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Environmental Conditions Producing Thunderstorms with Anomalous Vertical Polarity of Charge Structure

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***Abstract*—+CG flashes typically comprise an unusually large fraction of CG activity in thunderstorms with anomalous vertical charge structure. We analyzed more than a decade of NLDN data on a 15 km x 15 km x 15 min grid spanning the contiguous United States, to identify storm cells in which +CG flashes constituted a large fraction of CG activity, as a proxy for thunderstorms with anomalous vertical charge structure, and storm cells with very low percentages of +CG lightning, as a proxy for thunderstorms with normal-polarity distributions. In each of seven regions, we used North American Regional Reanalysis data to compare the environments of anomalous storms with those of normal-polarity storms. Our hypothesis was that environments producing mixed-phase regions with high liquid water contents would be conducive to anomalous thunderstorm charge distributions. Environments were consistent with this hypothesis, although different combinations of environmental parameters were responsible in different regions.**

***Keywords*—lightning, +CG, storm charge distribution**

I. INTRODUCTION

Electric field soundings and Lightning Mapping Arrays have confirmed the existence of thunderstorms having a vertical charge distribution whose polarity is inverted from the usual polarity (e.g., Rust and MacGorman 2002, Rust et al. 2005, MacGorman et al. 2005, Weins et al. 2005). This anomalous charge structure can be described grossly as a large upper-level negative charge, which lies above a large midlevel positive charge, and is often accompanied by a smaller negative charge at low levels. Cloud-to-ground (CG) flashes lowering positive charge to ground (+CG flashes) instead of the usual negative charge (-CG flashes) make up an unusually large fraction of CG activity in these anomalous storms (e.g., Tessendorf et al. 2007, Weiss et al. 2008, Fleenor et al. 2009, Emersic et al. 2011; DiGangi et al. 2016). Furthermore, previous studies have suggested that CG activity tends to be delayed tens of minutes longer in these anomalous storms than in most storms elsewhere (MacGorman et al. 2011).

For this study, we analyzed more than a decade of CG data from the National Lightning Detection Network throughout the contiguous United States to identify storm cells in which +CG flashes constituted a large fraction of CG activity, as a proxy for storms with anomalous vertical charge structure. Similarly, we identified storm cells characterized by very low percentages of +CG lightning, as a proxy for normal-polarity thunderstorms. Our goal was to compare the environments of these two categories of storms to try to identify environmental conditions conducive to storms with anomalous-polarity charge distributions in each of seven regions spanning the country.

Our hypothesis, as in many previous studies (e.g., Williams et al. 2005; MacGorman et al. 2005, 2012, 2017; Carry and Buffalo 2007; Lang and Rutledge 2011; Emersic et al. 2011; Calhoun et al. 2012, 2014; Bruning et al. 2012; Fuchs et al. 2015), is that the environmental conditions conducive to the formation of anomalous-polarity thunderstorms are those favoring positive charging of graupel during rebounding collisions with small ice particles in the mixed-phase region. Laboratory experiments (e.g., Takahashi and Miyawaki 2002; Emersic and Saunders 2010) indicate that, in mixed-phase regions with unusually large liquid water contents, graupel tends to gain positive charge during rebounding collisions, regardless of temperature. Therefore, most of the environmental parameters we analyzed are those thought to influence liquid water content in the mixed-phase region of the storm.

II. DATA SOURCES AND METHOD

This study analyzed CG data from Vaisala's National Lightning Detection Network from 2004 through 2014 within the region shown in Fig. 1. Because in anomalously polarized storms the NLDN often incorrectly classifies intracloud flashes as –CG flashes having small peak currents, we applied the same 15 kA peak current threshold to both +CG and –CG flashes detected by the NLDN, to minimize contamination of CG flashes by incorrectly identified intracloud flashes in our data set. +CG and –CG flashes having peak currents above this threshold were tabulated in a moving average of 15 km x 15 km x 15 min grid cells, stepped forward every 5 km and 5 min, to approximate storm cells.

