8.5 COMPLEMENTARY USE OF SHORT-RANGE ENSEMBLE AND 4.5 KM WRF-NMM MODEL GUIDANCE FOR SEVERE WEATHER FORECASTING AT THE STORM PREDICTION CENTER

Steven J. Weiss*[1], David. R. Bright[1], John S. Kain[2], Jason J. Levit[1],
Matthew E. Pyle[3], Zavisa I. Janjic[3], Brad S. Ferrier[3], and Jun Du[3]

[1]NOAA/NCEP/Storm Prediction Center, Norman OK
[2]NOAA/OAR/National Severe Storms Laboratory, Norman OK
[3]NOAA/NCEP/Environmental Modeling Center, Camp Springs MD

1. INTRODUCTION

Operational forecasting of severe convective weather at the Storm Prediction Center (SPC) has traditionally focused on the diagnosis and prediction of the synoptic and mesoscale environments associated with severe storms (e.g., Johns and Doswell 1992, Thompson et al. 2003). This is necessary because severe thunderstorms and tornadoes occur on 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,b) 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 is also used by SPC forecasters in many ways. For example, in the short-term model guidance is used 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. 1999), 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.

2. 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). 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 ~5 km or less, and have the capability to generate explicit convective systems such as

---

* *Corresponding author address: Steven J. Weiss, NOAA/NWS/NCEP Storm Prediction Center, 120 David L. Boren Blvd., Norman, OK 73072; E-mail: steven.j.weiss@noaa.gov.*

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) 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/National Severe Storms Laboratory Spring Experiment activities within the NOAA Hazardous Weather Testbed (HWT) in Norman. The HWT is designed to bring research scientists, model developers, and forecasters together to work on issues of mutual interest, facilitating the rapid transfer of severe weather related research to operations. See Kain et al. (2003a, 2003b) for a recent history of organized interactions between research and operations involving SPC and NSSL.

2.1 *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).

2.2 *NCEP 4.5 km WRF-NMM*

The EMC has also been running an experimental 4.5 km WRF-Non-hydrostatic Mesoscale Model (WRF-NMM4) for the SPC since April 2004. This model is run with 4.5 km grid length and 35 vertical levels over a domain covering approximately the eastern three-fourths of the United States. There is no parameterized convection; instead, all precipitation is produced from the Ferrier microphysics scheme. The WRF-NMM4 is currently 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 32 km grid, and provides forecasts through a 36 hour period. Over the last two years, the WRF-NMM4 has been periodically upgraded and currently runs using the community WRF version 2 framework. 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.

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

The incorporation of SREF and high resolution WRF-NMM4 guidance into an operational severe

Model	Convective Param.	Dx/ Vert. 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.*

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 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 are best suited to offer real-world insights on identifying new and unique meteorological information that may prove useful to forecasters, and to provide feedback on 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 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 that 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 WRF-NMM4 is most evident here, as it has capability to resolve near storm-scale convective characteristics, such as the development of discrete cells ahead of a line of storms, and the development of model storms with rotating updrafts. The operational application of these models for the tornado outbreak of 2 April 2006 is discussed in the next section.

4. APPLICATION OF SREF AND WRF-NMM4 GUIDANCE FOR 2 APRIL 2006 TORNADO OUTBREAK

A regional tornado outbreak occurred during the late afternoon and evening of 2 April 2006 resulting in numerous tornadoes and severe storms across the middle Mississippi and Tennessee river valleys (Fig. 1). These included five killer tornadoes that produced 26 fatalities in parts of southern Illinois, southeast Missouri, and western Tennessee. This was the largest number of tornado deaths in a single day during the Spring of 2006.

The synoptic pattern (not shown) was characterized by a strong middle and upper level trough moving eastward across the central and southern plains toward the Mississippi valley. The associated surface low was moving from Kansas toward Iowa, and a broad warm sector with surface dew points in the upper 50s and lower 60s (F) in advance of an eastward moving cold front. While the synoptic setup was well evident as being favorable for potentially significant severe storms and a Moderate Risk Outlook was in effect, details of the afternoon and evening convective evolution were complicated by the presence of morning thunderstorms across the middle Mississippi valley.

4.1 *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 are 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 $\mathrm{Jkg^{-1}}$ in the warm season but lowered to 500 $\mathrm{Jkg^{-1}}$ 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 15 hour forecast product valid 00 UTC 3 April for combined probabilities of CAPE $\geq$ 1000 $\mathrm{Jkg^{-1}}$, effective bulk shear (Thompson et al 2006) $\geq$ 40 kt, and convective precipitation $\geq$ 0.01 inch is shown in Fig. 2, during the time period of the most destructive storms. Highest probability values extend over the Mississippi Valley from southern Illinois and southeast Missouri into Arkansas, west Tennessee and northwest Mississippi, or over the area affected by the most destructive severe weather.

