: ***Zoom of WRF-NMM4 27 hr forecast of simulated reflectivity (color fill) and updraft helicity $\geq$ 50m^{2}s-$^{-2}$ (purple contours) valid 03 UTC 5 May 2007 over southern Kansas/northern Oklahoma. Star denotes location of Greensburg, KS.***

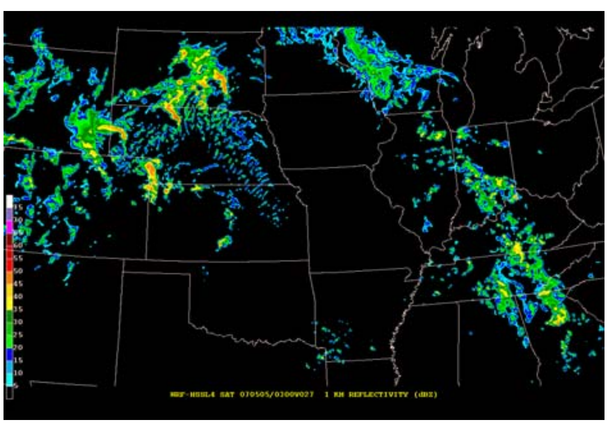

Figure 29: ***As in Fig. 28 except for WRF-ARW4.***

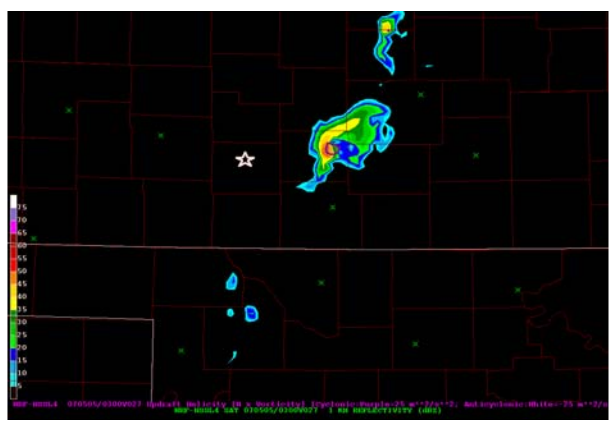

Figure 32: ***As in Fig. 31 except for WRF-ARW4.***