

AN ALGORITHM TO FORECAST LIGHTNING USING ONLY AFWA MM5 MODEL OUTPUT: "BOLT OF LIGHTNING TECHNIQUE" (BOLT)

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1) INTRODUCTION

Lightning forecasting is of importance to meteorology and human activity. Lightning is the second-leading cause of weather-related deaths in the United States (Holle et al. 1999). The U. S. Air Force must cease runway operations when lightning is observed within 5 nm of an airfield. In addition to the obvious hazard to human life and property, the ability to skillfully forecast lightning could be beneficial to other areas of forecasting. For example, the issuance of a convective severe weather forecast might be conditional upon whether the forecaster believes that lightning will occur.

There exist many examples of lightning forecasts based partly or completely upon model data. A regression equation by Knapp and Brooks (2000) forecasts lightning for a 12 hour period. Using multiple linear regression, Knapp and Brooks found a linear combination of the lifted index, the K index, and the SWEAT index that create an areal forecast of lightning comparable to human forecasts. The Meteorological Development Laboratory (MDL) forecasts lightning from model data using the Model Output Statistics approach (Hughes 2001, 2002). Also at the MDL, Kitzmiller (2002) made short-term lightning probability forecasts by extrapolating current lightning using radar, satellite, and model data. The Storm Prediction Center (SPC) forecasts an area of possible non-severe thunderstorms on their "AC" (area convection) product. Burrows et al. (2005) discussed the status of a statistical lightning forecast at the Meteorological Service Canada.

Keller (2004) describes The Bolt Of Lightning Technique (BOLT). BOLT differs significantly from the above lightning forecast methodologies in several ways. The BOLT algorithm attempts to parameterize conditions favorable and unfavorable to lightning. The convective cap is of importance to the forecasting of convection. BOLT explicitly utilizes two cap indices, whereas few lightning forecasts other than human forecasts have found cap indices to be of much significance. There is also a filtering parameter in BOLT that inhibits lightning from being forecast. And finally, the BOLT algorithm uses only model data. It does not require statistical development, nor observations of lightning data (or any other observational data).

Section 2 describes the data used in this work. Section 3 describes the BOLT algorithm in mostly meteorological terms. Section 4 presents results in qualitative and quantitative terms.

2. DATA

In this study, lightning is forecast using only Air Force Weather Agency (AFWA) MM5 model forecast data. Remotely-sensed cloud-to-ground lightning strikes from the National Lightning Detection Network (NLDN), described in Cummins et al. (1998), were used as verifying lightning data. The NLDN reports only cloud-to-ground lightning, not cloud-to-cloud lightning.

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AFWA MM5 model output was used as input to the BOLT lightning forecast algorithm. The MM5 with 45 km resolution is run four times daily over North America out to 72 hours, with data file output every three model hours. Predictors for the BOLT algorithm were raw model data and a large suite of parameters calculated by the post-processor at AFWA.

The goal of the BOLT algorithm development was to forecast lightning occurring at the instantaneous valid time of the forecast. Verifying data was therefore primarily the NLDN cloud-to-ground lightning data from the hour before and after the MM5 model output. During algorithm development the SPC outlooks of thunderstorms were sometimes referenced as a temporary target forecast early in the day before lightning strikes occurred.

BOLT is run over areas of the world outside of North America, but has not yet been rigorously evaluated outside of the United States.

3. ALGORITHM DEVELOPMENT AND DESCRIPTION

3.1 Algorithm development and algorithm overview

The development of the BOLT algorithm was done with an ad hoc method described in Keller and Kuchera (2005). Interactive visualization and data manipulation software was used to create lightning forecasts from model output data. Model output predictors were used individually and in combinations to create new predictors. BOLT algorithm output was compared primarily to lightning strikes and occasionally to SPC thunderstorm outlooks. The SPC outlooks were used only as guides during model development, not for quantitative evaluation or verification. The length of the model forecast was not a factor in the development of BOLT. Modification of the algorithm continued for as long as the developer's efforts seemed to be productive.

