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Factors Affecting Lightning Behavior in Various Regions of the United States

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Abstract— Lightning activity varies greatly on a global scale. Global maps of total flash density show a strong tendency for lightning to favor continental areas over the open ocean, even in regions with similar instability. Previous studies have attributed the difference to thermodynamic and aerosol differences over continental regions, but the exact cause is still elusive. While this is not a global study, we attempt to characterize lightning activity in 4 different regions of the United States with high resolution Lightning Mapping Array (LMA) networks over one warm season. The regions of study are Washington, D.C., northern Alabama, central Oklahoma and northeast Colorado. A wide spectrum of environmental characteristics is afforded by these regions. Lightning characteristics include storm total flash rates, positive cloud-to-ground (+CG) strikes and intra-cloud (IC) to CG ratio (IC:CG). This is accomplished by using the CSU Lightning, Environmental, Aerosol and Radar (CLEAR) framework, first developed by Lang and Rutledge (2011), to objectively analyze large amounts of storm data. Lightning activity is produced by a new flash clustering algorithm, which produces total flash rates and IC flash rates when combined with NLDN CG data.

The results have shown that lightning behavior has high variability throughout the regions of study. Median total storm flash rates range from approximately 1 flash min^{-1} in Alabama and DC to near 8 flashes min^{-1} in Colorado. Positive CG flash fractions exhibit a similar relationship with 10% of all CG flashes being positive polarity in Alabama and DC up to 45% in Colorado. The anomalous nature of the Colorado region is evident in all lightning metrics. Colorado is also characterized by an anomalous environment with high cloud base storms and coincident shallow warm cloud depths. Examination of all storms simultaneously has shown that relationships exist between total flash rate and environmental parameters. The similarity of these results to other studies on global scales is striking and provides evidence for the robustness of these relationships. Examination of relationships between radar and lightning intensity metrics are also performed. Similar behaviors between these intensity metrics are observed in all regions.

Keywords—component; formatting; style; styling; insert ***(key words)***

I. INTRODUCTION

The variations in lightning activity throughout the United States and the globe spark interest on the effects of local environments on storm radar and lightning characteristics. This is investigated by extending the Lang and Rutledge (2011) study, which developed the Colorado State University (CSU) Lightning, Environmental, Aerosol and Radar (CLEAR) framework as a tool to take advantage of various datasets currently available. CLEAR objectively analyzes large amounts and varieties of data to compile statistics on storms with specific properties (e.g. dominant cloud-to-ground (CG) flash polarity or total flash rate) in an effort to understand the factors that control or are related to lightning behavior. The regions of study include northern Alabama, central Oklahoma, northeast Colorado and the greater Washington, D.C. area. These regions were chosen for the availability of LMA networks in order to provide detailed investigations of storm lightning behavior. All periods of study were during the 2011 warm season with the exception of Colorado since installation of its LMA occurred in the spring of 2012.

This study utilizes total flash rates calculated by a novel flash clustering algorithm to understand the link between storm intensity from both radar and lightning perspectives in each region. The distinct lightning behaviors in each region are also documented, and an attempt to establish relationships between storm intensity and environmental parameters are performed in each region of study. Every storm from each study region will be investigated together in an attempt to determine the causes of the different lightning behaviors observed in each region. These results will be compared to other global studies with differing datasets to examine the robustness of the relationships.

II. Background

Thunderstorms are the most intense form of moist convection and represent a small portion of all moist convective clouds. Yet, lightning is of great interest to researchers from many different disciplines. Lightning can pose a great threat to human lives, cause countless dollars in damages and affect Earth's climate indirectly, for example through wildfires (Price and Rind 1994; Rorig and Ferguson 1999). The physics of lightning are still largely unknown. Moreover, the controls on lightning activity and global lightning distributions still remain a mystery.

Lightning activity in thunderstorms is a main focus investigated in this study, therefore it is necessary to explicitly define lightning activity in the context of this study. For the purposes of this study lightning activity is defined by (1) the total lightning flash rate, (2) the dominant cloud-to-ground (CG) lightning polarity, and (3) the ratio of intra-cloud flashes to CG flashes (IC:CG). These three quantities have all been studied individually in previous studies, however not coincidentally or in the specific regions outlined in this study.

Beginning with the fair-weather electric field studies conducted by Wilson (1916, 1920) and satellite measurements more recently, it is clear that lightning prefers continental regions over oceanic regions. This difference between land and ocean flash rates is roughly an order of magnitude, and has been documented by many studies (e.g. Boccippio et al. 2000; Williams and Stanfill 2002; Christian et al. 2003). However, this behavior is not coincident with the rainfall distribution over the same domain. This raises the question: what causes lightning to favor land when rainfall does not necessarily follow the same pattern?

