P348 THE INTRA-CLOUD LIGHTNING FRACTION IN THE CONTIGUOUS UNITED STATES

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1. INTRODUCTION

Lightning is dangerous and destructive; cloud-to-ground (CG) lightning flashes can start fires, interrupt power delivery, destroy property and cause fatalities. Its rate-of-occurrence reflects storm kinematics and microphysics. For decades lightning research has been an important focus, and advances in lightning detection technology have been essential contributors to our increasing knowledge of lightning. A significant step in detection technology is the Geostationary Lightning Mapper (GLM) to be onboard the Geostationary Operational Environment Satellite R-Series (GOES-R) to be launched in early 2016. GLM will provide continuous "Total Lightning" observations [CG and intra-cloud lightning (IC)] with near-uniform spatial resolution over the Americas by measuring radiance at the cloud tops from the different types of lightning (Goodman et al. 2003). These Total Lightning observations are expected to significantly improve our ability to nowcast severe weather (Schulz et al. 2011). It may be important to understand the long-term regional differences in the relative occurrence of IC and CG lightning in order to understand and properly use the short-term changes in Total Lightning flash rate for evaluating individual storms.

A typical (simplified) electrified cloud is explained as having vertical layers of electrical charge composed of an upper positive charge below the tropopause, a midlevel negative charge region just above the freezing level, and a much smaller positive charge layer below it (Williams 1989). IC flashes generally "neutralize" charge between the upper positive and midlevel negative charge regions in a cloud while CG flashes typically transfer negative charge to one or more locations on the ground (Cummins and Murphy 2009). The relative occurrence of IC and CG lightning is thought to be determined in-part by the relative locations of these charge centers, and their spatial relationship to the terrain below. For an in-depth explanation of lightning and thunderstorms, see books by Rakov and Uman (2003), and MacGorman and Rust (1998).

An important study of the relative occurrence of IC and CG lightning was carried out by Boccippio et al. (2001). Here they compiled a four year climatology using the Optical Transient Detector (OTD) (Boccippio et al. 2000) and the U.S. National Lightning Detection Network (NLDN) (Cummins and Murphy 2009) to compute an IC:CG ratio (Z) over the coterminous Continental United States (CONUS). They concluded that there is some correlation between terrain (Mountain ranges) and low Z values but the relationship is non-unique. Other results from this study show that high Z values are correlated with locations of severe weather events -- mostly areas where positive CG lightning is a large fraction of the CG flashes. This agrees with Carey and Rutledge's (1998, 2003) research indicating that thunderstorms that are typically "dominated" by positive CG lightning are frequently associated with severe weather (large hail, tornadoes, etc.) and high Z ratios. Other studies also indicate that severe storms typically produce unusually high rates of IC lightning and (to some degree) reduced CG lightning (MacGorman et al. 1989; Williams et al. 1999; Wiens et al. 2005).

Given the potential value of understanding long-term regional variations in the Z ratio, we have expanded upon the earlier analysis by Boccippio et al. (2001) through the use of additional and longer-term datasets. Section 2 describes the datasets and analysis methods. Results are presented in section 3 followed by the discussion (section 4) and conclusions (section 5).

2. DATA AND METHODS

This study uses the U.S. National Lightning Detection Network (NLDN), the Optical Transient Detector (OTD), the Lightning Imaging Sensor (LIS), and a combination of OTD and LIS (OTD/LIS). The

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following sub-sections briefly discuss these datasets and the methods used to evaluate and compare them.

