5.5 POST PROCESSED SHORT RANGE ENSEMBLE FORECASTS OF SEVERE CONVECTIVE STORMS

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1. INTRODUCTION

The Storm Prediction Center (SPC) issues forecasts for the contiguous United States and adjacent coastal waters pertaining to hazardous mesoscale weather including severe thunderstorms, tornadoes, excessive rainfall, extreme winter weather, and critical fire weather conditions. While all aspects of hazardous mesoscale weather are important functions of the SPC, the focus herein is short-range ensemble forecast (SREF) guidance developed specifically for the SPC severe convective weather program.

The flagship product of the SPC is the severe *convective weather watch*, an event driven product which includes the *severe thunderstorm watch* and *tornado watch*. These are deterministic forecasts of severe thunderstorms encompassing areas around 25,000 mi^2 for periods of three to eight hours. Severe thunderstorms are defined operationally as thunderstorms producing tornadoes, straight-line winds $\geq$ 26 ms^{-1} (50 kts), or large hail with a diameter $\geq$ 19 mm (0.75”). Recognizing the fact that uncertainty exists in all forecasts, the SPC now issues experimental probabilistic forecasts of specific hazards within the convective watch (e.g., the probability of 2 or more tornadoes), though meaningful ensemble guidance specifically for convective watches probably awaits the development of real-time storm scale ensembles (Levit et al. 2004; Weiss et al. 2004; Elmore et al. 2003).

SPC *convective outlooks* include both deterministic and probabilistic forecasts and are issued for the Day 1, Day 2, Day 3, and experimentally for the Day 4 to 8 periods. The Day 1 outlook is initially released at 06 UTC and is valid for the 24 hour period from 12 UTC through 12 UTC; it is subsequently updated four times daily. Its deterministic component expresses the total severe threat as a “slight,” “moderate,” or “high” risk, while its probabilistic component consists of individual probability forecasts of large hail, damaging wind, and tornadoes (Fig. 1). The Day 2 and Day 3 outlooks also consist of deterministic and probabilistic forecasts issued twice and once daily, respectively, but unlike the Day 1 outlook, the Day 2 and Day 3 probabilistic components are for the total severe threat (Fig. 2). The experimental Day 4 to 8 outlook is entirely probabilistic but indicates only where the probability of severe thunderstorms is $\geq$ 25% (example not shown). A *mesoscale discussion* (MD) is a free-format text and graphical forecast that serves, at least in part, as a bridge between the outlook and the convective watch. As such, the MD may express the forecast problem or forecast trends in terms of certainty, or the lack thereof, depending upon the situation.

Presently, the National Centers for Environmental Prediction (NCEP) SREF is a 15-member multi-model, multi-physics ensemble with initial perturbations derived through the breeding of growing modes (Toth and Kalnay 1993). Grid separation of the member models ranges from 32 km to 40 km and forecasts are produced twice daily through 87 hours. Accordingly, the spatial and temporal resolution of the NCEP SREF appears well-suited for use in the SPC Day 1 through Day 3 outlook program; for additional information on the operational NCEP SREF see Du et al. (2004). (Hereafter, the term SREF refers specifically to SPC post-processing of the NCEP SREF.) The SPC began exploring SREF