Williams (1985) has shown that lightning flash rates are directly linked to vertical air motions. Storms with stronger updrafts produce more lightning. There are numerous reasons for this. Recall that microscopic collisions (in the presence of supercooled liquid) and subsequent separation of small particles are responsible for thunderstorm electrification. Stronger updrafts are able to move air parcels through the warm-rain zone of the cloud faster, thereby suppressing collision-coalescence and supplying the mixed phase region with larger amounts of liquid water. Stronger updrafts are also more able to support the weight of any condensate that forms upon ascent of the parcel, either leading to larger amounts of liquid water supplied to the mixed-phase region or a greater amount of riming particles upon freezing of the droplets. These frozen droplets can become graupel and hail, via riming processes, necessary to facilitate electrification processes.

Multiple studies have found that characteristic updraft speeds are larger over land than over oceanic regions (Kyle et al. 1976; LeMone and Zipser1980, Williams and Stanfill2002). These stronger updrafts have also been found to be coincident with characteristically broader updrafts, therefore sparking interest in the relationship between these quantities. If updrafts over continental regions are stronger and broader than oceanic regions, there must be environmental factors explaining the characteristic differences in the updrafts. Current studies find that these differences are caused thermodynamically or by aerosol interactions (e. g. Williams and Stanfill 2002; Williams et al. 2002; Andreae et al. (2004). Both perspectives contend that continental regions will have stronger updrafts. The thermodynamic argument states that land regions have more buoyant thermals by virtue of the differential heat capacities between water and land. Williams and Stanfill (2002) and Williams et al. (2005) conclude that simple parcel theory is not adequate to explain the stronger updrafts over land. They argue that the higher cloud base height (CBH) values over land promote better conversion of potential energy to kinetic energy due in large part to decreased entrainment of more broad updrafts coincident with high CBH values. The aerosol perspective states that land regions have more cloud condensation nuclei (CCN) that can modify the drop size distributions and microphysics within a storm to invigorate the updrafts. These claims are investigated with the present dataset to identify the controls on storm total flash rates.

III. Data and Methods

The CLEAR analysis framework was developed by Lang and Rutledge (2011) in an effort to automate the analysis of large amounts of thunderstorm data from a variety of sources. The work discussed here improved upon elements of the CLEAR framework to be a more robust method to analyze storms. The framework is a fully modular collection of programs designed to merge a multitude of data and link these data to storms. Once data are attributed to identified cells, analysis can be performed and statistics and can be complied in an efficient and automated manner. The radar data used in this study are from the National Mosaic and Multi-Sensor Quantitative Precipitation Estimates (NMQ) mosaic 3D radar data (Zhang et al. 2011). NMQ mosaic data are arranged in latitude/ longitude coordinates with 0.1° x 0.1° horizontal resolution with a variable stretched vertical grid from 500 m to 18 km above mean sea level (MSL).

To objectively identify convective cells in the different regions, a cell-tracking algorithm similar to Rowe et al. (2011) and Lang and Rutledge (2011) was used. This algorithm is a variant of the Thunderstorm Identification, Tracking, Analysis and Nowcasting (TITAN) tracking methodology (Dixon and Weiner 1993), and uses a composite reflectivity field to locate individual cells or convective elements within a larger organized convective system. The main advantage of this type of identification is computational efficiency with isolated cells.

This study used 1-ms resolution NLDN flash-level data. Detection efficiencies in all regions of study are at or above 90% (Cummins et al. 1998; Cummins and Murphy 2009). Per their recommendations, any CG peak currents under 10 kA were reclassified as IC flashes and any IC flashes with peak currents over 25 kA were reclassified as CG flashes of appropriate polarity.

This study made use of 4 of them located in northern Alabama (Goodman et al. 2005), Washington, D.C. (Krehbiel 2008), central Oklahoma (Krehbiel et al. 2000) and northeast Colorado. LMAs use time-of-arrival (TOA) techniques from multiple detection stations to locate VHF radiation sources produced by the propagation of a breakdown channel or flash (Rison et al. 1999). A single flash may produce tens to thousands of VHF sources dependent on many factors including total channel length and network detection efficiency. Detection of many points along breakdown channels of flashes affords highly accurate 3D mapping of both IC and CG flashes.

A flash clustering algorithm based on spatial and temporal clustering of VHF sources has been developed by Prof. Eric Bruning (personal communication) and has been implemented into this framework. The algorithm is based on density based spatial clustering of objects (LMA sources in this case) based on specified space and time criteria. This algorithm produces total flash rates that can be used to calculate IC flash rates when used in concert with NLDN CG observations. This study is the first implementation of an automated and open source flash counting algorithm. This required some performance testing of the flash counting ability. Testing was performed by visual inspection of random cells in each region along with comparisons between flash counts produced by the XLMA program (Rison et al. 1999, Lang et al. 2004), considered to be the gold-standard in flash counting analysis. The algorithm is tuned for high flash rate storms with more numerous small flashes, as these are more difficult to detect. Subjective analysis of numerous storms in all regions show that reasonable flash rates are being produced as nearly all storm flash rates are within 10% of the XLMA flash rate values.

