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A Forecasting Methodology that Uses Moisture Parameters to Pinpoint Locations of Potential Lightning

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Abstract

Lightning is the number three weather-related killer in the United States (30-year average) and injures hundreds of people a year, as well as costing billions of dollars a year. With increasing concerns with public safety and improving economic efficiencies, there is an increasing need for accurate lightning forecasts. The National Weather Service office in Grand Junction, Colorado has developed a forecast methodology that combines moisture, convective available potential energy (CAPE), and lapse rates of equivalent potential temperature to derive a lightning potential index (LPI). The methodology relies on moisture and is defined as precipitation potential placement, mean relative humidity, maximum relative humidity and moisture transport magnitude in the ice crystal growth regime, and subtracting the difference of 100% and the minimum relative humidity in the ice crystal growth regime. The purpose of the LPI is to pinpoint lightning occurrence on a temporal and spatial scale using model data. The final result of this methodology is displayed on the Grand Junction LPI web page at http://www.crh.noaa.gov/gjt/?n=lightningpotentialindex. This paper also addresses where the methodology needs refinement. There are two regions of the country where the LPI does not perform as well as compared to the rest of the country. Two synoptic patterns have been identified where the LPI under-forecasts lightning. This lightning forecasting methodology offers a different paradigm in that instability only determines the area where lightning may occur; it is the moisture parameter as defined in this paper that determines the frequency of lightning on the spatial and temporal scale.

1. Introduction

The leading weather-related killer in Colorado and in most western states is lightning. Since 1996 across the country, lightning has been the number three weather-related cause of death, behind floods and tornadoes according to data compiled in *Storm Data* (see web link http://www.ncdc.noaa.gov/oa/climate/sd). On average, lightning injures hundreds of people a year in the nation, potentially inflicting severe lifelong debilitating injuries. However, this number may actually be higher since the number of injuries and deaths may be underreported (Lopez et al. 1993). Lightning casualties from outdoor sport activities increased substantially from 1950 to 1991 (Lopez et al. 1995). The number of deaths associated with lightning strikes has steadied recently, but the threat has not diminished. Even a seemingly benign, isolated, short-lived thunderstorm over a mountain top can cause a fatality as Hodanish et al. (2004) documented. Ashley and Gilson (2009) reassessed lightning mortality and illustrated that unorganized non-severe thunderstorms are more likely to be killers. In addition to the public safety issue is the economic cost of lightning, which includes 4 to 5 billion dollars in losses per year within the U.S. civilian sector (Kithil 2002).

Improved lightning forecasting is needed to increase public safety. Large crowds in sports stadiums may be vulnerable as stadium managers often do little about the threat of lightning (Gratz and Noble 2006). Other risk areas include ski lifts, as the incident at the Maggie Valley, North Carolina, amusement park exemplified when 38 people had to be rescued from a lightning caused accident on 30 July 2007 (reported by the *Charlotte Observer* on 30 July 2007). Lightning does not limit itself to outdoor targets; gases in underground mines (such as a mixture of methane and air) could ignite and pose a risk to worker safety (Sacks and Novak 2008). In addition to public safety, a rapid increase in the total flash rate frequently precedes severe weather (Williams et al. 1999). Improved lightning forecasting may have the potential to improve short-term severe weather forecasting. The expanding efforts to predict dry thunderstorms in the western states (Joint Fire Science Program 2008, 2012) reinforces the idea that there is a significant need for accurate lightning prediction, especially in areas where lightning is the major cause of large wildfires.

II. Background

Generating a useful lightning forecast for the end user is a challenge since lightning has high spatial and temporal variability. The ingredients necessary for lightning to occur are fairly well understood (i.e., moisture, lift and instability). However, the apparent "randomness" of lightning strikes makes it a challenge to forecast. Studies have examined stability indices and their usefulness as lightning predictors, such as the lifted index (e.g., Soloman and Baker 1994; Hoadley and Latham 1998). Rorig et al. (2007) found that dry thunderstorms (those with no significant rainfall at the ground) which produced fire-igniting lightning strikes occurred on days of high instability and low moisture at the lower levels of the atmosphere. Burrows et al. (2005) discovered several lightning predictors that were better correlated with lightning than CAPE, including Showalter index, mean sea level pressure, and precipitable water.

In recent years, there have been additional efforts in lightning prediction that go beyond standard meteorological parameters. Wallmann et al. (2010) modified a methodology (Wallmann et al. 2004) that used dynamic tropopause and the high level total totals index (Milne 2004) to create a dry lightning forecast procedure. Experimental probabilistic lightning products (Bothwell 2005, 2008, 2009) have been developed at the Storm Prediction Center (SPC) as an objective tool for dry thunderstorm forecasting. Two new approaches have been developed to provide quantitative short-term forecasts of lightning (McCaul Jr. 2009). One method uses the upward fluxes of precipitating ice hydrometeors in the mixed-phase region at the -15°C level; the second method is based on the vertically integrated amounts of ice hydrometeors in the model grid column. Gatlin and Goodman (2010) developed a lightning trending algorithm that uses observed trends in thunderstorm total lightning flash rates as a diagnostic operational forecast tool for severe thunderstorm potential.

III. Methodology

Empirical evidence suggests that stability indices alone are not good lightning indicators (Figures 1 and 2). Studying Figures 1 and 2 subjectively, one can arguably conclude that lightning is poorly correlated with the magnitude of lifted index or CAPE values. Obviously, instability is an essential requirement for the occurrence of lightning, but other meteorological parameters may dictate the frequency of lightning for a given area. One such parameter that forecasters rely on is moisture, and for good reason, as moisture is one of the three required elements for thunderstorms. When meteorologists or forecasters speak of "moisture," they tend to use it in general non-specific terms and sometimes they may be referring to relative humidity. For the purpose of this paper, "moisture" requires a specific definition, given later, when discussing it as a lightning predictor.

Research indicates that the -12° C to -18° C temperature layer is a very important lightning predictor when corresponding with high relative humidity. Experiments and observations suggest that high relative humidity within this temperature range promotes stronger negative charging (Figure 3 provides an observational example), which strengthens the electric field that precedes the occurrence of lightning (Berdeklis and List 2001).

Qualitative observations (Figure 4) have indicated a correlation between lightning and the precipitation potential placement. Noel and Dobur (2002) define the precipitation potential placement as the product of 0–3-km AGL mean relative humidity and precipitable water. The precipitation potential placement is a necessary parameter since moist convection, and therefore the production of lightning, is very sensitive to moisture availability. Conversely, low relative humidity aloft (e.g. 3-6 km AGL) can be detrimental for thunderstorm development as drier air may inhibit deep convection (this is not always the case and will be discussed later in section V), particularly over high terrain. For example, a dry layer immediately above a cloud layer may signify a subsidence inversion following a short-wave trough passage. In the methodology described in this paper, moisture is defined as the summation of the following parameters:

$$\text{Moisture} \equiv \text{PPP} + \text{MTM} + \text{RH} + \text{MaxRH} - (100 - \text{MinRH})$$

where

PPP: Precipitation potential placement (multiplied by 0.025),

MTM: Moisture transport magnitude in the 3–6-km AGL layer,

RH: Mean RH in the 3–6-km AGL layer,

MaxRH: Maximum relative humidity in the 3–6-km AGL layer,

MinRH: Minimum relative humidity in the 3–6-km AGL layer.

(Note: To keep PPP values the same magnitude as relative humidity, PPP is multiplied by a factor of 0.025.) Since the ice crystal growth regime has been demonstrated to be critical for lightning production, this is given extra weight in the methodology by using the 3–6-km AGL layer. Essentially, the “Moisture” term above is the core of the methodology.

Of the three essential ingredients needed for thunderstorm development, lift is the last remaining element that needs to be addressed. Incorporating upward vertical velocity or omega into the methodology would account for lift. Integrating omega (for example, using the 700-mb level or the 700–500-mb layer in the model data) into the algorithm proved challenging and any reliable correlation could not be found between lightning and omega. There are many factors that may cause upward vertical motion, such as positive buoyancy, synoptic-scale quasi-geostrophic lift, isentropic upglide, low-level boundaries or convergence zones, divergence aloft, orographic effects. However this is difficult to represent when using a certain level (e.g., 700 mb) or layer (e.g., 700-500 mb). Although higher relative humidity values may be a direct result from positive moisture advection, if positive upward vertical velocity exists and leads to higher relative humidity then the methodology accounts for this.

The magnitude of wind or bulk shear is seriously considered in investigating environments that favor severe convective storms. Other convective parameters, such as the Craven-Brooks significant severe parameter (Craven et al. 2002) that combines bulk shear and CAPE, can be used as a lightning predictor tool as well. Convective storms that produce large hail are likely to generate frequent to continuous cloud-to-ground lightning strikes. This methodology prefers elevated 3–6-km above ground level (AGL) moisture transport magnitude, a parameter that combines moisture and wind shear.

Higher values of moisture transport magnitude often suggest increased moisture advection and dynamical forcing that potentially aid thunderstorm development.

These moisture parameters are normalized and combined to produce an all-encompassing parameter, referred hereafter as lightning potential. In the algorithm, any instability is treated as a binary number, “yes-no” or “on-off” switch. The combination of best lifted index and most unstable 1–6-km AGL CAPE is used to check the area of instability. For elevated instability, the lapse rate of equivalent potential instability from 2–5- km AGL and at -10°C is determined (note: the 750–400-mb layer and 600–500-mb layer are used respectively for the GFE algorithm). Elevated instability may exist elsewhere, but personal observations suggest these are the best levels to evaluate mid-level instability. (Note: Examining other levels would be desirable, but there are limitations to the available data sets and computer resources.) If no instability is found, then the lightning potential goes to zero. If instability does exist, then the magnitude of the lightning potential value may correspond to the spatial coverage of lightning and cloud-to-ground flash rates (CG). Also this methodology is capable of providing a point forecast and showing a trend of increasing/decreasing convective activity.

