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An Investigation into the Impacts of Land-Use/Land-Cover on Cloud-To-Ground Lightning Activity

Nathan Oneal Owen

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By

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Cloud-to-Ground (CG) lightning activity was analyzed across the lower Mississippi River valley. The goal was to determine whether certain land use/ land cover (LULC) types supported convective thunderstorms' generation of CG lightning more than other LULC types. Results indicate that forested regions receive more CG lightning than any other LULC type represented in the study area. However, results also indicate that CG lightning activity can be enhanced locally by very large and/or sprawling areas of urban LULC. When cities from previous research, including Atlanta, GA, and Birmingham, AL, are combined in the rankings with cities in this study, the urban size difference between Little Rock, Arkansas, and Birmingham, Alabama, appears to highlight the area of urban LULC needed to enhance convection. Future research should focus on more cities within this gap of urban LULC area in order to identify the minimum areal expanse needed to alter convective ability over cities.

ACKNOWLEDGEMENTS

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

Lightning is a common natural phenomenon that occurs worldwide. It is no surprise that lightning constitutes a danger to human life and property. Therefore, it is important to understand all possible mechanisms that could attribute to the enhancement of lightning activity. For example, how does land-cover and land-use affect the distribution of lightning? Answering this question can lead to better forecasting of lightning frequency and can be included in public awareness discussions regarding the dangers of lightning.

Due to differential heating between agricultural crops, forests, pastures, urban areas, and water bodies, mesoscale atmospheric boundaries may form. This has been shown to promote convection, which is a necessary ingredient for lightning. Comparing the density of CG lightning between these land-cover types will help answer the question of whether land-cover and land-use can significantly alter lightning activity. This is a step forward into gaining a broader understanding of the interactions between surface characteristics and atmospheric behavior. For example, human-induced changes in land-use and land-cover (LULC) can have large impacts on cloud-to-ground (CG) lightning because of the significance of land-atmosphere interactions. Studies have shown that urbanization causes an enhancement of CG lightning density (Stallins and Bentley, 2008, Stallins and Bentley, 2006, Stallins et al. 2013). Stallins (2004) found that clusters of higher CG lightning activity exist downwind of the Atlanta, Georgia, urban center. This was shown to put suburban neighborhoods downwind of Atlanta at a higher risk of property damage due to CG lightning than those upwind of the urban center (Stallins, 2004). Rabin et al. (1990) found that man-made lakes lead to a decrease in cloud cover downwind of the lake. Clark and Arritt (1995) found, through numerical models, that denser vegetation cover, such as forests, aid in deep convection through the extraction of soil moisture and overall increase in available energy. These few examples of the interactions between LULC and atmospheric conditions illustrate how humans can potentially alter CG lightning densities through urbanization, deforestation, cultivation of crops, and construction of lakes. Alteration of LULC by humans occurs over a relatively short amount of time. Because of this, the impacts of LULC change could mask any larger signals that are typically associated with changes in atmospheric conditions, such as climate change and teleconnections. Therefore, any studies that investigate the interactions of teleconnections or climate change on CG lightning should also consider any changes in LULC.

General Lightning Climatology

While lightning can occur anytime during the year, the average number of strikes across the continental United States has been shown to peak during the months of June, July, and August (Orville and Huffines, 2001). Overall, the total number of strikes per year tends to accumulate within a short period of time, rather than being spread out temporally through the year. Case studies show that this pattern exists regardless of geographical climate regimes (Zajac and Rutledge, 2001). Areas with the highest average annual strike counts in the continental United States are generally located in the

Florida Peninsula, the northern coast of the Gulf of Mexico, and along the Texas–Louisiana border (Orville and Huffines, 2001) (Figure 1). Outside the peak summer months, the density of lightning is higher along the Gulf Coast than in more continental locations (Zajac and Rutledge, 2001). These climatological maxima are often attributed to the number of thunderstorms that occur in the area. For example, the number of thunderstorms during the summer months is much higher than the number of thunderstorms during the winter months (Williams et al. 2000). This helps explain why the annual peaks of lightning activity occur during June, July, and August. With respect to the maxima located along the Florida peninsula and northern coast of the Gulf of Mexico, the presence of sea breezes contributes to the increased number of thunderstorms (Smith et al. 2005). The Florida peninsula is known for having the highest annual frequency of lightning due to the convergence of the sea breezes coming off of the Gulf of Mexico and the Atlantic Ocean. The timing of the sea breezes in these areas also introduces a climatological pattern for the diurnal frequency of lightning along the coast. The mid-afternoon intensification of sea breezes leads to a higher frequency of lightning between the hours of 1400–1800 CST (Smith et al. 2005).

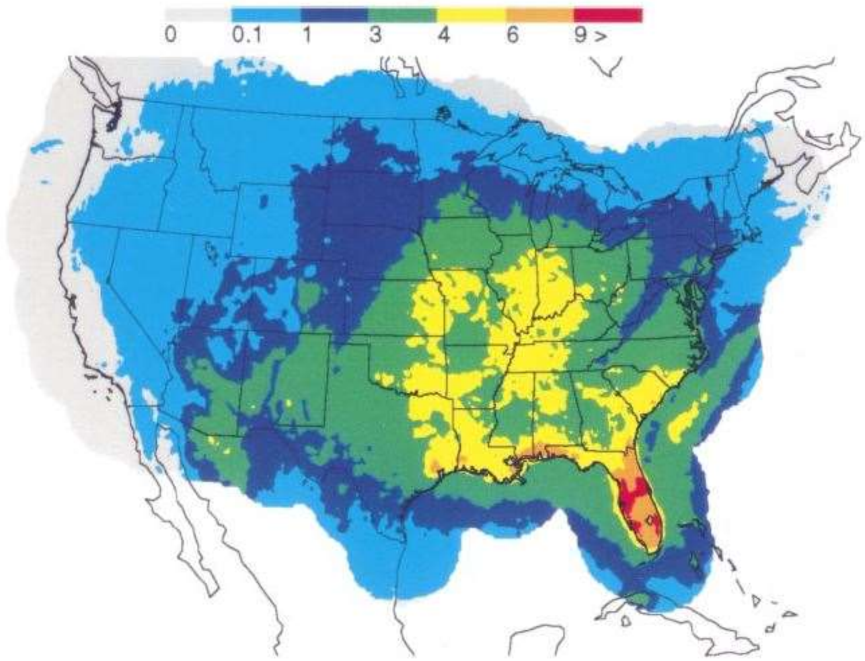

Figure 1 Orville and Huffines (2001) mean annual lightning flash densities per km