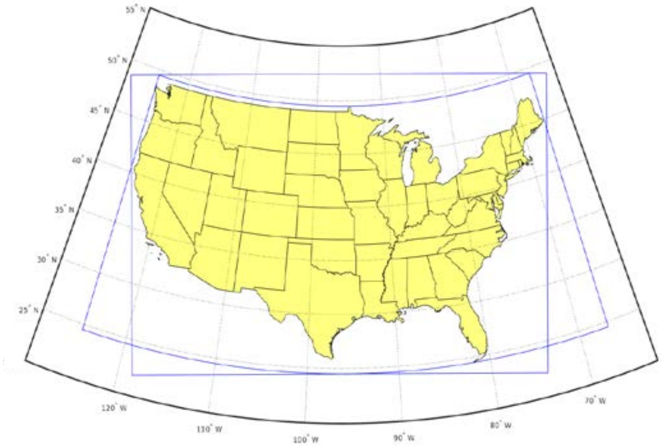

Figure 1. The analysis domain was the intersection of the two domains bounded by blue lines.

The goal of our study was to focus on deep convective storm cells having anomalous vertical polarity. The meteorology of the situation in which +CG flashes dominate CG activity in the stratiform precipitation region behind the deep convective region of a mesoscale convective system (MCS), such as a squall lines, is completely different and would contaminate our results if such cases were included. Because upscale growth from isolated convection to MCSs typically requires several hours, MCSs typically begin near or after midnight and continue through early morning hours. Thus, we restricted our analysis to storms that were more likely to have responded to solar heating, and so considered only storms that occurred between 1500 and 2300 local time during the warm season. Furthermore, we required at least 10 +CG flashes in a 15 km X 15 km X 15 min grid cell, because +CG flashes in stratiform regions typically are less frequent and are less dense. Although this likely did not completely eliminate MCS contamination, the contamination is expected to be minimal.

Estimates of the environment of cells for this study were obtained from North American Regional Reanalysis (NARR) environmental data, which are available on a 30 km grid every 3 hours. Environmental properties were interpolated from the NARR grid and times to the storm cell grid and time. For environmental analyses, we divided CONUS into seven regions, shown in Fig. 2, to examine the properties conducive to anomalous charge structure in each region. The following were the environmental parameters that were included: surface to equilibrium level Convective Available Potential Energy (CAPE) and NCAPE (NCAPE is CAPE in some layer divided by the depth of the layer), surface to -20°C CAPE and NCAPE, 0°C to -20°C CAPE and NCAPE, CIN, cloud base height, warm cloud depth, upper-level storm-relative wind speed, dew point depression, 0-3 km storm-relative helicity, equivalent potential temperature, precipitable water, and 0-3 km and 0-6 km vertical shear in the horizontal wind.

We used two statistical techniques to estimate relationships with various environmental properties. The simplest was a violin plot, which is similar to a box and whiskers plot, but differs in that its width for a given value of the environmental property is scaled by the number of cases at that level, as well as showing percentiles. To estimate confidence levels for the mean value of various environmental properties, we used a sample permutation test, as shown in Fig. 3: For this test, we determined the mean value of a given property for all +CG cases in a given region and compared that mean with the mean of data sets randomly selected from a data set that combined +CG and –CG cases. The combined data set from which a random sample was selected contained all of the +CG cases (a total number of N cases) and N cases randomly selected from the –CG cases. The distribution of mean values against which the +CG mean was compared were the means of the parameter for N cases selected randomly 10,000 times from the combined data set.

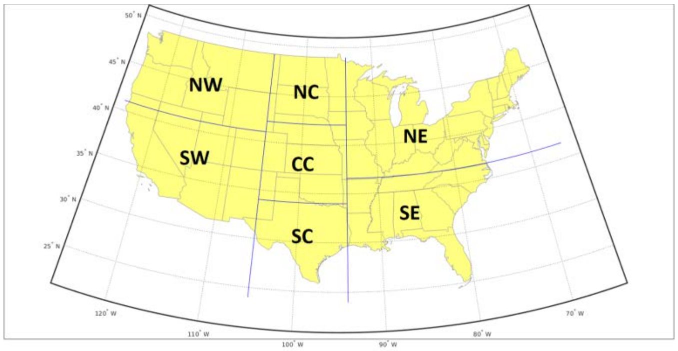

Figure 2. Analysis regions for evaluating environmental parameters affecting +CG production.

