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14.5 FORECASTING SUPERCELL STORMS: APPLICATION OF OPERATIONAL TOOLS AND CUTTING-EDGE NUMERICAL MODEL GUIDANCE IN VORTEX2

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1 VORTEX2

The Verification of the Origins of Rotation in Tornadoes Experiment-II (VORTEX2) field project was conducted in the spring of 2009 and 2010 (Wurman et al., 2010). VORTEX2 utilized an armada of 35-40 vehicles with a variety of mobile observing equipment. More than 100 scientists, students and media traveled over much of the Great Plains during the project.

The size and scope of the Verification of the Origins of Rotation in Tornadoes Experiment-II (VORTEX2) field project (Wurman et al., 2010) required accurate forecasts to be made in order to plan the mission of the day and set up for future missions on following days. In 2009, the steering committee was responsible for making the forecasts with input from the VOC. Each member of the steering committee would take turns producing the briefing for the daily morning PI mission planning-meeting.

Although successful forecasts were made, the amount of time required of the steering committee to create forecasts distracted from other mission planning duties. To remove this distraction in the 2010 field phase, the VORTEX2 Principal Investigators (PIs) decided that teams of experienced severe storms forecasters from the research and operations units affiliated with the VORTEX2 field project should prepare daily weather briefings and forecasts for the PIs. The forecasts were to cover specific forecasts of severe convective weather for the current day, the following day and an outlook for the 3-5 day period.

Figure 1. Michael Foster presents a VORTEX2 weather briefing to PI's in a typical motel setting. Michael Coniglio photo.

The forecast and briefing materials were prepared each morning and presented in person at the PIs' daily strategic planning meeting held each day, generally mid-morning (Fig. 1). Time permitting, the briefings were repeated for the entire VORTEX2 regiment just before leaving the hotel site. The briefing materials, in the form of pdf files, were also uploaded to the field catalog for access by project scientists participating in the meeting remotely and for the VORTEX2 field catalog.

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1.1 Guidance to Decisions

The PI's took the weather information from the briefing, and then considered their own weather assessment, group logistics, safety considerations, scientific goals and multi-day strategy to decide on a target region for the day and an overnight lodging location for the night.

Tactical decisions made after noon, to refine the target area or choose which storms to pursue were made using observational and high resolution model data that were received in the V2 Field Coordination vehicle throughout the day; one of the forecasters (KB) also provided mid-day summaries of storm-resolving output from high-resolution models initialized with morning data intended to help with those decisions.

The authors of this paper were the forecasters designated to prepare the briefings, and each served on a two-person team that traveled with the VORTEX2 armada, prepared and presented the briefings in-person each day for a two week period. Generally one person handled the current day while the second person focused on day two and beyond, with some variation depending on the weather situation. The PI meetings were often lively with new information coming in during the meeting and being reviewed on the fly.

In the course of working together, the forecasters learned from each other about the latest forecast tools, and at the conclusion of the field project we felt it would be of interest to the community to share the collection of weather data sources utilized, to document the state of the art as of 2010 and reflect on the usefulness of various tools and model data. That is the aim of this paper.

2 Numerical Weather Prediction Models

Recently there has been a rapid increase in the number and sophistication of numerical weather forecast model guidance available to the severe weather forecasting community. In this section some of the main sources of operational and experimental model data that were used in VORTEX2 are described. Models and forecast products that help determine the synoptic and meso-alpha scale storm environment are covered first, followed by a description of the convection-allowing and convection resolving models that were used in the briefings.

2.1 SREF Guidance

The VORTEX2 weather briefing teams made extensive use of forecast guidance produced by the National Centers for Environmental Prediction (NCEP) Short Range Ensemble Forecasting (SREF) system (http://www.dtcenter.org/ensemble_presentations/2-1_JunDu4NCARensemble.meeting2009.pdf), specifically the guidance that is post-processed routinely by the Storm Prediction Center (SPC). The SPC SREF guidance is constructed by post-processing all 21 members of the NCEP SREF plus the 3-hour time lagged, operational WRF-NAM (for a total of 22 members) every 6 hours (03, 09, 15, and 21 UTC). The SPC SREF output is made available at 3h intervals through 87 hours on a web page maintained by the SPC (http://w1.spc.woc.noaa.gov/exper/sref/). Each field is associated with a specific statistical attribute of the ensemble that is relevant to the prediction of thunderstorms and severe thunderstorms. For forecasts beyond 87h, the NCEP SREF web page (http://www.nco.ncep.noaa.gov/pmb/nwprod/analysis/) was used occasionally.

The 03 UTC SREF guidance was almost always the cycle used in the weather briefings since the briefings began around 1000 Central Time (15 UTC). Furthermore, given the increasing uncertainty in deterministic forecast guidance beyond 24 h, the majority of the SREF plots used were valid for the Day 2 to Day 4 periods.

Figure 2 shows counts of SREF products included in briefings. Sixty-six different fields from the SPC and NCEP SREF guidance were displayed in the weather briefings to the PIs, including 22 mean or median fields, 34 different probabilistic fields, and 10 different "spaghetti" plots of assorted variables.

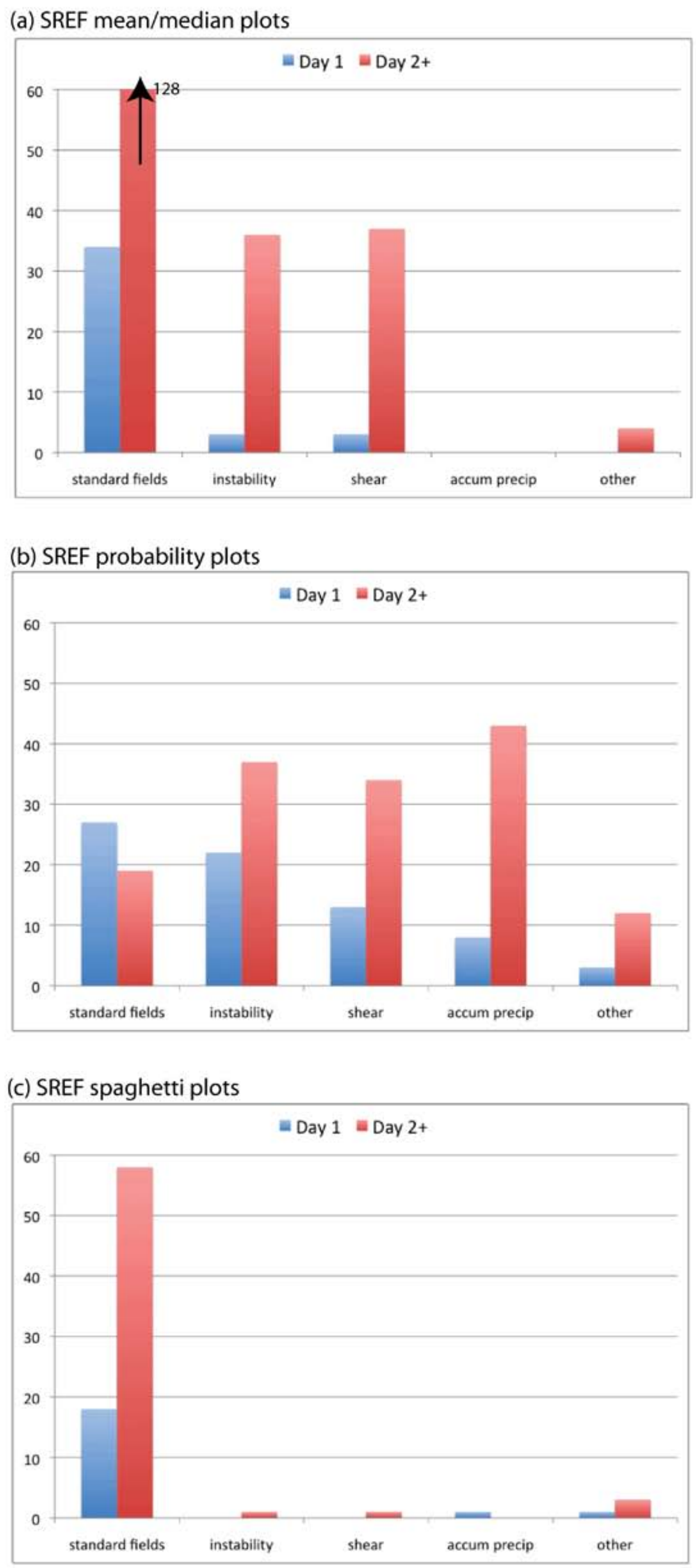

Figure 2. Counts of the number of SREF (a) mean and median, (b) probability, and (c) spaghetti plots used in the Day-1 (blue) and Day-2 and beyond (red) morning weather briefings in 2010 for various types of meteorological variables

