ORIGINS OF POSITIVE CLOUD-TO-GROUND LIGHTNING FLASHES IN THE STRATIFORM REGION OF A MESOSCALE CONVECTIVE SYSTEM

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Abstract

The origins of positive cloud-to-ground (+CG) lightning in the stratiform region of a leading-line, trailing-stratiform mesoscale convective system (MCS) are investigated. Data sources include radars, NLDN data, and a time-of-arrival VHF 3-D lightning mapping system. This study examines an asymmetric MCS that occurred near the Colorado-Kansas border in June 2000. In this storm 38 of the 269 +CGs produced over a nearly 5-hour period came to ground within the stratiform region. Of these, 29 initiated in the leading convective line and propagated rearward before coming to ground. Nine other +CGs originated within the stratiform region. Stratiform +CGs were observed to propagate mostly horizontally through vertically thin layers. The observations suggest that stratiform charge is a conduit for +CG lightning from the convective line, and can initiate +CGs as well. Other types of stratiform lightning in this MCS also are discussed.
1. Introduction

A bipolar pattern in cloud-to-ground (CG) lightning strike locations has been commonly observed in mature leading-line/trailing-stratiform mesoscale convective systems (LLTS MCSs). In such a pattern, negative CG lightning (-CG) is observed mostly within the leading convective line, whereas positive CG lightning (+CG) dominates within the trailing stratiform region (e.g., Rutledge and MacGorman 1988). Significant research has been devoted toward understanding the physical mechanisms that determine this bipolar CG structure. It is well known that electric fields and inferred charge densities in stratiform regions of MCSs are comparable to those observed in convection, and that stratiform charge layers are horizontally extensive (e.g., Stolzenburg et al. 1994). However, the source of these stratiform charge layers is still unclear.

Two well-known hypotheses to explain stratiform charging are charge advection and in situ charge generation (e.g., section 8.2.4 of MacGorman and Rust 1998). Charge advection refers to the rearward (in LLTS MCSs) advection of charge (on cloud and/or precipitation particles) from the convective line, which could form the observed charge layers in the stratiform region that could be tapped for +CG production. In situ charge generation refers to charging through ice particle collisions within the stratiform region itself. Currently, the relative importance of these two mechanisms has not been completely determined. In addition, the effects
of lightning itself on charge structure in the stratiform region of MCSs are not well understood.

Our understanding of stratiform-region charging is further complicated by uncertainty about the initiation locations of stratiform +CGs. We do not know whether these +CGs initiate within the convective line and propagate rearward through stratiform charge layers before coming to ground, or whether they originate within the stratiform region itself (or both). As an example of the implications of this issue, Shafer et al. (2000) hypothesized the convective line source for stratiform +CGs as a potential explanation for the simultaneous evolution in ground flash rates that they observed in the convective and stratiform portions of an MCS.

In this study we will show that for a single asymmetric LLTS MCS (e.g., Houze et al. 1989) observed during the Severe Thunderstorm Electrification and Precipitation Study (STEPS; e.g., Weisman and Miller 2000), most stratiform +CGs originated within the convective line. However, a small number of +CGs did originate within the stratiform region when it was well developed. Note that this study is not intended to be a detailed examination of MCS electrification, and instead simply addresses the long-standing question of stratiform +CG origins.

2. Data and Methodology

The STEPS project took place along the Colorado-Kansas border in the summer of 2000, and made use of three S-band Doppler radars – the
Colorado State University CSU-CHILL and NCAR S-Pol polarimetric radars, and the National Weather Service KGLD radar at Goodland, KS. The radars were aligned in a triple-Doppler configuration, and the LLTS MCS that occurred on 11-12 June 2000 (UTC time) was within scanning range of all three radars, all of which were used in our analysis.

CG lightning data were obtained from the NLDN, which has a 90%+ detection efficiency and a median location accuracy of less than 0.5 km in the STEPS region (Cummins et al. 1998). Only one +CG in our study (not a stratiform +CG) fell below the Cummins et al. (1998) 10-kA peak current threshold for intracloud flashes mis-identified as +CGs. It is included in our totals because it is close to the threshold (9.97 kA) and because including it does not change our results.

The New Mexico Tech Lightning Mapping Array (LMA) was the final component of this study. During STEPS the system located the sources of impulsive VHF radio signals from lightning by measuring the time that the signals arrived at 13 receiving stations deployed over a 60-80 km diameter area along the Kansas-Colorado border. This basic time-of-arrival (TOA) system for mapping lightning has a long history, going back to Proctor (1971). By considering spatial and temporal proximity of lightning VHF sources to one another, they can be grouped into individual flashes using special analysis software. The LMA is most sensitive to VHF radiation from negative breakdown occurring within regions of net positive charge (Rison et al. 1999). Thus, the LMA can be used to identify positive charge regions.
tapped by lightning based on analysis of VHF emission density. This makes the system well-suited for mapping +CG discharges.

