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A Study of NLDN Responses to Cloud Discharge Activity Based on Ground-Truth Data Acquired at the LOG

Yanan Zhu, Vladimir A. Rakov, Manh D. Tran
Department of Electrical and Computer Engineering
University of Florida
Gainesville, FL, USA
yananzhu@ufl.edu

Amitabh Nag
Vaisala Inc.
Louisville, USA
amitabh.nag@vaisala.com

***Abstract*— The NLDN detection efficiency and classification accuracy for cloud discharge activity (IC events) were evaluated using optical and electric field data acquired at the Lightning Observatory in Gainesville (LOG), Florida. The results correspond to the NLDN configuration and settings that existed in the summer of 2014. We defined the "IC event" as any sequence of electric field pulses, in either cloud (IC) or cloud-to-ground (CG) flash, that (1) had pulse waveshapes clearly different from those characteristic of return strokes and (2) were not associated with channels to ground in the corresponding high-speed video camera records. Our ground-truth "IC events" include 26 "isolated IC events" that can be viewed as complete IC flashes, 58 "IC events before 1st return stroke", and 69 "IC events after 1st return stroke". Events in the latter two categories occurred in 76 CG flashes. For the 153 "IC events", 33% (50 of 153) were detected by the NLDN, and the NLDN classification accuracy was 86% (43 of 50). For complete IC flashes, the detection efficiency and classification accuracy were 73% and 95%, respectively, and the average number of reported pulses was 3.1. We additionally identified 24 preliminary breakdown (PB) pulse trains in CG flashes, out of which 11 (46%) were detected and 9 (82%) of the 11 were correctly classified as cloud events. For the 9 correctly classified events, average number of NLDN-reported cloud pulses per train was 1.3. We have also estimated the detection efficiency and classification accuracy for return strokes in CG flashes (all confirmed by observed channels to ground). For both first and subsequent return strokes in both positive and negative CG flashes taken together, the NLDN stroke detection efficiency and classification accuracy were 93% (340 of 366) and 91% (311 of 340), respectively. Both the detection efficiency and classification accuracy for first strokes were higher than their counterparts for subsequent strokes.**

Keywords*— *NLDN; cloud discharge; detection efficiency; classification accuracy

I. INTRODUCTION

The NLDN consists of more than 100 sensors separated by typically 300–350 km and mostly covering the contiguous USA. A combination of TOA and MDF locating techniques is employed. Both cloud (IC) and cloud-to-ground (CG) lightning discharges are reported. Classification is accomplished by applying field waveform criteria to individual magnetic field pulses. Generally, pulses wider than certain threshold are interpreted as being produced by return strokes (RSs) in CG flashes and labeled "G", while narrower pulses are attributed to cloud discharge activity and labeled "C". Since any CG flash involves some cloud discharge activity (notably the preliminary breakdown process), both "G" and "C" pulses can be reported by the NLDN during CG flashes. Occasionally, pulses produced by return strokes are misclassified as "C" and those produced by cloud discharge activity as "G".

In general, the detection efficiency is the fraction (usually expressed in percent) of the total events occurred that are detected by the system and is ideally equal to 100%. While the CG stroke detection efficiency can be readily defined (since these strokes involve a unique and observable feature - luminous channel to ground - and the total number of occurred events can be practically determined), the cloud discharge detection efficiency concept is rather uncertain. Indeed, there are many cloud discharge processes (some of them poorly understood) occurring on different spatial and time scales and apparently exhibiting no unique and readily observable features. As a result, the total number of occurred events is generally unknown. In practice, if all cloud discharge pulses are accepted as ‘‘counts,’’ the number of detected cloud discharges may be largely determined by the local noise level and lightning locating system's signal transmission rate limit.

CG stroke and flash detection efficiencies have been investigated, using video cameras, in Southern Arizona, Oklahoma, and Texas [Biagi et al., 2007]. The stroke detection efficiency in Southern Arizona was estimated to be 76 % (N = 3620), and in Texas/Oklahoma it was 85 % (N = 885). The corresponding flash detection efficiencies were 93 % (N = 1097) and 92 % (N = 367). Additionally, classification of lightning events as a cloud of CG discharges was examined in this study, as well as in a similar study (but additionally, using independent (LASA) electric field waveform measurements) in the Colorado–Kansas–Nebraska region [Fleenor et al., 2009].