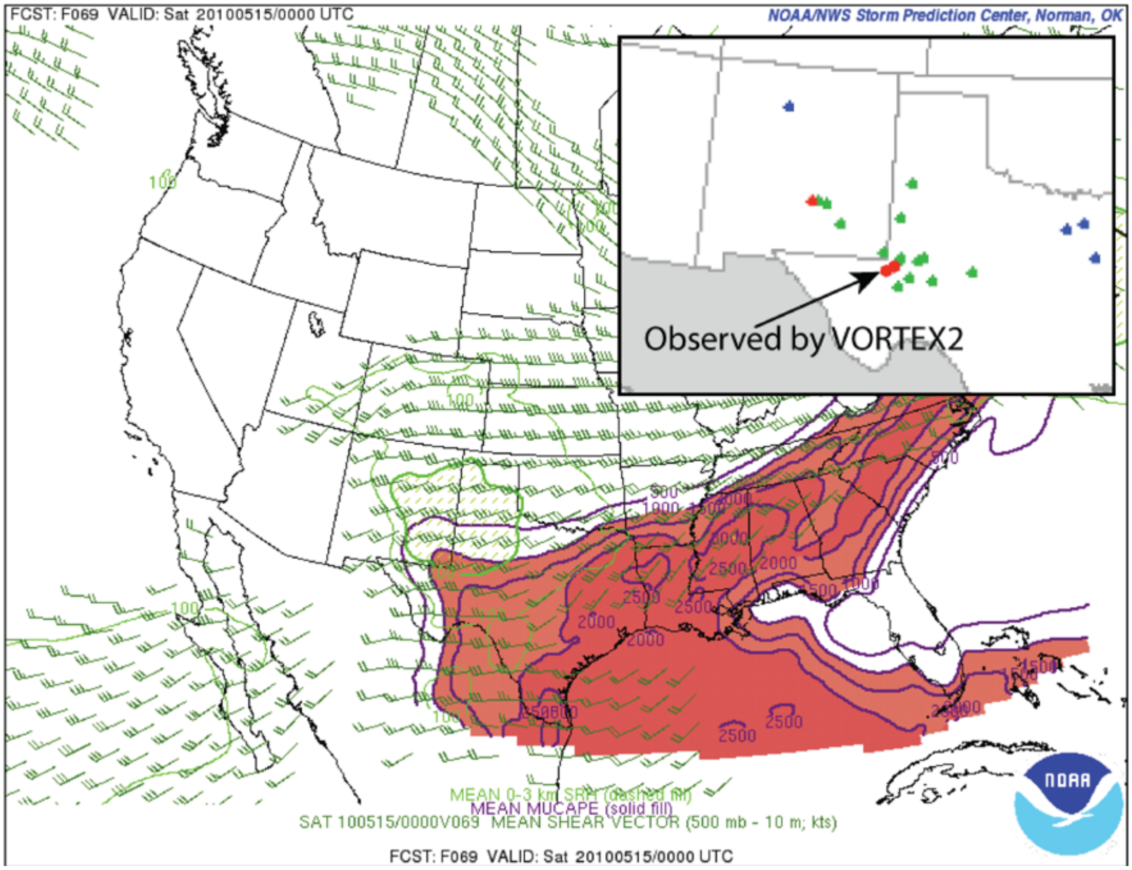

Figure 3. Example of a plot of SREF mean fields shown in the weather briefing the morning of 12 May. Displayed are the approximate ingredients that compose the supercell composite parameter (Thompson et al. 2004), the 0-3 km storm relative helicity (green contours with values ≥ 200 m^2 s^{-2} hatched), the most unstable CAPE (purple contours with values ≥ 1000 m^2 s^{-2} filled in orange and values ≥ 2000 m^2 s^{-2} filled in dark orange), and 10-m to 500-hPa vertical wind shear vectors (kt) for a 69-h forecast valid 00 UTC 15 May. Inset: The preliminary reports of severe weather received at SPC from 12 UTC 14 May to 12 UTC 15 May. The two tornado reports shown in Texas are not in the SPC logs but were observed by the VORTEX2 armada.

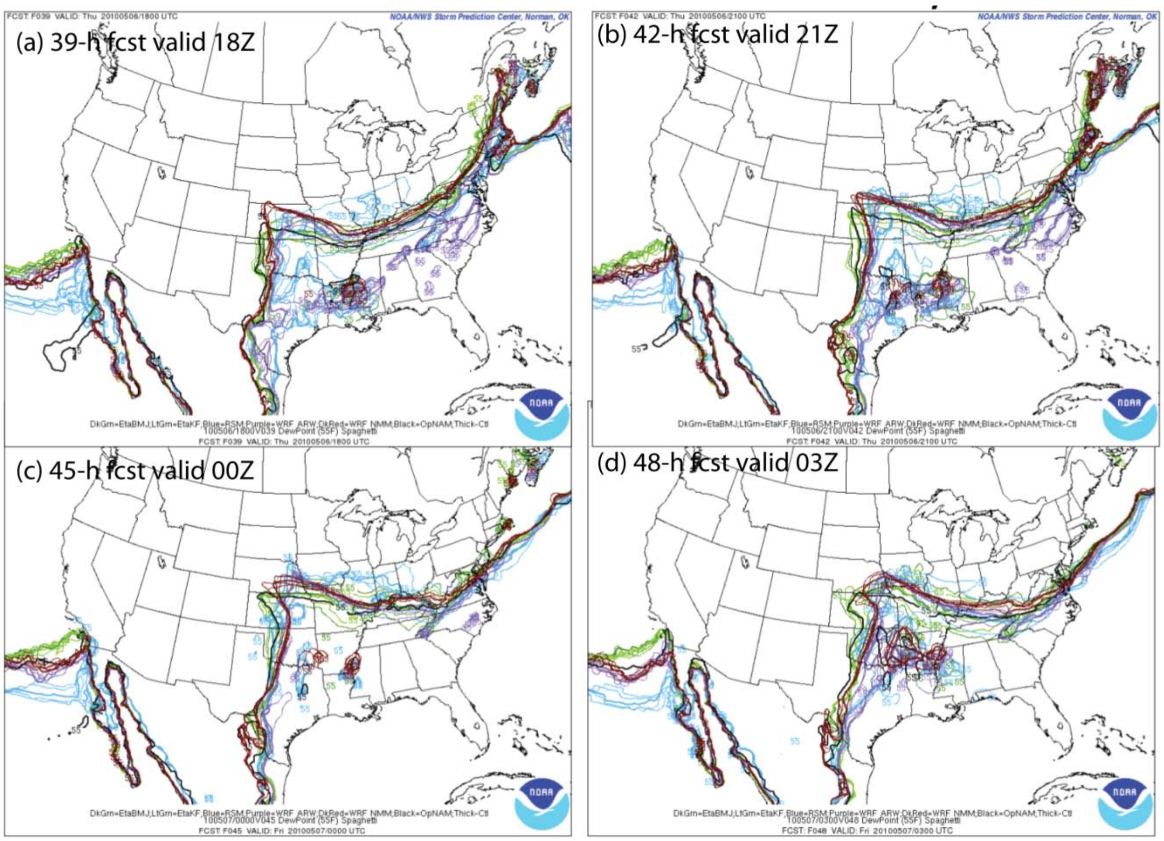

Figure 4. Example of a SREF spaghetti plot shown in the weather briefing the morning of 5 May 2010. Displayed are the forecasts of the 55 °F isodrosotherm for the 21 SREF members (green lines are the Eta members, purple lines are the WRF ARW members, red lines are the WRF NMM members) and the 00Z operational NAM forecast (black line) for 3-hourly periods valid 18 UTC 6 May to 03 UTC 7 May.

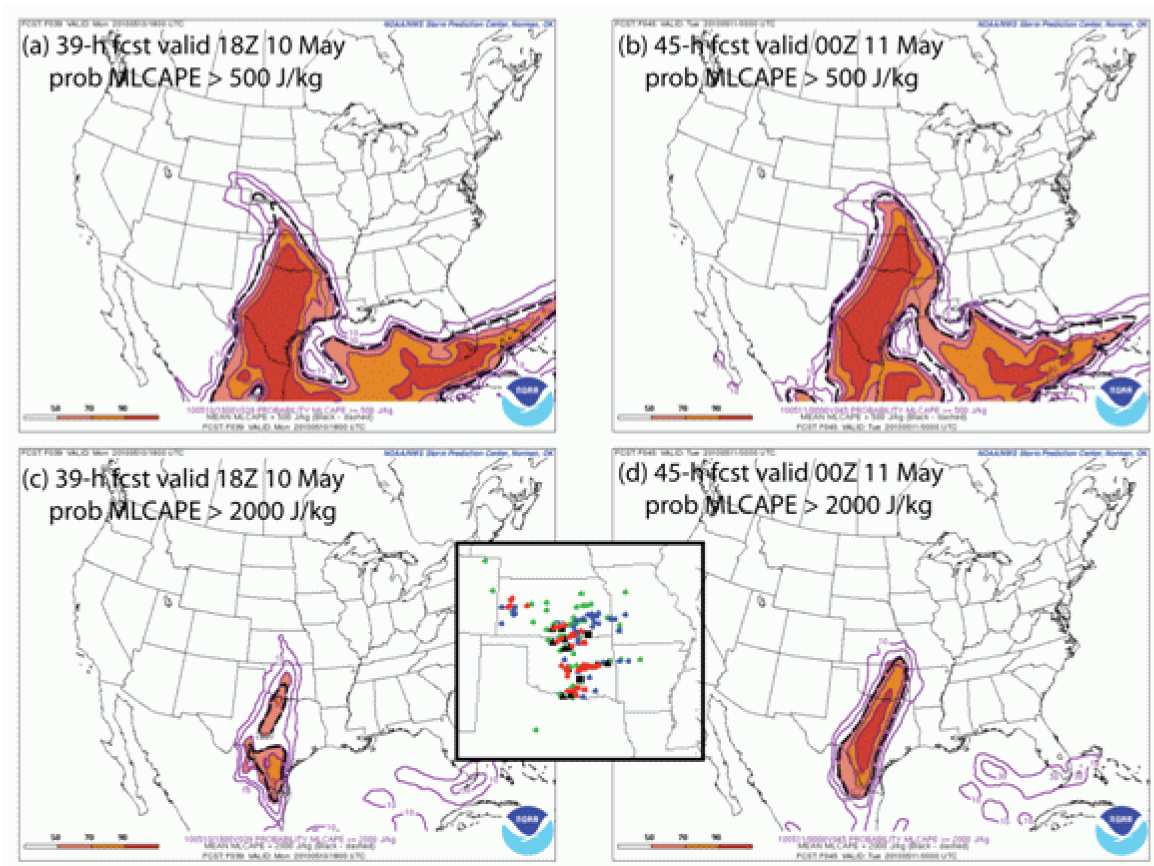

Figure 5. Example of a SREF probability plot shown in the weather briefing the morning of 9 May 2010. Displayed are the forecasts of the probability of mixed-layer CAPE exceeding 500 m^2 s^{-2} (top row) and 2000 m^2 s^{-2} (bottom row) for a 39-h forecast valid 18 UTC 10 May (left column) and a 45-h forecast valid 00 UTC 11 May (right column). Probability values are contoured in purple and are colored filled starting at values > 50% and the contour for the mean MLCAPE equal to each threshold is shown by the black dashed line. Inset: the preliminary severe weather reports received at the SPC for the period 12 UTC 10 May to 12 UTC 11 May.