Probability products for derived parameters such as the Significant Tornado Parameter (STP – Thompson et al. 2003) values $\geq$ 5 and the combined ingredients for STP=1 valid are shown in Figs. 3 and 4. These focus attention on the potential for significant tornadoes (F2+) over the middle Mississippi valley, and correspond well to the locations of observed F2-F3 tornadoes.

Nearly all SREF output products currently produced at SPC are computed from the raw output from the ensemble members. 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 (hail, wind, or tornado) valid for the 3 hour period from 21 UTC 2 April to 00 UTC 3 April (Fig. 5) and the calibrated SREF severe thunderstorm probability for the 24 hour convective day starting 12 UTC 2 April (Fig. 6) are shown. The calibrated products indicated relatively high probability values across much of the area affected by severe weather on this day.

4.2 *WRF-NMM4 Guidance*

Forecast output from the WRF-NMM4 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 domain and the unusually high data volume produced by high resolution models, and because the value of high resolution models at this time appears to be 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 correlation between vertical velocity and vertical vorticity in the low and mid levels. In this way, direct indication of supercell thunderstorm potential can be extracted from the output.

The WRF-NMM4 24 hr forecast of simulated reflectivity at 1 km AGL (Fig. 7) and the NEXRAD mosaic of 0.5 degree base reflectivity (Fig. 8) valid at 00 UTC 3 April allow comparison of the high resolution forecasts with observed radar. While specific details of storm placement and character do not match perfectly, the WRF-NMM4 accurately predicted the primary regions of severe convection over the Mississippi valley and eastern parts of Kentucky and Tennessee. Most importantly, the cellular nature of the tornadic storms from southern Illinois into southeast Missouri and northeast Arkansas provided unique information to SPC forecasters about potential storm mode and severe weather types. Computation of a measure of updraft rotation called the Supercell Detection Index (SDI) indicated the model trended toward supercell development by 01 UTC (Fig. 9) over southeast Missouri, northeast Arkansas, and northwest Tennessee where significant tornadoes occurred. In comparison, the operational mesoscale NAM model 24 hr forecast of 3-hour accumulated precipitation failed to develop precipitation over this region (Fig. 10). SPC forecasters used the detailed WRF-NMM4 guidance not only to adjust the NAM severe threat area southward into the region affected by significant tornadoes, but also to develop a more complete picture of the possible evolution of convective mode during this event.

5. CONCLUSIONS

The SPC is playing a leading role in the development, testing, and incorporation of SREF and high resolution WRF model data into the operational severe weather forecasting process. These efforts are the result of productive collaborations established with a number of agencies, especially NSSL and EMC, working through annual Spring Experiments within the NOAA Hazardous Weather Testbed in Norman. This has fostered a unique environment where operational forecasters and research scientists work together to further improvements in 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 high resolution model data for the prediction of severe weather.

6. ACKNOWLEDGMENTS

The expert assistance of Linda Crank (SPC in formatting the paper is greatly appreciated.

7. REFERENCES

Available upon request

8. FIGURES

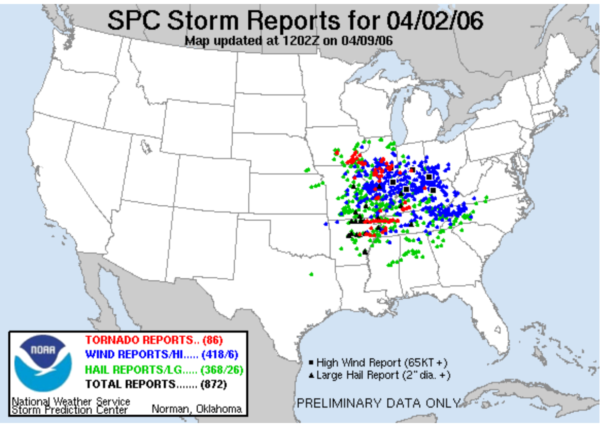

Fig. 1: Severe storm reports (red = tornado, blue = wind, green = hail) for the period 12 UTC 2 April 2006-12 UTC 3 April 2006.

