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USING CONVECTION-ALLOWING MODELS TO PRODUCE FORECAST GUIDANCE FOR SEVERE THUNDERSTORM HAZARDS VIA A "SURROGATE-SEVERE" APPROACH

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1. INTRODUCTION

Convection-allowing models (CAMs) with horizontal grid spacing as coarse as 4 km can provide useful predictions of convective morphology, or mode (e.g. Done et al. 2004). In particular, CAMs appear to have skill in discriminating between distinct severe convective modes such as bow echoes and discrete supercells (Kain et al. 2008). Thus, unlike traditional NWP models in which all convective activity is parameterized, CAMs add value by providing explicit predictions of extreme convective phenomena within the region where traditional models simply predict convective precipitation. Unfortunately, like coarser resolution models, CAMs typically produce forecasts that err in predictions of phase, amplitude, and sometimes even occurrence of weather events, especially small scale features such as individual thunderstorms. Furthermore, their placement of extreme phenomena within the envelope of overall activity can be far from perfect. Thus, it is desirable to introduce some measure of uncertainty into CAM guidance products, particularly those products related to the development of extreme phenomena.

One straightforward way to accomplish this is discussed in Theis et al. (2005) and Roberts (2005). Their approach is to define a "neighborhood" surrounding an event or phenomenon of interest (say a localized rainfall maximum or a mid-level mesocyclone) and assign non-zero probabilities for occurrence at all points in the neighborhood. In practice, the method for assigning these probabilities is quite simple: whereas a "literal" interpretation of the model output would suggest 100% probability of occurrence at any grid point where the phenomenon appears in the model output, the neighborhood approach applies a mathematical smoother that conserves total probability over the neighborhood but spreads non-zero values according to the specific formulation of the smoother.

This approach allows one to generate probabilistic forecasts from deterministic modeling systems. It is a pragmatic approach with many fewer degrees of freedom than methods based on ensemble modeling systems, yet it can be easily used in conjunction with ensembles (Theis et al 2005). In fact, Schwartz et al. (2010) showed that modification of ensemble-based probabilities using a neighborhood approach can enhance the predictive skill of an ensemble considerably. Furthermore, the neighborhood approach seems particularly well suited to predictions of severe thunderstorms, which are rare events. Indeed, the neighborhood concept was inspired by the work of Brooks et al. (1998), who started at the other end of the weather prediction spectrum with the question "given a set of severe weather reports from specific locations, what is the best probabilistic forecast that one could expect a human forecaster to have issued for this event?" They mapped the severe weather reports to a grid, initially assigned 100% probability to the active grid points, and applied various forms of a Gaussian smoother to generate sample probabilistic "forecast" fields corresponding to the known outcome. This process was used to help Storm Prediction Center (SPC) forecasters calibrate themselves when they were first tasked with issuing probabilistic Convective Outlooks in the mid 1990s.

The current study builds on the concepts introduced by Brooks et al. (1998) and Theis et al. (2005). Specifically, it introduces a method to identify extreme phenomena in CAM forecasts, treats the presence of these phenomena as "surrogates" for the occurrence of severe weather, then produces probability forecast fields based on the predicted location of these surrogate reports. Sobash et al. 2008 (SOB08) reported on an initial application of this approach, and Sobash et al. 2009 (SOB09) documented some preliminary verification results. The goal of the present study is to highlight the climatologies of the surrogate fields and to extend the verification results of SOB09, specifically by verifying the probabilistic forecast guidance.

2. METHODOLOGY

As in SOB08 and SOB09, this study focuses on daily model forecasts from the NSSL-WRF model. This system uses the Advanced Research WRF (ARW – Skamarock et al. 2005) model to produce daily, 36-hr, 4 km forecasts at the NSSL (National Severe Storms Laboratory) over the eastern three-fourths of the CONUS (CONtinental U.S.). The model is initialized at 00 UTC and is run to 12 UTC the next day (36 h forecast), in a timely enough manner to be used as guidance for forecasts of the next day's convective cycle. The initial and lateral boundary conditions come from the operational North American Mesoscale (NAM) model. No convective parameterization is used; all precipitation originates from the microphysical scheme.

