GEOPHYSICAL RESEARCH LETTERS, VOL. 31, LXXXXX, doi:10.1029/2004GL019823, 2004

Origins of positive cloud-to-ground lightning flashes in the stratiform region of a mesoscale convective system

Timothy J. Lang, Steven A. Rutledge, and Kyle C. Wiens
Colorado State University, Fort Collins, Colorado, USA

Received 25 February 2004; revised 26 April 2004; accepted 28 April 2004; published XX Month 2004.

[1] 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. Platforms include radars, NLDN data, and a VHF 3-D lightning mapping system. This study examines a small asymmetric MCS that occurred near the Colorado-Kansas border in June 2000. In this storm 39 of the 269 +CGs produced over a nearly 5-hour period came to ground within the stratiform region. Of these, 30 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. *INDEX TERMS:* 3304 Meteorology and Atmospheric Dynamics: Atmospheric electricity; 3324 Meteorology and Atmospheric Dynamics: Lightning; 3329 Meteorology and Atmospheric Dynamics: Mesoscale meteorology. **Citation:** Lang, T. J., S. A. Rutledge, and K. C. Wiens (2004), Origins of positive cloud-to-ground lightning flashes in the stratiform region of a mesoscale convective system, *Geophys. Res. Lett.*, *31*, LXXXXX, doi:10.1029/2004GL019823.

1. Introduction

[2] 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 origin of this bipolar structure.

[3] Electric fields and inferred charge densities in stratiform regions of MCSs are comparable to those observed in convection, and stratiform charge layers are vertically thin but horizontally extensive [e.g., *Stolzenburg et al.*, 1994]. There are typically 4–5 vertically stacked charge layers of alternating polarity in MCS stratiform regions, with a positive charge often located in the 0 to −10°C altitude range, and another positive charge layer located 3–4 km higher [*Marshall and Rust*, 1993; *Stolzenburg et al.*, 1994]. Lightning in the stratiform region likely follows horizontally extensive paths consistent with horizontally extensive charge layers [*Mazur and Rust*, 1983].

[4] However, the exact role stratiform charge plays in stratiform lightning is unclear. Specifically, we do not know whether stratiform +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.

[5] In this study we will show that, for a relatively small asymmetric LLTS MCS observed during the Severe Thunderstorm Electrification and Precipitation Study [STEPS; *Lang et al.*, 2004], 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. This study is not a detailed examination of MCS electrification, but simply addresses the long-standing question of stratiform +CG origins.

2. Data and Methodology

[6] The STEPS project, whose focus was not MCSs, took place along the Colorado-Kansas border in the summer of 2000, and made use of three S-band radars - the Colorado State University CSU-CHILL and NCAR S-Pol 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 in range of all three.

[7] 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.

[8] The New Mexico Tech Lightning Mapping Array (LMA) was the final component of this study. 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]. Negative breakdown often occurs as a flash travels through net positive charge; recent research indicates that this is usually true when the negative breakdown develops an extensive horizontal

branch [*Coleman et al.*, 2003]. 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.

[9] We used the xlma analysis software developed at New Mexico Tech to manually isolate all the VHF sources (typically 100s–1000s of sources per flash) associated with each +CG flash detected by the NLDN. This software displays VHF sources in both time and space. By iteratively constraining the temporal and spatial windows of displayed data, all the VHF sources associated with an individual flash can be isolated. As long as multiple flashes are not occurring within ~1 second in close proximity (within ~10 km) - not an issue with this storm - then manually isolating flashes yields unambiguous results. Stratiform +CGs were especially easy to pick out as they often propagated through electrically quiet areas.

[10] CGs were associated with the LMA flash most closely collocated and coincident with the NLDN-detected ground strike location. All stratiform +CGs during the study period struck within 130 km of the LMA network centroid (mean ground strike distance was 62.9 km), well within the ideal range for studying the 3-D structure of these discharges [*Lyons et al.*, 2003]. The vertical horizon for the LMA was under 2 km AGL within 100 km of the centroid, so often the LMA observed VHF sources almost to ground, and sometimes even resolved parts of the ground channels immediately above the NLDN strike. Thus, associating a CG strike location with the proper LMA-mapped flash was straightforward.

[11] Overlays of these lightning maps onto cross-sections of radar data from all available radars allowed determination 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 became ambiguous. Thus, we also examined the vertical structure of the radar echoes, since by definition stratiform echo lacks the vertical development of convection.

[12] 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, given the long-known relationship between convection and lightning [e.g., *Workman and Reynolds*, 1949]. For example, if a +CG both originated and came to ground rearward of electrically active cells in the convective line, it was determined to be a +CG that originated wholly within the stratiform region, provided the radar echo also was consistent with stratiform precipitation. There is a possibility of small-scale weak/decaying convection, which might meet our criteria for stratiform, playing a role in the initiation of some of these latter flashes. However, given the location of the initiation points well rearward of the main convective line, it is more consistent to consider them as stratiform initiated.