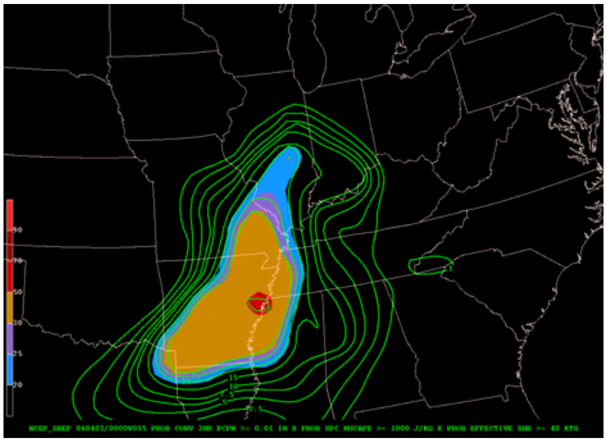

Fig. 2: *15 hr SREF forecast of combined probability of MUCAPE ≥ 1000 Jkg-1, effective bulk shear ≥ 40 kt, and 3-hr accumulated convective precipitation ≥ 0.01 inch valid 00 UTC 3 April 2006.*

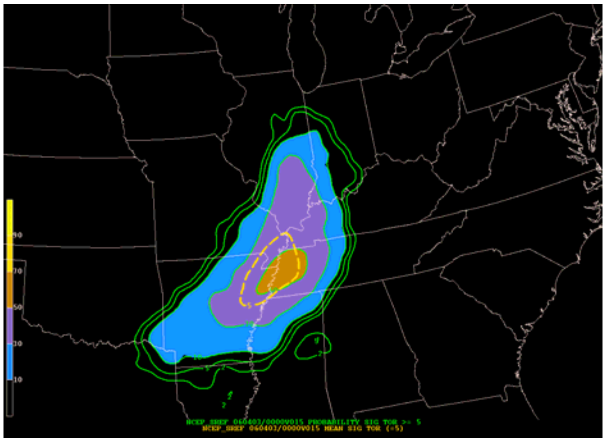

Fig. 3: *As in Fig. 2 except for probability of STP ≥ 5.*

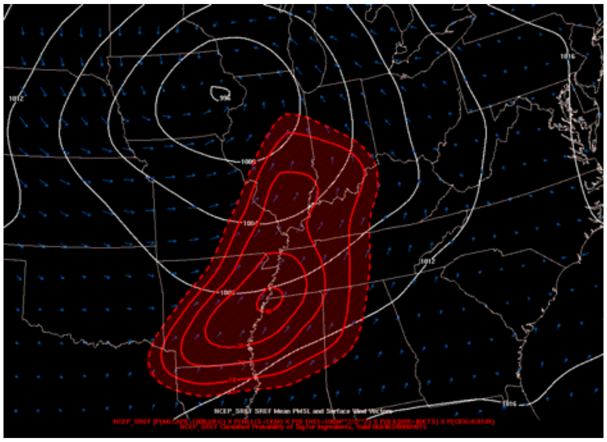

Fig. 4: *As in Fig. 2 except for combined probability of STP ingredients for MLCAPE ≥ 1000 Jkg^{-1}, 0-1 km SRH ≥ 100 m^{2}s^{-2}, 0-6 km shear ≥ 40 kt, MLLCL ≤ 1000 m, and 3-hr accumulated convective precipitation ≥ 0.01 inch.*

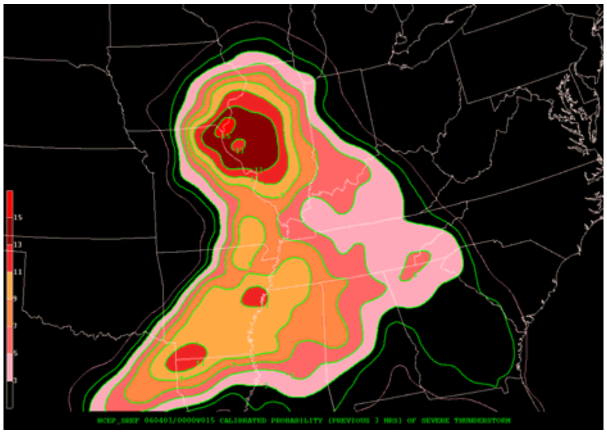

Fig. 5: *As in Fig. 2 except for calibrated 3-hr probability of severe thunderstorms.*

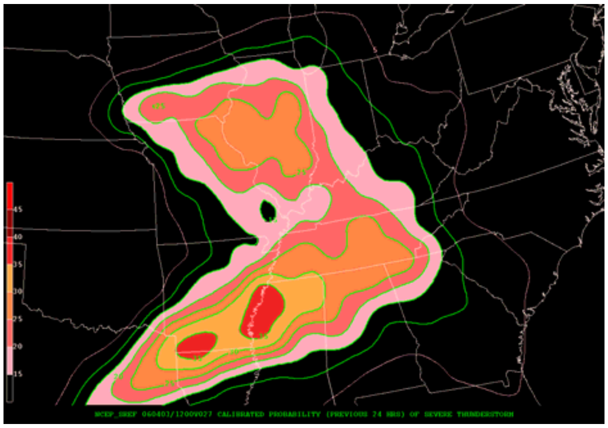

Fig. 6: *Calibrated 24-hr probability of severe thunderstorms valid 12 UTC 2 April 2006-12 UTC 3 April 2006.*