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The configuration of the model is summarized in Table 1.

The updraft helicity (UH) diagnostic parameter (Kain et al. 2008) is used to identify extreme phenomena in the NSSL-WRF model output. To identify intense circulations that occur between hourly output intervals, the intra-hourly maxima of the UH field in each grid column, or "hourly-maximum UH" was recorded each hour. This field provides a continuous view of the extreme phenomena throughout the model's integration period (Kain et al. 2010). Hereafter, "UH" denotes the hourly maximum quantity unless otherwise indicated. The UH diagnostic was formulated to identify mesocyclones in CAM output because mesocyclones may indicate the presence of supercells, which produce a disproportionate share of severe weather. Other hourly-maximum fields have been used to identify intense convection in model output; these will be discussed later. Surrogates are needed because severe phenomena such as large hail and tornadoes are not forecast explicitly in CAMs. Thus, UH acts as a surrogate for the occurrence, or at least potential occurrence, of these hazards.

The UH SSPF is based on the locations where the UH field exceeds a specified threshold, that is, the locations of surrogate severe weather reports (SSRs). For this study, the SSRs are placed at grid points exceeding the threshold value anytime during a 24 hour period, 12 UTC to 12 UTC (the 13 through 36 hour model output times), to be consistent with SPC daily convective outlooks. During SE2008, a single threshold value was chosen based on subjective experience with the UH field. This value was 50 m^2s^{-2}. Herein, a range of threshold values, based on quantiles in the cumulative frequency distribution of UH during all days of SE2008, is tested to investigate the sensitivity of the SSRs and resultant SSPFs to threshold. The specific threshold values range from approximately 34 to 103 m^2s^{-2}, corresponding to the 0.001 quantile increments in the frequency distribution, beginning at the 99.990th percentile and extending to the 99.999th percentile. The

NSSL-WRF Configuration	
Horizontal Grid	4.0 km
Vertical Levels	35
PBL/Turb. Param.	MYJ
Microphysics	WSM6
Radiation (SW/LW)	Dudhia/RRTM
Init. Conditions	40 km NAM

Table 1: *Configuration of the NSSL-WRF.*

subjectively determined threshold of 50 m^2s^{-2} lies near the middle of this distribution, at the 99.995th percentile.

For each 24-hour period during SE2008, binary grids of SSRs were generated separately for all ten threshold values by labeling each point where the threshold was exceeded at least once as a "hit" (value=1) while assigning all other points a value of zero. In addition, SSRs were filtered by removing all hits that fell outside the CONUS and by removing all SSRs that were not within 25 km and one hour in time of a point having simulated composite reflectivity greater than or equal to 35 dBZ. The latter filter was intended to remove SSRs not associated with convection in the model.

Although the raw field of SSRs on the NSSL-WRF grid is a useful guidance tool in itself (Fig. 1a), primarily in summarizing the specific locations in which the model predicts intense convection, the desire is to produce a probabilistic guidance product. The definitions of this product are meant to be consistent with the SPC's probabilistic convective outlooks, which forecast the likelihood of severe convection within 25 miles of a point between 12 UTC and 1159 UTC the next day. For the work presented here, the former criterion is approximately satisfied by performing calibration and verification on the NCEP 211 grid (hereafter, "211 grid"), which has a grid spacing of 81 km, or about 50 mi. This grid is populated by flagging the 211 grid point that is closest to each report on the

