9.1- **Fifth Conference on the Meteorological Applications of Lightning Data, January 26, 2011**

A Multiple Source Approach to Operational Lightning Prediction

Gail Hartfield
NOAA/NWS, Raleigh, North Carolina

1. Introduction.

Lightning is recognized as a significant weather threat, responsible for multiple deaths, injuries, and property damage every year (Curran et al. 2000). Given such potential dangers to life and property, accurate predictions of lightning activity would be of enormous benefit to the public as well as to other affected user groups such as the aviation, utilities, forestry, and recreation communities. Numerous observational studies have been conducted throughout the meteorological community seeking to achieve a thorough understanding of the mechanisms which produce lightning; however, such an understanding remains elusive. Nevertheless, great strides have been made in recent years with respect to testing and confirming the factors favoring lightning production. Improvements in observations (particularly through lightning mapping arrays) and modeling, as well as climatological studies, have produced several tools that can assist forecasters in preparing a good-quality prediction of lightning activity for the public and at-risk user groups.

Since 2007, the National Weather Service Forecast Office (NWSFO) in Raleigh, North Carolina, has been investigating several aspects of lightning activity in central North Carolina. The Analysis and Prediction of the Potential for Excessive Lightning (APPEL) project consists of an observational component (which includes case studies of excessive lightning events and an in-depth climatology) and a forecast component (3-12-hr forecasts of lightning activity in central North Carolina). Through this multi-pronged approach, we seek to reinforce and expand that which is known about lightning production, as well as provide the public and affected users with accurate information about the potential for excessive lightning, to help support decision-making by these groups.

2. Local lightning climatology.

Daily (24-hr period beginning at 1200 UTC) cloud-to-ground (CG) lightning strikes from June 2002 through August 2010 over central North Carolina and the immediate adjacent area (Fig. 1) were retrieved and analyzed using the National Weather Service's (NWS) Graphical Forecast Editor (GFE) application, contained in the NWS Advanced Weather Interactive Processing System (AWIPS). CG strike data were obtained from the National Lightning Data Network (NLDN). These data were logged in a spreadsheet, and various statistical analyses were performed. Figures 2 and 3 show the total CG strikes in the study area by day and by month, respectively, through the period. Lightning activity in central North Carolina typically peaks from late June through mid August. Figure 4 depicts the sum of CG strikes on the top 10 and top 25 most active lightning days (the days with the highest CG strike count in the study area) in each year. There were, on average, 100 "lightning days" (days of at least one strike) in the study area each year during this period, so these 10 most active days each year represented roughly the top 10 percent of all lightning days. On average, nearly 50 percent of each entire year's total lightning occurred on these top 10 most active days. A more detailed climatology, including maps of CG strikes and strike frequency, will be completed this summer.

An in-depth analysis of the top 10 days with the greatest CG strike count, and a comparison with 10 average lightning days (encompassing the median), revealed interesting but not unexpected results. Near-storm environmental parameters were retrieved for the affected area, valid one hour prior to the arrival of convection. This method attempted to gather the best estimate of conditions immediately prior to the onset of convection. These mesoscale parameters were gathered from RUC model proximity soundings, as well as from the RUC-based mesoscale analyses from the Storm Prediction Center (http://www.spc.noaa.gov/exper/mesoanalysis/). The focus was on two primary factors critical in lightning production: the presence of vigorous updrafts within convection; and the presence of moisture in the form of ice crystals, graupel, and supercooled water in the mixed-phase layer. For purposes of operational forecasting applications, these factors are represented by convective available potential energy (CAPE) and precipitable water (PW), respectively.

Table 1 shows the near-storm environmental parameters analyzed for the top 10 days of greatest lightning activity and for 10 average days (encompassing the median) of 2010. These parameters were assessed using RUC proximity soundings within 50 km of the area that experienced excessive lightning, within 1 hour prior to the onset or arrival of convection. Significant differences are seen in the degree of instability, as exemplified by the mixed-layer and most-unstable CAPE, and by the CAPE in the layer from -10°C to -30°C, representative of the mixed-phase layer where most electrification is thought to take place (van den Broeke et al. 2005). This layer CAPE aloft can be thought of as a surrogate for the "shape" of the CAPE – that is, an estimate of the potential for high instability and, hence, strong updrafts within this electrification zone that foster rapid charge separation. The days with greater lightning exhibited higher values of all forms of CAPE. While the importance of the role of thermodynamics within lightning production remains largely theoretical (Williams et al. 2005), these results do support a connection between vigorous instability in the mixed-phase region and the occurrence of excessive lightning.

The PW values just prior to the onset of convection as well as those values six hours prior to onset were also examined. Deierling et al. (2006) discussed the importance of ice mass and ice mass flux in lightning production. Mazany (2002) showed a positive correlation between PW (as well as a positive change in PW) and lightning activity just prior to the onset of convection, and Carey and Rutledge (2000) showed a strong correlation between total flash rate and total ice mass. The examination of the near storm environmental conditions preceding highly active lightning days and average lightning days in 2010 reveals a distinction between the two, with both higher PW (2.22 inches) and a more positive PW change in the 6 hours prior to convection onset (+0.18 inch) for the highly active days as compared to the average days (1.83 inches and +0.10 inch, respectively).