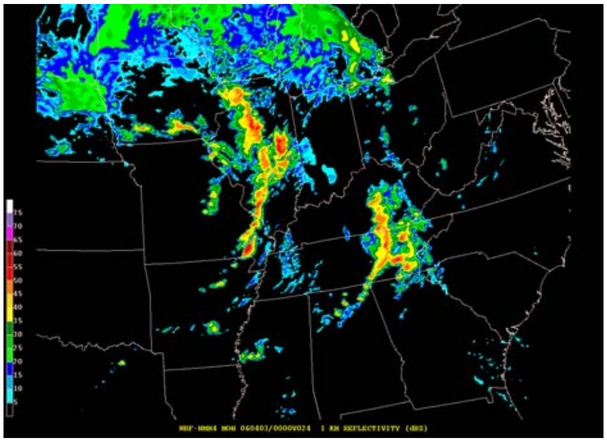

Fig. 7: *WRF-NMM4 24 hr forecast of 1 km AGL simulated reflectivity valid 00 UTC 3 April 2006.*

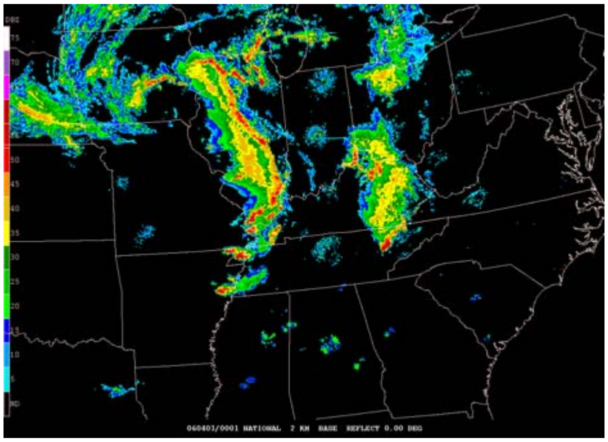

Fig. 8: *Mosaic of radar base reflectivity valid 0001 UTC 3 April 2006.*

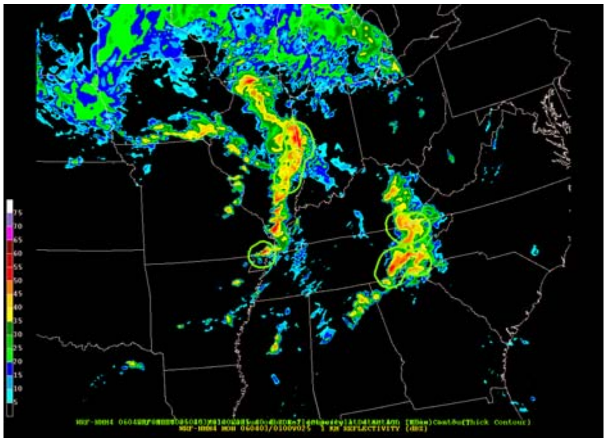

Fig. 9: *WRF-NMM4 25 hr forecast valid 01 UTC 3 April 2006 showing 1 km AGL reflectivity. Locations where SDI ≥ 3 within 25 miles of a point denoted by green contours indicating updraft rotation.*

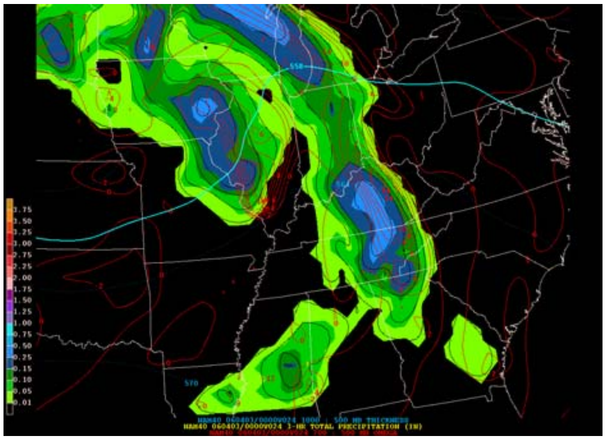

Fig. 10: *NAM-Eta 24 hr forecast valid 00 UTC 3 April 2006 of 3-hr accumulated precipitation (color fill) and mean 700-500 mb upward vertical velocity (red contours).*