P2.17 CLOUD-TO-GROUND LIGHTNING BEHAVIOR OF CONVECTIVE CELLS OBSERVED DURING STEPS

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1. INTRODUCTION

Several studies have clearly illustrated that a climatological regional maximum in the percent occurrence of positive cloud-to-ground (CG) lightning activity relative to total CG lightning activity exists in the U.S. High Plains (Orville and Huffines 2001, Zajac and Rutledge 2001, Carey et al. 2003). These studies have shown that the highest fractions of positive CG activity lie roughly in a corridor that extends from eastern Colorado and western Kansas northeast into Minnesota. Branick and Doswell (1992) and MacGorman and Burgess (1994) noted that on a given day the geographic region in which positive CG lightning dominated tended to be distinct from that where negative CG lightning was dominant. This observation led to suggestions that the dominant CG polarity may be controlled, in part, by some set of environmental variables characteristic of that region.

Recent studies have provided evidence that the thermodynamic environment may indeed have some influence on the polarity of CG lightning (Smith et al. 2000, Lake and MacGorman 2002, Carey et al. 2003, Williams et al. 2004, Carey and Buffalo 2004,2005). Smith et al. (2000) showed a striking relationship between CG polarity and surface equivalent potential temperature (θ_e) for storms that occurred during three severe weather outbreaks. Particularly, they found that predominantly positive CG (PPCG) storms tended to occur upstream of a θ_e ridge in a region of high θ_e gradients while negative-dominated storms were observed downstream of the ridge (and in a weak θ_e gradient). They also noted that storms that crossed the θ_e ridge reversed dominant polarity from positive to negative and that a high percentage of initially positive and reversal storms were severe. These results suggest that CG behavior and polarity might be useful as a severe weather nowcasting tool. Lake and MacGorman (2002) extended the Smith et al. (2000) study to include more storms (however, they narrowed their sample to severe storms only) and found similar results, though they observed 66% of initially negative storms upstream of the θ_e ridge. Williams et al. (2004) argued that a combination of higher instability (for which θ_e may serve as a proxy) and higher cloud base heights results in the right conditions for predominantly positive CG lightning.

The Severe Thunderstorm Electrification and Precipitation Study (STEPS; Lang et al. 2004a) was established to document storms in eastern Colorado and western Kansas, particularly those which exhibited PPCG lightning. Observations were conducted between 17 May 2000 and 20 July 2000. From this dataset, several cases exhibited PPCG lightning behavior and studies analyzing them on a storm-by-storm basis have begun to emerge (Kuhlman et al. 2004, Lang et al. 2004b, MacGorman et al. 2004, Tessendorf et al. 2004a,b, Weiss et al. 2004, Wiens et al. 2004). However, an overview of the CG behavior of all the cells observed during this experiment has not yet been compiled and a corresponding analysis of the environmental conditions for all cells has not been done. The goal of the present study is to present an overview of the CG behavior and severe weather production of cells that occurred during STEPS. In addition, this study provides a preliminary analysis of the relationship between surface θ_e, cloud base height, and CG polarity for cells during STEPS.

2. DATA AND METHODS

Isolated storms, multicell storms, and supercell storms were selected for this study based on results in Lang et al. (2004a, their Table 2). From those storm days, nine days were selected based on case overviews on the CSU-CHILL website[1]. The case overviews gave a preliminary glimpse at the nature of the convection on each day to help us determine if manual cell tracking would be feasible. Exceptions to this selection process include 10 July and 22 June. The 10 July case was listed as a multicell storm and had a case overview posted on the CSU-CHILL website, but convection was so numerous across the domain that it made manual cell tracking very difficult. In place of this day, 22 June was selected, even though the day was dominated by a convective line (as listed in the overview table

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[1] http://chill.colostate.edu/STEPS/index.html

Table 1. Overview of the nine days selected for analysis from STEPS 2000. The total number of cells, and the numbers of severe cells, PPCG cells, PNCG cells, and reversal cells are listed for each day. The percentages of cells for each category out of the total sample are in parentheses.

