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Key Points:

- A 20 year 500 m map of CG lightning over the United States reveals many isolated areas of high lightning frequencies collocated with towers
- These enhancements are correlated with tower height and highlight a possible human influence in localized CG flash rates
- Shorter towers were more susceptible to CG lightning during the cold season, likely due to lower charge centers in winter storms

Supporting Information:

- Supporting Information S1
- Table S1
- Table S2

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Antenna structures and cloud-to-ground lightning location: 1995–2015

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Abstract Spatial analyses of cloud-to-ground (CG) lightning occurrence due to a rapid expansion in the number of antenna towers across the United States are explored by gridding 20 years of National Lightning Detection Network data at 500 m spatial resolution. The 99.8% of grid cells with ≥100 CGs were within 1 km of an antenna tower registered with the Federal Communications Commission. Tower height is positively correlated with CG occurrence; towers taller than 400 m above ground level experience a median increase of 150% in CG lightning density compared to a region 2 km to 5 km away. In the northern Great Plains, the cumulative CG lightning density near the tower was around 138% (117%) higher than a region 2 to 5 km away in the September–February (March–August) months. Higher CG frequencies typically also occur in the first full year following new tower construction, creating new lightning hot spots.

1. Introduction

For over 80 years, tall structures have facilitated analyses on lightning production and its electrical characteristics for both lightning research and infrastructure protection [*McEachron*, 1939; *Rakov and Uman*, 2003]. In the last 30 years, humankind has observed an expansion in digital technologies and broadcasting capabilities [*Hilbert and López*, 2011]. Concomitant to this expansion is the construction of antenna towers across the contiguous United States (CONUS) with the number of Federal Communications Commission (FCC) antenna registrations increasing from 38,514 before 1995 to 130,883 after 2015. Parallel to this increase in antenna construction rates, the National Lightning Detection Network (NLDN), a lightning location system covering North America, was renovated with updated sensors to improve cloud-to-ground (CG) lightning detection efficiency (80%–90% for flashes ≥5 kA) and location accuracy (median error ~500 m) starting in 1995 [*Cummins et al.*, 1998]. Continued investment through the turn of the century has further improved these detection metrics with a uniform CG detection efficiency of 95% [*Cummins and Murphy*, 2009].

The performance of the NLDN has made it an essential tool in documenting the spatiotemporal distribution of lightning, as reviewed by *Holle et al.* [2016]. Due to the wide spatial area examined, many climatological studies rely on coarse gridding techniques (≥ 20 km) to summarize CG occurrence, disregarding smaller-scale features (e.g., antenna towers) that could modulate the frequency of lightning. *Berger and Vogelsanger* [1969] observed that lightning initiation was more prevalent from towers compared to mountain peaks of equal elevation, resulting in isolated regions of elevated lightning occurrence. The type of lightning occurring near a man-made structure can be either downward or upward [*Rakov and Uman*, 2003] with upward lightning documented to occur with either the presence or the lack of nearby flash activity [*Wang et al.*, 2008; *Mazur and Ruhnke*, 2011; *Warner et al.*, 2012; *Zhou et al.*, 2012]. Contemporary studies have examined this man-made modification in lightning using NLDN in the CONUS [*Stanley and Heavner*, 2003; *Warner et al.*, 2012, 2014], Canada [*Lafkovici et al.*, 2008], with analogous evaluations in Europe [*Diendorfer et al.*, 2009; *Azadifar et al.*, 2016], and Asia [*Wang et al.*, 2008; *Chen et al.*, 2012]. These studies have encompassed a limited geographic domain and/or a particular season; however, both geographic and seasonal mechanisms drive where lightning occurs [*Holle et al.*, 2016].

This study provides a geographic perspective on the prevalence of tower-initiated lightning by first examining lightning occurrence across the CONUS through a 20 year, 500 m spatial gridding of NLDN data. The spatial association of elevated CG lightning locations to FCC towers and the effects of tower height, age, and season have in modifying the local lightning density and peak current are addressed herein.