This study used hourly analysis from both the Rapid Update Cycle (RUC; Benjamin et al. 2004) and the Rapid Refresh (RAP; Benjamin et al. 2006) models. All model data were characterized by 13 km horizontal resolution and 37 vertical levels of varying resolution. Model environmental data were attributed to identified cells by an upwind method similar to that of Thompson et al. (2003).

The inclusion of aerosol observations is a new addition to the CLEAR framework. Satellite and ground-based aerosol optical depth (AOD) data were attempted in this study. Both types of data were attributed to cells by a simple spatial and temporal matching method. In most cases, satellite data were deemed unrepresentative and were not included in the results. The ground observations were also riddled with problems and largely deemed unrepresentative of storm environments. Future work includes the addition of other aerosol datasets, model or observational, to obtain a more accurate representation of storm environments and potential aerosol impacts on storm microphysics and dynamics.

IV. RESULTS

The analysis presented attempts to exclude outliers by using medians such that storms in the tails of the distribution are ignored. Median flash rates are presented for all storms within a particular bin for all examined variables (typically plotted on the horizontal axis). This is in an attempt to characterize "representative" storms to get an overall sense of thunderstorm behaviors.

First, the distributions of total flash rates in each region are examined. Figure 1 shows the cumulative distribution functions for storm total flash rates in each region. The majority of storms in each region produce less than 10 flashes min^{-1}. Storms in the Colorado region produce the most flashes overall as the lowest fraction of storms produce no flashes but the Colorado region also has the highest fraction of storms that produce more than 120 flashes min^{-1}. Storms in the Alabama and DC region produce the lowest flash rates of all regions, but it is important to note that superlative flash rate storms still occur in those regions. Those high flash rate storms are associated with severe weather. Storms in Oklahoma have higher overall flash rates than Alabama or DC but do not produce as many flashes as Colorado. These bulk flash rate differences should be explained by environmental differences between regions. We investigate this in the coming figures.

Our first step is to examine single variables thought to be important contributors to total flash rates and their relative frequencies in each region. Figure 2 shows the log of total flash rate as a function of LCL height for all included storms in the study. This results in a total sample size of around 4000 cell observations. Total flash rate is very well correlated with LCL height with an R^2 value of 0.95, albeit with considerable spread for each bin. This relationship is monotonic as represented by the Spearman rank coefficient of 1. The quasi-symmetric error bars on the log scale mean that the data is non-symmetric. A large portion of the flash rates are clustered at lower values while a long tail exists at larger flash rates. This strong relationship between the medians means that LCL height is a connecting factor between regions in determining the flash rate differences between the regions. The similarity between this figure and Figure 1 from Williams et al. (2005) is striking, given the drastically different datasets and regions of study. These similarities provide evidence for the robustness of this relationship.

Figure 3 shows the relationship between total flash rate and surface dry bulb temperature. The results presented here, while not exactly the same, follow a very similar trend to that of the Williams et al. (2005) study even though that study investigated tropical regions and this study investigates continental regimes, although Alabama and DC have a lot of maritime characteristics, namely low LCL heights and thick WCDs, especially in the framework of this analysis where outliers are not considered.

While single variable analysis has illuminated some very important relationships between total lightning activity, it does not take environmental interactions into account. This is precisely what will now be investigated. Figure 4 shows median flash rates for all storms within a 2D bin as determined by the variables on both axes. Note that the number of storms in a particular bin must meet a specified criterion to be plotted on the figure. This is because we do not want one outlier storm to affect or dwarf the rest of the results. In an effort to quantify the significance of the data, the number of cell observations in each valid bin is indicated by the white text. It is immediately clear that higher flash rates tend to favor storms with higher values of both CAPE and LCL height. The highest flash rates are observed in storms with high LCL heights and moderate CAPE values rather than high CAPE values and low LCL heights, consistent with Williams and Stanfill (2002) and previous figures.

While simple flash rate quantities have been shown to be related (strongly in some cases) to environmental variables, that is not the sole purpose of this study. We also want to investigate the role of charge structures in determining lightning characteristics and the relationships between these factors. This is shown in Figure 5 which illustrates the flash rate dependence on maximum flash height and LMA modal temperature (proxy for positive charge). The slope of the contours on Figure 5 represents the overall relationship between maximum flash altitude and positive charge temperature. Higher flashes are generally associated with colder LMA modal temperatures, which are both produced by stronger updrafts lofting charged particles to greater heights within a storm. The median flash rates for each bin show some interesting behaviors. There exist two maxima in flash rates, both at the highest flash altitudes. One of these maxima is located at the coldest positive charge temperatures indicative of strong normal polarity storms in all regions. Note these flash rates are near 100 flashes min^{-1} for the coldest positive charge regions. The other maximum is located at high flash altitudes but warm positive charge near -15 °C, these are indicative of electrically active storms with inverted charge structures. This is evidence that there exist at least two types of charge structures that are capable of producing superlatively electrified storms.