3. Composite plots.

In an effort to increase our understanding of the large-scale pattern typifying these highly active lightning days, we created composites of meteorological fields such as 500 hPa heights (Fig. 4), PW (Fig. 5), and lifted index (Fig. 6) for the 10 most highly active lightning days and for 10 average lightning days of 2010, using the National Centers for Atmospheric Prediction (NCEP) reanalysis dataset (Kalnay et al. 1996). The 500 hPa pattern shows less ridging over the Southeast U.S. than in the average composite, suggesting that the potential for better dynamic forcing and less subsidence, as well as stronger winds aloft, may help increase and organize convection. Interestingly, the 500 hPa composite for the top ten most active lightning days of 2009 (Fig. 7) shows a markedly different pattern with lower heights and a much deeper trough just west of North Carolina. The different patterns between the two years' composites may indicate that excessive lightning is possible within several different synoptic patterns, such as dynamically-driven mesoscale convective systems, or with slow-moving, outflow-dominant multicell clusters in highly unstable environments. The convection patterns favoring highly active lightning days warrant further investigation.

PW composites show a similar spatial pattern across the U.S. between the active and average lightning days, with higher values over the Southeast states and much lower values over the West, but magnitudes are markedly greater over the Carolinas for the active days. One might infer that the better moisture on the active lightning days supports the role of moisture in the mixed-phase layer in promoting lightning production; however, this conclusion cannot be drawn with confidence, as this greater moisture may have resided in the lower troposphere rather than in the mixed-phase layer, or the greater moisture may have simply led to greater coverage of convection as compared to the average lightning days. Further study and detailed investigation of individual cases is needed.

Composite plots of lifted index indicate greater instability on active lightning days (-3 to -3.5° C) than on average days (-1 to -2.5° C), supportive of the link between high instability and excessive lightning.

4. Lightning outlooks.

Accurate daily outlooks of lightning activity could greatly benefit recreation groups, utilities, and aviation communities (Keener 1997; Qualley 1997; Apt 2006). An outlook for lightning activity would strive to alert the public and other partners of the possibility of very high lightning strike frequencies (based on climatology), which could increase the potential for lightning fires (both structural and vegetative) and raise the danger to the public. The issuance of good-quality lightning activity outlooks is a primary component of the APPEL project.

Beginning in 2007, APPEL project leaders have conducted a review of peer-reviewed research pertaining to lightning production, specifically the near storm environmental (NSE) factors favoring lightning. Livingston et al. (1996) studied lightning events in the Southeast and found that CAPE and K-index were two critical NSE parameters supporting high lightning activity. Jayaratne and Kuleshov (2006), Williams et al. (1992), Cope (2006), and others have reported a comparable dependency of lightning activity on instability. In van den Broeke et al. (2005), frequent CG lightning strikes were associated with strong instability in the -10° C to -20° C layer. Similarly, Petersen (1997) and Carey and Rutledge (2000) confirmed the correlation between electrification (including lightning flash rate) and mixed-phase microphysics processes (including the collision of graupel and ice crystals in the presence of supercooled water) within strong updrafts in the -10° C to -20° C layer. Deierling et al. (2005 and 2008) noted the importance of falling graupel and upward-lofted ice crystals (ice mass flux) in charge separation and subsequent lightning production.

Based upon review of these and other studies, a forecast checklist (Fig. 8) was created to help guide NWSFO Raleigh forecasters in evaluating the anticipated pre-storm environment and assessing the risk of excessive lightning with the expected convection. Experimental thresholds for each parameter were derived from those suggested by these studies as well as those indicated by local studies of excessive lightning events. Checklist parameters include: 100-hPa mixed-layer CAPE, most-unstable CAPE, normalized CAPE (high values indicate the potential for strong updrafts; Blanchard 1998; Williams et al. 2005), CAPE in the -10° C to -30° C layer, PW, and 6-hr change in PW. (Note: CAPE in the -10° C to -30° C layer was chosen for the checklist due to the availability of forecast CAPE in this layer in the NWS AWIPS system and its availability as an observed parameter on the Storm Prediction Center's RUC-based mesoscale analysis page.) In addition to these parameters, forecasters assessed automated lightning-prediction output from the North American Model (NAM; Bothwell 2005 and 2006) and from the Short-Range Ensemble Forecast (SREF; Bright et al. 2005) as part of the forecast checklist.

From May through September of 2008 and 2009, NWSFO Raleigh forecasters completed the checklist daily on the night shift, usually between the hours of 0300 and 0600 Eastern Time. (Forecasts were temporarily suspended for the summer of 2010 so APPEL project leaders could devote more time to the compilation and analysis of the local lightning climatology.) Parameters were evaluated for the "day-one", or 3- to 24-hr, forecast time frame. If most or all parameters fell into the "high risk" category, based on the forecasters' evaluation, the threat of excessive lightning during the upcoming day was mentioned in the Hazardous Weather Outlook (HWO), which is issued by NWSFO Raleigh forecasters daily toward the end of the night shift.

