P8.4 **FORECASTING CLOUD-TO-GROUND LIGHTNING DATA WITH AFWA-MM5 MODEL DATA USING THE "BOLT OF LIGHTNING TECHNIQUE" (BOLT) ALGORITHM**

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1. INTRODUCTION

Many articles appear in formal meteorological journals about the science and physics of lightning and lightning strikes, but fewer have been published about forecasting lightning. A regression equation by Knapp and Brooks (2000) forecasts lightning for a 12 h 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. (2004) discussed the status of a statistical lightning forecast under development at the Meteorological Service Canada.

The forecasting of lightning is not of trivial importance. Lightning strikes rank as the second-leading cause of weather-related deaths in the United States (Holle et al. 1999). Air Force bases must cease refueling operations when lightning is within five miles due to fire danger. For severe weather forecasting applications, one of the most difficult tasks is to anticipate convective initiation. A good forecast of lightning would certainly assist in preparation of severe forecasts by helping to decide whether convection is likely or not.

An algorithm that forecasts lightning, "BOLT" (Bolt Of Lightning Technique), developed at the Air Force Weather Agency (AFWA) is described. Section 2 will describe the data utilized, section 3 describes details of the algorithm, case studies, and algorithm strengths and weaknesses. Section 4 contains a summary with possible future work.

2. DATA AND ALGORITHM DEVELOPMENT

Development of the lightning forecast algorithm began in October 2003. Regular archival of forecasts began in January 2004. The algorithm was designed only to forecast the occurrence or non-occurrence of lightning, not the number of strikes. Cloud-to-ground lightning strikes from the national remote-sensing network, described in Cummins et al. (1998), were used as the verifying lightning data. The network reports only cloud-to-ground lightning, not cloud-to-cloud lightning.

The algorithm was created using an "ad hoc" development methodology. The ad hoc methodology has been used successfully at AFWA to develop two other model post-processor algorithms (surface visibility and severe weather). Using appropriate visualization and data manipulation software, and meteorological experience, model predictors were selected, thresholds were determined, and parameterizations of atmospheric processes were derived in a very short time. A manuscript describing the algorithm development methodology has been submitted to the National Weather Digest.

3. RESULTS

3.1 *Terrain Height Under 1000 m*

Three mechanisms are associated with lightning in most of the CONUS according to the BOLT algorithm. The most common mechanism is boundary layer instability with a weak cap, familiar to most readers as basic building blocks of severe thunderstorms as well as non-severe thunderstorms. The second mechanism is elevated instability, but only when combined with sufficient model 700 hPa upward vertical velocity. And lastly, very strong boundary layer convergence, combined with a deep layer of high humidity and a moist adiabatic lapse rate, correspond to lightning. An example of this lightning producing mechanism would be a strong low-pressure center in the cold season. Besides these mostly thermodynamic mechanisms, lightning was also forecast where the MM5 convective parameterization indicated convective precipitation.

Boundary layer instability was parameterized by the lifted index. The lifted index seems to be a better choice for lightning forecasting than CAPE. BOLT's nominal value of the lifted index for lightning is -1 ºC. The value of the lifted index used by BOLT is modified by the model 700 hPa vertical velocity, where upward/downward motion makes the lifted index more/less unstable, and by higher terrain (one degree more unstable for every 1000

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m of elevation). Before this instability parameter can be associated with lightning, the AFWA Lid Strength Index must be under 6 ºC, and the convective inhibition must be under 100 J kg^{-1}. Most lightning is associated with boundary layer instability with weak capping.

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 of the parcel's wet-bulb potential temperature value from the environmental wet-bulb potential temperature was used as the value of mid-level instability. Experimentation showed that mid-level instability led to lightning only when there was also strong model upward velocity. To combine these two parameters, the mid-level instability was multiplied by the 700 hPa vertical velocity. A suitable threshold value was determined that corresponded to observed lightning. This lightning mechanism will be referred to as MidInst/UVV (Mid-level Instability with Upward Vertical Velocity). MidInst/UVV is associated with fewer lightning strikes than boundary layer instability, but still an appreciable number.

Occasionally during the cold season, lightning can occur without instability forecast by the model. However, if the model forecast sounding is nearly saturated, with a nearly moist adiabatic lapse rate several hundred hPa deep combined with strong low-level convergence, lightning can occur in the real atmosphere. Exact details of the parameterization will not be discussed here. Of the three BOLT lightning-producing mechanisms, this one is associated with the least number of lightning strikes.

