AN INVESTIGATION INTO THE CHARACTERISTICS OF LIGHTNING AS IT INTERACTS WITH TOWERS

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ABSTRACT

Tall structures can be the subject of lightning interaction and often lead to an increased cloud-to-ground (CG) flash rate in the vicinity. Lightning that interacts with towers can take the form of traditional CG flash, beginning in-cloud and propagating downward to connect with the tower, but flashes may also begin at the tower itself. However, the nature and overall percentage of lightning propagating from tower locations is unknown. This study examines lightning interactions with 10 communication towers from 213 to 610 m tall across Oklahoma using CG data from the National Lightning Detection Network (NLDN) and VHF data from the Oklahoma Lightning Mapping Array (LMA), and radar data from the Weather Service Radar - 1988 Doppler (WSR-88D) network. The NLDN data was used to first determine the specific time (in milliseconds), latitude, and longitude of lightning that potentially interacted with these towers. The LMA data was then used to examine the detailed breakdown of each flash as well as any nearby lightning flashes. 45 individual lightning flashes occurring within 1 km of these tower locations were examined in the winter, summer, and fall of 2010 to determine: (1) the initiation location and height, (2) the size (temporally and spatially) of the lightning flash, (3) any seasonal dependence, and (4) the associated the storm structure and storm type. Using these factors, these lightning flashes were classified to better understand the overall percentage of lightning triggered by the tower and the environmental factors contributing to the occurrence of upward-triggered lightning. Of the 45 flashes, 60% of CG flashes interacted directly with the tower, 20% were classified as in-cloud flashes, and 20% of flashes were classified as upward lightning, mainly triggered by a nearby preceding CG. The initiation distance between these three main flash types (44/45 overall flashes) occurred between 7-9 km from the tower. CG flashes, beginning in-cloud and terminating at the tower, were the dominant flash type across all seasons, independent of the convective mode and the storm structure.

1. Introduction

Communication towers are often used as platforms for detecting and studying lightning because they offer a pre-existing tall structure of known height and location. Due to their often isolated nature and taller structure, these communication towers are often the subject of lightning interactions. Lightning interacting with these towers can come as the form as a traditional cloud-to-ground (CG) flash, originating within the storm and terminating at the tower. However, previous research has documented that lightning flashes can also begin at the tower and travel upward into the the storm, a phenomenon called "upward lightning" (e.g., Warner et al. 2013).

Upward lightning can occur from two different mechanisms. First is lightning-triggered upward (LTU) lightning, where a preceding CG strike near the tower re-

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sults in a upward flash from the tower. Second is self-initiated upward (SIU) lightning, where lightning initiates from the tower without a preceding CG strike (Warner et al. 2012). Large-scale lightning detection systems, such as the National Lightning Detection Network (NLDN; Orville 2008) in the United States, cannot determine the direction lightning travels to or from a tall structure. However, this network can still identify areas with towers as they typically see a 29% to 147% increase in lightning detections over surrounding areas with no towers (Kingfield et al. 2017) across the United States. As focused analyses of lightning interactions with towers in South Dakota (Warner et al. 2013), China (Jiang et al. 2014), and Canada (Hussein et al. 1995) have shed light of lightning characteristics near towers, limited research has been done characterizing the frequency of type of lightning both occurring near or interacting with a tower within 1 km.

Currently the process for identifying and classifying upward lightning was to be done manually. Consequently, further examination of lightning as it interacts with towers is required in an effort to improve detection systems. This study aims to better understand the nature of upward lightning by mapping lightning as it interacts with towers.

2. Data and Methods

a. Towers

This research examined 10 Federal Communications Commission (FCC) communication towers across Oklahoma. The towers are primarily located in central Oklahoma as shown in Fig. 1. These towers were constructed over a wide range of time. The oldest of the towers was constructed in 1995, while the newest was built a decade later in 2005. The towers also stand at varying heights between 213 and 610 m.