Rigorous verification of these forecasts was complicated by several factors: confidence in using and applying the checklist varied among forecasters and was inconsistent at times; some checklist parameters were periodically unavailable for assessment due to computer or other problems; and inclusion of a lightning outlook in the HWO as well as the wording used was subjective and variable. Nevertheless, a review of HWOs issued in 2009 and the inclusion of lightning information therein revealed promising results. Of the 153 days when forecasts were made in 2009, the threat of excessive lightning was added to 24 of those days. On several occasions, forecasters noted the extreme nature of the expected lightning ("…lightning will be nearly continuous… as much as one strike every few seconds…"). Of the four days with the most CG strikes in 2009, a mention of excessive deadly lightning was included on three of those days. Broadcast meteorologists in the Raleigh area have taken notice of the mention of the excessive lightning threat in the HWO and in Area Forecast Discussions, and they have begun to highlight these occasions in their weather broadcasts.

5. Conclusion and Future Work.

Numerous laboratory and observational studies have shown a strong statistical link between excessive lightning activity and the combination of strong updrafts and the presence of moisture (specifically, graupel and ice crystals) in the mixed-phase layer aloft. Through the application of these studies and their findings to the operational forecasting environment, NWSFO Raleigh has created an experimental ingredients-based method for assessing the risk of excessive lightning in the upcoming 3- to 24-hr forecast period. The checklist was completed daily, from May through September, in 2008 and 2009. When parameters suggested an enhanced threat of excessive lightning, forecasters mentioned this risk in the HWO. While the specific degree of success cannot yet be determined, we have demonstrated that it is indeed possible to provide a quality, value-added lightning outlook for the public and other partners with a reasonable degree of accuracy.

NWSFO Raleigh expects to resume lightning forecasts for 2011. Since its inception in 2007, the checklist has already undergone format and content changes, primarily to adjust parameter thresholds based on newer case studies and to make it easier for forecasters to complete it. Further reformations to the checklist will be completed by spring 2011 to streamline it and allow for easier completion by forecasters, as well as to make forecast verification easier and more scientifically sound. Additional case studies of excessive lightning events will also be conducted to further test the significance and thresholds of the checklist parameters. We will also be constructing a detailed lightning climatology for North Carolina to help define a "significant" lightning day. Lastly, we will be incorporating into our prediction method the lightning forecast algorithm being developed for the National Severe Storms Laboratory (NSSL) Weather Research and Forecasting (WRF) model (McCaul et al. 2009). By refining and improving the forecast methodology, we hope to provide the public, partners, and users of our weather information with an accurate, high-quality, and reliable outlook for lightning activity.

Acknowledgments

Support and assistance from Jonathan Blaes, Barrett Smith, Brandon Vincent, Terry Click, Ronald Humble, and Morgan Brooks (all NWSFO Raleigh), and Jeremy Gilchrist and Whitney Rushing (North Carolina State University), are all greatly appreciated. Use of lightning data by the NWS provided through a license agreement with Vaisala/GAI.

References

Apt, Jay, 2006: Securing the Supply of Electrical Services, presented at the Carnegie Mellon Conference on Crisis Readiness, 2006.

Blanchard, D. O., 1998: Assessing the vertical distribution of convective available potential energy. *Wea. Forecasting*, **13**, 870-877.

Bothwell, P., 2005: Development of an operational statistical scheme to predict the location and intensity of lightning. Conference on Meteorological Applications of Lightning Data, San Diego, CA, Amer. Meteor. Soc., 6 pp.

___, 2006: Advances in the prediction of cloud-to-ground lightning events at the Storm Prediction Center, International Lightning Detection Conference, April 26-27, Tucson, AZ, Vaisala, Inc., Tucson, 8 pp.

Bright, D., and R. E. Jewell, M. S. Wandishin, and S. J. Weiss, 2005: A physically-based parameter for lightning prediction and its calibration in ensemble forecasts. AMS Conference on Meteorological Applications of Lightning Data, 2005.

Carey, Lawrence D., and S. Rutledge, 2000: The Relationship between Precipitation and Lightning in Tropical Island Convection: A C-Band Polarimetric Radar Study. *Mon. Wea. Rev.*, **128**, 2687–2710.

Cope, A., 2006: Toward better use of lightning data in operational forecasting. Preprints, Amer. Meteor. Soc. Annual Meeting, 2006.

Curran, E., and R. Holle, and R. López, 2000: Lightning casualties and damages in the United States from 1959 to 1994. *J. Climate*, **13**, 3448-3453.

Deierling, W., and W. Petersen, J. Latham, S. Ellis, and H. J. Christian Jr., 2005: Towards the relationship between total lightning activity and downward as well as upward ice mass fluxes in thunderstorms. Preprints, Amer. Meteor. Soc. Annual Meeting, 2005.

___, 2006: The relationship between total lightning and ice fluxes. Ph.D. dissertation, University of Alabama in Huntsville, 175 pp.

___, and W. Petersen, J. Latham, S. Ellis, and H. Christian, 2008: The relationship between lightning activity and ice fluxes in thunderstorms. *J. Geophys. Res.,* 113, D15210.