One parameter that is not part of the methodology but warrants discussion is model output of convective precipitation. A positive correlation exists between rainfall and CG flash counts (Petersen and Rutledge 1998), suggesting that model convective precipitation can be used as a lightning predictor and would be a great addition to the methodology. Unfortunately, this does not work because the model time-step increment of convective precipitation causes a temporal displacement. The distance of this displacement depends on the model choice. For example the 12-km NAM is 3 hours and

6 hours for the 40-km GFS; a higher time-step leads to a greater displacement. Higher resolution models pose a different problem as they depict individual convective bands that leave areas with no precipitation. If higher resolution convective precipitation were used, then lightning potential values would be low for areas where potential instability and moisture exist, and this would not be desirable. Lastly, Sheridan et al. (1997) pointed out that different locations have different precipitation-to-CG lightning ratios and also noted that less instability leads to higher precipitation-to-CG lightning ratios. This suggests there is significant variability for regions of the country between the relationship of convective precipitation and lightning. These reasons present a challenge for the methodology and therefore, convective precipitation is not used.

A brief discussion on the differences of this methodology described in this paper and those techniques used by Bothwell (2010) at SPC are cited here. Bothwell uses statistical analysis and regression equations (based on lightning climatology) to predict lightning and CG flash rates. The methodology used in this paper, fine tuned by observed lightning strikes, is strictly based on model data with an emphasis on elevated moisture within the dendritic ice crystal growth region. SPC provides an experimental probabilistic lightning forecast for a specified time period. For the lightning potential methodology, no probability is given but higher values mean higher potential for lightning and CG flash rates. The purpose of this methodology is twofold. First, provide National Weather Service forecasters visual guidance of lightning potential at their workstations. Secondly, this guidance can be transported to the web into a format that can be easily interpreted by users (discussed in the next section).

IV. Development of the Lightning Potential Index and Examples

The National Weather Service (NWS) in Grand Junction, Colorado, has created a lightning potential index (LPI), a graphical product designed for public use and possibly for use as a decision support service (DSS) tool in the future. Improved lightning forecasts have many benefits that encompass public safety, aviation, fire weather, and emergency managers. Another motivating factor to create such a product is that many outdoor recreationalists are passionate about hiking the numerous 14,000-foot mountain peaks in Colorado (known regionally as "fourteeners") and this tool provides them with information in advance of their hiking plans. Late spring through early autumn is the desirable time of the year when these peaks have easy access (snow may block access other times of the year), and the high terrain will often provide the triggering mechanism for thunderstorm development during the convective season. The LPI was an experimental product in 2008 and has been operational at the Grand Junction NWS office since 2009. This product defines the lightning risk from late morning through early evening and an outlook for the next day. The LPI is created around midnight using data from the 0000 UTC cycle of the 40-km resolution GFS (GFS40) and 12-km NAM (NAM12) model data (Figure 5).

Qualitative verification may be performed by overlaying the one-hour lightning data with the lightning potential graphic derived in the Advanced Weather Interactive Processing System (AWIPS). Examples provide a visual display of how the LPI can be used in an operational environment. Figure 6 shows the GFS40 lightning potential performance along the eastern seaboard on 1200 UTC 17 November 2011 with frequent lightning strikes overlayed. Removing areas that are considered stable, Figure 7 displays the final LPI output for the eastern seaboard. Higher resolution models, such as the 13-km RUC (RUC13; the RUC model has since been replaced by the Rapid Refresh model) should provide better detail. At 1700 UTC on 21 November 2011, four lightning clusters are observed over New Mexico and the Texas Panhandle (Figure 8 with the 1-hour lightning plot overlaid on the lightning potential.) Studying Figure 8 reveals that the RUC13 lightning potential accurately depicted the location of the lightning clusters. Accounting for instability, Figure 9 shows the final LPI output. From a verification standpoint, the LPI is reasonable but does under-forecast the lightning cluster along the New Mexico and Texas Panhandle border. On the other hand, the LPI accurately depicted that there would be no thunderstorms over most of eastern New Mexico.

The significant advantage of the LPI, whether in the short term or long term, is that it alerts forecasters to where lightning is more likely to occur. The LPI may be used as a situational awareness tool and provides visual guidance to forecasters. The LPI serves as a better predictor of lightning than model convective precipitation fields. For example, at 0600 UTC 19 March 2013, the LPI (Figure 10) captured the lightning much better than the convective precipitation (Figure 11) near the South Carolina coast.

For public safety use or as a DSS tool, the methodology uses algorithms that utilize Python scripts within the NWS Graphical Forecast Editor (GFE) in AWIPS; this allows forecasters to manipulate model data to create gridded data. Using the methodology described above, a script calculates the lightning potential with the output displayed in GFE and subsequently transferred to the NWS Grand Junction LPI web page. Appendix A reveals the calculations required to compute the LPI.

V. Over-performance or Underperformance of the LPI

Although the LPI has demonstrated skill across much of the continental United States during all four seasons, there are two locations and some synoptic weather patterns that the LPI forecast technique either underperforms or over-performs. These locations and synoptic patterns are discussed in the following sub-sections.

a. Pacific Northwest Coast and Florida Peninsula

Subjective observations have noted two regions of the country where the LPI methodology has less skill compared to the rest of the country, the Pacific Northwest west of the Cascade Range crest and the Florida peninsula. This suggests that marine environments impact lightning potential. For the Pacific Northwest, deep convection is rare as the cold stable marine layer along the coast keeps the air mass stable. For a detailed explanation on this phenomena, see the following link: http://earthobservatory.nasa.gov/IOTD/view.php?id=7007. For the Florida peninsula, surface based CAPE is constantly high with negative lifted indices very common during the convective months. In many instances, sea breeze-convergence zones are the primary trigger for deep convection across the Florida peninsula (Byers and Rodebush 1948; Gentry and Moore 1954). Today, higher resolution models provide improved spatial and temporal resolution (Welsh et al. 1999; Mroczka et al. 2010) of the sea breeze-generated convection across the Florida peninsula. To discount the marine layer, the methodology considers CAPE values above 1000 meters AGL (in GFE, mixed layer CAPE is used as

1000 meters AGL is not available). Not only does this improve the lightning forecasting skill for the Pacific Northwest and Florida peninsula, but it also improved the LPI performance for the entire country. Despite this adjustment, there remains a tendency for the LPI to over-forecast lightning west of the Cascades and along the Pacific Northwest coast. The opposite is true for the Florida peninsula. The LPI has a habit of under-forecast lightning there, although discounting CAPE within 1000 m AGL improved performance significantly. Continued enhancements to the LPI methodology for the Pacific Northwest coast and the Florida peninsula may lead to overall improvement for the remainder of the country.

b. Warm Moist Advection Isentropic Upglide

In addition, there are two notable synoptic patterns where the LPI has poor skill, typically occurring early in the spring. However it's possible that this may be a reflection of model performance and not necessarily of the methodology itself. During the transition from winter to spring, isentropic upglide in a warm advective pattern above a stable layer may trigger a lightning outbreak. In this situation, it is not unusual for the lightning outbreak to occur north of the area where the LPI shows a bulls-eye (see Figure 12).

c. Closed Low Circulations and Mid-level Dry Air

The second synoptic pattern involves closed low circulations. Figure 13 shows two closed low circulations at 0000 UTC on 16 February 2012 over southern Nevada and south-central Kansas. Figure 14 and 15 shows the LPI and lightning potential, respectively, and its performance verified by the 1-hour lightning plot. The LPI did depict the lightning associated with the southern Nevada circulation, but missed the lightning cluster along the Kansas and Oklahoma border that was almost beneath the closed low circulation. This could be a situation where mid-level dry air leads to greater conditional instability, assuming adequate low-level moisture is adequate. In the moisture term, the precipitation potential placement should compensate for drier humidity aloft. But there are instances when mid level dry air coincides with a strong lifting mechanism in a conditionally unstable environment. The LPI underperforms in these synoptic scale situations, typically occurring when closed low circulations or digging short waves become closed low circulations. Is this a case where the lightning forecasting methodology needs improvement, or is it an artifact that the model may have under-forecast moisture and instability?

d. Stratiform Precipitation

On occasions, widespread stratiform precipitation occurs in an area with conditional instability. When this occurs, moisture is plentiful and the value of the moisture term will be high. The CAPE is not released because of the extensive cloud shield and/or rain cooled air mass, and therefore the LPI over-performs in these instances.

Accounting for synoptic patterns where the LPI performance is sub-par may lead to overall improvement of the methodology. The LPI is designed as a situational awareness tool that requires refinements at or near specific marine environments (i.e., along the Pacific Northwest coast and Florida peninsula), and for certain synoptic-scale patterns. As of this time, there has been no effort to compare model performance with the LPI methodology.

VI. Conclusion

The results from this methodology suggest that lightning is not a “random” event and it is possible to forecast lightning spatially and temporally with skill. The results from this methodology offer a different paradigm when diagnosing lightning potential. Moisture, as defined in Section III (the summation of elevated 3–6-km AGL relative humidity, precipitation potential placement, elevated 3–6-km AGL moisture transport magnitude, and subtracting the difference of 100% and 3–6-km AGL mean relative humidity), is the most important parameter when diagnosing the lightning threat. Instability is essential, but the magnitude of instability is not considered important within the concepts described here; all that is required is that conditional instability exists, whether within a mixed layer or elevated.