Also, CG stroke and flash detection efficiencies have been also investigated, using as the ground-truth rocket-triggered-lightning data, in the Florida region [Jerauld et al., 2005; Nag et al., 2011; Mallick et al., 2014]. From the latest (2004–2012) study, the CG stroke and flash detection efficiencies were found to be 75 % and 94 %, respectively. Strokes in rocket-triggered flashes are similar to regular subsequent strokes (following previously formed channels) in natural lightning and, hence, the 75 % stroke detection efficiency value is applicable only to regular negative subsequent strokes in natural lightning. The flash detection efficiency is expected to be an underestimate of the true value for natural negative lightning flashes since first strokes typically have larger peak currents than subsequent ones.

Information about NLDN responses to cloud discharge activity is rather limited and may be outdated due to system upgrades (particularly the latest one completed in 2013). According to Cummins and Murphy [2009], the NLDN cloud-flash detection efficiency (a flash was considered detected if at least one VLF/LF pulse produced by that flash was detected) is in the range of 10–20%, depending on local differences in distances between stations. From a more recent study based on using data from two VHF lightning imaging systems (LMAs) as a reference, Murphy and Nag [2015] reported the cloud-flash detection efficiency to be in the 50-60% range. Wilson et al. [2013] stated that the NLDN typically reports 1–3 cloud pulses per flash. Nag et al. [2010] examined wideband electric fields, electric and magnetic field derivatives, and narrowband VHF (36 MHz) radiation bursts produced by 157 compact intracloud discharges (CIDs). The NLDN located 150 (96%) of those CIDs and correctly identified 149 (95%) of them as cloud discharges.

In this paper, we will focus on the NLDN detection efficiency (DE) and classification accuracy (CA) of cloud discharge activity based on the ground-truth dataset containing 153 IC events recorded at LOG. Additionally, a ground-truth dataset of 366 CGs recorded at LOG will be used to evaluate the DE and CA of CGs.

II. EXPERIMENTAL SETUP

Simultaneous electric field (low-gain and high-gain), electric field derivative (dE/dt), and high-speed video camera records are used in this study. All the records were obtained at the Lightning Observatory in Gainesville (LOG), Florida, in the summer of 2014. The low-gain electric field measuring system includes a circular flat-plate antenna followed by an amplifier with an RC time constant of 10 ms. The high-gain electric field measuring system includes an elevated antenna with a different amplifier having a higher-gain and an RC time constant of 420 μs, which allowed us to accentuate relatively small pulses. The bandwidths are 16 Hz to 10 MHz and 360 Hz to 10 MHz for the low-gain and high-gain electric field measuring systems, respectively. The upper-frequency response of the dE/dt measuring system is 10 MHz. The length of field records was 1 s with 100 or 200 ms pretrigger. The video data are obtained using an HHC-X2 high-speed video camera operated at 1000 fps with the resolution of 832×600 pixels. It was equipped with a fish-eye lens in order to have a wider (about 185°) field of view. The length of optical records was 1.2 s with 200 ms pretrigger. All the records were GPS time stamped. The field measuring system was synchronized with the high-speed video camera with precision better than 1 ms.

III. DATA AND METHODOLOGY

We defined the “IC event” as any sequence of electric field pulses, in either IC or CG flash, that (1) had pulse waveshapes clearly different from those characteristic of return strokes (RSs) and (2) were not associated with channels to ground in the corresponding high-speed video camera records (the camera had about 185^o wide field of view). Our ground-truth “IC events” include 26 “isolated IC events” that can be viewed as complete IC flashes and 127 IC events that occurred in 76 CG flashes. Out of the latter 127 events, 58 were “IC events before 1st RS” (including 24 preliminary breakdown (PB) pulse trains) and 69 were “IC events after 1st RS” (including pulses occurring between strokes and after the last stroke). Geometric mean durations for “isolated IC events”, “IC events before 1st RS”, and “IC events after 1st RS” were 504 ms, 23 ms, and 69 ms, respectively. The geometric mean duration for all the 153 “IC events” combined was 64 ms, and for 24 PB pulse trains it was 2.7 ms. The histogram of durations of IC events is shown in Figure 1. The IC event duration was limited by the electric field record length, which was 1 s.