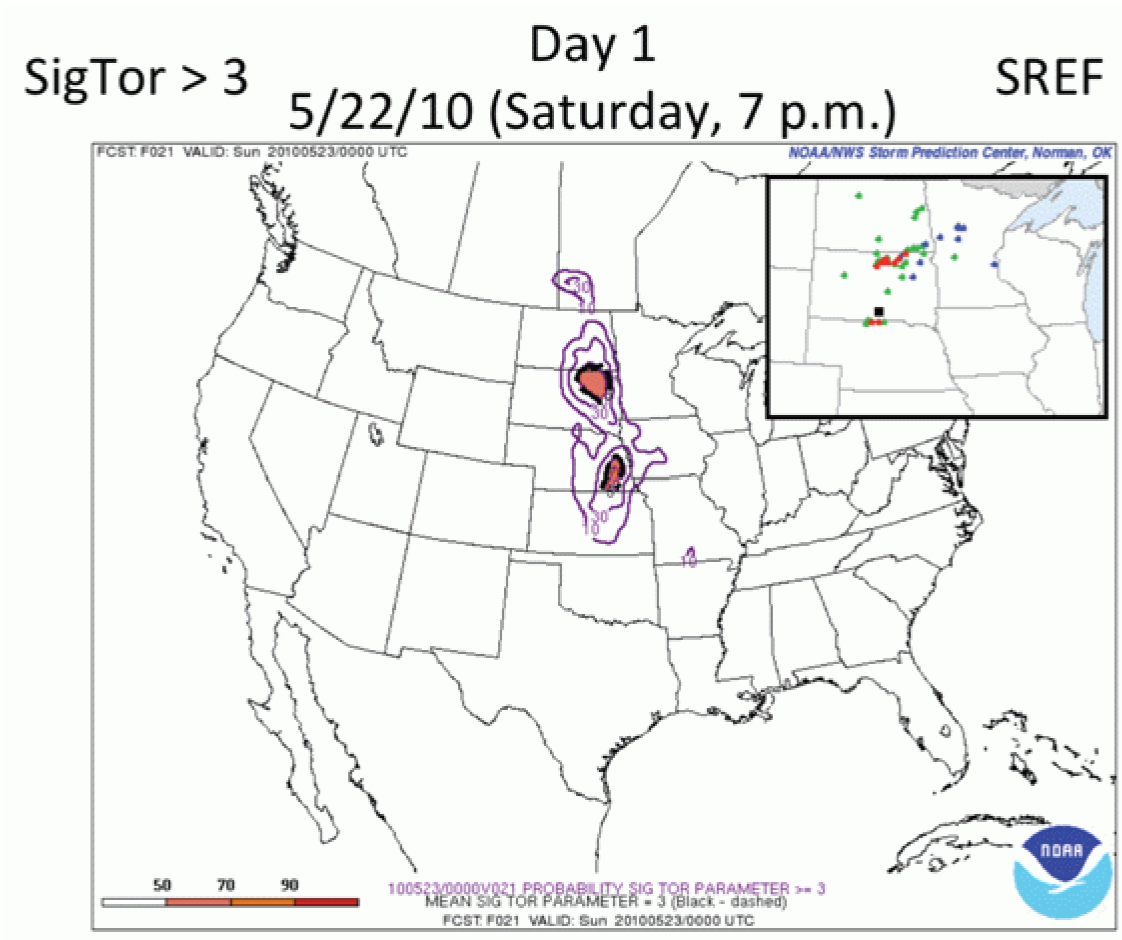

Figure 6. Example of a SREF probability plot shown in the weather briefing the morning of 22 May 2010. Displayed is the probability of the significant tornado parameter (STP) (Thompson et al. 2004) exceeding three (purple lines with values > 50% filled in orange) and the contour for the mean STP = 3 (black dashed line) for a 21-h forecast valid 00 UTC 23 May 2010. Inset: The preliminary severe weather reports received at the SPC for the period 12 UTC 22 May to 12 UTC 23 May 2010.

Most of the variables could be categorized into four categories, including standard variables (e.g. 500 hPa height/winds, 700 hPa temp), instability-related variables (e. g. lapse rate, CAPE), vertical-shear-related variables (e.g. SRH, bulk shear), and accumulated precipitation. Other derived variables not included in these four categories were also used occasionally, such as the supercell composite parameter (SCP) (Thompson et al. 2004) and calibrated severe thunderstorm probabilities (Bright and Wandishin 2006).

Mean or median standard variables were used most often among all of the types of fields available in the SPC SREF output. The mean or median variables, as well as the spaghetti plots, most often consisted of standard meteorological variables such as 500 hPa heights (Figs. 2a and 2c), whereas the probabilities of instability, shear, and accumulated precipitation above a certain threshold were used more often than the probabilities for the standard variables (Fig. 2b).

An overlay of the variables that compose the SCP was frequently used for Day-2 to Day-4 forecasts. Fig. 3 shows an example of a 69-h forecast valid 00 UTC 15 May 2010 that was used in the briefing the morning of 12 May 2010. Overlays of these ingredients highlighted southeast New Mexico and west Texas as a potential target area for Day-3 operations. Other SREF fields, such as a spaghetti plot of the 700 hPa +10 C isotherm and the probability of 3-h total precipitation $\geq$ 0.01 in (not shown), suggested a weak cap and that convection was likely to occur. The forecast guidance was helpful since widespread supercells and a few tornadoes were observed in this area the afternoon and evening of 14 May 2010 (inset Fig. 3).

Isodrosotherms were often examined in spaghetti plots (see Fig. 3 for an example) to help diagnose the uncertainty in low-level moisture return and compare the SREF members to the operational NAM forecast of moisture (black line in Fig. 4). Fig. 4 reveals a characteristic of the SREF, that the members tend to cluster by model type (Yussouf et al. 2004) and also illustrates a finding that the WRF-NMM members were often more moist than the other members and were often too early with the northward return of moisture across the southern and central Plains.

Probability plots were commonly used for a wide range of variable types. For example, the probability of MLCAPE exceeding a given threshold was used on several days. Thresholds of MLCAPE of 500 m^2 s^{-2} and 2000 m^2 s^{-2} for 39 and 45-h forecasts valid at 18 UTC 10 May 2010 and 00 UTC 11 May 2010 were used in the Day-2 forecasts the morning of 9 May (Fig. 5). These plots were used to help diagnose the northward extent and width of the warm-sector that was expected to return rapidly northward over the southern Plains on 10 May.

Probability plots were also used for derived variables, like the significant tornado parameter (STP) (Thompson et al. 2004). Plots of the probability of STP $\geq$ 3 for 21 h forecasts valid 00 UTC 23 May highlighted a region in South Dakota very near the region that was affected by a long-lived tornadic supercell that evening (but also highlighted an area in eastern Nebraska that did not see any severe weather in the valid time period) (Fig. 6).

2.2 Operational Models

The Operational 12-km resolution NCEP North American Model (NAM) or Weather Research and Forecasting Model – Non-Hydrostatic Mesoscale Model (WRF-NMM) (Rogers, et al., 2009) was used for all 53 Day One forecasts and the majority of Day Two forecasts. A primary reason was the 12 UTC run of the model had the latest data initialization at the time of forecast preparation and presentation. The NAM was generally available on several web sites but the preferred site was Twister Data (http://www.twisterdata.com) because of presentation and consistent timeliness of updates. The forecast fields used were those that characterized supercell parameter space, i.e., instability and deep layer shear. Within geographic areas that appeared to have favorable instability and shear, forecasters used the NAM fields that gave further insight into convective initiation, cap strength, low level instability and low level shear. Model data from the nine hour and twelve hour forecasts (valid times of 21 UTC and 00 UTC) were of greatest interest for the Day One forecasts. Instability was assessed by using the model forecast of CAPE and the capping strength was estimated from model CINH and temperatures at 700 hPa. The fields most frequently used to assess shear were the forecast winds and geopotential height at the surface and 850, 700, 500, 300 and 250 hPa. The vector wind difference between the surface and 500 hPa was used as a proxy for the deep layer (0-6km) shear.

GFS model

The Operational National Center for Environmental Prediction (NCEP) Global Forecast System (GFS) models was used in a majority of Day One forecasts and all of the Day Two and beyond forecasts during the experiment. For the most part the forecasters used the same model fields as used from the WRF to assess the forecast supercell parameters. The GFS use in Day One forecasts was generally to show consistency with the WRF or, in a few cases, to demonstrate significant differences between the two model forecasts. Forecasters relied upon the GFS for initial guidance for determining the location of likely supercell environments for the next several days. Those forecasts were used mainly to decide where to move the armada following Day One operations.

Other Synoptic-Scale Global Models

Primarily for interest of Day-2 and beyond, the forecasters utilized other global model products and ensembles from other operational centers. These included the North American Ensemble Forecasting System (NAEFS) from Environment Canada and the European Center for Medium Range Weather Prediction (ECMWF) model (images of a few standard meteorological variables from public web sites, such as the College of DuPage NexLab http://weather.cod.edu/).

2.3 Convection-Allowing Model Output

CAPS 4-km Ensemble

Ensembles run by CAPS on Athena at the National Institute for Computational Science (NICS) in Oak Ridge, Tennessee. The 4-km ensembles consist of 19 WRF-ARW (Skamarock et al., XXXX) members, 5 WRF-NMM (Janic' et al., XXXX) members and 2 ARPS (Xue et al., 2001, Xue et al., 2003) model members, for a total of 26 members using a total of 4488 cores of Athena (Xue et al., 2010, Kong et al., 2010). The runs were made once-daily Monday through Friday for the Spring Experiment at the Hazardous Weather Testbed (HWT) in Norman, Oklahoma, initialized at 00 UTC and generally completed by 09-10 UTC. Ensemble products from the suite of model runs were generated by CAPS from the individual runs and usually available on the web by 12 UTC.

http://www.caps.ou.edu/~fkong/sub_atm/spring10.html

As with the SREF output popular ensemble products were probabilities of various severe weather environment variables, but also modeled storm characteristics. The convection allowing models allowed for a look at the probabilities of echo top heights above key levels, such as 35 kft, probabilities of reflectivity above 35 dBZ, and probability of maximum updraft helicities in the preceding hour. The source website allowed looping of these fields and the forecasters often selected one or more key times in the afternoon to show ensemble probabilities of these key values and their forecasted progression through the late afternoon and evening.

CAPS 1-km CONUS Model

For the first time ever a real-time 1-km grid resolution model covering the entire CONUS was run in real time by CAPS for the HWT. The WRF ARW model was run on 12,800 cores of Athena at NICS. This model was initialized at 00 UTC five days a week, Monday-through-Friday, using standard surface and upper-air observations plus NEXRAD Doppler radar reflectivity and wind data. Model output graphics available on the Internet included standard model heights and temperature as well as forecast reflectivity and updraft helicity.

http://www.caps.ou.edu/wx/hwt/

CAPS 4-km VORTEX2 Domain Model

Seven days a week, a 4-km model run covering the VORTEX2 domain was produced at 09, 12, 15 and 18 UTC on the OU Supercomputing Center for Education and Research (OSCER) Sooner supercomputer. The 09 UTC model run was usually available by briefing time, and the 15 and 18 UTC model runs available by mid-day and often included in a mid-day modeling summary sent to the PI's in the field. These runs benefitted by having day-of-the event surface and radar data included in the initialization.

High Resolution Rapid Refresh

The high resolution rapid refresh (HRRR; see http://ruc.noaa.gov/hrrr/)is a 3-km version of the WRF-ARW core initialized with the Earth System Research Laboratory/Global Systems Division (ESRL/GSD) rapid refresh analysis system. The version of the HRRR used in 2010 was initialized with the latest 3-d radar reflectivity on a 13-km grid via the digital filter initialization technique. A full CONUS domain was used for the simulations in 2010.