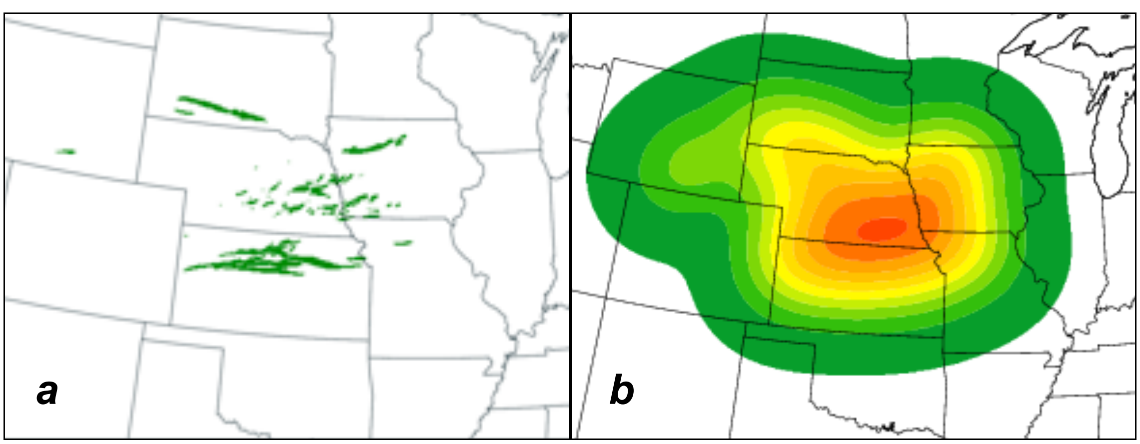

Fig. 1. *(a) UH SSR4s from the 24-hour period 12 UTC 29 May 2008 through 1159 UTC 30 May 2008. (b) SSPF produced from UH SSR4s.*

native grid. As is done on the higher resolution grid, all 211 grid points flagged at least once are assigned a value of 1. Hereafter, the field of SSRs on the 4-km grid will be referred to as SSR4s, while the remapped SSRs on the 211-grid will be called SSR81s.

To produce a probabilistic product, a neighborhood approach similar to that used by Brooks et al. (1998) and Theis et al. (2005) is utilized. This involves defining a neighborhood around the deterministic prediction in which there is a non-zero probability of event occurrence. Quantitatively, this can be accomplished by applying a spatial smoother to the SSR field. This effectively allows for spatial uncertainty to be introduced into a deterministic forecast. Brooks et al. (1998) used this technique to produce a “practically perfect” forecast (i.e. the best possible forecast an operational forecaster could be expected to make) from observed severe weather reports.

Specifically, Brooks et al. (1998) showed that a probability value could be derived at any grid point using a two-dimensional Gaussian smoother,

$$SSPF = \sum_{n=1}^{N} \frac{1}{2\pi\sigma^2} \exp\left(-\frac{d_n^{\,2}}{2\sigma^2} \right)$$

where d_n is the distance from the grid point to the point marking the nth report, N is the total number of reports, and sigma is the spatial smoothing parameter, which is the same in both the x and y directions (i.e. isotropic smoothing). The SSPF values are multiplied by 100 and usually contoured as in Fig. 1b.

For verification, preliminary observed storm reports (OSRs) were retrieved from the SPC’s online archive of storm reports. During the verification period, OSRs were received at SPC for tornadoes, hail greater than or equal 19 mm (¾ in.), and wind gusts greater than or equal to 26 m s^{-1} (58 mph). The OSRs were mapped to the 4-km NSSL-WRF grid and the 211-grid (OSR4s and OSR81s, respectively) to obtain fields that could be directly compared with the SSRs. In this work, no distinction is made between the three types of severe weather reports.

Verification of the SSPFs was accomplished using reliability diagrams (e.g. Wilks 2006) and relative operating characteristic (ROC) curves (e.g. Mason 1982). The area under the ROC curve (AUC) is used as a summary score for each ROC curve and is related to the forecast resolution. The ROC AUC is computed for each ROC curve using the trapezoidal approximation. The reliability diagram is a plot of the forecast probabilities (on the abscissa), and the corresponding observed frequencies of those forecasts (on the ordinate). To produce the reliability diagram, the forecast probabilities were binned in 5% increments (i.e. < 5%, 5%-10%, 10%-15%, etc.). The observed frequencies are plotted at each bin’s mean forecast value. An overall measure of reliability, equal to the frequency-weighted mean squared deviation of the reliability curve from the diagonal on the diagram, was also computed. For a perfectly reliable forecast system, this measure is zero, corresponding to the case where the reliability curve is aligned along the diagonal.