The MM5 convective precipitation forecast was also used as a predictor of lightning. The MM5 convective precipitation forecast consistently covers much less area than observed lightning. When model convective precipitation is forecast, it is usually a reliable indicator of lighting.

3.2 *A Filter of Lightning*

In order to reduce false alarms, an attempt was made to reduce the areal coverage of the BOLT lightning forecast by finding conditions under which lightning was unlikely to occur. Experimentation showed that lightning was unlikely unless a layer of high relative humidity existed above the lifting condensation level (LCL). Specifically, lightning was found to be unlikely unless the relative humidity was at least 90% at a level at least 75 hPa above the LCL.

A filter with fixed threshold values will surely fail in unanticipated situations. In those situations the threshold values must be altered. One failure was found in dryline situations, where the filter was found to be too strong, eliminating important thunderstorm events. Examination of case studies revealed that in most dryline situations, the MidInst/UVV mechanism was strong. Therefore, the filter's relative humidity value was reduced depending on the strength of the MidInst/UVV term. Also, the 75 hPa distance was lowered in high terrain to 50 hPa, discussed below. A manuscript is being prepared that will fully discuss this filter of lightning.

3.3 *High terrain algorithm*

The basic BOLT algorithm was found to be under-forecasting lightning in the Rocky Mountains, and the problem became worse in the summer months. A new algorithm was designed for locations where the terrain height was over 1000 meters. Figure 1 shows a typical model sounding associated with lightning in high terrain. The sounding has a deep (200-300 hPa) surface mixed layer, with a nearly constant mixing ratio and a nearly dry-adiabatic lapse rate. Convective inhibition is very low, and the lifted index is +1 ºC or less. A layer of high relative humidity is above the LCL, similar to the non-mountain lightning algorithm. These conditions were parameterized with the Gridded Analysis and Display System software package (GrADS) (Institute of Global Environment and Society 2004 http://grads.iges.org/home.html). Again it was found that the required layer of relative humidity, used as a filter of the lightning forecast, was sometimes too strict. If the lifted index becomes less than -1 ºC, the required depth of the relative humidity is reduced to 50 hPa, and the threshold value of relative humidity to 70%.

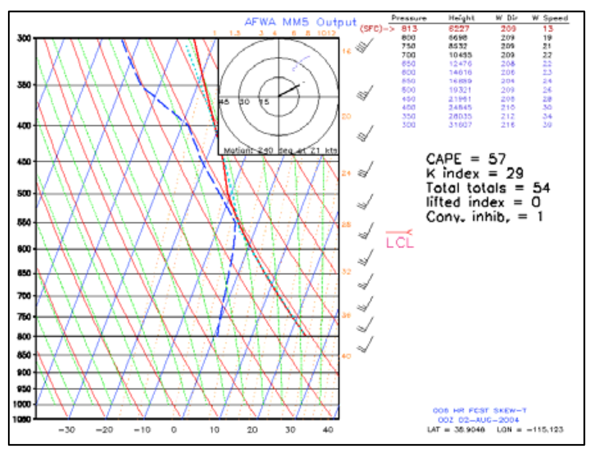

Fig. 1. Typical mountain sounding associated with lightning

The results were forecasts with good positional placement and surprisingly detailed forecasts of lightning where the terrain is over 1000 meters. A bias of the mountain algorithm is that it forecasts most lightning to cease between 0000 and 0300 UTC, but some lightning activity typically lasts a few more hours. The mountain algorithm has not yet been tested in the cold season.

3.4 *Statistical results*

A comparison was made of BOLT skill scores to the MM5 convective precipitation. The BOLT algorithm forecast much more lightning to occur than the MM5 convective parameterization. Model convective precipitation is a side effect of "convective adjustment": the modification of lapse rates as a result of parameterized convection. The convective precipitation output does not represent all convection in the model, but only that portion of convection not resolvable at the grid scale of the model. Therefore, the AFWA MM5 convective precipitation output tends to depict only "core" areas of thunderstorms, where thunderstorms are very likely to be occurring in the real atmosphere. The MM5 convective precipitation field, if used as a forecast of lighting, has a low false-alarm rate, but also a low detection rate. In contrast, the BOLT algorithm was designed to forecast almost any occurrence of lightning, and is very close in coverage to the SPC's areal thunder forecast. The result is that the BOLT algorithm has a probability of detection that is twice as high as the MM5 model convective parameterization, with a false alarm value that is 2.5 times as high. The threat scores of the MM5 convective parameterization and BOLT are nearly equal, as BOLT'S high detection rate is balanced by the false alarm rate (or, the MM5 convective parameterization's low detection rate is balanced by the low false alarm rate). These statistics are based on case studies during the spring of 2004. Lightning valid within an hour before and after the forecast valid time were used as the verifying events.