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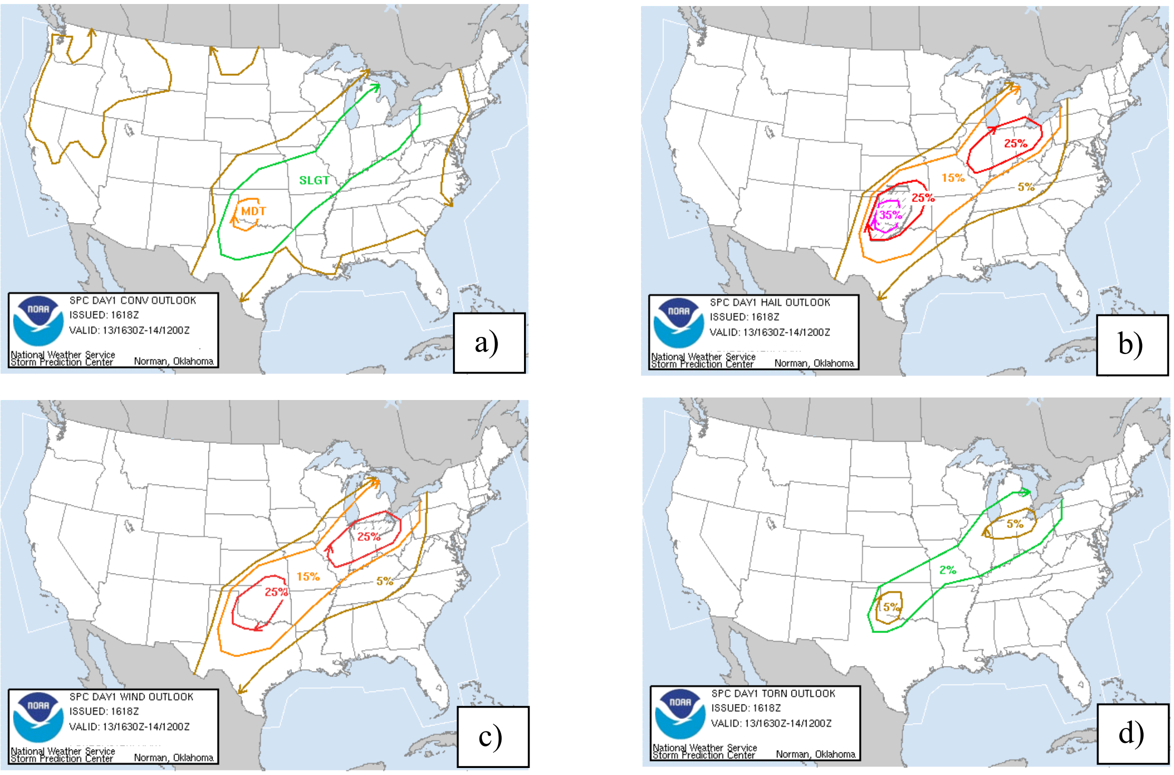

Fig. 1. An example of the operational Day 1 convective outlook produced by the SPC (13 May 2005). (a) is the deterministic forecast and panels (b) through (d) are the probabilistic forecasts of large hail, damaging wind, and tornadoes, respectively. The hatched areas in (b) and (c) are 10% or greater chance of significant severe (hail diameter $\geq$ 2”; wind $\geq$ 65 kts).

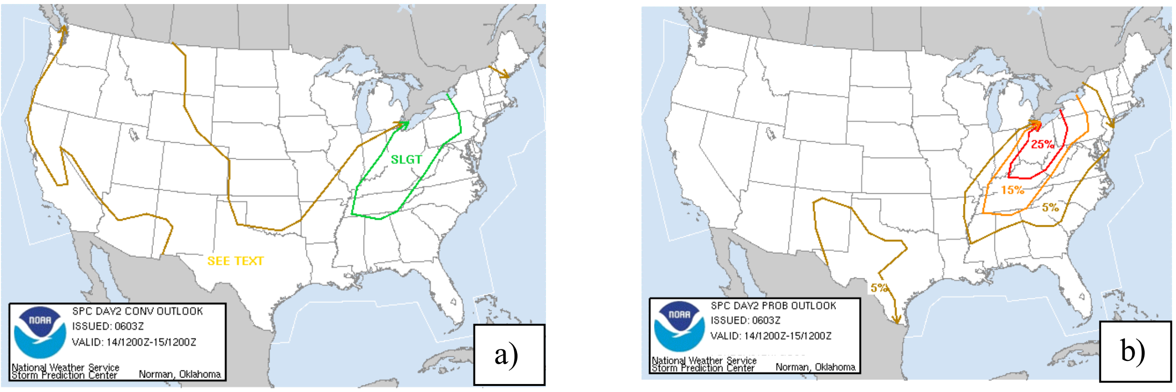

Fig. 2. An example of the operational Day 2 convective outlook produced by the SPC (13 May 2005). (a) is the deterministic forecast and (b) the probabilistic forecast of severe weather. The Day 3 format is identical to the Day 2 format.

techniques during the Spring Experiment in 2003 (Bright et al. 2004; Levit et al. 2004); the Spring Experiment is the cornerstone of the SPC/National Severe Storms Laboratory Hazardous Weather Testbed.

The purpose of this study is to investigate the SREF's ability to produce reliable and computationally inexpensive real-time probabilistic guidance of severe convective storms. The methodology and technique development are described in section 2, initial results presented in section 3, and a brief summary and synopsis of ongoing work in section 4.

2. METHODOLOGY

2.1 *Large-Scale Environmental Parameters*

Storm scale processes are not explicitly forecast in the current suite of operational mesoscale models, so severe weather forecasting relies on understanding the relationship between the large-scale and the storm-scale environment. Several authors have described methodologies for severe weather forecasting (Moller 2001; McNulty 1995; Doswell et al. 1993; Johns and Doswell 1992). Moller (2001) refers to the "SPC approach," which consists of parameter evaluation, pattern recognition, and climatology. The SPC approach can also serve as a useful template for developing SREF guidance; favorable patterns yield favorable parameters, and past events (i.e., climatology) can account for bias removal and statistical calibration.