Jayaratne, R. and E. Kuleshov, 2006: The relationship between lightning activity and surface wet bulb temperature and its variation with latitude in Australia. *Meteorology and Atmospheric Physics,* **91**, 17-24.

Kalnay, E. and M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, A. Leetmaa, R. Reynolds, M. Chelliah, W. Ebisuzaki, W.Higgins, J. Janowiak, K. C. Mo, C. Ropelewski, J. Wang, R. Jenne, and D. Joseph, 1996: The NCEP/NCAR Reanalysis 40-year Project. *Bull. Amer. Meteor. Soc.*, **77**, 437-471.

Keener, Jr., Ronald N., 1997: The Estimated Impact of Weather on Daily Electric Utility Operations. Workshop on the Social and Economic Impacts of Weather, 1997.

Livingston, E. and J Nielsen-Gammon and R. Orville, 1996: A climatology, synoptic assessment, and thermodynamic evaluation for cloudy-to-ground lightning in Georgia: a study for the 1996 Summer Olympics. *Bull. Amer. Meteor. Soc.*, **77**, Jul. 1996.

Mazany, Robert A., and S. Businger, S. Gutman, and W. Roeder, 2002: A Lightning Prediction Index that Utilizes GPS Integrated Precipitable Water Vapor. *Wea. Forecasting*, **17**, 1034-1047.

McCaul, E., and S. Goodman, K. LaCasse, and D. Cecil, 2009: Forecasting Lightning Threat Using Cloud-

Resolving Model Simulations. *Wea. Forecasting*, **24**, 709–729.

Petersen, W. , 1997: Multi-scale process studies in the tropics: Results from lightning observations. Ph.D. dissertation, Department of Atmospheric Science, Colorado State University, Paper No. 632, 354 pp.

Qualley, Warren L., 1997: Impact of Weather on and use of Weather Information by Commercial Airline Operations. Workshop on the Social and Economic Impacts of Weather, 1997.

van den Broeke, Matthew S., and D. Schultz, R. Johns, J. Evans, and J. Hales, 2005: Cloud-to-Ground Lightning Production in Strongly Forced, Low-Instability Convective Lines Associated with Damaging Wind. *Wea. Forecasting*, **20**, 517–530.

Williams, E., and S. Rutledge, S. Geotis, N. Renno, E. Rasmussen, and T. Rickenbach, 1992: A radar and electrical study of tropical “hot towers”. *J Atmos. Sci.*, **49**, 1386-1395.

___, and V. Mushtak, D. Rosenfeld, S. Goodman, and D. Boccippio, 2005: Thermodynamic conditions favorable to superlative thunderstorm updraft, mixed phase microphysics and lightning flash rate. *Atmospheric Research,* **76**, 288–306.

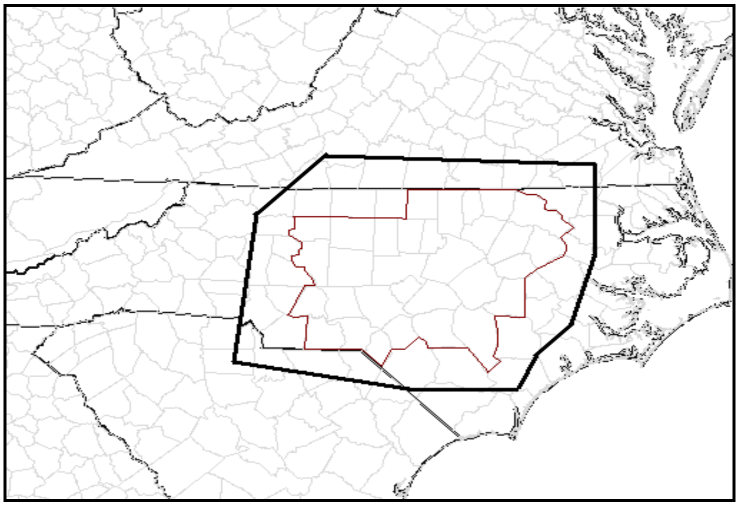


Figure 1. Area of study, designated by thick black line. Solid red line denotes the NWSFO Raleigh area of forecast and warning responsibility.

