7B.1 An Overview of the 2010 NOAA Hazardous Weather Testbed Spring Forecasting Experiment

Steven J. Weiss[1], Adam J. Clark[2], Israel L. Jirak[1], Christopher J. Melick[1,9], Christopher Siewert[1,9], Ryan A. Sobash[3], Patrick T. Marsh[2,3], Andrew R. Dean[1], John S. Kain[2], Michael Coniglio[2], Ming Xue[3,4], Fanyou Kong[4], Kevin W. Thomas[4], Jun Du[5], David R. Novak[6], Faye Barthold[6], Michael J. Bodner[6], Jason J. Levit[7], C. Bruce Entwistle[7], Russell S. Schneider[1], and Tara L. Jensen[8]

[1]NOAA/Storm Prediction Center, Norman, OK
[2]NOAA/National Severe Storms Laboratory, Norman, OK
[3]University of Oklahoma School of Meteorology, Norman, OK
[4]Center for Analysis and Prediction of Storms, Norman, OK
[5]NOAA/Environmental Modeling Center, Camp Springs, MD
[6]NOAA/Hydrometeorological Prediction Center, Camp Springs, MD
[7]NOAA/Aviation Weather Center, Kansas City, MO
[8]Developmental Testbed Center, Boulder, CO
[9]University of Oklahoma/CIMMS, Norman, OK

1. The NOAA Hazardous Weather Testbed

NOAA's Hazardous Weather Testbed (HWT) is a facility jointly 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 rooms of the SPC and OUN (Fig. 1), and a nearby development laboratory. 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 three primary overlapping program areas (Fig. 2). The first program area focuses on application of cutting edge numerical weather prediction models to improve severe weather forecasts under the auspices of the Experimental Forecast Program (EFP), and the second program tests research concepts and technology specifically aimed at short-fused warnings of severe convective weather under auspices of the Experimental Warning Program (EWP). A key NWS strategic goal is to extend warning lead times under the Warn-on-Forecast (WoF; Stensrud et al. 2009) through the development and application of convection-allowing numerical models to extend short-term predictability of hazardous convective weather. This provides a natural overlap between the EFP and EWP activities, and as the distinction between warnings and short-term forecasts of convective weather gradually diminishes, the degree of overlap is expected to increase. Both programs reside beneath the overarching HWT organization with a focus on national hazardous weather needs.

* *Corresponding author address*: Steven J. Weiss, NOAA/NWS/NCEP Storm Prediction Center, 120 David L. Boren Blvd., Suite 2300, Norman, OK 73072; E-mail: stephen.j.weiss@noaa.gov

In 2009, a GOES-R Proving Ground was established at the SPC to test prototype satellite products from the next generation of geostationary satellites. The mission of the Proving Ground encompasses both warning and forecasting applications for hazardous mesoscale weather and testing and validation activities occur in the EFP and EWP parts of the HWT.

The specific mission of each HWT program branch is:

The Experimental Forecast Program – EFP

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 annual SPC/NSSL Spring Experiments, and will be discussed in more detail in the following sections. An online resource for the EFP is found at http://www.nssl.noaa.gov/projects/hwt/efp/ .

The Experimental Warning Program – EWP

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. For more information about the EWP, see Stumpf et al. (2008, 2010) and http://www.nssl.noaa.gov/projects/hwt/ewp/.

The GOES-R Proving Ground – GOES-R PG

The GOES-R PG exists to provide pre-operational demonstration of new and innovative products as well as the capabilities available on the next generation GOES-R satellite. The overall goal of the Proving Ground is to provide day-1 readiness once GOES-R launches in late 2015. The PG interacts closely with both product developers and NWS forecasters. More information about the GOES-R PG is found in Szoke et al. (2009), Gurka et al. (2010), and http://cimss.ssec.wisc.edu/goes_r/proving-ground.html.

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

In 2010, the EFP operated 7:30 a.m.–4:00 p.m. Monday through Friday during May 17–June 18. More than 70 participants, including operational forecasters, research scientists, academic faculty, graduate students, and administrators from numerous organizations across the United States participated in the HWT (Fig. 3). External visitors generally participated for week-long periods, with several SPC and NSSL forecasters and scientists present through the experiment to provide continuity and training each week. Each weekly team completed a series of daily experimental forecasts and participated in a large range of evaluation and verification activities, followed by daily and weekly wrap-up discussions. The activities were conducted in a collaborative manner, such that results reflected a consensus decision. Appendix A contains the detailed daily operations schedule for the 2010 spring forecasting experiment.

Many of the weekly participants rotated through the activities in each EFP component (severe weather, QPF, aviation) during the week, spending 1–2 days in each section. This allowed participants to experience a broad range of convective storm impacts and forecasting challenges, and to gain a greater appreciation of the challenges faced by operational forecasters and those tasked with creating improved forecast guidance tools.

The following sections provide additional background information about the history of the EFP and motivation for the Spring Experiments, the SPC national severe weather forecasting mission and associated scientific and service challenges, an overview of the scientific goals of the 2010 Spring Experiment and its relevance to operational forecasting, and some preliminary results from the 2010 experiment. More details about the 2010 EFP Spring Experiment are found at http://hwt.nssl.noaa.gov/Spring_2010/, including a large inventory of model forecasts and verifying data used in the daily activities.

2. Historical Perspective of the EFP

Co-location of the Storm Prediction Center (SPC) with the National Severe Storms Laboratory (NSSL), the Oklahoma City/Norman Weather Forecast Office, and many University of Oklahoma meteorological organizations in the National Weather Center in Norman provides a unique opportunity to enhance long-standing community interactions and collaboration on a variety of operationally relevant research and experimental forecast programs. Since the re-location of the SPC to the previous NSSL facility Norman in early 1997, a wide cross section of local and visiting forecasters, research scientists, and model developers has participated in a number of experimental programs since the late 1990s. These include forecasting support for field programs such as the International H2O Project

(IHOP; Weckwerth et al. 2004) and VORTEX2 (Wurman et al. 2010), establishing the SPC winter weather mesoscale discussion product, evaluating operational and experimental NWP models for application in convective forecasting, including Short Range Ensemble Forecast (SREF) systems (e.g., Du et al. 2007, Bright and Wandishin 2006, Homar et al. 2006) and convection-allowing Weather Research and Forecasting (WRF) models (e.g., Weiss et al. 2004, Skamarock 2005, Kain et al. 2008, Weisman et al. 2008, Coniglio et al. 2010), and integrating new observational data, objective analyses (Bothwell et al. 2002), and display tools into forecast operations.

A key goal of these programs is to improve forecasts of hazardous meteorological phenomena by: 1) accelerating the transfer of new technology and research ideas into forecast operations at the SPC and other NWS offices, and 2) sharing new techniques, skills, and applied research results more freely with others in the operational forecasting community. Typical issues addressed in these activities include, but are not limited to: optimizing use of vast and ever increasing quantities of observational and model data in operational forecasting, testing and evaluation of new NWP models, better understanding of operational forecast problems, development and evaluation of diagnostic conceptual models, and new product development and display strategies utilizing operational workstations.

Each spring during the climatologically most intense severe weather period, annual multi-agency collaborative forecasting experiments known as the HWT EFP Spring Experiment (formerly called the SPC/NSSL Spring Program) have occurred since 2000. The only exception was in 2006 when the physical move to the new National Weather Center building precluded a large collaborative experiment. During that spring, SPC conducted a focused internal pre-implementation evaluation of the NCEP NAM-WRF model. Kain et al. (2003a, 2003b) provide a historical perspective on early EFP Spring Experiments.

3. Spring Experiment Background and Motivation

a. Operational forecasting of severe convective storms: Current state and challenges

The prediction of convective weather is important from both meteorological and public service/societal impact perspectives. A primary mission of the National Weather Service is the protection of life and property from hazardous weather phenomena, and applied research aimed at improving the prediction of high impact weather such as severe thunderstorms and tornadoes is a critical activity at the NSSL, SPC, OUN, and other NWS offices.

The SPC is responsible for the prediction of severe convective weather over the contiguous United States on time scales ranging from several hours to eight days. To meet these responsibilities, the SPC issues Convective Outlooks for the Day 1, Day 2, Day 3, and Day 4–8 periods to highlight regions with enhanced potential for severe local storms (defined as thunderstorms producing hail $\geq$ 1 inch in diameter, wind gusts $\geq$ 50 kt or thunderstorm-induced wind damage, and/or tornadoes). These Outlooks are issued in both categorical (slight, moderate, or high risk) and probabilistic formats, using graphical and text products, and are issued with increasing frequency as the severe weather time frame draws nearer. In addition to the scheduled Outlooks, Severe Thunderstorm and Tornado Watches are issued as needed to provide a higher level of alert over smaller regions in time and space when atmospheric conditions are favorable for severe thunderstorms and/or tornadoes to develop. The SPC also issues short-term Mesoscale Discussion products that emphasize hazardous weather on the mesoscale and often serve to fill the gap between the larger scale Outlooks and smaller scale Watches.

The suite of specialized hazardous weather forecast products depends on the ability of SPC forecasters to assess the current state and evolution of the environment over varied time frames, and to synthesize a wide variety of observational and numerical model data sources. In general, observational data play a dominant role in diagnostic assessment for short-term forecasting, however, the development of more accurate and higher resolution models in recent years has allowed model information to influence the short-term prediction of convection as well. This is especially evident in the use of the hourly Rapid Update Cycle (RUC) model (Benjamin et al. 2004), which forms a foundation for the SPC Mesoscale Analysis fields (Bothwell et al. 2002).

An effective NWS severe weather forecast and warning program should provide the public and other specialized users with sufficient advance notice of impending hazardous weather (e.g., Stensrud et al. 2009). Human response studies have shown that when a severe thunderstorm or tornado warning is issued, people are more likely to seek safe shelter if they have been made aware of the severe weather threat prior to the issuance of the warning. However, if they have not been pre-conditioned to the threat prior to hearing a warning, their first response is often to seek confirmation of the threat, rather than to seek shelter. This can result in the loss of critical reaction time when life and property are at immediate risk. Thus, there is a substantial need for the SPC to issue severe weather watches prior to the issuance of warnings by local NWS Weather Forecast Offices (WFOs) in order to allow WFO staffs, emergency managers, broadcast media, etc. sufficient time to implement contingency plans prior to the onset of severe weather.

b. The need for more detailed thunderstorm forecasts

This goal places additional requirements on SPC forecasters to determine in advance the characteristics of potential severe thunderstorm activity. Operational experience and research studies suggest that the type of severe weather that occurs (tornadoes, hail, or damaging winds) is often closely related to the convective mode (or morphology) exhibited by storms, such as discrete cells, squall lines (or quasi-linear convective systems - QLCS), and multi-cellular convective systems (e.g., Gallus et al. 2008, Thompson et al. 2008, Duda and Gallus 2010, Thompson et al. 2010). A disproportionate number of intense tornado and widespread straight-line wind damage events appear to be associated with two dynamically unique classes of thunderstorms: supercells (e.g., Moller et al. 1994, Bunkers et al. 2006a, 2006b) and bow echoes (e.g. Johns 1993, Przybylinski 1995). Thus, accurate severe weather watches are dependent on forecasters being able to predict properly not only where and when severe thunderstorms will develop and how they will evolve over the next 2–8 hours, but also the convective mode(s) that are most likely to occur.

There is also an increasing requirement to provide higher temporal resolution forecast information on thunderstorms and a variety of associated hazardous weather phenomena, including severe local storms, heavy rain/flash flooding, lightning strike potential, and aviation-related hazards of turbulence, icing, and low-level wind shear. Users such as emergency managers and other first responders, air traffic flow managers and others in transportation, power companies, etc., need greater time/space specificity in thunderstorm forecasts. The SPC is now providing higher temporal resolution thunder-storm forecasts on an experimental basis (see http://www.spc.noaa.gov/products/exper/enhtstm/, in part, to support aviation forecasters at the NOAA/NWS/NCEP Aviation Weather Center (AWC; see Fahey and Rodehuis 2004, Slemmer 2007) and air traffic managers at the FAA Air Traffic Control System Command Center (ATCSCC; Huhn et al. 2009, 2010).

Given the SPC's primary mission of mesoscale forecast responsibility, a strong emphasis is placed on assessing the current state of the atmosphere by using real-time observational data and derived diagnostic parameters for short-term thunderstorm prediction. The GOES-R PG plays a key role in developing and demonstrating real-time satellite-based diagnostic and short-term prediction products for use in convective forecasting. However, owing to insufficient sampling of the mesoscale environment (especially when the horizontal and vertical distribution of water vapor is considered – see Fritsch et al. 1998, Fritsch and Carbone 2004) coupled with limited scientific knowledge of important mesoscale and storm scale processes, considerable uncertainty exists in the prediction of deep convection. While traditional operational models such as the North American Mesoscale (NAM; Rogers et al. 2009) and the Global Forecast System (Environmental Modeling Center 2003) often can predict broader regions of precipitation utilizing parameterized convection, they are not capable of resolving important details of the smaller scale convective structure that are critical to severe weather forecasters. Furthermore, various proximity sounding studies using observed radiosondes and RUC model analyses indicate that the relationship between environmental characteristics (such as CAPE and vertical shear) and storm mode is not unique; rather it is found that similar storm types occur within different parts of the CAPE-shear parameter space, and different storm types occur within similar parts of parameter space (e. g., Rasmussen and Blanchard 1998, Craven and Brooks 2004, Thompson et al. 2003, Thompson et al. 2007, Thompson et al. 2010). Therefore, in recent years the Spring Experiment has been focusing on testing and evaluating cutting edge high resolution convection-allowing NWP models to determine potential contributions to operational severe weather forecasting (e.g., Weiss et al. 2007, Kain et al. 2008, Xue et al. 2008, 2009, 2010).

c. Evaluation of deterministic convection-allowing NWP in the Spring Experiment

Earlier research studies using idealized cloud resolving models to simulate deep convective storms at the National Center for Atmospheric Research (NCAR; e.g., Done et al. 2004) and the

University of Oklahoma Center for Analysis and Prediction of Storms (CAPS; e.g., Kong et al. 2006), among others, indicated that in some cases the models could replicate severe storm structures including supercells and bow echo systems. However, it was not until recently that sufficient computer resources, communications bandwidth, and advanced workstations became available to facilitate the testing of convection-allowing WRF model configurations over large domains in a semi-operational forecasting environment, and to assess their potential utility for severe weather forecasting. It has been demonstrated over the last seven years through Spring Experiments, field programs such as BAMEX (Davis et al. 2004) and VORTEX2 (Wurman et al. 2010), and daily use by SPC forecasters of 4 km WRF models from the NCEP Environmental Modeling Center (EMC) and NSSL, that convection-allowing configurations of the WRF model can predict convective storms that, at times, appear remarkably similar to actual storms as seen on radar (Fig. 4).

Progress has also been made in developing output fields such as simulated reflectivity (Koch et al. 2005) that displays model-generated precipitation systems and storms that are visually similar to radar-derived images of actual storms. This allows forecasters to apply their knowledge of storm structure, intensity, and associated severe weather threats gained through observation of radar detected storms to aid in their interpretation of model generated storms. Furthermore, extraction of new parameters such as updraft helicity (a marker for a rotating updraft – see Kain et al. 2008) has benefited forecasters by identifying explicit storm attributes that indicate enhanced severe potential. This is in contrast to traditional approaches where forecasters utilize mesoscale model output to provide information about evolution of the pre-convective environment (Johns and Doswell 1992, Moller 2001), and then they use their knowledge of model biases and thunderstorm physical processes to determine the spectrum of storms that are possible. The first generation of operationally applied convection-allowing models takes this one step further, as they provide explicit information about the types of storms that may develop within predicted mesoscale environments (Weisman et al. 2008, Kain et al. 2008).

Experiments with different WRF model configurations also indicate that it is not uncommon for each of the models to produce a variety of convective solutions for initiation, mode, and evolution, especially within more weakly forced environments. Thus, the model forecasts appear to reflect various uncertainties associated with real-world convective forecasting. These uncertainties arise primarily from: 1) the need to better sample and predict the pre-convective and near-storm environments, as deep convection can be sensitive to small variations in the mesoscale environment, and 2) limits in our understanding of smaller scale physical processes relevant to convection, which are modulated by mesoscale and stormscale forcing that are difficult to assess in the actual atmosphere.

Several years of experience with 00 UTC "cold start" WRF models using NAM model initial conditions and lateral boundary conditions (ICs/LBCs) have also revealed that it takes several hours of "spin up" time before the models can generate coherent, stable precipitation systems (Kain et al. 2010a, Jensen et al. 2010a). These "cold start" runs are typically unable to provide substantial short-term guidance in the 0–6 hour time frame, but they have often demonstrated value in providing useful guidance for next day's diurnal heating cycle during the 18–30 hour forecast period. It has also been seen that the larger scale forcing provided by the "parent" NAM ICs/LBCs modulates the areas of convective storm development in the WRF models (Weisman et al. 2008, Weiss et al. 2008). This is particularly evident within strongly forced environments where the WRF convective storms have a tendency to occur in regions where the NAM generates larger scale areas of precipitation.

