## 4.3 A Physically Based Parameter for Lightning Prediction and its Calibration in Ensemble Forecasts

David R. Bright*
NOAA/NWS/NCEP/Storm Prediction Center, Norman, Oklahoma

Matthew S. Wandishin
CIMMS/University of Oklahoma, Norman, Oklahoma

Ryan E. Jewell and Steven J. Weiss
NOAA/NWS/NCEP/Storm Prediction Center, Norman, Oklahoma

### 1. INTRODUCTION

The Storm Prediction Center (SPC) issues forecasts for the contiguous United States related to hazardous convective weather including thunderstorms, severe thunderstorms, tornadoes, and elements critical to fire weather such as dry lightning. In addition to severe weather products such as watches and outlooks, the SPC also issues "general" thunderstorm outlooks for the contiguous United States and adjacent coastal waters. These outlooks delineate a $\geq$ 10% chance of cloud-to-ground (CG) lightning within approximately 15 miles of a point. (For the purposes of this paper, a thunderstorm is defined as deep convection producing at least one CG lightning strike.)

In March 2003, the SPC added temporal and spatial resolution to the Day 1 general thunderstorm outlook by issuing experimental Enhanced Thunderstorm (ENHT) outlooks to Internet customers within the "noaa.gov" domain. The ENHT outlooks provide multiple thunderstorm probability contours of 10%, 40%, and 70% for two time periods corresponding to "today" (the 12 hour period ending at 00 UTC) and "tonight" (the 12 hour period ending at 12 UTC). National Weather Service (NWS) operational numerical weather prediction (NWP) guidance provided by the National Centers for Environmental Prediction (NCEP) Environmental Modeling Center (EMC) is a key component in the creation of the general and ENHT outlooks. Resolvable scales in the current suite of NWP operational models are such that moist convection is parameterized and the activation of a convective parameterization in no way assures CG lightning will accompany model convection. Even higher-resolution NWP models that explicitly predict moist convection do not predict the occurrence of lightning. Thus, after determining where moist convection is plausible, the potential for thunderstorms must be deduced through further interrogation of the data. In addition to deterministic NWP output, the NCEP/EMC Short Range Ensemble Forecast (SREF) is available to the SPC and attempts to account for initial condition, model, and convective physics uncertainty (Du et al. 2004). The SPC post-processes the NCEP SREF to create a suite of customized ensemble products specifically for thunderstorm and severe thunderstorm prediction (Bright et al. 2004). A subset of these products is available in real-time on the SPC web site at http://www.spc.noaa.gov/exper/sref/.

A new parameter that assists in thunderstorm prediction using either deterministic or ensemble NWP output is described. Its formulation is covered in section 2 and its application demonstrated using deterministic and ensemble output in section 3. Section 4 describes a simple statistical calibration technique for producing reliable probabilistic thunderstorm forecasts from ensemble guidance. Verification of the calibrated SREF probabilistic thunderstorm forecasts is in section 5. A brief summary is contained in section 6.

### 2. THE CLOUD PHYSICS THUNDER PARAMETER (CPTP)

#### *2.1 Lightning Production from an Atmospheric Physics Perspective*

A considerable amount of work has been published on the electrification of cumulonimbus and the physics of lightning. The summaries provided by Houze (1993) and MacGorman and Rust (1998) indicate that, at least to first order, the presence of ice particles in the mixed phase region (-10$^{o}$ C to -40$^{o}$ C) of a convective cloud are necessary for storm electrification. Additionally,

*Corresponding author: David Bright, NOAA, NWS Storm Prediction Center, 1313 Halley Circle, Norman, OK 73069-8493; email: david.bright@noaa.gov,

the convective updraft must be strong enough to ensure supercooled liquid water is replenished and graupel is lifted above the charge-reversal temperature zone ($-15^{o}$ C to $-20^{o}$ C). The amount of convective available potential energy (CAPE; CAPE herein is defined using the pseudo-adiabatic approximation and a virtual temperature correction) in the mixed-phase region necessary to accomplish the above is somewhat speculative, although it is believed that updraft speeds must attain minimum values of 6 to 7 $ms^{-1}$ (Zipser and Lutz 1994). Van Den Broeke et al. (2004) provide a more detailed summary of the above and show that pure parcel theory requires only about 25 $Jkg^{-1}$ of CAPE to meet the minimum vertical velocity threshold. Actual updraft velocities are generally much less than those predicted by pure parcel theory (Emanuel 1994) and therefore 100 $Jkg^{-1}$ to 200 $Jkg^{-1}$ of CAPE is perhaps a more realistic threshold to ensure sufficient updraft strength. Table 1 summarizes the *basic* conditions necessary for storm electrification.