McNulty (1995) succinctly describes the severe storm forecast problem as follows.

- *Will thunderstorms occur?*
- *If thunderstorms develop, will they become severe?*
- *If they become severe, what type of severe weather will occur (e.g., tornadoes, wind, and/or hail)?*
- *If thunderstorms occur, what type of storm is most likely (i.e., convective mode)?*

A similar evaluation can be applied to SREF-based guidance, except now the problems are posed in a probabilistic context.

- *What is the probability thunderstorms develop?*
- *Given a thunderstorm, what is the probability it will become severe?*
- *Given a severe thunderstorm, what is the probability of a tornado, damaging wind, or large hail?*
- *Given that thunderstorms develop, what is the probability of different convective modes (linear, cellular)?*

The first bullet requiring real-time probabilistic thunderstorm forecasts is already available (Bright et al. 2005). It is based on calibration of the Cloud Physics Thunder Parameter (CPTP) which is a physically based parameter incorporating thermodynamic and kinematic properties favoring charge separation in convective updrafts. This technique produces reliable forecasts of cloud-to-ground (CG) lightning on AWIPS grid 212 (Lambert Conic Conformal projection with 40 km grid spacing) over the contiguous United States (Fig. 3; verification of all 3h and 12h forecasts through 63 hours from 15 April 2005 to 15 September 2005). The CPTP and SREF calibration technique are described in detail in Bright et al. (2005). Attention is now focused on the second bullet, the probability of severe thunderstorms. (Probabilistic forecasts of the type of severe weather and the convective mode are still under development (bullets 3 and 4) and not discussed further.)

Following the SPC forecast approach, the first step is to isolate the problem to the parameter space of several well-resolved predictors considered important to the development of severe convective storms. The goal here is to produce a *total* severe probability, so parameters must spotlight environmental conditions differentiating severe thunderstorms from non-severe thunderstorms. Three known discriminating factors are the presence of large instability, strong vertical wind shear, and mid level dry air (McNulty 1995; Johns and Doswell 1992). The large-scale parameters chosen to evaluate instability, shear, and mid level dry air are the convective available potential energy (CAPE; Doswell and Rasmussen

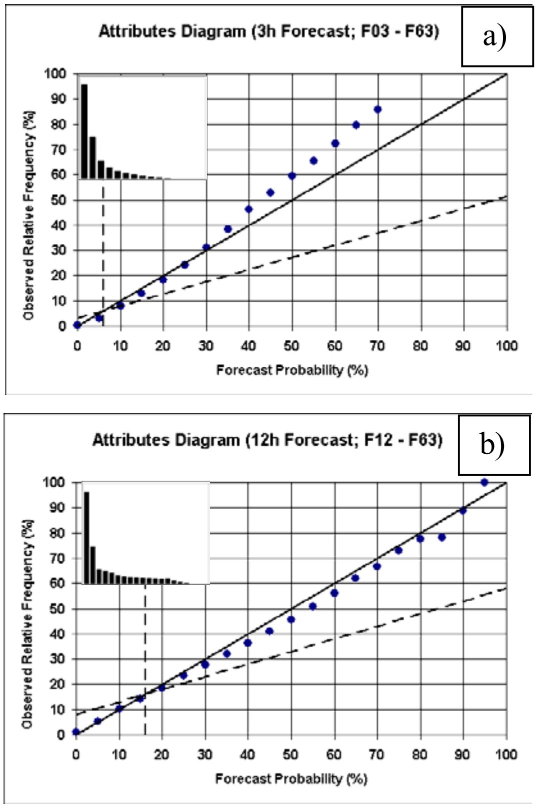

Fig. 3. Attributes diagrams for the calibrated probability of a thunderstorm over the United States at (a) 3h intervals and (b) 12h intervals. Verification period is 15 April 2005 through 15 October 2005. Inset represents the relative frequency of each forecast interval.

1994), effective shear (Thompson et al. 2004), and downdraft convective available potential energy (DCAPE; Emanuel 1994), respectively. (Effective shear is the bulk shear in the approximate lower half of the convective cloud and has been shown to have slightly better discriminating ability between severe and non-severe thunderstorms than surface to 6 km AGL bulk shear (Thompson et al. 2004)).

