8.2 CLOUD LIGHTNING PERFORMANCE AND CLIMATOLOGY OF THE U.S. BASED ON THE UPGRADED U.S. NATIONAL LIGHTNING DETECTION NETWORK

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ABSTRACT:
The 2013 upgrade of the U.S. National Lightning Detection Network (NLDN) was anticipated to provide uniform cloud lightning (IC) flash detection efficiency (DE) of about 50% over the entire continental U.S. In this study, we expand upon earlier, preliminary DE validation work that used Lightning Mapping Array (LMA) data. In this study, we add additional LMA data and additional case studies during 2014 to verify that the upgraded NLDN has a cloud lightning DE that is fairly uniform and is between 50 – 60%. Further, we utilize the first full year of data from the upgraded NLDN to offer the first IC-only lightning climatology of the continental U.S. We also provide an NLDN-based version of the climatology of the IC-CG ratio over the U.S., an initial version of which was published in 2001 based on comparisons of NLDN data with the low-earth orbiting satellite OTD (Optical Transient Detector).

1. Introduction

In 2001, Boccippio et al. published the first spatial map of the ratio of cloud flashes to cloud-to-ground (CG) flashes over the continental United States based on four years of combined observations from the low-earth orbiting Optical Transient Detector (OTD) and the U.S. National Lightning Detection Network (NLDN). This ratio is commonly referred to as the "IC-CG" ratio, and we employ that terminology throughout this paper as well. Prior to the Boccippio et al. (2001) study, a number of point measurements of the IC-CG ratio had been taken at various places around the world (see references within Boccippio et al. 2001), but no spatial map of the ratio had been presented. The prior point measurements had shown an approximate latitude dependence of the IC-CG ratio, albeit with a high degree of variability. The spatial map presented by Boccippio et al. gave a much richer picture of the variability in IC-CG ratio, with high values over the great plains and northwestern regions of the U.S. and low values over higher terrain in the Rockies, Appalachians, and Sierra Nevada, as well as the Great Lakes and parts of the southeastern U.S. Generally similar findings over all but the south-central U.S. are presented in this conference by Medici et al (2015) based on an expanded set of both satellite and NLDN data. The regional maximum in the plains is attributed to the relatively high proportion of strong to severe thunderstorms, which also produce higher amounts of positive CG lightning on average in that region. In Boccippio et al., the maximum in the northwestern U.S. was thought to be due possibly to biases in the data and could not definitively be attributed to a physical cause. The primary limitation cited by Boccippio et al. in the data set was the very limited temporal sampling afforded by the OTD.

In 2013, the U.S. NLDN underwent a complete upgrade to LS7002 sensors (Nag et al. 2014). The new sensors have greater sensitivity to the low-frequency (LF) pulses generated by cloud discharges (hereafter "cloud pulses") and can deliver data about pulse trains generated by in-cloud discharge processes such as preliminary breakdown (Murphy and Nag, 2014). One of the objectives of the 2013 NLDN upgrade was to provide continuous and uniform detection efficiency (DE) of cloud flashes over the continental U.S. Preliminary validation of the CG performance of the upgraded NLDN by Mallick et al. (2014), using rocket-triggered lightning in Florida, showed a CG flash DE of 100%, a CG stroke DE of 76%, and a median location accuracy of 173 meters. Preliminary validation of the cloud flash performance of the upgraded NLDN using Lightning Mapping Arrays (LMAs; Thomas et al. 2004) as reference was presented by Murphy et al. (2013a) and Murphy and Nag (2014). Those studies showed cloud flash DE ranging mostly between 40-60%, with one exception that was tentatively attributed to an area of slightly longer sensor baselines in northeastern Colorado. Further investigation of the issue was recommended at that time. A DE value in the 40s has also been found by Zhang et al. (2015, this conference) over Kansas using a combination of video and LMA data.

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The 2013 NLDN upgrade affords the opportunity to revisit the Boccippio et al. IC-CG ratio study with a single data source that provides continuous sampling of both cloud and CG flashes. Our first objective in this study is to expand upon the preliminary cloud flash DE analysis presented by Murphy et al. (2013a) and Murphy and Nag (2014) in order to provide further evidence that the cloud flash DE of the upgraded NLDN is indeed at the anticipated level of approximately 50%. With that as background, we then present one-year densities of CG flashes, cloud flashes, and the resulting IC-CG ratio, using data from 1 September 2013 through 31 August 2014 from the upgraded NLDN. The paper is organized as follows. Section 2 describes the flash grouping algorithm and methods of analysis applied in this study. Section 3 provides updated cloud flash DE based on further validation against LMA data. Section 4 presents the one-year CG flash, cloud flash, and IC-CG ratio climatologies, with comparisons to the satellite-based studies, and section 5 outlines future work.

2. Methods

a. Flash grouping algorithm

In prior versions of the NLDN, only CG strokes were grouped into flashes under the assumption that the cloud pulse DE was insufficient to warrant grouping the limited number of cloud pulses that were detected. As a result of the upgrade, however, the NLDN now detects many more cloud pulses, including those that are clearly associated with CG flashes, such as preliminary breakdown (Murphy et al., 2013a). Thus, we have developed a new flash grouping algorithm that allows cloud pulses and CG strokes to be grouped into the same flashes. The essential elements of the new flash grouping algorithm are the same as described by Cummins et al. (1998; Fig. 6). However, cloud pulses are grouped into the flashes with a somewhat larger spatial radius than CG strokes due to the greater spatial extent of in-cloud discharge activity. In addition, the maximum CG stroke limit of 15 in the original algorithm has been increased to 63, and the maximum number of cloud pulses that can be included in a single flash is 1023. We anticipate that these limits are sufficient to accommodate all possible flashes detectable by the NLDN, whose LF sensors do not detect the same high numbers of pulses observable by an LMA. Each flash produced by this new grouping algorithm contains a count of the number of CG strokes and a separate count of the number of cloud pulses. These counts allow us to define a ***CG flash*** in this paper as any flash containing at least one CG stroke, and a ***pure IC flash*** as any flash containing only cloud pulses.