2.1. NLDN data

The NLDN has been providing lightning data since the early 1980s and in 1989 began to be used for continental-scale lightning research in the United States (Cummins and Murphy 2009). The NLDN was originally made up of gated wide-band magnetic direction finders that employed magnetic field waveforms to determine the direction to the channel bases of lightning discharge to the ground (Krider et al. 1976). The first major improvement to the NLDN occurred in 1995 when the direction finders were upgraded to include GPS timing data, resulting in the so-called IMPACT (Improved Accuracy through Combined Technology) sensor (Cummins et al. 1998a). The IMPACT geo-location algorithm computes the latitude, longitude and discharge time using as few as two sensors (Cummins and Murphy 2009). The CG flash detection efficiency (DE) following this upgrade ranged between 80 and 90%, depending on location (Cummins et al., 1998a). In 2002–03, the NLDN improved as a result of replacing all NLDN sensors with better IMPACT-ESP sensors and also adding eight additional sensors to the network. This further improved the flash DE to between 90 and 95% (Cummins and Murphy 2009). The spatial boundaries of the NLDN are 250 km into Canada, 600 km into Mexico, 600 km into the Pacific and Atlantic Ocean (Holle 2014). The flash DE decreases in all directions outside CONUS except Canada since there is the Canadian Lightning Detection Network (CLDN) that operates in conjunction with the NLDN (Holle 2014). Figure 1 provides a contour map of the estimated flash DE for the combined NLDN and CLDN since late 1998. Finally, as a result of the 2013 NLDN upgrade, the estimated CG flash DE throughout CONUS is in excess of 95% (see Nag et al., 2013 for details). Prior to 1996, the NLDN did not report any discharges classified as cloud lightning. The number of reported IC flashes has steadily increased over the last 8 years. In the present study, only NLDN-reported CG flashes are employed. A history and implications of NLDN upgrades is provided in Koshak et al. 2014. Given the high CG flash DE for the NLDN, no DE corrections were applied to the NLDN flash density values.

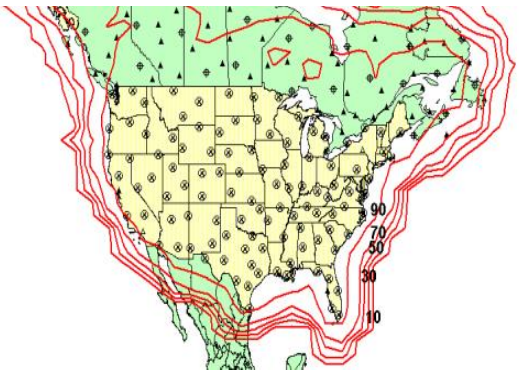

Figure 1: A contour map of the estimated flash Detection Efficiency for the combined NLDN and CLDN since late 1998. Reprinted with permission.

2.2. OTD and LIS

OTD orbited for 5 years (1995 -2000) on the Orbital Sciences Corporation Microlab-1 Satellite (OV-1) (Mach et al. 2007 and Christian et al. 2003). It detected and located lightning during both day and night due to its sensitivity and dynamic range (Christian et al. 2003). OTD recorded lightning between 75 degrees North and South due to its 70 degree inclination orbit (Christian et al. 2003). The flash DE has been reported to be between 49% and 65% (Boccippio et al. 2000 and Boccippio et al. 2001). OTD's field-of-view was about 1300×1300 km^2 with a spatial resolution of 10 km and about 14 orbits each day (Cecil et al. 2014).

LIS is part of the Tropical Rainfall Measuring Mission that was launched in 1997 and remains in orbit but it is on its last years. Like OTD, LIS detects the total lightning (IC and CG flashes), but is limited to 38° N to 38° S with a flash DE of about 69% during local noon and 88% at night (Cecil et al. 2014). LIS's field-of-view changed from about 600×600 km^2 to about 700×700 km^2 following a boost in the TRMM satellite average altitude from ~350 km before August 2001 to ~400 km after August 2001. The respective spatial resolution changed from ~5 km to ~6 km. LIS has about 16 orbits each day (Cecil et al. 2014).

This analysis uses the global Total Lighting gridded OTD and LIS datasets produced by NASA (see Cecil et al. 2014 for a detailed description). More specifically, we employ the gridded flash rate (flash density in units of flashes/km^2/yr) product which is part of the High Resolution Flash Climatology (HRFC) dataset with a spatial resolution of 0.5×0.5 degrees. The measured flash counts were scaled to correct for observation times and flash detection efficiency, as described in Cecil et al. 2014.