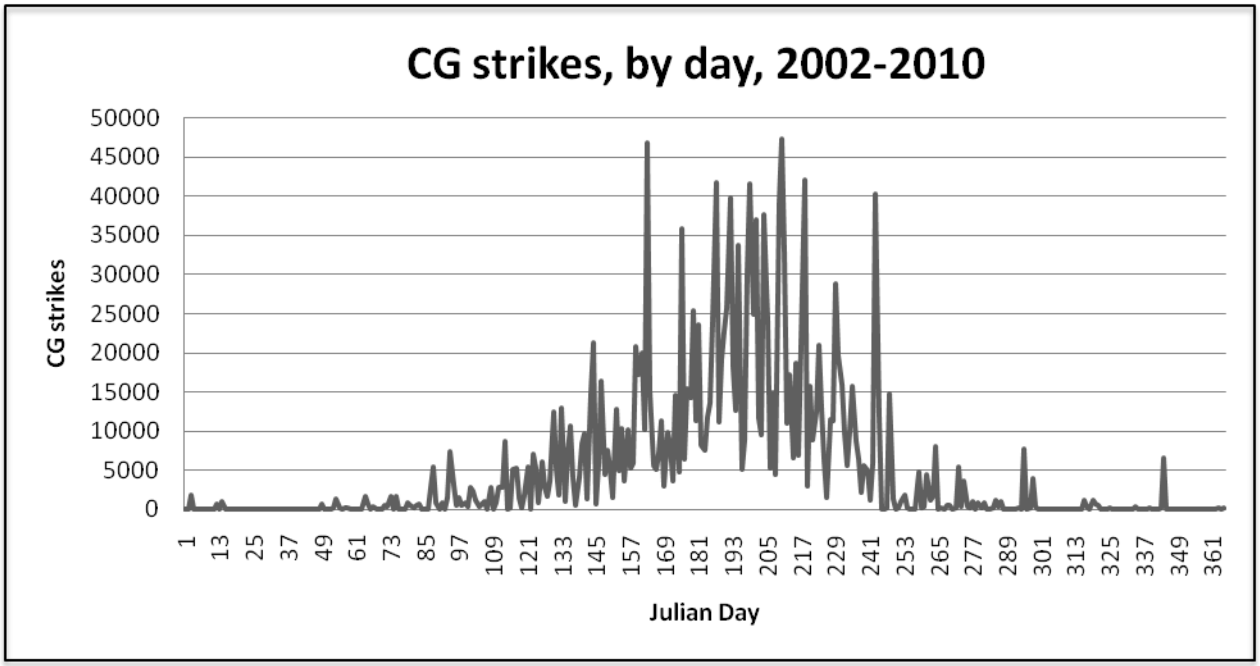


Figure 2. Total cloud-to-ground strikes in the area of study, by Julian day, 2002-2010.

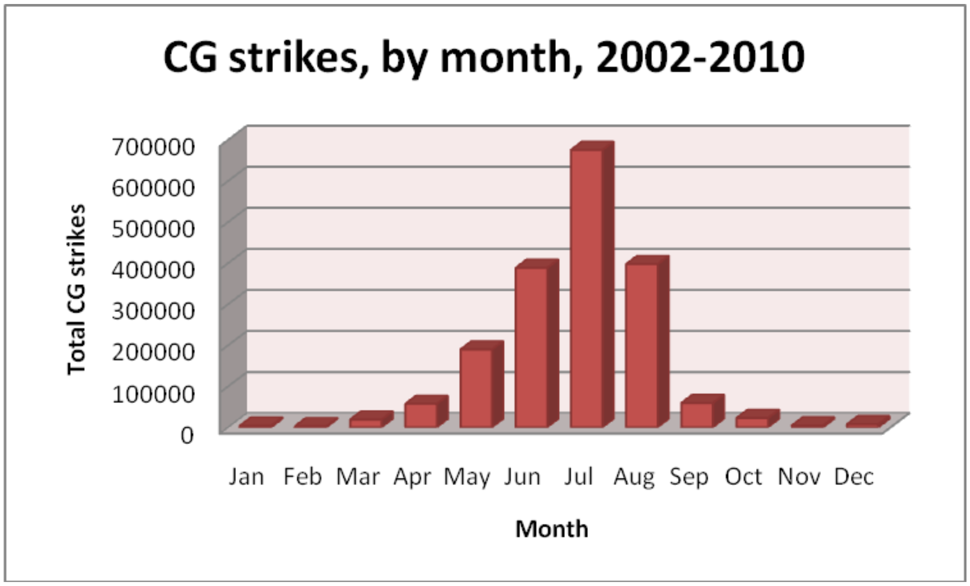


Figure 3. Total cloud-to-ground strikes in the area of study, by month, 2002-2010.

	High lightning activity days (top 10%)	Average lightning activity days
MLCAPE	**2550**	**1405**
MUCAPE	**3400**	**2110**
CAPE (-10°C to -30°C)	**620**	**390**
Normalized CAPE	**0.21**	**0.13**
Precipitable water	**2.22**	**1.83**
Δ PW (T-6hrs to T+0hrs)	**+0.18**	**+0.10**

Table 1. Comparisons of 100 hPa mixed-layer convective available potential energy (CAPE), most-unstable CAPE, CAPE in the -10°C to -30°C layer, normalized CAPE, precipitable water (PW), and 6-hr change in PW prior to convection onset, for the ten days with highest CG strike totals and for ten average (surrounding the median) lightning days in 2010.