Day (MMDD)	# tracked cells	# severe cells	# >50% +CG cells	# > 50% -CG cells	# reversal cells
0531	3	1	1	2	1
0603	2	1	0	1	0
0606	3	0	1	1	1
0619	5	1	0	4	3
0622	4	4	4	0	3
0623	11	2	4	7	4
0624	11	2	3	4	3
0629	5	2	2	3	2
0705	3	1	2	0	3
Total	**47**	**14 (30%)**	**17 (36%)**	**22 (47%)**	**20 (43%)**

in Lang et al. 2004a). The nine selected days are listed in Table 1.

NEXRAD radar reflectivity composites (2 km by 2 km resolution) were used to examine the basic cell structure and distinguish and track each cell's location in 15-minute intervals. This was done manually by assigning latitude and longitude boundaries that enclosed the majority of the cell's base reflectivity structure at every 15-min interval that the cell was detected. National Lightning Detection Network (NLDN; Cummins et al. 1998) data was used to locate the ground strike location and polarity of CG lightning for each cell. Positive CG flashes with peak currents <10 kA were not included in this study as recommended by Cummins et al. (1998). CG flashes were summed for each cell within the prescribed latitude/longitude boundaries during each 15-min interval. Severe weather reports were obtained from the National Climatic Data Center online Storm Events Database[2]. A severe storm was defined using the basic three National Weather Service criteria for a severe storm[3]: i) a tornado, ii) wind greater than 50 kts, iii) hail greater than .75 inches. A cell was classified as severe if at least one severe weather report occurred within one of its 15-min intervals (and corresponding prescribed latitude/longitude boundaries).

General statistics on cell CG behavior were then calculated using the dominant polarity of CG lightning with each 15-min interval. An initially positive (negative) storm was defined as a cell which had a positive (negative) CG to total CG ratio of >50% during the first 15-min interval that CG lightning was detected. A reversal storm was defined as a cell that demonstrated a change in 15-min dominant polarity at any point throughout its lifetime (even if the change was only for one 15-min interval). A storm was defined as an overall PPCG (PNCG) storm if its overall positive (negative) CG to total CG lightning ratio (during the entire period the storm was observed) was >50%. The “other” category was reserved for storms with no CG lightning or a 50/50 split in the percent of positive (negative) CG to total CG lightning. Of the two storms with an exact 50/50 split, the number of total CG flashes was small (one had 4 total CGs and the other 2).

Rapid Update Cycle (RUC) isobaric main analysis data were retrieved from the Atmospheric Radiation Measurement Program archive website[4] and were used to obtain environmental variables (such as surface θ_e, temperature, and dew point). These data have a horizontal spatial resolution of 40 km. Cloud base height (CBH) was calculated using the surface dew point depression method outlined in Williams et al. (2004). Data at 2100 UTC on each of the selected days were used for this analysis, though we did experiment with using 0000 UTC data and even with updating the data each hour when a new RUC file was available (to eliminate the steady-state assumption in using data at one constant time). It became clear that the data time used to plot hours of NLDN data onto was somewhat arbitrary and for the purpose of this preliminary analysis we chose to follow the method of Smith et al. (2000), which used 2100 UTC θ_e data.

[2] http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwEvent~Storms

[3] http://www.spc.noaa.gov/misc/about.html

[4] http://www.archive.arm.gov

3. RESULTS

a. Overview and general statistics

On a large spatial scale, a tendency for positive CG lightning to occur in the same region on a day-by-day basis was observed (Fig. 1 shows an example from 29 June 2000). This is consistent with the general findings of MacGorman and Burgess (1994) and is a driving factor for studying regional environments to determine whether some particular set of environmental characteristics leads to positive CG lightning production. The positive CG region was typically centered in northeastern Colorado and northwestern Kansas (i.e. within the STEPS observational domain) or generally along the Colorado-Kansas border, consistent with climatologies of positive CG lightning (Orville and Huffines 2001, Zajac and Rutledge 2001, Carey et al. 2003). Negative CG lightning thus tended to dominate both west and east of the Colorado-Kansas border, except when the CG lightning was associated with a mesoscale convective system (MCS; these systems were not included in our study). CG lightning associated with MCSs tended to have a high incidence of both positive and negative CG lightning across the entire area that the MCS traversed.