### *2.2 The Cloud Physics Thunder Parameter (CPTP)*

Using the criteria in Table 1 a single parameter defined as the Cloud Physics Thunder Parameter (CPTP) is devised. Consolidation of the three ingredients in Table 1 into a single parameter has the advantage of producing simple, plan-view maps of thunderstorm potential from grid point soundings. The CPTP is defined as follows:

(Equation 1)

$$CPTP = \frac{(-19^{o}\,C - T_{EL})\,(CAPE_{-20} - K)}{K}$$

where $T_{EL}$ is the equilibrium level temperature ($^{o}$ C), $CAPE_{-20}$ is the CAPE between the $0^{o}$ C to $-20^{o}$ C levels, and K a constant set to 100 $Jkg^{-1}$. The $CAPE_{-20}$ is from the most unstable parcel; its lifting condensation level (LCL) temperature must be > $-10^{o}$ C. If the LCL of the most unstable parcel is $\leq -10^{o}$ C then the CPTP is set to zero. (Strictly speaking, the units of the CPTP are in $^{o}$C; however, the parameter lacks physical meaning so its units are henceforth ignored.) Values of the CPTP $\geq$ 1 are considered favorable for cloud electrification; however, this parameter says nothing about the likelihood of convection. Thus, the CPTP is conditional on the occurrence of convection. For regions of deep, strong convection, values of CPTP easily reach $10^{2}$ or more and no attempts have been made to associate lightning production (or rate) with the actual value of the CPTP. Using a threshold constant of K = 50 $Jkg^{-1}$ rather than 100 $Jkg^{-1}$ generally over predicts regions of thunderstorm potential. Setting K = 100 $Jkg^{-1}$ appears to work quite well based on operational experience; additional testing is still required to determine an optimal value of K.

## 3. EXAMPLE OF THE CPTP IN DETERMINISTIC AND ENSEMBLE FORECASTS

Based on the simplified physics described in section 2, the CPTP produces a plan view depiction of where thermodynamics support thunderstorms given that a convective cloud can develop (Fig. 1). However, no information is provided as to the likelihood that a convective cloud actually develops. In this cool season example, thunderstorm potential exists over the southwest United States, extreme southern Florida, and the southern Gulf of California. The deterministic prediction shown in Fig. 1 is merely one of the 16 members included in the SPC post-processing of the NCEP SREF (Bright et al. 2004).

The percentage of SREF members with a CPTP $\geq$ 1 (i.e., an uncalibrated probability of CPTP $\geq$ 1) indicates more than half the SREF members meet the criteria over the southwest United States, southern Florida, and the Gulf of California (Fig. 2).

| Table 1. Basic Ingredients for Cumulonimbus Electrification | | |
|---|---|---|
| **Lifting Condensation Level** | >= $-10^{o}$ C | Ensures the presence of supercooled water |
| **CAPE in the $0^{o}$ C to $-20^{o}$ C layer** | >= 100 to 200 $Jkg^{-1}$ | Ensures sufficient vertical motion exists in mixed-phase region through the charge-reversal temperature zone |
| **Equilibrium Level Temperature** | <= $-20^{o}$ C | Ensures cloud top is above the charge-reversal temperature zone |

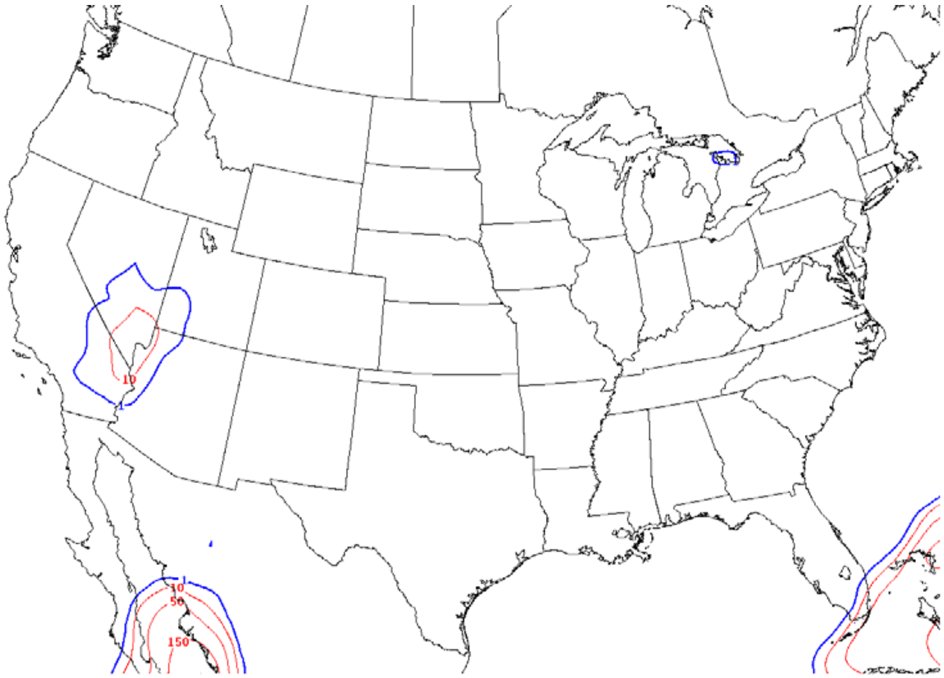


**FIGURE 1:** The predicted CPTP from the NCEP Eta model using the Kain-Fritsch convective parameterization. This 12h deterministic forecast is from the unperturbed (or control) member of the 09 UTC NCEP SREF on 08 November 2004. The forecast is valid at 21 UTC 08 November 2004. Actual CG lightning strikes occurring during the 18 to 21 UTC period are shown in Fig. 6.