3. RESULTS: OBSERVED AND SIMULATED CLIMATOLOGY

SSPFs were created from each day’s NSSL-WRF model output (when available) between 18 April 2008 and 8 June 2008, the SE2008 timeframe, one for each threshold value. Additional SSPFs were generated using different values of the Gaussian smoothing parameter σ .

The SE2008 time period encompasses the climatological peak of severe weather report frequency in the U.S. (Brooks et al. 2003, Doswell et al. 2005). 8,903 severe reports were received during SE2008. When these were mapped to the 4 km grid of the NSSL-WRF, some grid points received multiple hits, leading to only 8017 OSR4s over the period. This reduction was much greater after remapping to the 211 grid, yielding only 2691 OSR81s for the season.

Compared to the OSR4s, the UH SSR4s have a bias much greater than 1, especially at the lowest UH threshold where there are nearly 10 times more UH SSR4s than OSR4s. While some of this high bias maybe due to a real difference in the numbers of predicted and severe events, it seems more likely that it is related to a fundamental disparity in sampling of the

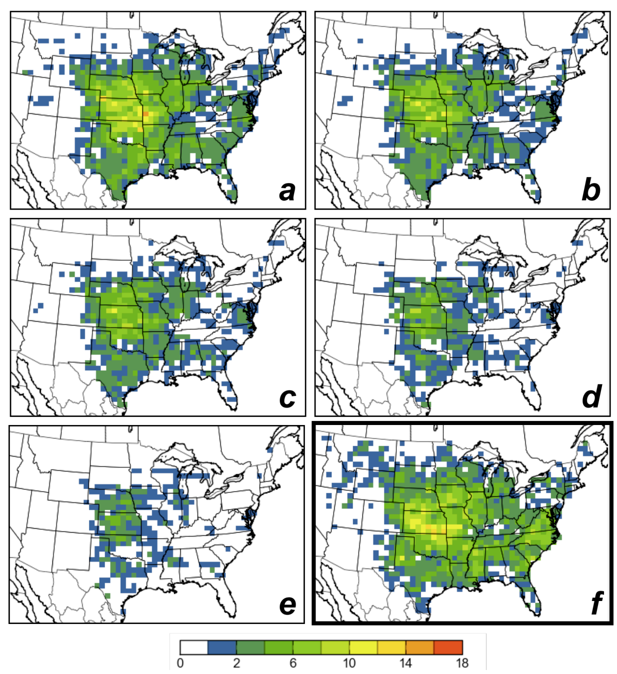

Fig. 2. *Number of UH SSR81s per grid box during SE2008 for (a) UH=34, (b) 45, (c) 56, (d) 78, (e) 103, and. (f) Number of OSR81s per grid box during SE2008. The model domain used in this study does not include portions of the western CONUS.*

observed and simulated events. For example, the 4-km grid spacing appears to be much less than the typical distance between observed severe weather reports in the SPC's database. The highest thresholds produce bias values near 1, but, again, this does not necessarily imply a better correspondence between numbers of observed and predicted events. Mapping both the SSR4s and the OSR4s to the 211-grid decreases the forecast bias significantly. The number of UH SSR81s ranges from 2,349 (bias=0.87) to 391 (bias=0.15).