The “Moisture” calculation in conjunction with areas of conditional instability may be used as a valuable forecast tool to pinpoint likely areas of lightning. A high value signifies deep layered moisture and therefore, the moderate to high potential for frequent lightning. This lightning forecasting methodology improves situational awareness on lightning potential and provides valuable information from a public safety and DSS standpoint. Possibly, this methodology may improve the skill of forecasting non-tornadic severe thunderstorms (Gatlin and Goodman 2010).

Lightning is a challenging weather phenomenon to predict as there are many factors to consider. This forecast technique combines many factors into one parameter that makes it easier for the forecaster to diagnose. With continued research, observations, and verification, skillful lightning prediction will improve and become increasingly valuable to the public, aviation and fire weather communities, and especially to those who plan a day hike to summit a Colorado “fourteener.”

Acknowledgements

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Appendix A

Calculation of the Lightning Potential Index

Lightning Potential Index (LPI) = (L1 + L2 + L3 + L4) * maxRH * 0.01

Where:

L1 = Moisture * finalCAPE * 0.002

finalCape = muCape – CIN, where
finalCape = minimum value of 0, maximum value of 100.
muCape = most unstable CAPE 1-6 km AGL
CIN = Mixed layer convective inhibition

L2 = Moisture * finalSSP * Θe (2-5 km AGL) * -0.2

finalSSP = SSP * 0.001, where
SSP = significant severe parameter
Θe = equivalent potential temperature lapse rate in the 2-5 km AGL layer

L3 = Moisture * finalSSP * Θe (-10°C – -20°C) * -0.2

finalSSP = same as finalSSP in L2
Θe = equivalent potential temperature lapse rate in the -10°C – -20°C layer

L4 = Moisture * finalSSP * BestLI * -0.02

finalSSP = same as finalSSP in L2 and L3
BestLI = Best Lifted Index in the 850 mb – 700 mb layer
BestLI = minimum value of -1, maximum value of 0.

maxRH = maximum relative humidity in the 3-6 km AGL

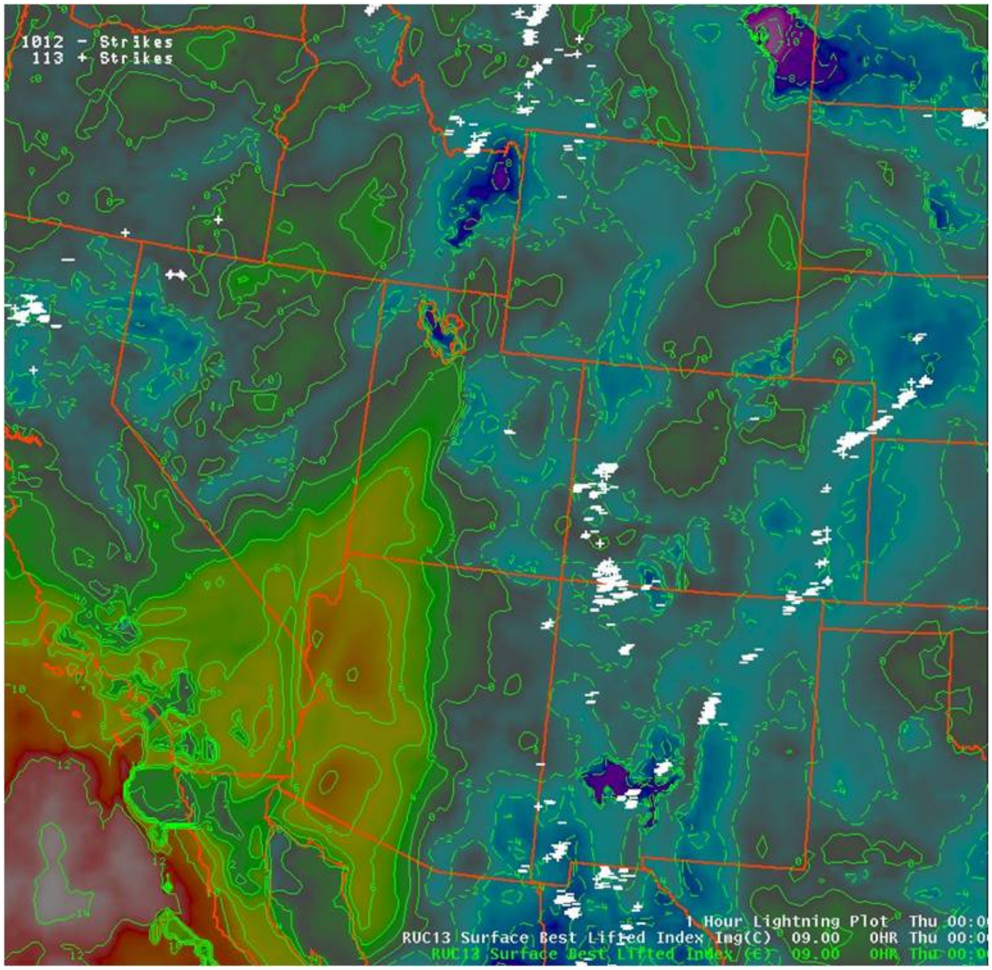

Figure 1 – An example of the 13-km RUC analysis of best lifted index (image and contours; contour interval of 2°C) and 1-hour lightning plot (+ indicates positive polarity flash, - indicates negative polarity flash).

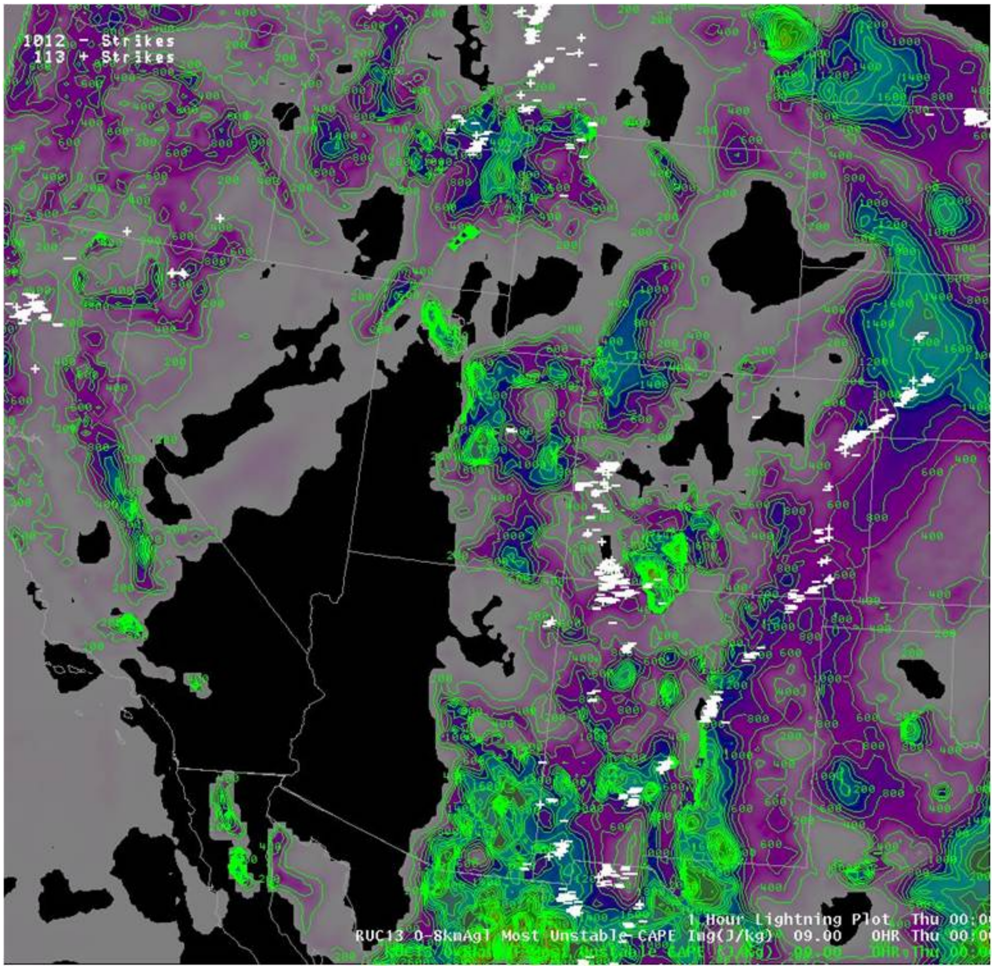

Figure 2 – An example of 13-km RUC analysis of most unstable CAPE (image and contours; contours every 200 J kg $^{-1}$) and 1-hour lightning plot (as in Fig. 1)