Our methodology was as follows. We first identified the start and end of an “IC event” (a sequence of pulses, for which no channel to ground was observed with our high-speed video camera) in our 1-s long electric field records and then searched NLDN data within that time window and within 40 km of the LOG. In order to be counted as a pulse in a given sequence, the pulse had to meet two requirements: 1) the amplitude of the pulse exceeds twice the noise level and 2) the time separation from the preceding pulse is less than 200 ms. There could be multiple IC events in a single 1-s record, particularly in the case of multiple-stroke CG flashes, in which pulse sequences occurring between the return strokes and after the last stroke were each treated as individual IC events after 1st return stroke. The onset of the first pulse and the end of the last pulse in the pulse sequence were considered as the start and end of the “IC event”. If the NLDN reported no pulses corresponding to the “IC event”, we regarded such an “IC event” as missed. If only “C” pulses (at least one) were reported, we regarded such “IC event” as correctly classified. If one or more “G” pulses were reported, we regarded such “IC event” as misclassified. The detection efficiency (DE) for “IC events” was defined as the fraction of LOG-observed “IC events” having as least one pulse reported by the NLDN (even if it was misclassified). The classification accuracy (CA) for “IC events” was defined as the fraction of NLDN-detected “IC events” for which the NLDN reported only “C” pulses and no “G” pulses.

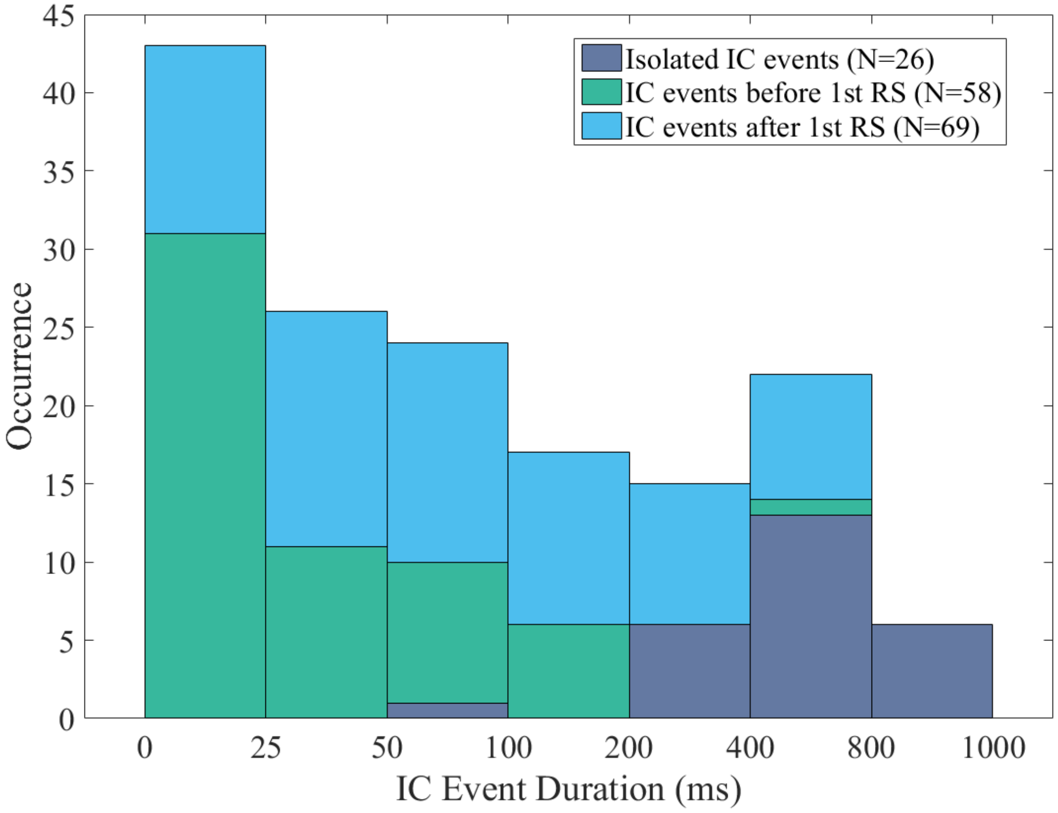

Figure 1. Histogram of durations of 153 IC events.