The result was a lightning forecast algorithm consisting of three separate lightning producing mechanisms, each of which by themselves are sufficient to cause lightning to be forecast. A filter is applied that reduces over-forecasting. A separate algorithm is used to forecast lightning when terrain height is over 1000 m. This algorithm attempts to parameterize a sounding profile typically associated with lightning in the Rocky Mountains.

3.2 Lightning-producing mechanisms (terrain under 1000 m)

There are three lightning producing mechanisms in BOLT for terrain under 1000 m. The predominant mechanism, accounting for the majority of the lightning forecast by BOLT, is an unstable and weakly capped boundary layer. This is quite similar to the thermodynamic prerequisite for *severe* convection. The stability index used is the lifted index. To be uncapped, two cap indices must be under threshold values. The convective inhibition (Colby 1984) must be weaker than -100 J kg^{-1} , and the AFWA version of the lid strength index (Graziano 1987) must be less capped than $6 \text{ }^\circ\text{C}$. Since more lightning seemed to be occurring over high terrain, the lifted Index was modified by subtracting one degree for every 1000 m of elevation.

A substantial amount of lightning in BOLT is forecast due to elevated instability in combination with upward vertical velocity. Mid-level instability was determined by lifting many combinations of low-level parcels (ranging from 900-600 hPa) to many higher levels (ranging from 850-250 hPa). The maximum difference in degrees between the parcel and the environmental temperature was used as a measure of mid-level instability. The process could be described as calculating the Showalter index, using the most-unstable combination of levels for the parcel base and top. It was found that lightning generally occurred only when mid-level instability was also coincident with model upward vertical velocity at 700 hPa. The instability was therefore multiplied by the upward vertical velocity to obtain a predictor for lightning. A suitable threshold value was determined such that the combined predictor's forecast area was comparable to the verifying lightning.

A small amount of lightning is forecast by BOLT if there is strong boundary layer convergence in combination with a deep, saturated moist-adiabatic thermodynamic profile. This corresponds to strong low-pressure centers in the cold season, and accounts for very little of the lightning forecast by BOLT.

3.3 Filter for lightning

Once the lightning producing mechanisms were developed for BOLT, an effort was made to reduce false alarms by identifying conditions that inhibited lightning. Inspection of model soundings in areas where lightning was over-forecast suggested a pattern. The soundings where lightning was over-forecast tended to have little moisture above the lifting condensation level (LCL). This pattern in the soundings was parameterized. The maximum relative humidity was found in the mid-troposphere, beginning 75 hPa above the LCL. Lightning was not forecast by BOLT unless the maximum relative humidity, 75 hPa above the LCL or higher, was at least 90 percent.

3.4 Terrain over 1000 m

During the first warm season forecast by BOLT, it became apparent that the algorithm was inadequate for the lightning that occurs commonly in the afternoons over the higher terrain of the Rocky Mountains. A separate algorithm was designed to forecast lightning for locations where the terrain was over 1000 m.

A typical model sounding associated with high-terrain lightning is shown in Fig. 1. The sounding has a very deep inverted-V structure, with a nearly dry-adiabatic temperature and nearly constant mixing ratio that is 250 hPa deep. There is little instability as measured by CAPE and the lifted index. There is also very little convective inhibition in this model sounding. Note there is also a layer of high relative humidity above the LCL. Lightning is therefore forecast for terrain over 1000 m when the convective inhibition is under 20 J kg^{-1} , the lifted index less than $-1 \text{ }^\circ\text{C}$, and there exists 70% relative humidity at a level at least 50 hPa above the LCL. The latter requirement is a relaxed version of the filter applied to terrain under 1000 m.