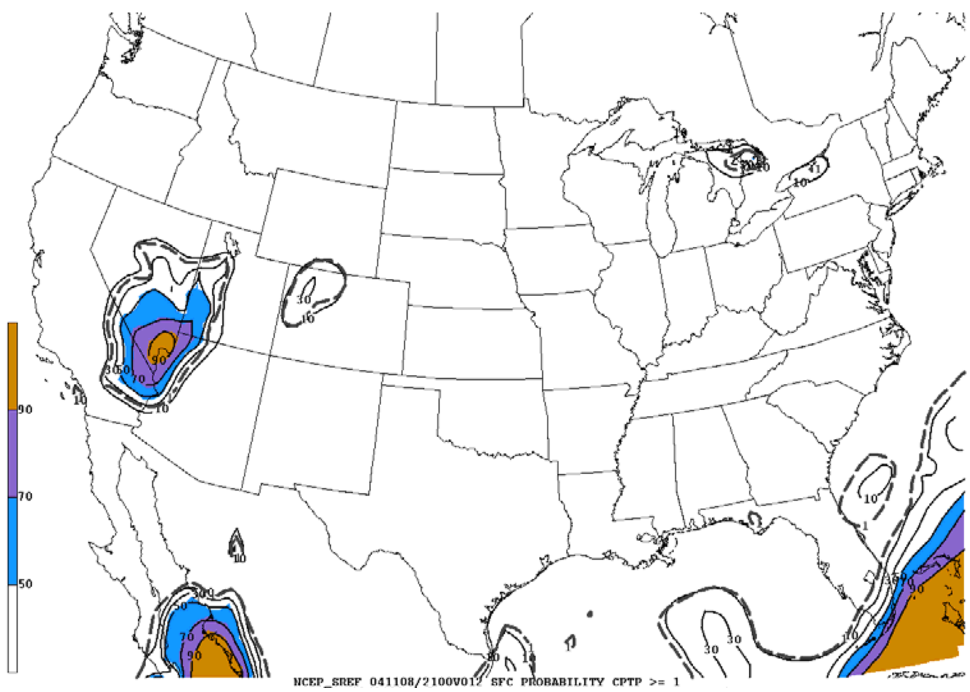


**FIGURE 2:** The (uncalibrated) probability of the CPTP $\geq$ 1 from the NCEP SREF for the date and forecast time described in Fig. 1. Color shading begins at 50%. The thick, dashed gray line is the location where the SREF mean is equal to 1.

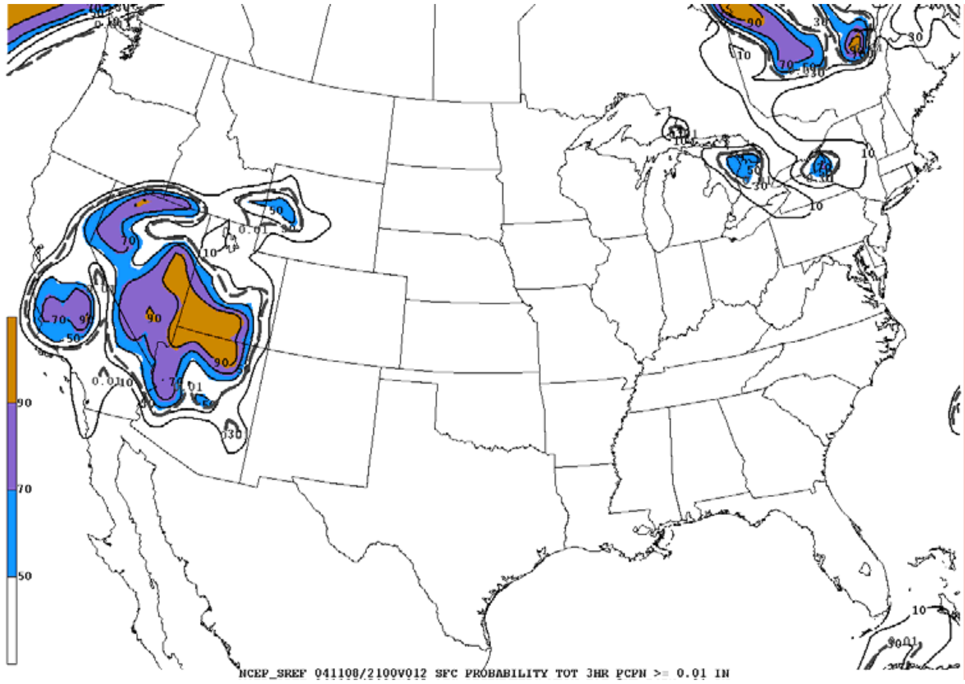


**FIGURE 3:** The (uncalibrated) probability of total precipitation ≥ 0.01" from the NCEP SREF for the date and forecast time described in Fig. 1. Color shading begins at 50%. The thick, dashed grey line is the location where the SREF mean is equal to 0.01".