By visually comparing NLDN and LMA data, we manually isolated all the VHF sources (typically 100s-1000s of sources per flash) associated with each +CG flash detected by the NLDN. Overlays of these lightning maps onto cross-sections of radar data allowed determination by visual inspection of whether the +CG came to ground in the leading convective line or trailing stratiform region. Furthermore, the location of the initial VHF sources of the flash could be used to determine where the +CG initiated. In order to account for advection of the storm we compared flashes to radar volumes completed within 5 minutes of the flash.

For convective/stratiform partitioning, we generally followed the methodology of Rutledge and MacGorman (1988), considering the region rearward of the 30-dBZ contour surrounding the main convective line to be stratiform. However, when peak radar returns exceeded 30-40 dBZ in the stratiform region horizontal radar-based partitioning in the 11 June MCS became ambiguous. Thus, we also examined the vertical structure of the radar echoes, since by definition stratiform echo lacks the vertical development of convection. Additionally, volumetric density of LMA sources was computed over varying time intervals (1-5 minutes) in order to locate convective centers relative to individual +CG flashes. This information was used to supplement the determination of +CG type, since convective regions are very easy to determine using total lightning data.
For example, if a +CG both originated and came to ground rearward of the electrically active cells (≥ 1 flash per minute) in the convective line, it was determined to be a +CG that originated wholly within the stratiform region. Despite its subjective nature, we consider this classification methodology superior for our purposes to that of automated stratiform/convective partitioning algorithms (e.g., Steiner et al. 1995), since it includes lightning and vertical radar structure information typically not used by such algorithms.

3. Results

We studied the period from 2100 UTC on 11 June to 0150 UTC on 12 June (Local time was UTC-6 hours). During this time period the storm was in range of both the radar and LMA networks and all radars were scanning this storm. The time period also encompassed the evolution of the system from a simple convective line to a mature asymmetric LLTS MCS, as well as later stages. To demonstrate this basic structure, Fig. 1 shows a horizontal radar cross-section of the MCS during its mature phase (0000 UTC). The NLDN detected 269 +CGs associated with the MCS during this ~5-hour time period, out of a total of 1214 CGs overall (22% positive).

Based on our classification work, the vast majority of +CGs in this storm originated and came to ground within the convective line. Only 38 came to ground in the stratiform region. Of these, 29 were determined to
have originated within the convective line ("stratiform from convective" or SfC), and the other 9 originated within the stratiform region itself (in situ stratiform or ISS). All of the latter +CGs occurred after 0000 UTC on 12 June, when the stratiform region was well developed, having reached \(~5000\ \text{km}^2\) in area and having peak radar echoes exceeding 40 dBZ (e.g., Fig. 1).

Figures 2 and 3 show examples of SfC (2) and ISS (3) +CG flashes. As suggested by Fig. 3, many stratiform +CGs originated from the same LMA-mapped parent flash. In fact, 6 LMA-mapped flashes accounted for 14 of the 29 SfC +CGs, and 2 LMA-mapped flashes accounted for 5 of the 9 ISS +CGs. Some SfC parent flashes produced convective line +CGs as well. Note that these individual +CGs came to ground at different times (often 10s of ms different) and different locations (e.g., Fig. 3) than their siblings, and are not just detections of multiple return strokes from the same strike location.

Median peak current for stratiform +CGs was 37.4 kA, about 20% higher than the median peak current for all +CGs in the MCS (31.5 kA), including those that struck in the convective line. Median altitudes of VHF sources for each of the 38 stratiform +CG flashes were calculated. This distribution of altitudes had a mean of 6.2 km with a standard deviation of 0.9 km. (In the case of a parent flash with multiple +CGs, the parent flash was only counted once.)
Based on a balloon-borne electric field meter sounding launched in the transition zone rearward of the northern convective line at 2302 UTC, 6.2 km MSL is approximately the –10 °C isotherm altitude. The sounding (not shown) was similar to other transition zone electric field soundings (e.g., Schuur et al. 1991), and indicated positive charge in the ~5.2-6.4 km MSL layer, roughly consistent with the mean altitude of stratiform +CGs. However, it is difficult to compare a single transition zone sounding to lightning occurring throughout the entire stratiform region.