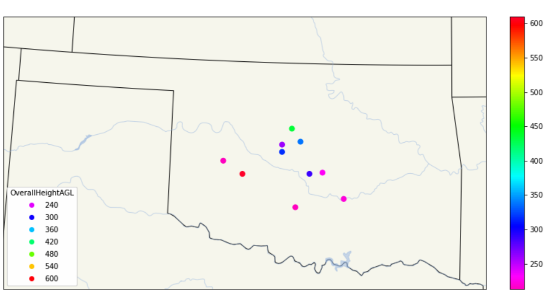

FIG. 1: Map of FCC communication towers across Oklahoma colored by height (AGL). Specific tower heights are listed in Table 1.

b. NLDN

Initial data for CG lightning flash locations and times were collected from the NLDN. The NLDN uses Improved Accuracy through Combined Technology (IMPACT) and was originally funded by the Electric Power Research Institute (EPRI) in 1983. The network detects the Very Low Frequency (VLF) radiation produced by lightning return strokes. The NLDN was upgraded in 1995, which resulted in a flash detection efficiency of 80%–90% and 0.5 km median location error in most regions (Cummins and Murphy 2009) in the 2010 period used in this study. An archive of quality-controlled NLDN flash data is maintained by the National Severe Storms Laboratory (NSSL) going back to 1989 (Kingfield et al. 2017). This study limited the scope of the data to January, Feburary, May, and August of 2010. These months offered high activity. This selection also allowed for the inclusion of seasonality comparison. The NLDN flash data was reprocessed by Viasala to provide timing of CG flashes in milliseconds and was filtered to flashes that traveled within 1 km of the towers.

c. LMA

The refined list of flashes was used to pull the corresponding Lightning Mapping Array (LMA) data. The LMA uses a three-dimensional Time-of-Arrival (TOA) technique to map lightning leaders. The system finds the source of impulsive very high frequency (VHF) radiation produced by lightning as it produces new channels to measure the total lightning activity of a storm (Krehbiel et al. 2002). The first lightning mapping array system was created in 1998 at the New Mexico Institute of Mining and Technology (Cummins and Murphy 2009); the Oklahoma LMA was installed in the early 2000s and has been the focus of multiple field research studies (MacGorman et al. 2008). For this study, LMA data were mapped using an IDL virtual machine using xlma software developed by New Mexico Tech. This program created several fields containing multiple views of the storm. The mapping process involved making increasingly narrow selections in these views until only the desired flash remained. Completed flash maps were exported as a Graphics Interchange Format (GIF) animation.

d. Radar

As part of this research, nearby Weather Service Radar - 1988 Doppler (WSR-88D) radars were used to determine storm type and reflectivity values near individual flashes. Radar data was collected from the site nearest each individual tower. The Oklahoma City, OK radar (KTLX) was used for seven towers in central Oklahoma, while the Frederick, OK (KFDR) radar was used for the remaining three. GIFs of the storms were created using radar data processed by the Warning Decision Support System – Integrated Information (WDSS-II; Lakshmanan et al. (2007)). LMA data for each flash was then overlaid on its corresponding storm to determine the reflectivity at the initiation location and at the associated tower and/or CG location. Storm type and reflectively of flash initiation and contact were determined manually.

e. Classification

Each flash was manually classified into categories representative of the type of flash in order to better understand the percentage of tower-lightning that begins in-cloud vs at the tower location. This research used four classifications:

- **Cloud-to-Ground (CG)** – Lightning that is initiated within the storm and comes to ground at the tower location.
- **In-Cloud (IC)** – Lightning that was classified by the NLDN as CG lightning at or near the tower location, but has no evidence in the LMA data as propogating to or from the ground.
- **Lightning-Triggered-Upward (LTU)** – Lightning that begins at the tower location, but only after a nearby CG flash or other IC lightning propogating nearby prior to the start of a new flash at the tower.
- **Self-Initiated-Upward (SIU)** – Lightning that begins at the tower location, but without any nearby lightning in the seconds proceeding the activity.

These four different types are illustrated for comparison in Fig. 2.

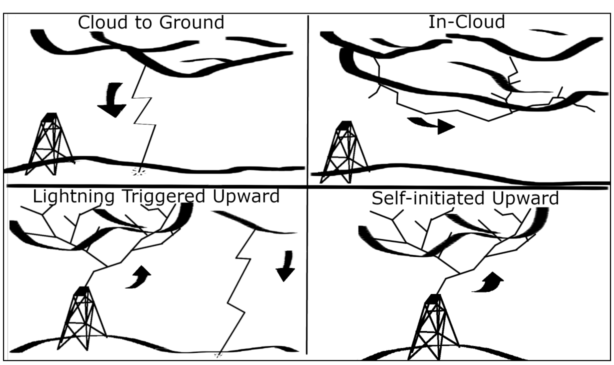

FIG. 2: Cartoon of the four classification categories for NLDN flashes associated with towers.