Convection and Lightning

Lightning occurs due to a charge separation within a convective storm. This charge separation has been attributed to the presence of both liquid water and ice within the cloud. Lightning can occur as either cloud-to-cloud (CC) lightning or cloud-to-ground (CG) lightning. It has been shown that CG lightning increases when there is an increase in hail and rain (Lang and Rutledge, 2001) (Figure 2). Hail production can only increase if the updraft speeds in the convective storm also increases. Therefore, with an increase in updraft speed, the occurrence of CG lightning will also increase (Lang et al. 2004). However, it has been observed in a case study from 1996 that during the weakening of a convective storm, the CG lightning rates actually increased (Lang et al. 1998). This indicates that the weakening of an updraft and decrease in hail production also lead to increase in CG lightning. Lang et al. (1998) continued to attempt to explain the possible causes for this anomaly. There could have been an interruption in the charge separation due to the melting of hail as the updraft weakened. Second, the precipitation itself could have contained enough electric charge to cause the charge separation to increase as the precipitation rate increased due to the weakening updraft. This increased charge separation due to the increased precipitation could have caused the increase in CG lightning (Lang et al. 1998). With respect to updraft velocities, the exact velocities required for promoting the electrification in thunderstorms are aspects that will be addressed in future research (Lang et al. 2004). It is suggested that the absence of sufficient updraft velocities would prevent the production of lightning due to the lack of supercooled liquid water (Zipser and Lutz, 1993).

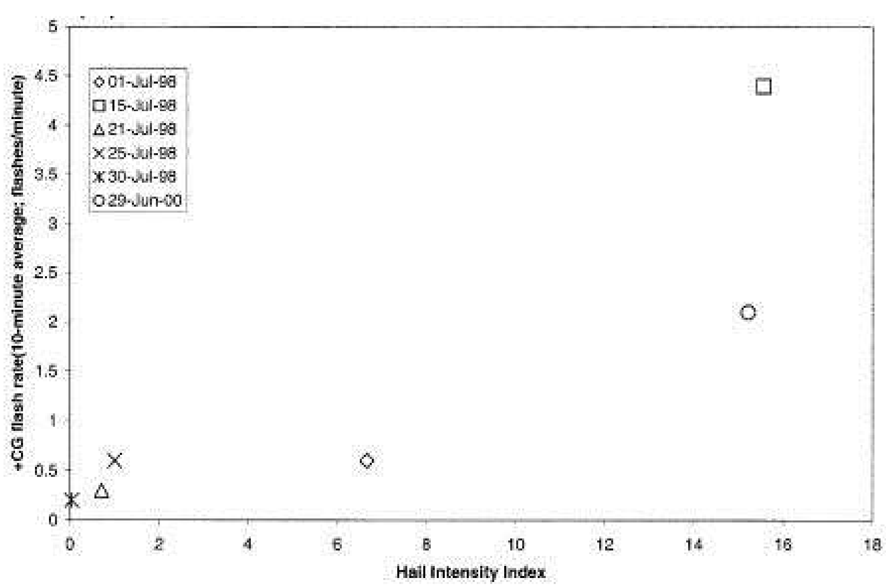

Figure 2 Lang and Rutledge (2001) hail intensity vs. positive CG flash rates

Influence of Land-Cover/ Land-Use on Surface Temperatures

A common variable that has been studied with respect to land-cover/ land-use is temperature. With respect to variations in vegetation, research in the Mississippi River alluvial valley has shown that minimum temperatures in the valley are typically higher than temperatures outside the valley. This results in smaller diurnal ranges, on average, in the valley (Brown and Wax, 2007). When researching the relations between diurnal temperature ranges and different land-cover and land-use types, it has been shown that agricultural and urban areas have the smallest range when compared to deciduous, evergreen, and mixed forests (Scheitlin and Dixon, 2010) (Table 1). Scheitlin and Dixon (2010) also suggest that, due to the similar trends in diurnal temperature ranges regardless of vegetation, variations in evapotranspiration rates do not explain the differences in the diurnal temperature ranges. Some research suggests that long-term changes in land-cover and land-use could change the distribution of latent and sensible heating, causing localized weather features to change climatologically. The changes in land-cover and land-use are proposed to be a cause of significant changes in the input of sensible and latent heat into the atmosphere (Mahmood et al. 2009).

Table 1 Scheitlin and Dixon (2010) mean diurnal temperature ranges across LULC classifications.

LULC	*S*	DTR
Urban	6	12.70
Deciduous	11	13.96
Evergreen	7	13.86
Mixed forest	39	13.53
Agriculture	57	12.67
Mean	—	13.34
Total	120	—

Land-Cover/Land-Use influences on Convection and Lightning

Changes in land-cover and land-use can cause mesoscale variations in temperature. These variations in temperature can lead to changes in convective intensity across the different landscapes. Studies involving the use of visible and infrared satellite images have shown that an enhancement of convection exists around landscapes that exhibit higher temperatures, such as recently harvested cropland (Rabin et al. 1990). Rabin et al. (1990) also noted regions of diminished convection in areas around lakes and heavier vegetated landscapes, such as forests (Rabin et al.1990). Related to the changes in temperature, some land-cover regimes may cause an enhancement of convective available potential energy (CAPE) where other regimes may suppress CAPE. The enhancement of CAPE may drive localized growth of cumulonimbus convection (Pielke, 2001). Because of the potential effects of land-cover and land-use on convection, a numerical model was created to incorporate vegetation and soil moisture of the underlying surface. Results from these models indicate that the presence of vegetation aids in convection but suppresses the overall precipitation. Also, areas of greater soil moisture were shown to increase the amount of precipitation (Clark and Arritt, 1994) (Figure 3).