Considering only the median altitude of the first 10 VHF sources of the parent flashes of SfC +CGs, we determined that on average these flashes originated at 6.4 km MSL altitude within the convective line, with a standard deviation of 1.8 km. (Origin altitudes of all stratiform +CGs, SfC and ISS, averaged 6.2 km MSL with a standard deviation of 1.7 km.) All parent flashes of convective line +CGs initiated on average at 6.8 km MSL, with a standard deviation of 1.9 km, suggesting that SfC and convective line +CGs originated within roughly the same altitude region.

To examine the vertical structure of individual stratiform +CGs in more detail, Fig. 4 shows an average vertical distribution VHF sources for stratiform +CGs. This distribution was derived by first separating VHF sources for each +CG parent flash into 0.25-km vertical bins and determining the altitude of the maximum number of VHF sources for each flash. Each flash’s distribution was then normalized by this maximum, and other altitude bins were adjusted to be relative to the altitude of this
maximum, which was set to be 0 km. Finally, the mean distribution for all stratiform +CGs was determined by averaging these normalized, altitude-adjusted distributions. Figure 4 shows that, on average, over 50% of all VHF sources in a flash were within ±1 km of the altitude of the maximum number of sources, demonstrating that most of the VHF sources were confined to a narrow vertical layer.

Horizontal extent of stratiform +CGs was estimated by determining the rectangle that encompassed all VHF sources associated with a parent flash, and then calculating the length of the rectangle's diagonal. For all stratiform +CG parent flashes, the mean length was 112.6 km with a standard deviation of 34.8 km. Therefore, stratiform +CG parent flash structure suggests horizontally large but vertically thin charge layers similar to those inferred from previous studies of MCS stratiform electrification (e.g., Stolzenburg et al. 1994).

It should be noted that +CGs were not the only types of stratiform lightning in this MCS. We also observed stratiform intracloud (IC) flashes, convective line +CGs and -CGs that had components that propagated into the stratiform region, stratiform -CGs similar to stratiform +CGs, and single parent flashes that produced both -CGs and +CGs in the stratiform region. Note that the +CGs from this latter flash type were included in our stratiform +CG statistics. A detailed investigation of these other stratiform flashes is beyond the scope of this study, but with the exception of stratiform -CGs, these flashes as a whole were far more
common than stratiform +CGs. For example, we have counted over 70 convective line +CGs with stratiform components, and at least 60 stratiform ICs, compared to 38 stratiform +CGs.

4. Discussion and Conclusions

In this storm the convective line played the dominant role in initiating stratiform +CGs (29 of 38 total). Positive CGs that originated within the stratiform region comprised only 9 flashes of the stratiform +CG population. All of these occurred later in the storm’s lifetime, when the stratiform region was well developed. Regardless of where they were initiated, stratiform +CGs in this storm followed pathways indicative of vertically thin but horizontally extensive charge layers.

The results of this study help to address the longstanding question of stratiform +CG origins in MCSs. They also suggest that stratiform charge is a conduit for +CG lightning from the convective line, and can initiate +CGs as well. In addition, we have pointed out several other types of stratiform flashes that are worthy of further investigation. Indeed, given the large number of stratiform flashes (+CG and otherwise) in this MCS an increased focus on charge deposition by lightning (e.g., Coleman et al. 2003) as a potential contributor to stratiform electrification could be warranted. A more detailed study of the kinematic, microphysical, and electrical evolution of this MCS is planned.
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References


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Figure Captions

Figure 1. Horizontal cross-section at 1.5 km MSL of reflectivity factor from the KGLD radar at 0000 UTC on 12 June. Note the northward bias for stratiform precipitation, while along the convective line the southern portion was strongest at this time, with weaker northern convection.

Figure 2. Horizontal cross-section at 1.5 km MSL of reflectivity factor from the KGLD radar (line contours, every 15 dBZ starting at 10), along with NLDN-detected +CG strike locations (+ signs), VHF source locations projected onto the horizontal plane (small gray diamonds), and intital VHF source location (large black diamond), for an SfC stratiform +CG. Flash started at 22:45:37 UTC, with radar data from 2245 UTC.

Figure 3. Same as Fig. 2 but for an ISS +CG flash starting at 01:01:57 UTC; radar data from 0101 UTC.

Figure 4. Mean distribution of VHF sources around the altitude of the maximum number of sources for parent flashes of stratiform +CGs. Annotation indicates mean percentage of all VHF sources within ±1 and ±2 km of this altitude.
VHF Distribution around Max

- 52.5% +/- 1 km
- 76.6% +/- 2 km