b. Assessment of the cloud flash DE of the NLDN

Data from a couple of LMAs were used as a reference with which to evaluate the cloud flash performance of the NLDN during several low flash-rate thunderstorms in 2014. The analysis procedures are similar in essence to those described in Murphy et al. (2013b) and Murphy and Nag (2014). The LMA data were first filtered to eliminate scattered non-lightning points, and then the data were processed with the VHF flash grouping algorithm described by Lojou and Cummins (2005). The manual flash counting analysis described in Murphy et al. (2013b) indicated that the default set of space and time parameters used by Lojou and Cummins produced reliable flash counts when used to process data from the São Paulo LMA during CHUVA. The same was found by Murphy and Nag (2014) using data from LMAs in Kansas and Colorado in 2013.

In this study, we use data from the same Colorado LMA as before, and we now also include data from the Oklahoma LMA (MacGorman et al., 2008). The data sets that we received from the latter system in near real-time showed evidence of data drop-outs and periods of time when only 7-8 LMA stations were operational. To work around these issues, we selected only time periods when all or nearly all NLDN-reported CG flashes had some associated in-cloud activity as reported by the LMA. Further complicating the analysis of the Oklahoma LMA data was a time offset of +1 second between the LMA data that we received and the NLDN data. Note that this time offset was not found in any other LMA data set that we analyzed either in 2013 or 2014. Finally, in order to get manual flash counts from low-rate storms in Oklahoma to match the automated flash counts generated by the Lojou and Cummins (2005) flash algorithm, we found it necessary to raise the time grouping parameter of the algorithm from 0.5 to 0.75 seconds. Again, this was only found to be necessary when processing the Oklahoma LMA data; otherwise, the default space and time parameters of the VHF flash grouping algorithm were used.

To examine the flash detection efficiency of the NLDN, we match LMA flashes either to the first return stroke in NLDN-reported CG flashes or to the first cloud pulse in NLDN-reported pure IC flashes. Similar to some of the flash-level analysis described in Murphy et al. (2013b), we used a spatial buffer of 10 km around each LMA flash and time buffer of 250 ms to match NLDN-reported flashes of either type (CG or pure IC) to the LMA flash data. In order to be less restrictive with the LMA data than Murphy and Nag (2014), we only eliminated LMA flashes having 1-2 sources in this analysis, rather than removing all flashes with fewer than 5 sources.

c. NLDN data processing

All NLDN data from 1 September 2013 through 31 August 2014 were used to produce the one-year densities of CG flashes, pure IC flashes, and the IC-CG ratio. The raw data from the sensors were first reprocessed in order to double check all angle error corrections and then were run through the new flash grouping algorithm described in part a of this section. Given the limitations of a one-year data set, we elected to present the spatial maps on a relatively coarse 0.25° by 0.25° latitude, longitude grid. The grid boxes have areas ranging from about 667 km^2 at 30° latitude to 590 km^2 at 40° and 495 km^2 at 50°. The CG flash density is plotted using a logarithmic color scale that saturates at 10^4 flashes per grid box. Taking 600 km^2 as the typical grid box size, the maximum value of the color scale corresponds to an annual flash density of 16.7 flashes km^{-2} yr^{-1}, near the upper end of CG flash density values reported over the southeastern U.S. in other studies using grids of comparable resolution (e.g. Holle 2014, Zajac and Rutledge, 2001). The pure IC flash density uses a similar logarithmic color scale that saturates at 10^5 flashes per grid box, corresponding to an annual flash density of approximately 167 flashes km^{-2} yr^{-1}.

3. Cloud lightning DE of the NLDN in 2014

Table 1 summarizes the results of the NLDN cloud lightning performance in 2014 estimated using the VHF Lightning Mapping Array data as ground truth. As in the recent studies by Murphy et al. (2013a) and Murphy and Nag (2014), the detection efficiency of CG flashes given here refers to the percentage of CG flashes that *also contain NLDN-reported cloud pulses.*

Table 1. Summary of NLDN cloud and total lightning detection efficiency in 2014 estimated using VHF Lightning Mapping Array data as ground truth

LMA	Date	Time (UTC)	CG flashes	IC DE, CG flashes (%)	Pure IC flashes	IC DE, pure IC flashes (%)	IC DE, all flashes	Total ltng. DE (%)
Oklahoma	2 Sept.	05:25-05:45	45	60.0	302	50.3	51.6	56.8
Oklahoma	22-23 May	23:40-00:27	143	76.2	669	53.5	57.5	61.7
Oklahoma	23 May	19:00-19:20	12	58.3	47	57.4	57.6	66.1
Oklahoma	26 May	15:27-16:06	49	83.7	177	46.3	54.4	58.0
Oklahoma	27 May	03:59-04:35	90	86.7	163	71.2	76.7	81.4
Oklahoma	consolidated		339	77.3	1358	54.1	58.8	63.3
Colorado	10 Aug.	18:00-19:00	42	59.5	77	51.9	54.6	68.9
Colorado	15 Aug.	01:15-03:15	28	82.1	134	61.9	65.4	68.5
Colorado	20 Sept.	00:46-02:00	44	68.2	109	47.7	53.6	62.7
Colorado	29 Sept.	18:00-19:15	26	69.2	59	37.3	47.1	56.5
Colorado	1 Oct.	19:00-20:30	40	80.0	201	42.3	48.5	51.9
Colorado	9 Oct.	18:00-24:00	25	80.0	83	18.1	32.4	37.0
Colorado	consolidated		205	72.2	663	44.8	51.3	57.8