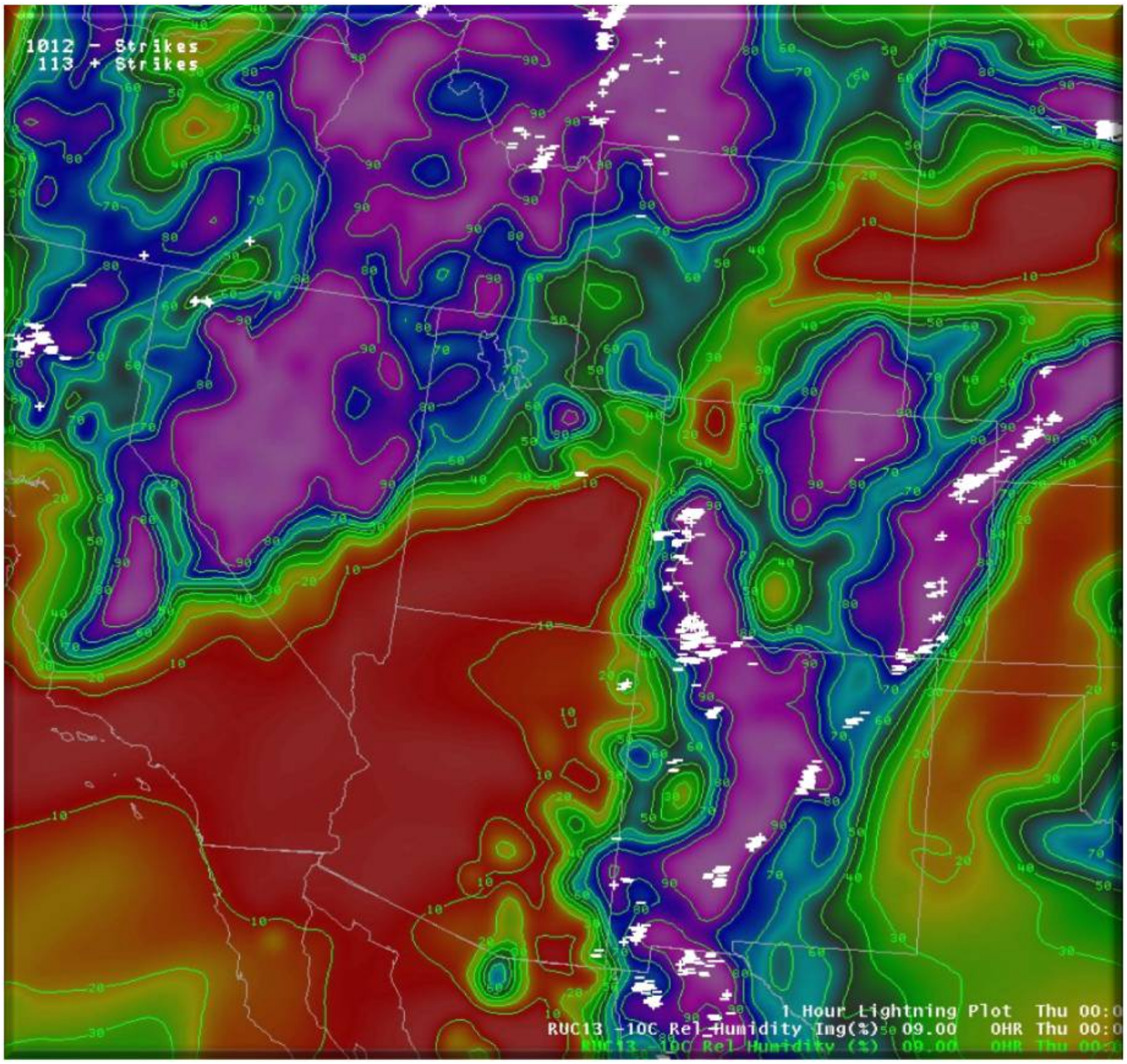

Figure 3 – An example of 13-km RUC analysis of relative humidity at -10° C (image and contours; contour interval is 10%) and 1-hour lightning plot (as in Fig. 1).

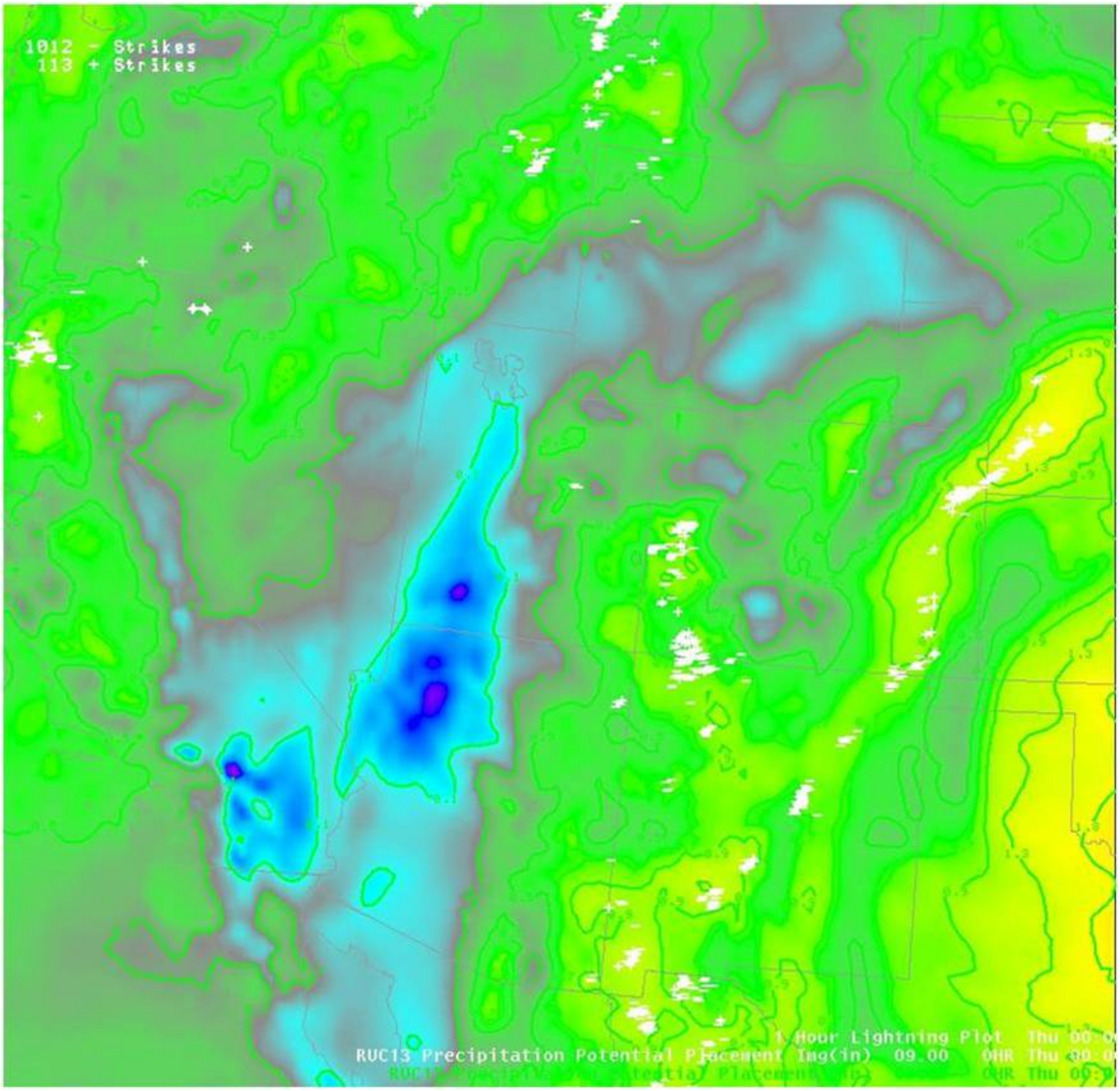

Figure 4 – An example of 13-km RUC analysis of precipitation potential placement (image and contours; contour interval is 0.5 in.) and 1-hour lightning plot (as in Fig. 1).

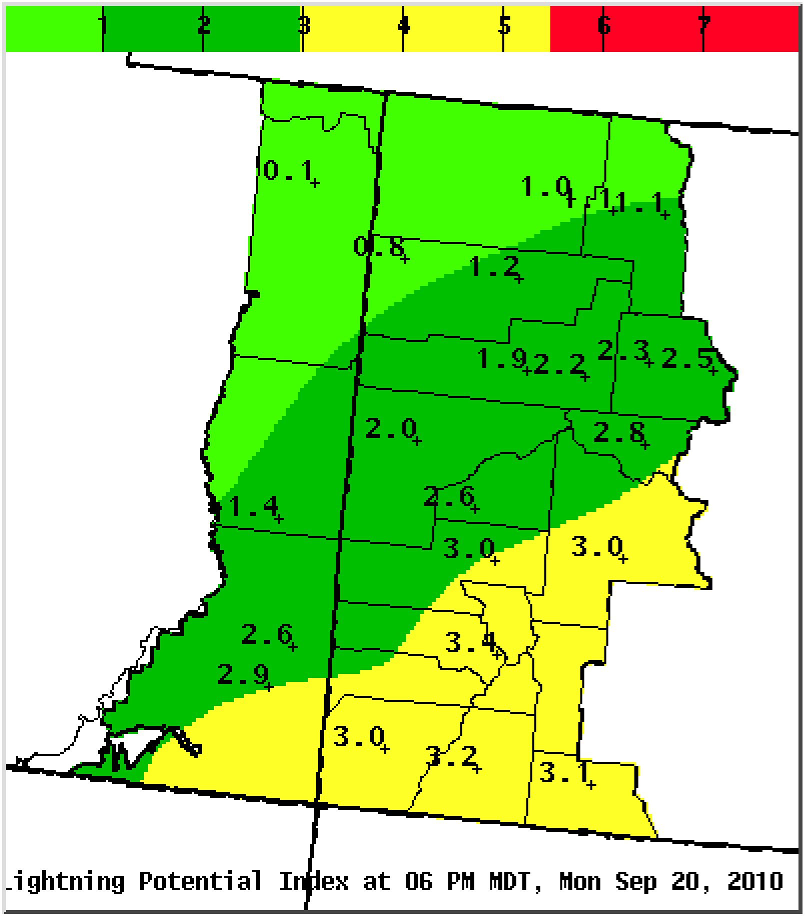

Figure 5 – An example of the lightning potential index
derived at the National Weather Service Grand Junction office.