Table 1 Summary of the Ground-Truth Dataset for IC Events

Event Type	**Isolated IC Events**	**IC Events Before 1st RS**	**IC Events After 1st RS**	**All IC Events**	**PB Pulse Trains**	**Regular Pulse Bursts**
Sample Size	26	58	69	153	24	19
GM Duration (ms)	504	23	69	64	2.7	1.5

Table 2 Summary of the Ground-Truth Dataset for CG Strokes

Stroke Type	**Negative First Strokes**	**Negative Subsequent Strokes**	**All Negative Strokes**	**Positive First Strokes**	**Positive Subsequent Strokes**	**All Positive Strokes**	**Total**
Sample Size	84	256	340	21	5	26	366

We additionally identified 24 preliminary breakdown (PB) pulse trains within “IC events before 1st return stroke” of CG flashes and 19 regular pulse bursts (RPBs), studied by Krider et al. [1975] and Rakov et al. [1996], within “IC events after 1st return stroke” and “Isolated IC events”. The DE and CA for these two types of IC events were computed separately, in addition to three main “IC event” categories; that is, PB pulse trains and RPBs were not counted as separate “IC events” in calculating the DE and CA of “IC events”.

The ground-truth dataset for CGs includes 366 strokes recorded by both the electric field measuring system and the high-speed camera, so that the lightning channel to ground was unambiguously documented. A summary of the CG data is given in Table 2. Out of the 366 strokes, 27 were from single-stroke flashes and the other 339 strokes were from multiple-stroke flashes. Most of the flashes were within 20 km of LOG. By using a 5-ms time window (±2.5 ms relative to the GPS time of ground-truth stroke), we identified all the NLDN-reported events (if any) in that time window and within 40 km of the LOG. If no events were reported by the NLDN in the search window, we regarded this stroke as a missed event. If a CG was reported in the window, we regarded this stroke as a correctly classified event. If only one or more cloud pulses were reported in this window, we regarded this stroke as a misclassified event.

IV. ANALYSIS AND DISCUSSION

A. Detection Efficiency and Classification Accuracy of IC Events

Out of the 153 IC events, 26 were isolated IC events that could be viewed as complete IC flashes, 58 were IC events before first return strokes, and 69 were IC events after first return strokes. The overall detection efficiency and classification accuracy of IC events were 33% and 86%, respectively. More detailed results for IC detection efficiency (DE), classification accuracy (CA), and the average number of reported cloud pulses per detected event are given in Table 3. DE for isolated IC events was 73%, which is 2-3 times higher than that for the other two IC-event categories. This disparity might have been related to the significantly longer durations for isolated IC events, whose GM value is about 21 and 7 times larger than those of IC events associated with CG flashes (occurring before 1st RS and after 1st RS). Further, the GM duration for 50 detected IC events was 135 ms, which is a factor of 3 larger than 45 ms for 103 undetected IC events. The DE for cloud flashes reported by Murphy and Nag [2015] was about 50-60%, which is somewhat lower than the 73% found for our complete IC flashes, but higher than the 33% for all IC events in our study. For detected IC events, the number of NLDN-reported cloud pulses was counted and the average number was found to be 2.6. The maximum number of NLDN-reported cloud pulses was 12 and they were observed in the isolated IC event whose duration was 980 ms, almost twice larger than the GM of 504 ms found for all isolated IC events. The average number of NLDN-reported cloud pulses for complete IC flashes was 3.1, which is higher than that for the other two categories. Classification accuracies for isolated IC events, IC events before 1st RS, and IC events after 1st RS are 95%, 88%, and 73%, respectively.

Due to their very small amplitude, none of the 19 regular pulse bursts (in both IC and CG flashes) was detected by the NLDN. Out of the 24 preliminary breakdown pulse trains in CG flashes, 11 (46%) were detected and 9 (82%) were correctly classified as cloud events. The two misclassified events are relatively high-intensity PB pulse trains, one of which preceded a positive return stroke and the other one occurred before a negative return stroke. The two misclassified IC events are shown in Figure 2.