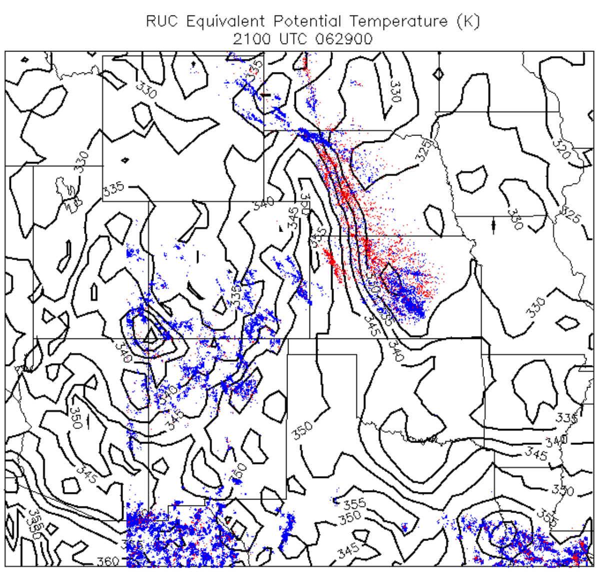

Figure 1. 2100 UTC RUC surface equivalent potential temperature (black contours) for 29 June 2000 with NLDN CG strike locations between 1800-0600 UTC overlaid (red = positive CG, blue = negative CG).

On the nine selected days, a total of 47 cells were identified and tracked. Thirty percent of all the cells were severe, with 26% associated with hail reports (Table 2). Only one tornado was reported out of all of these cases. The cells were classified into three categories (positive, negative and other) based on their dominant CG behavior over their entire lifetimes (Table 2). The percentage of PPCG storms that were severe was 53% compared to only 14% of PNCG storms. One quarter of the 'other' storms were severe. Of the PPCG storms, most (47%) were severe because they produced large hail. The cells were also classified as initially positive, initially negative, and reversal storms (see definition in section 2). Just over half (55%) of the storms exhibiting a 15-min dominant polarity reversal were severe (Table 2). Forty-two percent of the initially positive storms were severe, while only 28% of initially negative storms were, regardless of whether or not a polarity reversal occurred.

This study identified 20 reversal storms (as defined in section 2; see Table 2). Yet, the nature of the CG polarity reversal was not always consistent with that of Smith et al. (2000) who referred to reversal storms as those that were initially positive-dominant and switched to negative-dominant. In this study, we found reversal cases that were initially negative and then switched to be positive-dominated (65% of the reversals were of this nature), in addition to some (35%) that were initially positive and switched to negative-dominated. Furthermore, there were a few cases in which the 15-min dominant polarity reversed multiple times. However, in those cases, the dominant polarity reversed for only one 15-min interval and then switched back to its initial dominant polarity (Fig. 2), which casts doubt upon whether or not that storm was a 'true' reversal storm. Nonetheless, in order to remain objective we have included those cases as reversals.

Next, we focused on the subset of all the cells which were severe, in order to characterize the CG behavior of the severe storms from this dataset (see Table 3). As might be expected, a large percentage (64%) of the severe storms produced predominantly positive CG lightning overall. Further, 79% of the severe storms exhibited a 15-min dominant polarity reversal at some point in their lifetime. However, one statistic that stands out in Table 3 is that 57% of the severe storms were actually initially negative CG lightning producers in this dataset, even though only 28% of all initially negative storms were severe (Table 2). Thus, initially negative storms may not be a good indicator that a storm will become severe, yet severe storms from STEPS did exhibit negative CG lightning initially in many instances and then switched to positive-dominated CG lightning. On a related note, it was common that the initial negative CG dominance was only

Table 2. Percentages of each storm lightning type that was severe and more specifically, percentages of each lightning type that produced hail, wind, or was tornadic. Numbers in parentheses indicate the total number of cells in that category.