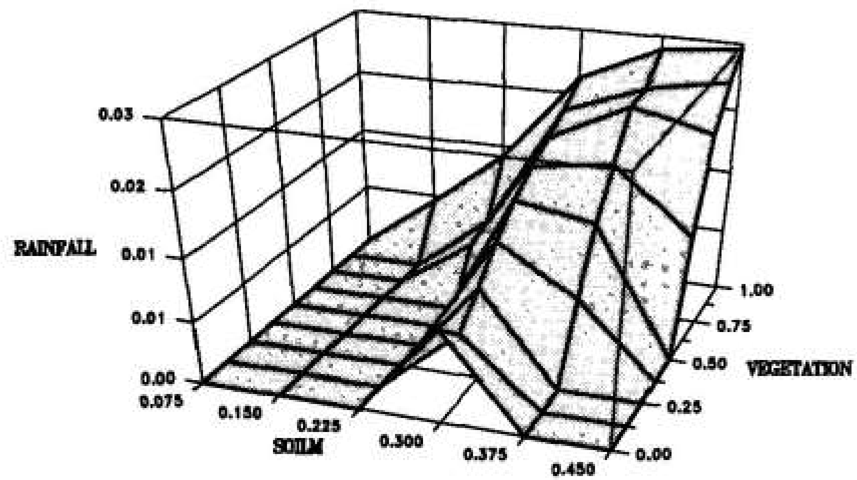

Figure 3 Increased vegetation and soil moisture is associated with increased rainfall (Clark and Arritt 1994)

In relation to the land-cover and land-use influences on lightning, studies have focused on elevation changes and overall Normalized Differential Vegetation Index (NDVI) values. NDVI values that correlate with forested regions have been shown to correspond with increased CG lightning observations (Figure 4). In regards to elevation changes, CG lightning increased with increasing elevation up to 1000–1500 m (Lopes et al. 2011). Lopes et al. (2011) also mentions the need for further research using higher-resolution grids for both the NDVI and the elevation. Similarly, the region of terrain elevation rise in central Georgia, referred to as the “fall line”, experiences enhanced convection and lightning frequency due to upslope flow (Bentley and Stallins 2005). Studies around the Great Lakes region suggest that bodies of water would suppress CG lightning, and that the water temperatures could play a role in the variation in seasonal CG lightning (Clodman and Chisholm, 1994).

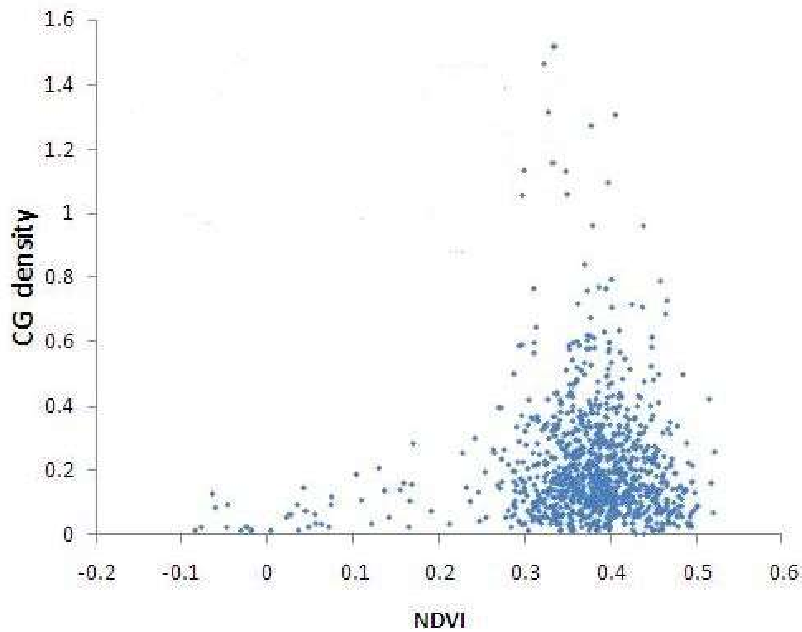

Figure 4 Forested regions denoted with NDVI values of 0.3 – 0.5. NDVI vs. CG density (Lopes et al. 2011)

Impacts of Urban versus Rural landscapes on Convection and Thunderstorms

A specific land-use type that has been the focus of continued research is urban areas. Research indicates that thunderstorms can be altered by urban environments. The larger cities have a more pronounced impact, while smaller cities, such as Jackson, MS, and Montgomery, AL, have somewhat less of an impact on thunderstorm alterations (Ashley et al. 2012). There are a few suggested causes for these urban influences. First, the urban heat island effect might provide some explanation. It has been shown that urban heat island effects on temperature aid in the initiation of convection (Dixon and Mote, 2003). The urban heat island theory was linked to an increase in medium and high reflectivities over Atlanta, GA. This is more pronounced on synoptically benign days (Ashley et al. 2010). Research in Sydney, Australia, determined that convection associated with synoptic forcing was not affected by the land-cover change. Also, isolated convective storms seemed to be more dependent on local temperature and moisture influences rather than land-cover change (Gero et al. 2006). Second, localized wind patterns might play a role in the enhancement of convection. As the city warms faster during the day than the rural areas surrounding the city, a relative low pressure could develop inside the city, promoting localized convergence similar to sea breezes (Findlay and Hirt, 1969). Research focusing on Memphis, TN, and Atlanta, GA, has shown that the two cities experience more thunderstorms, and more intense thunderstorms, than surrounding areas (Ashley et al. 2010). Finally, the pollution associated with larger cities could be ingested into the updrafts of thunderstorms moving over the city. The presence of pollution, commonly in the form of aerosols, could act as condensation nuclei allowing more condensation of cloud droplets (Van de Heever and Cotton, 2006). With the condensation of more cloud droplets, more latent heat would be released. This could possibly lead to more intense convection. However, other research has shown that the convergence downwind of urban areas is more prominent for the development of convection than the aerosol concentration. The study found that convergence was more important to the initiation of convection, and that aerosols had a more pronounced influence after convection was already established (Van de Heever and Cotton, 2006).