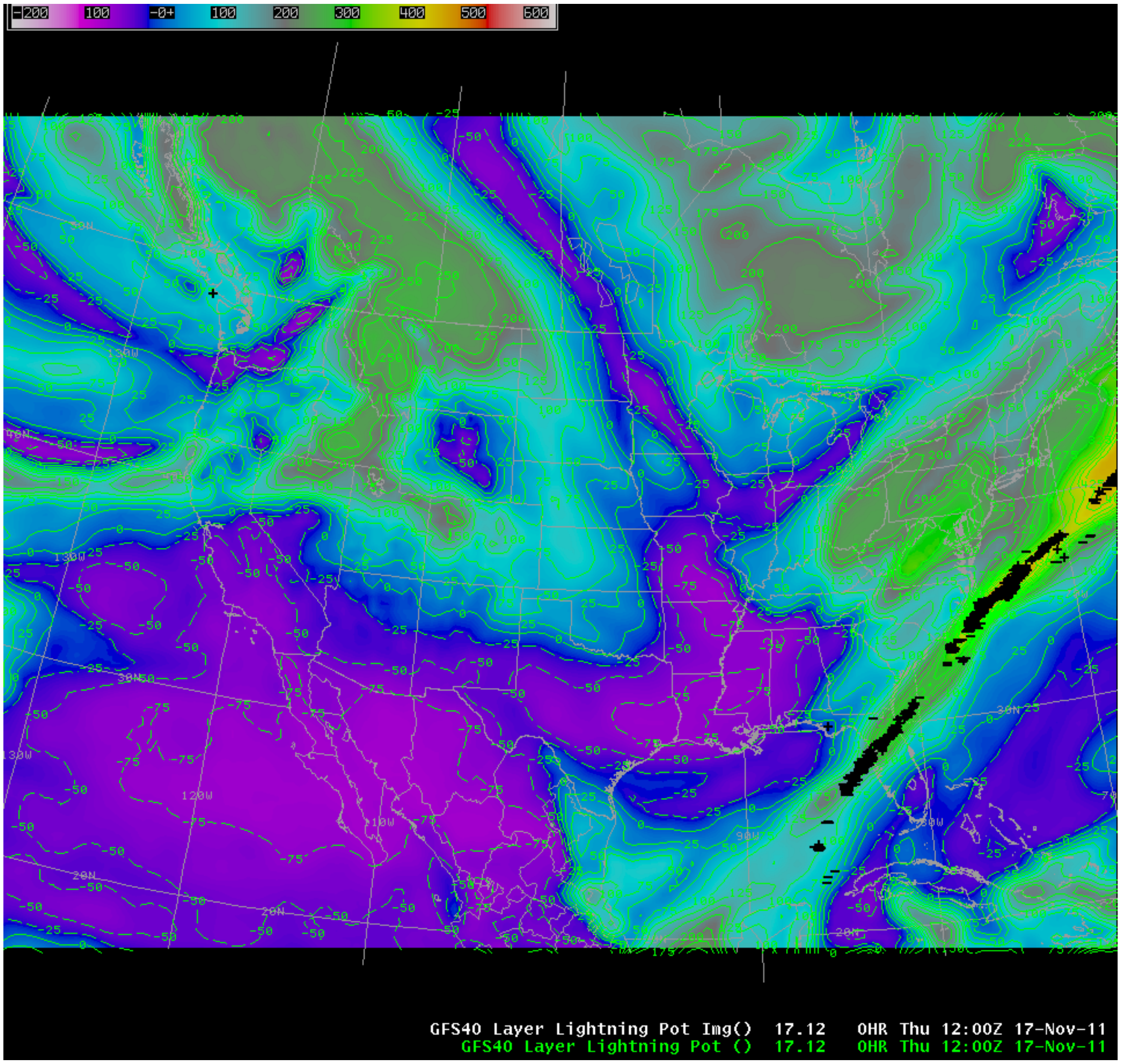

Figure 6 – Lightning potential parameter (image and contours; contour interval 25 units) and 1-hour lightning plot (as in Fig. 1) from the 40-km GFS, valid 1200 UTC 17 November 2011.

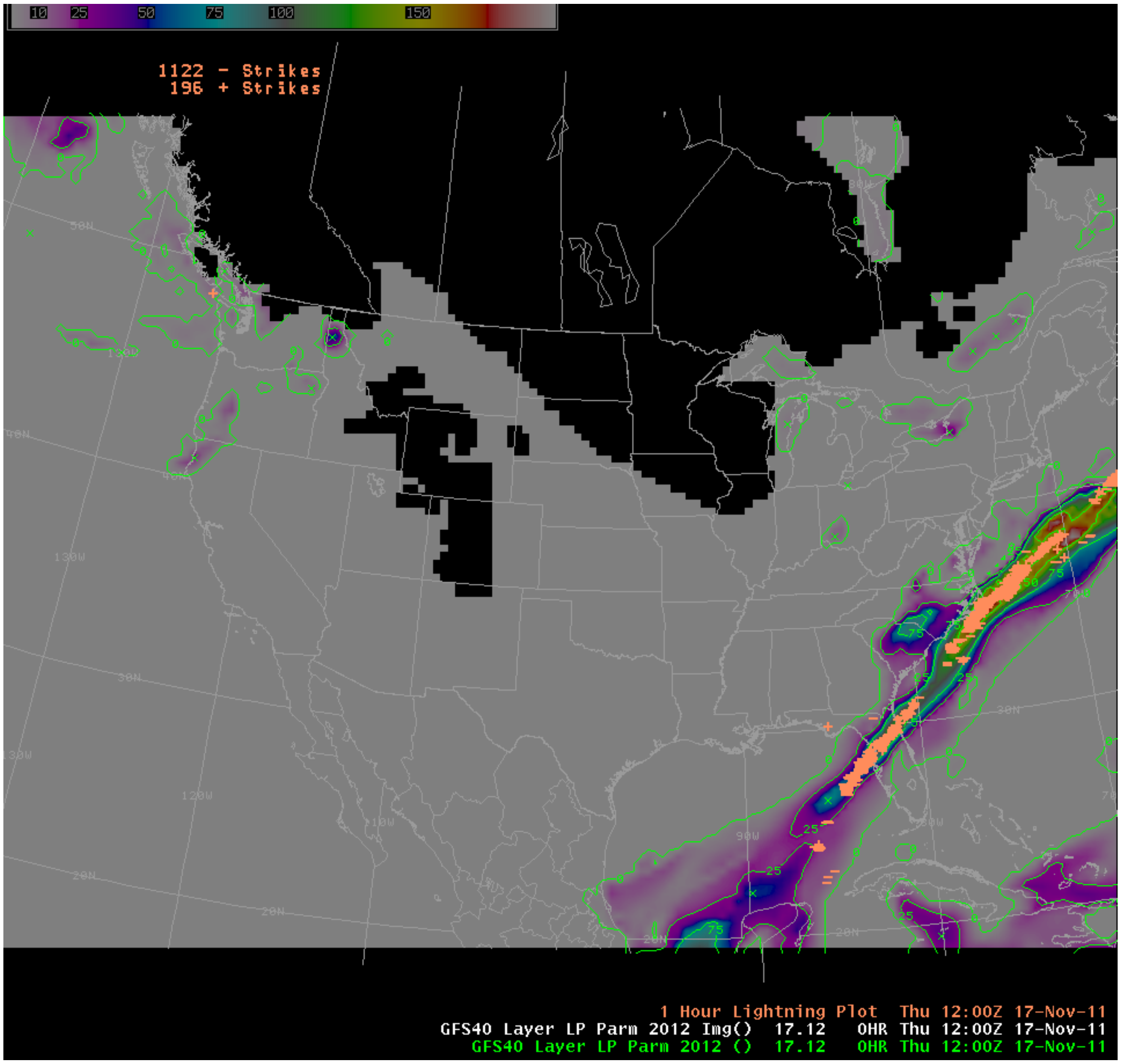

Figure 7 – LPI (image and contours; contour interval 25 units) with 1-hour lightning plot (as in Fig. 1) from the 40-km GFS, valid 1200 UTC 17 November 2011.