The different perspectives of the LMA mapping software provided the necessary views to classify each of the flashes. The top most box shows the flashes altitude over time, which was used to determine when the flash came to ground or if it remained in the cloud above. In Fig. 3, this flash clearly began at a high altitude (near 10 km AGL) and arced down over time to come to ground at the tower location, classifying this in the first category of a "CG flash". The middle and bottom right fields show different cross-sectional views of the storm. These views further reinforce that the flash began in cloud and traveled downward as it propagated (Fig. 3). The bottom left view shows a top down view of the storm. Here the flash moved northeastward towards the tower and potentially made contact (Fig. 3). From this information, the flash is classified as a CG. CGs are flashes that begin in cloud and follow a charge down to contact the ground or other tall structures. This process, known as a stepped leader, is most commonly negative polarity. This particular flash was produced in a single cell storm (Fig. 4). Interestingly, the flash began in the center of the storm in the region of higher reflectivity and arced out toward the tower with time (Fig. 4). Flashes like this one at 0008 UTC on 9 Aug 2010 are considered "bolts from the blue" because they connect to ground (or a tower) outside of the storm precipitation under an area of blue sky (Cherington et al. 1997).

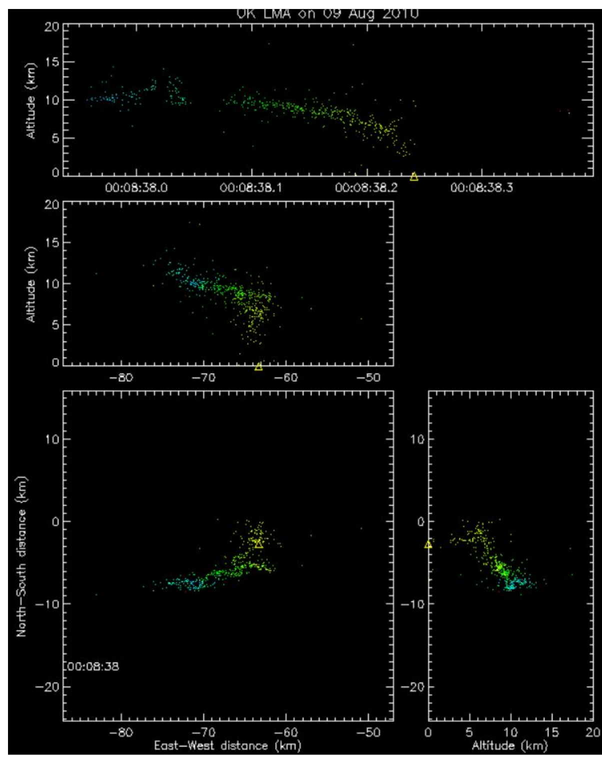

FIG. 3: VHF LMA points of CG flash associated with tower at 0008 UTC on 8 Aug 2010, colored by time. Top panel: Time-height plot. Middle panel: x–z projection. Lower left panel: The x–y projection. Lower right panel: y-z projection.

In the altitude over time box of Fig. 5, it is clear that the flash remained at a high altitude and never dropped low enough to make contact, unlike in Fig. 3. Thus, this flash is classified as an IC flash. IC lightning is lightning

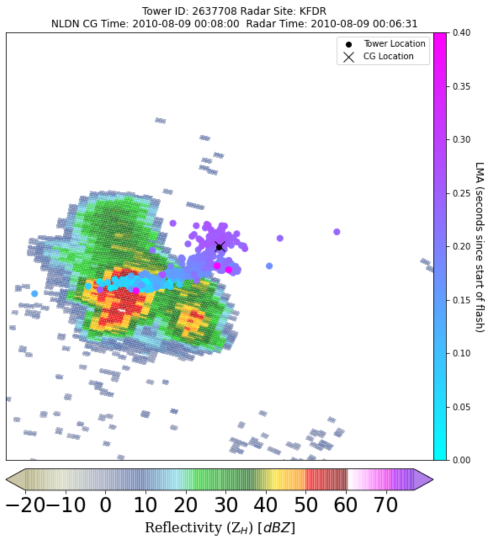

FIG. 4: LMA points (blue-to-pink with time) of CG flash shown in Fig. 3 over 0.5° reflectivity from KFDR WSR-88D radar at 0631 UTC.