Urban versus Rural Land-Cover on Lightning

Research has shown that in larger cities, such as Atlanta, GA, lightning flash counts can vary around the periphery of the city based on the prevailing wind direction (Rose et al., 2008). Rose et al. (2008) also suggest that the variability based on wind direction is more pronounced during synoptically benign days. This is in agreement with the previously-mentioned studies on the urban impacts on convection. There are two common approaches to investigating lightning: lightning flash counts and lightning days. Lightning flash counts are more representative of isolated, surface-based convective storms, while lightning days are more representative of synoptic forcing (Stallins and Bentley, 2006). Stallins and Bentley (2006) discuss the problems with smoothing the flash data and suggest that future research be focused on linking specific storms to human and natural surface features. Later research investigated the variability of lightning flash counts and strength between weekday and weekend storms. That study looked at the aerosol concentrations around Atlanta, GA, as a contributing variable in lightning production. On weekdays, there was higher CG lightning around Atlanta. On the weekends, this area of higher CG lightning contracted closer to the city. The study found that the peak lightning currents were more regional and did not correspond to the city (Stallins et al. 2013).

CHAPTER II

METHODS

The data used in this study include cloud-to-ground lightning data and land-use/land-cover (LULC) data. The domain of this study does not include areas subject to sea-breeze convection or significant orographic lifting (Figure 5). It also does not include areas where substantial land-cover change occurred due to Hurricane Katrina in 2005.

The cloud-to-ground lightning data were obtained through the National Lightning Detection Network (NLDN). Complete coverage of the United States began in 1989 (Orville and Huffines, 2001). The NLDN is comprised of more than 114 sensors spread throughout the United States (National Lightning Detection Network). The accuracy of the NLDN varies due to the variation of distance between sensors across the United States (Orville and Huffines 2001); however, Cummins et al. (1998) found the mean accuracy of the NLDN to be approximately 500 m. Furthermore, Cramer et al. (2004) determined the detection efficiency of the NLDN to be greater than 90%. This study uses lightning data for synoptically weak days over the study area for the years 2001–2011, which encompasses the full period of the NLDN lightning data that were obtained. Cloud-to-ground lightning strikes with a positive polarity of less than 15 kA were removed from this study due to the likelihood of them being cloud-to-cloud strikes (Biagi et al. 2007). This is a suggested method by Biagi et al. (2007) because the threshold of 15 kA is where false reports equal the number of correct reports.

Air-mass data were obtained from the Spatial Synoptic Classification (SSC; available online at http://sheridan.geog.kent.edu/ssc.html). The SSC, detailed in Sheridan (2002), classifies air masses as being:

1. Dry moderate (DM)
2. Dry polar (DP)
3. Dry tropical (DT)
4. Moist moderate (MM)
5. Moist polar (MP)
6. Moist tropical (MT)
7. Transition (TR)
8. Moist tropical plus (MT+)
9. Moist tropical double plus (MT++)

The moist tropical plus and moist tropical double plus were considered moist tropical for this study. Study area sites with available SSC values include (Figure 5):

1. Meridian, Mississippi
2. Jackson, Mississippi
3. Memphis, Tennessee
4. Little Rock, Arkansas
5. Shreveport, Louisiana
6. Ft. Smith, Arkansas

To ensure that the convective storms causing lightning were not initiated due to frontal lifting mechanisms or other synoptic forces, only synoptically weak days were used in this study. This was determined using the air-mass data obtained from the SSC. If multiple air mass classifications were present across the study area, a synoptic boundary separating the air masses is likely to also be present and therefore provide synoptic-scale lifting. If all six SSC sites were under the influence of the same air mass classification, the day was considered synoptically weak.

Figure 5	Study area outlined in black box and Spatial Synoptic Classification sites denoted.

The LULC data were obtained through the United States Geological Survey's (USGS) Multi-Resolution Land Characteristics Consortium (MRLC) National Land Cover Dataset 2006 (NLCD2006). The NLCD2006 was created through the collaboration of a group of federal agencies, and is based on the unsupervised classification of Landsat Enhanced Thematic Mapper+ (ETM+). The NLCD2006 has a spatial resolution of 30 m, and provides a 16-class land-cover classification scheme (Fry et al. 2011). The 16 classes were merged into 8 relevant classifications for the purposes of this study (Table 2). Because barren land covered less than 1% of the study area, it was not included in the statistical analysis. Mixed forest was also taken out of the statistical analysis because there was not a large representative grouping of mixed forest. Many of the mixed forested regions, rather, existed as transitions between deciduous to evergreen forested regions.

Table 2 LULC classifications from NLCD2006 and classifications used in this study.

NLCD2006	Study	Study area coverage (%)
Open Water	Open Water	3
Perennial ice/snow	N/A	0
Developed-open space Developed-low intensity Developed-medium intensity Developed-high intensity	Urban	7
Barren land	Barren land	0
Deciduous forest	Deciduous forest	15
Evergreen forest	Evergreen forest	18
Mixed forest	Mixed forest	6
Shrub/scrub Grassland/herbaceous Pasture/hay Cultivated cropland	Agriculture	39
Woody wetlands Herbaceous wetlands	Wetland	12

Because the NLDN has an accuracy of approximately 500 m, the 30-m resolution of the NLCD2006 was expanded to a larger grid scale for more accurate comparison with the cloud-to-ground lightning data. Three different grid sizes (1 km, 4 km, and 16 km) were analyzed in this study to account for varying accuracies of the NLDN and the varying sizes of convective storms. The grids and NLCD2006 were joined by assigning the most dominant LULC classification to each grid cell, similar to the procedures done by Scheitlin and Dixon (2010). Only grid cells where a single LULC type accounted for ≥50% of the total area were used in statistical analysis.

Lightning data for the chosen, synoptically weak days were overlaid on the 1-km, 4-km, and 16-km LULC grid layers. The number of lightning strikes for each grid cell was joined to the LULC grid layers using the spatial join based on location. This gave the number of strikes within each grid cell and the associated LULC of that grid cell.