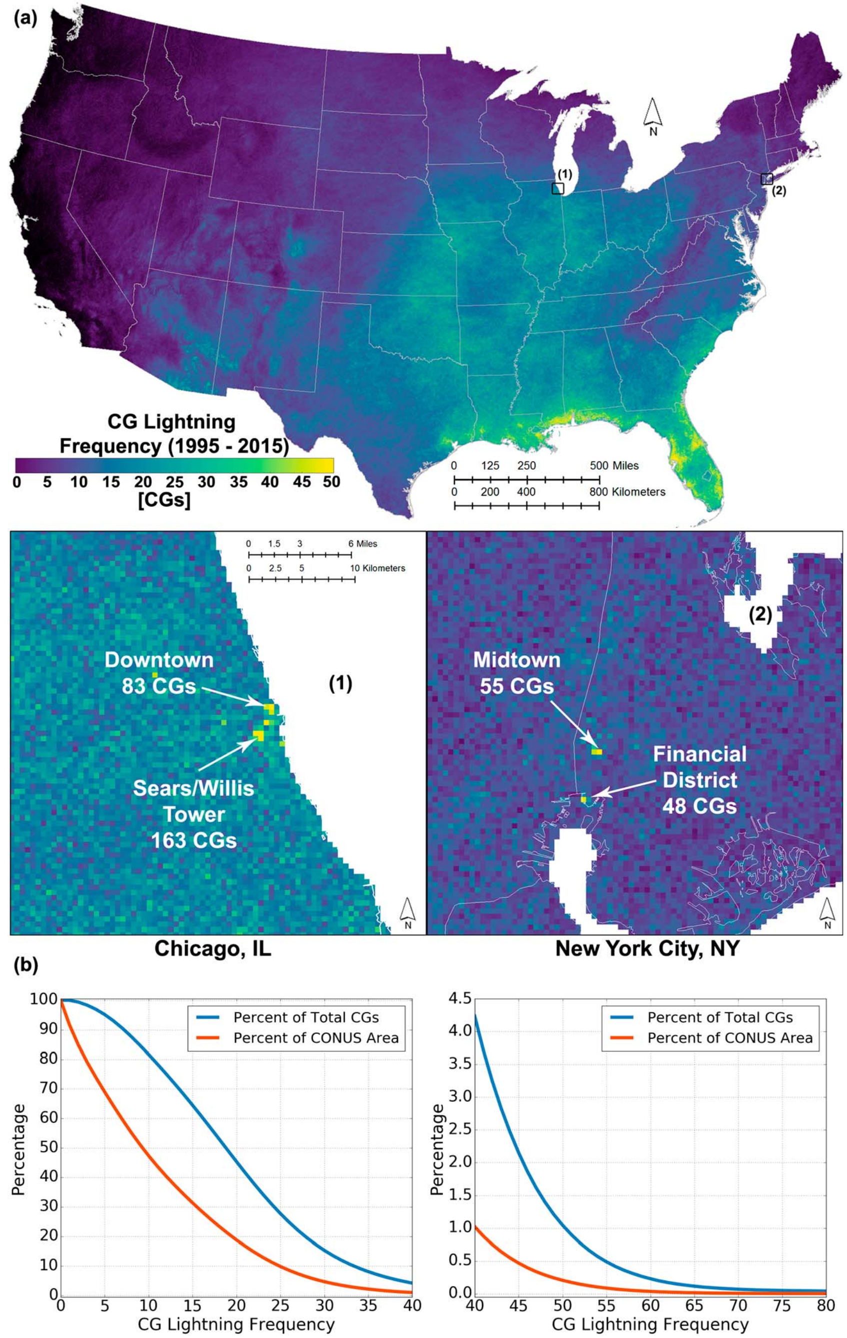

Figure 1. (a) The 20 year 500 m spatial resolution map of lightning frequency across the CONUS with inset maps of (1) Chicago, IL, and (2) New York City, NY. (b) Associated CDF plots summarizing the accumulated percentage of total CGs (blue line) and CONUS area (orange line) exceeding a specified CG frequency. Around 10% of the CONUS area had no CGs, and 1% had ≥40 CGs.

2. Data and Methods

2.1. NLDN

The National Severe Storms Laboratory maintains an archive of quality-controlled NLDN flash data back to the first full operational year in 1989. Detection time, location, polarity, and multiplicity are included for each CG flash. The study period starts in 1995 following the first network upgrade [*Cummins et al.*, 1998]. However, this upgrade increases the detection efficiency of lower amplitude events, which several studies reveal to be intracloud (IC) flashes [e.g., *Cummins et al.*, 1998; *Biagi et al.*, 2007; *Cummins and Murphy*, 2009; *Fleenor et al.*, 2009; *Emersic et al.*, 2011]. Following those results, all positive CGs (+CGs) and negative CGs (−CGs) with a peak current less than 15 kA and 10 kA respectively were discarded. This removed 46.5% (23.7%) of +CGs (−CGs) detected over the 20 year period. With a focused interest in FCC-registered towers, the 29,196,768 +CGs and 316,893,494 −CGs detected over the CONUS were gridded at 500 m spatial resolution (Figure 1a).