If WRF models initialized at 00 UTC are to provide useful forecast guidance for the next day's diurnal heating cycle, they must correctly spin up deep convection during the evening, then predict properly the evolution of the storms and their impact on the environment during the overnight hours. If this sequence of events is poorly represented, the pre-convective environment in the model during the subsequent afternoon may not replicate the actual environment, and the model prediction of storms may reflect errors in the environment specification. For example, if the 00 UTC model forecast erroneously maintains convective storm systems too late into the morning, the effects of precipitation, clouds, and an expanding low-level cold pool/convective outflow may maintain a stable environment that is unfavorable for later storm development. When this type of error occurred during the 2008 Experiment, the model(s) typically underpredicted afternoon storm development in areas where the spurious cold pool was located. On the other hand, when the 00 UTC models predicted correctly the evolution of nocturnal storms, they were much more likely to produce skillful forecasts of storms for the next afternoon and evening. See

Weiss et al. (2008) for examples of these occurrences.

These findings stress the critical importance of predicting correctly the evolution of the mesoscale environment, and suggest that the ability to run "update" models at later times with new ICs/LBCs can be of value to forecasters. In 2008, the EMC High Resolution Window WRF-NMM models initialized at 12 UTC were often compared with 00 UTC WRF runs on days when the earlier runs were determined to have predicted inaccurate environmental conditions by late morning (e.g., misplaced surface boundaries and errors in thermodynamic fields). In many of these cases, the 12 UTC update run predicted the afternoon environment more accurately and this translated into improved convective forecasts.

d. Hourly maximum fields from WRF models

Traditionally, output from numerical weather prediction (NWP) models has been presented to forecasters as a series of snapshots in time (an exception is accumulated precipitation). As model resolution and transmission bandwidth have increased, the time interval between these snapshots has decreased. For most forecasting applications, hourly output is adequate because the evolution of common larger-scale features of interest (i.e., fronts, jet streaks, low and high pressure centers, etc.) is well sampled by the hourly frequency. Furthermore, this frequency is a pragmatic choice because the sheer volume of data associated with more frequent output files would exceed the capacity of current dissemination, processing, and storage systems. However, as NWP applications move to higher resolution, the features of interest begin to change and hourly sampling can become inadequate.

Simulated convective storm features such as reflectivity and updraft helicity (UH) features often evolve on convective time scales commonly measured in minutes, not hours. Thus, it is important to monitor model storm behavior at a higher frequency than hourly output provides. This rationale is similar to operational monitoring of actual storms using radar, where no one would consider hourly snapshot images of storms to be adequate. Rather than simply outputting model fields on a much more frequent basis, a strategy has been developed to monitor and track small-scale, rapidly changing convective storm features every model time step between regular hourly model output times. The individual grid point temporal maxima during each hour are saved and output at the regular hourly intervals, providing a useful perspective on the maximum intensity and track of strong convective phenomena in the model forecasts (Kain et al. 2010b).

This data processing is intended to fill in the temporal gaps between the standard top of the hour model output and provide unique information about the most intense storm attributes, which are unlikely to occur only at the hourly output times. Currently, the tracking of "history variables" is applied to low level simulated reflectivity, updraft speed, downdraft speed, updraft helicity, 10 m wind speed, and vertically integrated graupel grids.

The computation of hourly maximum fields (HMFs) was first introduced in the NSSL WRF model, and has been subsequently incorporated into WRF models run by a number of major modeling centers (including EMC, GSD, CAPS, NCAR, and AFWA). These fields were available from all WRF model configurations used in the Spring Experiment. This approach represents an important first step in exploring ways to extract new output fields and/or compute new diagnostics from convection-allowing models, and the output has been utilized in SPC operations for two years with promising results.

e. Radar assimilation into convection-allowing models

To fully capitalize on high resolution models to provide short-term forecast guidance on convective scales, advanced data assimilation techniques that include 3D radar reflectivity and velocity fields are necessary in order for the models to "know" where storms are located at the start of the model run. This very challenging task was introduced into the Spring Experiment in 2008, as CAPS used a real-time 3DVAR system (Xue et al. 2003, Gao et al. 2004) to assimilate radar and other data over a three-fourths CONUS domain for the first time (Xue et al. 2008). Although the impact of the radar assimilation on the model forecasts typically appeared to diminish after several hours (Kain et al. 2010a, Jensen et al. 2010a), this experimental area will be a focus of activity in coming years.

NOAA/ESRL/GSD has been developing an experimental 3 km WRF version called the High Resolution Rapid Refresh (HRRR) model (Alexander et al. 2010) for several years, and output from this system was examined more closely this year. The HRRR is nested within the hourly 13 km backup RUC model, and uses the RUC 3DVAR data assimilation system (including radar data) and the Diabatic Digital Filter Initialization (DDFI) procedure (Weygandt et al.

2007). This cycled system creates realistic vertical thermal and convergence-divergence couplets in the model atmosphere based on the presence of radar and lightning indicated convection, which allows improved dynamical balance to support existing convection in the short-term model forecasts. The HRRR uses a 1 hr RUC forecast of reflectivity at the initial time, and taking advantage of the DDFI it is able to downscale from the 13 km RUC to the 3 km HRRR grid within the first 15–30 minutes of the integration (Benjamin, personal communication 2010).

f. Convective predictability on the grid scale and storm scale ensemble forecast system

Our experience has also shown that variations in WRF model convective storm predictions are at times difficult for operational forecasters to reconcile, in part because all solutions may appear to be plausible for a given mesoscale environment. Thus, the forecaster must determine how much confidence to place in specific model solutions, which is often difficult to assess because very high resolution models will attempt to predict phenomena (such as thunderstorms) on scales that are inherently less predictable (e.g., Elmore et al. 2002, Zhang et al. 2006, Hohenegger and Schar 2007). The uncertainty in thunderstorm prediction suggests at least several possible research approaches to explore: 1) development of appropriate data assimilation systems for convection-allowing models to better resolve the initial conditions, and 2) improvement in the model itself with more realistic physics and increased resolution. However, inherent predictability limits at convective scales necessitate development and application of ensemble forecasting strategies, similar to those currently used operationally for synoptic scale and mesoscale forecasting, to address challenges of convective-scale forecasting. For operational forecasting applications, a well-designed convection-allowing ensemble should provide improved probabilistic guidance on high impact convective weather events by quantifying aspects of uncertainty and offering further insights about a possible range of solutions.

A Storm Scale Ensemble Forecast (SSEF) system produced by CAPS has been tested in Spring Experiments since 2007 to systematically explore aspects of uncertainty in thunderstorm prediction (e.g., Xue et al. 2008, Kong et al. 2008, Schwartz et al. 2010, Harless et al. 2010). Although questions remain concerning appropriate perturbation strategies for a convection-allowing ensemble system, experiments with 10–20 member SSEF systems in 2007–2009 have shown promising results. As computing resources have expanded, the SSEF evolved from a 10 member WRF-ARW ensemble in 2007 that contained 5 mixed-physics only members and 5 mixed-physics + perturbed IC/LBC members, to a 20 member multi-model (ARW, NMM, ARPS) ensemble in which 17 members contained both mixed physics and IC/LBC perturbations in 2009. Further refinement of the SSEF occurred this year as additional members containing more sophisticated physics and stochastic perturbations are added, with a total of 26 members in the SSEF (Xue et al. 2010). In addition, development of new display tools for probabilistic assessment of thunderstorm potential and model-generated storm characteristics utilizing "neighborhood" approaches that more properly reflect limits to grid scale predictability were tested to enhance the ability of forecasters to utilize SSEF output (Marsh et al. 2010).

This work links directly toward the WoF concept that envisions the use of an ensemble system that assimilates observations of convective storms and their environments into high-resolution, explicit convective-scale numerical weather prediction models, creating a probabilistic convective scale analysis and forecast system. The SSEF system includes all the fundamental components of WoF - e.g., assimilation of radar and environmental data, model configurations capable of explicitly resolving deep convective storms (no parameterized convection), and ensemble-based probabilistic prediction - but all of these components will need considerable improvement before WoF reaches fruition (Marsh et al. 2010). However, our experience over the past few years suggests that progress in convective scale probabilistic prediction is occurring first on somewhat larger time/space scales compared to true WoF, and the SSEF is a logical first step in this direction.

Finally, a key component of the annual experiments is the participation of operational forecasters from the SPC, other NCEP Centers, NWS WFOs, Environment Canada, and several private sector companies. Their insights and experience provide a real-world severe weather forecasting perspective when assessing the usefulness of convection-allowing WRF modeling systems, and provide them with opportunities to become familiar with cutting-edge science and technology applications before they are implemented operationally. This operational-research link increases the likelihood that HWT activities will result in improved severe weather forecasts and better public service. Forecaster interactions with model developers, research scientists, university faculty, and graduate students create a unique forum where a diverse mix of scientific backgrounds and insights work together to advance operationally relevant research and improve forecasts of hazardous convective weather (Kain et al. 2003).

4. Additional HWT Focus Areas in 2010 – Aviation-Impacts and QPF

Convective storms have a wide variety of societal impacts that range beyond the traditional HWT focus on severe convective weather. According to NOAA economic statistics, warm-season thunderstorms cause ~70% of air traffic delays in the U.S. and cost the economy upwards of $4 billion dollars each year (see http://www.economics.noaa.gov/). In addition, thunderstorm-generated heavy rain and flash floods are one of the leading causes of weather-related fatalities, averaging ~130 deaths per year. Improved forecasts of thunderstorms will result in large societal benefits, and it is appropriate for the HWT to explore additional thunderstorm hazards during the Spring Experiment. In 2010, the HWT included experimental components lead by the AWC and the NCEP Hydrometeorological Prediction Center (HPC) to examine the ability of convection-allowing models to provide useful guidance for thunderstorm-aviation impacts and heavy rain forecasting.

The daily activities schedule (Appendix A) was designed to have each team (severe weather, QPF, and aviation) conduct forecasting and evaluation activities at similar times of the day, providing common discussion periods so each forecast/evaluation team could share their insights with the other teams. This was intended to provide a forum whereby cross cutting relationships between the severe weather, aviation, and QPF communities would begin to be developed, including identification of shared (as well as different) thunderstorm forecast challenges. Indirectly it also allowed exploration of convective forecast consistency between the three forecast desks, although the different hazardous weather phenomena each was focused on meant some forecast differences were likely to occur.

a. Applications to thunderstorm impacts on warm-season aviation operations

To assist the AWC in the development of their Aviation Weather Testbed, the HWT Spring Experiment included an aviation-impacts component to complement the traditional HWT focus on severe convection. Thunderstorms are responsible for many air traffic delays across the National Airspace System (NAS) each year (e.g., Huhn et al. 2010). They are also considered a threat to aviation safety due to their ability to produce both en route and terminal weather-related hazards such as lightning, hail, turbulence, microbursts, and low-level wind shear. The Federal Aviation Administration (FAA) plans traffic flow management (TFM) to avoid thunderstorms utilizing a 6 hour forecast product designed for aviation. The AWC plays a key role in providing detailed short-term thunderstorm forecasts through the Collaborative Convective Forecast Product, which is issued every two hours and provides thunderstorm forecasts valid at 2 hour intervals out to 6 hours that include information on storm coverage, growth rates, movement, thunderstorm tops, presence of thunderstorm lines, and forecaster confidence (for more information about the CCFP, see http://aviationweather.gov/products/ccfp/).

Convection-allowing WRF model output has potential to provide very detailed hourly forecasts of convective storms, especially related to storm coverage and mode, and can provide forecasters and aviation traffic flow managers with potentially useful information about future storm impacts on en route aircraft as well as threatening storm conditions near hub airports. In more strongly forced situations, lines may be more confidently predicted, but small errors in timing on the order of 1 to 2 hours can create large disruptions in the NAS. The generally limited predictability of storms on the grid scale must be acknowledged when utilizing high resolution WRF model forecasts of storms, and results from previous years suggests that while deterministic forecasts may be compatible with historical TFM practices, the forecast process is better suited to probabilistic convective weather information given the uncertainty in predicting exact times and locations of thunderstorms.

Thus, the use of SSEF output fields in combination with traditional mesoscale model output (NAM, SREF), deterministic convection-allowing WRF model forecasts, and statistical thunderstorm guidance from the Local Aviation MOS Program (LAMP; Charba and Samplatsky 2009) were tested and evaluated during the 2010 Spring Experiment. Experimental output from the Consolidated Storm Prediction for Aviation (CoSPA; Pinto et al. 2010) were also available for use during the latter part of the Spring Experiment. Aviation forecasters from AWC and NWS offices worked with traffic managers from the FAA ATCSCC in the HWT aviation-impacts component to assess the ability of the new guidance to improve thunderstorm forecasts for aviation interests. The primary focus was on afternoon thunderstorms over the eastern half of the CONUS, especially over the northeast corridor where storm disruptions can impact traffic flow across large parts of the country. Finally, to begin addressing a new strategic planning initiative to provide next day guidance on potential thunderstorm impacts, an experimental Day 2 aviation thunderstorm forecast was also created each afternoon as part of a Collaborative Strategic Planning Process at the FAA ATCSCC.

b. Applications to quantitative precipitation forecasting

To assist the HPC in the development of their Hydrometeorological Testbed (HMT), the HWT Spring Experiment also included a QPF component. It has been long noted that QPF scores exhibit lower skill during the warm season (e.g., Olson et al. 1995, Fritsch and Carbone 2004), and this is largely attributable to the dominant contribution from convection on warm season precipitation. Traditional synoptic scale and mesoscale NWP models such as the GFS and NAM use convective parameterization schemes (CPS) to account for the sub-grid scale effects of deep convection, and the CPS have tendencies to exhibit a number of systematic errors. These include: erroneous precipitation "bulls-eyes", considerable phase errors in time and space, especially for MCS development that accounts for much of the warm season rainfall across the U.S., and a low bias for the most critical heavy rain producing thunderstorm events. Previous studies have found that convection-allowing models have the ability to better predict convective mode (Weisman et al. 2008, Kain et al. 2008), provide more realistic amplitude of rainfall (Schwartz et al. 2009), and better represent the diurnal cycle and propagation of rainfall systems (Weisman et al. 2008). It has also been demonstrated that a SSEF with a relatively small number of members has improved QPF skill compared to a larger mesoscale ensemble using parameterized convection (Clark et al. 2009).

For an initial test and evaluation, the QPF forecast teams incorporated guidance from convection-allowing WRF models including the SSEF to produce experimental probabilistic QPF forecasts for 6 hour periods valid 18–00 UTC and 00–06 UTC that cover the primary diurnal convective storm periods. (It is recognized that the climatological nocturnal precipitation maximum over the plains during the warm season may occur after 06 UTC, but the SSEF forecast period ends at 06 UTC and restricts the experimental forecasts to the 18–06 UTC period.) The QPF forecast teams used the experimental model guidance to supplement traditional model guidance (e.g., NAM, GFS, SREF) in the forecasting process. The experimental forecasts will depict contours for the probability of exceeding (POE) 0.5" and 1" thresholds for each 6 hour period. In addition, to explore the utility of the convection-allowing models to better predict localized heavier precipitation amounts, each forecast that included a probability of 1" or greater also identified a maximum predicted rainfall amount within the 1" POE for each 6 hour period.

The HWT activities occurred in conjunction with an initial in-house experiment at the HPC to familiarize QPF forecasters with the experimental model output, and to begin assessing the challenges as well as the potential value and utility of convection-allowing model guidance for QPF application.

5. Developmental Testbed Center Objective Evaluation

Subjective verification of model forecasts has been a cornerstone to HWT activities in previous years (Kain et al. 2003b). This approach has provided valuable insights into how forecasters use numerical models and facilitates the gathering of information about the value of new guidance tools from the perspective of a forecaster. In addition, it has been found that traditional verification measures (e.g., Equitable Threat Score or ETS) used for synoptic scale and mesoscale model forecasts of discontinuous variables such as precipitation typically provide less useful information (and even misleading information) about forecast accuracy as the scale of the phenomena being evaluated decreases (Baldwin and Kain 2006). This is because the ETS is proportional to the degree of grid scale overlap in space and time between the forecasts and observations, and there is typically low predictability on convective scales. Despite these limits, operational severe weather forecasters have often found value in WRF forecasts of thunderstorms and convective systems, since they can provide unique information about convective mode, coverage, and evolution that is not resolved by mesoscale models using parameterized convection. In recent years, we have found that subjective evaluation has great potential to serve as a comparative benchmark for assessing new objective verification techniques designed for high resolution NWP, and has had a significant positive impact on model development strategies.

In order to better utilize subjective and objective verification techniques in a complementary manner, simulated composite reflectivity and 1 hr QPF output from several model runs were evaluated using subjective visual comparisons and objective statistical measures produced by the Developmental Testbed Center's (DTC) Meteorological Evaluation Tool (MET; Davis et al. 2009). The focus this year was on probabilistic predictions, particularly of extreme precipitation events and aviation impacts of thunderstorms. All members of the SSEF were evaluated for select variables. Ensemble post-processed products from the 15 members of the SSEF with mixed IC-physics perturbations also were evaluated. Operational (or near-operational) models were used as a baseline for comparison, including the NAM, HRRR, and SREF. Other contributing models will be archived for retrospective studies.

MET is designed to be a highly-configurable, state-of-the-art suite of verification tools. Emphasis was placed on the use of the object-based verification called Method for Object-based Diagnostic Evaluation (MODE) that compares gridded model data to gridded observations for the QPF and simulated reflectivity forecasts. MODE output will be tested to evaluate its ability to diagnose different types of convective modes considered important in forecasts and observations of convective weather, such as linear systems, discrete cells, and MCSs. Traditional verification statistics will also be computed. Verification "truth" is provided by NSSL National Mosaic and Multi-Sensor QPE (NMQ) multi-sensor Quantitative Precipitation Estimates (QPE) and three-dimensional radar reflectivity data bases (Vasiloff et al. 2007). Some DTC verification results are provided by Jensen et al. (2010a, 2010b) and Harrold et al. (2010).