Bootstrap resampling techniques were performed on the mean and variance using the CG lightning counts between the different LULC types to determine if a statistically significant difference in cloud-to-ground lightning density exists. Bootstrap resampling results form Gaussian distributions (Figure 6). Because the CG lightning data follow a right-tailed, Gamma distribution, the bootstrap results were needed to more accurately compare the CG lightning counts across the different LULC types (Figure 7). The upper, median, and lower confidence levels (α=0.05) of the bootstrap means and variances using the grid cell values from across the entire study area were then plotted to visually determine the significance of the differences in CG lightning counts across each LULC classification.

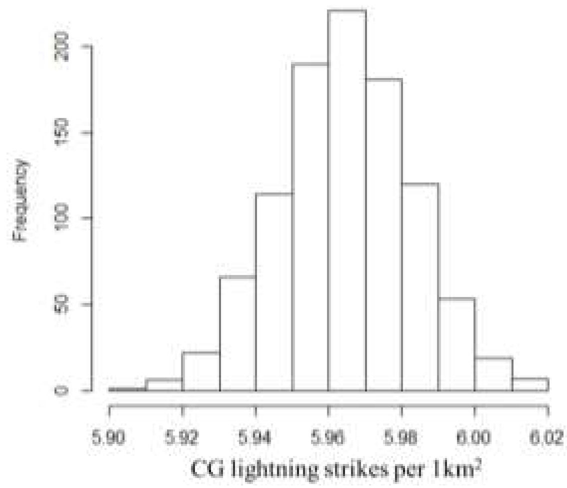

Figure 6 Gaussian distribution of bootstrap means (1000 replications) of CG strikes using 1-km grid cells

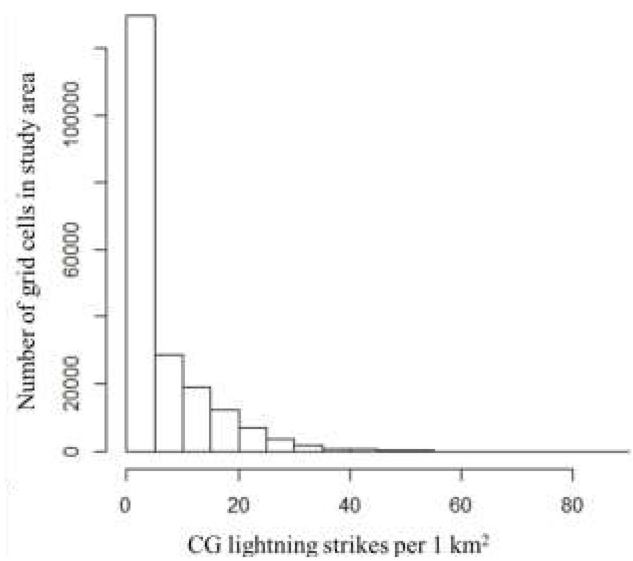

Figure 7 Right-tailed gamma distribution of CG lightning strikes using 1-km grid

Finally, 50-km insets were made in the study area. Each inset was placed over cities of varying urban extents across the study area to help determine how the amount of urban development might alter the CG lightning densities over the cities (Figure 8).

There were six cities chosen for this study. The cities chosen for this study were then combined with the cities used by Ashley et al. 2010 to build on the relationship between urban size and its influence on thunderstorm activity (Table 3). A similar bootstrap resampling technique as used before was performed within each city inset. Upper, median, and lower percentiles (α=0.05) of the means were then plotted for each city.

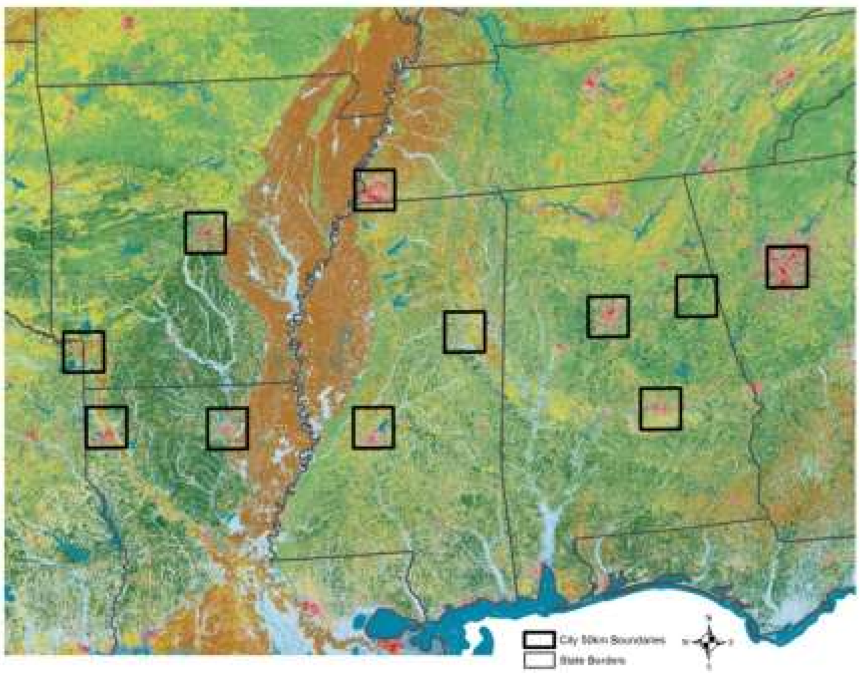

Figure 8 Selected cities for individual investigation and cities used by Ashley et al. 2010

Urban LULC areas are shown in red.

Table 3 Cities used for urban analysis for this study and in Ashley et al.

Study Cities	**Area (sq.km)**
Memphis, TN	1034.73
Little Rock, AR	546.51
Texarkana, AR	285.07
Shreveport, LA	478.14
Monroe, LA	297.07
Jackson, MS	543.2
Ashley et al. (2010) Cities	
Starkville, MS	168.78
Birmingham, AL	887.31
Montgomery, AL	397.02
Heflin, AL	222.26
Atlanta, GA	1739.5

Areas calculated from urban LULC within the 50-km inset

CHAPTER III

RESULTS

Using the Spatial Synoptic Classification to identify the synoptically weak days resulted in 780 total days in the 11-year study period (Figure 9). During those 780 synoptically weak days, there were a total of 1,610,352 CG lightning strikes recorded in the study area. Most of the CG lightning strikes occurred during the months of May, June, July, and August (Figure 10). This is expected due to the warmer temperatures that lead to more instability during those synoptically weak days.