It is clear from the previous results that high altitude flashes and echo top heights are coincident with higher flash rates. This has also been documented in previous studies (e.g. Shackford 1960; Jacobson and Krider 1976; Williams 1985) where a fifth-power law was determined between cloud top height that Price and Rind (1992) used to build a simple global lightning parameterization. This parameterization is used in some global models to produce lightning-generated NO_x, for example. It is then important to have correct total lightning relationships. This is the purpose of Figure 6. It shows the median flash rate for each height bin for 0-50 dBZ echo top heights. The near-linear relationships are evident in all regions and for all reflectivity values. Given that 0 dBZ height is most comparable to the relationships used in Price and Rind (1992) it is surprising that the slopes are near 10 in all regions, indicating that flash rates are proportional to the 10^{th} power of cloud top height. The general trend is for the slope to decrease and the intercept to increase with higher reflectivity values. Inter-region comparisons reveal that different fit parameters exist in different regions, especially at higher reflectivities. This may have implications on future flash rate parameterizations.

V. SUMMARY

In this study we have demonstrated the use of an automated objective analysis tool to analyze a large number of storms and multiple types of storm data in distinct regions of the CONUS. This work has helped characterize the electrical behavior of thunderstorms in various regions in the context of environmental variables. The vast amount of data included in this study comprises a complete investigation that has never been carried out before.

The novel flash clustering algorithm unveiled in this study has been shown to perform very well. This algorithm is based on open-source code distributed in the Python programming language which means that anyone will be able to use and modify the code as they see fit. One of the goals of this study was to demonstrate the validity of an automated flash counting algorithm that avoids tedious GUI interfaces in order to provide efficient quantities of electrical behavior in a storm. We believe this has been accomplished and hope that future studies are able to utilize this new tool to further the field of lightning research.

Examination of all storms simultaneously revealed clear relationships between total flash rate and select environmental parameters. LCL heights were found to be very well correlated with the log of total flash rates, suggesting this quantity to be a very important influence on total flash rates. Dry bulb temperatures and CAPE values were also found to correlate with total flash rate but the correlation coefficient was not as good with LCL heights, possibly suggesting these quantities are not as influential as LCL heights in determining lightning activity. The similarity between the LCL height and flash rate relationship observed here and the Williams et al. (2005) study is striking. The data and the regime of study are markedly different between the two studies, yet the same result is observed. This suggests that these relationships may be robust. Nonetheless, these results suggest that the relationships found here may have impacts beyond this study on global variations of flash rates.

References

Andreae, M. O., D. Rosenfeld, P. Artaxo, A. A. Costa, G. P. Frank, K. M. Longo, and M. A. F. Silva-Dias (2004) Smoking rain clouds over the Amazon. Science, 303, 1337-1342.

Benajamin, S., D. Devenyi, and S. S. Weygandt (2004), An hourly assimilationforecast cycle: The ruc. Mon. Wea. Rev., 132, 495-518.

Benjamin, S. G., et al., (2006), 9.1 from the 13-km ruc to the rapid refresh.

Boccippio, D. J., S. J. Goodman, and S. Heckman (2000), Regional differences in tropical lightning distributions. J. Appl. Met., 39, 2231-2248.

Cummins, K., M. Murphy, E. Bardo, W. Hiscox, R. Pyle, and A. Pifer (1998), A combined TOA/MDF technology upgrade of the US national lighting detection network. Geophys.Res., 103, 9035-9044.

Cummins, K. and M. Murphy (2009), An overview of lighting locating systems: History, techniques, and data uses, with an in-depth look at the US NLDN. Electromagnetic Compatibility, 51, 499-518.

Goodman, S. J., et al., (2005), The north alabama lighting mapping array: Recent severe storm observations and future prospects. Atmos. Res., 76, 423-437.

Jacobson, E. A. and E. P. Krider (1976), Electrostatic field changes produced by Florida lightning. J. Atmos. Sci., 33, 103-117.

Krehbiel, P., R. J. Thomas, W. Rison, T. Hamlin, M. Davis, and J. Harlin (2000), Lightning mapping observations in central Oklahoma. Eos, 81 (3), 21-25.

Krehbiel, P. (2008), The DC lightning mapping array. Preprints, 3rd Conf. on Meteorological Applications of Lightning Data, New Orleans, LA, Amer. Meteor. Soc, Vol. 3.

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. Geophysical research letters, 31 (10).