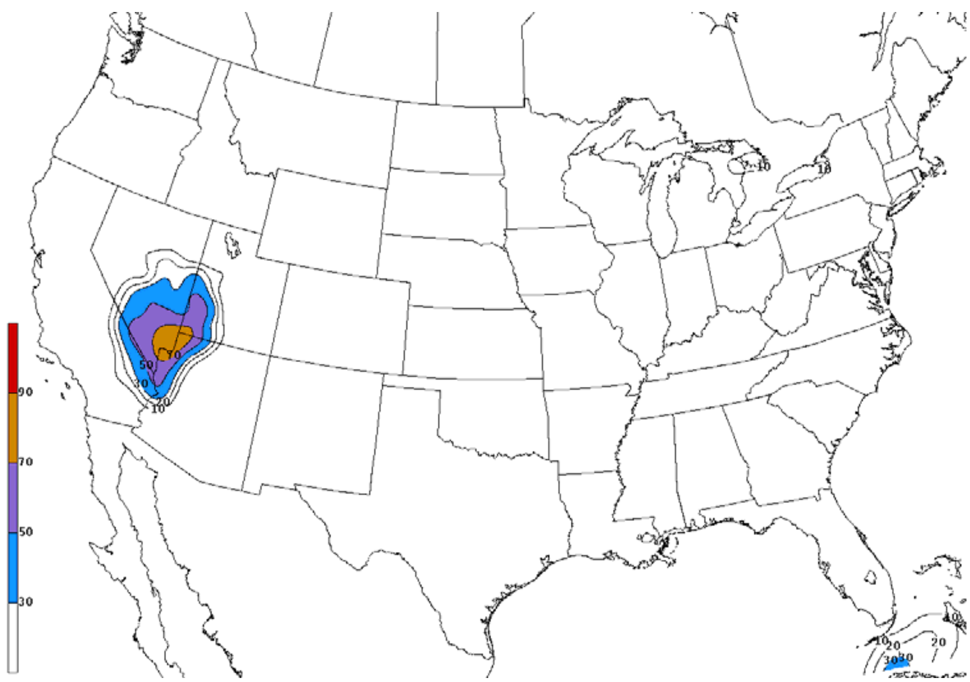


**FIGURE 4:** The (uncalibrated) probability of total precipitation ≥ 0.01" multiplied by the (uncalibrated) probability of the CPTP ≥ 1 (i.e., the product of Fig. 2 and Fig. 3) from the NCEP SREF for the date and forecast time described in Fig. 1. The product of the two fields is a good approximation to their joint probability. Color shading begins at 50%.1

To determine if precipitation is likely to occur, the SREF probability of precipitation ≥ 0.01” is invoked (Fig. 3). Simply multiplying the probability of precipitation ≥ 0.01” and the probability the CPTP ≥ 1 provides a very good approximation to the joint probability and better delineates areas where thunderstorms may actually occur (Fig. 4). (We are essentially treating the probability of CPTP ≥ 1 as the conditional probability of lightning given precipitation (p(o|x)) and the probability of precipitation ≥ 0.01” as the marginal probability of precipitation (p(x)). Thus the unconditional probability of lightning (p(o)) is defined by p(o) = p(o|x)p(x).)

In fact, if it is assumed that the SREF CPTP and total precipitation probabilities are entirely independent then Fig. 4 is the uncalibrated probability of a thunderstorm. Utilizing the probability of *total* precipitation rather than the probability of *convective* precipitation is preferred as the convective parameterizations may not activate if convection is elevated more than about 250 mb above the surface (e.g., elevated thunderstorms over a warm frontal zone). However, grid scale precipitation often accompanies these cool season, elevated events. Thus, for this purpose the SREF convective precipitation may occasionally be an inferior subset of the total precipitation.

## 4. CALIBRATED THUNDERSTORM FORECASTS FROM ENSEMBLES

From the SREF probabilistic fields described in Section 3 (CPTP ≥ 1 and total precipitation ≥ 0.01”), a simple method of creating a calibrated, probabilistic thunderstorm forecast is now presented. First, at each grid point the probability of the CPTP ≥ 1 and the probability of total precipitation ≥ 0.01” are each rounded into one of eleven bins: 0-5%; 5-15%; … ; 85-95%; 95-100%. Then, the two probabilistic forecasts are considered in tandem and placed into one of 121 possible combinations of the two predictors: (0%,0%); (0%,10%); (0%,20%); … (100%,100%). For every grid box over the calibration area (the calibration area extends approximately 300 km beyond the border of the contiguous United States), the frequency of occurrence of CG lightning associated with each predicted combination is computed over the previous 30-day period. The (calibrated) predictive component consists of binning the two predictors into one of the 121 possible combinations and assigning the actual lightning frequency associated with that bin over the previous 30 days as the probability of a thunderstorm. Results are improved when separate calculations are made for the 09 UTC and 21 UTC SREF start times and for each 3h forecast interval from forecast hour 03 through forecast hour 63. In other words, calibration/prediction is a function of forecast time and model start time. Fig. 5 is an example of the calibrated prediction based on the SREF run illustrated in Figs. 1 to 4, and Fig. 6 shows the same plot with the observed CG lightning during the 3h forecast period. Work is currently underway to implement a regionalized weighting technique into the calibration process.

All forecasts and gridded National Lightning Detection Network (NLDN) CG lightning data are on the approximately 40 km NWS grid 212 (grid information is available at http://www.nco.ncep.noaa.gov/pmb/docs/on388/tableb.html). One or more CG lightning strike(s) in a 40 km grid box during the previous 3h period constitutes a “hit.” Thus, the technique is designed to yield a calibrated probability of at least one CG lightning strike inside a 40 km grid box (or within about 15 statute miles of a point). The calibration tables are updated daily using data from the previous 30 days. The optimal training period is yet to be determined but 30 days worked well over the 2004 warm season.

## 5. STATISTICAL RESULTS OF THE CALIBRATED SREF THUNDERSTORM FORECASTS

The SREF calibrated thunderstorm probabilities are verified on the 40 km grid 212 where one or more NLDN CG lightning strikes within a grid box constitute a thunderstorm. A mask is applied such that verification is over the continental United States only. Objective measures of forecast skill are determined using: (1) the forecast reliability from an attributes diagram (Wilks 1995); (2) the Brier Skill Score (BSS) relative to sample climatology (Wilks 1995); and (3) the area under the Relative Operating Characteristic (ROC) curve (Mason 1982). The BSS is commonly used to verify probabilistic forecasts and improvement herein is expressed as the percentage improvement over *sample* climatology during the previous three-month period. (Sample climatology is generally considered a more robust measure of skill than actual climatology due to its intrinsic “knowledge” of the event.) Thus, positive BSS values reflect forecast skill. The ROC is also useful for verifying probabilistic forecasts and their ability to discriminate occurrences from non-occurrences. If the area under the ROC curve is integrated then


**FIGURE 5:** The calibrated probability of a thunderstorm from the NCEP SREF for the date and forecast time described in Fig. 1. The forecast is valid for the 18 to 21 UTC period.