Storm lightning type		**% Severe**	**% Hail**	**% Wind**	**%Tornadic**
Positive (17)		53	47	18	6
Negative (22)		14	9	5	0
Other (8)		25	25	0	0
	Initially positive (12)	42	33	17	8
	Initially negative (29)	28	24	7	0
	Reversal (20)	55	45	20	5
Total (47)		**30 (14)**	**26 (12)**	**9 (4)**	**2 (1)**

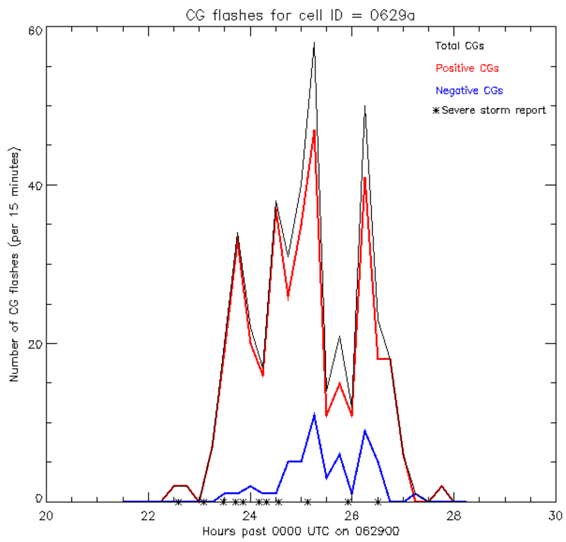

Figure 2. This CG lightning flash time series of cell ‘A’ from 29 June 2000 is an example of a storm classified as reversal though only one 15-min interval was reversed (near 27.5 hours) in dominant polarity, and the total number of CG flashes in that interval were minimal. Otherwise, this cell was clearly dominated by positive CG lightning its entire lifetime. See also Fig. 6.

during the first 15-min interval, and then the storms switched to be positive-dominated storms for the remainder of their lifetime. Additionally, the number of CGs in the first 15-min interval for these cells was typically very low. An example case is on 22 June (Fig. 3). There were four cells (all severe and PPCG overall) identified on this day, three of which were initially negative storms. Cells ‘B’ and ‘D’ exhibited negative CG dominance only in their first 15-min period and a low number of total CG flashes in that period (Fig. 4 illustrates this for cell ‘D’ and also shows that severe weather was not reported with this storm until after the reversal occurred). Cell ‘C’, on the other hand, did exhibit higher numbers of negative CG flashes initially and was negative-dominated for longer than just the first 15 minutes (Fig. 5). However, severe weather reports occurred prior to the reversal to positive-dominated CG lightning for this cell.

b. Relationships to environmental variables

The relationship between dominant CG polarity and surface θ_e was not as well defined in these cases as it was in Smith et al. (2000) and Lake and MacGorman (2002). However, a general trend of positive lightning occurring in regions of higher θ_e was observed (see example in Figs. 1 and 6). Yet, one inconsistency with Smith et al. (2000) was that we observed negative-dominated storms upstream of the θ_e ridge as well as downstream (Fig. 6). Lake and MacGorman (2002) also observed this inconsistency. Additionally, the polarity reversals we detected did not appear to occur as a storm crossed the θ_e ridge. Rather, we detected reversals in areas of both strong and weak θ_e gradient, in addition to upstream, downstream and north of θ_e ridges (see Figs. 3, 6, 7).

Table 3. Percentages of the 14 severe storms that fell into each storm lightning type category. Numbers in the parentheses indicate the total number of cells in that category.