III. ANALYSIS RESULTS

Figure 4 shows an example of one of the violin plots, the one for cloud base height. One frequently mentioned hypothesis for anomalous charge structure is that storms having a higher cloud base will have a shallower depth below the freezing level for warm cloud processes, and so will have less depletion of cloud liquid water below the mixed phase region. Cloud base heights in the south-central and central-central region do tend to be somewhat higher for +CG dominated storms than for –CG dominated storms. However, there is little, if any, discernable difference in cloud base heights between normal and anomalous polarity storms in the north-central region, or in the southeast or northeast, and the relationship is actually reversed from the hypothesized relationship in the southwest region.

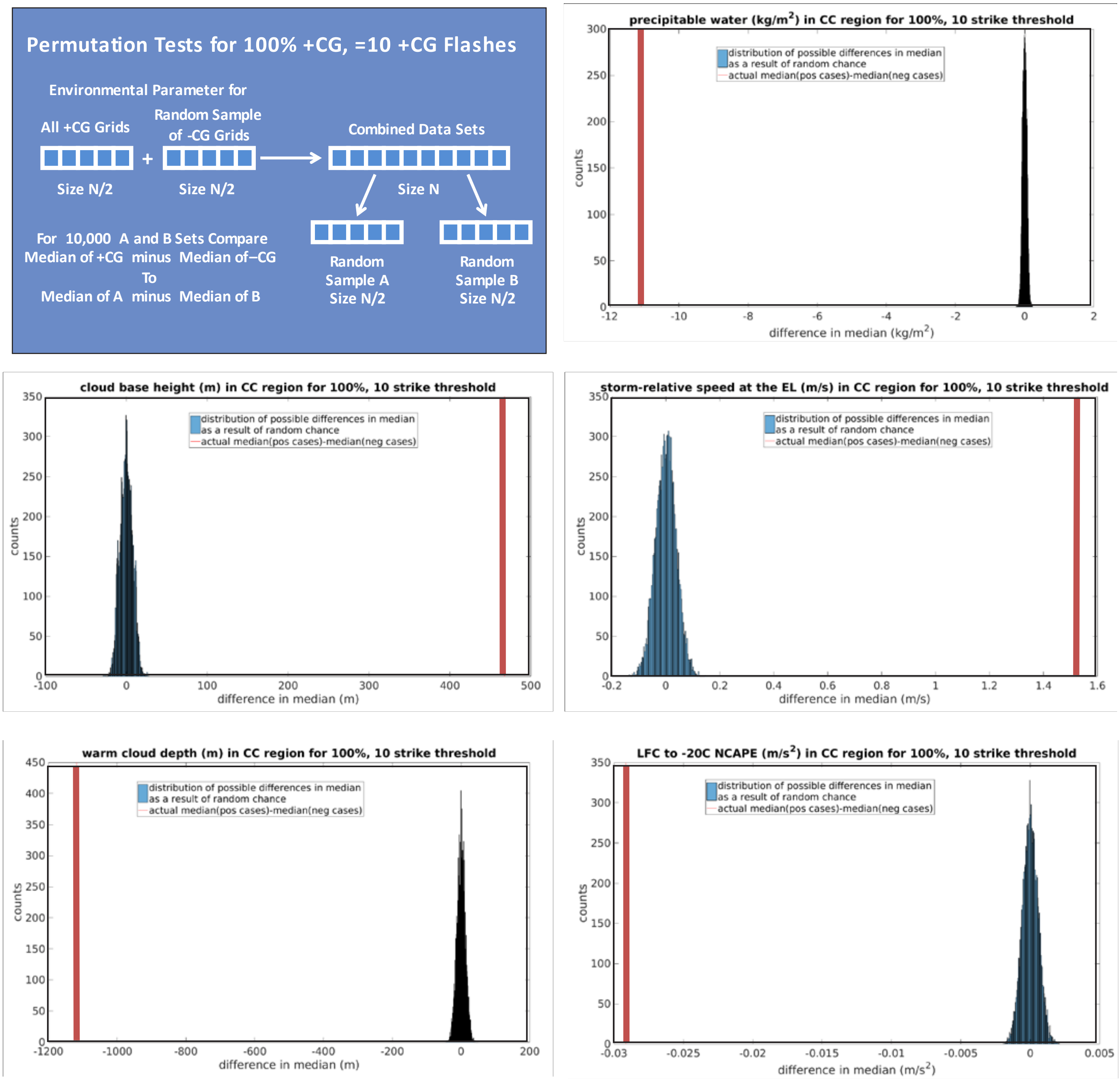

Figure 3. Permutation test for environmental parameters. Red line indicates the displacement of the median of the parameter for +CG dominated storm cells from the distribution of the displacement of medians for 10,000 trials. Each trial evaluated a collection of cells selected randomly from an ensemble composed of equal numbers of +CG dominated and –CG dominated storm cells.