2.2. *SREF Application and Calibration*

To determine the SREF severe thunderstorm probabilities, 21 predictors comprised of paired ingredients are evaluated based on various thresholds of the three previous parameters (Table 1). Each pair of predictors is called a *layer*. Because the NCEP SREF is available on AWIPS 212 grid (40 km grid spacing), all SPC post-processing is performed on grid 212.

TABLE 1. The 21 SREF layers used to produce probabilistic guidance of severe thunderstorms.

LAYER	SREF INGREDIENT 1	SREF INGREDIENT 2
1	Prob(MUCAPE ≥ 500 Jkg^{-1})	Prob(Effective Shear ≥ 30 kts)
2	Prob(MUCAPE ≥ 500 Jkg^{-1})	Prob(Effective Shear ≥ 40 kts)
3	Prob(MUCAPE ≥ 1000 Jkg^{-1})	Prob(Effective Shear ≥ 30 kts)
4	Prob(MUCAPE ≥ 1000 Jkg^{-1})	Prob(Effective Shear ≥ 40 kts)
5	Prob(MUCAPE ≥ 2000 Jkg^{-1})	Prob(Effective Shear ≥ 30 kts)
6	Prob(MUCAPE ≥ 2000 Jkg^{-1})	Prob(Effective Shear ≥ 40 kts)
7	Prob(MUCAPE ≥ 3000 Jkg^{-1})	Prob(Effective Shear ≥ 20 kts)
8	Prob(MUCAPE ≥ 3000 Jkg^{-1})	Prob(Effective Shear ≥ 30 kts)
9	Prob(MUCAPE ≥ 3000 Jkg^{-1})	Prob(Effective Shear ≥ 40 kts)
10	Prob(MUCAPE ≥ 250 Jkg^{-1})	Prob(Effective Shear ≥ 30 kts)
11	Prob(MUCAPE ≥ 250 Jkg^{-1})	Prob(Effective Shear ≥ 40 kts)
12	Prob(MUCAPE ≥ 250 Jkg^{-1})	Prob(Effective Shear ≥ 50 kts
13	Prob(MUCAPE ≥ 500 Jkg^{-1})	Prob(DCAPE ≥ 1000 Jkg^{-1})
14	Prob(MUCAPE ≥ 500 Jkg^{-1})	Prob(DCAPE ≥ 2000 Jkg^{-1})
15	Prob(MUCAPE ≥ 1000 Jkg^{-1})	Prob(DCAPE ≥ 1000 Jkg^{-1})
16	Prob(MUCAPE ≥ 1000 Jkg^{-1})	Prob(DCAPE ≥ 2000 Jkg^{-1})
17	Prob(MUCAPE ≥ 500 Jkg^{-1})	Prob(DCAPELCL ≥ 1000 Jkg^{-1})
18	Prob(MUCAPE ≥ 1000 Jkg^{-1})	Prob(DCAPELCL ≥ 1000 Jkg^{-1})
19	Prob(MUCAPE ≥ 500 Jkg^{-1})	Prob(500hPa_TMPC ≤ -15 C)
20	Prob(MUCAPE ≥ 500 Jkg^{-1})	Prob(500hPa_TMPC ≤ -20 C)
21	Prob(MUCAPE ≥ 500 Jkg^{-1})	Prob(500hPa_TMPC ≤ -25 C)

MUCAPE refers to the CAPE of the most unstable parcel evaluated from the surface to 500 mb above the surface (the most unstable parcel is where a 50 hPa vertically averaged parcel contains the highest equivalent potential temperature in the sounding). Layers 1 through 12 are designed to assess various combinations of instability and vertical shear ranging from low-CAPE/high-shear environments (layer 12) to high-CAPE/low-shear environments (layer 7). Layers 13 through 18 evaluate downdraft potential through various combinations of updraft instability (MUCAPE) and downdraft instability (DCAPE), acting as a proxy for the existence of midlevel dry air. DCAPE uses the "traditional" calculation based on mid-tropospheric descent from the level of minimum equivalent potential temperature, while DCAPELCL is a trial parameter, admittedly untested, that evaluates DCAPE in moist adiabatic descent from a parcel originating at the lifting condensation level (i.e., a proxy for sub-cloud evaporation in the absence of mid-level entrainment). The last three layers (layers 19 through 21) roughly account for "cold low" situations that may lead to hail and/or tornadoes provided that sufficient instability exists (e.g., Davies and Guyer 2004; Johns and Doswell 1992).