Storm lightning type		**% of severe storms**
Positive (9)		64
Negative (3)		21
Other (2)		14
	Initially positive (5)	36
	Initially negative (8)	57
	Reversal (11)	79

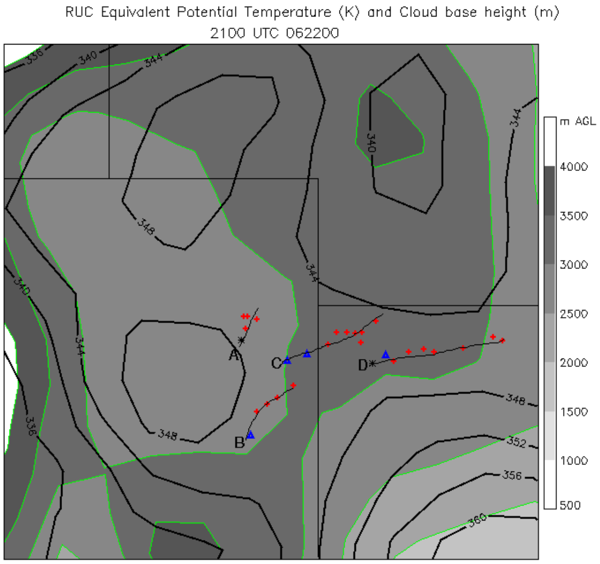

Figure 3. The dominant polarity of CG lightning along storm tracks for 22 June 2000 plotted at every 15-min interval of the storm's life. Positive lightning dominance is denoted by a red '+' sign, negative CG dominance by a blue triangle, and no CG lightning in the 15-min interval by a black asterisk. Black contours represent the 2100 UTC RUC surface equivalent potential temperature. Grayscale (with green outlining contours) are 2100 UTC calculated cloud base heights (meters AGL). The northernmost end of the θ_e ridge on this day can be seen in the lower right portion of the figure, thus the reversals depicted here are occurring north of the ridge and in a region of weak θ_e gradient.

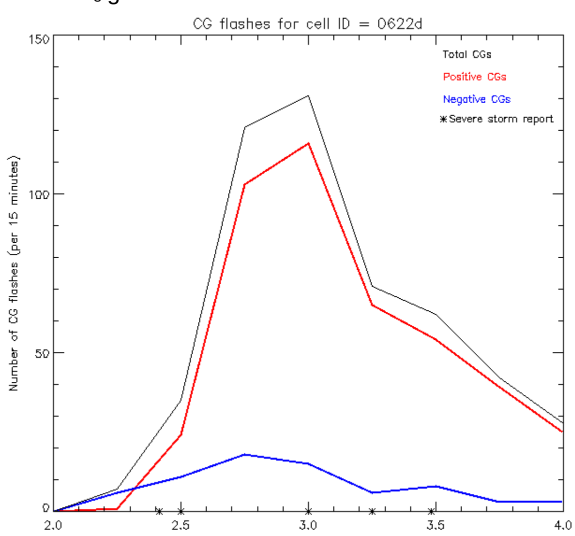

Figure 4. Time series of the number of total CG flashes (black), positive CG flashes (red), and negative CG flashes (blue) in 15-min intervals for the duration of cell 'D' on 22 June 2000. Black asterisks indicate the time of a severe weather report.

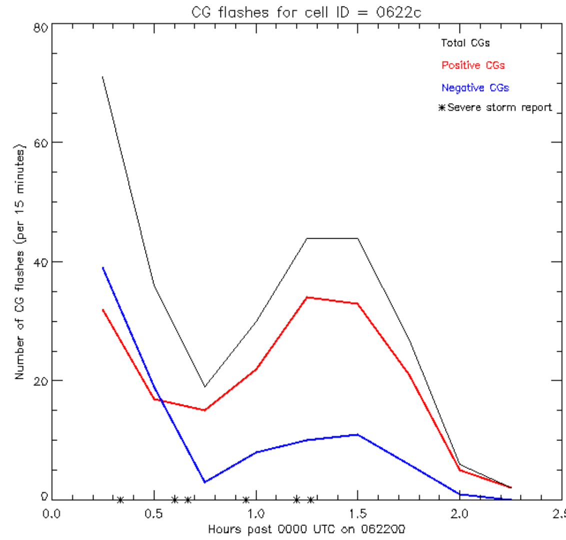

Figure 5. Same as Fig. 4 except for cell 'C' on 22 June 2000.