2.2. Antenna Tower Locations

The FCC Antenna Structure Registration database contains records of construction history, location, and heights for all new and proposed structures that require Federal Aviation Administration notification. This database contains records for both free-standing antenna structures and towers attached to buildings. This database had 130,883 records with a construction date before 1 January 2016. From these records, 1725 towers had a height above ground level (AGL) exceeding 200 m. The spatiotemporal accuracy of these records was evaluated using satellite imagery within Google Earth. In 77 cases, a tower was missing or was located within 500 m of another tower. In cases where two towers were collocated, the taller tower was retained and the smaller tower was removed. In 45 cases where towers were demolished and replaced, these records were combined with the mean of the two tower heights recorded. Querying the tower proposal applications revealed seven cases where construction occurred but no FCC paperwork was filed. These towers were included and had their construction dates estimated by finding the first satellite image date where the tower existed. After quality control, 1610 towers exceeding 200 m remained in the database.

In order to examine the effects of tower height on lightning frequency while normalizing for thunderstorm occurrence, we first applied a 10 km spatial buffer to each of the towers exceeding 200 m and removed towers that overlapped spatially. This reduced the number of towers to 675. To maintain a consistent 20 year study period around each tower, only the 443 towers built before 1995 were examined (Figures 2b and 2c). These towers had their lightning density calculated within 1 km (inner domain) and between 2 and 5 km away (outer domain). Finally, in order to mitigate outliers due to low thunderstorm occurrence, eight towers where the outer domain flash density was ≤2 CGs/km^2 were removed.

3. Results

The 20 year CG lightning climatology spatially reveals an increase in lightning occurrence from the northwest to southeast regions of the CONUS (Figure 1a), comparable to *Holle et al.* [2016]. Elevated lightning frequencies are observed along the coastlines of the Gulf Coast states and northward up to North Carolina. The primary driver for this enhancement is land- and sea breeze-driven convergence zones creating favorable thunderstorm updraft environments [e.g., *Hill et al.*, 2010]. The high spatial resolution of this climatology reveals an exponential decline in the percentage of CONUS area with higher lightning frequencies (Figure 1b). The number of grid cells with 40+ CGs only makes up around 1% of the CONUS area but corresponds to approximately 4.25% of the cumulative 20 year lightning frequency (N = 346,090,262).

While the southeast CONUS, particularly near the coastline, provides a conducive environment for enhanced lightning production, grid cells exceeding progressively higher CG counts are located away from this region (Figure 2a). At 75+ CGs (N = 1412; not shown), only 52.2% of grid cells were located ≥100 km from the southeastern coastline (gray shading; Figure 2a). At 100+ CGs (N = 613) and 200+ CGs (N = 154), 76.2% and 81.2% of the grid cells were located ≥100 km away from the coasts. Localized cells of higher CG counts are prevalent across the Great Plains, Midwest, and Ohio Valley regions. The highest CG count in a single grid cell (619) was located at 35.81°N/94.03°W, 30.5 km southeast of Fayetteville, Arkansas. For comparison, 163 CGs occurred near the Sears/Willis Tower (520 m AGL) in Chicago, Illinois, and 55 CGs occurred in the Midtown area of New York City, NY, over the 20 year period (insets in Figure 1a).

Overlaying the entire FCC database reveals that 99.8% of grid cells with 100+ CGs also had a tower located within 1 km of its center (Figure 2b). The single location with no FCC tower was located in Georgia where visual examination reveals a naval communications tower that likely contributed to the 105 CGs registered in this area. The 98.2% (24.8%) of matches were associated with a tower height exceeding 200 (500) m. Tower height is correlated with lightning occurrence with towers ≥500 m tall having a median frequency of 173 CGs compared to 138 CGs around shorter towers. In 76.6% of cases, the tallest tower existed prior