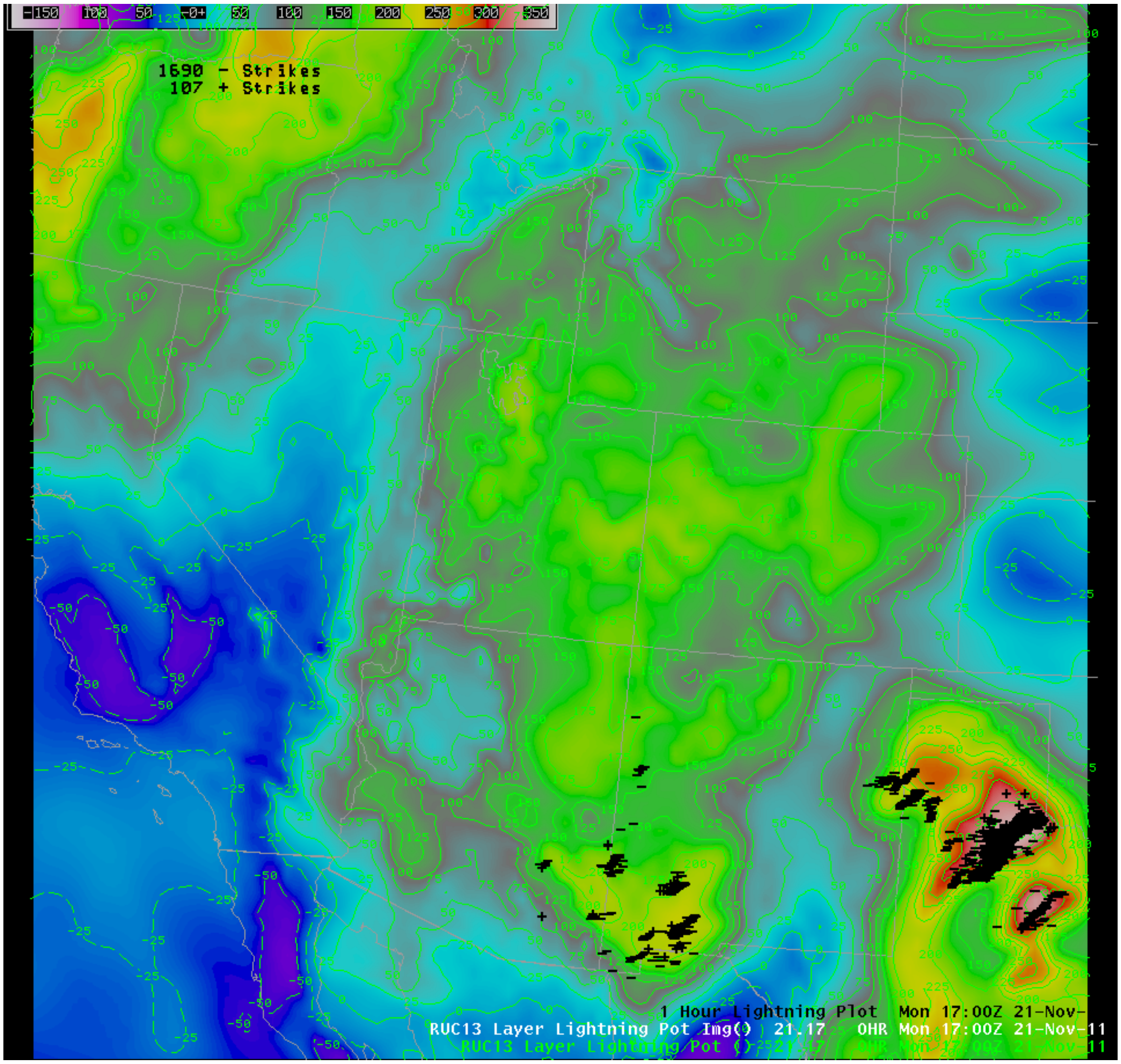

Figure 8 – Lightning potential parameter (as in Fig. 6) derived from the 13-km RUC data with 1-hour lightning plot (as in Fig. 1) valid 1700 UTC 21 November 2011.

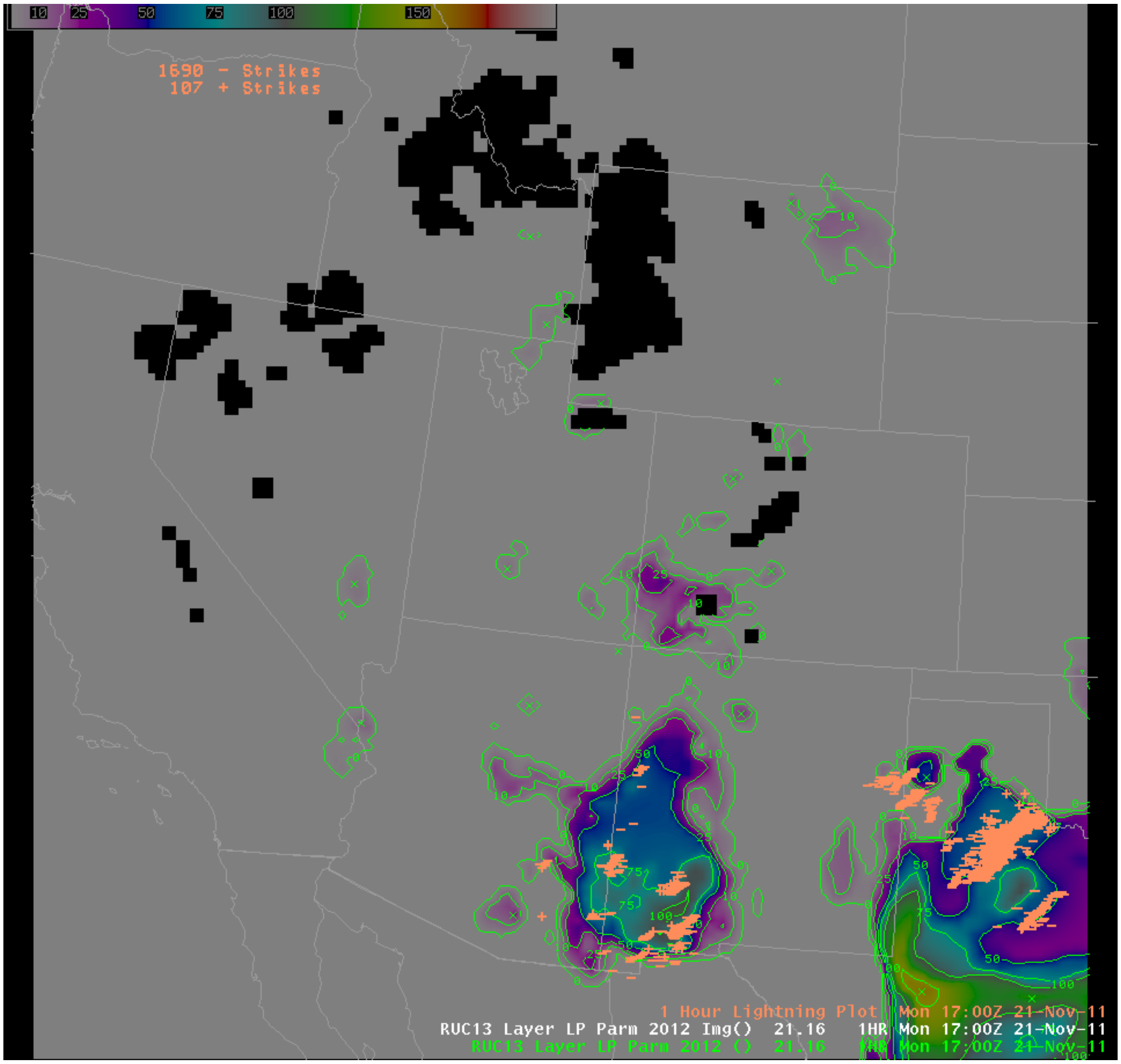

Figure 9 – LPI (as in Fig. 7) and 1-hour lightning plot (as in Fig. 1) from the 13-km RUC valid 1700 UTC 21 November 2011.

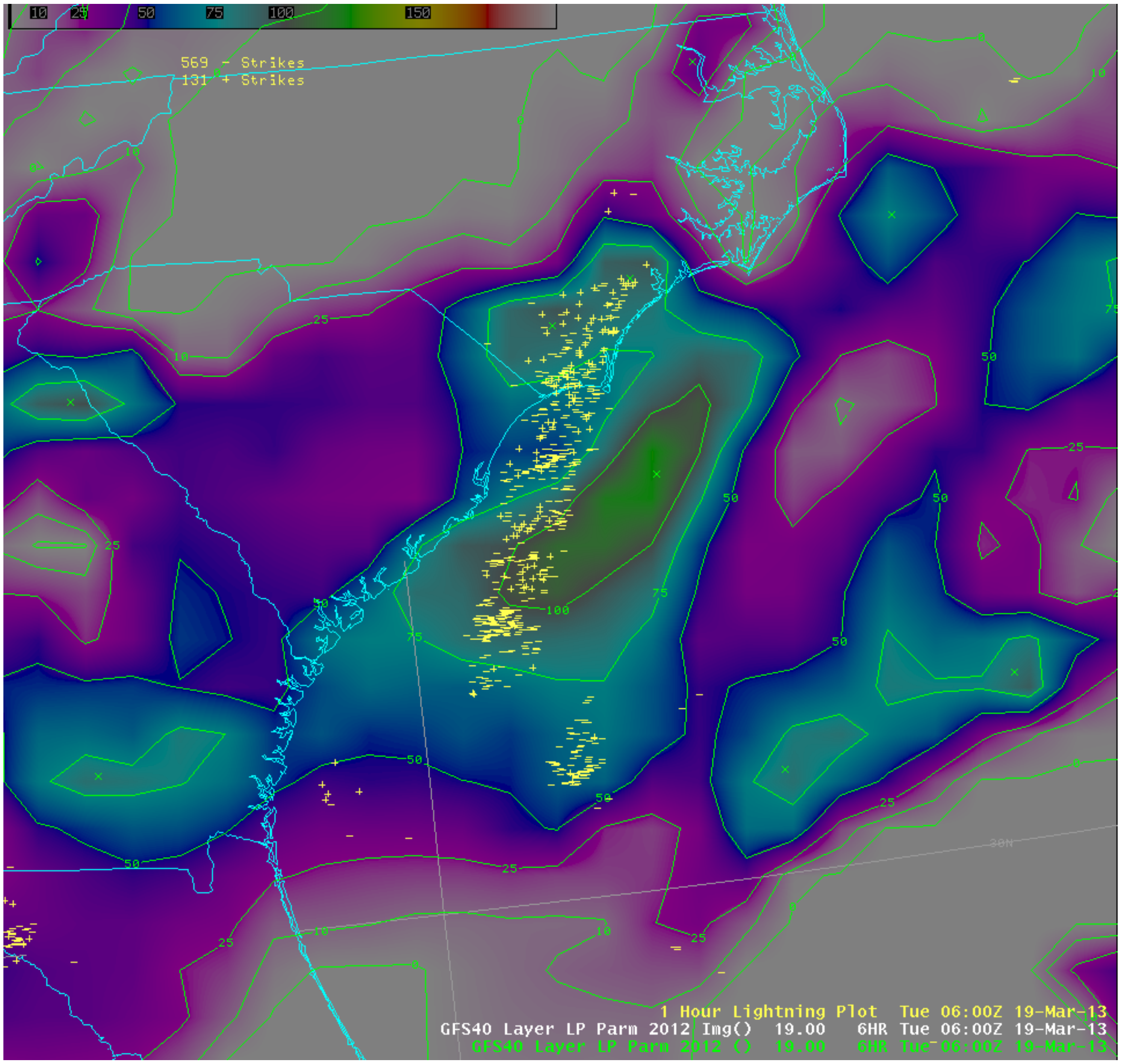

Figure 10 – Six-hour forecast of the LPI (as in Fig. 7) and 1-hour lightning plot (as in Fig. 1) from the 40-km GFS, valid 0600 UTC 19 March 2013.