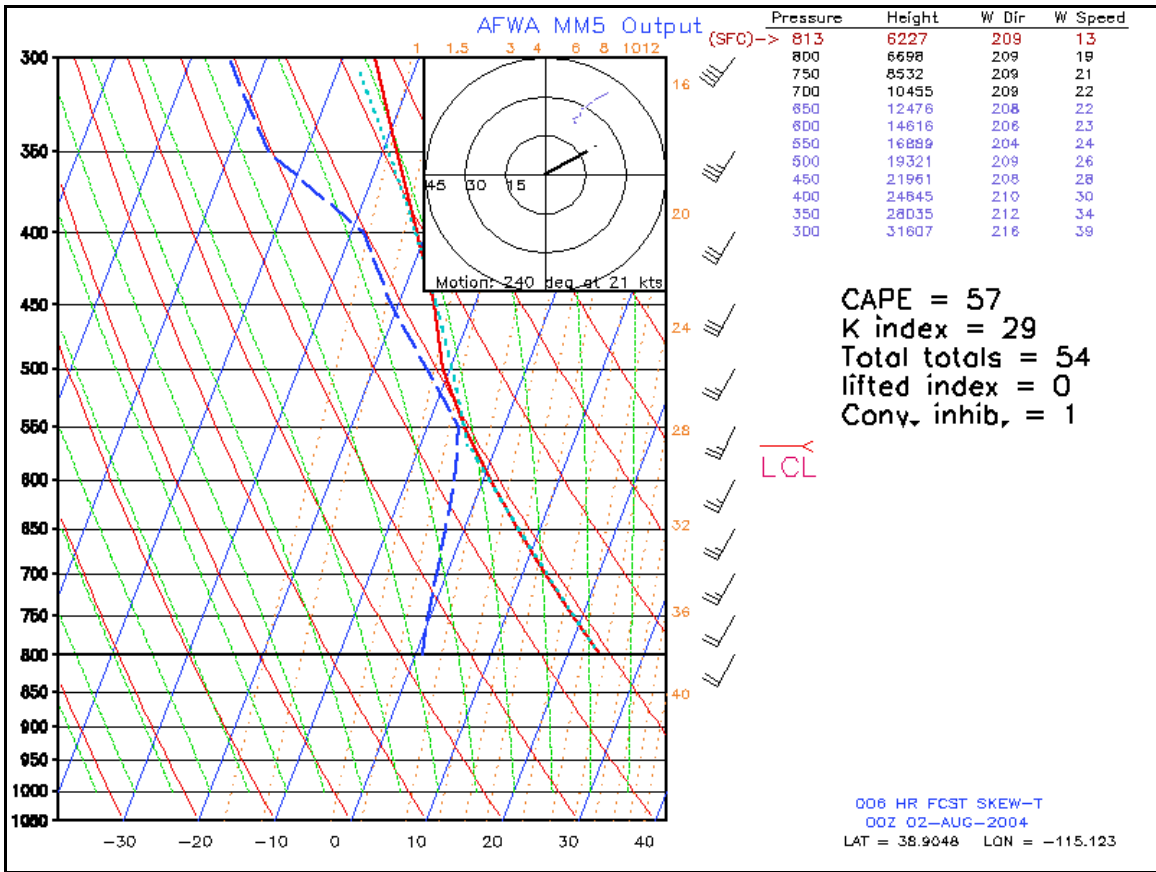


Figure 1. Typical mountain sounding associated with lightning

Note that the under-1000 m algorithm is applied first to the entire domain. The over-1000 m algorithm is subsequently applied, and therefore has precedence. The rule modifying the lifted index by one degree for every 1000 m therefore applies only in the range of 0 to 1000 m.

4) RESULTS AND DISCUSSION

4.1 Qualitative evaluation and case studies

BOLT lightning forecasts are qualitatively similar to those of the SPC, with occasionally impressive details, often due to terrain. Forecast lightning propagates smoothly across the United States, with an appropriate diurnal tendency.

BOLT subjectively seems to forecast “no lightning” quite well during the cold season. Statistics have not been compiled for any cold season, but an example BOLT forecast with very little lightning is shown in Fig. 2. A strong upper trough on the west coast caused only a small area of lightning to be forecast by BOLT. No lightning was observed during the hour before and after the valid time of the forecast (0000 UTC 19 February 2006), and no lightning was forecast by the SPC outlook valid 1200 UTC on the 19th to 1200 UTC the 20th.