6. Experimental Models

The 2010 Spring Experiment benefited from the continued participation and key contributions from CAPS, EMC, GSD, and NCAR. Each of these collaborators (along with NSSL) generated convection-allowing model guidance initialized at 00 UTC, and most provided additional model runs at 12 UTC and/or other times during the convective day. Model domains covered from three-fourths to full CONUS regions, and most 00 UTC models produced forecasts to at least 30 hrs. The hourly GSD HRRR runs provided forecasts to 15 hours. (CAPS also produced a subset of WRF runs at 09, 12, 15, and 18 UTC for the VORTEX2 field program domain centered over the plains states with forecasts out to 06 UTC, but these were not a primary component of the Spring Experiment and they will not be discussed further.)

a. CAPS models: 4 km storm scale ensemble forecast and 1 km WRF-ARW

A major CAPS contribution was a 26 member *Storm Scale Ensemble Forecast (SSEF) system* with grid spacing of 4 km and forecasts to 30 hours, utilizing the resources of the National Institute for Computational Sciences (NICS)/ University of Tennessee located at Oak Ridge National Laboratory. The SSEF is a multi-model ensemble with 19 ARW (Skamarock et al. 2005), 5 NMM (Janjic 2003), and 2 ARPS (Xue et al. 2003) members. The SSEF incorporated additional initial condition (IC) and physics diversity from mixed IC/physics perturbations in 15 members (12 ARW and 3 NMM), with new physics diversity provided in many ARW members through the introduction of two new PBL and three new double moment microphysics schemes. The ARW and ARPS members (1160x720 horizontal grid points) and NMM members (999x790 grid points) are all integrated on a full CONUS domain.

In all members, the background initial condition came from interpolation of the 12 km NAM analysis. Mesoscale atmospheric perturbations were introduced in the initial and lateral-boundary conditions of 10 ARW and 3 NMM members by extracting perturbations from EMC's operational Short Range Ensemble Forecast (SREF) system and applying them to the 13 members. In addition, random/recursive perturbations were applied to 3 ARW members. Convective-scale perturbations were introduced in the initial conditions of 23 members by assimilating reflectivity and velocity data from the national NEXRAD radar network and a cloud analysis as part of a CAPS 3DVAR system. For the remaining two ARW, two NMM, and two ARPS members, identical model configurations were used for each pair and there were no other IC or physics perturbations applied. Radar data was assimilated into one of the two ARW, NMM, and ARPS members (the C0 control member), but not the other (Cn member). Comparison of output from these two pairs of ARW, NMM, and ARPS members allowed further examination of the impact of the radar and other observational data from other sensitivities at 4 km grid spacing.

Overall, the SSEF configuration builds upon lessons learned from the earlier SSEF systems tested during the 2007–2009 Spring Experiments, and the development this year of a larger multi-model, multi-physics, multi-IC SSEF over a full CONUS domain should, in principle, be more robust and contain improved statistical performance. More details about the SSEF design and performance are found in Xue et al. (2010), Kong et al. (2010), Jirak et al. (2010), and Melick et al. (2010).

CAPS also ran a CONUS domain *single WRF-ARW forecast at 00 UTC with a 1-km grid length* (4640×2880 grid points) integrated to 30 hours. Radar and other observational data were identically assimilated into the 1 km ARW but there were no SREF-based perturbations. This allowed a direct comparison with the SSEF 4 km ARW control member and a clean measure of sensitivity to 1 versus 4 km grid spacing when radar data are assimilated. Statistical verification measures from Spring Experiments in 2007 and 2008 indicated similar forecast results from the 2 and 4 km ARW forecasts (Schwartz et al. 2009), suggesting that the benefit gained by increasing horizontal resolution was not sufficient to justify the approximate eight-fold increase in computational resources to produce the 2 km run. However, results from 2009 comparing the 1 km run with the SSEF indicated that 1 km ETS and Bias scores for precipitation forecasts were generally superior to all members, as well as the probability matched ensemble mean (Xue et al. 2009). This is consistent with other high resolution modeling studies that found more realistic convective storms in terms of structure, size, and number of storms beginning to appear when the grid spacing approaches 1 km (e.g., Adlerman and Droegemeier 2002; Bryan et al. 2003).

The CAPS SSEF member configuration is provided in Tables 1, 2, and 3.

b. EMC 4 km WRF-NMM model

SPC forecasters have used output from earlier versions of the EMC WRF-NMM model since the spring of 2004. The current version is nested within the 12 km NAM and incorporates NAM ICs/LBCs. It is run throughout the year over a CONUS domain (1239x920 horizontal grid points) twice daily at 00 and 12 UTC with forecasts to 36 hrs, and output is available to all forecasters via a web page at http://www.emc.ncep.noaa.gov/mmb/mpyle/cent4km/conus/00/. The latter run time provides a morning update for afternoon and evening guidance (Weiss et al. 2008). In addition, the 12 UTC run was used to provide day 2 guidance for the afternoon aviation experimental forecast for the next day.

c. NSSL 4 km WRF-ARW model

SPC forecasters have used output from a 4 km WRF-ARW produced by NSSL since the fall of 2006. This WRF model is run once daily at 00 UTC throughout the year over a full CONUS domain (1200x800 grid points) with forecasts to 36 hrs. Output is also available on the internet at http://www.nssl.noaa.gov/wrf/.

The NSSL-WRF began producing several new experimental fields to test and evaluate in spring 2010.

1. Total Lightning Threat (units: flashes km^{-2} per 5 min)

There are three total lightning threat experimental parameters that represent microphysical properties of hydrometeor types and charge separation processes within the WRF model convective storms (McCaul et al. 2009).

Lightning Threat 1: Upward flux of ice hydrometeors at the -15^{o}C level.

Lightning Threat 2: Column integrated ice hydrometeors.

Lightning Threat 3: Blended solution of Threats 1 and 2 that optimizes temporal variability best depicted by Threat 1 and areal coverage that is best depicted by Threat 2. Threat 3 is very heavily weighted by Threat 1.

These three fields are based on the hourly maximum of the ice hydrometeor fields and therefore should be considered to represent the hourly maximum total lightning threats. During the experiment, forecast teams focused primarily the Lightning Threat 3 field since it statistically combines attributes of the two fundamental physical processes represented in Threats 1 and 2.

The explicit total lightning is highly dependent on the ability of the NSSL-WRF to predict timing and location of convective storms, but, as with applications of storm attributes such as UH, this is another step in extracting explicit storm characteristics from convection-allowing models.

The lightning threat was examined extensive as part of the aviation-impacts component. Preliminary verification results by Miller et al. (2010) indicate that the NSSL-WRF lightning forecasts were highly reliable when a spatial density filter (Sobash et al. 2009) was applied to the gridded output fields.

2. Simulated Satellite Imagery
Working with collaborators at both CIRA/CSU and CIMSS/UW, simulated satellite imagery was created from the NSSL-WRF model gridded fields to represent output from a number of channels

planned for the GOES-R satellite. The simulated imagery is generated from model gridded surface fields and vertical profiles of predicted moisture, temperature, and clouds, and is sensitive to the microphysics scheme employed in the numerical model.

Selected WRF forecast grids are distributed to both CIRA and CIMMS, where local versions of radiative transfer models are applied to create simulated radiance/brightness temperature fields (e.g., Grasso et al. 2008a, 2008b; Otkin and Greenwald 2008; Otkin et al. 2009). The images are then sent to the HWT for display in the N-AWIPS system. CIRA produced images from 4 infrared channels, and CIMSS created output from 8 infrared channels.

This new capability allows users to directly infer the 4–D evolution of model dynamic processes and associated moisture fields, and to make visual comparisons between satellite observations and operational model output at resolutions comparable to current GOES satellite imagery. The simulated GOES imagery allows forecasters to rapidly discern model forecasts of moisture transport, regions of ascent and subsidence, and indications of the vertical extent of clouds including shallow and deep convection. An animated loop of model-derived simulated GOES imagery can allow forecasters and model developers to subjectively ascertain dynamic processes within the model atmosphere very quickly and improve our understanding of model forecast evolution.

The simulated satellite imagery was available for teams formulating experimental forecasts in the severe storm, aviation-impacts, and QPF components. Preliminary results from WRF simulated satellite imagery are presented by Lindsey et al. (2010).

d. GSD 3 km High Resolution Rapid Refresh (HRRR) model

The 3 km HRRR model is nested within the hourly 13 km RUC model, which provides ICs/LBCs for the HRRR. The HRRR uses a version of the WRF-ARW with generally “RUC-like” physics. A unique aspect of the RUC is the hourly 3DVAR data assimilation system that incorporates a wide array of observational datasets including radar reflectivity via the radar-Diabatic Digital Filter Initialization. The HRRR integration is run over a full CONUS domain (1800x1060 grid points) with forecasts to 15 hrs. At the initial time, the simulated HRRR reflectivity comes from a 1 hr RUC forecast; downscaling from the RUC 13 km grid to the HRRR 3 km grid occurs quickly during the first hour.

The HRRR is being developed to serve users needing frequently updated short-range weather forecasts, including those in the U.S. aviation and severe weather forecasting communities. It is expected to primarily provide guidance for the severe storm and aviation-impacts components of the Spring Experiment, especially during the afternoon updates to the experimental forecasts. More details about the HRRR are found in Benjamin et al. (2007) and Alexander et al. (2010).

e. NCAR 3 km WRF-ARW model

NCAR produced a 3 km WRF-ARW that utilized initial conditions from the 13 km RUC that assimilated radar data via the Diabatic-Digital Filter Initialization. This used the same ICs that were used by the HRRR, but the LBCs for the NCAR WRF were provided by the GFS model. The choice of RUC ICs and GFS LBCs will allow further examination of the sensitivity of model forecasts to initial condition specification. It has been noted over the last few years that ICs and forcing attendant to large scale systems provided by the “parent” models played a role in the timing and location of convection in the WRF model forecasts, especially in more strongly forced situations (e.g., Weisman et al. 2008, Weiss et al. 2008, Weisman et al. 2010).

The NCAR 3 km WRF-ARW will be run twice daily at 00 and 12 UTC with forecasts out to 48 hrs over a three-fourths CONUS domain (1320x1000 grid points). The 12 UTC run will also be used to provide Day 2 guidance for the afternoon aviation experimental forecast for the next day. Some performance results of the NCAR WRF precipitation forecasts during the Spring Experiment are found in Manning et al. (2010).

The configuration of the deterministic convection-allowing WRF models for the 2010 Spring Experiment is found in Table 4.

7. Primary objectives

The severe weather, QPF, and aviation components of the 2010 EFP defined objectives and goals related to mission specific needs that were modulated by each NCEP Center’s previous experience in examining and utilizing convection-allowing models in either experimental or operational settings. For example, SPC forecasters have been utilizing convection-allowing WRF models since 2004, whereas HPC and AWC forecasters have had considerably less background and experience. An overarching goal for all participants to was to explore the utility of convection-allowing output to provide useful guidance to convective forecasters who are tasked with different types of thunderstorm hazards. Extraction of model guidance relevant for each forecast desk proved more challenging for some purposes compared to others. For example, explicit QPF guidance is a direct NWP output field, whereas the determination of output fields to identify severe thunderstorms produced by WRF models are still the subject of ongoing research. Overall, each forecast component was designed in a similar manner, in order to: 1) familiarize forecasters on potential operational uses of WRF models and ensemble systems, 2) explore creation of probabilistic forecast products, and 3) provide feedback to model developers on strength and weaknesses of current systems and products. Basic objectives for each component are listed below.

a. Severe convective storm component (leader: SPC)

- Continue test and evaluation of high-resolution convection-allowing models (CAMs) and SSEF to provide useful guidance to severe weather forecasters for high-temporal resolution experimental probabilistic severe weather forecasts. This will focus on improving forecasts of initiation, evolution, mode, and intensity of convective storms.

- Assess the perceived value of probabilistic products and other unique guidance from the SSEF to aid in the forecaster formulation of experimental probabilistic 4 hr severe weather forecasts. These products are designed to complement the current Day 1 experimental enhanced resolution probabilistic thunderstorm products issued by the SPC. Examples of SSEF products for neighborhood exceedance probability fields and maximum HMFs are shown in Figs. 5–6. See Jirak et al. 2010 for an analysis of SSEF HMF performance.

- Using experimental and operational data sets, determine if forecasters can create reliable probabilistic severe weather products for the occurrence of severe storms (tornadoes, large hail, damaging wind gusts) for two 4 hour periods of 20–00z and 00–04z encompassing the diurnal convective cycle (Fig. 7). The forecasts will also include potential for significant severe weather (tornado EF2+, hail $\geq$2”, wind gust $\geq$65 kt).

b. Aviation thunderstorm-impacts component (leader: AWC)

- Initial exploration of high-resolution convection-allowing models (CAMs) and SSEF to provide useful guidance to aviation forecasters for the creation of experimental probabilistic thunderstorm forecasts. These will focus on improving forecasts of timing, location, coverage (porosity), and tops of thunderstorms that are critical for the efficient management of the NAS. Fig. 8 contains examples of SSEF output fields used by aviation desk forecasters.

- Test and evaluate the ability of aviation forecasters to create reliable probabilistic snapshot products for the occurrence of 40 dBZ echoes, especially in lines or clusters, and the likelihood of echo tops exceeding critical flight levels. The snapshot times of 21, 23, and 01z will be valid during the peak convective diurnal period (Fig. 9).

- Familiarize air traffic management specialists from ATCSCC and airlines with experimental probabilistic thunderstorm forecasts. Obtain feedback from specialists to identify ways to improve forecast product display and effectively interpret probabilistic forecast information in order to more effectively manage NAS.

- Share knowledge and experience between the Hazardous Weather Testbed and the new Aviation Weather Testbed which will subsequently serve as a focus for aviation collaborations for years to come.

c. QPF component (leader: HPC)

- Explore utility of 00z high-resolution convection-allowing models (CAMs) and SSEF system to provide useful guidance to hydrometeorological forecasters in creation of experimental probabilistic 6 hr QPF products (Fig. 10). Document strengths and limitations of high resolution models for precipitation forecasting, and determine appropriate ways to use operational mesoscale (e.g, NAM, GFS, SREF) and experimental CAMs/SSEF in a complementary manner.

- Assess the perceived value of probabilistic output and other unique guidance from the SSEF to aid forecasters in the formulation of experimental 6 hr QPF products, consistent with current HPC operational requirements.

- Using experimental and operational data sets, determine if forecasters can create reliable probabilistic QPF products for 0.5" and 1.0" precipitation thresholds, valid for the 18–00z and 00–06z periods encompassing the diurnal convective cycle (Fig. 11).

- Share knowledge and experience between the Hazardous Weather Testbed and the Hydrometeorological Testbed at HPC, which serves as a focus for QPF collaborations.

8. Summary and Discussion

The NOAA Hazardous Weather Testbed conducts annual spring forecasting experiments organized by the Storm Prediction Center (SPC) and National Severe Storms Laboratory (NSSL) to test and evaluate emerging scientific concepts and technologies for improved analysis and prediction of hazardous mesoscale weather. A primary goal is to accelerate the transfer of promising new tools from research to operations through the use of intensive real time experimental forecasting and evaluation activities conducted during the spring and early summer convective storm period. From May 17 through June 18, 2010, more than 70 participants including operational forecasters, research scientists, academic faculty, graduate students, and administrators from numerous organizations across the United States, participated in the HWT focusing on application of cutting edge numerical weather prediction systems to address high impact convective weather forecasting challenges.

This year, in addition to the traditional HWT focus on severe convective storms producing tornadoes, damaging wind gusts, and large hail, collaborations with two other NCEP Centers were established within the HWT to help address a wider range of convective weather hazards. The Hydrometeorological Prediction Center (HPC) led an initial effort to explore high resolution model forecasts of precipitation and excessive rainfall associated with warm season convection, and the Aviation Weather Center (AWC) tested and evaluated new forecasting tools to improve thunderstorm forecasts for aviation. The three convective forecasting components operated simultaneously within the HWT conducting structured forecast and evaluation activities each day.

Detailed information was collected and archived each day to document experimental forecasts, perceived value of model guidance during the forecast formulation, and next-day subjective evaluation of the model guidance performance, including an assessment of numerous output fields and display formats. In addition, participants were asked to complete a questionnaire at the end of each week providing feedback and suggestions about the experiment design, HWT facilities and IT systems, utility of experimental models, and the role of the HWT in enhancing research-to-operations (R20) and operations-to-research (O2R) activities.

A key aspect of the HWT success has been the daily real time forecast and evaluation exercises that are conducted. All participants share in the challenges (and frustrations!) of making experimental forecasts and then evaluating those forecasts and experimental model guidance, for different weather regimes across different parts of the CONUS. And because the weather each day is "live" (as opposed to using displaced real time (DRT) cases as part of the forecasting exercises), no one knows what the correct "answer" is, and this contributes to the sense of realism and operational urgency in the forecasting activities.

The HWT serves as an effective facilitator bringing together different parts of the larger meteorological community to work together in real time, addressing a variety of hazardous convective weather topics. Given the historically large separation between operational forecasting and research components within the U.S. meteorological community, the HWT provides many of the participants with a unique opportunity to interact with operational forecasters and/or research scientists on subjects of mutual interest. The HWT has been very successful in fostering community-focused collaborative research, in part because of the public safety and economic importance of convective weather to society, but also because the structure of the spring experiments enables forecasters to better understand how research is conducted, and researchers to better understand operational requirements and constraints. In short, all participants are taken out of their respective "comfort zones" when they participate in the HWT, but this results in numerous benefits as part of a two way R20–O2R dialog that is established. To illustrate this, a high percentage of participants in

2010 indicated that the HWT experience was extremely beneficial to their professional work (Fig. 12).