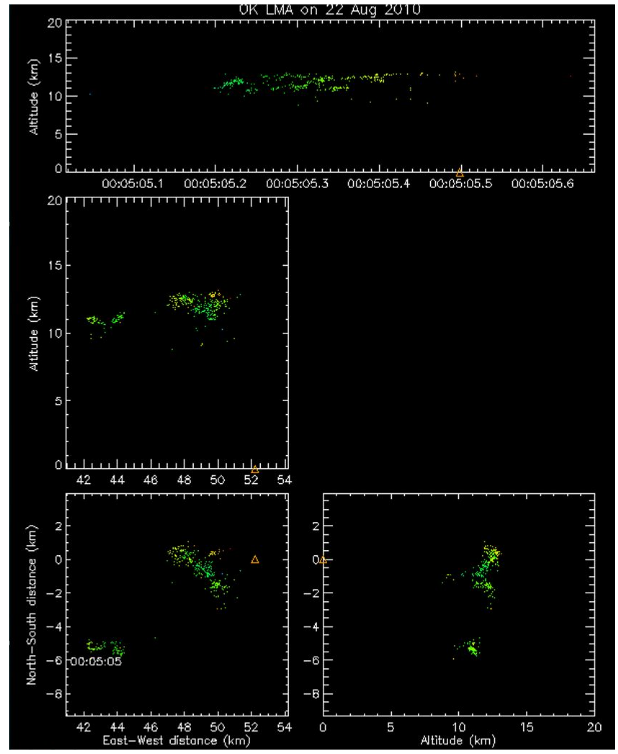

FIG. 5: As in Fig. 3 but for an IC flash beginning at 0005 UTC on 22 Aug 2010.

that remains in the cloud and never reaches the ground. These are classified as IC flashes even though the NLDN documented this flash as a CG flash. However, there is no evidence of return strokes or flash propagation below 5 km AGL. Fig. 6 shows that this IC flash occurred on the periphery of the higher reflectivity values during a single cell storm.

Both the top down view and the the time-height plots of Fig. 7 illustrate that the LMA points on 1 August 2010 at 0003 UTC were two distinct separate flashes occurring in close proximity. The altitude over time view shows the first flash descends low enough to be a CG and the second flash begins at a low height before traveling upward (Fig 7). This particular flash was classified as a LTU flash. LTU lightning results from an initial lightning discharge (typically including a nearby CG flash) followed by an opposite change resulting from the development of an upward positive leader (Warner et al. 2013). The KFDR radar data for this flash shows it initiated in the reflectivity core of a multicell storm and has a clear separation in space and time between the initial flash and the second upward flash (Fig 8).

This flash began at a low altitude over the tower before traveling upward (Fig. 9). Without any previous flash activity, this flash would be classified as a SIU. SIU lightning is a positive leader from a tall object that was not triggered by preceding flash activity (Warner et al. 2013). The radar data for this SIU flash was not analyzed for this storm.

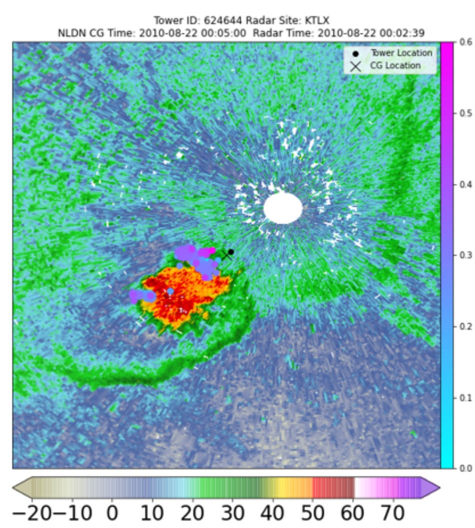

FIG. 6: LMA points of IC flash shown in Fig. 5 over 0.5° reflectivity from the KLTX radar at 0002 UTC on 22 Aug 2010.