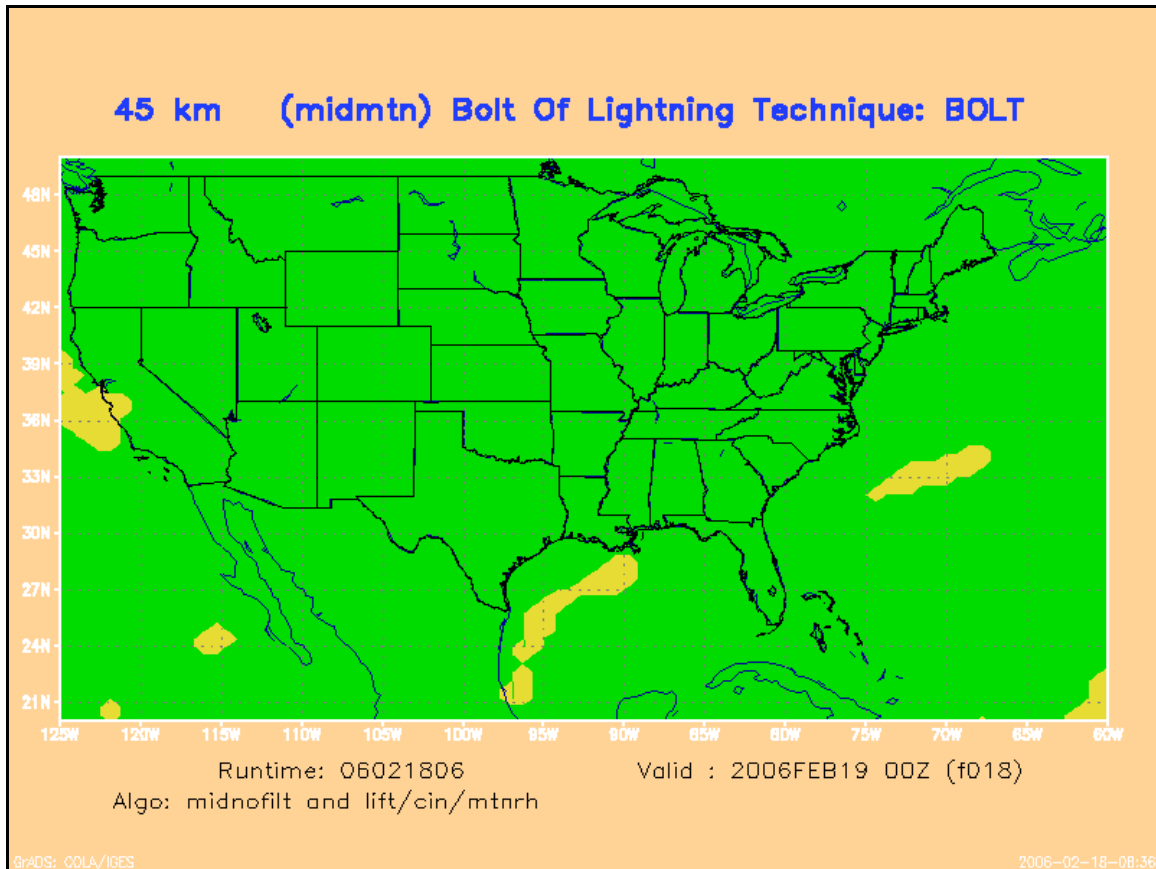


Figure 2. Case where BOLT forecasts very little lightning in the cold season.

Figure 3 shows the 18 hour BOLT forecast from the 28 July 2004 0600 UTC run of the MM5 valid 0000 UTC (at the normal diurnal peak of lightning activity in the CONUS). Lightning strikes that occurred one hour before until one hour after the valid time are plotted. There is excellent agreement in the areal coverage. A case with good detail in high terrain areas is seen in Fig. 3, where lightning is correctly forecast in a narrow band over the Sierra Nevada Mountains, and over high terrain in northwestern California. Excellent overall agreement exists with the verification of this three hour forecast, with a notable failure to forecast lightning in the Gulf Coast states. Examination of model forecast soundings revealed that the filter was too strict, since the layer of high relative humidity over the LCL was only about 50 hPa thick, where the filter requires 75 hPa. Model soundings in the Gulf Coast states looked much like the typical mountain sounding of Fig. 1, with a deep surface boundary layer 200 hPa thick. Perhaps by borrowing features from the mountain algorithm this deficiency can be corrected.