NSSL 4-km WRF-ARW

Since 2007, NSSL has been running a CONUS WRF-ARW core simulation with a 4-km horizontal grid spacing and the same set of physics packages (see http://www.nssl.noaa.gov/wrf/). The initial and boundary conditions are defined from the 00Z NAM analysis and forecast cycle and the forecast length is 36 h.

NCAR 3-km WRF-ARW

The National Center for Atmospheric Research (NCAR) has also been producing daily WRF-ARW core simulations over a CONUS domain for the past several years at 3-km horizontal grid spacing (http://www.wrf-model.org/plots/realtime_3kmconv.php). In 2010, the simulations used the 13-km RUC from ESRL/GSD for initial conditions and the forecasts from the GFS for the boundary conditions. Simulations were initialized at both 00 and 12 UTC, and output was made available out to 48 h for both cycles.

NCEP/EMC 4-km WRF-NMM

In the fall of 2007, a 4 km version of the WRF-NMM core (Janjic et al. 2005) was implemented in the National Centers for Environmental Prediction (NCEP) High Resolution Window operational run slot. The domain covers the eastern 2/3rds of the CONUS and is run twice daily (at 00 and 12 UTC), with both runs producing forecasts out to 48 h (http://www.nco.ncep.noaa.gov/pmb/nwprod/analysis/).

LEAD-II 1-km Limited Area Model

Linked Environments for Education and Discovery (LEAD) is a project, which, in part, builds and executes complex workflows for weather modeling (Droegemeier et al., 2005). Each morning during the VORTEX2 operating period LEAD-II ran a series of 1-km WRF-ARW runs over a 1000x1000 domain using workflows on a Trident workstation and BigRed, a supercomputer at the Univ. of Indiana, to create a lagged-time-ensemble. The center of the domain was specified by one of the forecasters (KB) and a few products were made available via the web with mobile-phone enabled graphics. Some of the LEAD-II results were used in the mid-day model summaries provided to the PIs, and all of the WRF output is available for research use. http://dataandsearch.org/dsi/vortex2

2.4 Cycles of the Convection-Allowing Models Used

Because the morning weather briefings typically began around 9:30-10am central daylight time (15 UTC), most of the convection-allowing models used in the briefings were initialized with 00Z analyses and forecasts from either the North American Mesoscale (NAM) model or the Global Forecast System (GFS). Given the computational resources needed to produce forecasts out to 24 h on large domains with grid spacing O(1-4 km), output from any runs initialized with data later than 00Z typically could not be made available in time to be used by the morning forecasters. Two exceptions were the hourly-initialized HRRR and the 4-km VORTEX2 Domain ARPS initialized at 09 UTC initialized prior to 11 UTC and the CAPS Advanced Research WRF (ARW) model forecast initialized at 09 UTC.

3 Model Derived Products

There were a few special model-derived products used in the briefings and uploaded model summary materials. They are described in this section.

3.1 Updraft Helicity

The output that was used most frequently from the models for identifying likely rotating storms was simulated radar reflectivity and the updraft helicity (UH) diagnostic described in Kain et al. (2008). Both instantaneous forecasts of UH at hourly intervals and the "hourly-maximum UH" (the display of the accumulation of the maximum UH at every grid point each hour) were used, the latter gauged the occurrence of cyclonically rotating updrafts in the model forecasts on convective time scales (Kain et al. 2010). An example of the UH output from HRRR forecasts the morning of 10 May 2010 is shown in Section 5.1.

3.2 Individual Model Extracted Soundings

Along with examining horizontal contours of various stability and shear indices, the forecasters found it invaluable to plot and examine individual soundings at key points in potential target regions. This was particularly important for examining details in the wind hodograph, depth of low-level moisture as well as perturbation in the temperature profile that might affect vertical acceleration at key levels. The forecasters found interactive websites that allowed on-demand sounding generation to be most useful. One website often used for this product was http://www.twisterdata.com. The NCEP Operational RUC and NAM were most often consulted.

3.3 Model Sounding Ensembles

A new method to visualize ensemble model forecast soundings was developed and used by the forecast team. The kind of visualization to adequately display ensemble soundings was still a relatively new field; however an experimental version of BUFKIT (BUFKIT 2010) became available to visualize ensemble soundings for up to 16 members of the WRF model. Known as the WRFensemble (available at http://wrfensemble.wdtb.noaa.gov), 16 ensemble elements of the 12 km workstation WRF model (STRC 2010) were generated twice daily centered over the V-II domain. The ensemble members were derived from changing the model core between that of the NMM and the ARW, changing convective schemes between Betts Miller Janjic (BMJ; Betts 1986) and Kain Fritsch (KF; Kain 2004), and changing the initial boundary conditions from that of the GFS and the operational NAM. For each ensemble member, a model sounding was generated for multiple locations within the VORTEX-2 domain. BUFKIT was then used to display all of the ensemble members for the entire forecast period at a particular location.

An example of how the WRFensemble was is in the forecast products is described in detail in Section 5.2.

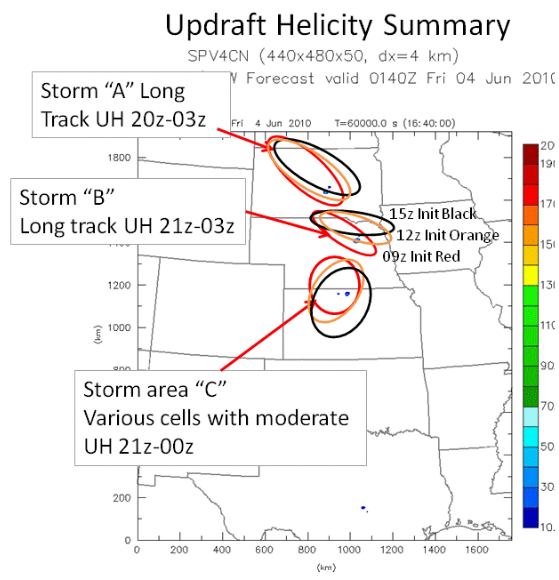

Figure 7 Model Updraft Helicity summary prepared at 18 UTC, 3 June 2010.

3.4 Updraft Helicity Composites

While it is good to have a number of models being run over the domain of interest, summarizing the detailed result of several model runs was challenging, as each might have different convection initiation times and slightly different locations of cells.

For VORTEX2 identifying rotating supercells was key. As mentioned, the morning forecasters and the PI's making tactical decisions leaned on updraft helicity as an indicator of favored storms. In order to summarize the updraft helicity trends and favored areas for rotating storms in a number of the CAPS forecast runs and LEAD-II runs, on many days a graphic was created that showed the general pattern of UH development. This was done manually (by KB) and drawn as an overlay on a single representative model output chart during the time of interest. See Fig 7 for an example from the mid-day update that was produced from the ARPS forecasts from 09 UTC, 12 UTC and 15 UTC and uploaded on 3 June 2010. A similar graphic was prepared in the morning model summary materials based on the convection-resolving runs available at that time. In this case, the set of elongated ovals in extreme northeast Nebraska verified fairly well. A complete summary of the events of 3 June is presented in Section 5.3. It would be useful to develop an objective automated method to annotate a suite of model results in the same way, perhaps beginning with a multi-hour track of local UH maxima.

4 Observations Remain Key

Certainly there was no forecast preparation done without careful analysis using the observed data. However, the time constraints imposed on the forecasters affected which analyses were included in the prepared materials. At the beginning of the project, there was a slightly wider variety of real-time data products presented during the Day 1 briefings. As time went by, the variety of products fell as the forecasters gravitated toward six major types of observations. In terms of number of days a particular product was used, raw surface plots were used 42 of the 45 days of the project.

After surface data, soundings, GOES visible imagery, GOES water vapor imagery, upper-air analysis, and morning radar data were used most frequently as shown in Figure 9. On several days GOES water vapor channel loops were used to track small-scale short waves that are often not well-resolved in the 12 UTC upper-air data and corresponding operational analyses. Morning visible satellite and radar were, of course, used to assess morning precipitation and cloudiness trends, particularly as they might affect mid-day insolation or indicate shortwaves.

Some of the products were hand analyzed, especially the surface data, however most of the upper air plots already contained some kind of basic height, temperature and moisture analysis. Just about all of the products were extracted from popular websites such as the NCAR/RAP site and SPC.

There were some novel products used during the briefings in order to bring up salient points. For instance, a blended precipitable water product was used early in the project to show the state of the Gulf of Mexico moisture return as described by Kidder and Jones, 2007 from http://amsu.cira.colostate.edu/gpstpw/ This is labeled special satellite in Fig. 9. In addition, a stage-IV 24 hour precipitation analysis (Lin and Mitchell, 2005) was presented to highlight potential flooding hazards the armada may experience during operations. http://water.weather.gov

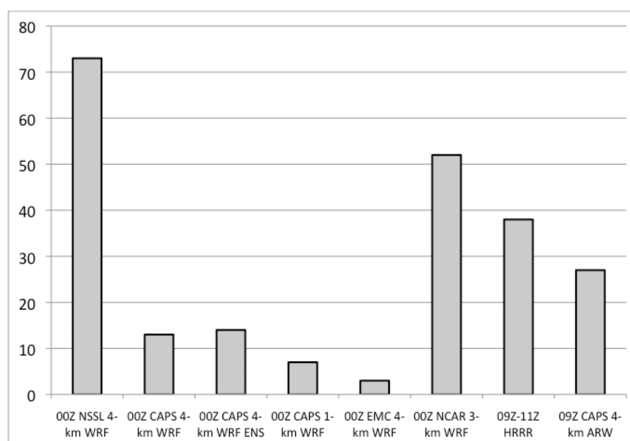

Figure 8. A count of the number of times a high-resolution model forecast product was used in the morning weather briefings. See text for details. The 00Z CAPS 4-km WRF ENS refers to output from the 26-member 4-km WRF ensemble produced by CAPS. See Xue et al. (2010, this conference) .

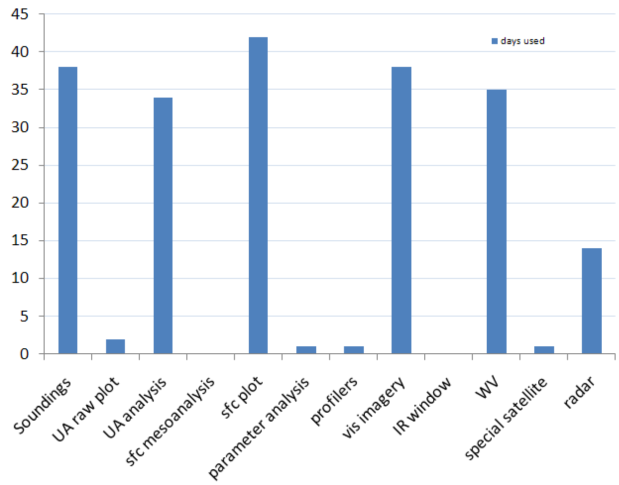

Figure 9. Number of days in the VORTEX2 project that each product was presented in the Day 1 briefings in 2010.