This study examines the OTD and LIS data for the period of May of 1995 to December 2012. The combined OTD/LIS data provide the Total Lightning portion while NLDN is used for CG flashes, making it possible to determine the Z ratio in the same manner as Boccippio et al. (2001) who utilized four years of OTD and NLDN data. The result is a 17.5 year flash density climatology below 38° N and a 5-year climatology above 38° N.

For most of the analyses the data were smoothed based on Gaussian smoothing with a standard deviation of one grid (0.5 degrees) using 5×5 grid points. All smoothing was preformed prior to any arithmetic manipulations (ratios, differences, etc.).

This improves numerical stability since the data sets (OTD in particular) are small due to orbital sampling. Smoothing also helps reduce the impact of inter-annual variability.

In this work, we also compare the individual OTD and LIS datasets below 38° N to evaluate instrumentation or calibration biases in the datasets and set expectations for the variability in the 5-year OTD climatology in the northern latitudes. The comparisons are carried out in two different ways -- one is a signed (+/-) spatial bias percent for each grid point and the other is a magnitude error percent. The spatial bias percent shows locations where there is a strong bias towards one data set, using the equation:

$$\frac{100 * (OTD - LIS)}{(OTD + LIS)/2} \ . \qquad (1)$$

The magnitude error percent is simply the absolute value of the signed error, and is used to show the locations where the two data sets are very different.

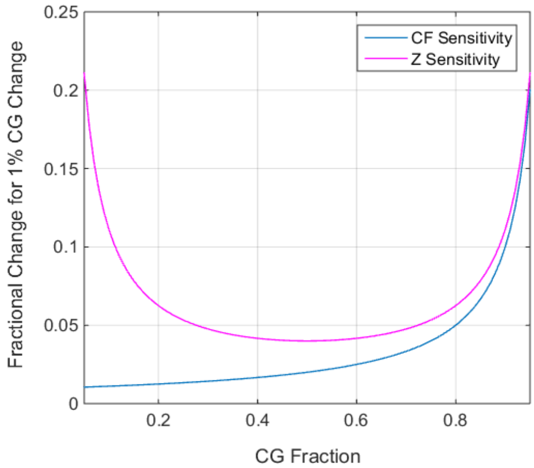

Figure 2: The fractional sensitivity of Z and CF to a 1% change in CG fraction, determined from the derivative of these functions with respect to CG Fraction.

An NLDN "composite" CG flash density dataset was constructed to match the time periods of the satellite-derived climatologies. For the composite OTD/LIS dataset, the NLDN data above 38°N was limited to the early 5 years period, and the NLDN data below 38°N included all 17.5 years of data.

A "composite" Z was also calculated using the combined OTD/LIS data set that is from May 1995 – December 2012 and the NLDN data as described above. Z is calculated for each grid point using:

$$Z = \frac{Total - CG}{CG} \qquad (2)$$

where *Total* is the composite OTD and LIS density, and *CG* is the composite NLDN cloud-to-ground density. Spatial maps of Z were computed and represented in two different ways. In the *Results* section, Z is plotted as a smoothed grid map with the "native" 0.5×0.5 degree resolution. The *Discussion* section includes Z plotted as a highly smoothed contour map for direct comparison with Fig. 2 in Boccippio et al (2001). When the CG flash density is small, the calculated value of Z will be sensitive to small random variations in that value. The "cloud fraction" (CF) does not suffer from this instability as much as Z, and is given by the following equation:

$$CF = \frac{Total - CG}{Total} \qquad (3)$$

Figure 2 shows the fractional sensitivity of Z and CF to a 1% change in CG fraction (S_z and S_{CF}, respectively), determined from the derivative of these functions with respect to CG fraction. The sensitivity equations used are presented below:

$$S_{CF} = \frac{\Delta CG}{CF} \ . \qquad (4)$$

$$S_z = \Delta CG \frac{\left[\frac{CGF - 1}{CGF^2} - \frac{1}{CG}\right]}{Z} = \frac{S_{CF}}{CGF} = \frac{\Delta CG}{CF * CGF} \ . \qquad (5)$$

where the absolute value is taken and the CG Fraction (*CGF*) = 1-*CF*. It is evident that CF is more stable than Z for small values of CGF. S_z is inversely related to the smaller of *CF* and *CGF* and is therefore insensitive to the CG Fractions between 0.2 to 0.8 (see Fig. 2), but has high sensitivity elsewhere. S_{cf} is inversely related to Cloud Fraction, resulting in fairly unstable behavior for CG Fraction > 0.8. Since real storms do not produce 4 times more CG flashes than IC flashes, this sensitivity is not a practical problem.