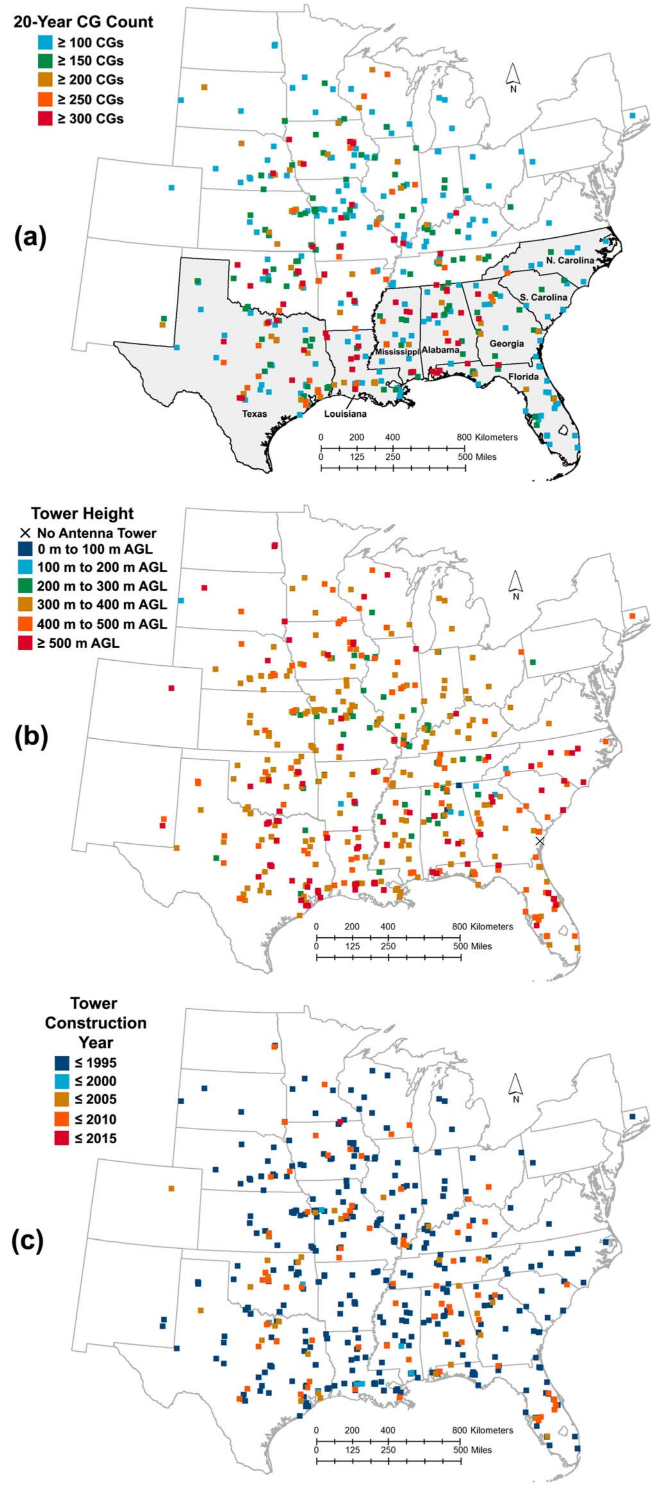

Figure 2. (a) Map of grid cells exceeding 100 CGs (light blue boxes) up to 300 CGs (red boxes); southeastern states are shaded in gray. Locations where an FCC tower was within 1 km of a grid cell in Figure 2a, (b) the tallest tower had its maximum height (AGL), and (c) construction date plotted. A cross denotes the one location without a registered tower in Figure 2b.