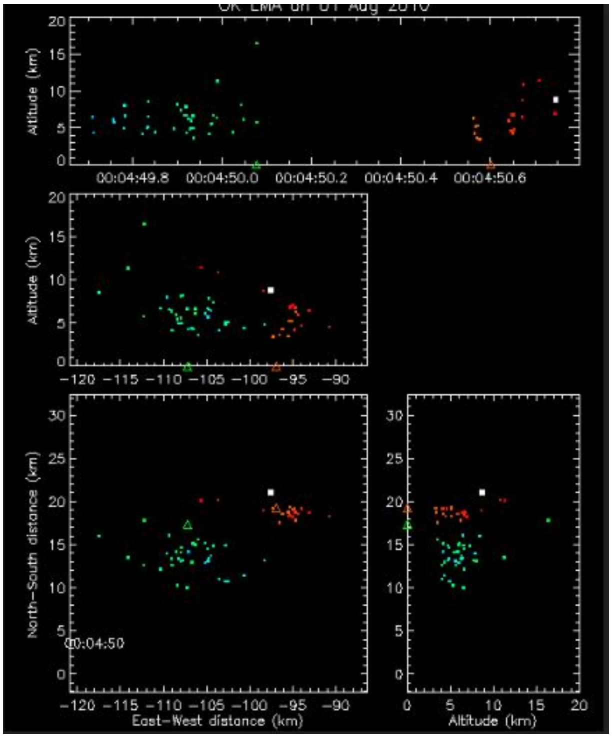

FIG. 7: As in Fig. 3 but for an LTU flash beginning at 0003 UTC on 1 Aug 2010.

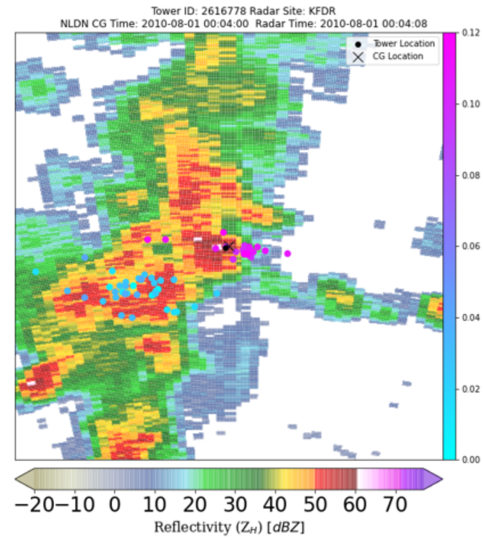

FIG. 8: LMA points of IC flash shown in Fig. 7 over 0.5° reflectivity from the KFDR radar at 0004 UTC on 1 Aug 2010.

3. Results

a. Classification Distribution

In total, 45 individual flashes were examined. Fig. 10 shows the percentage of each flash type for all flashes recorded. CGs were the most common flash accounting for 60% of recorded flashes. Conversely, SIU flashes were the least recorded with only one case or 2% of flashes. In cloud and LTU flashes were in the middle with 20% and 16% respectively.

Fig. 11 shows flash classifications for each month observed. Warmer months (May and August) generally had greater storm activity as is expected. CGs were the most common flash type for each month, with the exception of a tie in January. During warmer months, reclassified IC flashes were the second most common flash, but had no recorded cases in the colder months (January and February). Notably, the only SIU flash was recorded in May, though few conclusions can be draw without more data.

b. Classification Initiation Distance

The average distance at which each flash initiated is similar across most classifications (Fig. 12). With the exception of SIU, flashes occurred around 8 km from the tower. Due to the nature of SIU flashes, having no prior flash activity and beginning at the tower, a small initiation distance is expected.

Fig. 13 shows the distribution of flash classification for flashes that initiated within 5 km of the tower. The distribution remains similar to Fig. 10, with some slight changes. CGs remain the most common flash type and saw a 7% increase. The SIU flashes did see an increased in percentage by 5%. However, with still only one recorded case this was largely due to the decreased data pool. LTU and IC flashes become 13% decreasing by 5% and 7%, respectively.

c. LMA Points

Lightning during summer months generally had fewer LMA points than winter flashes (Fig. 14). Summer LTU flashes had the fewest LMA points on average with a mean of 42.25 points. Summer CGs had the seconds lowest with a mean of 228.2 points, followed by summer IC flashes at 436 mean points. A valid average could not be determined for SIU with only one case. LTU flashes during winter had a higher mean of 1303.33 compared to CGs with a mean of 1128.6 points.

d. General Results

Of the flashes recorded, CGs were very common compared to the overall rarity of SIU flashes (Table 1). Possibly due to the limited nature of the data set, tower height had little influence on the distribution of lightning activity.