The SPC real-time severe storm database includes all severe weather reports received from the National Weather Service Weather Forecast Offices. A gridded severe weather analysis is created on the same AWIPS 212 domain the SREF is post-processed on. Grid cells containing ≥ 1 severe convective weather report *and* ≥ 1 CG lightning strike (based on real-time data provided by the National Lightning Detection Network) are flagged as having experienced a severe thunderstorm. Calibration tables are then built for each of the 21 layers over the previous 366 days in a manner directly analogous to the calibration process described in Bright et al. (2005); a corrected probability is produced for each of the 21 layers listed in Table 1. Only grid points with $\geq$ 1 CG lightning strike are considered in the calibration process; thus, the calibrated guidance is actually a *conditional probability of a severe thunderstorm (conditional on the occurrence of a thunderstorm)*. Presently, the conditional probability assigned to each grid point is simply the maximum calibrated probability from any of the 21 layers. The *unconditional (or total) probability of severe* is then the product of the conditional severe probability and the calibrated probability of a thunderstorm described in Bright et al. (2005). Forecasts are produced for 3h valid periods (e.g., 18 UTC through 21 UTC) from forecast hour 03 through forecast hour 87.

2.3 *Expanding from 3h Probabilities to 12h and 24h Probabilities*

The 3h forecasts are combined into 12h and 24h probabilistic forecasts using the Hughes and Sangster (1979) statistical model. This model uses past forecasts and verification to determine an optimal dependency parameter (0=Dependent; 1=Independent) so that convective probabilistic forecasts can be combined into longer time periods. Based on archived SREF data the 3h dependency parameter over all forecast times and the entire United States is found to be 0.74.

2.4 *Adjusting to the Probability Within 25 miles of a Point*

Since the SREF is post-processed to AWIPS grid 212, all results heretofore are applicable to the 40 km grid. A 40 km grid cell has an area about equivalent to a circle of radius 14 miles. The SPC operational outlooks are defined as the probability of a severe thunderstorm within 25 miles of a point (Brooks et al. 1998). For consistency with the operational outlooks, the SREF guidance is adjusted to reflect the probability within about 25 miles of a point. Applying equal area considerations, a circle of radius 25 miles is approximately the same area as a grid cell on AWIPS grid 211 (identical to AWIPS grid 212 except 80 km grid spacing). Based on the fortuitous relationship between grid 211 and 212 a conversion factor to adjust to within about 25 miles of a point is calculated by gridding all severe reports from the SPC database to the AWIPS 211 (80 km) grid. Then, for each 3h and 24h period over the entire year, the number of unique 40 km grid boxes to record a severe weather report inside each 80 km grid box that recorded a severe event(s) is counted. Possible values range from one (if only one 40 km grid box inside the 80 km grid box receives a report) to four (all four interior 40 km grid boxes log at least one severe report). Using the one year sample, linear regression is applied to predict an 80 km (within about 25 miles) probability from the native 40 km (within about 14 miles) probability. The resulting 3h and 24h equations are:

(3 hour) $y = 0.11x + 1.19$,
(12 hour) Use the 24h result,
(24 hour) $y = 0.04x + 1.28$,

where x represents the native 40 km calibrated probability and y is the estimated 80 km probability.

3. RESULTS

3.1 *3h Forecasts*

Figure 4 is a 12h forecast of 500 hPa geopotential height, temperature, wind vectors, and isotachs from the 09 UTC SREF on 11 May 2005 (valid at 21 UTC 11 May 2005). The 3h calibrated probability of a thunderstorm indicates a chance of thunderstorms between 18 UTC and 21 UTC over much of the central and eastern United States (Fig. 5). The SREF-based probability of a severe thunderstorm (adjusted to within about 25 miles of a point) valid at the same time indicates the greatest threat of severe weather (5% to 10%) is east of the upper low from the central Plains into the Ohio River Valley (Fig. 6); the conditional probability of severe is not shown. The probabilistic forecast is rather seamless despite most of the 21 layers contributing to the forecast mosaic (Fig. 7). Examining the forecast layers in more detail, it appears CAPE and vertical shear are the primary contributor from Kansas to eastern Nebraska and east of the dry line in central Texas (layers 1 to 12). CAPE and DCAPE

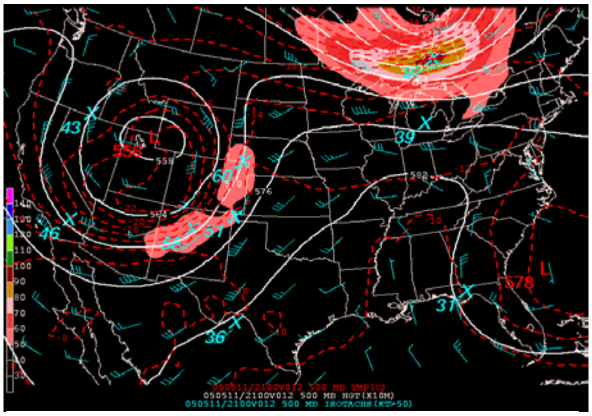

Fig. 4. SREF mean geopotential height (solid), isotachs (shaded), wind vectors, and temperature (dashed) at 500 hPa valid 21 UTC 11 May 2005 (12 hour SREF mean forecast).