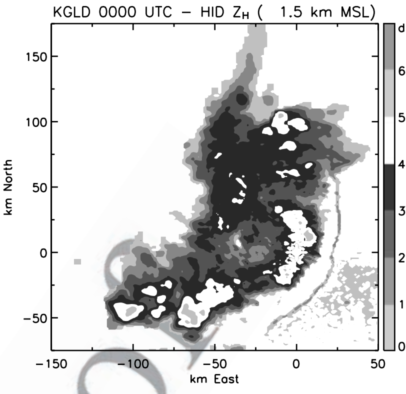

Figure 1. Horizontal cross-section at 1.5 km MSL of reflectivity factor from the KGLD radar at 0000 UTC on 12 June. Note the northward bias for stratiform precipitation, while along the convective line the southern portion was strongest at this time, with weaker northern convection.

[13] 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

[14] 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, Figure 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).

[15] Based on our classification work, the vast majority of +CGs in this storm originated and came to ground within the convective line. Only 39 came to ground in the stratiform region. Of these, 30 originated within the convective line (“stratiform from convective” or SfC), and the other 9 originated within the stratiform region (*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 km^2 in area and having peak radar echoes exceeding 40 dBZ (e.g., Figure 1).

[16] It is important to distinguish between a CG lightning flash and a return stroke, which is part of the overall flash. Each CG location refers to the ground strike location of an individual return stroke. Sometimes all of the return strokes of a parent flash contact the ground at the same point, but a flash can have different return strokes contacting the ground at different locations. The latter will be detected as separate CG strikes by the NLDN.

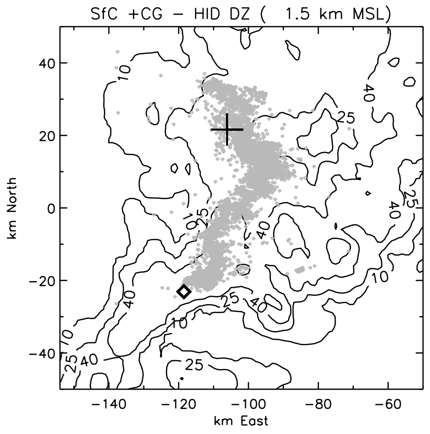

Figure 2. Horizontal cross-section at 1.5 km MSL of reflectivity factor from the KGLD radar (line contours, every 15 dBZ starting at 10), along with NLDN-detected +CG strike locations (+ signs), VHF source locations projected onto the horizontal plane (small gray diamonds), and intitial VHF source location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

[17] Figures 2 and 3 show examples of SfC (2) and ISS (3) +CG flashes. As suggested by Figure 3, many stratiform +CGs originated from the same LMA-mapped parent flash. In fact, 6 LMA-mapped flashes accounted for 14 of the 30 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. These results demonstrate that many NLDN-detected CGs in this storm were separate ground strokes associated with the same parent flash. Despite this, we consider these CGs separately for statistical purposes, to be consistent with past CG studies.

[18] Median peak current for stratiform +CGs was 36.8 kA, about 17% 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 39 stratiform +CG flashes were calculated. This distribution of altitudes had a mean of 6.2 km (approximately –10°C) 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.) This is approximately 5.1 km AGL relative to KGLD, 1 km higher than the mean altitude associated with the sprite-producing +CGs studied by *Lyons et al.* [2003], but still within their range of variability. It is not known whether any 11 June MCS +CGs produced sprites; much of the storm's lifetime was during daylight hours.

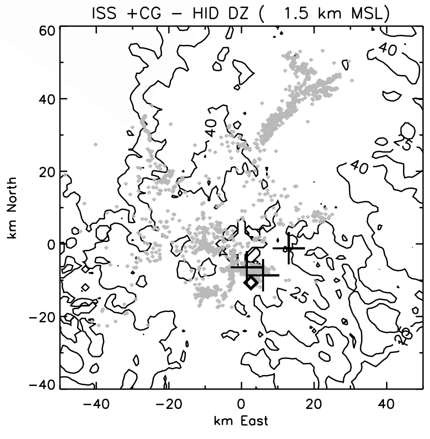

Figure 3. Same as Figure 2 but for an ISS +CG flash starting at 01:01:57 UTC; radar data from 0101 UTC.

[19] 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 6.3 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.

[20] To examine the vertical structure of individual stratiform +CGs in more detail, Figure 4 shows an average vertical distribution of 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. Examination of individual SfC +CG behavior often indicated a variable degree of downward sloping in VHF source altitudes immediately rearward of the convective line. This sloping was not always present, however, and flashes tended to propagate with a near-constant altitude within the stratiform region proper.