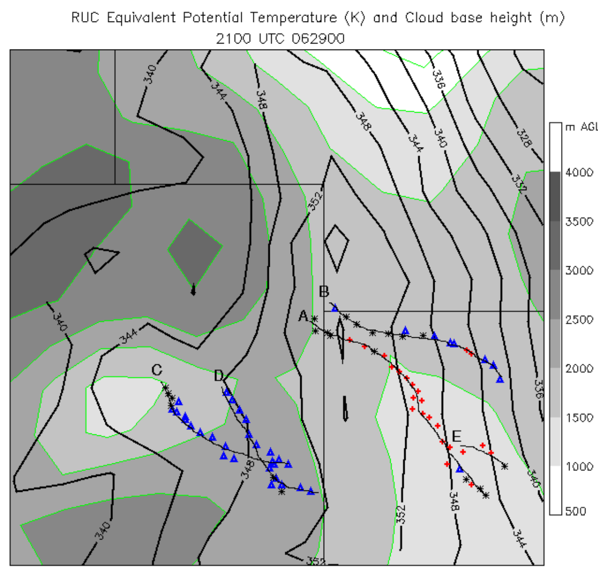

Figure 6. Same as Fig. 3 except for 29 June 2000. The reversals here are occurring downstream of the θ_e ridge axis, in a strong θ_e gradient, and negative dominated storms are occurring upstream of the ridge.

An analysis of cloud base height was included in this study based on the conclusions of Williams et al. (2004). They proposed that higher cloud base heights lead to larger updrafts that are less susceptible to entrainment, which leads to higher cloud liquid water contents (CLWC) in the mixed phase region. This could favor positive CG lightning since laboratory studies (Takahashi 1978, Saunders et al. 1991) have shown that positive charging of graupel/hail occurs when CLWC is sufficiently high. However, in these cases, CBH did not have a striking tendency to be higher when positive CG lightning dominated. Instead, it was often lower in the region where PPCG storms occurred (see Fig. 6). This may be due to the fact that CBH (calculated as it was for the Williams et al. 2004 paper) relies heavily on surface moisture and therefore may be related to surface θ_e. For the case of 29 June (Fig. 6), the positive CG lightning occurred just in and downstream of the highest surface θ_e, thus the surface moisture in this region was also probably higher (on the east side of the dry line) leading to the lower CBH relative to the surrounding area.

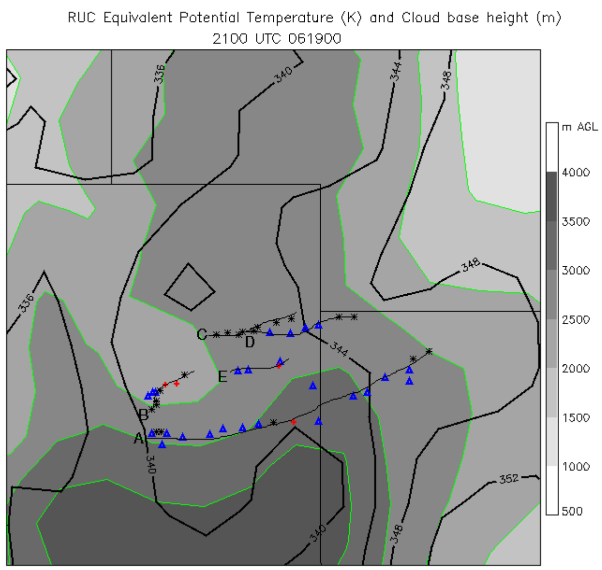

Figure 7. Same as Fig. 3 except for 19 June 2000. The storm tracks here are upstream of a weakly defined θ_e ridge in central Kansas, thus the reversals depicted are occurring upstream of that ridge in a region of weak θ_e gradient.

