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Lightning Meteorology II: An Advanced Course on Forecasting with Lightning Data

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1. INTRODUCTION

The Virtual Institute for Satellite Integration Training (VISIT) provides National Weather Service forecasters with training on a number of topics in remote sensing using distance education techniques. VISIT has developed a two-part course on forecasting with cloud-to-ground (CG) lightning data. The first course, "Lightning Meteorology I: Electrification and Lightning Activity in Typical Storms" discusses thunderstorm electrification, charge distributions and CG lightning activity in most warm season isolated storms and mesoscale convective systems (Zajac and Weaver 2002). The second course, "Lightning Meteorology II: Atypical Storms and Advanced Theory" examines CG lightning activity in other storm types including severe storms and winter storms. This article gives an overview of Lightning Meteorology II.

2. COURSE OBJECTIVES

The broad objective of Lightning Meteorology II is to teach forecasters how to utilize CG lightning data in storms that are atypical when compared to the more common storms examined in Lightning Meteorology I. This objective is met by 1) distinguishing between typical and atypical storms, 2) introducing theory on electrification, charge distributions and CG lightning production, and 3) presenting research results and AWIPS[1] case studies that demonstrate consistency between theory and observation. Specific course objectives are:

- to know the definitions of CG flash rate and percent +CGs[2] and the factors that control these two parameters
- to be familiar with the terms, Negative Strike Dominated (NSD) and Positive Strike Dominated (PSD)
- to identify the differences between warm and cold season lightning and the factors that may be responsible
- to see why severe NSD storms may exhibit unusually high and variable CG flash rates
- to be familiar with severe PSD storms and hypotheses used to explain these storms

Lightning Meteorology II is organized into five sections, which are summarized here in Secs. 3–7.

3. REVIEW OF LIGHTNING METEOROLOGY I

This section highlights the main points from Lightning Meteorology I. Isolated storms are reviewed first; mesoscale convective systems (MCSs) are reviewed second.

In isolated storms, electrification is caused by charging collisions between graupel particles (negative) and smaller ice crystals (positive). The normal dipole charge distribution (+ above –) forms as ice crystals are lofted to upper-levels while graupel particles are suspended by the updraft at mid-levels or fall out. The normal dipole evolves into a tilted dipole as positive charge advects downshear in the anvil. In terms of CG lightning production, –CGs are associated with convective precipitation (the fallout of graupel) while +CGs are associated with upper-levels, especially the anvil. Negative CGs outnumber positive CGs by roughly 10 to 1.

Mesoscale convective systems are often divided into convective and stratiform regions. MCS convective regions are similar to isolated storms in terms of electrification, charge distributions and CG lightning production: graupel-ice crystal collisions produce normal or titled dipoles which, in turn, produce many –CGs in and around the precipitation core and a few +CGs beneath the anvil. MCS stratiform regions are more complex with positive charge at upper-levels and an inverted dipole in the mid-level updraft (– above +). The inverted dipole results from charging collisions between aggregates (positive) and smaller ice crystals (negative). Stratiform regions produce significantly less CG lightning than convective regions, but more CG lightning than anvils. Stratiform regions are dominated by +CGs.

4. LIGHTNING PARAMETERS

CG flash rate and percent +CGs are examined in this section. The terms, NSD and PSD, are also discussed.

CG flash rate can be calculated in a number of ways depending upon how polarity is specified (–CGs, +CGs, or all CGs) and depending upon how time and area are specified (flash count [#], flash rate [# min^{-1}], or flash density [# min^{-1} km^{-2}]). Percent +CGs is the number of +CGs divided by the number of all CGs, multiplied by 100.

Flash rate for either polarity of CG lightning depends upon three factors: density of charge, distance between charge and the surface, and shielding by the opposite charge. For example, +CG flash rate ***increases***

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[1] The Advanced Weather Interactive Processing System (AWIPS) is the main tool used by National Weather Service forecasters. AWIPS is a computer system that centralizes weather observations and numerical model output.

[2] Positive CGs are defined as strikes that neutralize positive charge within the cloud. Negative CGs neutralize negative charge within the cloud.

as the density of positive charge ***increases***, as the distance between positive charge and the surface ***decreases***, and as shielding by negative charge ***decreases***. This discussion leads into a forecaster exercise that demonstrates how the three factors control CG flash rate and percent +CGs in typical isolated storms and MCSs.

The terms, Negative Strike Dominated and Positive Strike Dominated, are based on the percentage of +CGs: less than 50% indicates NSD, greater than 50% indicates PSD. These terms can be used to describe different regions of a thunderstorm as well as different portions of the storm lifecycle.

5. COLD SEASON LIGHTNING

This section is organized into three parts. First, climatology is used to identify differences between warm and cold season lightning. Next, AWIPS examples are presented to show the characteristics of cold season lighting. Finally, hypotheses are offered to explain cold season lightning.