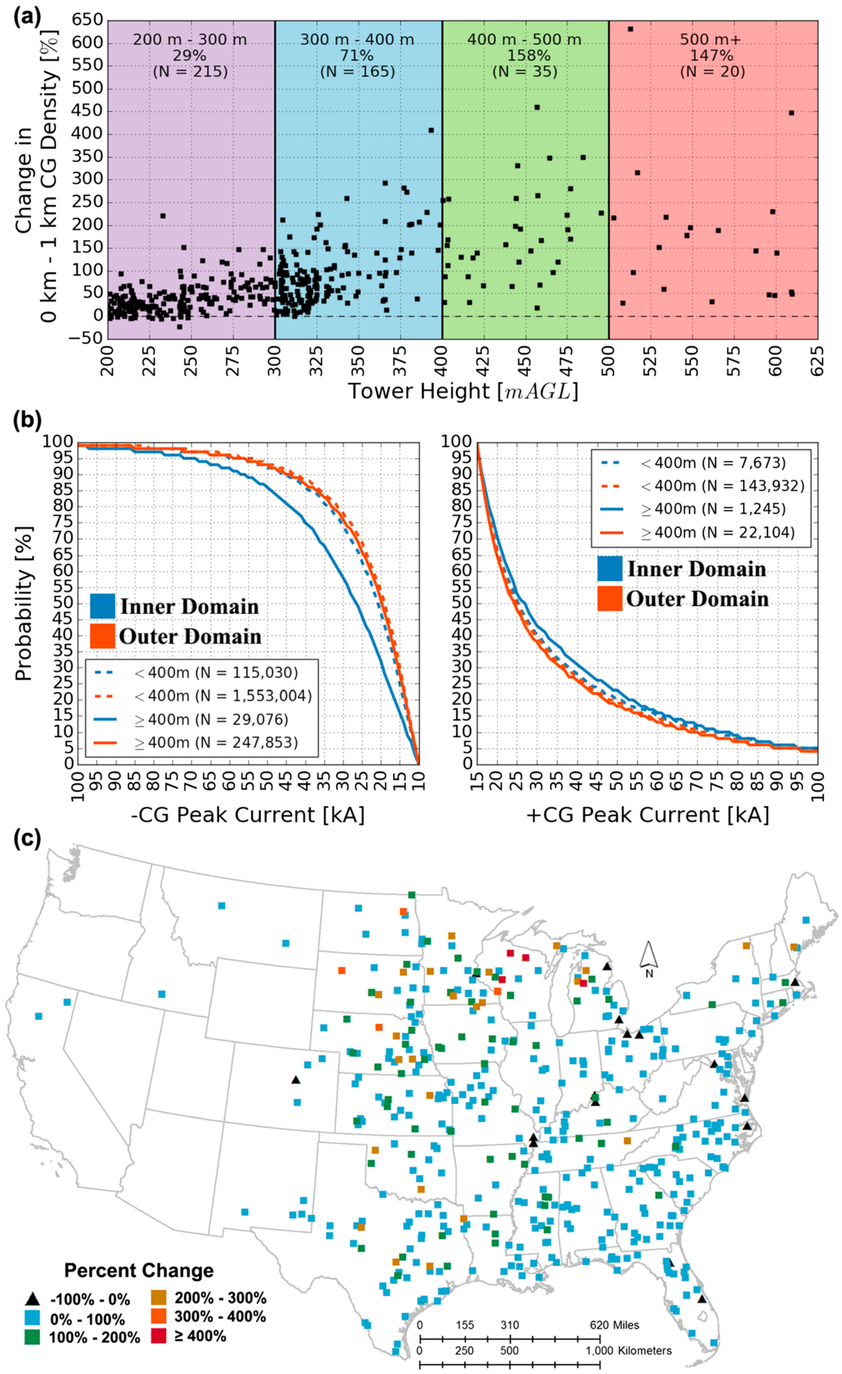

Figure 3. (a) Scatterplot of the percent change in CG density between the inner and outer domains, segmented by tower height. The median percent is annotated at 100 m intervals. (b) CDF plots of peak current measured in the inner (blue line) and outer (orange line) domains by polarity and tower height <400 m (dashed lines) and ≥400 m (solid lines). (c) A map of the percent change for the 435 FCC towers that were ≥200 m tall and ≥10 km from another FCC tower ≥200 m.

to 1996 (Figure 2c). Towers built before 1996 had a wider range of CG counts (100 to 619) compared to towers built after 1996 (100 to 465).

Departing from fixed CG frequency thresholds and examining modifications in lightning density around towers again reveals a positive correlation with height (Figure 3a). Around 96% of the 435 isolated towers had a higher lightning density within 1 km from the tower (inner domain) compared to the density