3. RESULTS

3.1. LIS and OTD differences

Figures 3 and 4 show the OTD and LIS Flash densities (respectively) taken from the HRFC. LIS was limited to 37° N to discard the bias error from the edges due to smoothing. The Total Lightning flash densities range from 35-40 fl/km^2/yr in Florida and western Mexico, to less than 1 along the U.S. west coast and north-eastern Canada. It is clear that both OTD and LIS generally agree about the maxima over Florida, Cuba, and western Mexico, but there are some differences between the datasets over the rest of the domain.

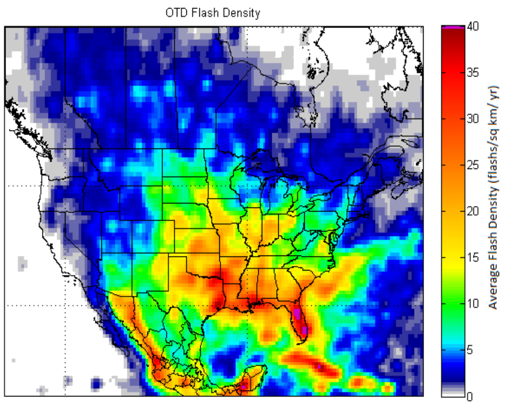

Figure 3: The average flash density over CONUS from OTD data from 1995–99.

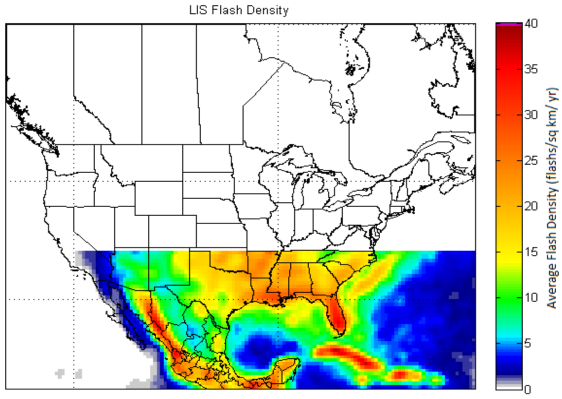

Figure 4: The average flash density over CONUS from the LIS data from 1998–2012.

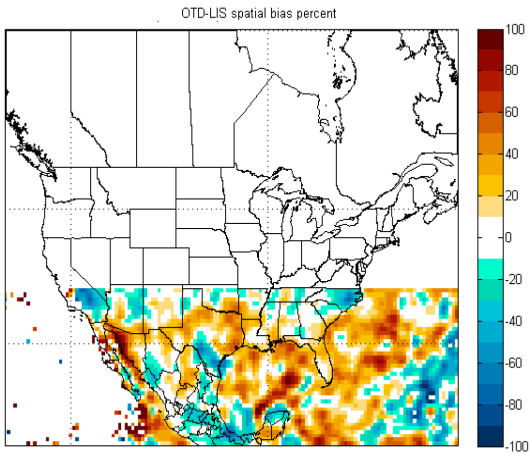

Figure 5: The signed difference between OTD and LIS flash densities, illustrating the spatial bias of the data being used.