The HWT EFP has established very effective collaboration with a number of major government and academic NWP modeling centers in the United States, including EMC, GSD, NCAR, AFWA, CAPS, and the DTC. This success is based, in part, on the testing and evaluation of NWP hazardous weather applications in a simulated operational environment by teams of researchers and forecasters during the prime severe storm season, focusing on identifying strengths and limitations of model guidance, and providing useful feedback to model developers in an unbiased manner. This organizational structure allows all major partners in the EFP to benefit, which is especially important since the HWT does not provide funding support to primary partners and collaborators.

There are numerous scientific challenges ahead in the development of reliable probabilistic stormscale guidance for convective prediction, requiring improvements in data assimilation, models, extraction of post-processed fields, and appropriate use of the guidance by forecasters and other users. The HWT is well positioned to play a key role in these tasks in upcoming years.

Acknowledgments

Special thanks and appreciation is extended to many people for their creative insights and assistance in Spring Experiment preparations, planning, and execution of numerous complex and ground-breaking technical and scientific activities. Without the combined efforts of many SPC and NSSL staff, the Spring Experiment could not be conducted. In particular, special thanks go to SPC's Gregg Grosshans for helping to establish model data flow and configuring the experimental forecasts for transmission and archival and for helping to organize model display files, and Jay Liang and Joe Byerly for expertise in configuring and upgrading hardware/software, network and workstations in the HWT. Expert NSSL technical support was provided by Brett Morrow, Jeff Horn, Steve Fletcher and Brad Sagowitz to address networking, data flow, hardware, and archive requirements. Linda Crank (SPC), Peggy Stogsdill (SPC), and Linda McGuckin (NSSL) ably assisted with logistical and budget support activities. J. J. Gourley's assistance in organizing the NSSL Seminar Series for visiting scientists during the experiment is also greatly appreciated.

The experimental activities could not take place without the dedicated collaborative efforts of many people at CAPS, EMC, GSD, and NCAR who are working to enhance community efforts to improve severe weather forecasting. We acknowledge the expertise of CAPS scientists Kelvin Droegemeier, Yunheng Wang, Jidong Gao, and Keith Brewster for contributions in developing and running the SSEF and the 1 km WRF models; the National Institute for Computational Sciences/University of Tennessee, and the University of Oklahoma Supercomputing Center for Education and Research for providing technical support and computer facilities for the CAPS model runs; NCAR scientists Morris Weisman, Wei Wang, Greg Thompson, and Jimy Dudhia for providing the NCAR WRF runs and offering technical support and advice on the ARW system and configuration of the SSEF; EMC scientists Matt Pyle, Zavisa Janjic, Brad Ferrier, and Geoff DiMego for developing and contributing the WRF-NMM models and for scientific input and infrastructure support for the SSEF; Stan Benjamin, Steve Weygandt, John Brown, and Curtis Alexander at ESRL/GSD for development of the CONUS HRRR model and establishment of data flow to SPC for use in the Spring Experiment; Barbara Brown, David Ahijevich, Jamie Wolff, Michelle Harrold, Steve Sullivan, Paul Oldenberg and colleagues from the DTC for their expert development of the MET and MODE verification systems and special efforts to tailor it for application during the Spring Experiment; Bill McCaul, Jon Case, Scott Dembek and colleagues at NASA/SPoRT/Huntsville for implementation of the WRF Total Lightning Threat products in the NSSL-WRF model; Louie Grasso and Dan Lindsey at CIRA, and Jason Otkin and Justin Sieglaff at CIMSS for creating and providing simulated satellite imagery from the NSSL-WRF model; Wayne Feltz, Jason Brunner, and Justin Sieglaff of CIMSS for the enhanced-V/overshooting tops satellite products; John Mecikalski, Wayne MacKenzie, and John Walker of UAH, and Wayne Feltz and Justin Sieglaff of CIMSS and Kris Bedka of NASA/Langley for convective initiation satellite products. We are especially appreciative for the insights, feedback, and recommendations provided by Tony Eckel (NWS/OST) regarding development of improved statistical post-processing of SSEF fields.

Special thanks go to the GOES-R Program Office, the National Weather Service, and the National Severe Storms Laboratory for providing visitor travel support. We further wish to recognize the full support of SPC and NSSL management; the leadership provided by SPC forecasters in helping to guide the severe weather forecasting

component each year; and the numerous contributions and insights provided by the many participants who clearly demonstrated the value of collaborative experiments involving the research, academic, and forecasting communities, and whose presence and enthusiasm resulted in a positive learning experience for everyone.

10. References

Adlerman, E. J., and K. K. Droegemeier, 2002: The sensitivity of numerically simulated cyclic mesocyclogenesis to variations in model physical and computational parameters. *Mon. Wea. Rev*., **130**, 2671–2691.

Alexander, C. R., S. S. Weygandt, T. G. Smirnova, S. Benjamin, P. Hofmann, E. P. James, and D. A. Koch, 2010: High resolution rapid refresh (HRRR): Recent enhancements and evaluation during the 2010 convective season. *25th Conf. on Severe Local Storms*, Denver, CO, Amer. Meteor. Soc., 9.2.

Baldwin, M. E., and J. S. Kain, 2006: Sensitivity of several performance measures to displacement error, bias, and event frequency. *Wea. Forecasting*, **21**, 636-648.

Benjamin, S. G., and Coauthors, 2004: An hourly assimilation-forecast cycle: The RUC. *Mon. Wea. Rev*., **32**, 495-518.

Benjamin, S., S. S. Weygandt, J. M. Brown, T. G. Smirnova, D. Devenyi, K. J. Brundage, G. A. Grell, S. Peckham, T. W. Schlatter, T. L. Smith, and G. S. Manikin, 2007: From the radar-enhanced RUC to the WRF-based Rapid Refresh. *22nd Conference on Weather Analysis and Forecasting/18th Conference on Numerical Weather Prediction*, Park City, UT, Amer. Meteor. Soc., J3.4.

Bothwell, P. D., J. A. Hart, and R. L. Thompson, 2002: An integrated three-dimensional objective analysis scheme in use at the Storm Prediction Center. Preprints, *21st Conf. on Severe Local Storms,* San Antonio, TX, Amer. Meteor. Soc., J117–J120.

Bright, D. R. and M. S. Wandishin, 2006: Post Processed Short Range Ensemble Forecasts of Severe Convective Storms. *Preprints*, *18th Conf. Probability and Statistics in the Atmos. Sciences*, Atlanta, GA., Amer. Meteor. Soc.

Bryan, G. H., J. C. Wyngaard, and J. M. Fritsch, 2003: Resolution requirements for the simulation of deep moist convection. *Mon. Wea. Rev*., **131**, 2394-2416.

Bunkers, M. J., M. R. Hjelmfelt, and P. L. Smith, 2006a: An observational examination of long-lived supercells. Part I: Characteristics, evolution, and demise. *Wea. Forecasting*, **21**, 673-688.

Bunkers, M. J., J. S. Johnson, L. J. Czepyha, J. M. Grzywacz, B. A. Klimowski, and M. R. Hjelmfelt, 2006: An observational examination of long-lived supercells. Part II: Environmental conditions and forecasting. *Wea. Forecasting*, **21**, 689-714.

Charba, J. P. and F. G. Samplatsky, 2009: Operational 2-h thunderstorm guidance forecasts to 24 hours on a 20-km grid. *23rd Conference on Weather Analysis and Forecasting/19th Conference on Numerical Weather Prediction*, Omaha, NE, Amer. Meteor. Soc., 15B.5.

Clark, A. J., W. A. Gallus Jr., M. Xue, and F. Kong, 2009: A comparison of precipitation forecast skill between small convection-allowing and large convection-parameterizing ensembles. *Wea. Forecasting*, **24**, 1121-1140.

Coniglio, M. C., K. L. Elmore, J. S. Kain, S. J. Weiss, M. Xue, M. L. Weisman, 2010: Evaluation of WRF model output for severe weather forecasting from the 2008 NOAA Hazardous Weather Testbed spring experiment. *Wea. Forecasting,* **25**, 408-427.

Craven, J. P., and H. E. Brooks, 2004: Baseline Climatology of Sounding Derived Parameters Associated with Deep Moist Convection. *Nat. Wea. Digest*, 28, 13-24.

Davis, C. and Coauthors, 2004: The bow echo and MCV experiment: Observations and opportunities. *Bull. Amer. Meteor. Soc*., **85**, 1075-1093.

Davis, C. A., B. G. Brown, R. Bullock, and J. Halley-Gotway, 2009: The method for object-based diagnostic evaluation (MODE) applied to numerical forecasts from the 2005 NSSL/SPC spring program. *Wea. Forecasting*, **24**, 1252-1267.

Done, J., C. Davis, and M. Weisman, 2004: The next generation of NWP: Explicit forecasts of convection using the Weather Research and Forecasting (WRF) model. *Atmos. Sci. Lett.*, **5** (6), 110–117.

Du, J., J. McQueen, G. DiMego, T. Black, H. Juang, E. Rogers, B. Ferrier, B. Zhou, Z. Toth and M. S. Tracton, 2004: The NOAA/NWS/NCEP short-range ensemble forecast (SREF) system: evaluation of an initial condition vs. multi-model physics ensemble approach. *Preprints, Sixteenth Conf. on Numerical Weather Prediction,* Seattle, Washington, Amer. Meteor Soc., Seattle, WA.

Du, J., G. DiMego, J. McQueen, Z. Toth, S. Tracton, B. Zhou, D. Jovic, G. Manikin, B. Ferrier, E. Rogers, H. Juang, H. Y. Chuang, D. Stensrud, S. J. Weiss, R. H. Grumm, P. Manousos, and S. Silberberg, 2007: 12 Years of NCEP short-range ensemble forecasting (SREF) system from 1995 to 2006**.** *22nd Conference on Weather Analysis and Forecasting/18th Conference on Numerical Weather Prediction*, Park City, UT, Amer. Meteor. Soc., J4.2

Duda, J. D., and W. A. Gallus, Jr., 2010: Spring and summer Midwestern severe weather reports in supercells compared to other morphologies. *Wea. Forecasting*, **25**, 190-206.

Elmore, K. L., D. J. Stensrud, and K. C. Crawford, 2002: Explicit cloud-scale models for operational forecasts: A note of caution. *Wea. Forecasting,* **17,** 873–884.

Environmental Modeling Center, 2003: The GFS Atmospheric Model. NCEP Office Note 442, Global Climate and Weather Modeling Branch, EMC, Camp Springs, Maryland. (Available at http://www.emc.ncep.noaa.gov/officenotes/newernotes/on442.pdf)

Fahey, T. and D. Rodenhuis 2004: Continual evolution of CCFP – User needs for extended range prediction. *11th Conference on Aviation, Range, and Aerospace Meteorology,* Hyannis, MA, Amer. Met. Soc.

Fritsch, J. M., R. A. Houze, Jr., R. Adler, H. Bluestein, L. Bosart, J. Brown, F. Carr, C. Davis, R. H. Johnson, N. Junker, Y-H. Kuo, S. Rutledge, J. Smith, Z. Toth, J. W. Wilson, E. Zipser, D. Zrnic, 1998: Quantitative precipitation forecasting: Report of the eighth prospectus development team, U.S. Weather Research Program. *Bull. Amer. Meteor. Soc*., **79**, 285-299.

Fritsch, J. M., and R. E. Carbone, 2004: Improving quantitative precipitation forecasts in the warm season: A USWRP research and development strategy. *Bull. Amer. Meteor. Soc*., **85**, 955-965.

Gallus, W. A., Jr., N. A. Snook, and E. V. Johnson, 2008: Spring and summer severe weather reports over the Midwest as a function of convective mode: A preliminary study. *Wea. Forecasting*, **23**, 101–113.

Gao, J.-D., M. Xue, K. Brewster, and K. K. Droegemeier, 2004: A three-dimensional variational data analysis method with recursive filter for Doppler radars. *J. Atmos. Ocean. Tech*., **21**, 457-469.

Grasso, L. D., M. Sengupta, J. F. Dostalek, R. Brummer, and M. DeMaria, 2008a: Synthetic satellite imagery for current and future environmental satellites. *Int. J. Remote Sensing*, **29,** 1366-5901.

Grasso, L. D., M. Sengupta, J. F. Dostalek, R. Brummer, and M. DeMaria, 2008b: Synthetic satellite imagery for current and future environmental satellites. *Int. J. of Remote Sensing*, **29,** 4373-4384.

Gurka, J. J**.,** S. J. Goodman, T. J. Schmit, C. W. Siewert, M. DeMaria, and G. T. Stano, 2010: Warning related satellite products to be demonstrated in the GOES-R Proving Ground. *25th Conf. on Severe Local Storms*, Denver, CO, Amer. Meteor. Soc., 7B.6.

Harless, A. R., I. L. Jirak, R. S. Schneider, S. J. Weiss, M. Xue, and F. Kong, 2010: A report and feature-based verification study of the CAPS 2008 storm-scale ensemble forecasts for severe convective weather. *25th Conf. on Severe Local Storms*, Denver, CO, Amer. Meteor. Soc., 13B2.

Harrold, M., T. L. Jensen, B. G. Brown, S. J. Weiss, P. T. Marsh, M. Xue, F. Kong, A. Clark, K. W. Thomas, J. S. Kain, M. C. Coniglio, and R. S. Schneider, 2010: Spatial verification of convective systems during the Hazardous Weather Testbed 2010 Spring Experiment. *25th Conf. on Severe Local Storms*, Denver, CO, Amer. Meteor. Soc., P7.9.

Hohenegger, C., and C. Schär, 2007: Atmospheric predictability at synoptic versus cloud-resolving scales. *Bull. Amer. Meteor. Soc.,* **88,** 1783–1793.

Homar V., D. J. Stensrud, J. J. Levit, and D. R. Bright, 2006: Value of human-generated perturbations in short-range ensemble forecasts of severe weather. *Wea. Forecasting*, **21**, 347-363.

Huhn, J., M. Duquette, D. R. Bright, S. J. Weiss, R. S. Schneider, J. Racy, and B. Sherman, 2009: Use of operationally available weather forecast products beyond 6 hours for air traffic strategic planning. *13th Conf. on Aviation, Range, and Aerospace Meteorology*, Phoenix, AZ, Amer. Meteor. Soc., 4.1.

Huhn**,** J., M. Duquette, D. Bright, J. Racy, G. Grosshans, and B. Sherman, 2010: Translating an Ensemble Weather Forecast into Operational Disruption for the National Airspace System**.** *14th Conf. on Aviation, Range, and Aerospace Meteorology*, Atlanta, GA, Amer. Meteor. Soc., 178.

Janjic, Z. I., 2003: A nonhydrostatic model based on a new approach. *Meteor. Atmos. Phys*., **82**, 271–285.

Jensen, T., B. Brown, M. Coniglio, J. S. Kain, S. J. Weiss, and L. Nance, 2010a: Evaluation of experimental forecasts from the 2009 NOAA Hazardous Weather Testbed spring experiment using both traditional and spatial methods. *20th Conf. on Probability and Statistics*, Atlanta, GA, Amer. Meteor. Soc., 527.

Jensen, T. L., M. Harrold, B. G. Brown, S. J. Weiss, P. T. Marsh, M. Xue, F. Kong, A. J. Clark, K. W. Thomas, J. S. Kain, and R. S. Schneider, 2010b: An Overview of the objective evaluation performed during the Hazardous Weather Testbed (HWT) 2010 Spring Experiment. *25th Conf. on Severe Local Storms*, Denver, CO, Amer. Meteor. Soc., 13B.1.

Jirak, I. L., S. J. Weiss, C. J. Melick, P. T. Marsh, J. S. Kain, A. J. Clark, M. Xue, F. Kong, and K. W. Thomas, 2010: Evaluation of the performance and distribution of hourly maximum fields from storm-scale ensemble forecasts. *25th Conf. on Severe Local Storms*, Denver, CO, Amer. Meteor. Soc., 13B.3.

Johns, R. H., 1993: Meteorological conditions associated with bow echo development in convective storms. *Wea. Forecasting*, **8**, 294-299.

Johns, R. H., and C. A. Doswell III, 1992: Severe local storms forecasting. *Wea. Forecasting*, **7,** 588-612.

Kain, J. S., P. R. Janish, S. J. Weiss, M. E. Baldwin, R. S. Schneider, and H. E. Brooks, 2003a: Collaboration between forecasters and research scientists at the NSSL and SPC: The Spring Program. *Bull. Amer. Meteor. Soc*., **84**, 1797–1806.

Kain, J. S., M. E. Baldwin, S. J. Weiss, P. R. Janish, M. P. Kay, and G. Carbin, 2003b: Subjective verification of numerical models as a component of a broader interaction between research and operations. *Wea. Forecasting*, **18**, 847–860.

Kain, J. S., S. J. Weiss, D. R. Bright, M. E. Baldwin, J. J. Levit, G. W. Carbin, C. S. Schwartz, M. L. Weisman, K. K. Droegemeier, D. B. Weber, and K. W. Thomas, 2008: Some practical considerations regarding horizontal resolution in the first generation of operational convection-allowing NWP. *Wea. Forecasting*, **23**, 931-952.