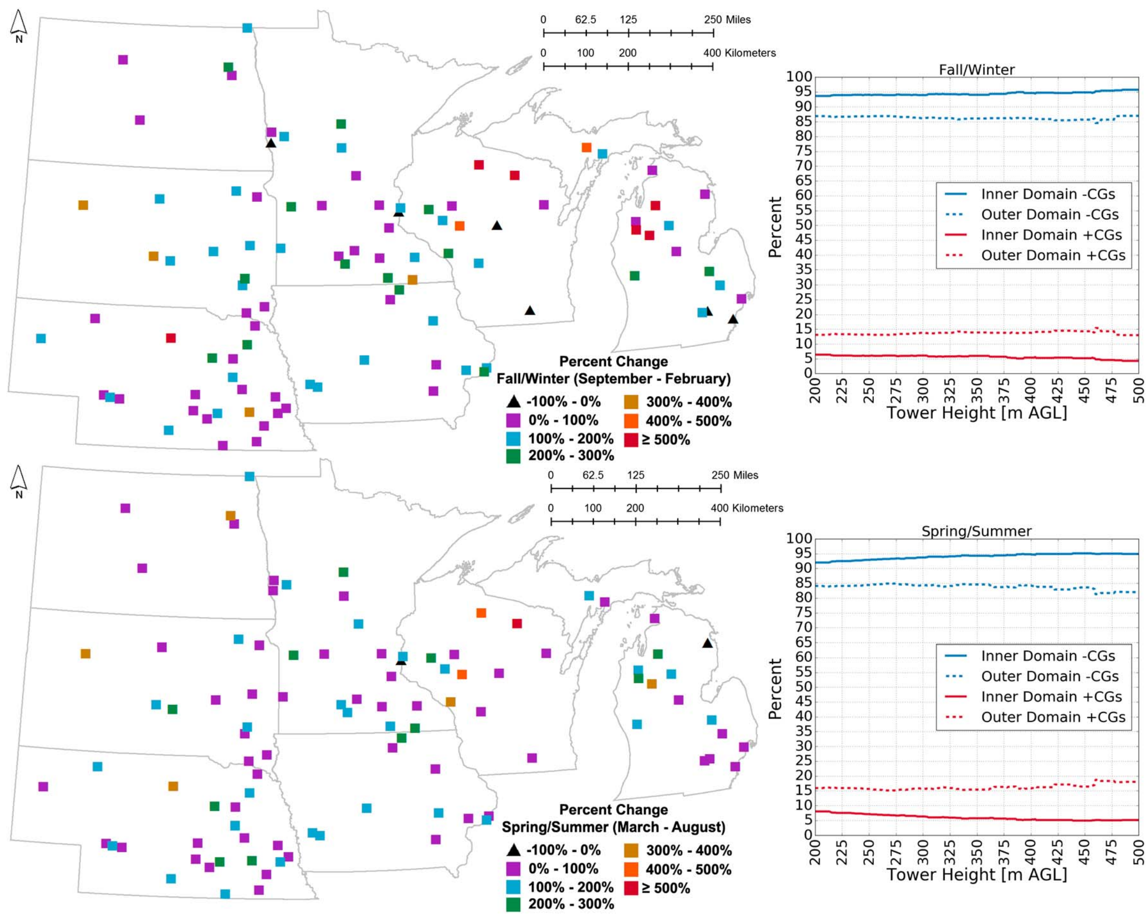

Figure 4. Percent change in CG density between the inner and outer domains in the meteorological (top) fall/winter and (bottom) spring/summer. Percent of −CGs and +CGs in both domains are plotted as a function of tower height (right).

measured 2–5 km away (outer domain). The median increase was 29% for towers between 200 and 300 m tall and near 150% for towers ≥400 m tall. Comparing peak currents reveals that a larger percentage of −CGs and +CGs recorded higher peak currents within the inner domain, particularly for CGs occurring near towers ≥400 m AGL (Figure 3b). This separation is more defined for −CGs; approximately 55% (35%) of inner (outer) domain −CGs had a peak current ≥25 kA. For +CGs, the separation in the distributions is smaller; around 55% (50%) of inner (outer) domain +CGs had a peak current ≥25 kA. Thus, there is a strong likelihood that ground flashes either initiated by or interacting with these towers will register higher peak amplitudes than nontower flashes. In addition, flashes near towers ≥400 m tended to have a lower multiplicity than flashes 2–5 km away. This difference was not observed in comparisons between domains for towers <400 m.

Mapping the percent change in the inner region (Figure 3c) reveals that much of the CONUS experiences up to a 100% increase in the inner domain lightning density compared to the outer domain, particularly through the south central and southeast CONUS. The northern Great Plains and upper Midwest (Figure 4) measure larger departures; 47% of towers had a ≥ 100% higher CG density in the inner domain, and 87% of these towers were ≥300 m. The highest percentage change of 631% occurred near a 512 m tower in Wisconsin (45.66°N/89.21°W) where 159 (22) CGs/km^2 occurred within the inner (outer) domains.

This region is also prone to experiencing both rain and snowfall regimes compared to southern latitudes [e.g., *Groisman and Easterling*, 1994]. Segmenting lightning occurrence into either the cold season (meteorological fall/winter—September to February; Figure 4a) or the warm season (meteorological spring/summer—March to August; Figure 4b) reveals that 94% (98%) of cold (warm) season towers (N = 100) had an elevated CG density in the inner domain. While a greater percentage of towers had an overall increase in CG density during