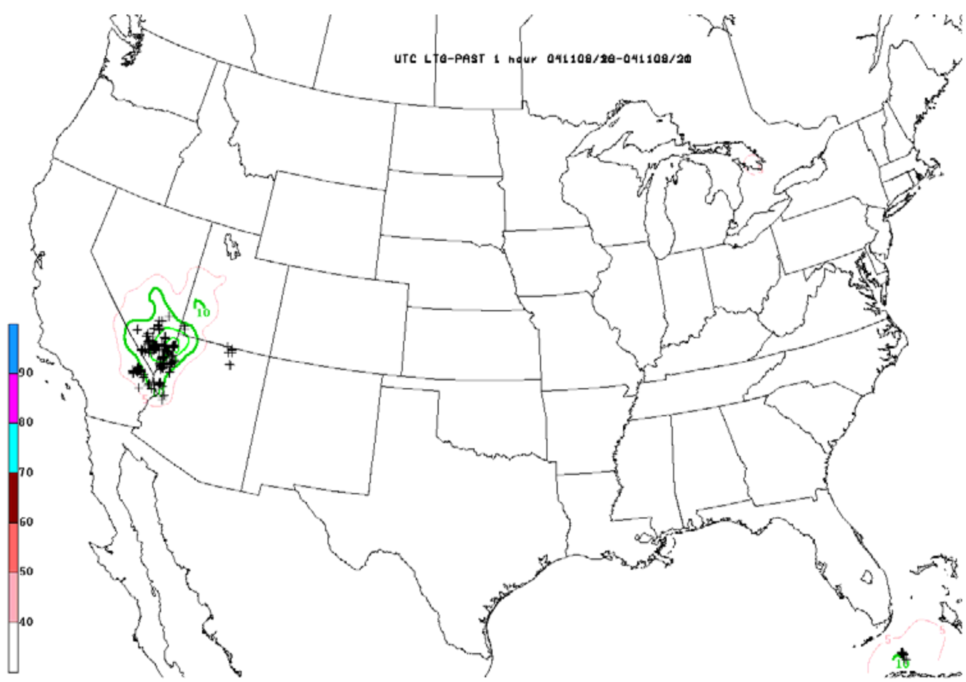


**FIGURE 6:** As in Fig. 5 with CG lightning strike data overlaid.

values range from a perfect score of 1 to a useless score of ≤ 0.5; ROC-area values greater than 0.7 indicate reasonable discriminating ability. All results presented herein are for the three month period from 5 August 2004 through 5 November 2004. (The NCEP SREF was upgraded on 17 August 2004; its affect on the SREF calibration and prediction is ignored.) The calibrated thunderstorm forecasts available to SPC forecasters are displayed via a nine point smoother. Thus, the forecast grids are first passed through a nine point smoother prior to verification to replicate what is viewed operationally.

Reliability is calculated by comparing all grid boxes with a particular forecast probability to the observed frequency of occurrence and plotting the results on an attributes diagram (Wilks 1995). Results from *all* 3h forecasts (i.e., 09 UTC and 21 UTC SREF starts using all 3h forecast periods from 03 through 63 hours) indicate good reliability and resolution (Fig. 7). The system is skillful at all probabilities; although, 3h thunderstorm probabilities do not exceed 70%. Sample climatology is indicated by the dashed lines and most points fall very close to perfect reliability line and are well removed from the no skill line. Data are also verified every 3 hours using the BSS (Fig. 8) and the ROC-area (Fig. 9) considering both the 09 UTC and 21 UTC SREF start times.

The BSS is a 10 to 15% improvement over sample climatology during the first 15 hours of the forecast and decreases gradually to just below 10% improvement during the latter half of the 63 hour forecast period. Similarly, the 3h ROC-area scores range from an impressive 0.9 early in the period to a still very skillful 0.82 late in the period. Indeed, the BSS, ROC-area, and attributes diagram all indicate very skillful 3h probabilistic thunderstorm forecasts.

The BSS is a function of sample climatology and therefore changes over the forecast period with which sample climatology is based. Fig. 10 shows the BSS over the first 12 hours of the forecast, the second 12 hours of the forecast, the first 24 hours of the forecast, and the entire 63 hour forecast (for both the 09 UTC and 21 UTC start times). When the entire 63 hour period is considered, the BSS shows a 23% improvement over sample climatology. Likewise, the ROC-areas all exceed 0.85 for the same time intervals (Fig. 11).