In a climatological sense, the SSRs are able to capture the geographic distribution of the frequency maxima and minima in OSRs during SE2008. Focusing on the coarser grid for this analysis, Figure 2a-e shows the number of days each 211-grid box was activated (i.e. produced an SSR81) for the lowest, highest, and three intermediate thresholds. For comparison, the number of days OSR81s were present in each grid box is shown in Figure 2f. The SSR81s corresponding to the lower thresholds reproduce the observed peak frequency in the central CONUS and the minima in Appalachia and the northeastern U.S. SSR81s produced using higher thresholds (e.g. Fig. 2e) tend to be restricted to the central CONUS.

4. RESULTS: SSPF VERIFICATION

In this section, the SSPF dataset will consist of SSPFs created using a value of 120 km for σ, the Gaussian smoothing parameter. These will henceforth be referred to as the SSPF120 forecasts. This value of σ was used by Brooks et al. (1998) to create the "practically perfect" forecasts in that study, and will provide an initial point of reference in this work. As with the deterministic verification above, the verification scores are aggregated over the SE2008 period. This will allow for a demonstration of the overall ability of the SSPF120s to produce valuable forecast guidance during a period of time where severe convection is prevalent.

The area under the ROC curve is commonly used as a verification measure. An area of 1.0 indicates a perfect probabilistic forecasting system, 0.7 is considered the lower limit of a useful probabilistic forecast system, and an area less than 0.5 indicates a useless forecast (Buizza et al. 1999). The SSPF120 ROC curve AUCs ranged from 0.88 for forecasts using the lowest UH threshold to 0.74 for forecasts using the highest threshold (Fig. 3). The eight additional ROC curve AUCs fell in between these extremes. Most AUCs are greater than 0.8, reflecting a high degree of skill in the SSPF120 forecasts' ability to correctly identify severe weather events, in contrast to non-events. Generally, as the threshold is decreased, the incremental gain in ROC curve area tends to decrease, suggesting that the AUCs are asymptoting towards some maximum value.

Although the SSPF120 forecasts show skill in distinguishing between severe and non-severe weather events, it is desirable that the forecasts provide reliable probabilities as well. Reliability diagrams

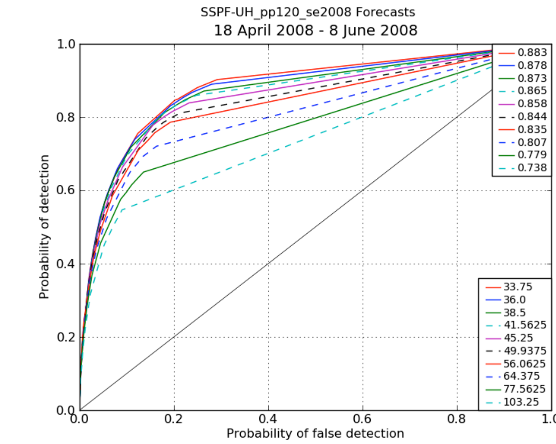

Fig. 3. *ROC curves for SSPF-UH120 forecasts during SE2008. ROC curve areas are listed in the upper right corner, while surrogate thresholds are in the lower right corner.*

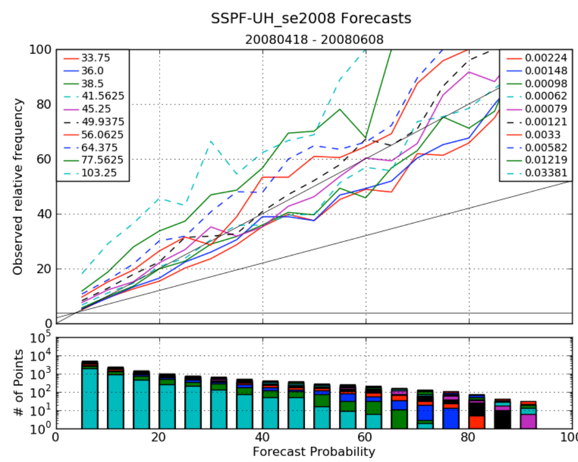

Fig. 4. *Reliability diagram for SSPF-UH120 forecasts during SE2008 (top). Histogram of forecast points for each forecast probability bin plotted on a log-linear scale (bottom). Bins are 1%-<5%, 5%-<10%, 10%-<15%, etc. The reliability component of the Brier Score for each forecast is inset.*