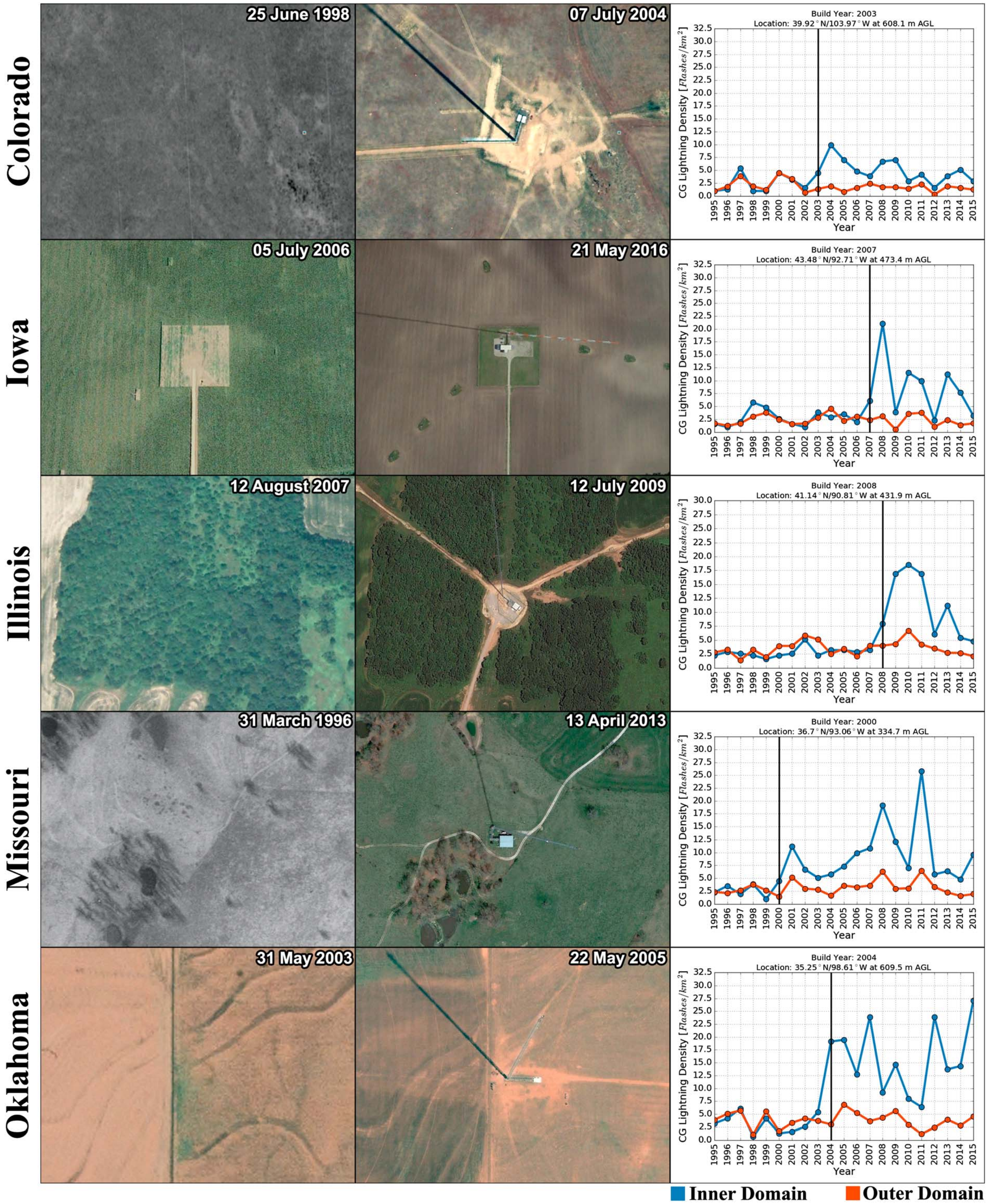

Figure 5. Google Earth imagery (left column) before and (middle column) after antenna tower construction and (right column) a 20 year time series of the yearly CG densities in the inner (blue line) and outer (orange line) domains. The black line denotes the tower construction year.

the warm season, more towers exhibited a greater positive increase in CG density in the inner domain during the cold season. Eight towers (343–609 m) had a 400+% increase in CG density in the cold season compared to three warm season towers (457–609 m). Accumulating these densities by season reveals that the inner domain had a 138% (117%) higher lightning density in the cold (warm) season. Segmenting by polarity yields that around 94% (86%) of CGs in the inner (outer) domain were −CGs in both seasons. The percentage of −CGs is correlated with tower height and reaches 95% in regions where the tower height exceeds 400 m.

Heretofore, the tower data set has been constrained to construction dates prior to 1995. For the 236 towers ≥200 m tall built after 1 January 1995, approximately 74% had a higher inner domain CG density the year following construction. For the 10 towers taller than 500 m, nine measured a higher inner domain CG density in the next full year. This elevated CG density persists and is observable across different CONUS regions (Figure 5). For example, in Colorado, the inner domain saw a fourfold increase in lightning density (~10 CGs/km^2) in 2004 after construction of a 608 m tower. Similar trends are observed in other states where many of the yearly CG densities in the outer domain are ≤7.5 CGs/km^2 while towered locations frequently see higher densities, up to 27.5 CGs/km^2 as measured near a 609 m tower in Oklahoma in 2015.

4. Discussion

While it has long been understood that lightning is attracted to and initiated by tall objects [e.g., *Mazur and Ruhnke*, 2011], the change in CG density (e.g., median ~150% increase for towers ≥400 m) near towers throughout the CONUS is more than a natural occurrence. Some flashes are likely the result of natural terminations; however, it is highly likely that others were either lightning-triggered or self-initiated upward lightning [e.g., *Wang et al*., 2008; *Mazur and Ruhnke*, 2011; *Warner et al*., 2014]. Thus, a majority of these flashes would not have occurred at or near the tower location if the tower did not exist.

Supporting evidence of upward lightning is seen with a greater percentage of −CGs occurring near the tower (95%) compared to farther away (84%). As noted by both *Mazur and Ruhnke* [2011] and *Warner et al.* [2012], initial positive upward leaders from towers are unlikely to be recorded by the NLDN due to their low continuing current. Once an attachment happens, connecting with either a preceding IC flash or following a subsequent initiation within the storm charge center, the recoil streamers and/or return strokes will be recorded as a −CG or potentially multiple −CGs. This is likely why the overall percentage of −CGs is correlated with tower height and implies that some of these CG flashes are likely the modification of what would be an IC flash otherwise.