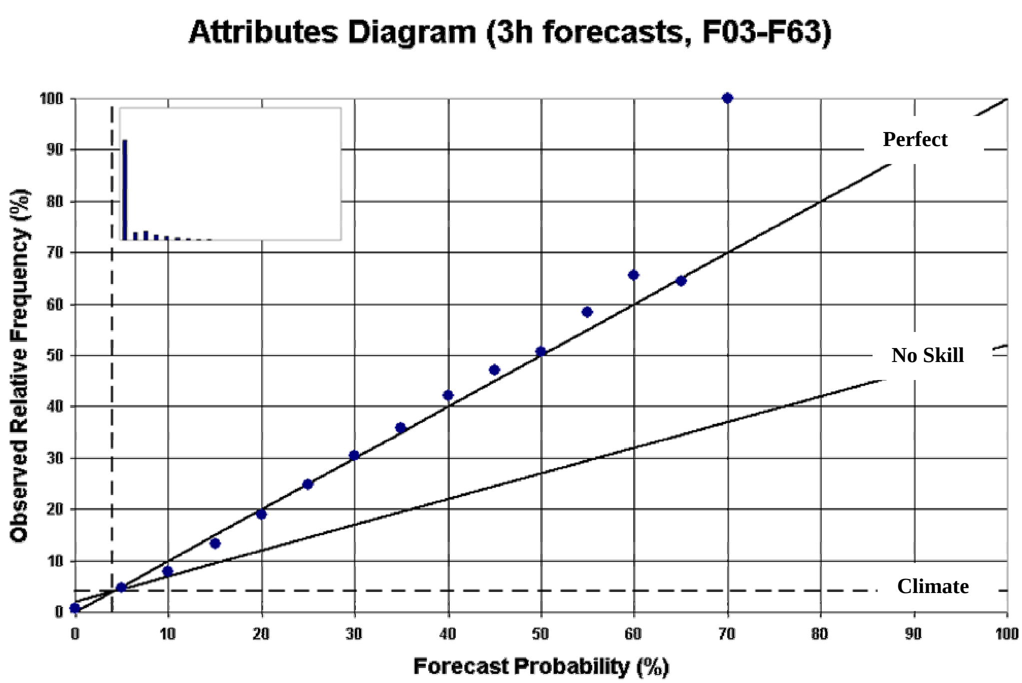


**FIGURE 7:** Attributes diagram of the verification of the SREF calibrated thunderstorm product for the period 5 August through 5 November 2004. Inset diagram shows the frequency of usage for each forecast probability bin (the number of *correct* forecasts at 0, 10, 20, 30, 40, 50, 60, 70% are 89826, 94997, 87921, 60721, 30798, 6860, 632, 2, respectively). Skillful forecasts are found between the no skill line (solid) and the vertical sample climatology line (dashed); all forecasts are skillful from 0% through 70%

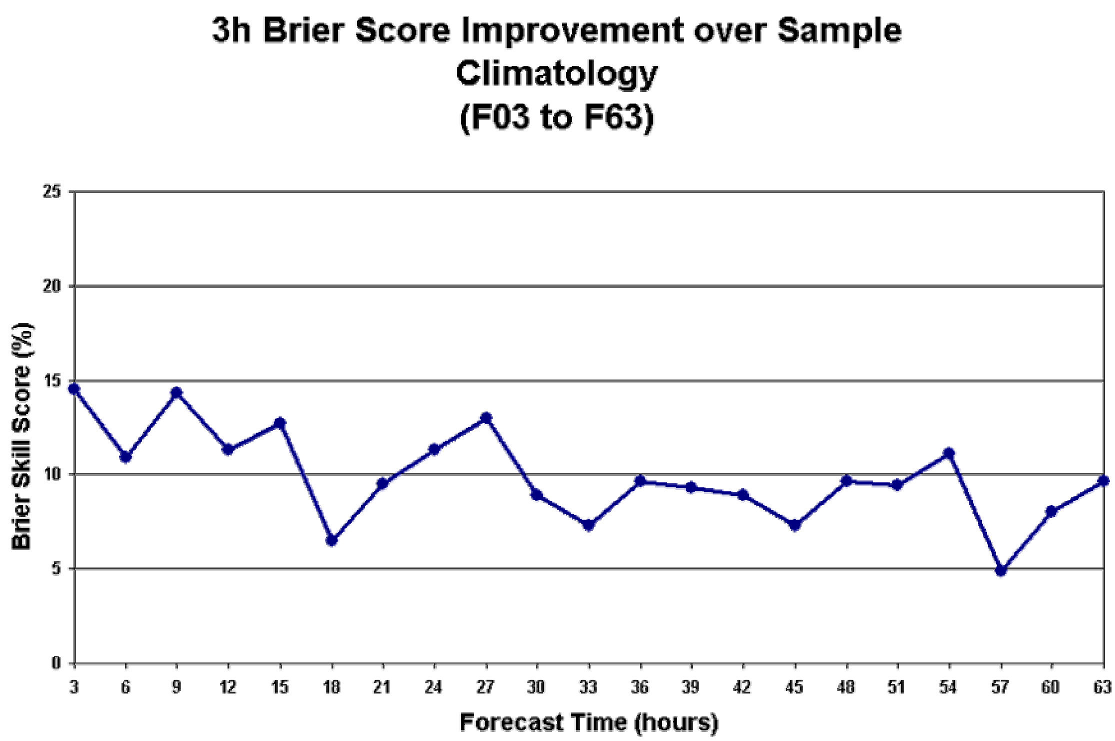


**FIGURE 8:** Three-hour Brier Skill Scores (BSS) relative to sample climatology for the SREF calibrated probability of a thunderstorm (as in Fig. 7).