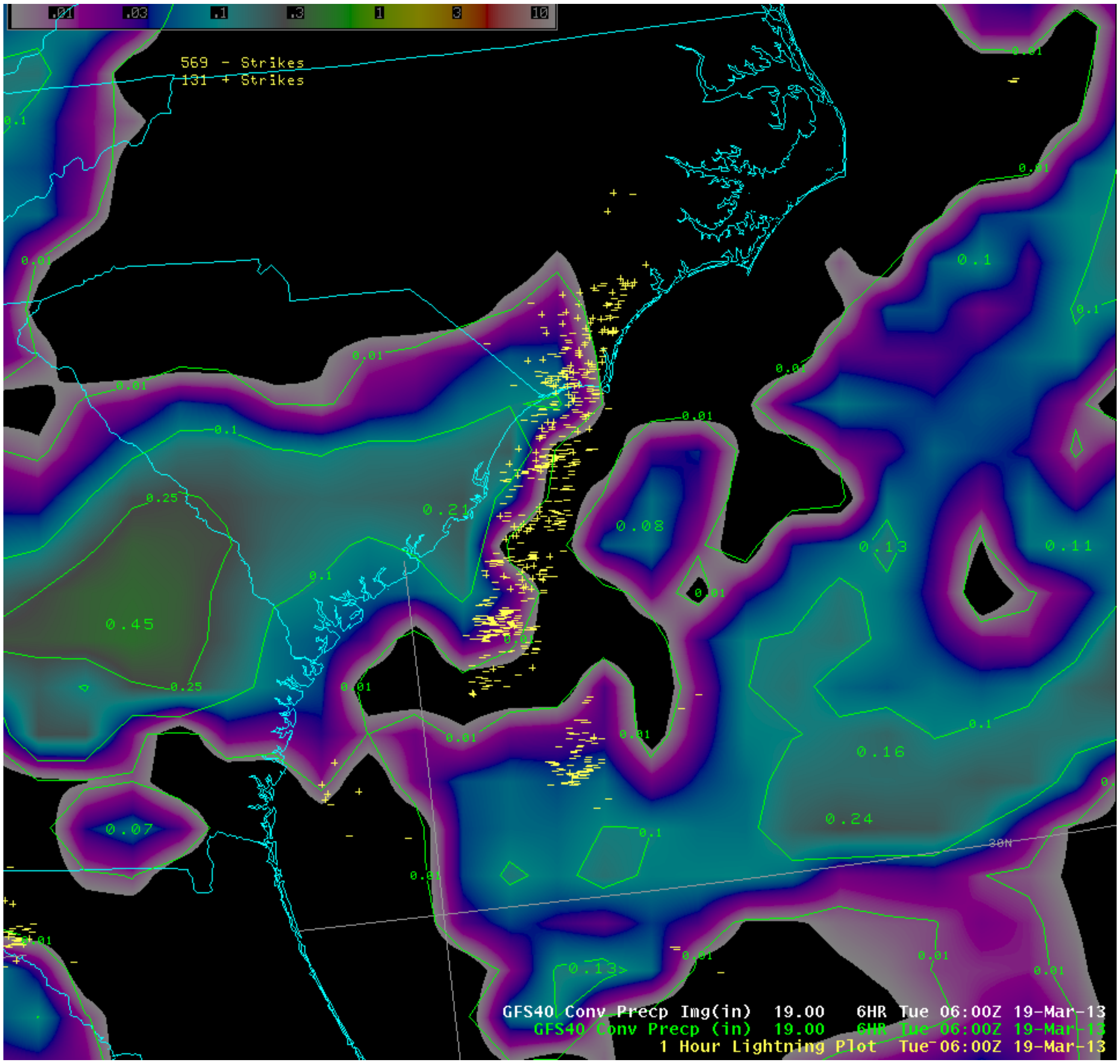

Figure 11 – Six-hour forecast of convective precipitation (image and contours; contours at 0.01, 0.10, and 0.25 inches) and 1-hour lightning plot (as in Fig. 1) from the 40-km GFS, valid 0600 UTC 19 March 2013.

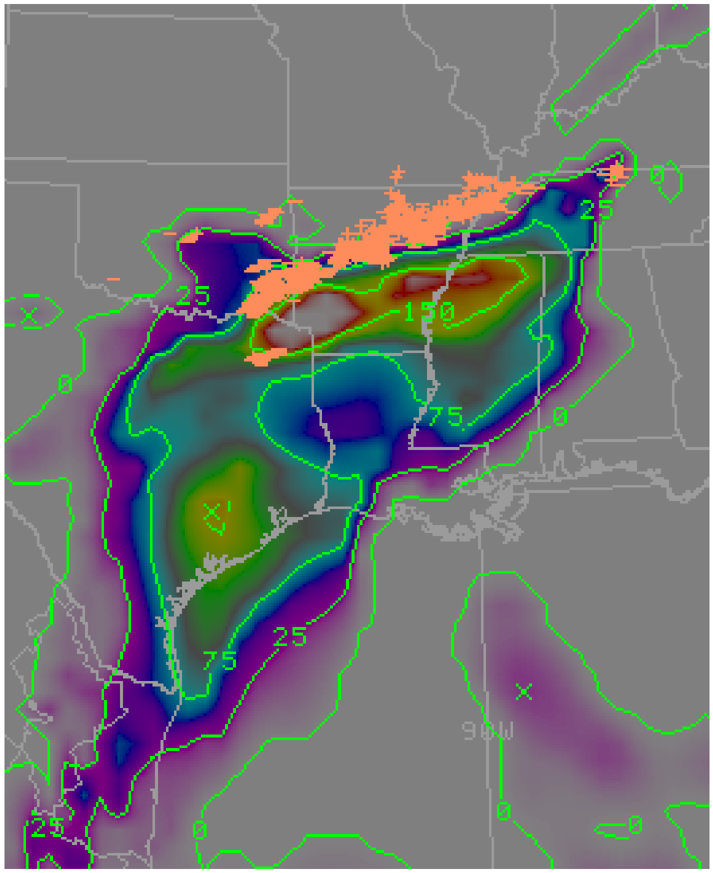

Figure 12 – As in Fig. 9 except 40-km GFS data valid 1800 UTC 08 March 2012.