Overall, we find that the CG flashes tend to have a higher IC DE than the pure IC flashes, consistent with the 2013 studies and consistent with the fact that preliminary breakdown pulse trains are fairly well detected by the upgraded NLDN. The overall IC detection efficiency, given in the second last column, refers to the fraction of all flashes that have at least one NLDN-detected cloud pulse. The last column in Table 1, total lightning DE, is the fraction of all flashes that were detected by NLDN, either with CG strokes, cloud pulses, or both. In both Oklahoma and Colorado, the overall IC DE value (2nd last column) is between 50 – 60%, somewhat higher than indicated by our cloud flash detection efficiency model. The case of anomalously low DE in Colorado, 9 October, appears to be attributable to a lower average number of sensors contributing to low-amplitude discharge positions in the region. We have not been able to identify any network effect in this case; rather, it appears that there was simply a lower average amplitude of the cloud pulses in this case. Our tentative overall conclusion, based on the analysis presented previously by Murphy and Nag (2014) and the current results, is that the cloud flash DE of the NLDN is generally uniform over the states of Oklahoma, Kansas, and Colorado.

4. One-year data analysis

Figure 1 shows the CG flash density over the one year of the study. As mentioned in section 2c, the color scale is logarithmic and saturates at a value of approximately 16-17 flashes km^{-2} yr^{-1}, comparable to maximum values found in prior CG lightning climatologies that used comparable grid resolutions and were based on NLDN data. As expected, the maximum CG flash densities are found over Florida and along the Gulf coast. Overall, Figure 1 matches prior CG flash climatologies of the U.S., but because this is just a single year of data, some of the detailed features observed in previous lightning climatologies are washed out in our Figure 1. Nevertheless, we do observe a local minimum in CG flash density over the Appalachians and a local maximum over the high terrain areas affected by the North American summer monsoon in the southwestern U.S. and northwestern Mexico (Holle and Murphy, 2015).

Figure 2 shows the corresponding pure IC flash density, not corrected by the expected cloud flash detection efficiency of the network. As discussed in section 2c, this map has a color scale that saturates at 10 times the value of Figure 1, that is, up to about 160-170 flashes km^{-2} yr^{-1} over the typical grid box size of 600 km^{2}. This saturation value is not actually reached, although some areas of Florida and the Gulf coast approach it. In general, the pattern is very similar to that of the CG flash density, although the cloud flash density falls off more rapidly off the coasts and into parts of Mexico and Canada, consistent with the fact that LF cloud pulses have mostly lower amplitudes than CG strokes, such that the cloud flash DE is expected to drop more rapidly outside the boundaries of the NLDN than it does in the CG density analysis.

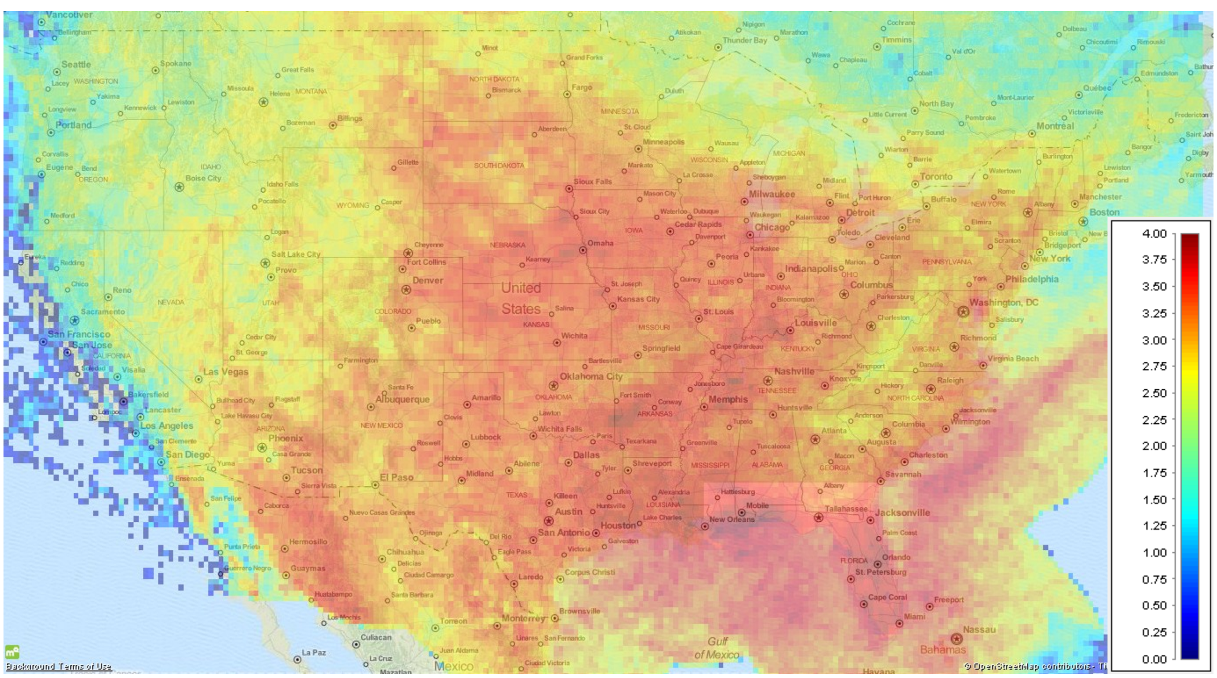

Figure 1. One-year density of CG flashes in grid boxes of 0.25° latitude by 0.25° longitude. The color scale in the legend is logarithmic (see section 2c).