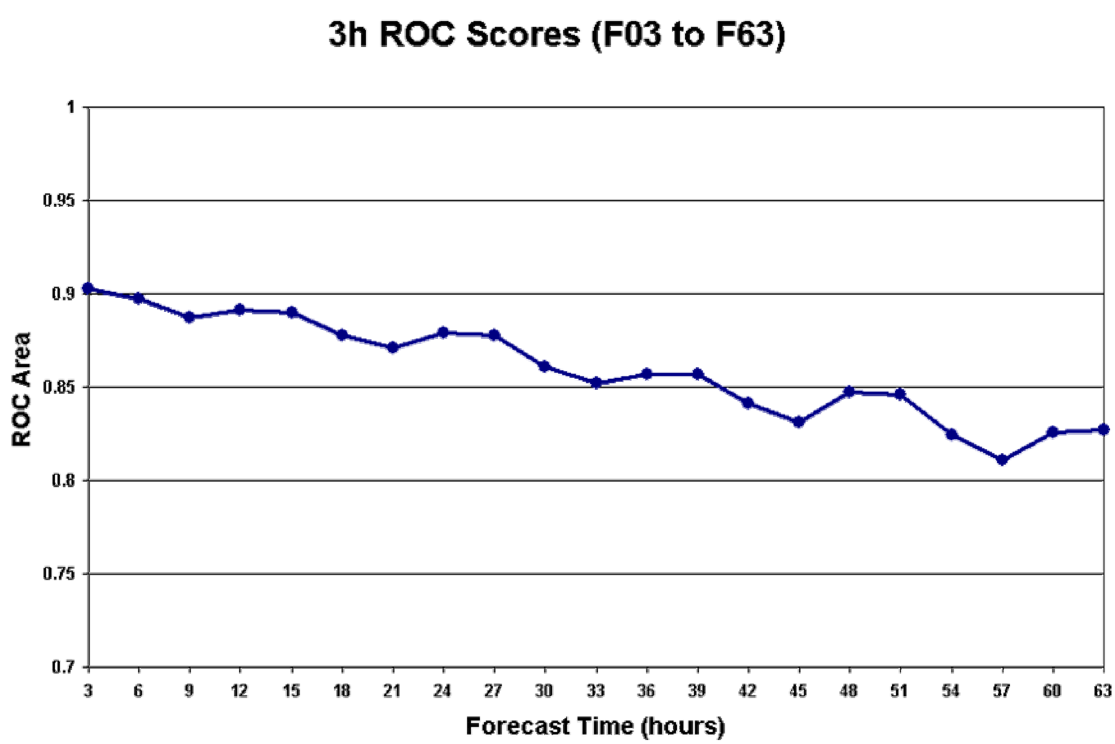


**FIGURE 9:** Three-hour ROC-area scores for the SREF calibrated probability of a thunderstorm (as in Fig. 7).

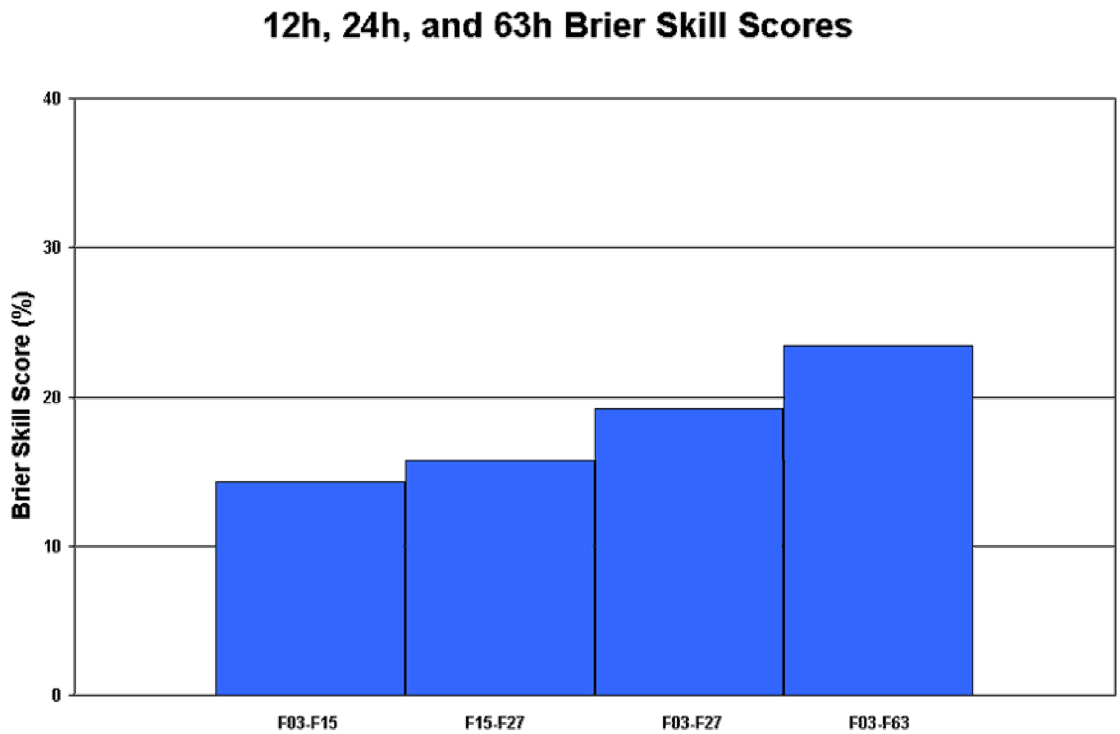


**FIGURE 10:** BSS for 12, 24, and 63 hour periods from the SREF calibrated probability of a thunderstorm for the 5 August 2004 through 5 November 2004 period.