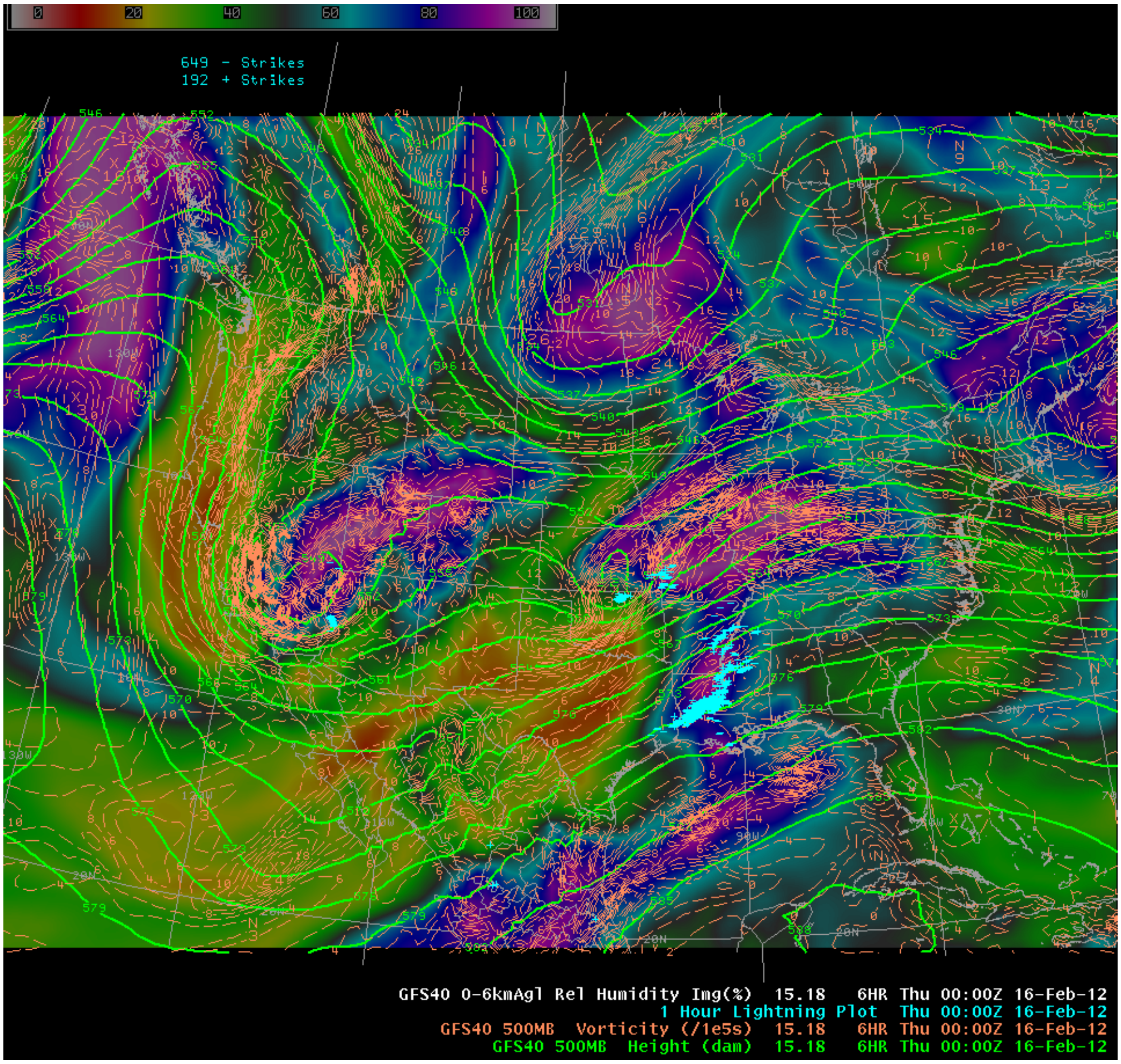

Figure 13 – Six-hour forecast of 500-mb height (green contours, 30-m interval) and vorticity (dashed orange), relative humidity (image) and 1-hour lightning plot (as in Fig. 1) from the 40-km GFS valid 0000 UTC 16 February 2012.

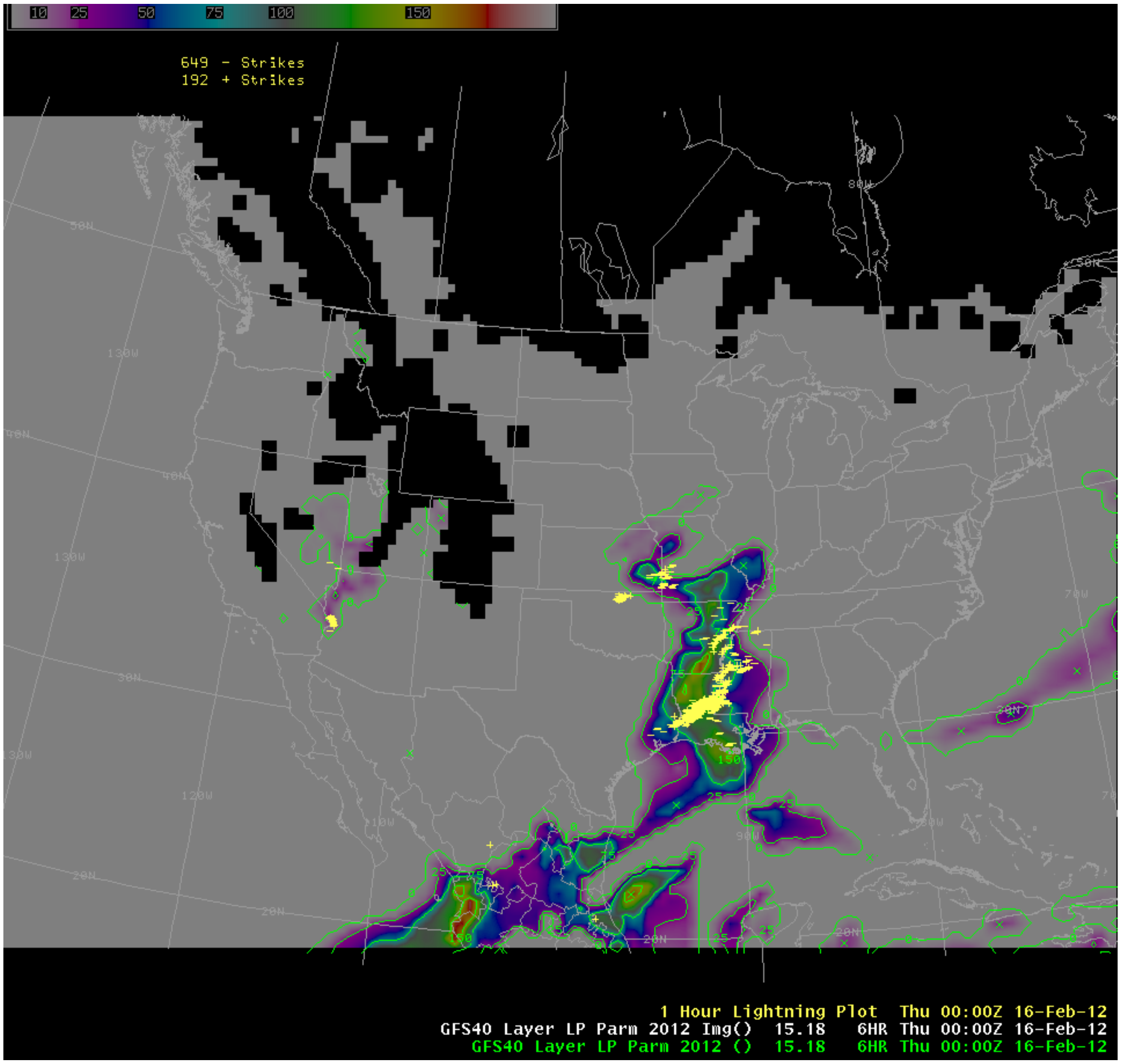

Figure 14 – Six-hour LPI forecast (green contours, 25-unit interval) from the 0000 UTC 16 February 2012 40-km GFS and 1-hour lightning plot (as in Fig. 1).

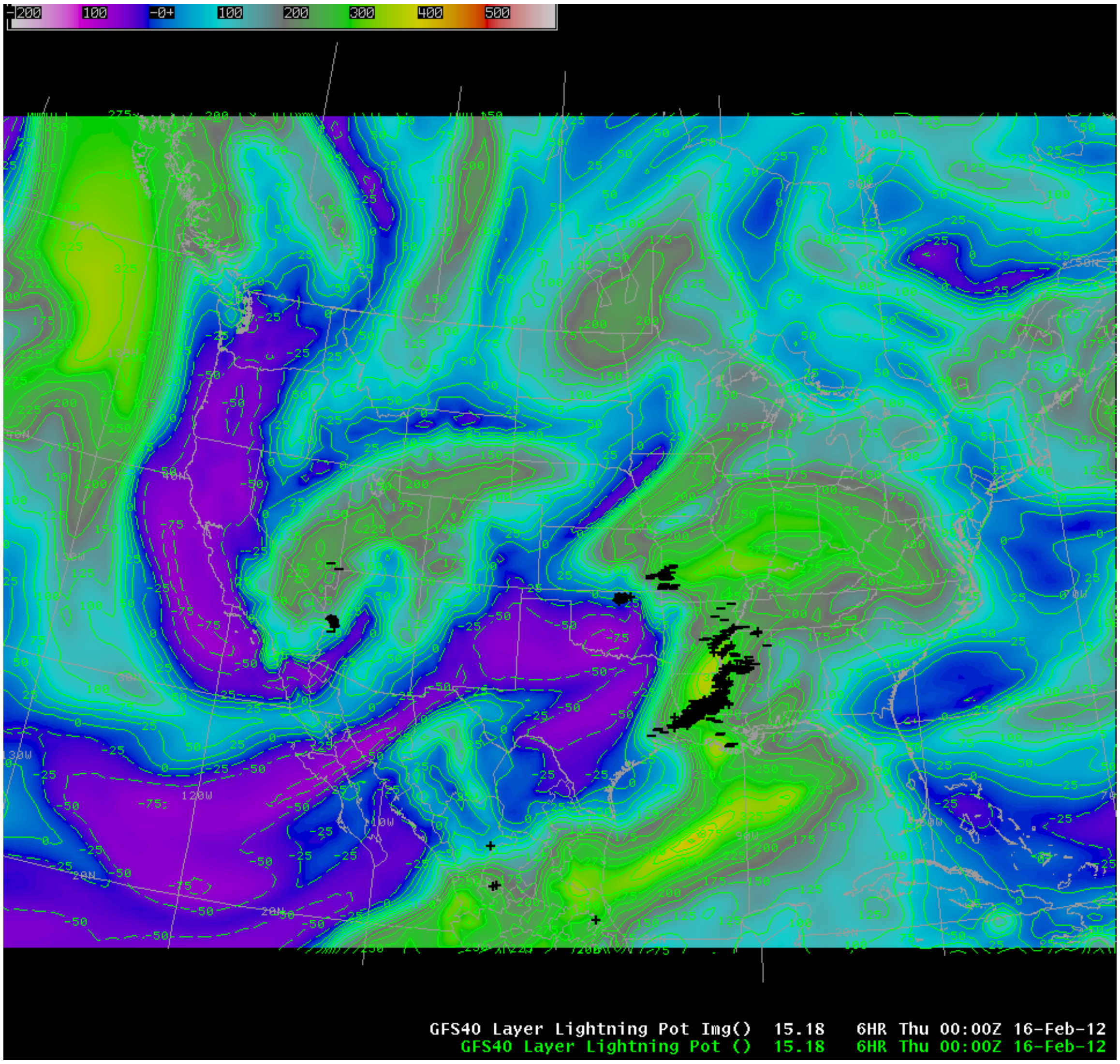

Figure 15 – Six-hour forecast of lightning potential parameter (as in Fig. 6) from the 0000 UTC 16 February 2012 40-km GFS and 1-hour lightning plot (as in Fig. 1).

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