Climatology indicates substantial differences between warm season lightning (Apr–Sep) and cold season lightning (Oct–Mar). Warm season lightning is characterized by a high CG flash count and percent +CGs less than 15%; cold season lightning is characterized by a low CG flash count and percent +CGs greater than 15% (Fig. 1).

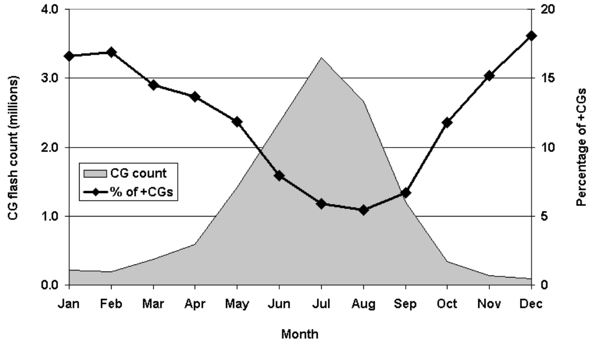

Fig. 1. Mean monthly CG flash count and percentage of +CGs over the contiguous U.S. from 1995–99. Figure adapted from Zajac and Rutledge (2001)

Five AWIPS examples illustrate the lower CG flash count and the higher percent +CGs during the cold season. These examples also illustrate regional variations in cold season lightning seen in climatological maps. In the first example, an extratropical cyclone produces CG lightning in relatively large numbers over the south-central and southeast U.S. with roughly 20% +CGs. In the second example, an extratropical cyclone produces CG lightning in smaller numbers over the Midwest with percent +CGs around 40%. In the third and fourth examples, extratropical cyclones produce CG lightning in low numbers along the Pacific coast with 80% +CGs. In the fifth example, a lake effect snow band over Lake Erie produces just a few –CGs.

Differences between warm and cold season lightning reflect general differences between the two seasons. CG flash count is lower during the cold season primarily due to less solar insolation. The percentage of +CGs is higher during the cold season for three main reasons. First, cloud tops are lower and the distance between upper-positive charge and the surface is decreased. Second, vertical wind shear is greater and upper-positive charge is less shielded by negative charge (tilted dipole). Third, cloud liquid water is less and aggregate growth and inverted dipoles more likely. Lake effect snow may be an exception to higher percent +CGs: a warm and moist boundary layer favors graupel growth and a more typical percentage of +CGs (< 15%).

It should be noted that cold season storms and typical warm season storms are similar in terms of CG lightning production by storm region. In most cases, –CGs are associated with convective precipitation while +CGs are associated with anvils and stratiform precipitation. In the case of Pacific coast storms, however, the relationship between CG lightning and storm regions has not been documented.

6. SEVERE NSD STORMS

This section focuses on the behavior of CG lightning parameters in severe negative strike dominated storms. The relationship between CG flash rate and updraft strength is considered first and a rule that describes CG flash rate in severe NSD storms is developed. This rule is then tested in a forecaster exercise and an AWIPS case study. Finally, the behavior of percent +CGs in severe NSD storms is examined.

CG flash rate may provide information about updraft strength since electrification requires supercooled liquid water, riming and graupel-ice crystal collisions. CG flash rate tends to increase as an updraft strengthens since more liquid water is condensed, more graupel is produced, and more collisions between graupel and ice crystals occur. This tendency is called enhanced charge: storms with vigorous updrafts produce more charge and higher CG flash rates (Fig. 2). However, CG flash rate can also decrease as an updraft strengthens. A vigorous updraft displaces charge-carrying ice particles away from the surface, reducing the likelihood of CG lightning. This tendency is called elevated charge (MacGorman et al. 1989).

This discussion of CG flash rate and updraft strength suggests a competition between enhanced charge and elevated charge in severe NSD storms. This competition can be pictured as a large reservoir of charge moving up and down as updraft strength varies. Since vigorous, long-lived updrafts exhibit at least some degree of time evolution (Foote and Frank 1983), we can expect a severe NSD storm to produce an overall high CG flash rate with dramatic variations superimposed.

Forecasters are now asked to indicate the likelihood of severe weather based on time series of CG flash rate. Three cases from Kane (1991) are presented. Forecasters usually identify periods of high and variable CG flash rate as having the greatest potential for severe weather. They later learn that severe weather did occur during these time periods. However, no consistent relationship is found between CG flash rate maxima/minima and severe weather. In other words, a high and variable CG flash rate indicates an increased potential for severe weather, but specific variations in CG flash rate do not appear to have forecast value. This last statement is substantiated by Fig. 3, which shows CG flash rate and tornado damage rating during the Birmingham F-5 tornadic storm. The storm exhibits an extremely high and variable CG flash rate around the time of the three tornadoes, but CG flash rate maxima/minima and tornado times show no consistent correlation.