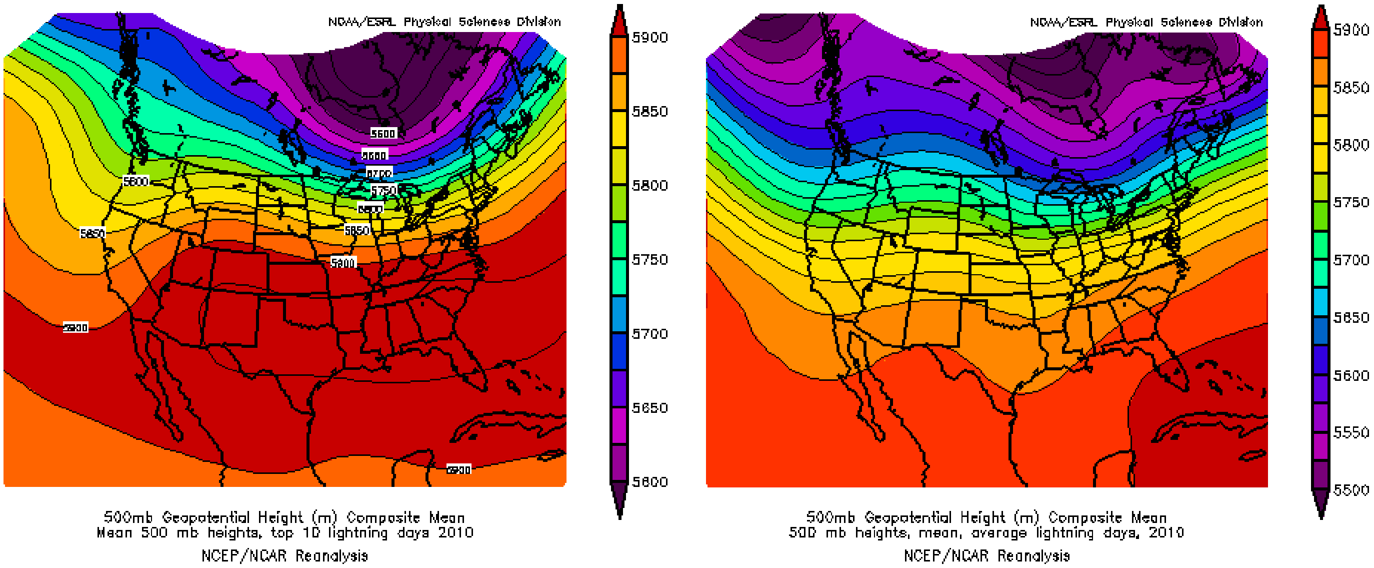


Figure 4. NCAR reanalysis composites of 500 hPa heights, in meters, for 2010's ten most active lightning days (l.) and ten average lightning days (r.). Images provided by the NOAA/ESRL Physical Sciences Division, Boulder, CO, from their Web site at http://www.esrl.noaa.gov/psd/.

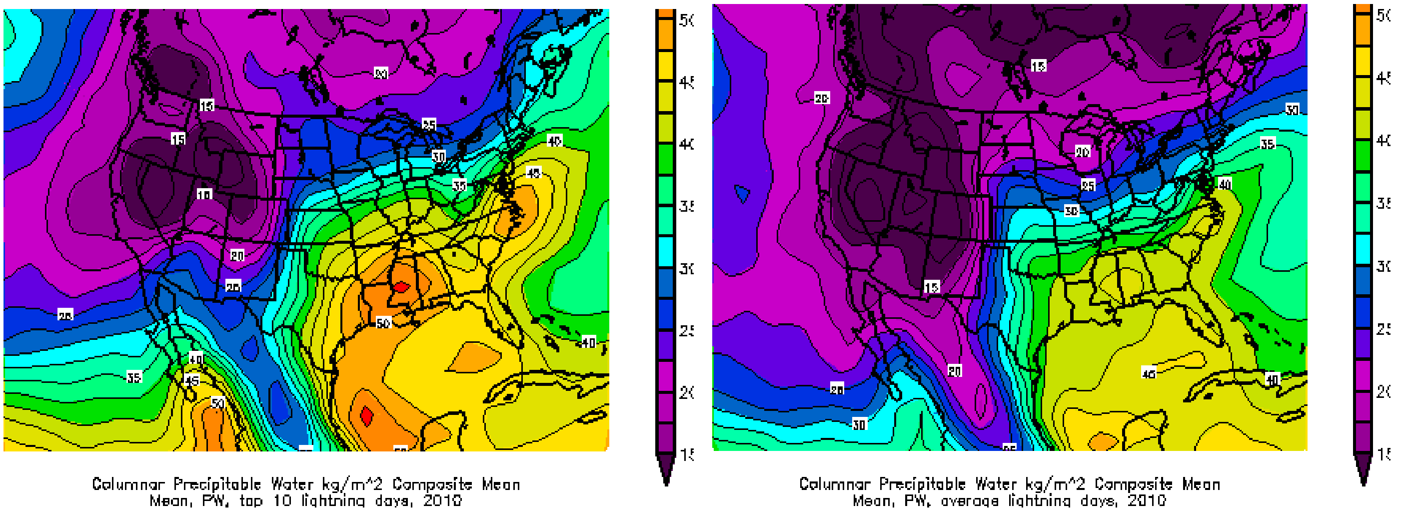
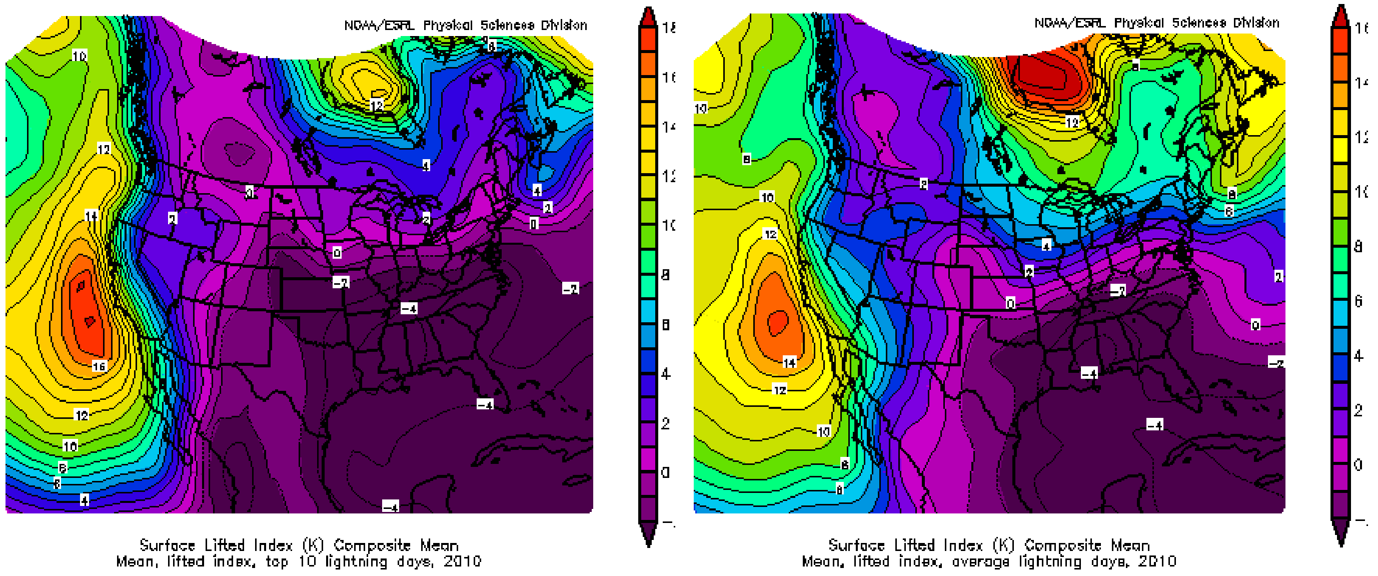