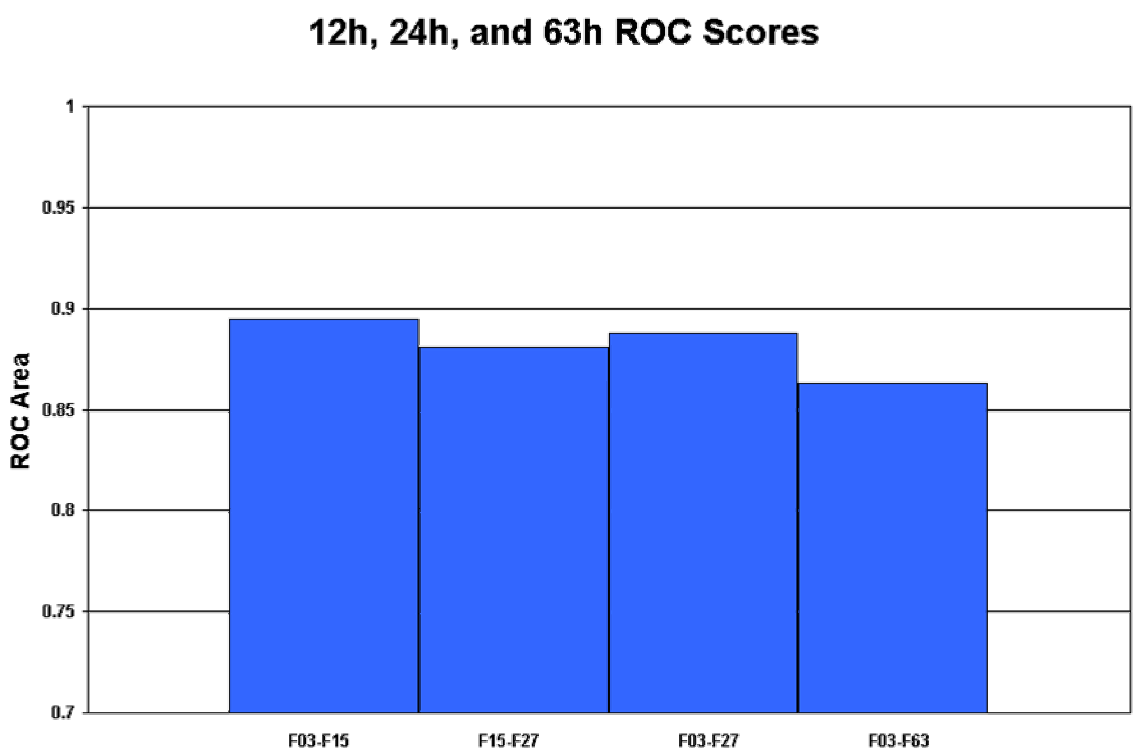


**FIGURE11:** As in Fig. 10 except ROC-area results.

The 09 UTC and 21 UTC SREF starts were also verified separately (results not shown) with similar skill, although a diurnal oscillation exists such that skill is maximum during the afternoon/evening hours (~21 UTC to 03 UTC) and minimum during the late night/early morning hours (~09 UTC to 15 UTC). This result is not surprising given climatological increase in "afternoon" thunderstorms and the additional challenges associated with predicting nocturnal convection.

## 6. SUMMARY

A simple, physically-based parameter known as the Cloud Physics Thunder Parameter (CPTP; equation 1) was presented. It aids in delineating potential thunderstorm areas by determining if instability and appropriate thermodynamics for charge separation are coincident in observed or model forecast soundings. The appropriate thermodynamics include a lifting condensation level $\geq$ -10$^{o}$ C and an equilibrium level temperature $\leq$ -20 $^{o}$ C such that mixed phase hydrometeors extending above the charge-reversal temperature zone are present. Furthermore, CAPE > about 100 Jkg$^{-1}$ must exist in the 0 $^{o}$ to -20 $^{o}$ C layer to ensure the updraft is capable of replenishing supercooled liquid water and lifting graupel above the aforementioned charge-reversal zone. The CPTP is scaled so that values $\geq$ 1 indicate a vertical profile that should support cloud electrification given the development of deep convection. When the CPTP is calculated using NCEP SREF output, an uncalibrated probabilistic forecast of thunderstorm potential is produced. By itself, though, the CPTP does not provide a probabilistic forecast of thunderstorms.

By using the probability of total precipitation, the SREF can provide the necessary information concerning the likelihood of thunderstorms. SREF probabilistic forecasts of CPTP $\geq$ 1 and total precipitation $\geq$ 0.01" can be combined to produce an uncalibrated probability of thunderstorms. Using the calibration technique described in section 4, skillful probabilistic forecasts of thunderstorms are produced from an ensemble forecast.

The calibration technique described here is computationally efficient and easy to implement, producing skillful and reliable probabilistic forecasts of thunderstorms. The system used a calibration period of the previous 30 days. Results do improve when each forecast hour (e.g., 03, 06, …. , 63) is calibrated independently and the 09 UTC and 21 UTC SREF runs are considered separately. Skillful results were still obtained, albeit to a lesser extent, by combining the 09 and 21 UTC SREF runs and creating just one calibration table for all forecast hours. The optimal calibration period still needs to be determined, as does any potential improvement through grid point weighting or regionalization of the calibration area. Future work will also include improvements to the CPTP formulation, perhaps converting even it from a parameter value to a binary predictor (1 or 0) indicative of vertical profiles that do or do not meet deep convective cloud electrification criteria.

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