associated with the SSPF dataset are displayed in Figure 4. Overall, the forecasts produce reliability curves above the no-skill line and climatology lines. The most reliable forecasts are produced using a threshold near 41 m^2s^{-2}. The lowest UH threshold (34 m^2s^{-2}) tends to produce SSPF120s which overforecast, while using the highest threshold (103 m^2s^{-2}) leads to significant underforecasting.

5. RESULTS: SSPFs WITH VARIED σ

The previous section demonstrates that the SSPF120s can provide probabilistic severe weather guidance characterized by large ROC curve areas and reliable probabilities although a tradeoff exists between the UH threshold which produces the largest ROC curve areas (lowest thresholds) and the thresholds which produce the most reliable forecasts (slightly higher thresholds). The tendency for the lowest thresholds to lead to overforecasting at most probability ranges can potentially be accounted for by adjusting the value of the smoothing parameter in the Gaussian probability density function.

To investigate, SSPFs were created using values of σ, the Gaussian smoothing parameter, at 20 km increments between 80 km and 300 km. Changes in σ tend to result in a decrease in the amplitude of SSPFs, with more modest changes to the shape and an increase in coverage of lower probabilities. Thus, changes to σ could potentially improve forecast reliability.

Increasing σ to a value of ~200 km (from 120 km) improves the reliability of SSPFs produced with the lowest UH threshold. This threshold produces a maximum ROC curve area. These SSPF parameters appear to produce an optimal arrangement of maximum ROC curve area and reliability for the UH surrogate field (Fig. 5).

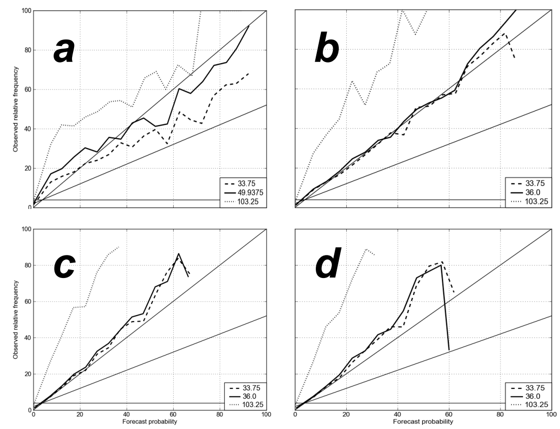

Fig. 5. *SSPF-UH forecasts during SE2008 with (a) σ =80 km, (b) σ =160 km, (c) σ =220 km, and (d) σ =260 km. The solid line is the threshold with the best reliability, the dashed (dotted) line is the lowest (highest) threshold.*

6. RESULTS: BEYOND UH

In addition to UH, SSPFs were produced using surrogates from 4 additional hourly-max fields: 10 m wind speed (UU), 1 km AGL reflectivity (RF), maximum column updraft (UP) and maximum column downdraft (DN). The thresholds were chosen using the same quantiles used in the UH threshold selection process. It is presumed that these fields bear a relationship to the intensity of modeled convection.

Overall, SSPFs produced with these fields do not possess the degree of skill associated with the UH SSPFs. As with UH, the ROC AUCs decrease with increasing threshold for each of these 4 fields, but the maximum AUC achieved is less in the case of UU, RF, and UP (not shown). The DN AUC maximum is comparable to that of the UH AUC maximum. The reliability of these 4 fields is substantially decreased compared to the UH SSPF reliability. All four fields lead to overforecasting to a degree that cannot be adjusted by simplying changing σ.