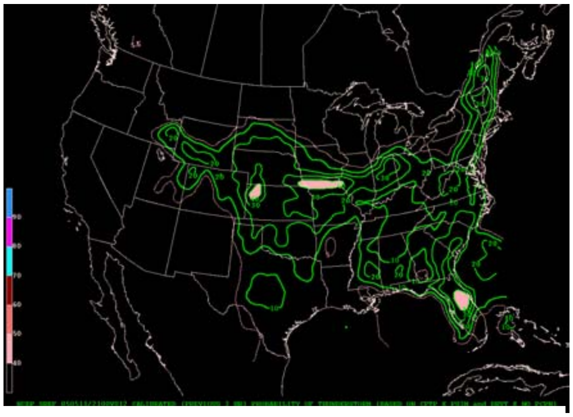

Fig. 5. SREF 3h calibrated probability of a thunderstorm over the United States valid between 18 UTC and 21 UTC 11 May 2005 (12 hour SREF guidance forecast).

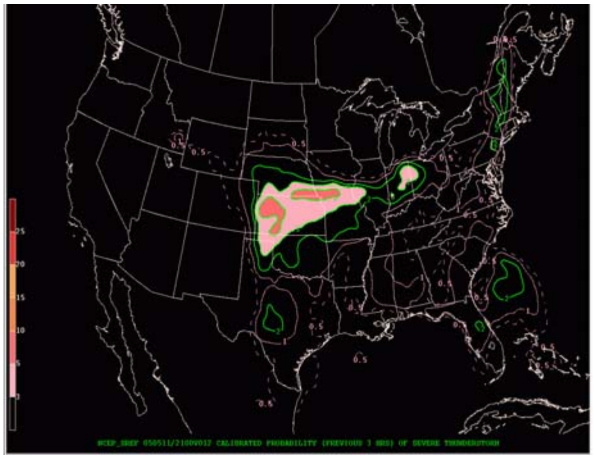

Fig. 6. SREF 3h calibrated probability of a severe thunderstorm over the United States valid between 18 UTC and 21 UTC 11 May 2005 (12 hour SREF guidance forecast).

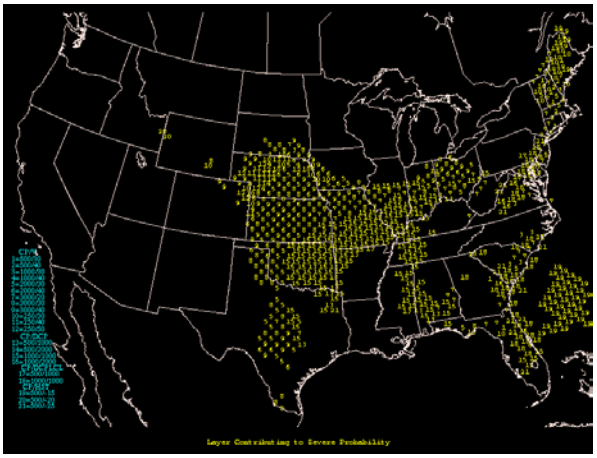

Fig. 7. The SREF layer (see Table 1) contributing to the calibrated probability of a severe thunderstorm shown in Fig. 6.

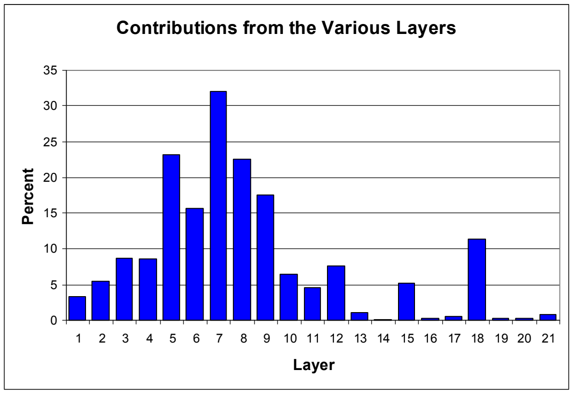

Fig. 8. The percentage of time a SREF layer contributed to the calibrated severe thunderstorm forecast between 12 July 2005 and 30 September 2005.