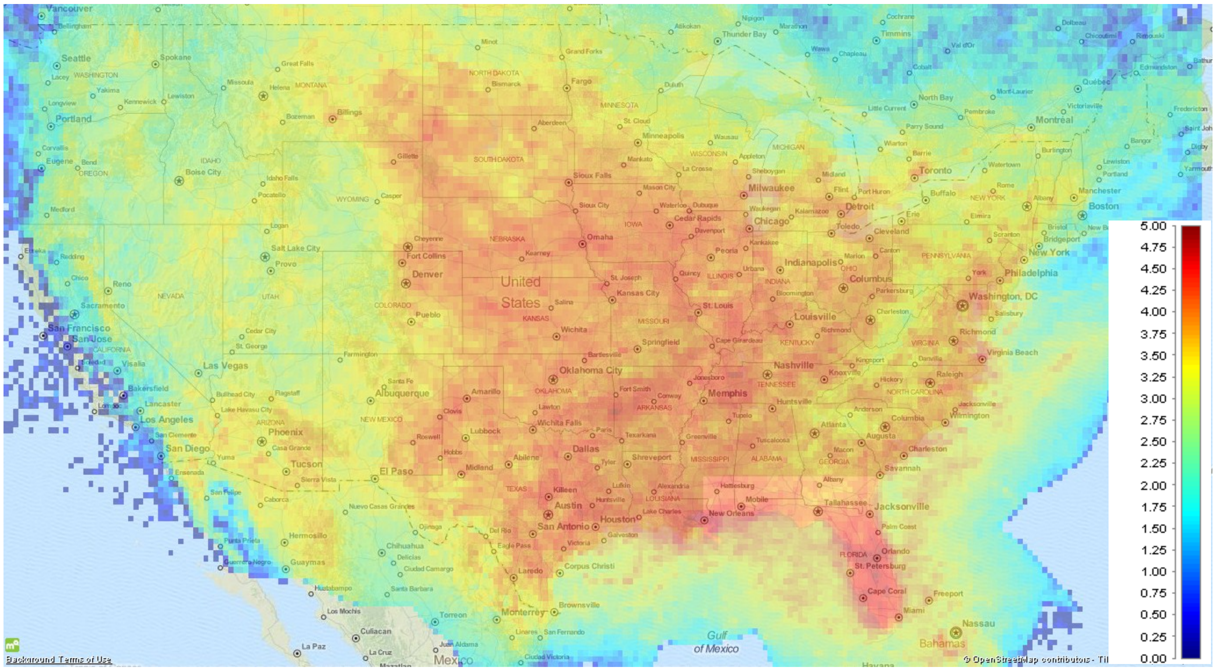

Figure 2. One-year density of cloud flashes in grid boxes of 0.25° latitude by 0.25° longitude. The color scale in the legend is logarithmic (see section 2c), and note that the maximum here is 5, as opposed to 4 in Fig 1.

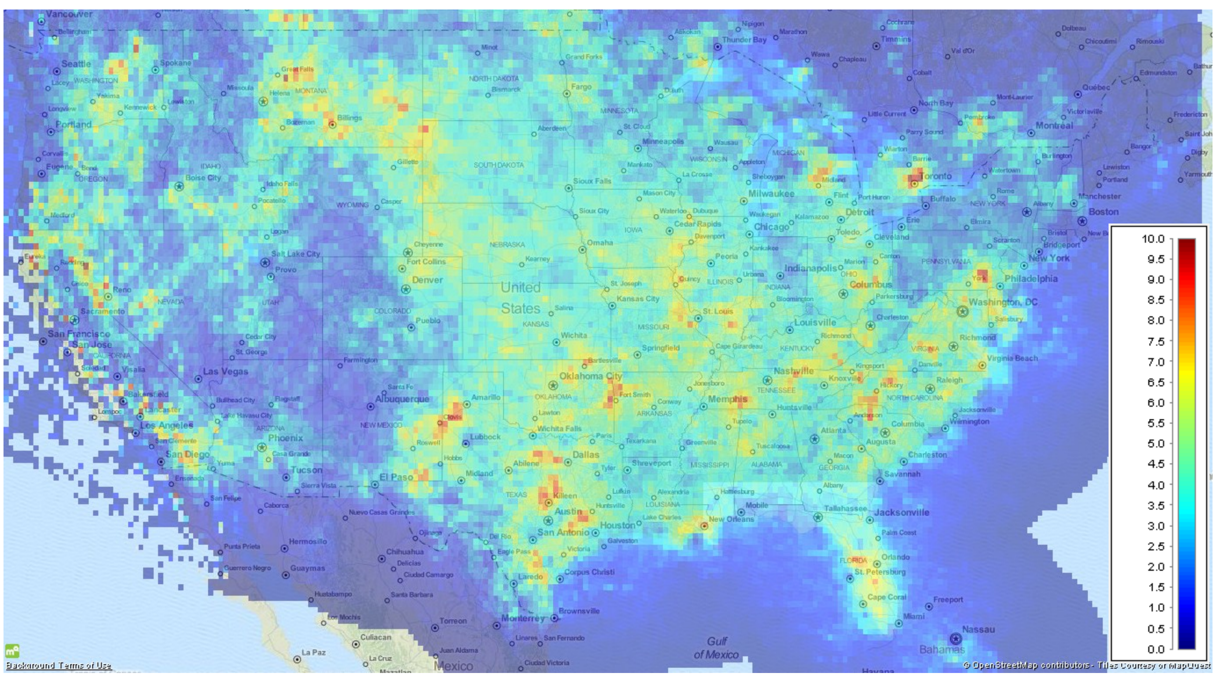

Figure 3. One-year analysis of the IC-CG ratio in grid boxes of 0.25° latitude by 0.25° longitude. The color scale is linear from 0.0 to 10.0.