Lang, T. J. and S. A. Rutledge (2011), A framework for the statistical analysis of large radar and lightning datasets: Results from steps 2000. Mon. Wea. Rev., 139, 2536-2551.

Price, C. and D. Rind (1992), A simple lightning parameterization for calculating global lightning distributions. J. Geophys. Res., 97, 9919-9933.

Price, C. and D. Rind (1994), The impact of a 2 x co2 climate on lightning-caused fires.J.Climate, 7, 1484-1494.

Rison, W., R. Thomas, P. Krehbiel, T. Hamlin, and J. Harlin (1999), A gps-based three-dimensional lightning mapping system: Initial observations in central New Mexico. Geophys. Res. Lett., 26, 3573-3576.

Rorig, M. L. and S. A. Ferguson (1999), Characteristics of lightning and wildland fire ignition in the pacific northwest. J. Appl. Meteor., 38, 1565-1575.

Rowe, A. K., S. A. Rutledge, and T. J. Lang (2011), Investigation of microphysical processes in isolated convection in name. Mon. Wea. Rev., 139, 424-443.

Shackford, C. R. (1960), Radar indications of a precipitation-lightning relationship in new england thunderstorms. J. Meteor., 17, 15-19.

Thompson, R. L., R. Edwards, J. A. Hart, K. L. Elmore, and P. Markowski (2003), Close proximity soundings within the supercell environments obtained from the rapid update cycle. Wea. and Fore., 18, 1243-1261.

Williams, E. R. (1985), Large-scale separation in thunderclouds. J. Geophys. Res., 90, 6013-6025.

Williams, E. R. and S. Stanfill (2002), The physical origin of the land-ocean contrast in lightning activity. Comp. Rend. Phys., 3, 1277-1292.

Williams, E. R., D. Rosenfeld, N. Madden, J. Gerlach, and coauthors (2002), Contrasting convective regimes over the Amazon: Implications for cloud electrificiation. J. Geophys. Res., 107, 501-520.

Williams, E. R., V. Mushtak, D. Rosenfeld, S. Goodman, and D. Boccippio (2005), Thermodynamic conditions that lead to superlative updrafts and mixed-phase microphysics. Atmos. Res., 76, 288-306.

Wilson, C. T. R. (1916), On some determiniations of the sign and magnitude of electric discharges in lightning flashes. Phil. Trans. Roy. Soc. London, 555-574.

Wilson, C. T. R. (1920), Investigations on lightning discharges and on the electric field of thunderstorms. Phil. Trans. Roy. Soc. London, 73-115.

Zhang, J., K. Howard, C. Langston, and coauthors (2011), National mosaic and multi-sensor QPE (NMQ) system: Description, results, and future plans. Bull. Amer. Meteor. Soc., 92, 1321-1338.

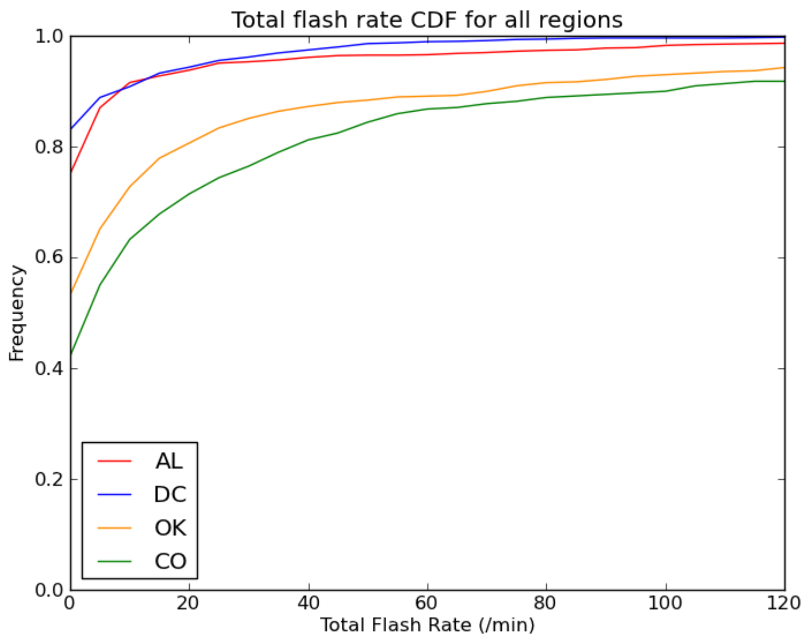

Figure 1: Cumulative distribution function (CDF) of storm total flash rates in each region. Regions are indicated in the legend.