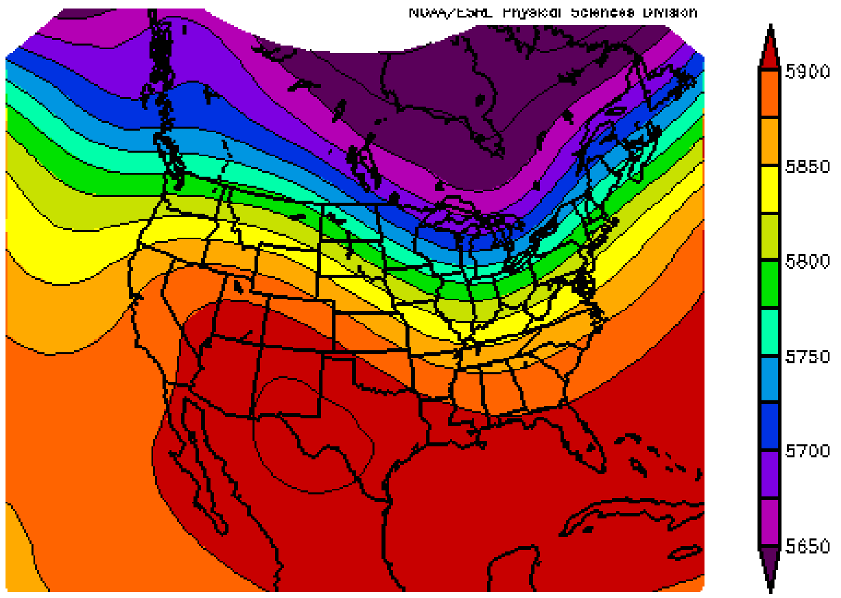
Figure 5. As in Fig. 4, except column precipitable water, in kg m^{-2}.



Surface Lifted Index (K) Composite Mean
Mean, lifted index, top 10 lightning days, 2010