5 Some Forecasting Case Studies

To give some detail of how the information described was utilized and integrated some brief case studies are presented.

5.1 High-Resolution Model Output Used on 10 May 2010:

The potential for a significant outbreak of supercells and tornadoes the afternoon and evening of 10 May 2010 was recognized several days in advance by the VORTEX2 team and the National Weather Service operational centers. However, significant uncertainty about how the event would unfold remained the morning of 10 May 2010, largely because of the uncertainty in the extent of the warm, unstable airmass. Although the return of abundant low-level moisture was expected, it was not clear how far north the moisture would reach and how wide the associated warm sector air mass would become over Oklahoma, given that low cloudiness and light precipitation covered much of the region that morning, which limited the instability initially.

Significant uncertainty in the areal coverage, location, and timing of convection was noted among the suite of 00Z model forecasts for the afternoon and evening of 10 May (Figs. 10-12). The 00Z NSSL WRF 4-km forecasts suggested initiation between 19 and 20 UTC in northwest Oklahoma and southwest Kansas, with storms moving rapidly to the east-northeast and a few less-intense storms initiating a little further south along the dryline into central Oklahoma a few hours later and moving into northeast Oklahoma by 00 UTC (Fig. 10). The 00Z NCAR WRF 3-km forecasts were similar to the 00Z NSSL forecasts, but produced many more significant long-lived storms from central Oklahoma southward all the way to central Texas after 22 UTC (Fig. 11). The 00Z CAPS ARW 4-km forecasts produced the fewest storms among all of the 00Z convection-allowing models examined that morning (Fig. 12), with no significant long-lived storms forecast in Oklahoma and weaker convection forecast in southern Kansas. The uncertainty in these 19 – 25 h explicit forecasts of convection for the 10 May 2010 event was also seen on many other days and illustrates a finding that significant uncertainty was still present among the 00Z model guidance even on the more “synoptically-evident” severe-weather days.

The 09Z CAPS ARW run also showed a lack of strong, long-lived convection in the forecasts (Fig. 13). Examination of the forecast of the environment from that solution along with observational trends showed that the model was likely not forecasting the northward extent and width of the warm sector air mass accurately and is the reason that the 00Z and 09Z CAPS ARW solutions were not given much weight in the final forecast. Confidence in the scenario with a significant number of storms increased that morning upon an examination of the 10Z HRRR run (Fig. 14). This forecast suggested a wider warm sector would spread over much of Oklahoma by 21 UTC, along with a few, strongly-rotating storms spreading across south central Kansas between 19 and 22 UTC and even stronger storms spreading across central and northeast Oklahoma between 22 and 01 UTC (Figs. 14 and 15).

Several tornadic supercells indeed occurred this day (see inset of Fig. 5), with the 00Z NCAR 3-km WRF solution and 10Z HRRR forecasts providing, arguably, the best guidance, as many storms developed as far south as the Oklahoma/Texas border (which was not anticipated) and the most significant supercells of the day occurred in central Oklahoma (but occurred about 2-3 counties to the south and initiated about an hour earlier than suggested in the forecasts). The use of the morning HRRR solution in the final forecast on 10 May was typical of many other days during VORTEX2; the HRRR forecasts in the 09Z-11Z runs seemed to be given more weight than the other model solutions.

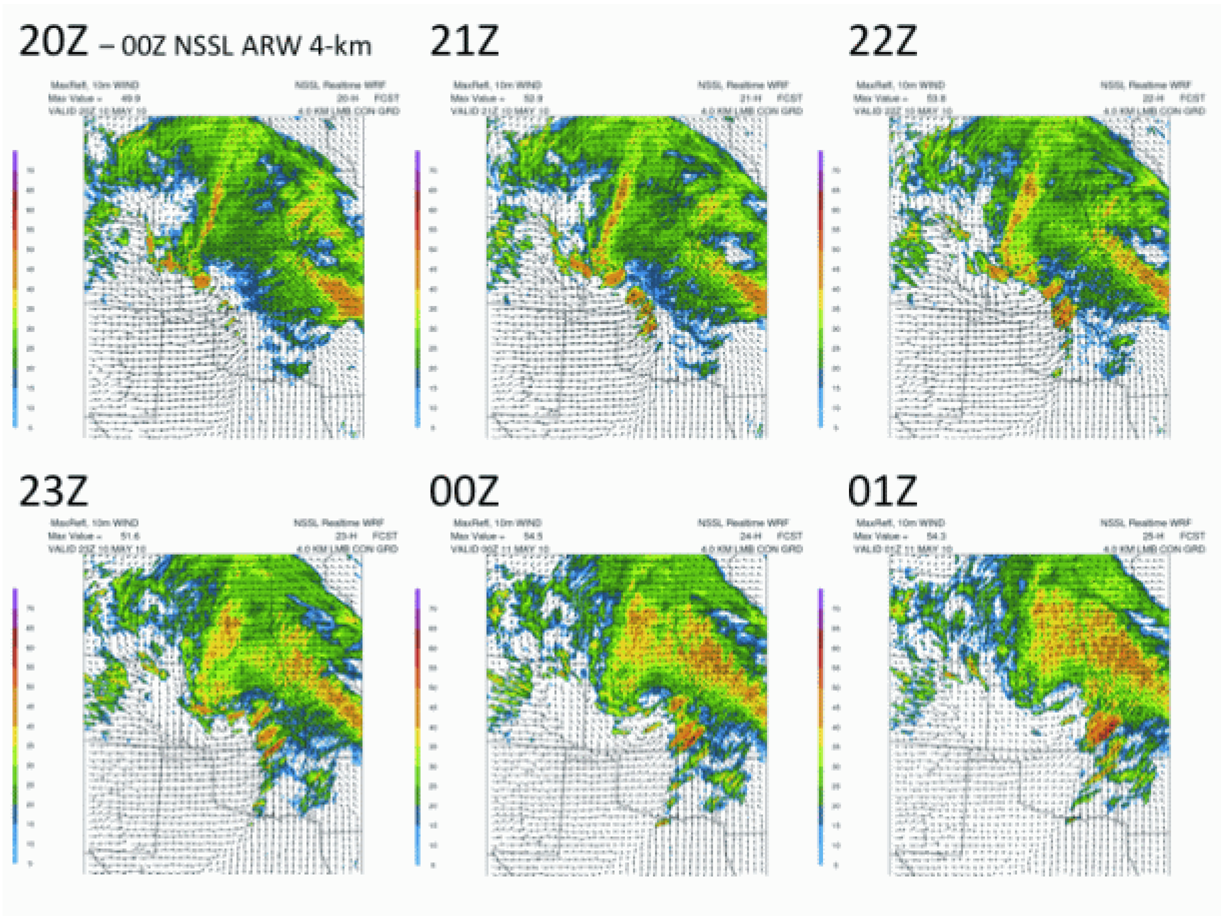

Figure 10. Forecasts of the maximum 1-km reflectivity over the previous hour for the afternoon and evening of 10 May 2010 from the 00Z initialized NSSL 4-km WRF forecasts that were shown in weather briefing that morning.

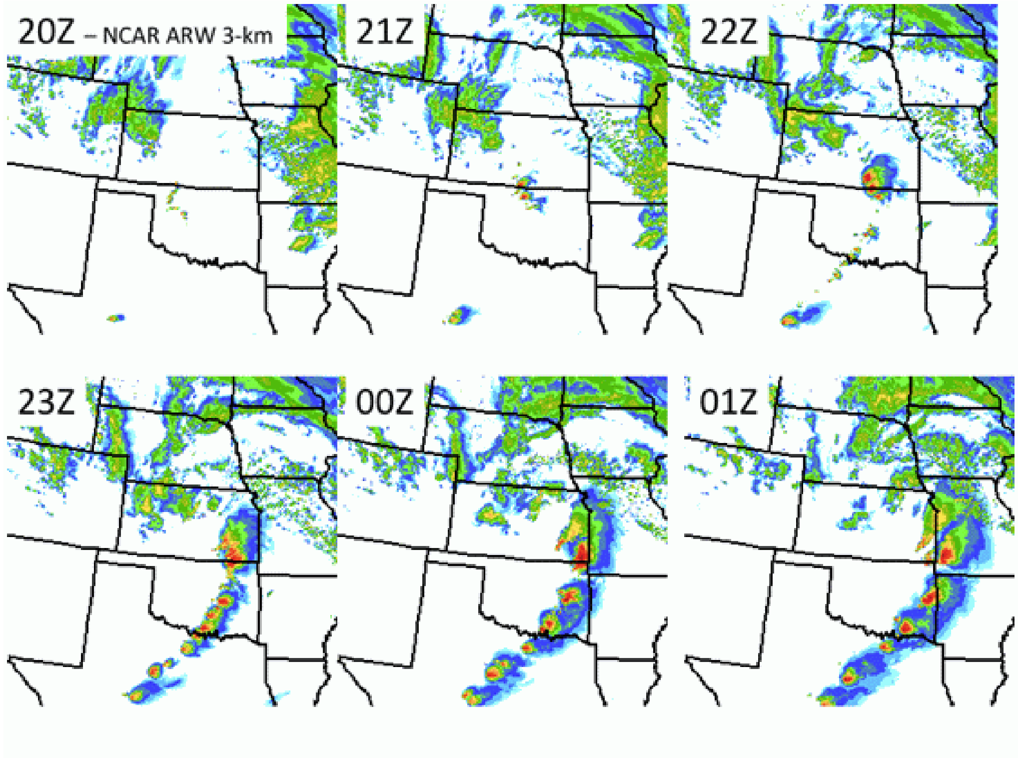

Figure 11. Simulated composite reflectivity for the afternoon and evening of 10 May 2010 from the 00Z initialized NCAR 3-km WRF run that were shown in the weather briefing that morning.