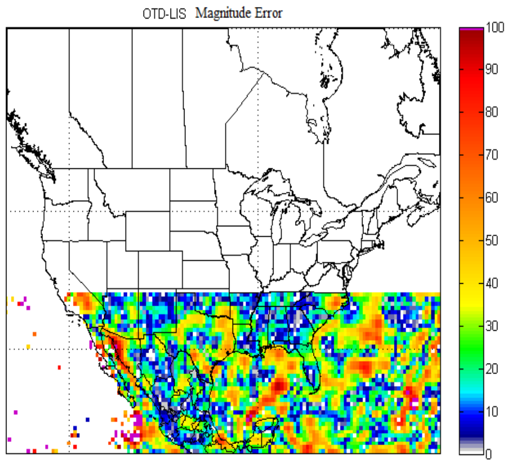

Figure 6: The absolute difference between OTD and LIS flash densities.

Figure 5 shows the signed spatial bias percent flash densities,between the two sets. Negative (green/blue) values represent a bias towards LIS and positive (orange/red) values represent a bias towards OTD. White regions are either "no data" or indicate biases less than 10%. The values mostly vary between ± 40% with the highest locations of spatial bias in parts of the Gulf of Mexico, along the west coast of the Gulf of California, and east of the Gulf Stream off the east coast. For most of the United States (below 37° N) and over the water, visual inspection suggests that there may be some bias towards higher OTD density since there are more positive values. However, the average over the whole domain shows that the LIS reported 4% more lightning than OTD. If the bias were due to instrumental differences one would expect a more uniform bias towards either LIS or OTD. However, the largest variations between the two are spatially very close to each other, going from a negative extreme to a positive extreme. This finding is more likely due to the orbital sampling and year-to-year variations in storm location since these two datasets only have two years of overlap. Given that the LIS data is a 14-year climatology, it would be reasonable to ascribe most of the variability to the OTD dataset.

There are moderate magnitude differences over CONUS as shown in Fig. 6, with the larger variations of roughly 50% in south-central and eastern Texas. The same "heterogeneous" pattern seen in the spatial bias plot is also seen in Fig. 6. A histogram of the magnitude differences for all grids is shown in Fig. 7 (bar graph), along with the associated cumulative distribution (line graph). About 90% of the grids have a variation of 50% or less, with steadily decreasing likelihood of larger variations.

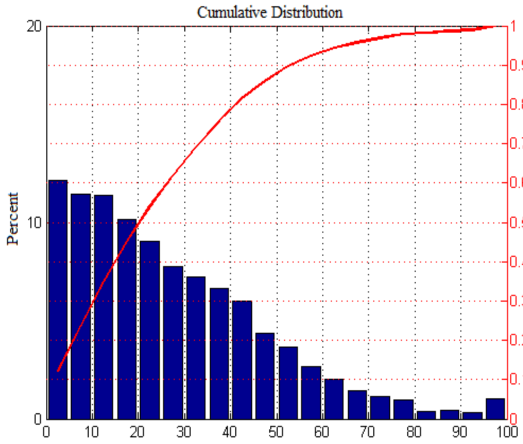

Figure 7: Cumulative sum (line plot) and the histogram (bars) for the magnitude error over CONUS between OTD and LIS.

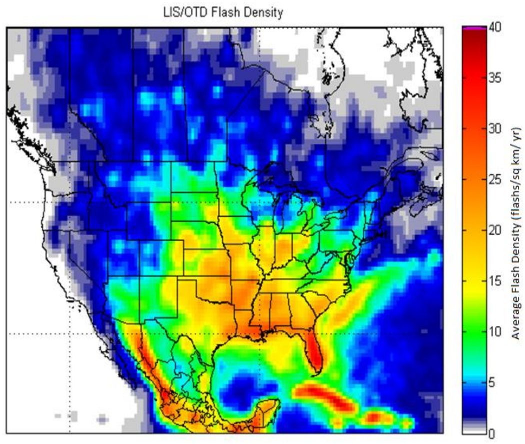

Figure 8: The 17.5 year climatology of the average flash density over CONUS from the combination of LIS and OTD data from HRFC.