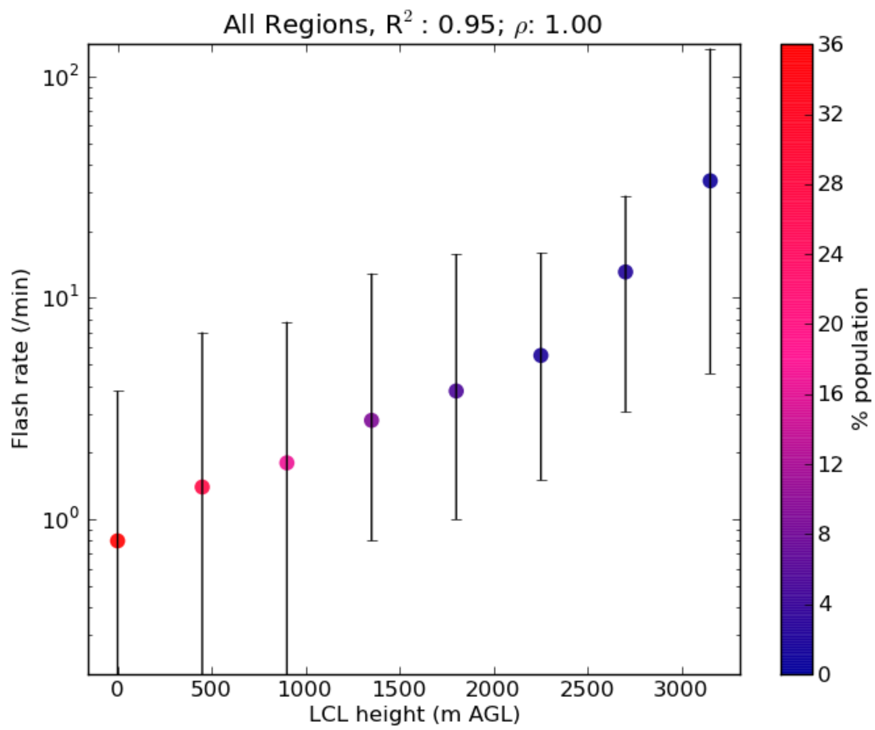

Figure 2: Log flash rate and LCL heights for all storms in all regions of study. Points denote the median flash rates for each LCL bin. Bottom error bar denotes the 25th percentile of the flash rate distribution for each LCL bin. Top bar denotes the 75th percentile of flash rate distribution for each LCL bin. Color of point indicates relative population of LCL heights following the colorbar.

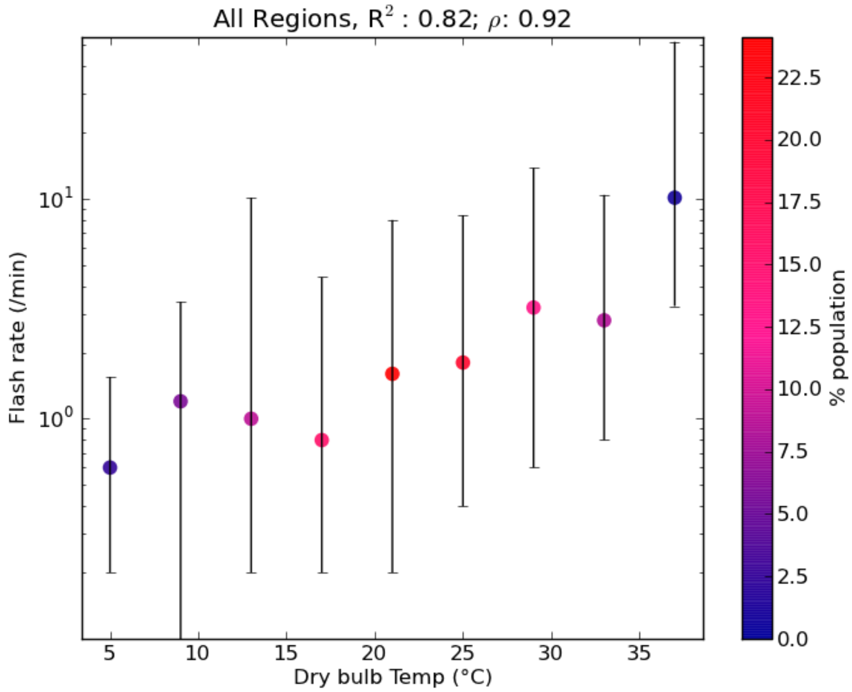

Figure 3: Log flash rate and surface dry bulb temperature for all storms in all regions of study. Points denote the median flash rates for each temperature bin. Bottom error bar denotes the 25th percentile of the flash rate distribution for each LCL bin. Top bar denotes the 75th percentile of flash rate distribution for each temperature bin. Color of point indicates relative population of temperatures following the colorbar.