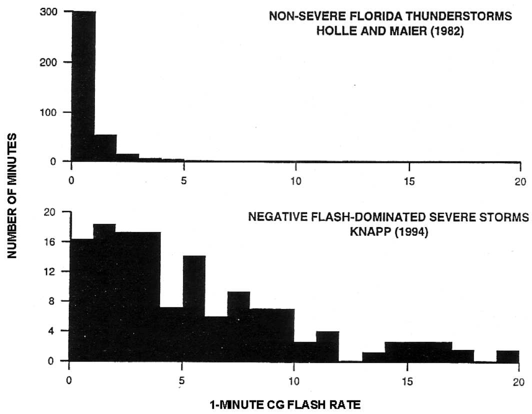

Fig. 2. Histograms of 1-minute CG flash rate for non-severe NSD storms and severe NSD storms. Roughly 380 minutes are analyzed in the top panel, 140 minutes in the bottom panel. Figure adapted from Williams (2001).

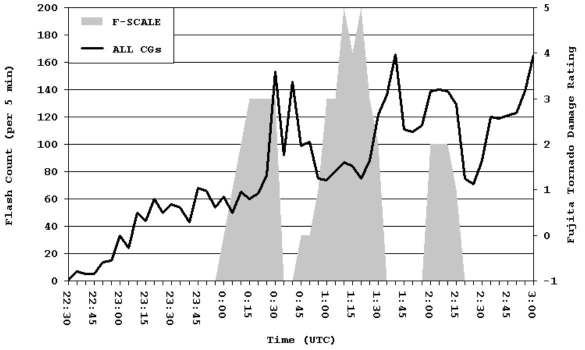

Fig. 3. Time series of 5-minute CG flash rate (all CGs) and Fujita tornado damage rating for the Birmingham F-5 tornadic storm on 8 April 1998. Data on tornado damage provided by NWS/BMX.

The percentage of +CGs may provide information about storm severity. Percent +CGs is affected by the shielding of upper-positive charge by lower-negative charge. Since the precipitation core of severe NSD storms is often tilted, percent +CGs may be elevated above 15% as positive charge is displaced downshear, not only in the anvil, but also in overhanging radar echo structures such as a bounded weak echo region. The Birmingham storm, for example, exhibited a titled precipitation core and produced roughly 35% +CGs during the time period displayed in Fig. 3. Despite this result, forecasters are cautioned that elevated percent +CGs is a weak signal for indicating storm severity; most severe storms produce less than 15% +CGs.

A final note: severe NSD storms and typical warm season storms are similar in terms of CG lightning production by storm region: –CGs are associated with convective precipitation while +CGs are associated with anvils and stratiform precipitation.

7. SEVERE PSD STORMS

Severe positive strike dominated storms were first documented in the early 1980s. These storms are poorly understood due to their anomalous nature. However, the characteristics of severe PSD storms are becoming more well known and research is progressing on several fronts including climatology, electrification and charge distributions.

Severe PSD storms are loosely defined as severe storms dominated by +CGs in the precipitation core for a significant time period during the mature phase (e.g., Fig 4). The literature suggests that PSD storms with frequent +CGs usually produce large hail and sometimes tornadoes (e.g., MacGorman and Burgess 1994). Severe PSD storms are major weather producers; they are associated with severe weather outbreaks, long-track tornadoes and F-5 tornadoes (Perez et al. 1997).

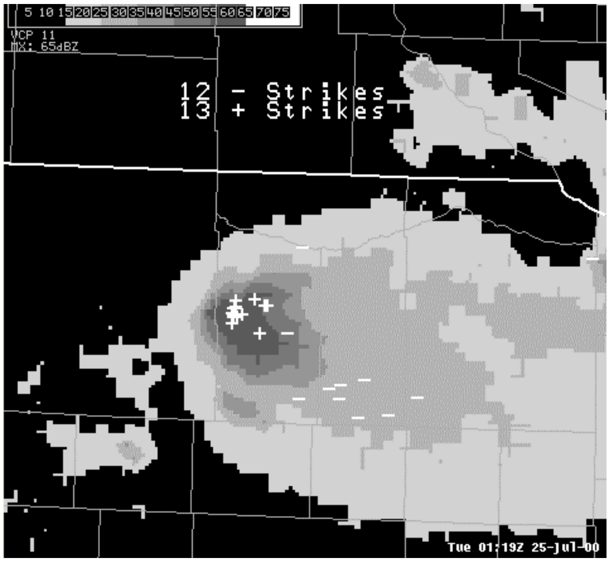

Fig. 4. Composite radar reflectivity from the WSR-88D in North Platte, NE and CG lightning from the National Lightning Detection Network. Radar scan time is 01:19 UTC on 25 July 2000. CG strikes from 01:15–01:20 UTC are plotted. County borders and the NE-SD border are displayed. This storm produced large hail and tornadoes.