Kain, J. S., M. Xue, M. C. Coniglio, S. J. Weiss, F. Kong, T. L. Jensen, B. G. Brown, J. Gao, K. Brewster, K. W. Thomas, Y. Wang, C. S. Schwartz, and J. J. Levit, 2010a: Assessing advances in the assimilation of radar data and other mesoscale observations within a collaborative forecasting-research environment. *Wea. Forecasting,* **25**, 1510-1521.

Kain, J. S., S. R. Dembek, S. J. Weiss, J. L. Case, J. J. Levit, and R. A. Sobash, 2010b: Extracting unique information from high resolution forecast models: Monitoring selected fields and phenomena every time step. *Wea. Forecasting,* **25**, 1536-1542.

Koch, S. E., B. Ferrier, M. Stolinga, E. Szoke, S. J. Weiss, and J. S. Kain, 2005: The use of simulated radar reflectivity fields in the diagnosis of mesoscale phenomena from high-resolution WRF model forecasts. *Preprints, 12th Conf. on Mesoscale Processes*, Albuquerque, NM, Amer. Meteor. Soc., J4J.7.

Kong, F., K. K. Droegemeier, and N. L. Hickmon, 2006: Multiresolution ensemble forecasts of an observed tornadic thunderstorm system. Part I: Comparison of coarse- and fine-grid experiments. *Mon. Wea. Rev.*, **134**, 807-833.

Kong, F., M. Xue, M. Xue, K. K. Droegemeier, K. W. Thomas, Y. Wang, J. S. Kain, S. J. Weiss, D. Bright, and J. Du, 2008: Real-time storm-scale ensemble forecast experiment - Analysis of 2008 spring experiment data. *24th Conf. Several Local Storms*, Savannah, GA, Amer. Meteor. Soc., 12.3.

Kong**,** F., M. Xue, K. W. Thomas, Y. Wang, K. Brewster, X. Wang, J. Gao, S. J. Weiss, A. Clark, J. S. Kain, and M. C. Coniglio, 2010: Evaluation of CAPS multi-model storm-scale ensemble forecast for the NOAA HWT 2010 Spring Experiment. *25th Conf. on Severe Local Storms*, Denver, CO, Amer. Meteor. Soc., P4.18.

Lindsey, D. T., L. Grasso, J. Sieglaff, J. A. Otkin, R. M. Rabin, and J. S. Kain, 2010: Simulating GOES-R satellite imagery from WRF output. *25th Conf. on Severe Local Storms*, Denver, CO, Amer. Meteor. Soc., P7.5.

Manning, K. W., M. L. Weisman and A. J. Clark, 2010: Neighborhood-based evaluation of WRF-ARW precipitation forecasts for the 2010 NOAA Hazardous Weather Testbed Spring Experiment. *25th Conf. on Severe Local Storms*, Denver, CO, Amer. Meteor. Soc., 7B.5.

Marsh, P. T., J. S. Kain, S. J. Weiss, I. L. Jirak, R. Sobash, F. Kong, K. W. Thomas, and M. Xue, 2010: Investigating a fundamental component of a Warn-on-Forecast system in a collaborative real-time experiment. *25th Conf. on Severe Local Storms*, Denver, CO, Amer. Meteor. Soc., 14.4.

McCaul, E. W., Jr., S. J. Goodman, K. M. LaCasse, and D. J. Cecil, 2009: Forecasting lightning threat using cloud-resolving model simulations. *Wea. Forecasting*, **24**, 709-729.

Melick, C. J., I. L. Jirak, S. J. Weiss, A. J. Clark, P. T. Marsh, J. S. Kain, M. Xue, F. Kong, and K. W. Thomas, 2010: An environmental climatology of the CAPS Storm-Scale Ensemble Forecast system during the 2010 HWT Spring Experiment. *25th Conf. on Severe Local Storms*, Denver, CO, Amer. Meteor. Soc., 13B.5.

Miller, S. D. Jr., G. W. Carbin, J. S. Kain, E. W. McCaul, C. J. Melick, and A. R. Dean, 2010: Preliminary investigation into lightning hazard prediction from high resolution model output. *25th Conf. on Severe Local Storms*, Denver, CO, Amer. Meteor. Soc., 4B.1.

Moller, A. R., C. A. Doswell III, M. P. Foster, and G. R. Woodall, 1994: The operational recognition of supercell thunderstorm environments and storm structures. *Wea. Forecasting*, **9**, 327-347.

Moller, A. R., 2001: Severe local storms forecasting. In *Severe Convective Storms*, Edited by C. A. Doswell III. AMS Meteorological Monograph Series, 28 (50), Amer. Meteor. Soc., Boston, MA., 433-480.

Olson, D. A., N. W. Junker, and B. Korty, 1995: Evaluation of 33 years of quantitative precipitation forecasting at the NMC. *Wea. Forecasting,* **10**, 498-511.

Otkin, J. A. and T. J. Greenwald, 2008: Comparison of WRF model-simulated and MODIS-derived cloud data. *Mon. Wea. Rev.*, **136,** 1957-1970.

Otkin, J. A., T. J. Greenwald, J. Sieglaff, and H.-L. Huang, 2009: Validation of a large-scale simulated brightness temperature dataset using SEVIRI satellite observations. *J. Appl. Meteor. Climatol.*, **48,** 1613-1626.

Pinto, J., J. Williams, M. Steiner, D. Albo, S. Dettling, W. Dupree, D. Morse, H. Iskenderian, T. Xiaofeng, M. Wolfson, C. Reiche, S. Weygandt, S. Benjamin, and C. Alexander, 2010: Advances in the collaborative storm prediction for aviation (CoSPA), *14th Conference on Aviation, Range, and Aerospace Meteorology*, Atlanta, GA, Amer. Meteor. Soc., J11.2.

Przybylinski, R. W., 1995: The bow echo: Observations, numerical simulations, and severe weather detection methods. *Wea. Forecasting*, **10**, 203-218.

Rasmussen, E. N., and D. O. Blanchard, 1998: A baseline climatology of sounding-derived supercell and tornado forecast parameters. *Wea. Forecasting,* **13,** 1148–1164.

Rogers, E., G. DiMego, T. Black, M. Ek, B. Ferrier, G. Gayno, Z. Janjic, Y. Lin, M. Pyle, V. Wong, W. S. Wu, and J. Carley, 2009: The NCEP North American Mesoscale modeling system: Recent changes and future plans. *23rd Conference on Weather Analysis and Forecasting/19th Conference on Numerical Weather Prediction*, Omaha, NE, Amer. Meteor. Soc., 2A.4.

Schwartz, C. S., J. S. Kain, S. J. Weiss, M. Xue, D. R. Bright, F. Kong, K. W. Thomas, J. J. Levit, M. C. Coniglio, 2009: Next-day convection-allowing WRF model guidance: A second look at 2-km versus 4-km grid spacing. *Mon. Wea. Rev.*, **137**, 3351-3372.

Schwartz, C. S., J. S. Kain, S. J. Weiss, M. Xue, D. R. Bright, F. Kong, K. W. Thomas, J. J. Levit, M. C. Coniglio, and M. S. Wandishin, 2010: Toward improved convection-allowing ensembles: Model physics sensitivities and optimizing probabilistic guidance with small ensemble membership. *Wea Forecasting*, **25,** 263-280.

Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, W. Wang, and J. G. Powers, 2005: A description of the Advanced Research WRF version 2. NCAR Tech Note NCAR/TN-468_STR, 88 pp. [Available from UCAR Communications, P. O. Box 3000, Boulder, CO 80307.]

Slemmer, J. W., 2007: Skill of the Aviation Weather Center's collaborative convective forecast product (CCFP). 16th Conference on Applied Climatology, San Antonio, TX, Amer. Meteor. Soc., 3.8.

Sobash, R., J. S. Kain, D. R. Bright, A. R. Dean, M. C. Coniglio, S. J. Weiss, and J. J. Levit, 2009: Forecast guidance for severe thunderstorms based on identification of extreme phenomena in convection-allowing model forecasts *23rd Conference on Weather Analysis and Forecasting/19th Conference on Numerical Weather Prediction*, Omaha, NE, Amer. Meteor. Soc., 4B.6.

Stensrud, D. J., L. J. Wicker, K. E. Kelleher, M. Xue, M. P. Foster, J. T. Schaefer, R. S. Schneider, S. G. Benjamin, S. S. Weygandt, J. T. Ferree, and J. P. Tuell, 2009: Convective-scale warn-on-forecast system. *Bull. Amer. Meteor. Soc.*, **90**, 1487-1499.

Stumpf, G. J., B. C. Baranowski, D. M. Kingfield, K. M. Kuhlman, K. L. Manross, C. W. Siewert, T. M. Smith, and S. Stough, 2010: Real-time severe convective weather warning exercises at the Experimental Warning Program 2010 (EWP2010). *25th Conf. on Severe Local Storms*, Denver, CO, Amer. Meteor. Soc., 7B.2

Stumpf, G. J., T. M. Smith, K. Manross, and D. L. Andra, 2008: The Experimental Warning Program 2008 spring experiment at the NOAA Hazardous Weather Testbed. *24th Conf. on Severe Local Storms*, Savannah, GA, Amer. Meteor. Soc., 8A.1

Szoke, E., and Coauthors, 2009: An overview of the GOES-R proving ground: Current forecaster interactions and future plans. *23rd Conf. on Weather Analysis and Forecasting/19th Conf. on Numerical Weather Prediction*, Omaha, NE., Amer. Meteor. Soc./NWA, 12B3.

Thompson, R. L., R. Edwards, J. A. Hart, K. L. Elmore, and P. M. Markowski, 2003: Close proximity soundings within supercell environments obtained from the Rapid Update Cycle., **18,** *Wea. Forecasting*, 1243–1261.

Thompson, R. L., C. M. Mead, and R. Edwards, 2007: Effective storm-relative helicity and bulk shear in supercell thunderstorm environments. *Wea. Forecasting*, **22**, 102-115.

Thompson, R. L., J. S. Grams, and J. Prentice, 2008: Synoptic environments and convective modes associated with significant tornadoes in the continental United States. Preprints, *24th Conf. on Severe Local Storms*, Savannah, GA., Amer. Meteor. Soc.

Thompson, R. L., B. T. Smith, J. S. Grams, A. R. Dean, and C. Broyles, 2010: Climatology of near-storm environments with convective modes for significant severe thunderstorms in the contiguous United States. *25th Conf. on Severe Local Storms*, Denver, CO, Amer. Meteor. Soc., 6B.6

Vasiloff, S. V., K. W. Howard, R. M. Rabin, H. E. Brooks, D.-J. Seo, J. Zhang, D. H. Kitzmiller, M. G. Mullusky, W. F. Krajewski, E. A. Brandes, B.G. Brown, D. S. Berkowitz, J. A. McGinley, and R. J. Kuligowski, 2007: Improving QPE and very short term QPF: An initiative for a community-wide integrated approach. *Bull. Amer. Meteor. Soc*., **88**, 1899-1911.

Weckwerth, T. W., D. B. Parsons, S. E. Koch, J. A. Moore, M. A. LeMone, B. B. Demoz, C. Flamant, B. Geerts, J. Wang, and W. F. Feltz, 2004: An overview of the International H_2O Project (IHOP_2002) and some preliminary highlights. *Bull. Amer. Meteor. Soc.*, **85**, 253-277.

Weisman, M. L., C. Davis, W. Wang, K. W. Manning, and J. B. Klemp, 2008: Experiences with 0–36-h explicit convective forecasts with the WRF-ARW model. *Wea. Forecasting*, **23**, 407–437.

Weisman, M. L., C. Evans, and L. Bosa, 2010: The 8 May 2009 "Super Derecho": Analysis of a 3 km WRF-ARW realtime forecast. *25th Conf. on Severe Local Storms*, Denver, CO, Amer. Meteor. Soc., 3B4.

Weiss, S. J., J. S. Kain, J. J. Levit, M. E. Baldwin, and D. R. Bright, 2004: Examination of several different versions of the WRF model for the prediction of severe convective weather: The SPC/NSSL Spring Program 2004. *Preprints, 22nd Conf. on Severe Local Storms,* Hyannis, MA, Amer. Meteor. Soc., 17.1.

Weiss, S. J., J. S. Kain, D. R. Bright, J. J. Levit, G. W. Carbin, M. E. Pyle, Z. I. Janjic, B. S. Ferrier, J. Du, M. L. Weisman, and M. Xue, 2007: The NOAA Hazardous Weather Testbed: Collaborative testing of ensemble and convection-allowing WRF models and subsequent transfer to operations at the Storm Prediction Center. *22nd Conf. Wea. Anal. Forecasting/18th Conf. Num. Wea. Prediction*, Park City, Utah, Amer. Meteor. Soc., 6B.4.

Weiss, S. J., M. E. Pyle, Z. Janjic, D. R. Bright, J. S. Kain, and G. J. DiMego, 2008:
The operational High Resolution Window WRF model runs at NCEP: Advantages of multiple model runs for severe convective weather forecasting. *24th Conf. Several Local Storms*, Savannah, GA, Amer. Meteor. Soc., P10.8.

Weygandt S., and S. Benjamin, 2007: Radar reflectivity-based initialization of precipitation systems using a diabatic digital filter within the Rapid Update Cycle. *22nd Conf. Wea. Anal. Forecasting/18th Conf. Num. Wea. Prediction*, Park City, Utah, Amer. Meteor. Soc.,1B.7.

Wurman, J., L. J. Wicker, Y. P. Richardson, E. N. Rasmussen, P. M. Markowski, D. Dowell, D. W. Burgess, and H. B. Bluestein, 2010: An overview of the VORTEX2 field campaign. *25th Conf. on Severe Local Storms*, Denver, CO, Amer. Meteor. Soc., 5.1.

Xue, M., D.-H. Wang, J.-D. Gao, K. Brewster, and K. K. Droegemeier, 2003: The Advanced Regional Prediction System (ARPS), storm-scale numerical weather prediction and data assimilation. *Meteor. Atmos. Physics*, **82**, 139-170.

Xue, M., F. Kong, D. Weber, K. W. Thomas, Y. Wang, K. Brewster, K. K. Droegemeier, J. S. K. S. J. Weiss, D. R. Bright, M. S. Wandishin, M. C. Coniglio, and J. Du, 2007: CAPS realtime storm-scale ensemble and high-resolution forecasts as part of the NOAA Hazardous Weather Testbed 2007 spring experiment. *22nd Conf. Wea. Anal. Forecasting/18th Conf. Num. Wea. Prediction*, Amer. Meteor. Soc., 3B.1.

Xue, M., F. Kong, K. W. Thomas, J. Gao, Y. Wang, K. Brewster, K. K. Droegemeier, J. Kain, S. Weiss, D. Bright, M. Coniglio, and J. Du, 2008: CAPS realtime storm-scale ensemble and high-resolution forecasts as part of the NOAA Hazardous Weather Testbed 2008 Spring Experiment. *24th Conf. Several Local Storms*, Savannah, GA, Amer. Meteor. Soc., 12.2.

Xue, M., F. Kong, K. W. Thomas, J. Gao, Y. Wang, K. Brewster, K. K. Droegemeier, X. Wang, J. Kain, S. Weiss, D. Bright, M. Coniglio, and J. Du, 2009: CAPS realtime multi-model convection-allowing ensemble and 1-km convection-resolving forecasts for the NOAA Hazardous Weather Testbed 2009 Spring Experiment. *23rd Conf. Wea. Anal. Forecasting/19th Conf. Num. Wea. Prediction*, Omaha, NB, Amer. Meteor. Soc., 6A.2.

Xue, M**.,** F. Kong, K. W. Thomas, Y. Wang, K. Brewster, J. Gao, X. Wang, S. J. Weiss, A. J. Clark, J. S. Kain, M. C. Coniglio, J. Du, T. L. Jensen, and Y. H. Kuo, 2010: CAPS realtime storm scale ensemble and high resolution forecasts for the NOAA Hazardous Weather Testbed 2010 Spring Experiment. *25th Conf. on Severe Local Storms*, Denver, CO, Amer. Meteor. Soc., 7B.3

Zhang, F., A. M. Odins, and J. W. Nielsen-Gammon, 2006: Mesoscale predictability of an extreme warm-season precipitation event. *Wea. Forecasting,* **21,** 149–166.

Appendix A. 2010 EFP Spring Experiment Daily Operations Schedule

Participants in the experiment will create experimental forecast products and conduct evaluation activities in the HWT from 7:30 a.m. – 4:00 p.m. on Monday–Friday. Each afternoon at 3:00 p.m. a daily summary session is held, and each Friday a weekly summary will be conducted. We anticipate that many weekly participants will rotate through the activities in each component (severe, aviation, QPF) during the week, spending 1–2 days in each section. This will allow participants to experience a broad range of convective storm impacts and forecasting challenges, and gain a greater appreciation of the challenges faced by operational forecasters and those tasked with creating improved forecast guidance tools.

Participants are expected to perform forecast and evaluation activities in a collaborative manner, such that results reflect a consensus decision. A break for lunch is scheduled during the ~Noon–12:30 p.m. period, but may eat lunch while conducting program activities or at their discretion any time during the day. Visitors may purchase lunch at a food court located on the south side of the first floor of the NWC. Below is a basic outline of the daily schedule for activities during the experiment.

a. Severe convective storms component

Daily activities conducted in northeast corner of HWT. *Italics denotes Monday-only activities*

7:30 a.m. – 8:00 a.m.: Weekly Orientation. (Some morning forecast and evaluation activities will be truncated on Mondays to permit sufficient time for the orientation.)

7:30 a.m. – 8:15 a.m.: Subjective verification of yesterday's experimental severe weather forecasts compared to severe storm report maps and post-processed "practically perfect" hindcasts.