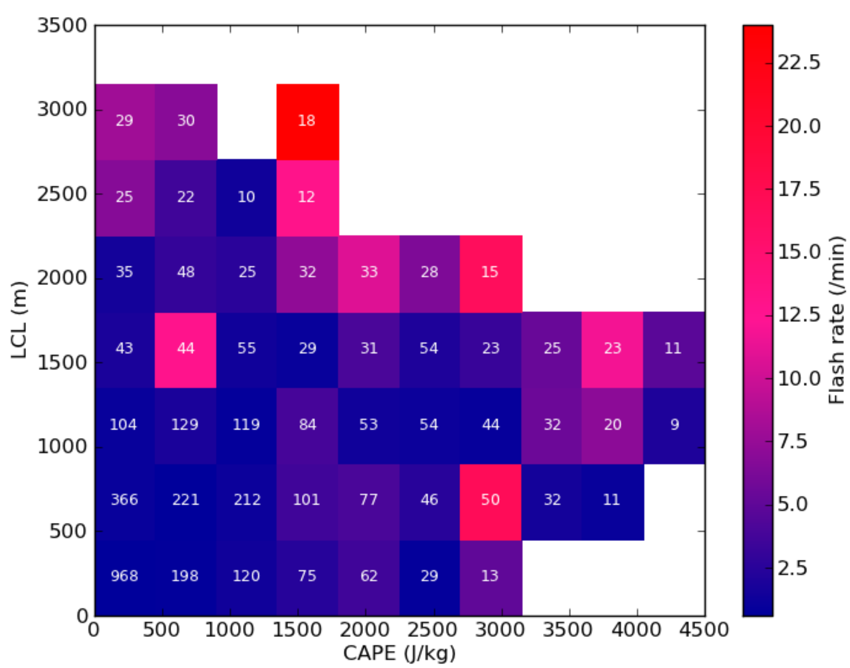

Figure 4: Flash rates as a function of LCL height and CAPE for all storms of study. Median flash rate for each 2D bin is colored following the colorbar. The white numbers denote the number of storm observations in the bin.