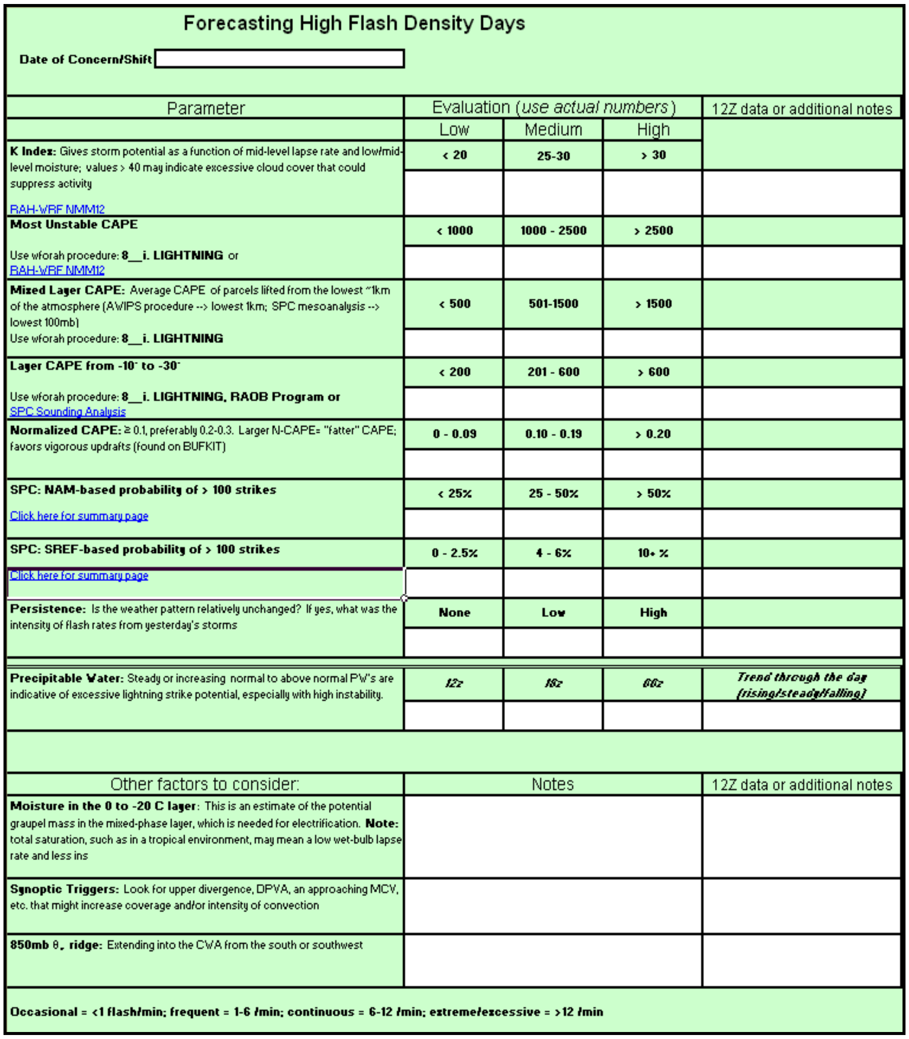
Surface Lifted Index (K) Composite Mean
Mean, lifted index, average lightning days, 2010

Figure 6. As in Fig. 4, except surface lifted index, in K.



500mb Geopotential Height (m) Composite Mean
Mean 500 mb heights, top 10 lightning days, 2009
NCEP/NCAR Reanalysis

Figure 7. As in Fig. 4, except for 2009’s ten most active lightning days.



Forecasting High Flash Density Days

Date of Concern/Shift ____________

Parameter	Evaluation (*use actual numbers*)			12Z data or additional notes
	Low	Medium	High	
K Index: Gives storm potential as a function of mid-level lapse rate and low/mid-level moisture; values > 40 may indicate excessive cloud cover that could suppress activity RAH-WRF NMM12	**< 20**	**25-30**	**> 30**	
Most Unstable CAPE Use wforah procedure: **8__i. LIGHTNING** or RAH-WRF NMM12	**< 1000**	**1000 - 2500**	**> 2500**	
Mixed Layer CAPE: Average CAPE of parcels lifted from the lowest ~1km of the atmosphere (AWIPS procedure --> lowest 1km; SPC mesoanalysis --> lowest 100mb) Use wforah procedure: **8__i. LIGHTNING**	**< 500**	**501-1500**	**> 1500**	
Layer CAPE from -10° to -30° Use wforah procedure: **8__i. LIGHTNING, RAOB Program or** SPC Sounding Analysis	**< 200**	**201 - 600**	**> 600**	
Normalized CAPE: ≥ 0.1, preferably 0.2-0.3. Larger N-CAPE= "fatter" CAPE; favors vigorous updrafts (found on BUFKIT)	**0 - 0.09**	**0.10 - 0.19**	**> 0.20**	
SPC: NAM-based probability of > 100 strikes Click here for summary page	**< 25%**	**25 - 50%**	**> 50%**	
SPC: SREF-based probability of > 100 strikes	**0 - 2.5%**	**4 - 6%**	**10+ %**	
Click here for summary page				
Persistence: Is the weather pattern relatively unchanged? If yes, what was the intensity of flash rates from yesterday's storms	**None**	**Low**	**High**	
Precipitable Water: Steady or increasing normal to above normal PW's are indicative of excessive lightning strike potential, especially with high instability.	***12z***	***18z***	***00z***	***Trend through the day (rising/steady/falling)***

Other factors to consider:	Notes	12Z data or additional notes
Moisture in the 0 to -20 C layer: This is an estimate of the potential graupel mass in the mixed-phase layer, which is needed for electrification. **Note:** total saturation, such as in a tropical environment, may mean a low wet-bulb lapse rate and less ins		
Synoptic Triggers: Look for upper divergence, DPVA, an approaching MCV, etc. that might increase coverage and/or intensity of convection		
850mb θ_e ridge: Extending into the CWA from the south or southwest		

Occasional = <1 flash/min; frequent = 1-6 /min; continuous = 6-12 /min; extreme/excessive = >12 /min

Figure 8. An early version of the lightning forecast checklist.