3.2. Combined OTD/LIS and NLDN

An underlying limitation of this analysis is the short (5-year) observation period for the combined satellite-derived climatology above 38° N, shown in Fig. 8. It might be possible to gain some insight into the implication of this limitation by comparing the NLDN climatologies in Figs. 9 and 10. Figure 9 is the NLDN CG flash density that is time-associated with the combined OTD/LIS flash density, as described in the Methods section. Figure 10 shows the NLDN CG flash density for the whole 17.5 year period over CONUS. Noteworthy contrasts between Figs. 9 and 10 are lower-density "dips" seen in Missouri and Ohio with differences in the northern plains from northwest Kansas northward, Pennsylvania and parts of New York. There were a lot of storms over the 17.5 year period that are not included in the smaller 5 year climatology, resulting in a less-representative flash density in the north. Also, as latitude increases the flash density decreases so this area may be more sensitive to changes of sample size than the southeastern U.S. Among all the density maps it is clear that off the coast of the Carolina's the density transitions from high values over land, decreasing to smaller values over the Ocean, and enhancing again over the Gulf Stream. This is discussed further in section 4.

3.3. Z and Cloud Fraction

Z and Cloud Fraction are plotted in Figs. 11 and 12 respectively based on the modified NLDN sample which matches the OTD and LIS periods. There is no clear transition from land to water, with the possible exception off the coast from New Jersey, and there is no clear anomaly over the Gulf Stream. The high Z boundaries over the ocean and northern Mexico are due to the fall-off of NLDN DE with increasing distance from CONUS, as shown in Fig. 1. Most of the United States exhibits values of Z between 1 and 4 (CF between 0.5 and 0.8), with some notable exceptions. Distinctly high Z values occur in parts of Northwest Texas, Kansas, Nebraska and South Dakota, more-clearly illustrated in Fig. 11. This region is known from previous studies to be associated with high percentages of positive CG flashes and severe weather (Carey and Buffalo 2007; Carey et al. 2003; Orville et al. 2011).) Large Z values (>8) are also seen in the Northwest U.S., Vancouver Canada, and off the

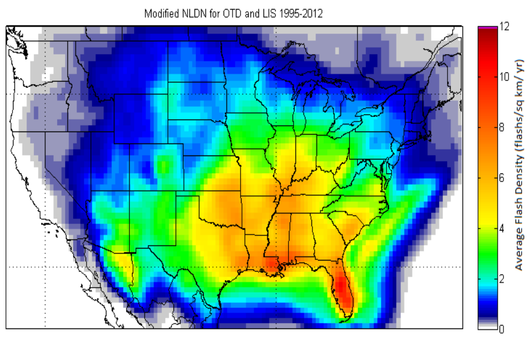

Figure 9: The National Lightning Detection Network's Ground Flash Density over CONUS where below 38° N the climatology is 17.5 years and above 38° N the climatology is 5 years following OTD.

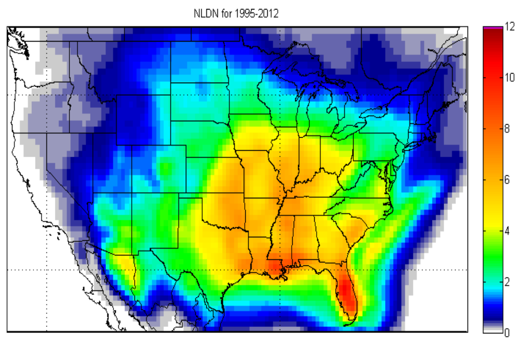

Figure 10: The National Lightning Detection Network's Ground Flash Density (flashes km-2 yr-1) over CONUS based on a 17.5 year climatology.

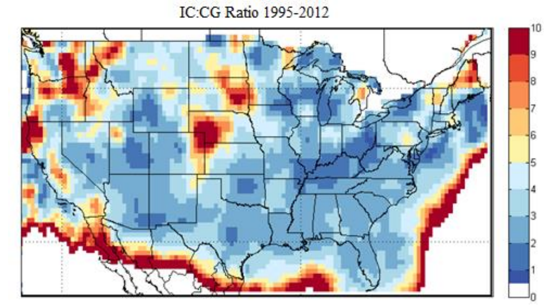

Figure11: The Z ratio using LIS/OTD and NLDN for a 17.5 year period.