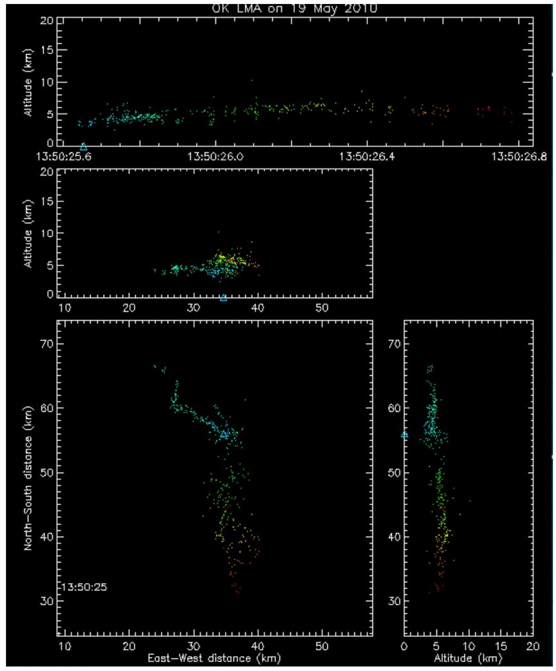

FIG. 9: As in Fig. 3, but for an SIU flash on 19 May 2010 at 1350 UTC.

Tower Number	100648	102840	129530	2602927	2606652	2609624	2616778	2637708	2645144	624644
Tower Height [m]	220.9	213.4	435.2	228.7	317	260	213.1	609.5	338.3	288
Flash Interactions	1	1	9	3	0	4	17	3	2	5
CG	1	0	7	0	0	4	10	3	1	1
IC	0	0	1	1	0	0	3	0	0	4
LTU	0	1	1	2	0	0	4	0	0	0
SIU	0	0	0	0	0	0	0	0	1	0

TABLE 1: Table of FCC towers along with height and number of flash interactions.

The tower with the highest percentage of lightning flashes (17 of 45) in the vicinity was 213 meters tall, while the tallest tower at 609 meters only recorded three flashes. Flashes began on average 8.19 km from the tower and lasted an average of 0.65 seconds. On average each flash contained around 480 points of LMA data.

4. Discussion and Conclusions

Starting with 45 CGs detected by the NLDN near a tower, 60% were manually classified as traditional CGs, 20% were upward flashes, and 20% were IC flashes. As expected, due to the higher number of electrified storms during spring/summer months, more tower lightning flashes were detected in warmer months than cooler months, similar to results observed in Kingfield et al. (2017). However, the winter flashes had a greater number of points per flash, perhaps due in part to larger horizontally continuous regions of similar charge, as well as a greater proclivity for lightning-triggered upward lightning (at roughly 40%) than the summer months (approximately 13%). The spring/summer months are more likely to contain small single cell or multicell in addition to supercell storms. These bring stronger updraft dynamics with increased turbulence leading to flash initiations higher in the cloud with fewer points per flash due to the complexity of smaller pockets of similar storm charge compared with winter storms.

While the data showed no relationship between tower height and the percentage of total flashes in the vicinity or the classification of those lightning flashes, no definite conclusion can be made regarding tower height and flash type due to the limited case selection process performed in this study. More data is required for true statistical analysis.

It is important to note that this data serves mostly as a starting point for further tower lightning research. The combination of several isolated tall structures within the

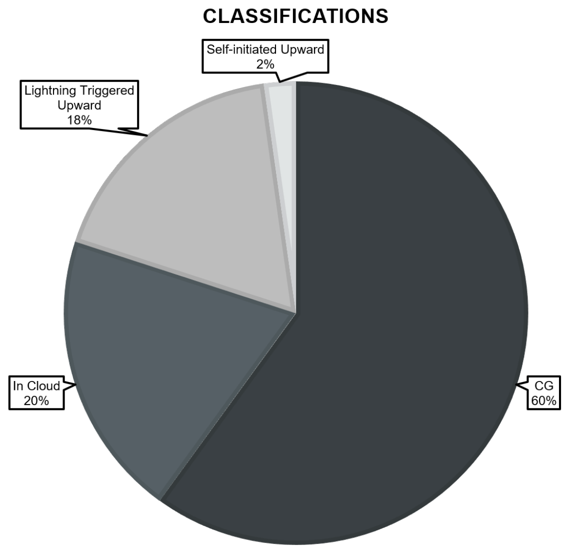

FIG. 10: Total distribution of classification categories for NLDN flashes associated with towers.