Table 3 Summary of the NLDN Detection Efficiency (DE) and Classification Accuracy (CA) for IC Events

Type of IC Events	**DE**	**CA**	**AM Number of NLDN-Reported Cloud Pulses per Event**
Isolated IC Events	19/26 (73%)	18/19 (95%)	3.1
IC Events Before 1st RS	16/58 (28%)	14/16 (88%)	1.6
IC Events After 1st RS	15/69 (22%)	11/15 (73%)	2.5
All IC Events	50/153 (33%)	43/50 (86%)	2.6
PB Pulse Trains	11/24 (46%)	9/11 (82%)	1.3
Regular Pulse Bursts	0/19 (0%)	-	-

B. Detection Efficiency and Classification Accuracy of CG Strokes

Out of the 366 positive and negative CG strokes, 26 were missed by the NLDN. For the detected 340 strokes reported by the NLDN as either CG or IC pulses, 311 were correctly classified as CGs and 29 were misclassified as cloud pulses. The resultant stroke detection efficiency (DE) is 93% and classification accuracy (CA) is 91%. Our results for negative subsequent strokes, DE = 91% and CA = 90%, can be compared with their counterparts (75% and 96%) for negative stokes in rocket-triggered lightning, which are similar to subsequent strokes in natural lightning [Mallick et al. 2014]. Our results for CG stroke detection efficiency and classification accuracy for different categories of strokes are summarized in Table 4 and Table 5, respectively. One can see from these tables that both detection efficiency (DE) and classification accuracy (CA) of +CGs are higher than those of –CGs, and that DE and CA of the first strokes are higher than those of subsequent strokes. Both DE and CA for the only strokes in single-stroke flashes are 100% (N=27), while for first strokes (N=78) in multiple-stroke flashes they are 97% and 93%. For all strokes (first and subsequent strokes combined) in multiple-stroke flashes, the DE and CA are 92% and 91%.