3.5 *Cases*

Figure 2 shows the 18-h BOLT forecast from the 28 July 2004 06 UTC run of the MM5 valid 00 UTC in the late afternoon (at the normal diurnal peak of lightning activity in the CONUS). Lightning strikes that occurred 1 h before until 1 h 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 3-h forecast, with a notable failure to forecast lightning in the Gulf Coast states. Examination of model forecast soundings

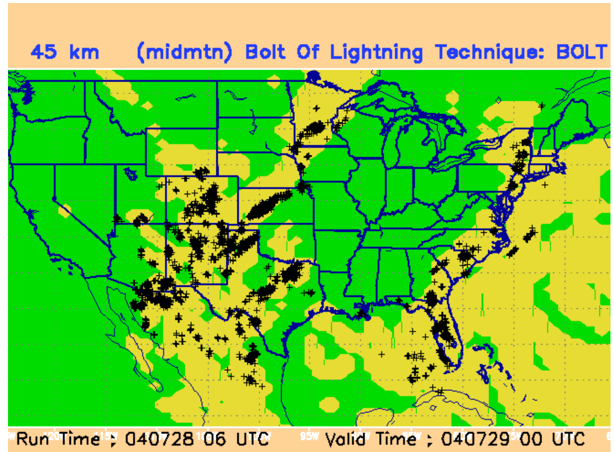

Fig. 2. 18 h BOLT forecast (yellow) valid 00 UTC 2004 July 29, and lightning strikes (small black crosses) within 1 h of the forecast valid time.

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.

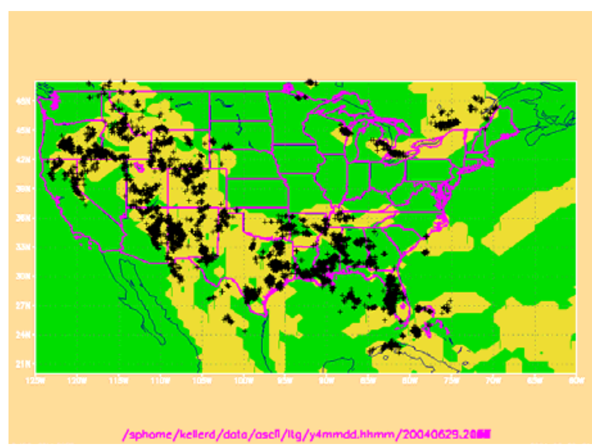

Figure 3. 3 h BOLT forecast valid 26 June 2004 2100 UTC (yellow), with cloud-to-ground lightning strikes plotted (small black crosses) between 2000 and 2159 UTC.

At the present time, near real-time BOLT forecasts can be seen at http://wxforecasting.org/keller/bolt.html.

3.6 *Strengths and weaknesses*

The areal coverage of the BOLT algorithm is very similar to that of the SPC's thunder outlook. The BOLT algorithm has the advantage of having output every 3 h. BOLT rarely forecasts more lightning than the corresponding SPC outlook. BOLT occasionally has excellent detail, especially where instability is enhanced by high terrain that can be resolved by the 45 km MM5.

BOLT unfortunately fails to forecast lightning for some dryline type situations, mostly due to the filter, even though enhancements were made to the filter. There are other occasions, such as the example in Fig. 3, when the filter is too strict in the Gulf Coast states. BOLT underforecasts lightning in the first 6 h. This is assumed to be due to a model spin-up issue.

4. SUMMARY

An algorithm, the "Bolt Of Lightning Technique", was created to forecast lightning using only MM5 grid output. BOLT was developed using an "ad hoc" methodology, which was very efficient for this application. Areal coverage of BOLT is very similar to that of the Storm Prediction Center's thunder outlook, with the advantage that BOLT outputs a forecast valid every 3 h. The algorithm subjectively appears to work equally well in the warm and the cold seasons. Statistics show that compared to the convective parameterization of the AFWA MM5, BOLT has twice the detection rate at the expense of a false alarm rate 2.5 times higher. The mountain lightning algorithm appears to be quite successful, but has only been running in the summer months. So far, limited validation has been done in non-CONUS locations.

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