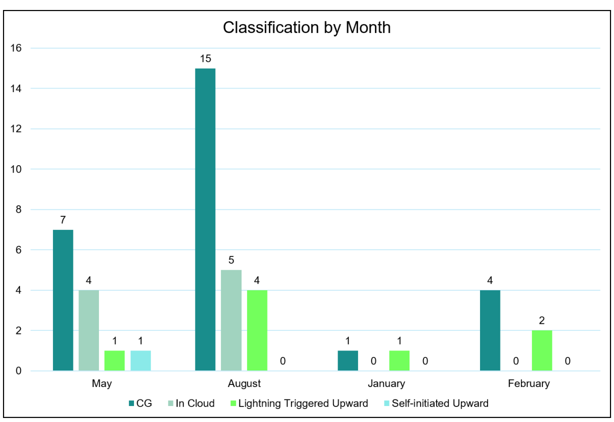

FIG. 11: Distribution of classification categories by month for NLDN flashes associated with towers.

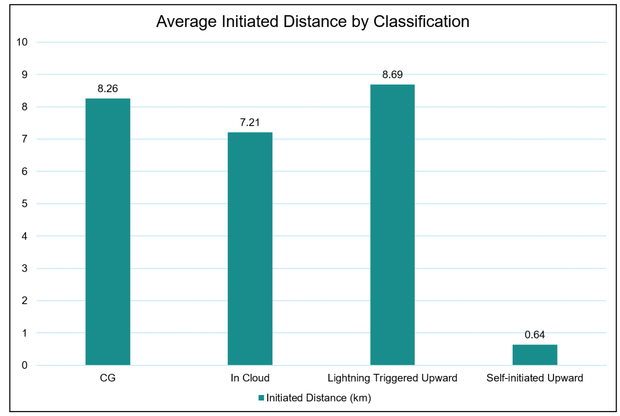

FIG. 12: Average initiation Distance by classification categories for NLDN flashes associated with towers.

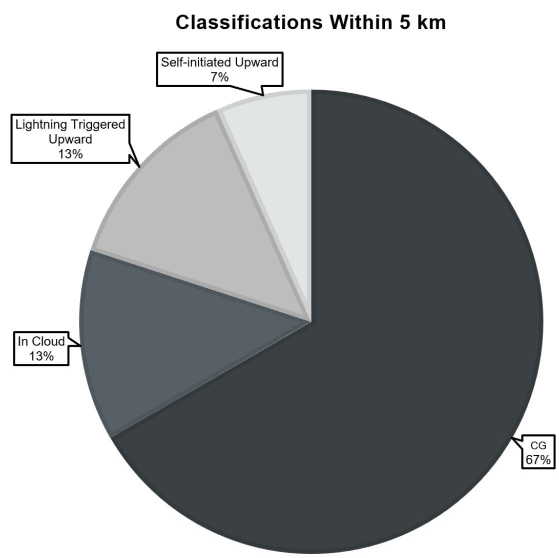

FIG. 13: Distribution of classification categories for NLDN flashes associated with towers within 5 km.

3D mapping region of the Oklahoma LMA with WSR-88D coverage provides a wealth of information to continue this research.

This research could one day lead to determining the conditions required for upward lightning. As Warner et al. (2013) discussed, there are questions that must be answered to understand the nature of upward flashes. What types of flashes are critical for the initiation of upward leaders from tall towers? What types of storms are present when upward lightning occurs? What conditions are required for triggering upward leaders on multiple tall objects during the same flash? While this research was limited by time, the methods it produced can answer these questions.

5. Acknowledgments

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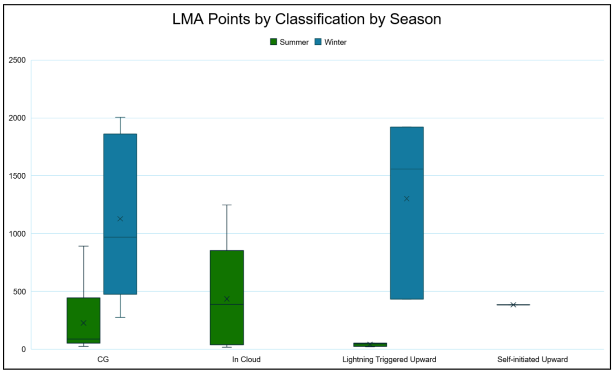

FIG. 14: VHF points detected by the LMA for each classification categories by Season.

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