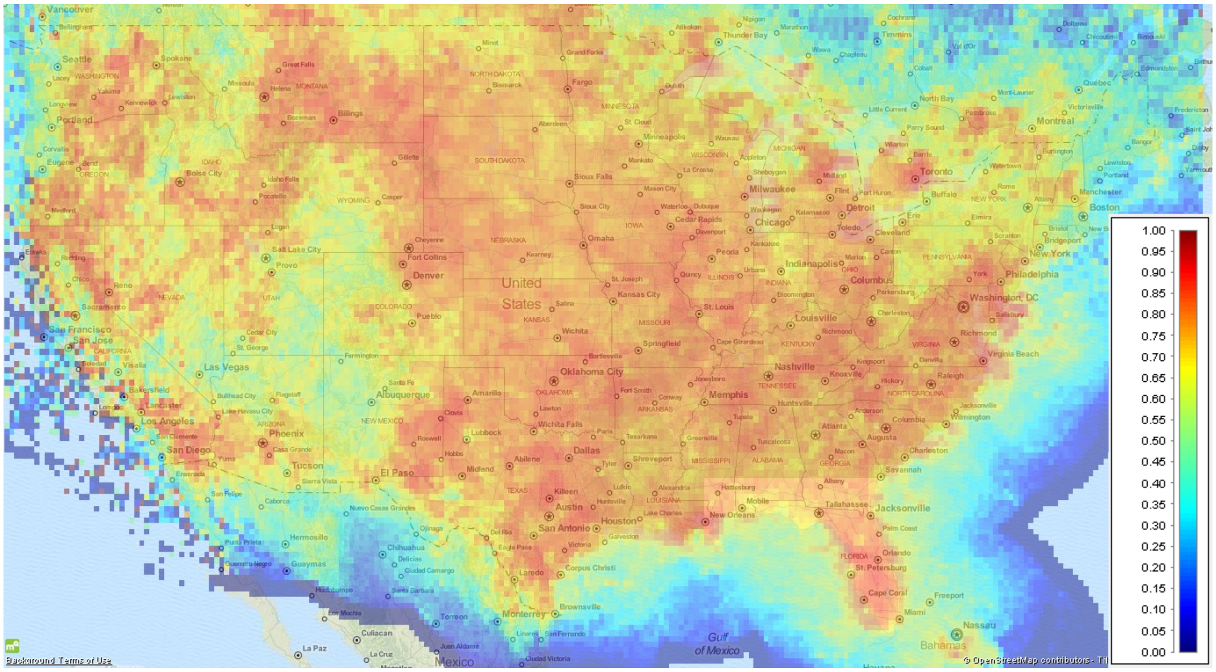

Figure 4. One-year analysis of the IC flash fraction in grid boxes of 0.25° latitude by 0.25° longitude. The color scale is linear from 0.0 to 1.0.

Figure 3 presents the IC-CG ratio derived from Figures 1 and 2, using a linear color scale ranging from 0 to 10. As in Fig. 2, no detection efficiency correction has been applied to Fig. 3 (see further discussion below). Although the IC-CG ratio is needed in order to make comparisons with the results of Boccippio et al. (see below), we also present the IC flash fraction derived from Figures 1-2 in Figure 4, on a linear scale ranging from 0 to 1. The IC flash fraction is, of course, a numerically stable quantity. It is particularly suitable when working with small sample sizes such as this, and especially storm-scale analyses where one might be interested in the relationship between the total lightning activity and severe weather, for example.

a. Comparisons with the Boccippio et al. IC-CG ratio climatology

Figure 3 shows a broad minimum in IC-CG ratio over the Rocky mountain region, including western Montana and northern Idaho but not the Snake River valley, which has previously been shown to have a local minimum in CG flash density. The broad minimum in IC-CG ratio over the interior western U.S. is very similar to that shown by Boccippio et al. (2001).

Also similar to Boccippio et al. is the local maximum in IC-CG ratio over the northwestern U.S. Interestingly, this maximum occurs mostly over higher terrain, including portions of northern California in the Sierra Nevada and southern Cascades. Note that the Sierra Nevada was a local minimum in IC-CG ratio in Boccippio et al. Although the rather low flash densities over California preclude drawing too many conclusions too far south, the fact that the local maximum in IC-CG ratio in the northwestern U.S. and the local minimum over most of the interior western U.S. both occur mainly over high terrain suggests that terrain altitude may not, by itself, be singularly associated with low IC-CG ratio, at least not in the western U.S.

In the eastern U.S., Boccippio et al. observed a local minimum in IC-CG ratio over the Appalachians but also extending westward to the Mississippi River. In our Figure 3, we find a local minimum that is confined to the northern Appalachians only, mainly in the states of Pennsylvania and New York. Farther south and west, we observe IC-CG ratio values mostly between 4-8. This is obviously a significant departure from the satellite-based climatologies presented by both Boccippio et al (2001) and Medici et al. (2015). Some preliminary investigation of this discrepancy is provided in section b below.

b. Detailed discussion

Over the eastern and central U.S., Fig. 3 also shows a variety of local minima and maxima in IC-CG ratio. These local minima and maxima could either be due to (1) inhomogeneities in the cloud flash DE of the NLDN that are not sampled by our localized LMA-based validation, or (2) statistical variations due to the fact that this is just a one-year sample (e.g., a couple of very large thunderstorm days with, perhaps, extreme values of IC-CG ratio dictate some of the regional maxima in our sample). To investigate this question, we ran a model of cloud flash DE over the continental U.S. using the identical grid resolution as Figures 1-3, and then correlated the modeled DE values with the observed IC-CG ratios from Figure 3. The result of this analysis is shown in Figure 5. We find a decent correlation only when the modeled DE is lower than about 15%, which corresponds to areas off the coasts and in northern Mexico and parts of Canada. Over the continental U.S., where the majority of grid points are predicted to have cloud flash DE values ranging from the mid-30s to mid-60s (in percent), the observed IC-CG ratio values vary mostly between 1-8 regardless of the modeled DE. This suggests that statistical fluctuations in our limited, one-year sample are the dominant cause of the local minima and maxima in the IC-CG ratio seen in Figure 3. The dominance of statistical variations also makes sense when we consider that only the first cloud pulse in pure IC flashes was used to generate the IC flash density. Cloud flashes often have large horizontal extents, as observed in LMA data, and thus, representing them by a single point can contribute additional spatial variability to the density map, beyond that created by the limited sample size.