8:15 a.m. – 10:30 a.m.: In a semi-operational forecasting environment, the severe weather team will use guidance from 00z high resolution WRF and SSEF, and 09z SREF/12z operational models and observational data to formulate probabilistic severe storm forecasts valid for the 20–00z and 00–04z time periods. The forecasts will be made over a movable mesoscale domain placed over the part of the central-eastern US where the severe threat is deemed to be greatest and/or substantial forecasting challenges exist. The process will include collaboration discussions between the severe, aviation, and QPF components prior to product completion to enhance consistency among the convective forecasts.

10:30 a.m. – noon: Subjective/objective evaluation of previous day's model guidance compared to observed radar and severe weather reports, focusing on the ability of the models to provide useful guidance to severe weather forecasters.

Noon – 12:30 p.m.: Lunch.

12:30 p.m.–2:30 p.m.: Update two-period severe weather forecasts focusing on use and perceived value of hourly guidance from the HRRR model. CoSPA forecasts are expected to be available in June and guidance from that system may also be examined for the afternoon update forecasts. The process will include collaboration discussions between the severe and aviation components prior to product completion to enhance consistency among the convective forecasts.

2:30 p.m. – 3:00 p.m.: Break and preparation for briefing.

3:00 p.m. – 4:00 p.m.: Daily briefing and discussion of today's forecast and evaluation activities from the severe weather, aviation, and QPF teams, summarizing new insights, preliminary findings, lessons learned, and topic areas needing further examination. On Fridays, a weekly wrap-up is provided.

b. Aviation impacts component

Daily activities conducted in northwest corner of HWT. *Italics denotes Monday-only activities*

7:30 a.m. – 8:00 a.m.: Weekly Orientation. (Some morning forecast and evaluation activities will be truncated on Mondays to permit sufficient time for the orientation.)

7:30 a.m. – 8:15 a.m.: Subjective verification of yesterday's experimental aviation thunderstorm forecasts compared to observed radar data and NAS flight disruption data.

8:15 a.m. – 10:30 a.m.: In a semi-operational forecasting environment, the aviation desk will use guidance from 00z CAMs and SSEF, 09z SREF/12z operational model guidance, and morning HRRR, LAMP, and, after June 1, CoSPA guidance to create probabilistic aviation thunderstorm forecasts of areas with ≥40 dBZ echoes, including delineation of broken or solid lines, at 21, 23, and 01z. In addition, a probabilistic forecast of echo tops ≥250 will be made for only the 23z snapshot time. The forecasts will generally be made over a fixed domain covering parts of the central and eastern US, although this can be adjusted to focus on smaller regions when necessary. The process will include collaboration discussions between the severe, aviation, and QPF components prior to product completion to enhance consistency among the convective forecasts.

10:30 a.m. – noon: Subjective/objective evaluation of previous day's model guidance compared to observed radar (and NAS flight disruption data), focusing on the ability of various guidance tools to provide useful guidance to aviation forecasters.

Noon – 12:30 p.m.: Lunch.

12:30 a.m. – 2:30 p.m.:
Break into two aviation teams

Team 1: Morning Update Team
Update the morning snapshot forecasts using observational data and guidance from the HRRR, LAMP, CoSPA (after June 1), etc. The process will include collaboration discussions between the severe and aviation components prior to product completion to enhance consistency among the convective forecasts.

Team 2: Day 2 Strategic Forecast Team
Using latest SREF output, operational model guidance, and 12z CAM output, issue an experimental probabilistic forecast of ≥40 dBZ echoes over the same central-eastern US fixed domain valid for the Day 2 period of 18–00z. (This may be modified to conform to Collaborative Strategic Planning Process requirements.)

2:30 a.m. – 3:00 p.m.: Break and preparation for briefing.

3:00 a.m. – 4:00 p.m.: Daily briefing and discussion of today's forecast and evaluation activities from the severe weather, aviation, and QPF teams, summarizing new insights, preliminary findings, lessons learned, and topic areas needing further examination. On Fridays, a weekly wrap-up is provided.

c. QPF component

Daily activities conducted in north center part of HWT. *Italics denotes Monday-only activities*

7:30 a.m. – 8:00 a.m.: Weekly Orientation. (Some morning forecast and evaluation activities will be truncated on Mondays to permit sufficient time for the orientation.)

7:30 a.m. – 8:15 a.m.: Subjective verification of yesterday's experimental QPF products compared to NSSL QPE ("truth").

8:15 a.m. – 10:30 a.m.: In a semi-operational forecasting environment, the QPF desk will use guidance from 00z CAMs and SSEF, 09z SREF/12z operational model guidance and observational data to create experimental probabilistic QPF products valid for 18–00z and 00–06z time periods. The forecasts will be over the same mesoscale domain selected for the HWT severe convective weather component, and will be for exceedance thresholds of 0.5" and 1.0" per 6 hrs. In addition, forecasts that contain a probabilistic 1" contour will include a maximum basin-average rainfall amount within the 1" region during the 6 hour period. The process will include collaboration discussions between the severe, aviation, and QPF components prior to product completion to enhance consistency among the convective forecasts.

10:30 a.m. – noon: Subjective/objective evaluation of previous day's experimental model guidance compared to NSSL QPE, focusing on model and product ability to provide useful guidance to QPF forecasters.

Noon – 12:30 p.m.: Lunch.

12:30 p.m. – 2:30 p.m.: QPF participants will work with either the aviation-impacts or severe weather teams during the afternoon forecast update activities.

2:30 p.m. – 3:00 p.m.: Break and preparation for briefing.

3:00 p.m. – 4:00 p.m.: Daily briefing and discussion of today's forecast and evaluation activities from the severe weather, aviation, and QPF teams, summarizing new insights, preliminary findings, lessons learned, and topic areas needing further examination. On Fridays, a weekly wrap-up is provided.

Table 1. Configurations for ARW members. NAMa and NAMf refer to 12 km NAM analysis and forecast, respectively. ARPSa refers to ARPS 3DVAR and cloud analysis

member	IC	BC	Radar data	Microphy	LSM	PBL
arw_cn	00Z ARPSa	00Z NAMf	yes	Thompson	Noah	MYJ
arw_c0	00Z NAMa	00Z NAMf	no	Thompson	Noah	MYJ
arw_m3	arw_cn + random pert	00Z NAMf	yes	Thompson	Noah	MYJ
arw_m4	arw_cn + recursive pert	00Z NAMf	yes	Thompson	Noah	MYJ
arw_m5	arw_cn + em-p1 + recur pert	21Z SREF em-p1	yes	Morrison	RUC	YSU
arw_m6	arw_cn + em-p1_pert	21Z SREF em-p1	yes	Morrison	RUC	YSU
arw_m7	arw_cn + em-p2_pert	21Z SREF em-p2	yes	Thompson	Noah	QNSE
arw_m8	arw_cn – nmm-p1_pert	21Z SREF nmm-p1	yes	WSM6	RUC	QNSE
arw_m9	arw_cn + nmm-p2_pert	21Z SREF nmm-p2	yes	WDM6	Noah	MYNN
arw_m10	arw_cn + rsmSAS-n1_pert	21Z SREF rsmSAS-n1	yes	Ferrier	RUC	YSU
arw_m11	arw_cn – etaKF-n1_pert	21Z SREF etaKF-n1	yes	Ferrier	Noah	YSU
arw_m12	arw_cn + etaKF-p1_pert	21Z SREF etaKF-p1	yes	WDM6	RUC	QNSE
arw_m13	arw_cn – etaBMJ-n1_pert	21Z SREF etaBMJ-n1	yes	WSM6	Noah	MYNN
arw_m14	arw_cn + etaBMJ-p1_pert	21Z SREF etaBMJ-p1	yes	Thompson	RUC	MYNN
arw_m15	arw_cn	00Z NAMf	yes	WDM6	Noah	MYJ
arw_m16	arw_cn	00Z NAMf	yes	WSM	Noah	MYJ
arw_m17	arw_cn	00Z NAMf	yes	Morrison	Noah	MYJ
arw_m18	arw_cn	00Z NAMf	yes	Thompson	Noah	QNSE
arw_m19	arw_cn	00Z NAMf	yes	Thompson	Noah	MYNN

Table 2. Configurations for each individual member with NMM core

member	IC	BC	Radar data	mp_phy	lw_phy	sw-phy	sf_phy
nmm_cn	00Z ARPSa	00Z NAMf	yes	Ferrier	GFDL	GFDL	Noah
nmm_c0	00Z NAMa	00Z NAMf	no	Ferrier	GFDL	GFDL	Noah
nmm_m3	nmm_cn + nmm-n1_pert	21Z SREF nmm-n1	yes	Thompson	RRTM	Dudhia	Noah
nmm_m4	nmm_cn + nmm-n2_pert	21Z SREF nmm-n2	yes	WSM 6-class	RRTM	Dudhia	RUC
nmm_m5	nmm_cn + em-n1_pert	21Z SREF em-n1	yes	Ferrier	GFDL	GFDL	RUC

* For all members: *pbl_physics*=MYJ; *cu_physics*= NONE

Table 3. Configurations for each individual member with ARPS

Member	IC	BC	Radar data	Microphy.	radiation	sf_phy
arps_cn	00Z ARPSa	00Z NAMf	yes	Lin	Chou/Suarez	Force-restore
arps_c0	00Z NAMa	00Z NAMf	no	Lin	Chou/Suarez	Force-restore

* For all members: no cumulus parameterization

Table 4. Configurations of deterministic WRF models. The GSD-HRRR3 is initialized hourly with forecasts to 15 hrs; the EMC-NMM4 is initialized at 00 and 12 UTC with forecasts to 36 hrs; the NCAR-ARW3 is initialized at 00 and 12 UTC with forecasts to 48 hrs; the NSSL-ARW4 is initialized at 00 UTC with forecasts to 36 hrs; and the CAPS-ARW1 is initialized at 00 UTC with forecasts to 30 hrs.

	GSD-HRRR3 (ARW)	**EMC-NMM4**	**NCAR-ARW3**	**NSSL-ARW4**	**CAPS-ARW1**
Horiz. Grid (km)	3.0	4.0	3.0	4.0	1.0
Vertical Levels	50	35	34	35	51
PBL/Turb. Parameterization	MYJ	MYJ	MYJ	MYJ	MYJ
Microphysical Parameterization	Thompson	Ferrier	Thompson	WSM6	Thompson
Radiation (SW/LW)	Dudhia/RRTM	GFDL/GFDL	Goddard/RRTM	Dudhia/RRTM	Goddard/RRTM
Land Surface Model	RUC-Smirnova	Noah	Noah	Noah	Noah
Initial Conditions	13 km RUC	32 km NAM	13 km RUC	40 km NAM	CAPS-3DVAR

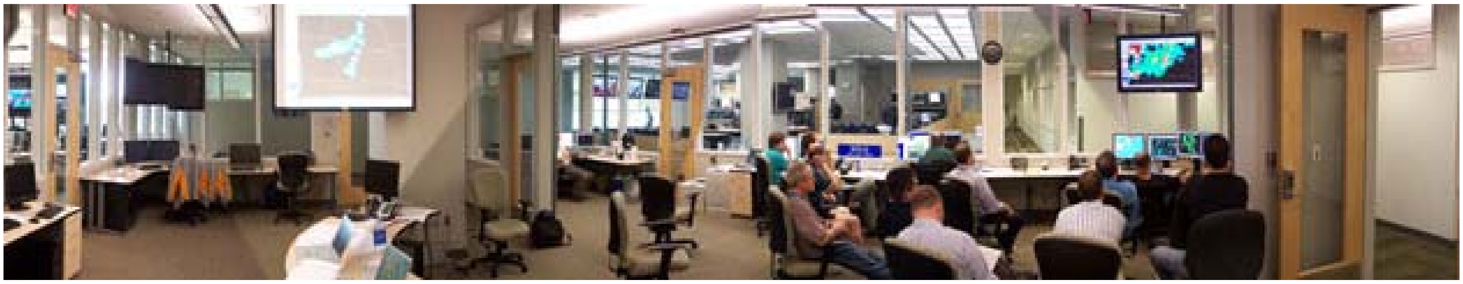

Figure. 1. Wide angle view of the HWT facility in the National Weather Center. The SPC Operations Area is located beyond the glass windows (looking straight ahead), and the WFO-OUN Operations Area is located left of the windows on the extreme left side of the picture.

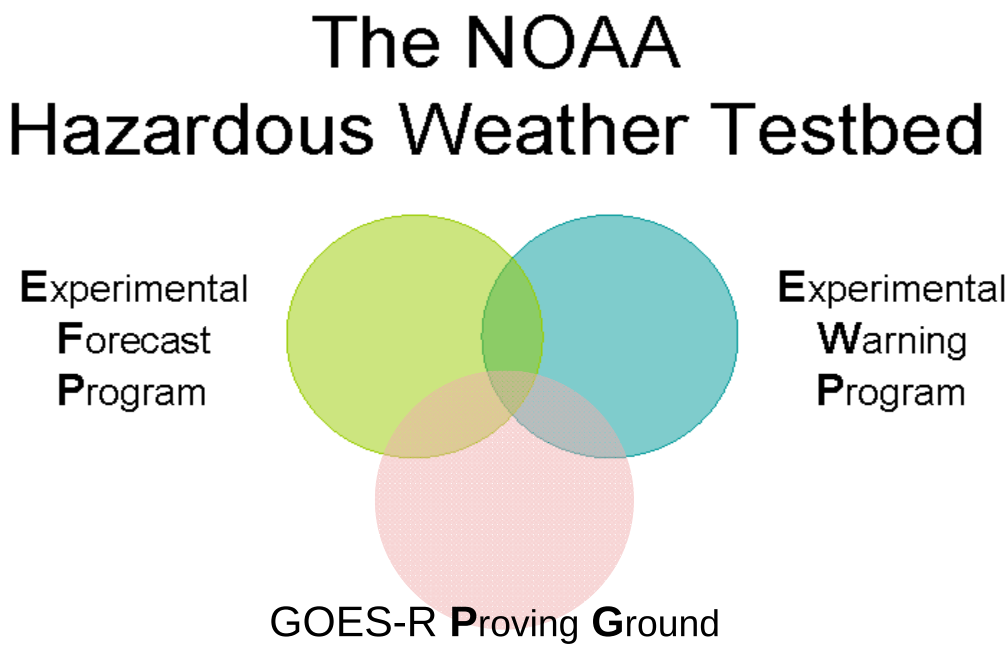

Figure 2. The umbrella of the NOAA Hazardous Weather Testbed (HWT) encompasses three program areas: The Experimental Forecast Program (EFP), the Experimental Warning Program (EWP), and the GOES-R Proving Ground (GOES-R).

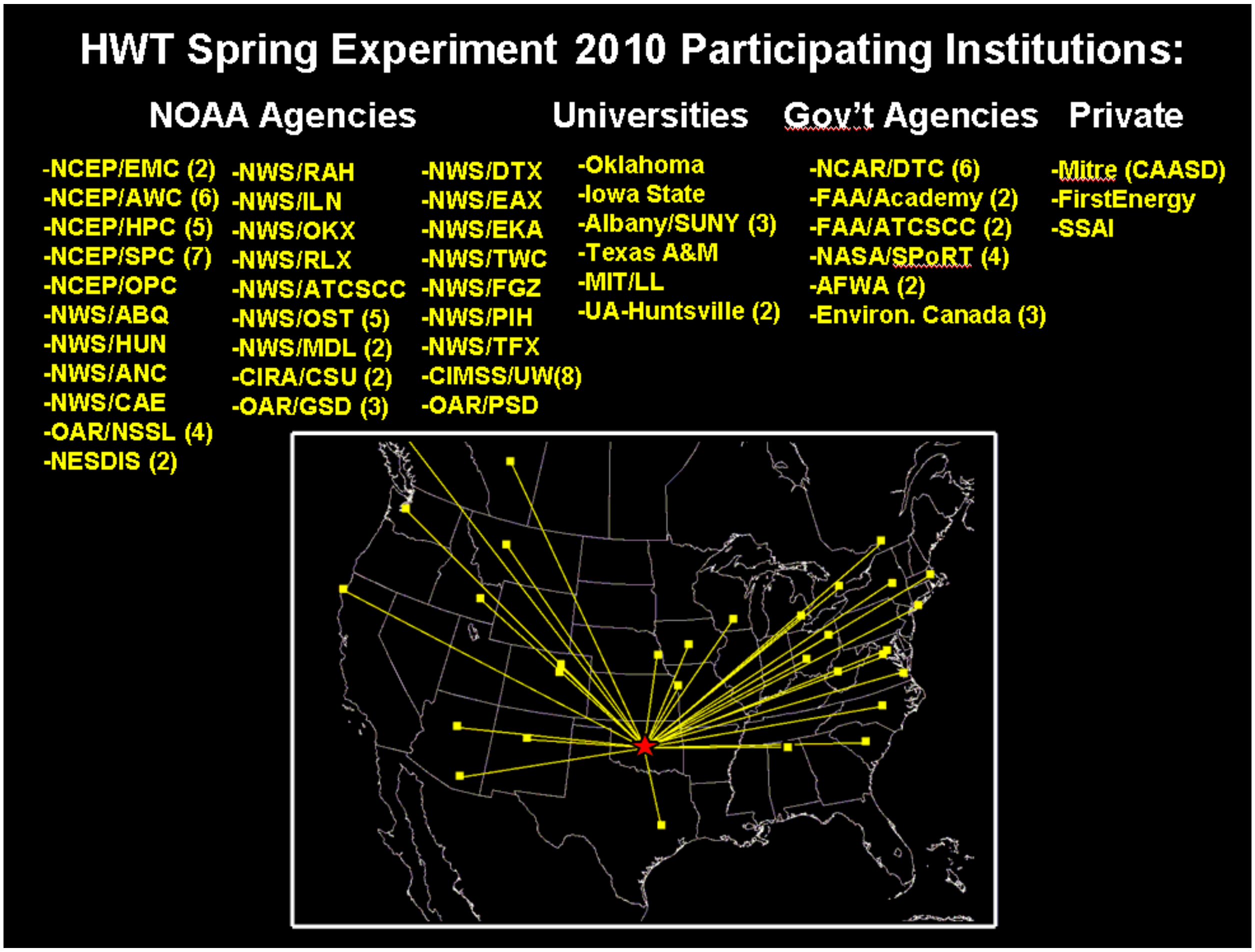

Figure 3. Map showing the locations of 2010 HWT EFP Spring Experiment participant organizations, with tabular listing indicating number of participants from each organization.