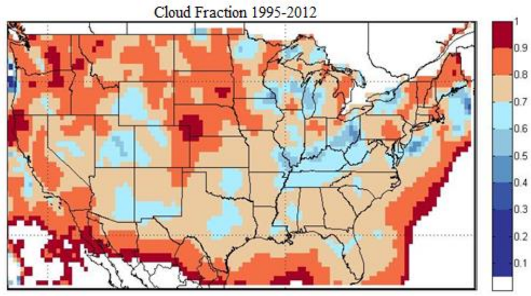

Figure 12: The Cloud Fraction using LIS/OTD and NLDN for a 17.5 year period.

northern California coast. This finding may not be significant due to the low flash density in these areas. Small regions of high Z that occur over the Great Salt Lake, Lake Huron, and Vermont could be significant. They are all within large regions of low ground flash density (0.5 – 2 fl/km^2/yr), but their feature size is much smaller than the surrounding regions of low ground flash density.

4. DISCUSSION

4.1 Overall Lightning Climatology

Both the Satellite and NLDN observations reveal similar general patterns of flash density over CONUS. The greatest CONUS flash densities are in Florida and the Gulf Coast, with a nearly steady fall-off to the west, northwest, and north. The 17.5-year satellite climatology shows flash density maxima along the west coast of Mexico, as indicated by Murphy and Holle (2005). Other maxima regions include the Gulf Stream and south-central U.S. Furthermore, the Front Range of the Rocky Mountains has relatively greater density values when compared to the central Rockies.

An important contributor for lightning along the Gulf Coast is deep low-level moisture driven from the very warm ocean waters (Holle 2014). When supplemented by coastal land-mass heating, conditions are ideal for strong convection (Stroupe et al. 2004). There is also an area of high flash density over Florida. The driving factor for lightning here is the differential heating resulting from the thermal contrasts between land and water, helping to create convergent boundaries that help trigger convection (Hodanish et al. 1996).

The well-defined lightning increase across the Gulf Stream off the East Coast is because the Gulf Stream consists of warm waters that favor deep convection (Christian et al. 2003). The increased lightning over this area compared to near-coastal waters has been associated with almost stationary convective clouds and precipitation associated with large fluxes of heat and water vapor from the warm waters of the Gulf to the colder air above (Biswas and Hobbs 1990). A more in-depth discussion on the meteorological mechanisms for lightning in the U.S. can be found in Holle et al. (2010) and Holle (2014). Other notable references are Smith et al. (2005), and Lopez and Holle (1986).

4.2 LIS/OTD

The largest differences between the OTD and LIS climatologies are seen in the Gulf of Mexico, parts of Mexico, and the Caribbean. The largest source of variability seems to be OTD and LIS covering different time periods, interacting with inter-annual variability and the limited sampling period for orbital satellites. Additional work is required to demonstrate this quantitatively. There does not appear to be significant instrumental biases. An important fact is that OTD is only for 5 years while LIS is for 14 years, suggesting that most of the variability is in the OTD climatology. Thus, the composite satellite-derived climatology will have more variability and uncertainty north of 38° latitude, with an expected percent variability similar to those depicted in Figs. 5-7.

4.3: Z and Cloud Fraction

Very high Z values occur over the Northwest U.S., near Vancouver Canada, and off the northern California coast. This finding may not be significant due to the low flash density in this area, but it is interesting that this general area also exhibits high percentages of positive CG lightning (see Orville et al. 2011, Fig. 4j). The low flash densities in this area may result from the cold water and large-scale sinking which inhibits deep convection, with local variations produced by the terrain-driven convection typically seen in the West (Reap 1986).