Note also that the model-estimated cloud flash DE values in Figure 5 are almost all lower than we find by way of the LMA-based validation (section 3). In addition, we observe clusters of model-estimated DE values. Over the interior of the NLDN, two primary clusters occur, one in the high 40s of percent and another in the low to mid-30s. A preliminary detailed examination of our cloud flash DE model suggests that it over-predicts the fraction of flashes detected by only 2 sensors. This tendency leads both to the clustering of modeled DE values and to the general underestimation of cloud flash DE

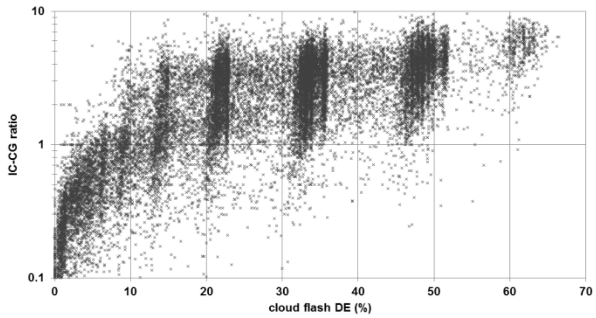

Figure 5. Observed IC-CG ratio from Fig. 3 vs. modeled cloud flash DE in percent.

relative to the LMA validations. Further study of the cloud flash DE model is currently underway. The discrepancy between the model and LMA-based validation is the reason why no DE correction of our IC density or IC-CG ratio maps has yet been attempted.

We have also considered whether the new NLDN flash grouping algorithm, and specifically, the spatial parameter used to associate cloud pulses in this flash algorithm, might be a source of higher numbers of pure cloud flashes, and thus higher IC-CG ratio, over the eastern half of the U.S. To investigate this question, we have varied the cloud pulse spatial grouping radius of the new NLDN flash algorithm over a factor of 3 in discrete steps: 10 km, 30 km, as well as its default value of 20 km, used to produce Figs. 1-4. We computed the spatial maps of IC-CG ratio under both of the altered cloud pulse grouping radius values, and finally, we computed a spatial map of the ratio of the largest IC-CG ratio to the smallest IC-CG ratio obtained among the three flash algorithm runs (default IC grouping radius of 20 km, plus the 10- and 30-km runs). In what follows, we refer to this ratio simply as the "*flash algorithm sensitivity*" of the IC-CG ratio. Wherever its value is 1, the IC grouping radius has no effect on the IC-CG ratio, and wherever its value is relatively large, there is substantial sensitivity.

The map of flash algorithm sensitivity was calculated using the final two months of our study period – July and August, 2014 – and is shown in Figure 6, on a color scale going from 1.0 (dark blue) to 1.6 (dark red). From the Great Plains eastward, the sensitivity is generally somewhat higher than it is over the western U.S., but it is still less than 1.3 almost everywhere. That is, we can vary the IC spatial grouping radius by a factor of 3 without changing

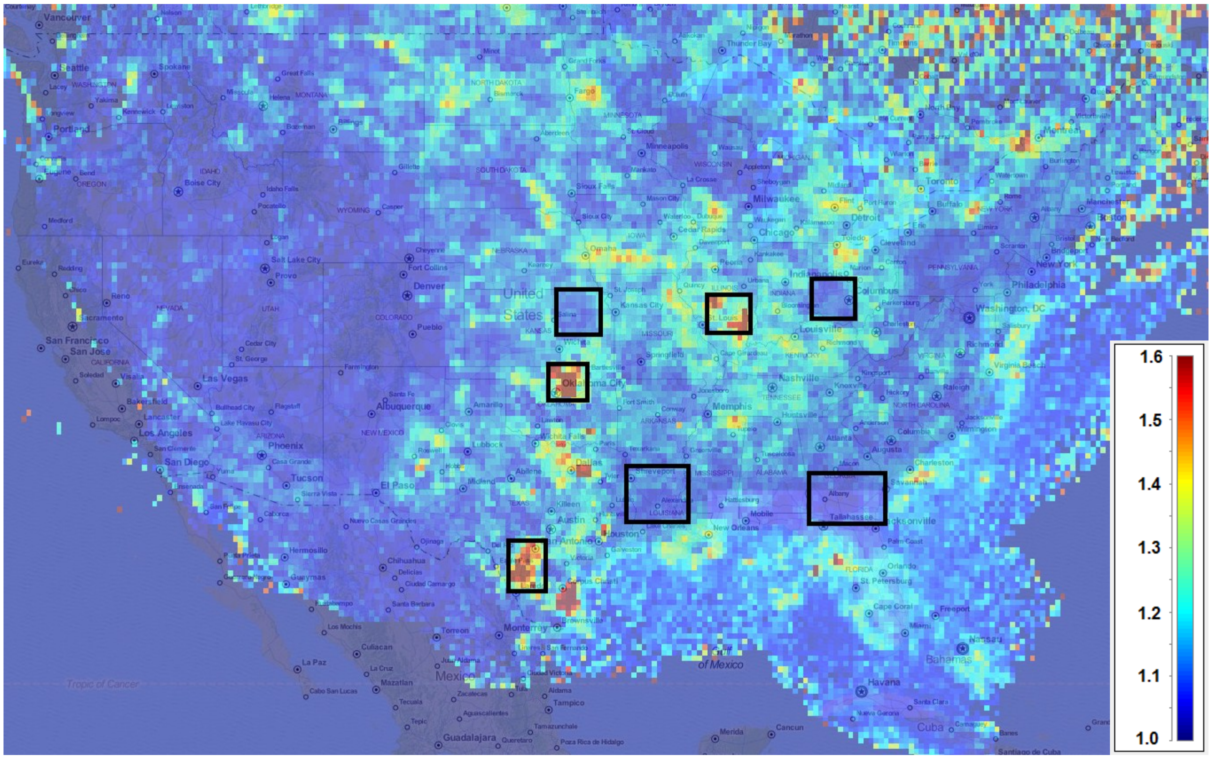

Figure 6. Map of flash algorithm sensitivity in the IC-CG ratio; definition in text of section 4b. The seven boxes show regions of hourly lightning density analysis described in the text.