A specific example that warrants further study is the marked difference in CG behavior between cells ‘A’ and ‘B’ on 29 June. Though they occurred in similar θ_e and CBH conditions and at nearly the same time, they exhibited opposite CG polarity dominance (Fig. 6). This example illustrates that θ_e and CBH alone cannot distinguish PPCG from PNCG storms, and therefore more research on this subject is needed.

4. CONCLUDING REMARKS

This study documented the CG behavior of cells observed on nine days during the STEPS field campaign. Positive CG lightning tended to occur in the same region on a day-by-day basis, and to some extent corresponded to the areas of higher surface equivalent potential temperature. Just over half of the PPCG storms were severe (53%), whereas only 14% of the PNCG storms were severe, and most of the PPCG storms were severe because they produced hail. 55% of reversal storms were severe.

It is apparent that PPCG storms, and storms that exhibit a polarity reversal, have a greater tendency to be severe than PNCG storms in this region. Though the percentages of severe storm occurrence with these CG behaviors were not much greater than 50%, which could lead to a high false alarm rate, there still exists a potential for nowcasting severe weather using CG lightning polarity and patterns. What is needed is a greater understanding of the processes that result in CG lightning of either polarity and further studies of its relation to severe weather and environmental conditions.

The relationship between θ_e and CG polarity was not well defined for these STEPS cases. In general, positive CG lightning did occur in regions of higher θ_e, yet this relationship has not been quantified. PNCG storms were observed both upstream *and* downstream of the θ_e ridge, contrary to Smith et al. (2000) but in agreement with Lake and MacGorman (2002). A general relationship between PPCG storms and CBH was not evident in this study, but could be due to the method of calculating CBH, and/or lack of quantitative analysis.

There are some additional caveats of this study that we recognize may have influenced the results presented herein. First of all, using steady-state thermodynamic data to compare with the NLDN data, especially over a 12-hour period, may not be representative of the storm’s environment since it is probable that the thermodynamic environment changed over that time. Manually tracking each cell using rectangular latitude and longitude boundaries may not have always encompassed the entire cell (especially when a neighboring cell was close). We question whether or not some of the storms that were objectively classified as a reversal storm, which includes cells that only switched polarity briefly and at low flash counts, should truly be classified as such. Also, using a 15-min interval to determine dominant polarities rather than a shorter time interval might have smoothed the temporal polarity dominance trends. Finally, this study lacked quantitative measurements of the relationships between θ_e, CBH, and CG polarity. As we pursue this research in the future, we will attempt to reconcile these caveats.

This was a preliminary study and thus much more should be done to characterize the environments that distinguish PPCG from PNCG storms from the STEPS dataset. Our future work will continue this analysis for all STEPS days and investigate relationships with other environmental variables. Similar to the work of Carey and Buffalo (2004, 2005), we hope to quantify the relationships between CG polarity and environmental variables and will certainly explore those variables that were found to have high statistical significance in their work. In addition, we will perform in-depth case studies on these cells to study dynamical and microphysical controls on the resulting electrification.

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REFERENCES

Branick, M.L., and C.A. Doswell, 1992: An observation of the relationship between supercell structure and lightning ground-strike polarity. *Wea. Forecasting*, **7**, 143–149.

Carey, L.D., and K.M. Buffalo, 2004: Environmental control of cloud-to-ground lightning polarity in severe storms during IHOP. *Preprints*, 22nd Conference on Severe Local Storms, Hyannis, MA, CD-rom.

Carey, L.D., and K.M. Buffalo, 2005: Environmental control of cloud-to-ground lightning polarity in severe storms during IHOP. *Preprints*, this conference, paper 8.1.