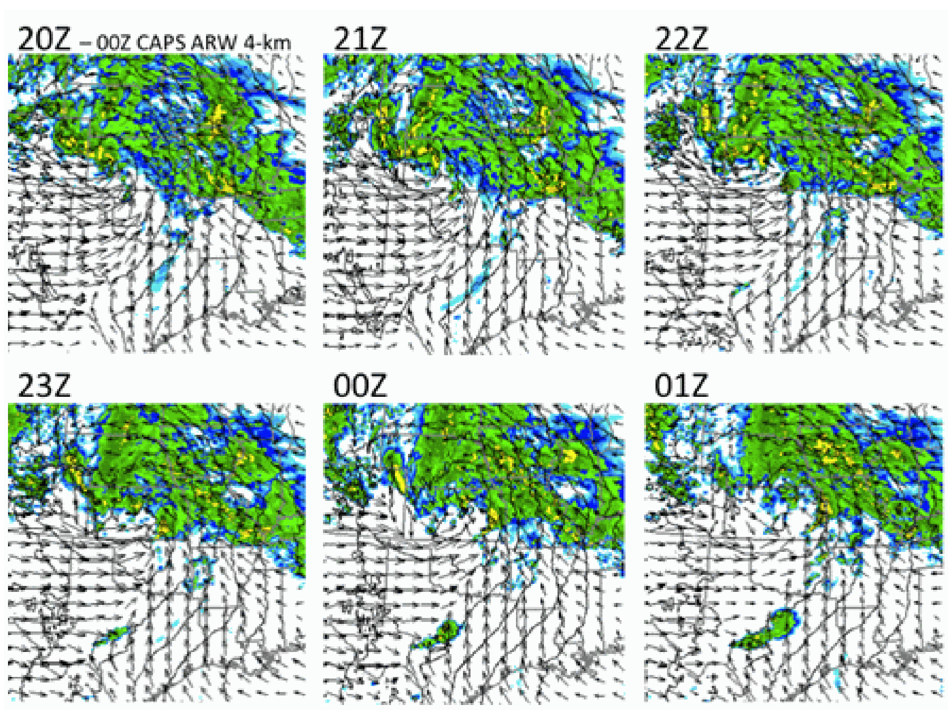

Figure 12. Simulated composite reflectivity for the afternoon and evening of 10 May 2010 from the 00Z initialized CAPS 4-km ARW WRF forecasts that were shown in the weather briefing that morning.

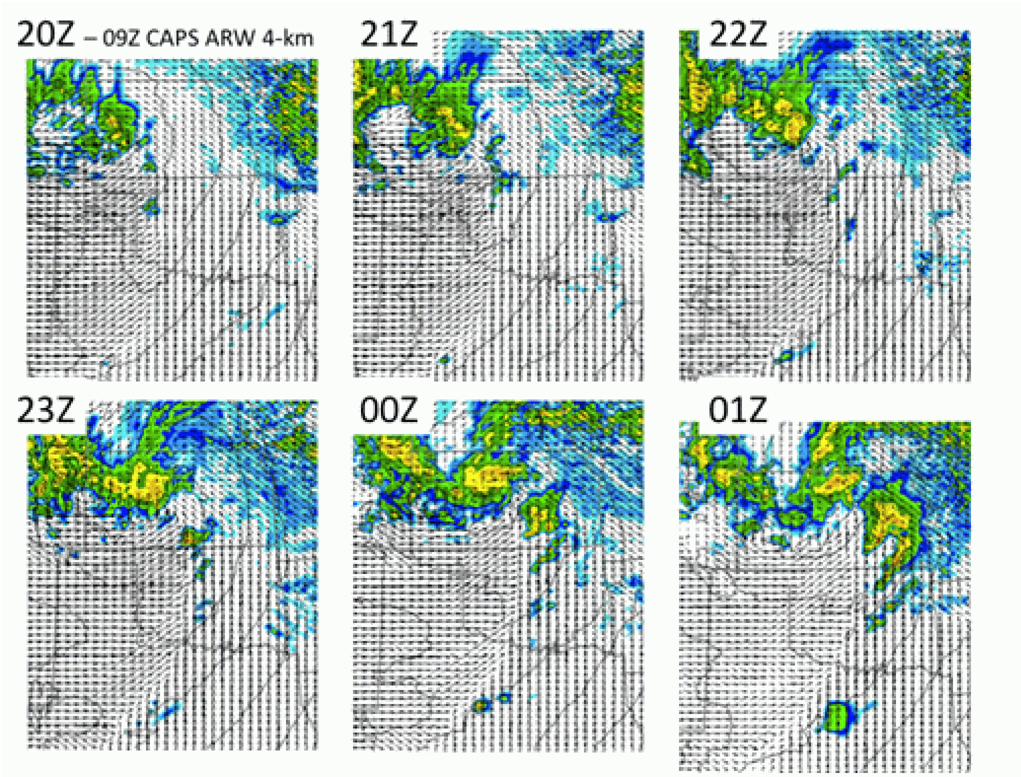

Figure 13. Simulated composite reflectivity for the afternoon and evening of 10 May 2010 from the 09Z initialized CAPS 4-km ARW WRF forecasts that were shown in the weather briefing that morning.

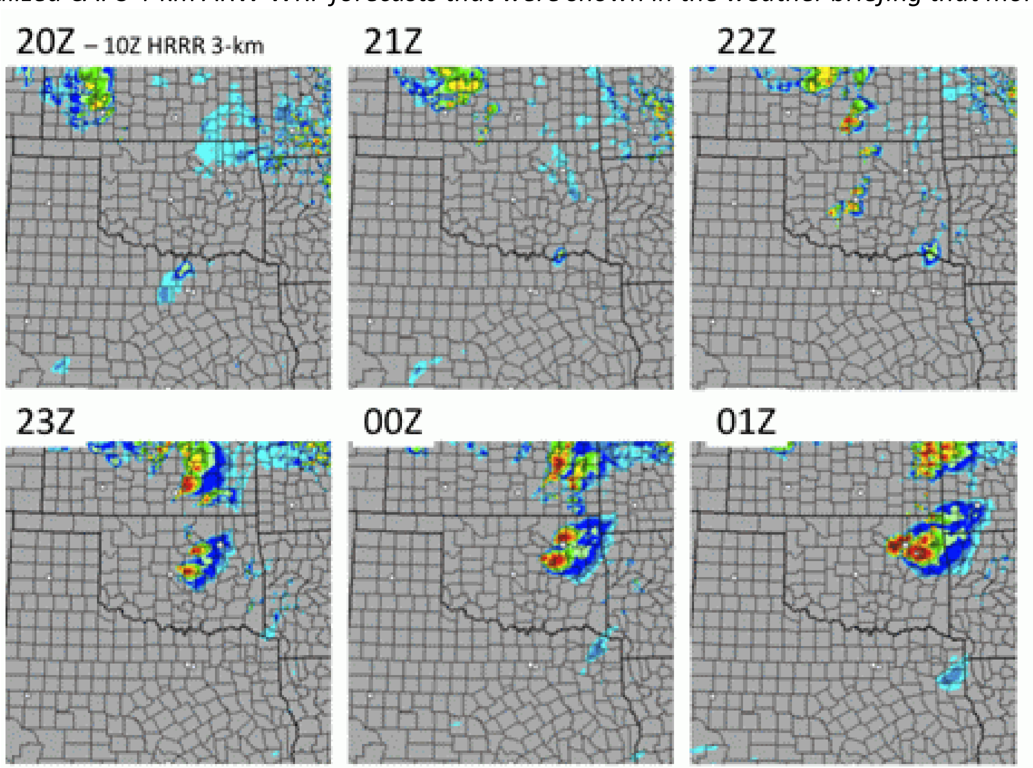

Figure 14. Simulated composite reflectivity for the afternoon and evening of 10 May 2010 from the 10Z initialized HRRR 3-km forecasts that were shown in the weather briefing that morning.

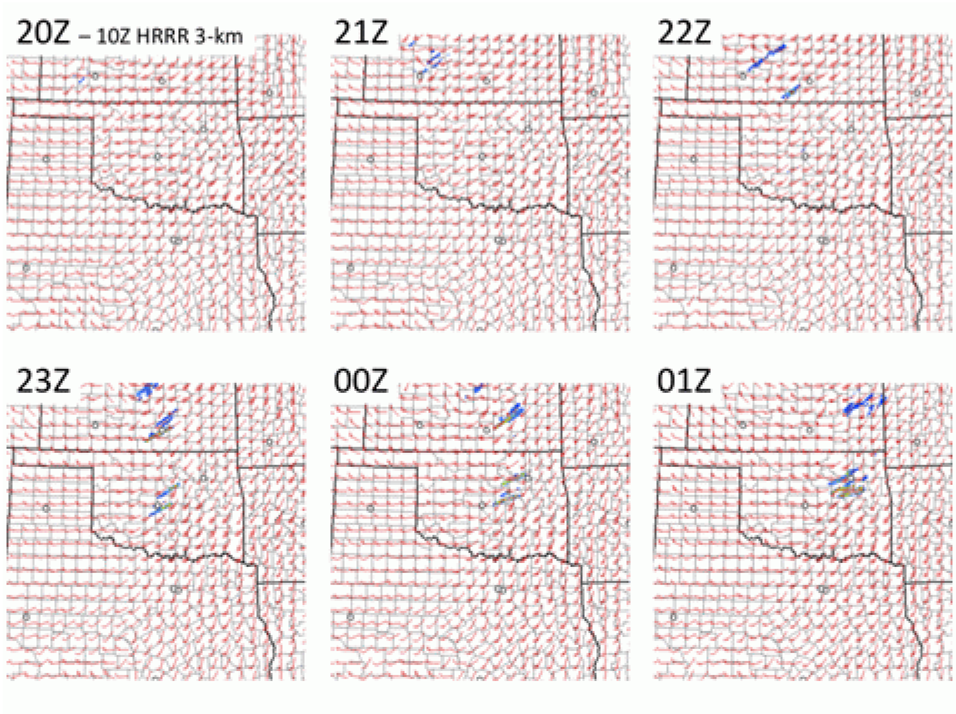

Figure 15. Forecasts of the maximum updraft helicity over the previous hour for the afternoon and evening of 10 May 2010 from the 10Z initialized HRRR 3-km forecasts that were shown in weather briefing that morning.