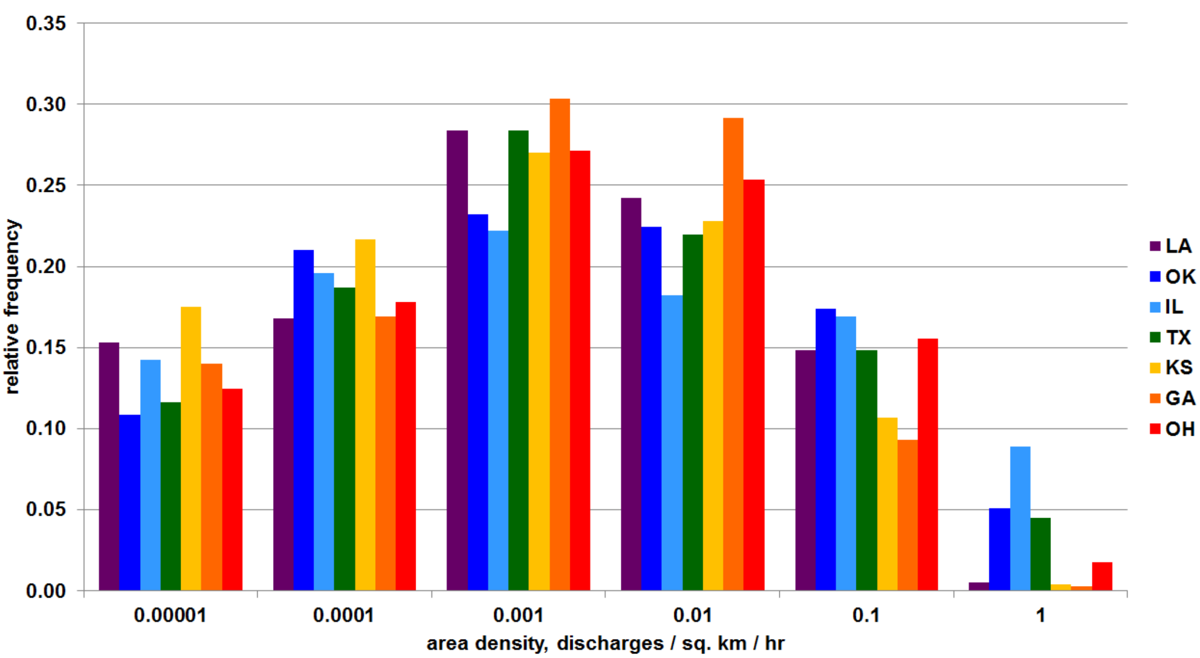

Figure 7. Distribution of the hourly density of all discharges (CG strokes plus cloud pulses) in UTC hours that had lightning activity during July and August, 2014, within each of the seven boxes shown in Figure 6.

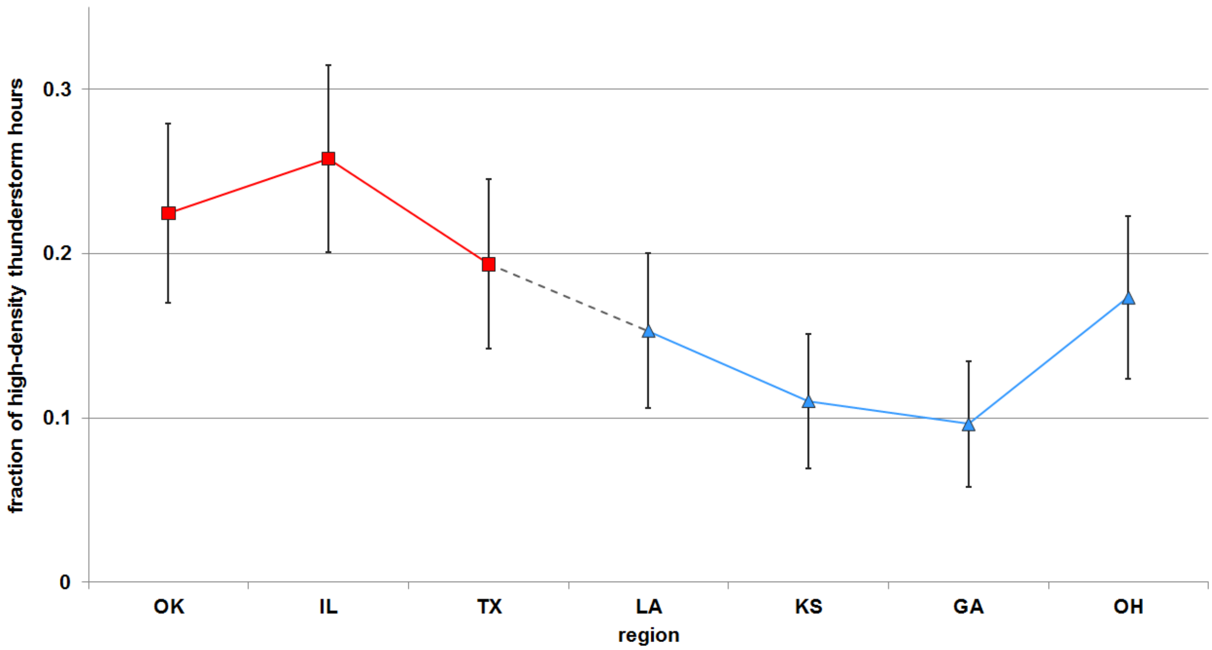

Figure 8. Fraction of lightning-containing hours in which the area density of discharges exceeded 0.1 km^{-2} hr^{-1} in each region, together with approximate 95% confidence intervals (error bars). The three red dots show the regions with highest flash algorithm sensitivity in Fig. 6, and the four blue dots show the regions with very low flash algorithm sensitivity in Fig. 6.