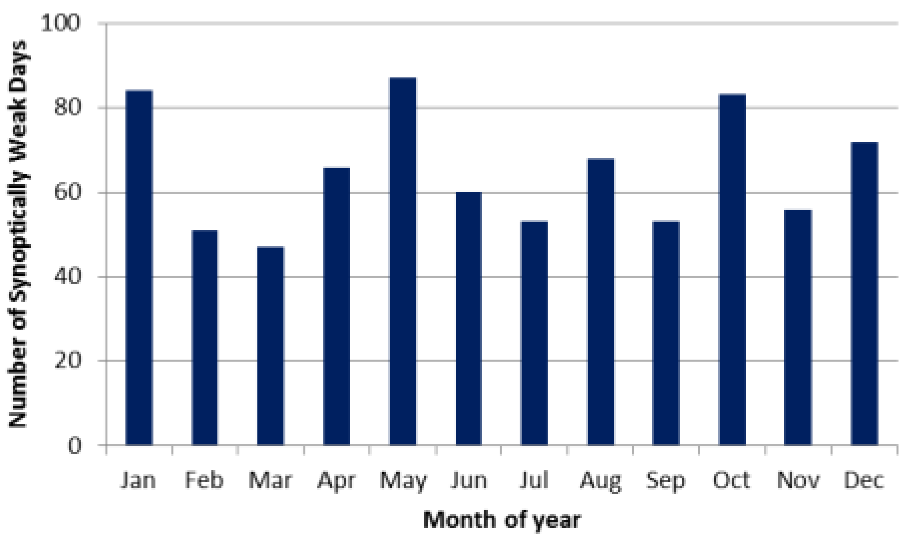

Figure 9 Synoptically weak days per month for the 11 years used in this study

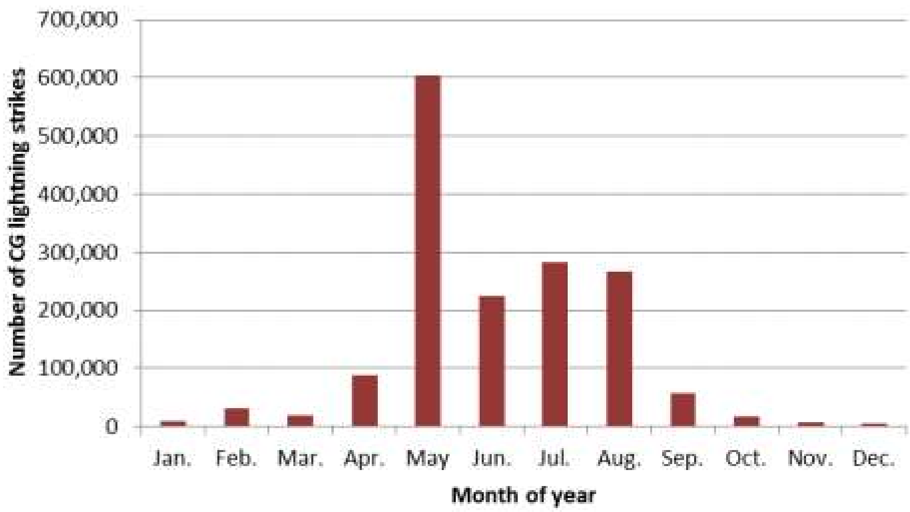

Figure 10 Monthly distribution cloud-to-ground lightning strikes on synoptically weak days used in the study

Agriculture is the foremost LULC type through the region, followed by evergreen and deciduous forests (Figure 11). The smallest percentage, which represents the water bodies through the region, is primarily made up of the Mississippi River, associated oxbow lakes, and several small man-made lakes and reservoirs.

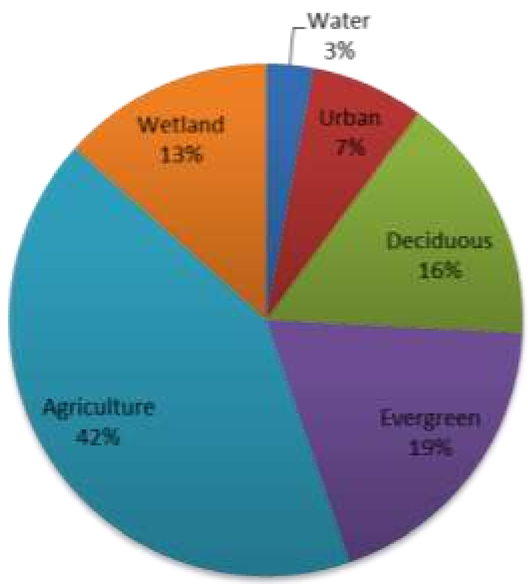

Figure 11 Percentages of LULC types across entire study area

16-km Grid Layer

The 16-km grid layer does not provide much detail in the spatial variation that exists in CG lightning and LULC because of its large spatial resolution (Figure 12 – 13). The results of the bootstrap means show evergreen forests and urban LULC as having statistically higher CG lightning counts than deciduous forests, agriculture, wetlands, and water (Figure 14). Evergreen forests also show a significantly higher variance when compared to the other LULC types (Figure 15).