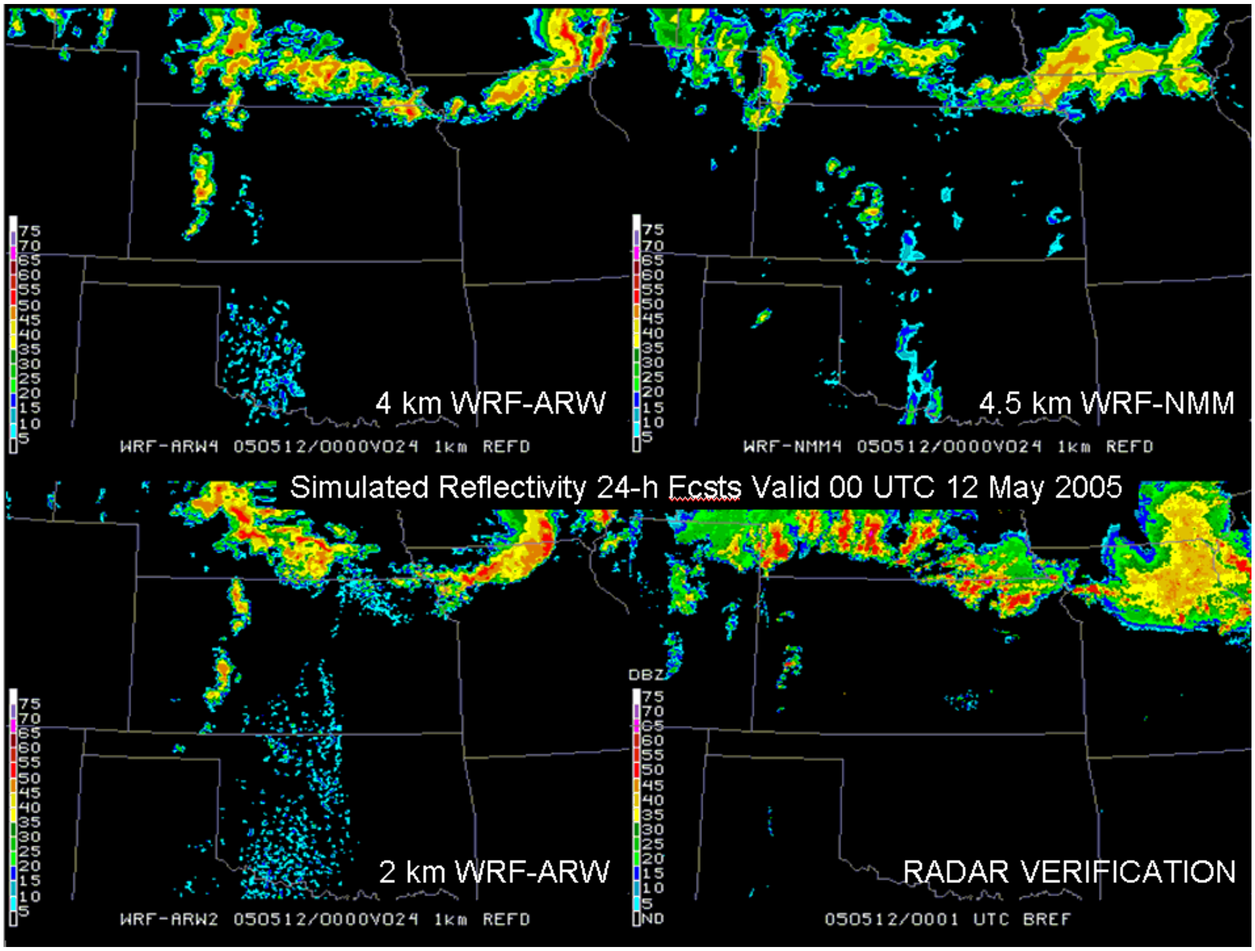

Figure 4. 24-hr simulated 1 km AGL reflectivity forecasts valid at 00 UTC 12 May 2005 from 4 km WRF-ARW (upper left), 4 km WRF-NMM (upper right), 2 km WRF-ARW (lower left), and verifying mosaic base reflectivity (lower right).

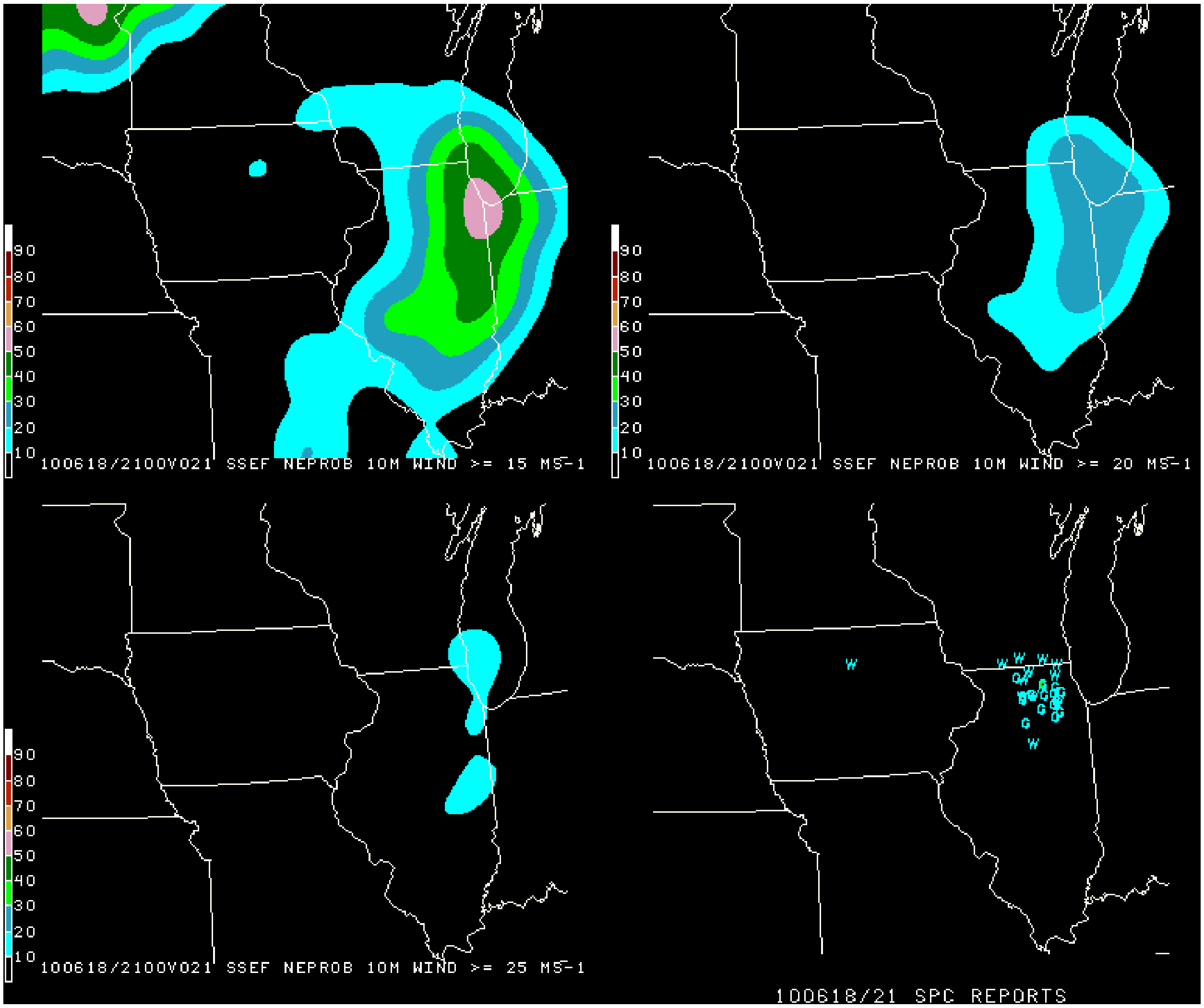

Figure 5. 21-hr SSEF forecasts of neighborhood exceedance probability of 10 m wind speeds ≥30 kt (upper left), ≥40 kt (upper right, and ≥50 kt (lower left) valid at 21 UTC 18 June 2010. Severe weather reports during the hour ending 21 UTC plotted in lower right, with "W" and "G" denoting locations of wind damage and severe wind gusts, respectively.

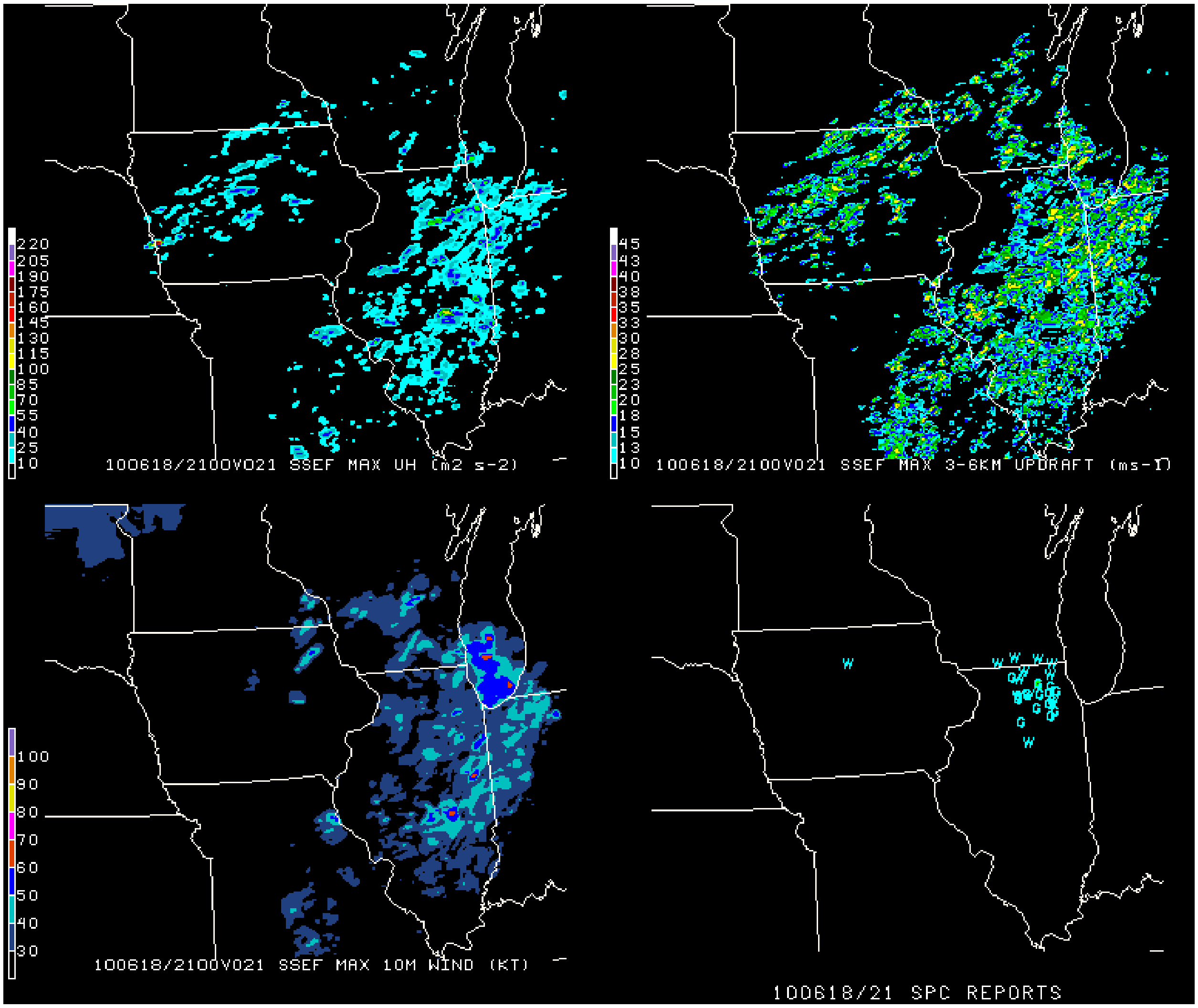

Figure 6. 21-hr SSEF forecasts of maximum from any member of hourly maximum fields of updraft helicity (m^2s^{-2}; upper left), updraft speed (ms^{-1}; upper right), and 10 m wind speed (kt; lower left) valid at 21 UTC 18 June 2010. Severe weather reports during the hour ending 21 UTC plotted in lower right, with "W" and "G" denoting locations of wind damage and severe wind gusts, respectively.

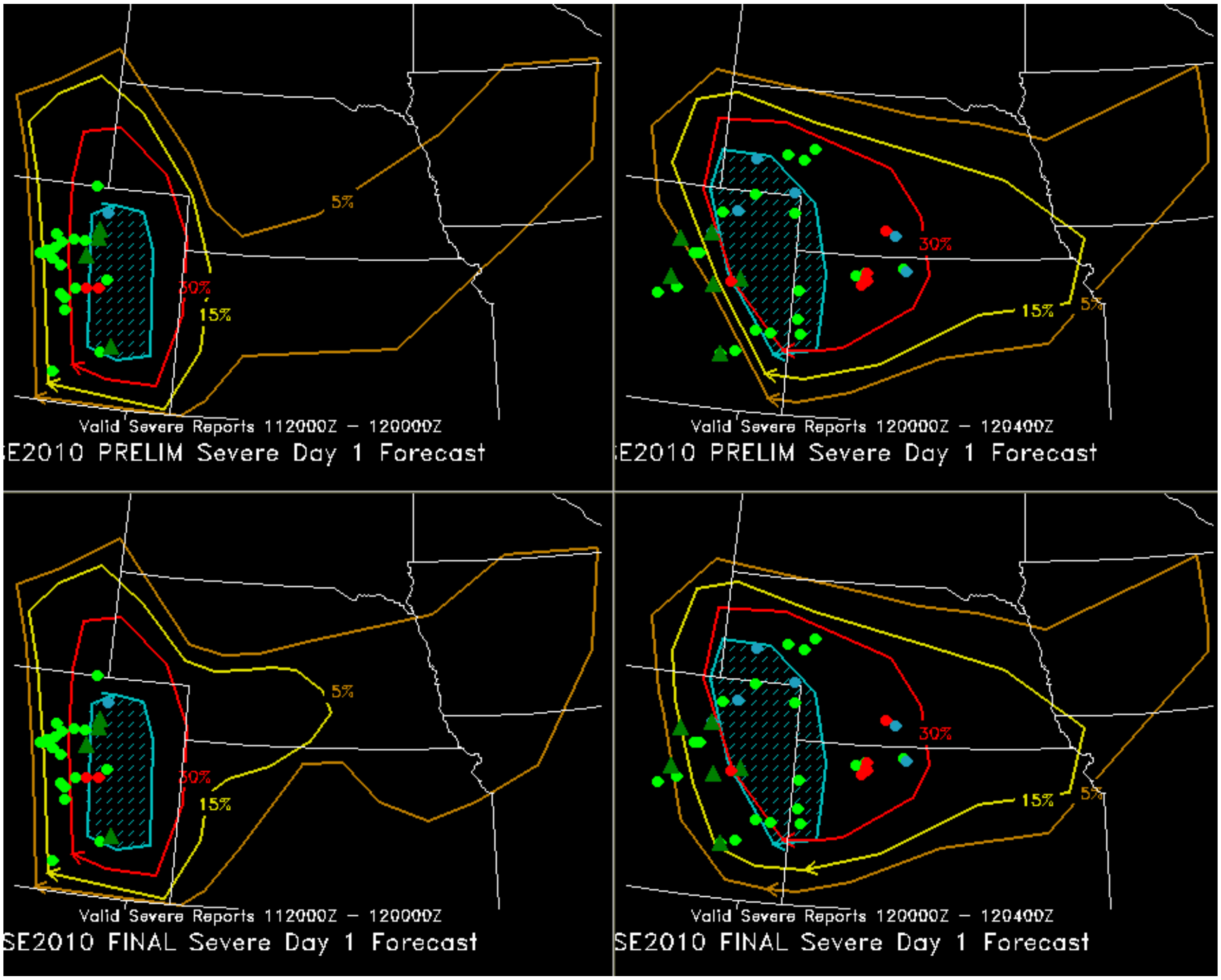

Figure 7. Severe forecast team experimental probabilistic preliminary morning forecasts valid 20-00 UTC (upper left) and 00-04 UTC (upper right) 11-12 June 2010. Final afternoon update forecasts for the same valid periods are in lower panels. Contours indicate 5% (brown), 15% (yellow), and 30% (red) probability values, and cyan hatched area denotes ≥10% probability of significant severe events (≥65 kt wind gusts, ≥2 inch diameter hail, and/or ≥F2 tornado). Severe weather reports during each valid period are indicated by green (hail), blue (wind), and red (tornado) markers.