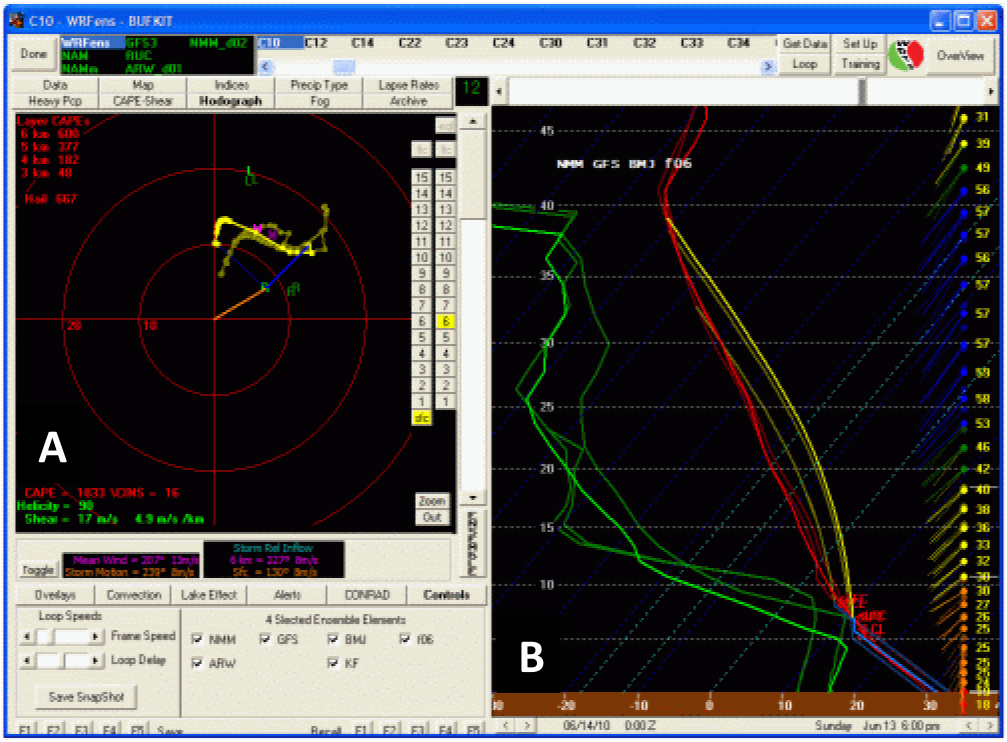

Figure 16. WRF ensemble sounding valid for Plainview, TX at 00 UTC 14 June 2010. There are four ensemble elements on display. The hodograph is displayed in panel(A). In (A), the element highlighted in the brighter color is associated with the parameters on display in the lower left and upper left side. The mean convective layer steering wind for the lowest 6 km is labeled 'M' for each element. In addition, the right (left) moving supercell motion is labeled as 'R' ('L') for each element. The dark blue lines represent the storm-relative flow for the upper and lower bounds of the displayed wind profile. These bounds are highlighted on the left side. In the Skewt in panel (B), the details of the ensemble element are shown in white text at the top of the Skewt plot. The parcel ascent curves in the Skewt represent the MLCAPE for each ensemble element. The LFC and LCL are plotted for each element, as are the wind vectors on the right side. However the wind vector labels are only plotted for the highlighted ensemble element. The height labels are in kft AGL.

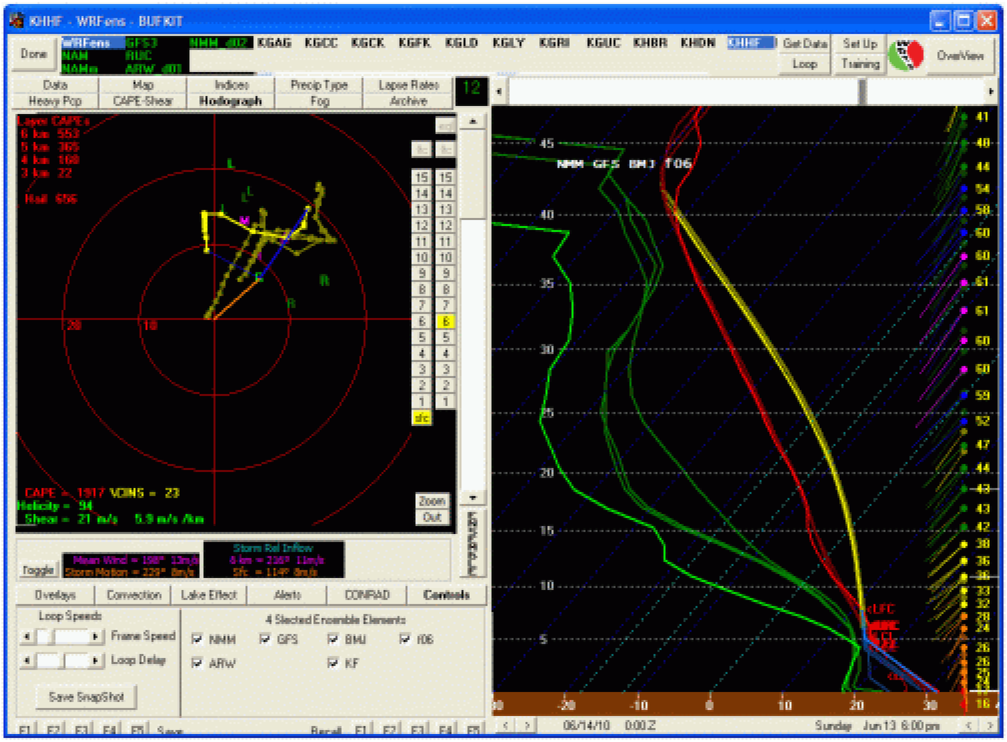

Figure 17. Similar to Figure 16 except for Canadian, TX.

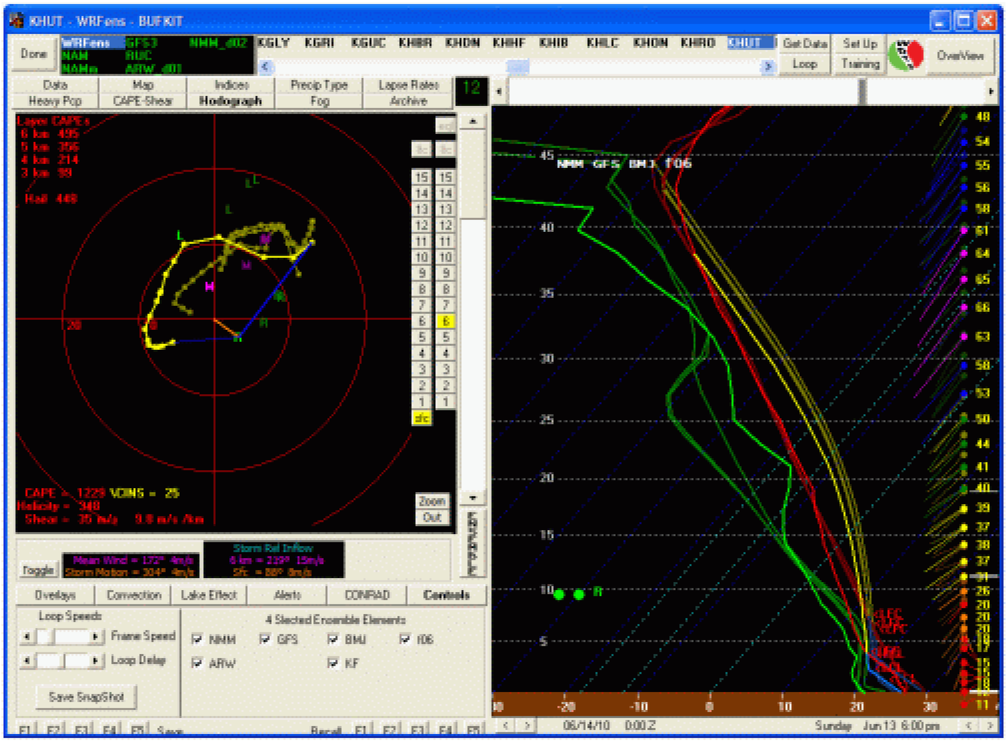

Figure 18.   Similar to Figure 16, except for Hutchinson, KS.

5.2 Use of WRFensemble Products 13 June 2010

To examine how the WRFensemble was used in the forecast process, we discuss an operations day from 13 June 2010. The morning of June 13 featured the same stationary front that produced the storms for which VORTEX2 operated on from the previous day but this time there was a much stronger dryline evident in the morning observations in the western TX Panhandle. In addition, the mid- and upper-levels featured a likely shortwave trough embedded in large scale cyclonically curved flow with a stronger wind speed maximum coming out of NM. The morning convection was quite vigorous in central KS relative to the previous day and this complex led to a substantial outflow boundary that appeared initially to be intersecting the front in southwest KS east of DDC. At the time of the forecast preparation, the operational NAM and the RUC were forecasting a dryline with strong, deep convergence and an intersection with the front just north of Amarillo with likely convective initiation to occur in this vicinity.

An understanding of the model's confidence in thermodynamics and shear in the two areas of interest would help decide which target VORTEX2 would ultimately choose, ahead of the dryline in the eastern TX Panhandle or northeast to where the outflow boundary intersected the front in southwest KS. . To evaluate such confidence, we decided to utilize the WRF ensemble forecasting system. On this day, several soundings were selected ahead of the dryline and front. A representative sounding along the dryline was taken from Plainview, TX (Fig. 16) and it showed a deep, mixed boundary layer with little inhibition and steep lapse rates above the LFC. However, the low-level shear was too weak for a significant threat of mesocyclonic tornadoes. Further northeast, another sounding Fig. 17) taken from Canadian, TX showed a boundary layer with higher RH and a little more CIN. All the models agreed with this thermodynamic scenario. However, the low-level shear proved to be still weak, except for the NMM core with the BMJ precipitation scheme where the hodograph (yellow) showed a considerably stronger low-level shear profile, backed low-level winds and thus, stronger deep layer shear too. Finally a sounding taken well within the cold pool taken at Hutchinson, KS showed most ensemble elements with strong low-level and deep-layer shear even though the CIN was stronger (Figure 18).

Further analysis showed that in fact the outflow boundary did extend further southwest than the Hutchinson, KS sounding and it intersected just south of Liberal, KS where the VORTEX2 armada was located for the night. The intersection point was also an area that the 11 UTC 11 hour HRRR, and the 00 UTC 22 hour NSSL WRF run produced a broken line of convection oriented to the northeast, along the primary synoptic front. These runs also indicated some of this convection would contain significant updraft helicity near and just northeast of where the OFB was intersecting the front. Based on all the evidence that we discussed in the briefing, the VORTEX2 armada chose a target in the northern TX Panhandle. The ensembles helped to show that large hodographs may have extended as far southwest as Canadian, TX.

5.3 JUNE 3, 2010 CASE STUDY

The forecast issued at 1416 UTC on 3 June 2010 was for supercells to form in eastern South Dakota by 0000 UTC, between Huron and Mitchell and move east-southeastward (Fig. 19). The target town was Chamberlain on Interstate 90. That morning, there was a surface low between Chadron and Valentine, Nebraska. Dry surface air remained over the target area. However, surface dewpoints of 15 to 16 C were located in southern Iowa and northern Missouri and southeast surface winds were expected to transport this moisture northwestward, up the Missouri River Valley. A concern for the initiation of deep convection was the extensive cirrus cloud deck over the area which thickened to the north and west of the target area due to an approaching short wave. The nearest sounding to the target town was at Aberdeen which showed a pronounced thermal inversion just above the surface that would mix out during the day.

There was marginal deep layer speed and directional shear for tornadoes, with relatively weak flow between 850 and 600 mb.