are the main parameters from eastern Oklahoma toward the Ohio Valley and in the Southeast (layers 13 to 16), with instability combined with cool temperatures aloft contributing to severe probabilities off the Southeast coast (east of Georgia), New England, and isolated grid points over extreme eastern Idaho (layers 19 to 21). DCAPE originating at the LCL contributed to the severe mosaic over the Atlantic coastal region (layers 17 and 18). Considering a longer period of time from mid summer through early fall (12 July 2005 through 30 September 2005) the largest contributors to the SREF probabilistic forecast are high-CAPE/low-shear parameters (layers 5 to 9) with a significant contribution from DCAPE

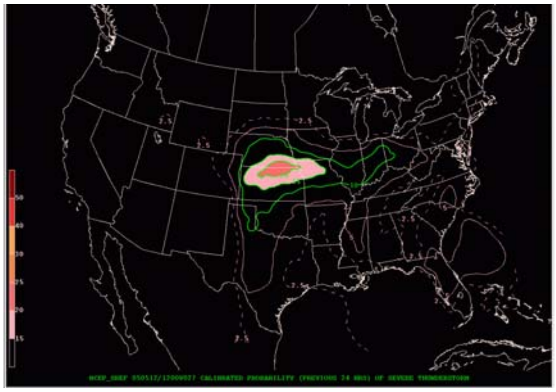

Fig. 9. SREF 24h calibrated probability of a severe thunderstorm over the United States valid between 12 UTC 11 May and 12 UTC 12 May 2005 (24 hour SREF guidance forecast).

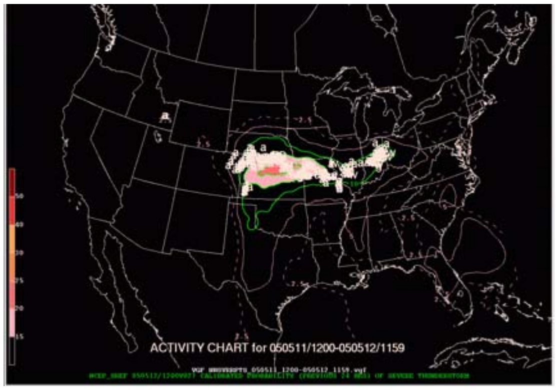

Fig. 10. As in Fig. 9 with severe storm reports. a=severe hail; A=significant hail (≥ 2" hail); w=severe wind; W=significant severe wind (≥ 65 kts); t=tornado; T=significant tornado (≥ F2 intensity)

below the LCL (layer 18) (Fig. 8). Although the shape of the histogram in Fig. 8 is probably seasonally dependent, every layer contributes to the forecast even during this late summer period.

3.1 *24h Forecasts*

The 24h probability of severe yields 20% to 25% values over northern Kansas and southeast Nebraska, and 10% to 15% from the panhandle of Oklahoma to western Ohio (Fig. 9; forecast valid 12 UTC 11 May 2005 to 12 UTC 12 May 2005). Observed severe thunderstorm reports extend from northeast Colorado to the upper Ohio River Valley with an orientation in good agreement with the SREF guidance (Fig. 10).

Statistical verification of the 24h forecasts (every 3 hours from forecast hour 24 through forecast hour 63; including both the 09 UTC and 21 UTC SREF combined) during the 6 month period from 15 April 2005 through 15 October 2005 is shown as an attributes diagram in Fig. 11. The system tends to over-predict the probability of severe thunderstorms but still contains reasonably good statistical resolution and skill at all forecast probabilities; although, evidence of the small sample size is apparent above 70%. The over-prediction may be the result of applying the maximum calibrated probability from any of the 21 layers; a technique incorporating more than one layer may produce a better result. The area under the ROC curve (Stanski et al. 1989; values > 50% indicative of skill relative to climatology and values > 70% indicative of reasonable discriminating ability) is a respectable 84.3%, and the average probability in all grid boxes with ≥ 1 severe weather report is 15% while the average probability in all grid boxes without severe weather is 2%. These values suggest the SREF guidance reasonably discriminates severe events from non-severe events. The improvement over sample climatology is about 8%. (Admittedly, this could be an overestimate of skill as it is based on the climatological value over the entire domain and not at each grid point (Hamill and Juras 2005)). An action associated with a probabilistic weather forecast may be based on a cost-loss ratio model, in which an economic burden is expected regardless of the decision, but over time an optimal decision minimizes expected expense. Using the cost-loss ratio model from Murphy (1977) and Richardson (2000), a potential value, V, is computed. V indicates the fractional savings incurred relative to a climatological forecast (V=0)