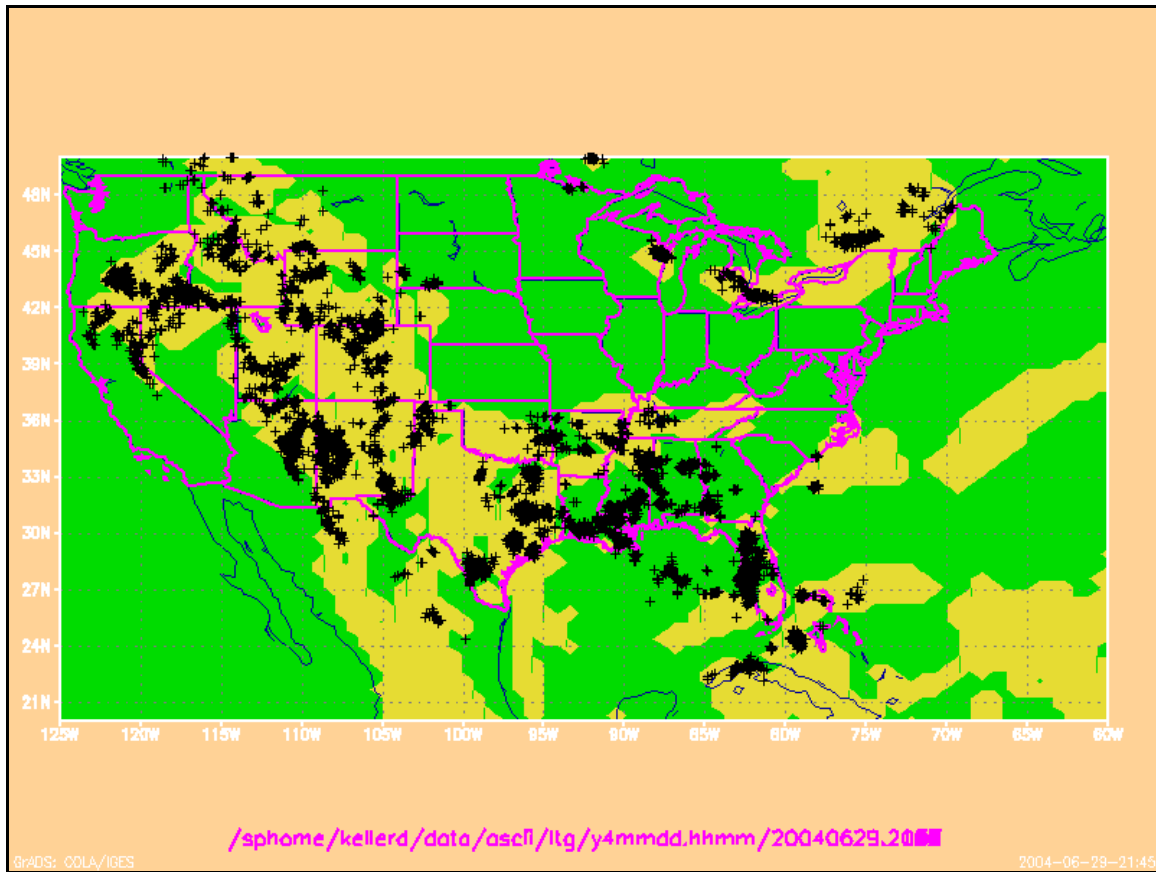


Figure 3. Three hour BOLT forecast valid 26 June 2004 2100 UTC (yellow), with cloud-to-ground lightning strikes plotted (small black crosses) between 2000 and 2159 UTC.

A weakness was found in that BOLT can under-forecast squall lines associated with drylines. An attempt was made to alleviate this by relaxing the filter when the mid-level instability with upward vertical velocity mechanism was especially strong. It is likely that a better parameterization is still needed for this type of thunderstorm complex. BOLT tends to over-forecast mountainous lightning in the United States at 0300 UTC.

An advantage of BOLT is that it forecasts lightning using only model data. Output is available every three hours (corresponding to the AFWA MM5 output frequency). BOLT 3-hourly output can also be combined to produce forecasts for any desired time period.