The NAM, GFS and RUC models moved the surface low to central South Dakota by 0000 UTC. All three models increased the dewpoints over the target area to greater than 15 C and had forecasted CAPES around 2000 j/kg. Also, all three models kept the surface winds backed to the southeast over the target area. The 1630 UTC forecast by the Storms Prediction Center (SPC) was for a slight risk of severe storms with a five percent chance of tornadoes in the target area.

The 24 hour GFS precipitation forecast valid 0000 UTC showed isolated signals of light precipitation in southeast South Dakota. However, the 12 hr NAM forecast, valid for the same time, had convection farther to west, in south-central South Dakota and northern Nebraska. The 10 hr HRRR composite reflectivity forecast agreed with the GFS with isolated cells developing in southeast South Dakota by 0000 UTC (Fig. 20). SPC had issued a severe thunderstorm watch (number 253) for eastern South Dakota and northeast Nebraska valid at 2300 UTC (Fig. 21). Deep convection did develop about 30 km south of Chamberlain around 2300 UTC and the Vortex II armada conducted operations on a non-tornadic, HP supercell.

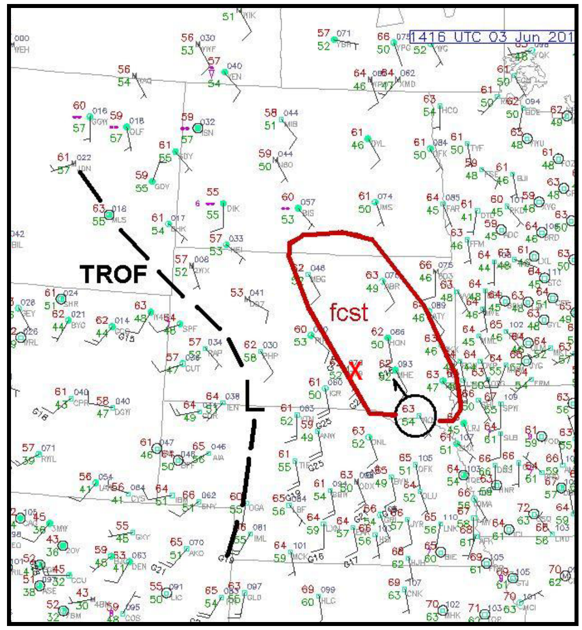

Figure 19. Surface weather map for 1416 UTC on 3 June 2010 with target forecast indicated. The station with the highest temperature and dewpoint is circled.

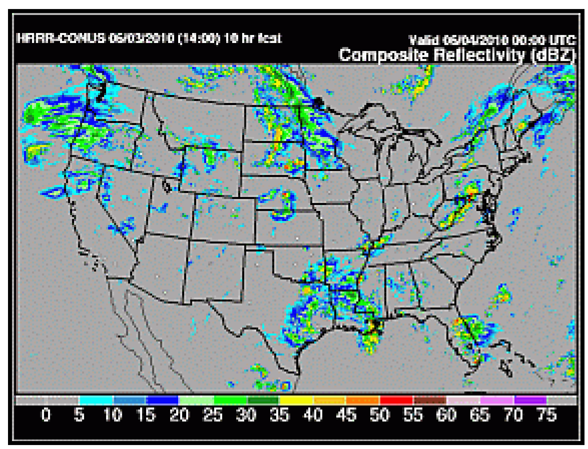

Figure 20. HRRR Composite Reflectivity forecast for 0000 UTC showing isolated convection in southeastern South Dakota.

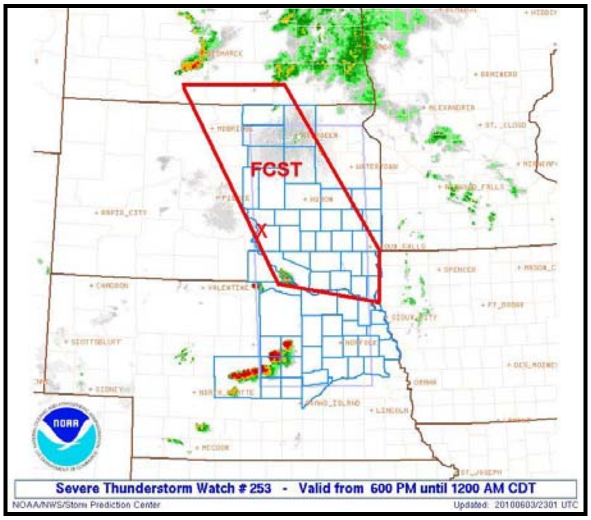

Fig. 21. Severe thunderstorm watch issued at 2300 UTC with the initial radar overlaid with the morning forecast.

5.4 JUNE 4, 2010 CASE STUDY

The forecast issued at 1300 UTC on 4 June 2010 was for supercells to form in northwest Missouri by 0000z and move southeast into hilly and forested terrain (Fig. 22). The target town was Nishnobotna along Interstate 29. That morning, a short wave had lifted up into Canada with a trailing, weak cold front extended southward through central Minnesota and central Iowa. The cold front curved westward and became stationary along the Kansas-Nebraska border. A large cold pool had been generated by ongoing convection over Minnesota. Warm temperatures and high dewpoints were in place south of the front where dewpoints reached 19 C in northern Kansas and Missouri. However, surface winds were veered substantially. Clear skies remained over the target area but there was concern over isolated storms that had developed west of Topeka by 1200 UTC. The morning sounding at Topeka showed a thick capping inversion with weak west-northwesterly flow between 850 and 600 mb. The 1630 UTC forecast by the SPC was for a slight risk of severe storms extending east of a Lincoln to Topeka line to the East Coast with a two percent chance of tornadoes in the target area.

The 18 hr NAM forecast, valid at 0000 UTC, had strong west winds aloft with a 120 knot jet at 250 mb extending across the Dakotas and Minnesota, behind the surface front, and 50 kts at 500 mb. Winds weakened to 20 kts at 700mb. A strong capping inversion was located west of the target area with 700 mb temperatures of 11 C at Dodge City and 12 C at Denver. The NAM had the capping inversion building north and east throughout the day with 10 C or greater temperatures at 700 mb west of an Omaha to Topeka line by 0000 UTC. At the same time, the NAM had forecasted CAPES of 3000 j/kg along the Kansas-Nebraska border. The NAM composite reflectivity forecast had convection east of an Omaha to Topeka line by 0000 UTC, while the 24 hr NSSL WRF, valid for the same time, had a line of convection from near Olathe, Kansas to South Bend, Indiana (Fig. 23). The RUC forecast had the precipitation in the same areas as the WRF but was not as aggressive. SPC had issued a severe thunderstorm watch (number 256) at 1955 UTC extending from southeast Nebraska and northeast Kansas eastward to western Illinois (Fig. 24). Supercells did develop about 30 km southeast of the target town with one tornado being reported on a supercell about 60 km east of the target town.

However, the PIs elected not to operate outside the VORTEX2 domain in a difficult area for radar deployment (due to hills and trees). Therefore, the consensus opinion was to head west to Kearney, Nebraska with the hope that storms would develop in western Nebraska. But, Mother Nature had other plans, as the capping inversion prevented deep convection from occurring until a short wave approached the area around 0600 UTC on 5 June 2010.

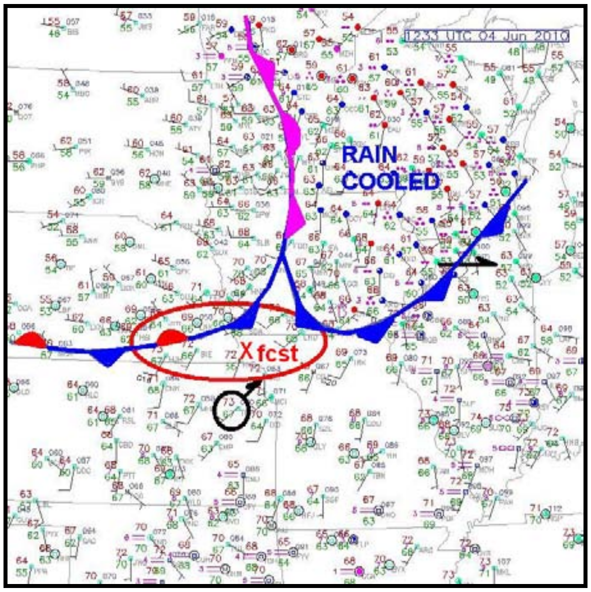

Figure 22. Surface weather map for 1233 UTC on 4 June 2010 with target forecast indicated. The station with the highest temperature and dewpoint is circled.

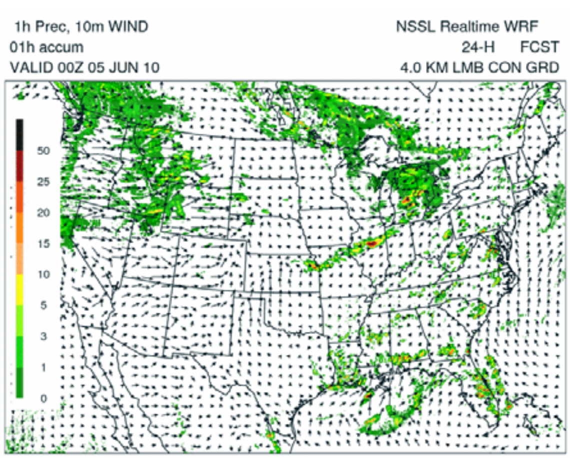

Figure 23. NSSL WRF model one hour precipitation forecast valid 0000 UTC on 5 June 2010 shows a line of convection across northern Missouri with the western edge in extreme northeast Kansas.

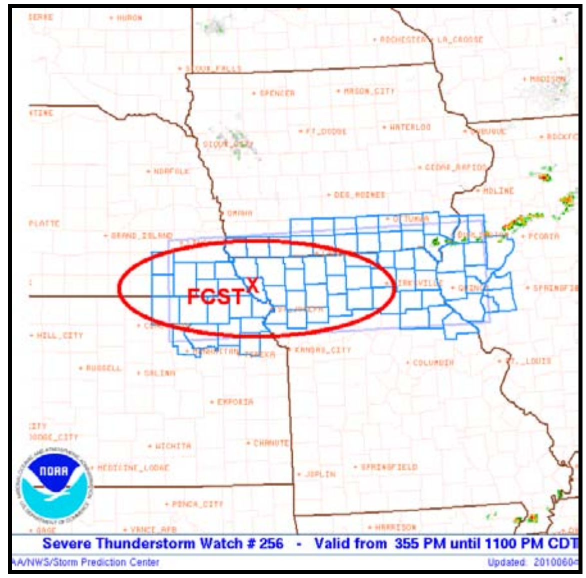

Figure 24 Severe thunderstorm watch issued at 1955 UTC with the initial radar overlaid with morning forecast.

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Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the National Science Foundation, NOAA or the University of Oklahoma.

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