Figure 3 shows the permutation plots for five environmental parameters in the central-central region that includes eastern Colorado and western Kansas. Compared with the mean values for randomly selected storms, +CG dominated storms had less precipitable water, larger upper-level storm-relative wind speeds, higher cloud base, shallower warm cloud layers, and less NCAPE between the level of free convection and -20°C. However, these tendencies are sometimes reversed in other regions; no trend combination is valid in all regions.

To illustrate the differences in tendencies from one region to another, consider the percent differences in the means for seven parameters in four of the regions (Table 1). As found in previous studies, +CG dominated storms in the central-central region do tend to have higher cloud base heights and shallower warm cloud depth. However, these environmental parameters were almost equal for +CG and –CG dominated storms in the north-central region; +CG dominated storms there tended to have more instability below -20°C. In the southwest region, +CG dominated storms actually tended to have lower cloud base heights and deeper warm cloud depths, but tended to have much greater instability below -20°C. +CG dominated storms in the southeast region tended to have lower cloud base heights and less instability below -20°C than –CG dominated storms, but had much greater 0-6 km shear (which is related to the potential for supercell storms) and the largest upper level storm-relative wind speeds (which affects how much precipitation is recycled into the updraft to collect cloud liquid). These last two parameters were the only two shown here that were consistently favorable for +CG dominated storms in all four regions.

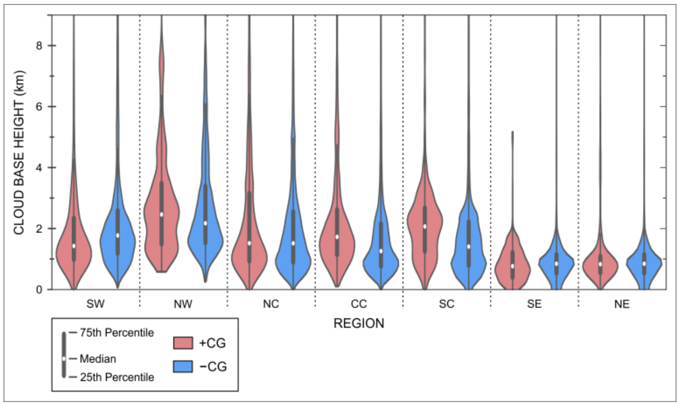

Figure 4. Violin plots for +CG dominated cells and –CG dominated cells in each of the seven regions shown in Fig. 2

IV. PRELIMINARY CONCLUSIONS

The following parameters appeared to be important for +CG domination in one or more regions:

- Higher cloud base height
- Smaller warm cloud depth
- Less precipitable water
- Greater NCAPE from the surface to -20°C
- Greater 0-6 km shear
- Greater storm-relative wind speed at the equilibrium level

However, the role played by various parameters varied from one region to another. Stronger dynamic variables such as NCAPE, shear, or storm-relative upper level wind appeared to offset less favorable microphysical parameters such as warm cloud depth.

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Table 1. Percent Difference in Means of Environmental Parameters[1]

Environmental Variable	SW	CC	NC	SE
Warm Cloud Depth	26.8	-40.1	-1.64	-8.64
Cloud Base Height	-19.4	37.1	0.237	-9.52
Precipitable Water	1.19	-25.9	-2.14	-13.0
Surface to -20°C NCAPE	40.5	-17.4	21.8	-16.2
0-6 km Wind Shear	19.7	14.0	7.72	53.6
Storm Relative Speed at Equilibrium Level	14.6	12.7	8.61	36.3

[1] Percentage was computed by taking the the mean of the parameter for the +CG dominated cells minus the mean for the parameter in 10,000 trials of randomly selected cells and then dividing this difference by the mean for the randomly selected cells and multiplying by 100. Values are positive if +CG dominated storms had a larger mean value.