4.2 Quantitative evaluation

BOLT forecasts for 24 to 48 hours were merged to create a “day 2” forecast similar to that produced by the SPC. BOLT forecasts for 24, 27, 30, 33, 36, 39, 42, 45, and 48 hours, based on the 1200 UTC MM5 run, were combined to produce the day 2 forecast. The combined BOLT forecast was compared to the SPC’s day 2 forecast normally produced at 1730 UTC the preceding day. Both forecasts cover the day 2 “convective day”, which is from 1200 UTC to 1200 UTC. The rationale for comparing a 24 to 48 hour forecast is that both the BOLT and SPC forecasts for this time range are almost completely dependent upon interpretation of model data. The SPC has an advantage for short-term forecasts since forecasters know the position of existing lightning; BOLT does not. SPC forecasters still can take advantage, for day 2 forecasts, of recent days lightning trends, climatology, and analog cases, in addition to their interpretation of model data.

The period of comparison was the warm season of 2005, corresponding to months of high lightning frequency. Every fourth day from 01 May 2005 to 30 Sept 2005 was verified. BOLT forecasts were created in real time and saved as GIF images. SPC map image forecasts were derived from the appropriate text bulletins. Corresponding lightning images from every other hour were created (every other hour to save computing time). Some SPC forecasts were not correctly decoded by the author's software, therefore they were thrown out, and this may be an indirect source of bias. Nevertheless, 29 days spanning a five month period were compared, and it is believed that the results are meaningful. Each forecast image in a map form was visually inspected to insure correctness. SPC thunderstorm areas were visually compared to the GIFs archived directly from the SPC's web page to ensure that each case was correct.

Statistics and skill scores were calculated by counting image pixels. Images were created for the BOLT and SPC forecasts, and a corresponding image of lightning strikes. A lightning strike was plotted as a cross seven pixels high and seven pixels wide. Therefore, a lightning strike is manifest as 13 image pixels, as seen in Figs 3 and 5. Statistics were collected only over the continental United States, not over oceans, Canada, or Mexico. Hits, misses, false alarms, and "none forecast / none observed" were tallied. Skill scores were calculated for each day-long forecast. In order to provide a simple measure of comparison, the median of the daily statistics was calculated. The results are shown in Table 1. Definitions and merits of the POD, FAR, CSI, and Heidke scores are described in Doswell et al. (1990). The ETS is described by Schaefer (1990). The Heidke skill score and correlation coefficient are described by Woodcock (1976). It is seen that the BOLT "day 2" forecasts are quite comparable to those produced by the SPC.

Table 1: Median value of individual day statistics for warm season of 2005

	Hits	Miss	False	None	POD	FAR	CSI	ETS	Heidke	Correlation
SPC	17194	1131	45140	54159	0.94	0.74	0.25	0.12	0.22	0.33
BOLT	15258	1829	36504	67163	0.92	0.70	0.30	0.16	0.27	0.35

To provide the reader with a feeling for the significance of the scores due to daily variation, the Heidke skill score for individual days forecasts are plotted in Fig. 4. The numbers from 1 to 29 correspond to a date during the warm season of 2005.