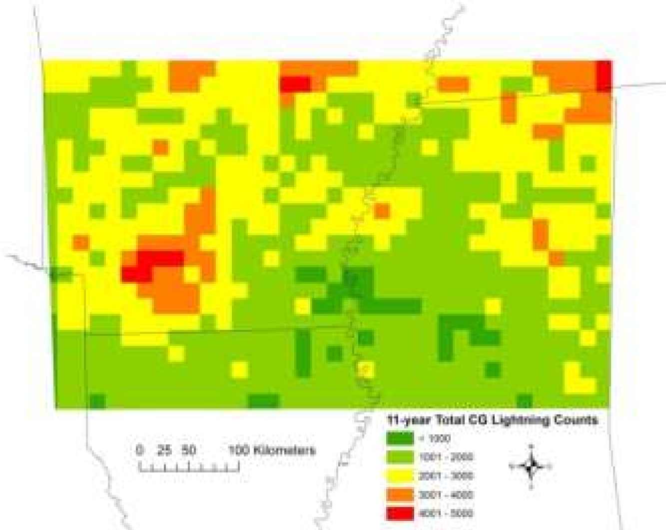

Figure 12 CG lightning counts per 16-km grid cell

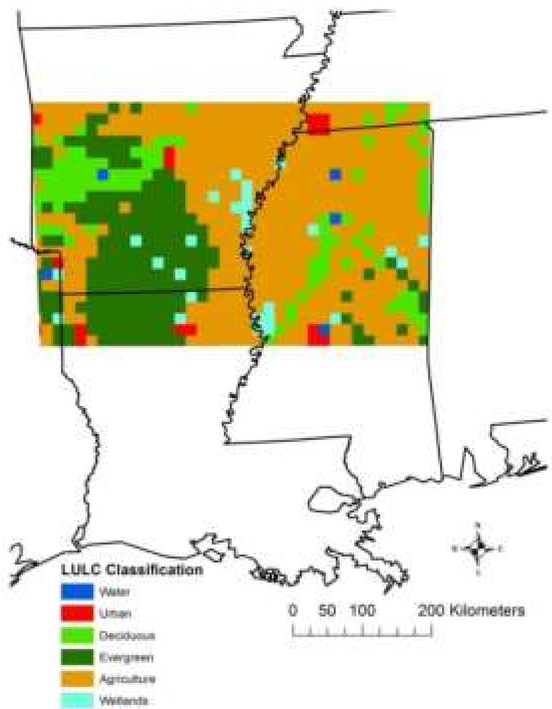

Figure 13 LULC classification per 16-km grid cell

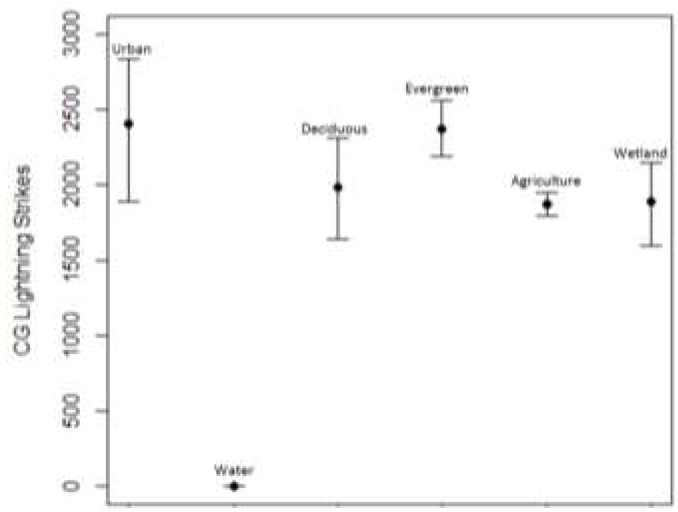

Figure 14 Bootstrap Mean confidence interval ranges for 16-km grid cells

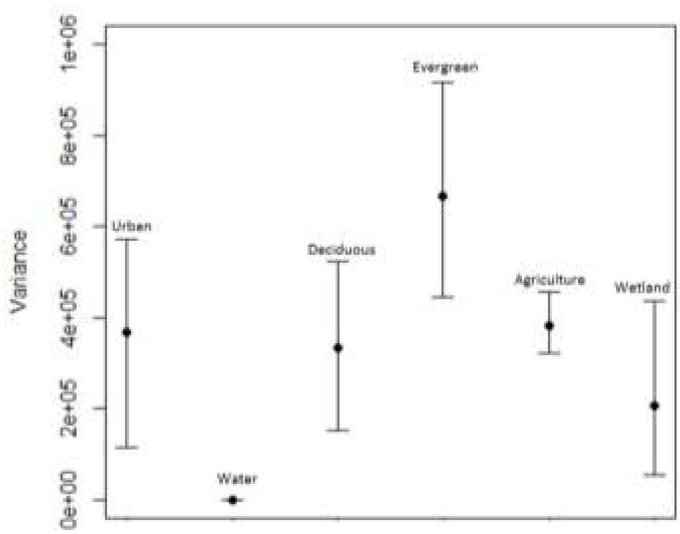

Figure 15 Bootstrap variance confidence interval ranges for 16-km grid cells

To help determine whether the sample size of grid cells for each LULC type influenced the bootstrap mean results, a scatterplot was created and a best-fit trend line was applied to visualize the relationship between number of grid cells used in the bootstrap analysis for each LULC type and the normalized CG lightning frequency (Figure 16). With an r^2 value of 0.0339, there was not a statistically significant relationship between the number of grid cells used in the bootstrap resampling technique and the number of CG lightning strikes for the LULC types.

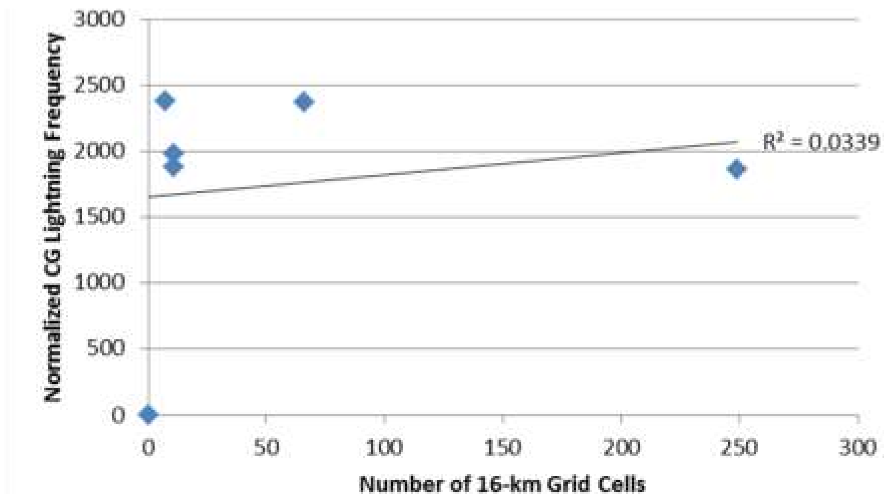

Figure 16 Number of grid cells for each LULC type vs. CG lightning frequency

4-km Grid Layer

The 4-km grid layer offers better spatial resolution when assessing LULC impacts on CG lightning activity (Figure 17 – 18). As shown in the LULC classification map (Figure 18), the larger rivers and water bodies are better represented than they were in the 16-km grid layer.