Peak currents of flashes interacting with towers or other tall objects have so far been evaluated in fixed geographical locations [e.g., *Diendorfer et al*., 2002; *Lafkovici et al*., 2008; *Garolera et al*., 2015]. Within this study, the population of −CGs and +CGs near towers had higher peak currents than the population of flashes in the outer region. These differences were largest when comparing strikes occurring near towers ≥400 m, around 20% (5%) more −CGs (+CGs) registered a peak current ≥25 kA. While *Diendorfer et al.* [2002] found that the Austrian Lightning Detection and Information System underestimated peak currents measured from the Gaisberg tower, recent work by *Lafkovici et al.* [2008] and *Pavanello et al.* [2009] reveals that the Canadian Lightning Detection Network and NLDN tended to overestimate measurements of currents when compared to instruments located on the 553 m CN tower. Given that peak current measurements within the inner domain near towers ≥400 m were larger than the outer domain strikes, it is possible that towers at these heights are modulating the radiated electromagnetic fields to a greater extent than shorter towers (≤ 400 m) and ground flashes.

As expected, CG lightning is less frequent during the colder months (September–February). The 84% fewer CGs were recorded in the Great Plains during these seasons. However, shorter towers (> 340 m) in this region registered higher percentage increases in CG density (i.e., eight towers ≥400%) compared to their outer domains in the cold season. Furthermore, 56% of towers also registered a higher percentage change in the cold season over the warm season. This is indicative of towers being more susceptible to lightning due in part to generally lower altitude cloud bases and charging regions observed in winter convective modes [*Schultz and Vavrek*, 2009] and prevalence of winter storms in this region. Warm season increases in this region as seen in Figure 4 are likely the result of a combination of factors including, but not limited to, the presence of large charged areas of stratiform areas/anvils associated with Mesoscale Convective Systems and supercell thunderstorms [e.g., *Lang et al*., 2004; *Weiss et al*., 2012]. Flashes associated with these regions may be more likely to become CG instead of IC with the influence of a tower.

The strong relationship between amplified CG rates and towers may allow for the use of CG lightning records to determine the construction dates of tall structures in the absence of formal records. The examples in

Figure 5 all denote an increased CG lightning density by more than 100% in the year following construction. Though these flashes represent a small percentage of the overall NLDN record, continued construction of new structures could increase the number of lightning hot spots across the CONUS.

5. Summary

A 20 year, high-resolution climatology of NLDN CG lightning reveals that while higher lightning frequencies are more prevalent along the coastline in the southeastern CONUS, isolated areas with very high lightning frequencies (≥100 CGs) were observed in locations extending throughout the CONUS. Subsequently, this study is the first to document and quantify the spatial distribution of lightning enhancements caused by antenna structures across the CONUS. Given the close spatial associations between towers and lightning maxima, we feel that NLDN serves as a beneficial tool not only in broad mapping analyses of lightning occurrence but also in documenting and examining these smaller-scale influences.

A majority of pixels with ≥100 CGs were located at least 100 km inland. Spatial comparisons with FCC towers reveal that all grid cells exceeding 105 CGs had a registered tower within 1 km. Additionally, 76.7% of matching towers were constructed before 1995, allowing for two decades of thunderstorm opportunities and tower interactions. CG frequency was positively correlated with tower height with 98.2% of matching towers having a height ≥200 m.

This positive correlation was corroborated when comparing the CG lightning densities within 1 km from a tower to an area 2–5 km away. The 96% of towers had a higher density closer to the tower with the median percentage increase being around 29% for towers between 200 and 300 m and increasing to around 150% for towers above 400 m. Flashes near towers ≥400 m registered higher peak currents and lower multiplicities than around shorter towers. These departures in CG lightning density between the inner and outer domains are amplified in the north central CONUS where towers are generally struck by a higher percentage of less frequent thunderstorm events compared to the southeast CONUS where thunderstorm events are more prevalent. This departure in CG density is even more disparate in the meteorological fall/winter with towered locations seeing a higher overall percentage of lightning compared to events in the spring/summer. Additionally, a fourfold increase in CG densities was measured around shorter tower heights during the fall/winter. Finally, these trends were also observed around new tower constructions. In the five towers examined, there was a threefold increase in the lightning density within 1 km of the tower in the first year after construction, even in regions with fewer thunderstorm opportunities. This is a notable concern as additional communications and wind power turbines [e.g., *Hitaj*, 2013] fill the skyline in the future.

Acknowledgments
Tables containing information about the 675 towers evaluated above and the CG flash locations near each tower have been included in the supporting information to this research letter. The authors thank Patrick Marsh for his guidance on building Figure 1. We also thank the two anonymous reviewers as their feedback improved the content and clarity of this research letter. Funding was provided by the NOAA/Office of Oceanic and Atmospheric Research under the NOAA-University of Oklahoma Cooperative Agreement NA11OAR4320072, U.S. Department of Commerce, and the NASA Interdisciplinary Science Program project NNX12AM89G led by Geoffrey Henebry.

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