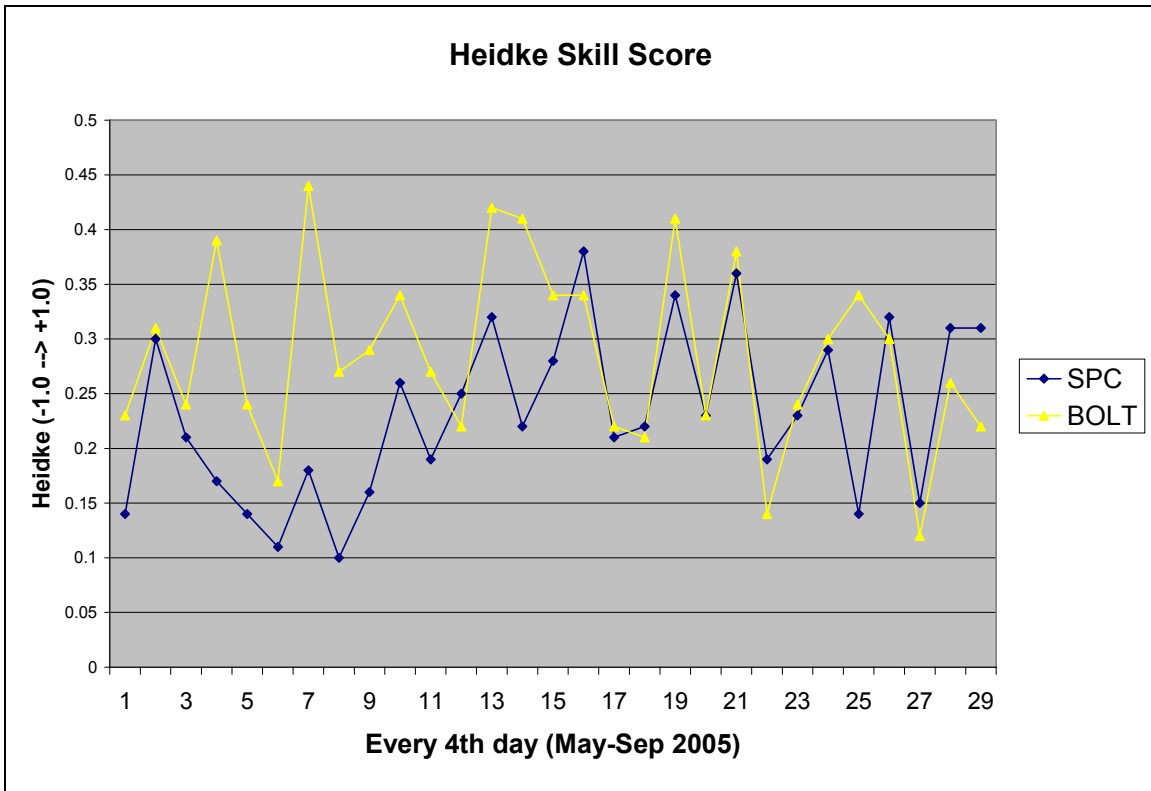


Figure 4. Heidke skill score for SPC (blue) and BOLT (yellow) “Day 2” forecasts during the warm season of 2005.

Case number four in Fig. 4 was examined due to the large difference in the Heidke skill score between the SPC and BOLT. The forecasts are shown in Fig. 5. One reason for the surprising skill of BOLT relative to the SPC appears to be due to the high variability of lightning strike density. Note the large area of widely scattered lightning, seemingly well forecast by the SPC. BOLT however also appears visually to do quite well by not forecasting the same area. The low density of reports appears to have benefited BOLT in terms of the skill scores listed. Specifically, most of the scores benefit BOLT due to the lower number of false alarms compared to the SPC. It appears that the density of reports needs to be considered when verifying lightning forecasts. According to their web page, (Storm Prediction Center 2006) the SPC forecasts lightning when “Within this area, a 10% or greater probability of thunderstorm occurrence is forecast.” This concept, the density of lightning reports, has not been taken into account in this study, and should be a topic of future work elsewhere.