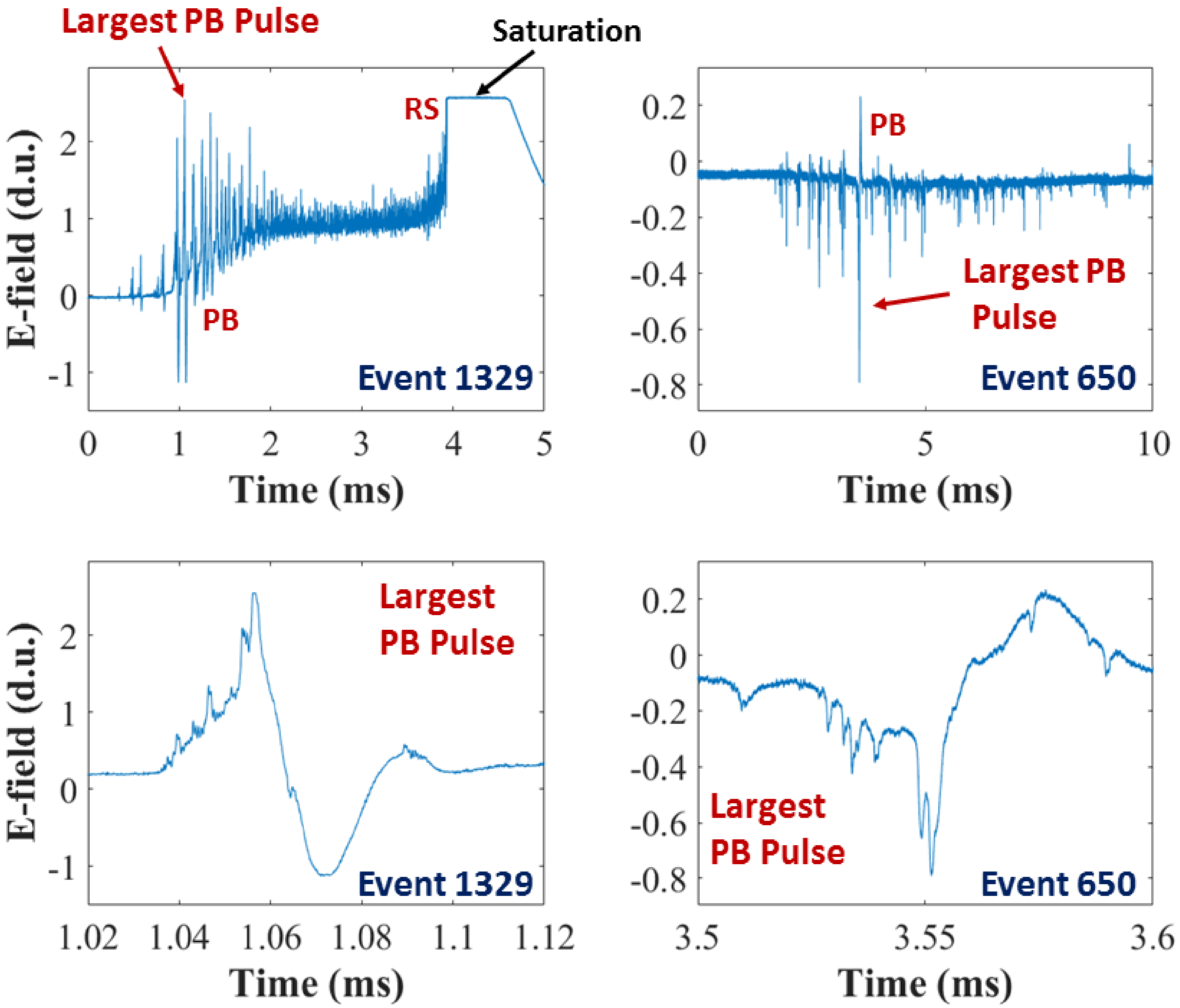

Figure 2. Top two panels show the two relatively high-intensity PB pulse trains of CG flashes 1329 (negative, left panel) and 650 (positive, right panel). Bottom two panels show expansions of the largest pulses in those two trains. The largest pulses were misclassified by the NLDN and reported as a 45-kA negative CG stroke and a 30-kA positive CG stroke, respectively. RS stands for return stroke (not shown for event 650).

Table 4 Summary of the NLDN Detection Efficiency (DE) for CG Strokes

Stroke Type	**DE**	**Stroke Type**	**DE**
Negative First Strokes	82/84 (98%)	All Negative Strokes	314/340 (92%)
Negative Subsequent Strokes	232/256 (91%)	All Positive Strokes	26/26 (100%)
Positive First Strokes	21/21 (100%)	All First Strokes	103/105 (98%)
Positive Subsequent Strokes	5/5 (100%)	All Subsequent Strokes	237/261 (91%)
Total	340/366 (93%)		

Table 5 Summary of the NLDN Classification Accuracy (CA) for CG Strokes

Stroke Type	**CA**	**Stroke Type**	**CA**
Negative First Strokes	78/82 (95%)	All Negative Strokes	286/314 (91%)
Negative Subsequent Strokes	208/232 (90%)	All Positive Strokes	25/26 (96%)
Positive First Strokes	20/21 (95%)	All First Strokes	98/103 (95%)
Positive Subsequent Strokes	5/5 (100%)	All Subsequent Strokes	213/237 (90%)
Total	311/340 (91%)		

V. SUMMARY

The NLDN detection efficiency (DE) and classification accuracy (CA) for cloud discharge activity (IC events) and CG strokes in Florida were evaluated by using the electric field and optical data acquired at LOG. For 153 ground-truth IC events, the DE and CA were 33% (50/153) and 86% (43/50), respectively. The average number of NLDN- reported cloud pulses per IC event was 2.6. Compared to IC events associated with CG flashes, isolated IC events (complete IC flashes) were found to have higher DE , CA, and average number of NLDN-reported cloud pulses, which were 73% (19/26), 95% (18/19), and 3.1, respectively. The GM duration for 50 detected IC events was 135 ms, which is a factor of 3 larger than 45 ms for 103 undetected IC events. Out of the 24 preliminary breakdown pulse trains in CG flashes, 11 (46%) were detected and 9 (82%) of the 11 were correctly classified as cloud events. None of the 19 regular pulse bursts was detected.

For CG strokes, the DE and CA were 93% (340/366) and 91% (311/340), respectively. The DE for negative subsequent strokes was 91%, which is appreciably higher than the 75% estimated based on the triggered-lightning data, while the CA was 91%, somewhat lower than the 96% based on the triggered lightning data. Both the detection efficiency and classification accuracy for first strokes were higher than their counterparts for subsequent strokes. It is important to note that the results presented in this paper correspond to the NLDN configuration and settings that existed in the summer of 2014. The cited values of DE and CA for triggered lightning strokes are based on data acquired in 2004-2012, so the disparities may be related to the NLDN upgrade in 2013.

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