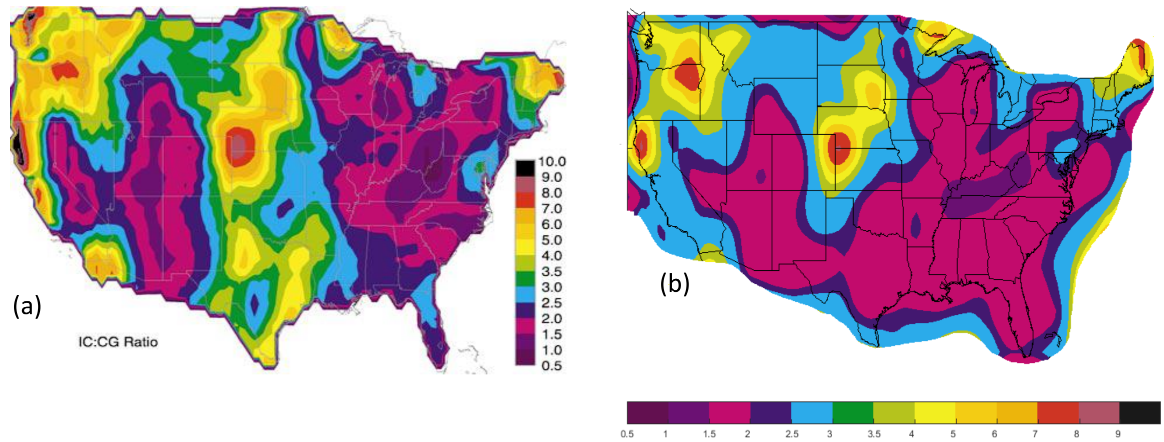

Figure 13:(a) Boccippio et al. 2001 IC:CG ratio and (b) new IC:CG ratio. Both are smoothed and contoured the same.

Both Z and Cloud Fraction exhibit high values in parts of northwest Texas, Kansas, Nebraska, and the Dakotas, which is a stable and dominant feature. Carey and Rutledge (2003) observed that in the Upper Great Plains, severe storms have a large impact on the mean annual Z and the associated high percentage of positive CG lightning. Typically what is seen throughout CONUS is that around 80% of warm-season severe storms produce mostly negative CG flashes, but about 20% have a large (>25%) fraction of positive polarity CG flashes (Carey and Buffalo 2007). They also note that a large fraction of severe storms are “positive dominant” storms in central and Northern plains from the Texas Panhandle northwestward to Minnesota. The meteorological reasons for these anomalies are discussed in Carey and Buffalo (2007) and Bruning et al. (2012).

Figure 13 compares the Boccippio et al. (2001) 4-year Z ratio climatology and our new 17.5 year climatology. Both studies show a clear maximum over Kansas, Nebraska, and the Dakotas, as well as maxima over Washington, Idaho, Oregon, and Northern California. This is expected given that our climatology above 38°N is only 25% larger (5 years vs. 4 years). Similar patterns are seen over Eastern United States and over the Rocky Mountains. However, there are significant differences over Texas with lower Z values for the updated climatology, resulting in nearly-constant Z values between 1.5 and 2.0 from the southern inter-mountain west, through the gulf coast, and throughout the eastern U.S. We ascribe these differences to a much longer observation period south of 38°N.

5. CONCLUSIONS AND FUTURE WORK

This study extends the IC:CG ratio (Z) climatology study carried out by Boccippio et al. (2001) by employing larger datasets and including a Cloud Fraction analysis. It used OTD, LIS, and NLDN data for a 17.5 year period from May 1995 through December 2012 (OTD for the first 5 years). The strong correlation between high Z and positive CG lightning in the Central United States observed by Boccippio et al. (2001) remains as a key observation. High Z ratio values along the U.S. west coast may be an observational problem associated with the low flash densities that occurs in those areas.

This work provides the first assessment of Z over coastal waters. Both the NLDN and satellite dataset reported enhanced lightning over the Gulf Stream, but there was no clear variation in the Z ratio in this region.

Future work will address the sources of variability (inter-annual variability vs. satellite sampling limitations) in order to place quantitative bounds on uncertainty in the Z ratio and Cloud Fraction climatologies**.** Our long-term objective is to extend this analysis to a global IC:CG climatology employing the complete OTD/LIS dataset and the Global Lighting Dataset (GLD360), in order improve our understanding of lightning behavior throughout the world.

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