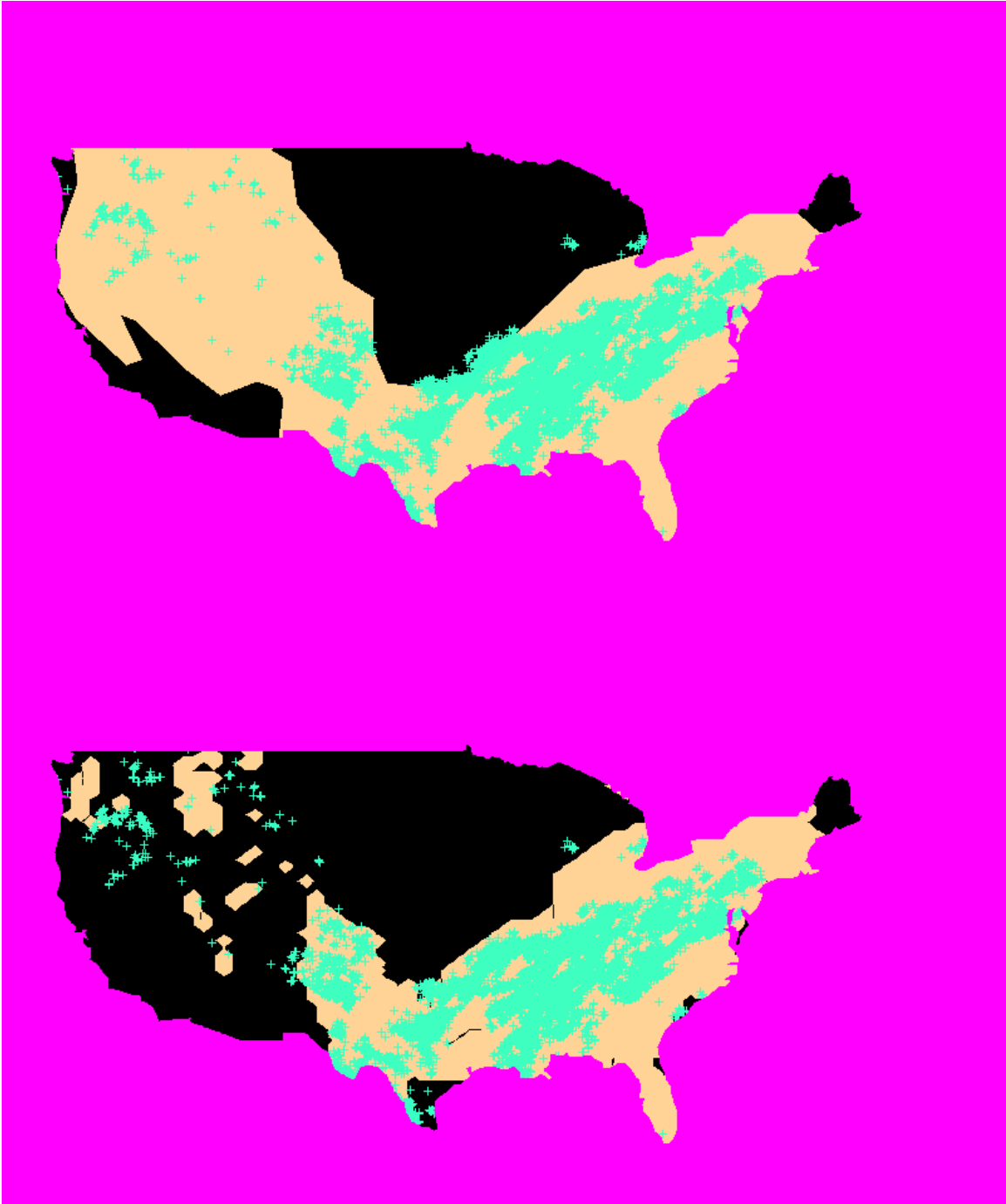


Figure 5. "Day 2" forecasts made 13 May 2005 for 14 May 2005: SPC (top) and BOLT (bottom).

Table 2. Case #4 (13 May 2005) statistics for BOLT and SPC "Day 2" lightning forecasts

	Hits	Miss	False	None	POD	FAR	CSI	ETS	Heidke	Correlation
SPC	21089	1199	58831	38694	0.95	0.74	0.26	0.09	0.17	0.28
BOLT	20243	2045	31538	68288	0.91	0.61	0.38	0.24	0.39	0.46

5) SUMMARY/DISCUSSION

Cloud-to-ground lightning strikes are forecast using only AFWA MM5 model forecast output data. Lightning producing mechanisms in the BOLT algorithm are 1) boundary layer instability and weakly capped; 2) mid-level instability in combination with upward vertical velocity and 3) deep moist-adiabatic lapse rates with strong convergence. A separate algorithm used for terrain above 1000 m. A filter, the maximum relative humidity found at least 75 hPa above the LCL, is used to reduce false alarms.

The qualitative and quantitative skill of BOLT forecasts seem to be quite good. Areal coverage of BOLT forecasts, especially when combined to make a 24 hour forecast, is very similar to equivalent forecasts produced by the SPC. Day 2 forecasts during the warm season of 2005 showed skill scores that were quite close to those of the SPC.

A case study comparing BOLT and SPC shows that the method of verifying lightning forecasts is still an open issue.

BOLT forecasts have the advantage of being available as instantaneous forecast, or forecasts covering a range of times can be created. BOLT has shown good detail in lightning forecasts, especially in areas where terrain is a factor. BOLT fails to forecast some significant dryline-type storms.

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