[21] Horizontal extent of stratiform +CGs was estimated by determining the rectangle that encompassed all VHF

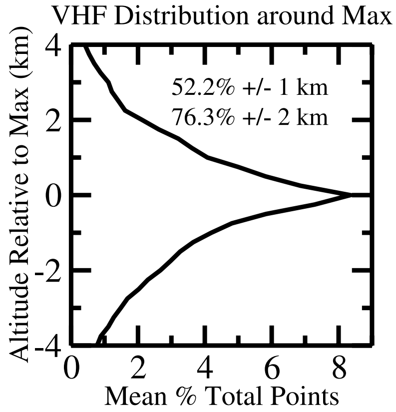

Figure 4. Mean distribution of VHF sources around the altitude of the maximum number of sources for parent flashes of stratiform +CGs. Annotation indicates mean percentage of all VHF sources within ±1 and ±2 km of this altitude.

sources asssociated with a parent flash, and then calculating the length of the rectangle's diagonal. For all stratiform +CG parent flashes, the mean length was 112.3 km with a standard deviation of 34.3 km. Vertically thin, horizontally extensive lightning branches have been observed in New Mexico thunderstorms by *Coleman et al.* [2003]; they attributed the thin vertical depth to lightning traveling in an electric potential well associated with a thin horizontal layer of charge. 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].

[22] Positive 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. 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.

4. Discussion and Conclusions

[23] In this storm the convective line played the dominant role in initiating stratiform +CGs (30 of 39 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 followed pathways indicative of vertically thin but horizontally extensive charge layers.

[24] The results of this study help to address the long-standing 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. More case studies of stratiform +CGs in other MCSs are needed to establish the generality of this study's results. Also, a more detailed study of the kinematic, microphysical, and electrical evolution of this MCS is planned.

[25] **Acknowledgments.** KGLD and S-Pol radar data were obtained from NCAR. We thank the staffs of these facilities, as well as the staff of the CSU-CHILL radar, for data collection and distribution. We thank Paul Krehbiel, William Rison, Ron Thomas, Tim Hamlin, and Jeremiah Harlin of New Mexico Tech for the LMA data and software. NLDN data were provided by Vaisala. This research was supported by NSF through grant ATM-030930.

References

Coleman, L. M., T. C. Marshall, M. Stolzenburg, T. Hamlin, P. R. Krehbiel, W. Rison, and R. J. Thomas (2003), Effects of charge and electrostatic potential on lightning propagation, *J. Geophys. Res.*, *108*(D9), 4298, doi:10.1029/2002JD002718.

Cummins, K. L., M. J. Murphy, E. A. Bardo, W. L. Hiscox, R. B. Pyle, and A. E. Pifer (1998), A combined TOA/MDF technology upgrade of the U.S. National Lightning Detection Network, *J. Geophys. Res.*, *103*(D8), 9035–9044.

Lang, T. J., et al. (2004), The Severe Thunderstorm Electrification and Precipitation Study (STEPS), *Bull. Amer. Meteorol. Soc*, in press.

Lyons, W. A., T. E. Nelson, E. R. Williams, S. A. Cummer, and M. A. Stanley (2003), Characteristics of sprite-producing positive cloud-to-ground lightning during the 19 July 2000 STEPS mesoscale convective systems, *Mon. Wea. Rev.*, *131*, 2417–2427.

Mazur, V., and W. D. Rust (1983), Lightning propagation and flash density in squall lines as determined with radars, *J. Geophys. Res.*, *88*, 1495–1502.

Proctor, D. E. (1971), A hyperbolic system for obtaining VHF radio pictures of Lightning, *J. Geophys. Res.*, *76*, 1478–1489.

Rutledge, S. A., and D. R. MacGorman (1988), Cloud-to-ground lightning activity in the 10–11 June 1985 mesoscale convective system observed during the Oklahoma-Kansas PRE-STORM project, *Mon. Wea. Rev.*, *116*, 1393–1407.

Shafer, M. A., D. R. MacGorman, and F. H. Carr (2000), Cloud-to-ground lightning throughout the lifetime of a severe storm system in Oklahoma, *Mon. Wea. Rev.*, *128*, 1798–1816.

Steiner, M., R. A. Houze Jr., and S. E. Yuter (1995), Climatological characterization of three-dimensional storm structure from operational radar and rain gauge data, *J. Appl. Meteorol.*, *34*, 1978–2007.

Stolzenburg, M., T. C. Marshall, W. D. Rust, and B. F. Smull (1994), Horizontal distribution of electrical and meteorological conditions across the stratiform region of a mesoscale convective system, *Mon. Wea. Rev.*, *122*, 1777–1797.

Workman, E. J., and S. E. Reynolds (1949), Electrical activity as related to thunderstorm cell growth, *Bull. Amer. Meteorol. Soc.*, *30*, 142–144.

T. J. Lang, S. A. Rutledge, and K. C. Wiens, Department of Atmospheric Science Colorado State University, Fort Collins, CO 80523, USA. (tlang@atmos.colostate.edu)