the IC-CG ratio by more than 30% over most of the central and eastern U.S. Thus, flash algorithm sensitivity does not appear to be the primary factor behind the relatively high IC-CG ratios that we observe east of the Mississippi river relative to the satellite-based studies.

In Figure 6, we see that there are a few spots where the flash algorithm sensitivity reaches 1.5 – 1.6, as well as some areas where it is much closer to 1.0. Several of these regions are marked with black boxes in Figure 6. One question is whether high flash rates contribute to the break-up of flashes by the flash algorithm, and thus lead to higher sensitivity to the flash algorithm parameters. A strong correlation between high flash algorithm sensitivity and a preponderance of high lightning-rate storms would indicate that high flash rates are indeed a source of bias in our IC-CG ratio numbers.

To investigate this question, we selected three areas from Figure 6 where the flash algorithm sensitivity is rather high – northern Oklahoma (OK), southern Texas (TX), and south-central Illinois (IL) – and four areas where there is almost no flash algorithm sensitivity – Louisiana (LA), northeastern Kansas (KS), south Georgia (GA), and southwestern Ohio (OH). Within each of these regions, we looked at all UTC hours in July and August 2014 that had at least some lightning. Using the hourly counts of total discharges, that is, CG strokes plus cloud pulses, and the approximate area of each region, we computed the hourly discharge density (discharges km^{-2} hr^{-1}) and made a distribution of that quantity in each region, using a logarithmic bin width in the distribution. The results are shown in Figure 7, color-coded by region. Note that we specifically use the area density of *raw discharges* per hour, rather than flashes, because the former are the pure inputs to the flash algorithm and we want to avoid convolving the flash algorithm output into this aspect of the analysis. It appears that there is a slight tendency for the OK, IL, and TX regions – the ones with high flash algorithm sensitivity – to have higher relative frequencies in the upper two bins of the hourly discharge density distribution. That is, these three regions appear to have a somewhat higher proportion of lightning-containing hours that have high lightning rates, averaged over the region areas.

To examine that trend in more detail, in Figure 8, we show the fraction of all lightning-containing hours whose area density of discharges is 0.1 km^{-2} hr^{-1} or greater. These fractions are also plotted together with approximate 95% confidence bounds to address the question of significance. The three regions with high flash algorithm sensitivity are on the left, and the four regions with almost no sensitivity are on the right. In general, the fraction of high-density hours is higher in the OK, IL, and TX regions than in the other four regions. However, there is also significant overlap of confidence bounds between the OK and TX regions and the LA and OH regions where flash algorithm sensitivity is very low. The distinction becomes greater if we look at the fraction of hours having an area density of discharges of 1.0 km^{-2} hr^{-1} or greater, although there is still overlap of confidence regions especially between the OK, TX, and OH regions. It may be important to note, however, that the hours with discharge densities greater than or equal to 1.0 km^{-2} hr^{-1} contain a much higher fraction of all of the lightning observed in the three high-sensitivity regions, OK, IL, and TX; in these regions, 61-76% of all discharges were observed during hours when the area-averaged density was 1.0 km^{-2} hr^{-1} or greater, whereas in the other four regions, only 8-38% of all observed discharges occurred during such hours. Thus, it is possible that high lightning rate is a dominant factor in producing relatively high sensitivity to the flash algorithm parameters.

As noted above, flash algorithm sensitivity itself does not appear to explain fully the high IC-CG ratios that we observe over the east-central U.S. relative to the satellite-based climatologies. As of this writing, however, we are not able to rule out the possibility that the new flash algorithm may have a general tendency to break up cloud flashes. If such an overall bias exists, it may not manifest itself much in terms of sensitivity to the flash algorithm parameters. We have initiated an investigation of this issue but detailed discussion is not possible at the present time.

5. Conclusions and Future Work

This study provides a one-year cloud flash climatology of the continental U.S. based on the 2013 upgrade of the NLDN, together with a preliminary IC-CG ratio analysis as a follow-up to the Boccippio et al. (2001) study and complement to the new study by Medici et al (2015). We find that our analysis reproduces some of the broad, dominant features of the IC-CG ratio that were pointed out in the satellite-based studies, but not others. Specifically, we find broad minima in IC-CG ratio over the interior western U.S. and the northern Appalachians, and maxima over the Great Plains and northwestern U.S. In contrast to the satellite-based studies, however, we find larger IC-CG ratios over almost the entire area east of the Mississippi river except the northern Appalachians. Local minima and maxima that are scattered throughout the eastern and central parts of the country are due primarily to the short sample period. Future studies will utilize longer periods of study in order to investigate some of the features of the IC-CG ratio climatology in greater detail, especially the eastern U.S. discrepancy.

We note that Figures 3-4 were generated without any DE correction. Our LMA-based validations over portions of Kansas, Oklahoma, and Colorado suggest that the cloud flash DE of the upgraded NLDN is fairly uniform and approximately 50 – 60%. This is higher than indicated by our cloud flash DE model. Further investigation of our cloud flash DE model is a major goal of future studies, and that work can hopefully lead to an appropriate DE correction to apply to the results given in this study or future studies.

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