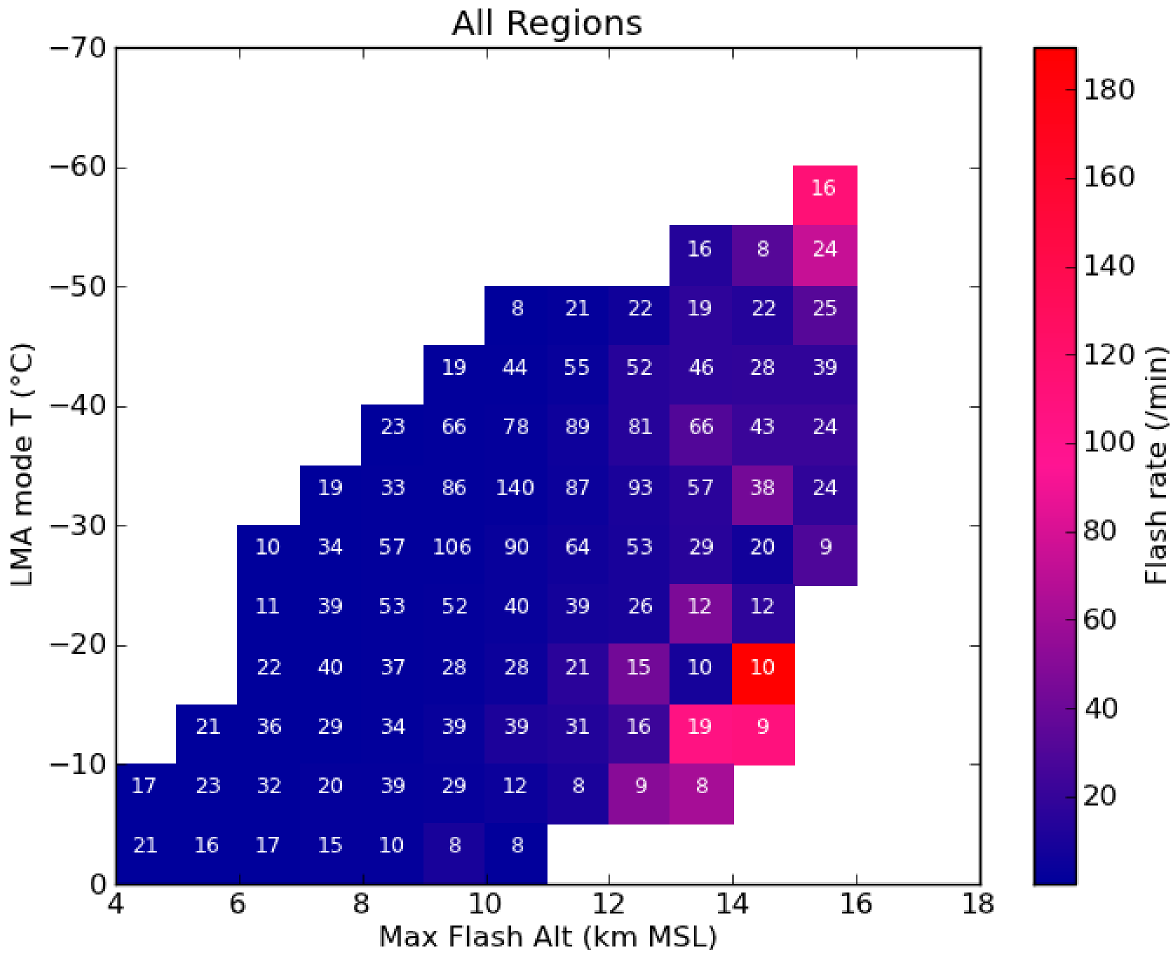

Figure 5: Same as previous figure, but for maximum flash altitude and LMA modal temperature.

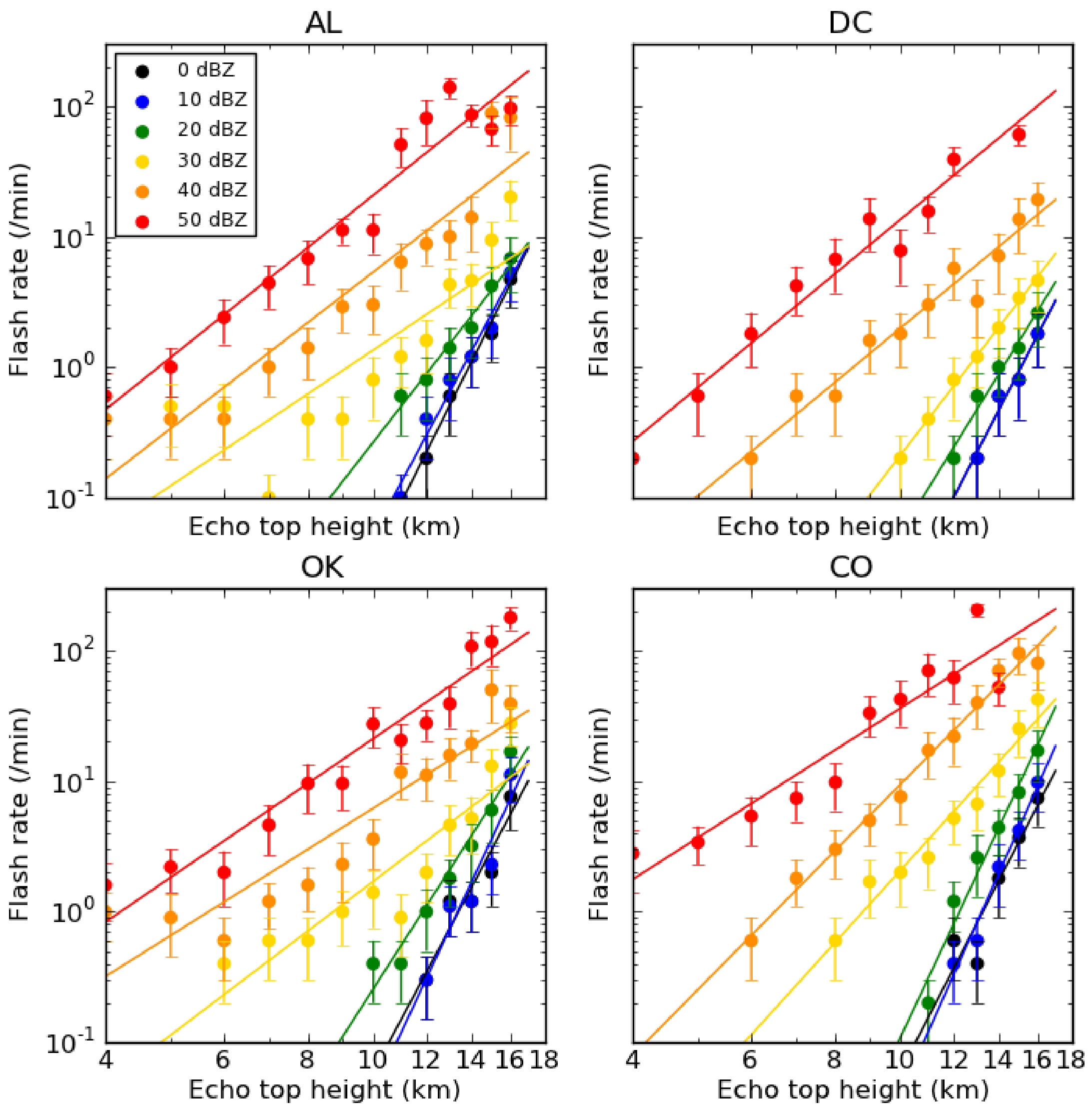

Figure 6: Median flash rate dependence on echo top heights for 0 to 50 dBZ in each region. Bars represent the median absolute deviation for the flash rate distribution for each height bin.