Severe PSD storms account for less than 5% of severe storms over most of the eastern and western U.S., but account for greater than 30% of severe storms over large parts of the central U.S. (Fig. 4). This spatial pattern appears to reflect an association between dominant CG lightning polarity and surface equivalent potential temperature (θ_e). Storms forming upstream of surface θ_e ridges tend to be PSD, while storms forming downstream of θ_e ridges tend to be NSD; storms that cross the θ_e ridge transition from PSD to NSD (Fig. 5).

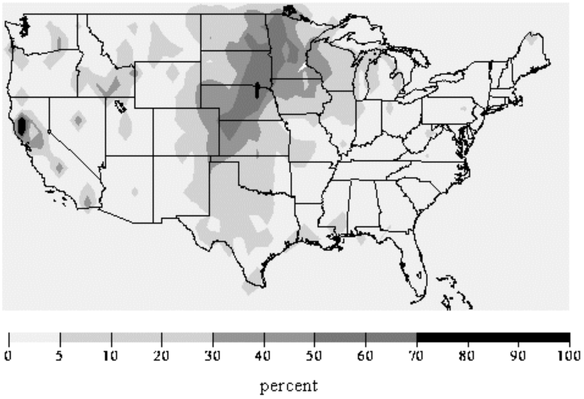

Fig. 4. Percentage of large hail and tornado reports associated with PSD storms. Dominant polarity is calculated using CG lightning data during the hour around severe weather. SPC reports analyzed from Apr–Sep 1989–98. Contours are 0–5%, 5–30%, 30–50%, 50–70%, and 70–100%. Figure adapted from Carey et al. (2002)

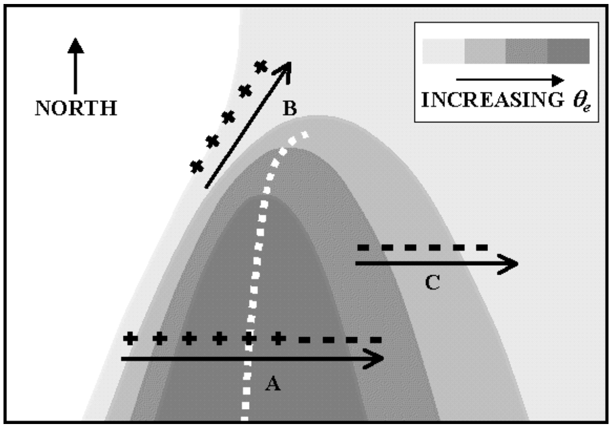

Fig. 5. Storms tracks and dominant CG lightning polarity with respect to a surface θ_e ridge. Figure adapted from Smith et al. (2000).

Electrification and charge distributions in severe PSD storms are not well known. However, positive CGs in the precipitation core and negative CGs in the anvil (Fig. 3) suggest an inverted dipole with positive charge on graupel particles and negative charge on smaller ice crystals. Cloud chamber-electrification studies show that graupel particles charge positive in clouds with low or extremely high cloud liquid water (Takahashi 1978) or with a narrow droplet size distribution (DSD; Avila et al. 1999). Low cloud liquid water or narrow DSD seem the best explanations. Severe PSD storms occur in a region where dry, continental air is commonly found at mid-levels. It is plausible that severe PSD storms entrain this air at mid-levels — the level where charging takes place. Dry, continental air may also explain the tendency for severe PSD storms to be low-precipitation or classic supercells, but not high-precipitation supercells (e.g., MacGorman and Burgess 1994).

8. CONCLUSIONS

Cloud-to-ground lightning behavior is summarized in typical warm season storms, cold season storms, severe NSD storms and severe PSD storms.

Typical warm season storms usually produce less than 15% +CGs over their lifecycle. Negative CGs are associated with convective precipitation, while positive CGs are associated with anvils and stratiform precipitation.

Cold season storms are similar to typical warm season storms with respect to CG lightning production by storm region, but differ with respect to CG flash rate and percent +CGs. Forecasters can expect lower CG flash rates and higher percent +CGs in most cold season scenarios.

Severe negative strike dominated storms are similar to typical warm season storms with respect to CG lightning production by storm region, but differ with respect to CG flash rate and percent +CGs. Unusually high and variable CG flash rates may identify periods of severe weather. Percent +CGs may be elevated above 15% in some cases.

Severe positive strike dominated storms are anomalous when compared to typical warm season storms: +CGs are associated with convective precipitation while –CGs are associated with anvils. These storms tend to occur in the central U.S. upstream of surface θ_e ridges. Frequent +CGs in the precipitation core is a strong signal for large hail.

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