Carey, L.D., S.A. Rutledge, and W.A. Petersen, 2003: The relationship between severe storm reports and cloud-to-ground lightning polarity in the contiguous United States from 1989 to 1998. *Mon. Wea. Rev.*, **131**, 1211–1228.

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.

Kuhlman, K.M., E. R. Mansell, C. Ziegler, D. MacGorman, and J. M. Straka, 2004: Numerical simulations of the 29 June STEPS supercell. *Preprints*, 22nd Conference on Severe Local Storms, Hyannis, MA, CD-rom.

Lake N.R., and D.R. MacGorman, 2002: A relationship between surface theta-e ridge and dominant lightning polarity. *Preprints*, 21st Conference on Severe Local Storms, San Antonio, TX, 431-434.

Lang, T.J., and co-authors, 2004a: The Severe Thunderstorm Electrification and Precipitation Study. *Bull. Amer. Meteor. Soc*., **85**, 1107–1125.

Lang, T.J., S.A. Rutledge, and K.C. Wiens, 2004b: Origins of positive cloud-to-ground lightning flashes in the stratiform region of a mesoscale convective system. *Geophys. Res. Lett*., **31**, DOI:10.1029/2004GL019823.

MacGorman, D.R., and D.W. Burgess, 1994: Positive Cloud-to-Ground Lightning in Tornadic Storms and Hailstorms. *Mon. Wea. Rev.,* **122**, 1671–1697.

MacGorman, D.R., W.D. Rust, P. Krehbiel, E. Bruning, and K. Wiens, 2004: The electrical structure of two supercell storms during STEPS. *Mon. Wea. Rev*., in review.

Orville, R.E., and G.R. Huffines, 2001: Cloud-to-ground lightning in the United States: NLDN results in the first decade, 1989–98. *Mon. Wea. Rev.,* **129**, 1179–1193.

Smith, S.B., J.G. LaDue, and D.R. MacGorman, 2000: The relationship between cloud-to-ground lightning polarity and surface equivalent potential temperature during three tornadic outbreaks. *Mon. Wea. Rev.,* **128**, 3320-3328.

Saunders, C. P. R., W. D. Keith, and R. P. Mitzeva, 1991: The effect of liquid water on thunderstorm charging. *J. Geophys. Res*.,

96, 11,007-11,017.

Takahashi, T., 1978: Riming electrification as a charge generation mechanism in thunderstorms. *J. Atmos. Sci.,* **35**, 1536-1548.

Tessendorf, S.A., L.J. Miller, K.C. Wiens, and S.A. Rutledge, 2004a: The 29 June 2000 supercell observed during STEPS. Part I: Kinematics and microphysics. *J. Atmos. Sci.,* in review.

Tessendorf, S.A., K.C. Wiens, and S.A. Rutledge, 2004b: Lightning and radar observations of two storms observed during STEPS. *Preprints*, 22nd Conference on Severe Local Storms, Hyannis, MA, CD-rom.

Weiss, S.A., W. D. Rust, D. MacGorman, E. Bruning, T. Schuur, P. Krehbiel, B. Rison, and T. Hamlin, 2004: Lightning, electric field, and radar observations of the STEPS 25 June 2000 storm. *Preprints*, 22nd Conference on Severe Local Storms, Hyannis, MA, CD-rom.

Wiens, K.C., S.A. Rutledge, and S.A Tessendorf, 2004: The 29 June 2000 supercell observed during STEPS. Part II: Lightning and charge structure. *J. Atmos. Sci.,* in review.

Williams, E.R., V. Mushtak, D. Rosenfeld, S. Goodman, and D. Boccippio, 2004: Thermodynamic conditions favorable to superlative thunderstorm updraft, mixed phase microphysics and lightning flash rate. *Atmos. Res*., in press.

Zajac, B.A., and S.A. Rutledge, 2001: Cloud-to-ground lightning activity in the contiguous United States from 1995 to 1999. *Mon. Wea. Rev.*, **129**, 999–1019.