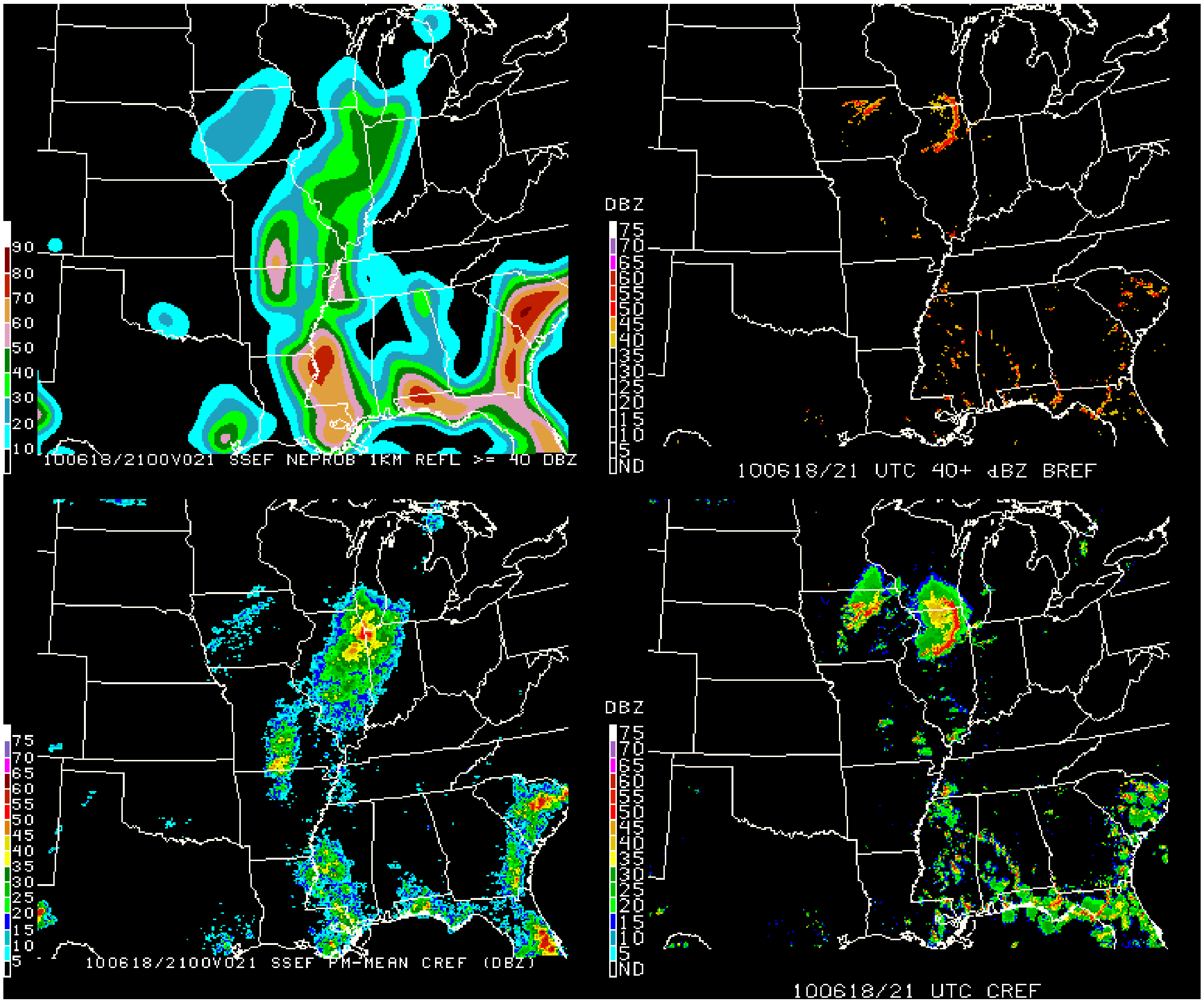

Figure 8. 21-hr SSEF forecasts of neighborhood exceedance probability of 1 km AGL simulated reflectivity ≥40 dBZ (upper left) and probability matched mean composite reflectivity (dBZ; lower left) valid at 21 UTC 18 June 2010. Verifying observed base reflectivity ≥40 dBZ (upper right) and observed composite reflectivity (dBZ; lower right).

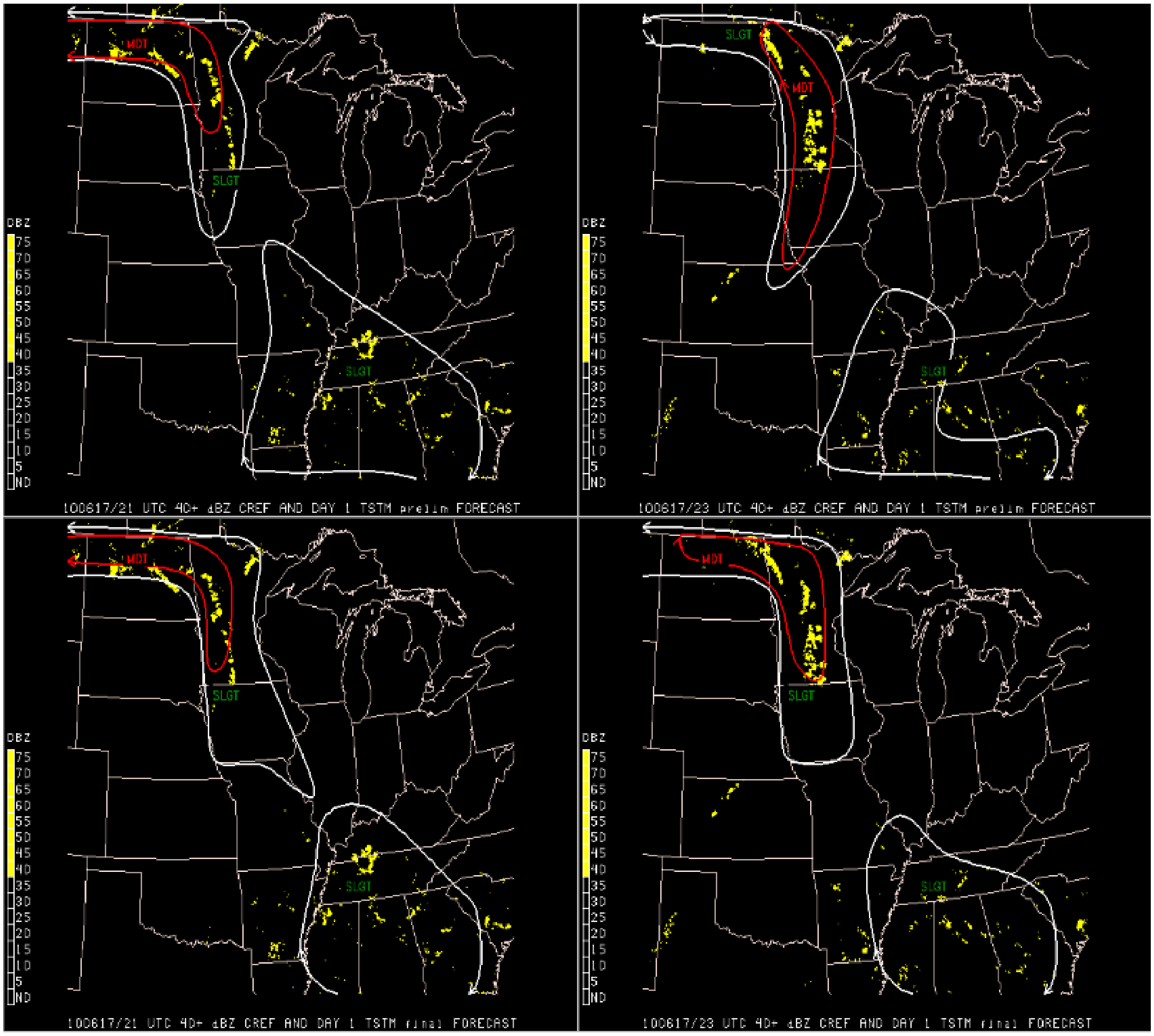

Figure 9. Aviation forecast team experimental probabilistic preliminary morning forecasts valid 21 UTC (upper left) and 23 UTC (upper right) 17 June 2010. Final afternoon update forecasts for the same valid periods are in lower panels. Contours indicate 25% (white) and 50% (red) coverage of thunderstorms at the snapshot times. Yellow dots are verifying lightning strikes occurring ±15 minutes from each forecast time.

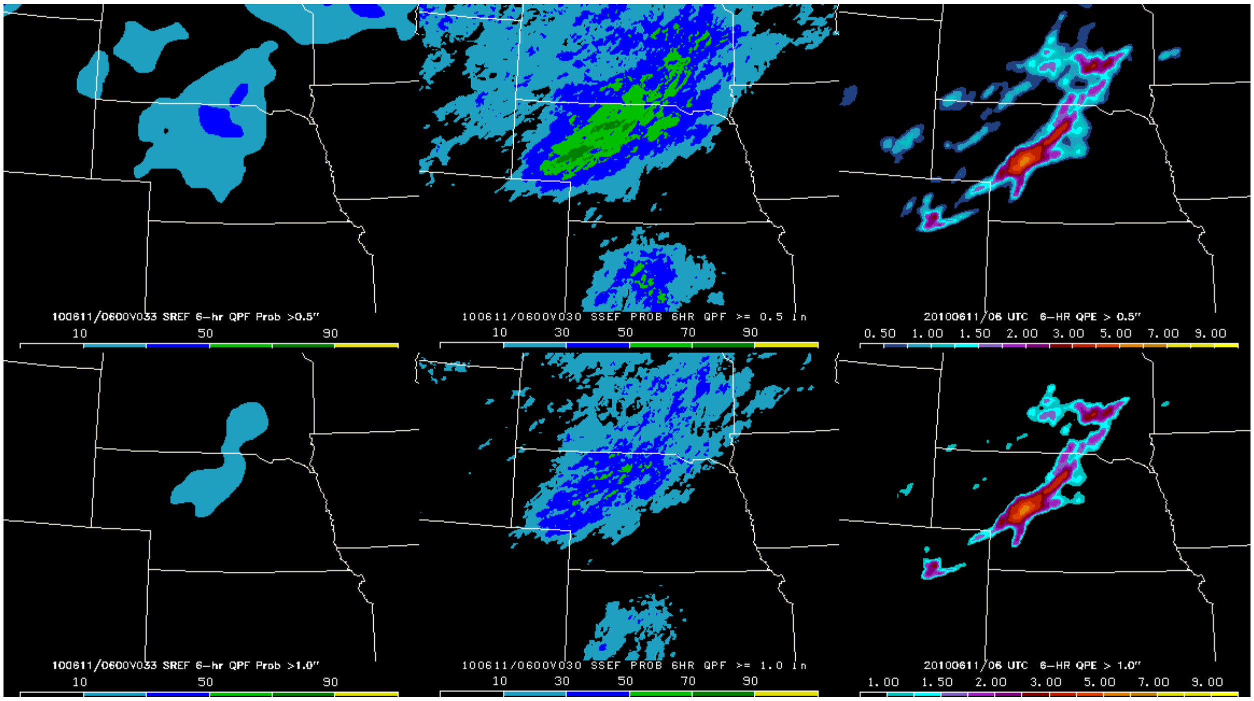

Figure 10. 33-hr exceedance probability forecasts from SREF (left column) and SSEF (middle column) for ≥0.50 inch (top row) and ≥1.0 inch (bottom row) for 6-hr period ending at 06 UTC 11 June 2010. Verifying QPE images are in right column.

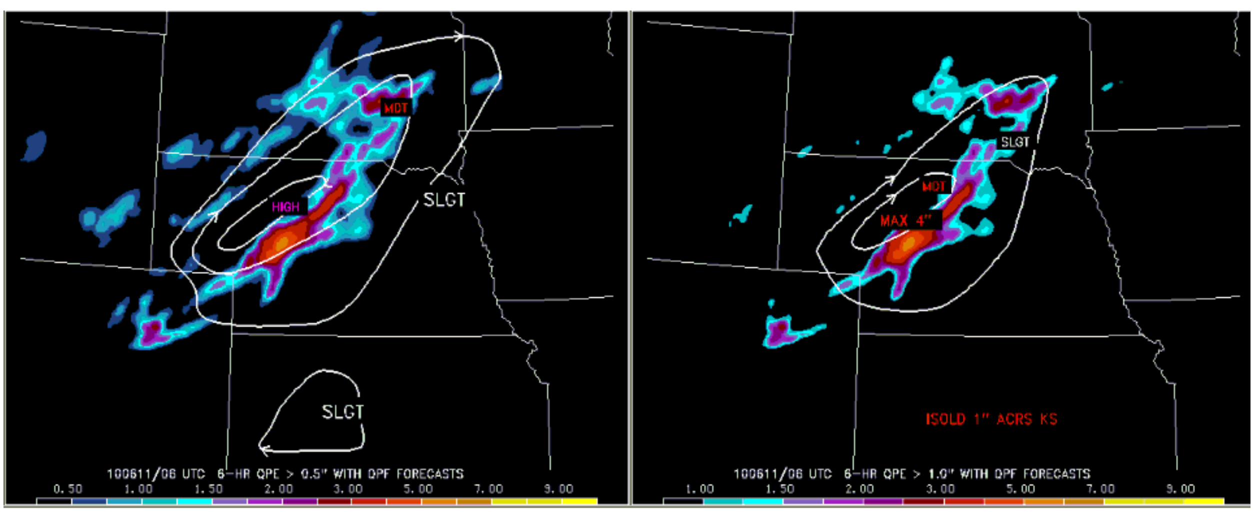

Figure 11. QPF forecast team experimental probabilistic morning forecasts valid 00-06 UTC 11 June 2010 for ≥0.50 inch (left) and ≥1.0 inch (right). Outer white contour indicates a team forecast of 25% exceedance probability, with subsequent contours inside 25% contour denoting 50% and 75% probability lines. Verifying QPE images are shown by color-filled areas.

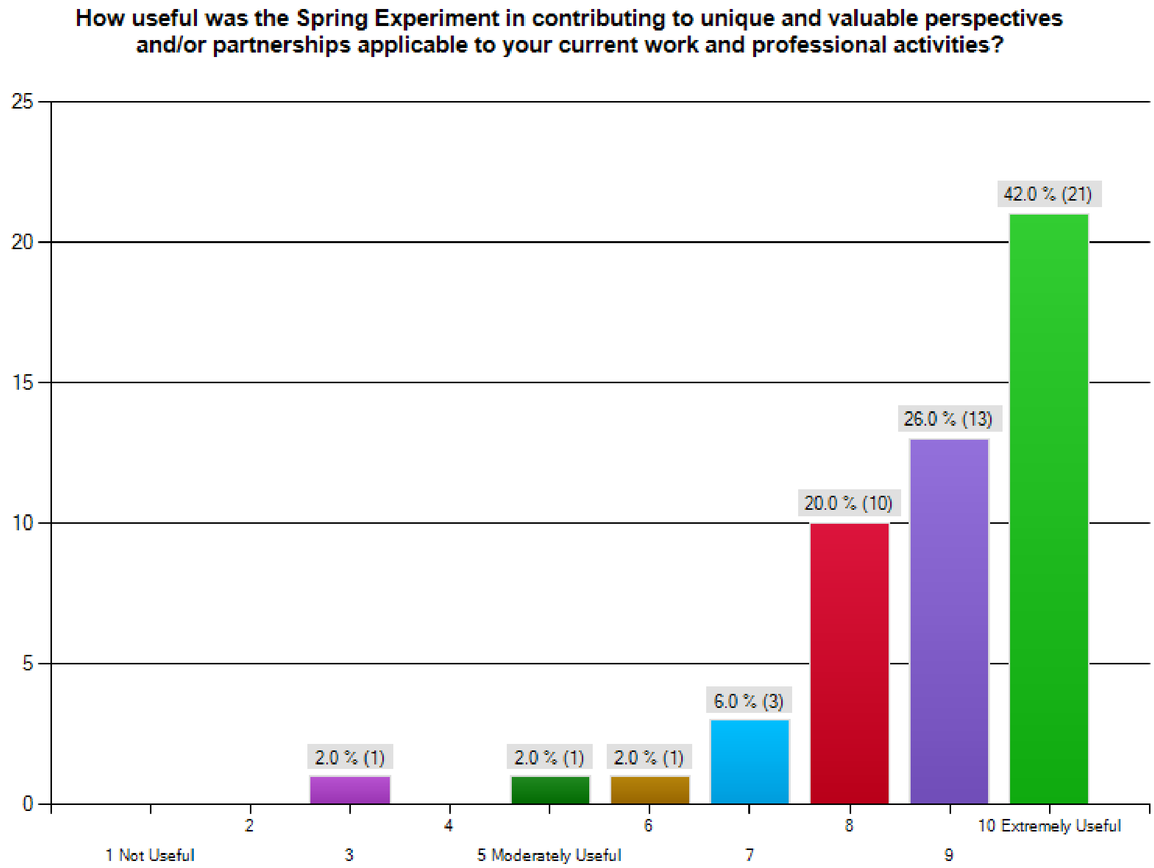

Figure 12. Post-experiment feedback received from 50 HWT EFP participants regarding the usefulness of the Spring Experiment in contributing unique and valuable perspectives and/or partnerships applicable to current work and professional activities. Subjective ratings were on a scale from 1 (Not Useful) to 10 (Extremely Useful).