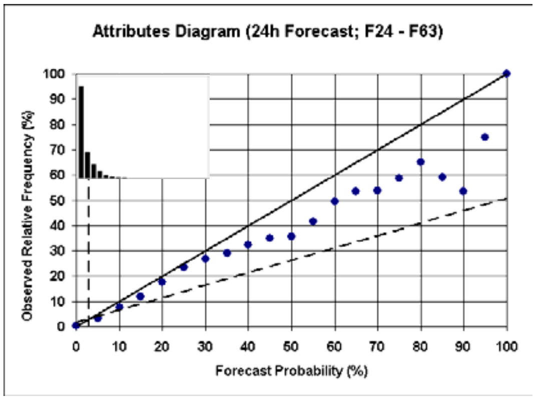

Fig. 11. Attributes diagram for the calibrated 24h probability of a severe thunderstorm over the United States for all forecasts (09 UTC and 21 UTC SREF) from forecast hour 24 through forecast hour 63 between 15 April 2005 and15 October 2005. Inset represents the relative frequency of each forecast interval.

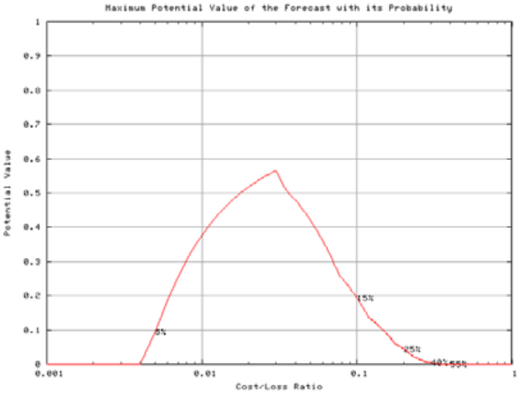

Fig. 12. Economic potential value for the calibrated 24h probability of a severe thunderstorm over the United States for all forecasts (09 UTC and 21 UTC SREF) from forecast hour 24 through forecast hour 63 between 15 April 2005 and15 October 2005.

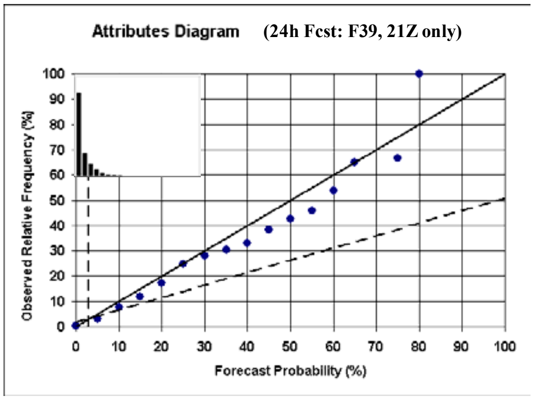

Fig. 13. As in Fig. 11 but only considering the 21 UTC SREF forecasts ending at forecast hour 39.

and a hypothetical perfect forecast (V=1); values of V > 0 indicate profit potential from the forecast system. The maximum potential value from the SREF severe guidance probabilities is about 0.57 and is positive for a range of users with cost-loss ratios from 0.004 to about 0.3 (Fig. 12).

A subset of the 6 month sample for all 24h forecasts from the 21 UTC SREF valid at forecast hour 39 (i.e., valid for a 24h period from 12 UTC to 12 UTC) is examined to evaluate the statistical capabilities of the SREF guidance available in real-time for the SPC initial Day 1 severe thunderstorm outlook issued at 06 UTC. The reliability of the subset is slightly improved although the tendency to over-predict the probability of severe thunderstorms remains (Fig. 13). Again, the ROC-area is quite good at 86.0% indicating useful discriminating ability between severe and non-severe events. The potential value is also improved at all cost-loss ratios, and now peaks at about 0.59 (not shown).

4. SUMMARY AND ONGOING WORK

A method of producing calibrated probabilistic severe thunderstorm guidance from the NCEP SREF is described. Its development parallels the SPC approach to forecasting severe weather by inspecting the basic large-scale environmental parameter space considered important in the development of severe convective storms. The SREF calibrated probability of severe thunderstorms produces statistically reliable and skillful guidance. Results are available for 3h periods and are extendable to 12h and 24h periods. Ongoing work includes refinement of the layers used in the prediction of severe storms, additional parameters that isolate the probability of hail, wind, or tornadoes, and better methods of extracting an overall probability from the various layers.

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