7. DISCUSSION

Using the UH surrogate field to generate SSPFs produces skillful forecast guidance. This result is particularly compelling because while it clearly shows promise, there is also much room for improvement. For example, there are questions to address in regard to the model output: 1) the concept of using data mining to identify and characterize severe convective phenomena in real-time model output is relatively new (Kain et al. 2010), 2) the UH diagnostic is only one possible formulation that could be used to identify supercells, and 3) there is still some question about a model's ability to simulate supercells and other convective phenomena with 4km grid spacing. While it is undoubtedly important to include some measure of uncertainty in forecasts for rare events, the Gaussian kernel applied here is by no means the only possible tool for that. In spite of these deficiencies, a clear signal for a powerful proof-of-concept emerges from this preliminary exploration of the SSPF strategy.

This procedure appears to result in more skillful guidance than using the model output or the raw field of surrogate reports without inclusion of some measure of uncertainty. In general, the ability of the SSPFs to distinguish between events and non-events (based on ROC curve area) is increased as the threshold is decreased. Refinements in the field threshold selection technique are needed, but it appears that this work demonstrates that a quasi-subjective selection technique is sufficient to produce skillful probabilistic severe weather guidance. Although this conclusion is based on a rather limited sample of meteorological regimes, the concept should be more widely applicable. Further investigation over a broader range of regimes (i.e., seasons, geographic regions, etc) is needed and will be the subject of future work.

8. APPLICATIONS AND FUTURE WORK

The recent proliferation of high-resolution convection-allowing NWP guidance has presented opportunities for the creation of new severe weather guidance products. This work documents a simple phenomenon-based technique to create a probabilistic severe weather guidance product (the surrogate severe probability forecast, or SSPF) from a deterministic, high-resolution, modeling system (the NSSL-WRF) and provides a proof of concept by demonstrating the skillfulness of the approach during an active severe weather time period across the CONUS. Although this preliminary development focuses on a series of daily forecasts from a single WRF configuration, this approach would be even more powerful if applied in an ensemble prediction system.

It is demonstrated that SSPFs derived from the updraft helicity (UH) field possess the resolution and reliability that is desired in a probabilistic forecast, even without extensive calibration, but additional surrogate fields (or variations of current fields) are likely needed to improve forecast skill. Although four additional fields did not demonstrate increased skill, future work could focus on other fields. For example, diagnostics based on the graupel or hail fields which likely are related to severe hail. Likewise, adjusting the layer over which UH is computed into the lower troposphere could provide a better predictor for low-level rotation, which may be more closely related to severe reports (e.g. tornadoes). In general, future work should investigate the relationship between hazard type and surrogate field.

The current work uses a deterministic modeling system to produce probabilistic forecasts of severe weather hazards. Implementing such an approach within an ensemble forecast system would allow for a broader quantification of uncertainty in a guidance product, likely producing more reliable probabilities. A straightforward approach was used by Schwartz et al. (2010) to produce probabilistic QPFs from a mesoscale ensemble using a neighborhood technique within each of the ensemble members. The probabilities from each member were combined to produce one forecast from the ensemble. Implementing this approach using the current methodology would be challenging, because SSPFs in each member would have to be calibrated separately. Future work on SSPF sensitivities to resolution and physics should help address this issue.

The SSPFs have been used in an experimental forecast setting during the 2008 and 2009 NSSL/HWT Spring Experiments. Assuming the above research issues are addressed in the future and the utility of the SSPF guidance is proven, then efforts should be made to integrate this product into the operational suite of data utilized by forecasters. This integration should prove to be natural due to the similarity in the definitions of the SSPF and SPC probabilistic forecasts. In addition, interaction with severe weather forecasters will be an important part of this infusion process.

9. ACKNOWLEDGEMENTS

We are grateful to Harold Brooks for many useful discussions related to this work and to many individuals at CAPS, NCAR, and NCEP/EMC who worked to contribute high-resolution model output to the 2008 Spring Experiment. We thank Scott Dembek of NSSL/CIMMS and NASA/USRA for writing and implementing the code to extract hourly-maximum values of selected fields from the WRF model.

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