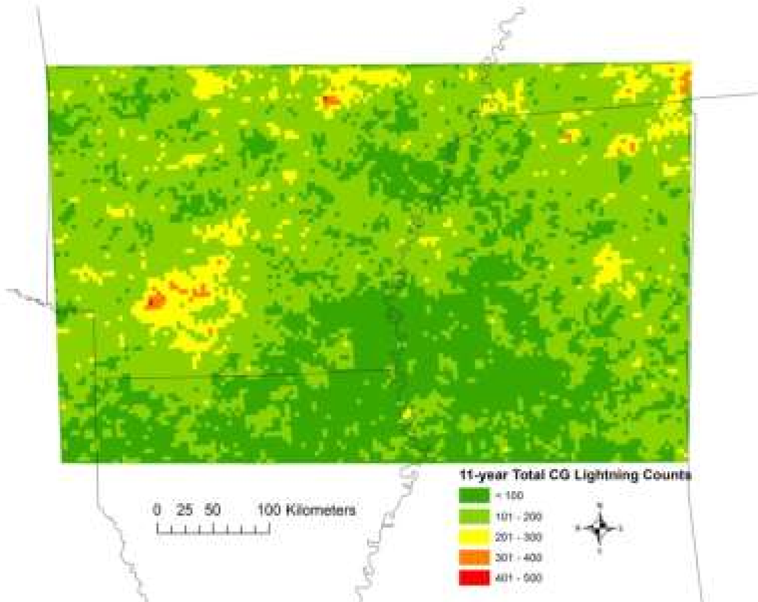

Figure 17 CG lightning counts per 4-km grid cell

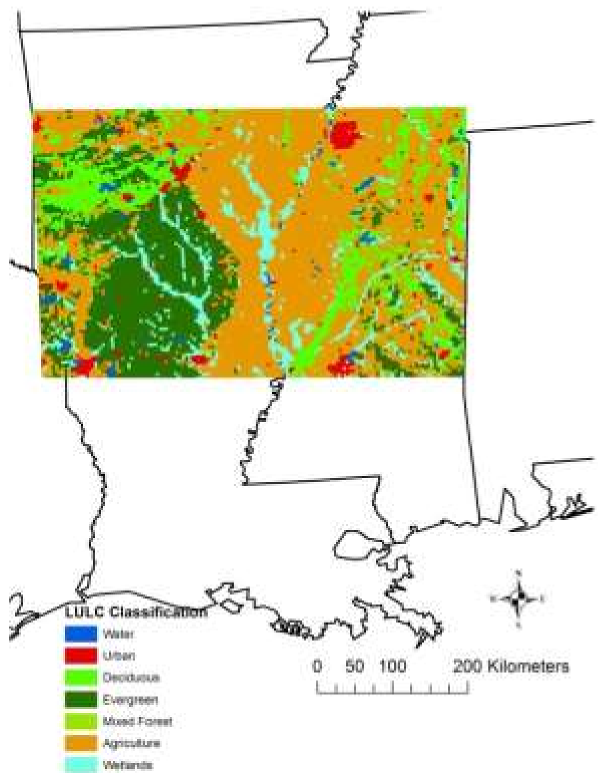

Figure 18 LULC type for each 4-km grid cell across study area

The results of the bootstrap mean statistical tests show a larger separation in CG lightning counts associated with evergreen LULC when compared with the other LULC types (Figure 19). Evergreen LULC has statistically significantly higher values for CG lightning. Urban LULC shows the next-highest values. Water has a large confidence interval range, making it not statistically different than deciduous, agriculture, or wetland LULCs. Agricultural areas are shown, however, to have the lowest values of CG lightning. Regarding the variance results, the only statistically significant difference exists in the evergreen LULC having a higher variance than the other LULC types (Figure 20). CG frequency for each LULC type is not statistically related to the number of grid cells for the 4-km grid layer, similar to the 16-km grid layer (Figure 21).

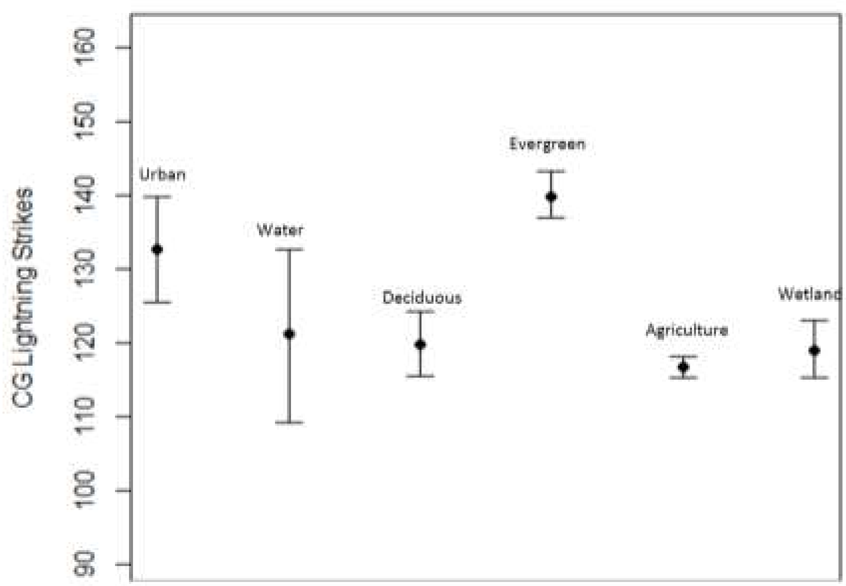

Figure 19 Bootstrap mean confidence interval plots for 4-km grid cells

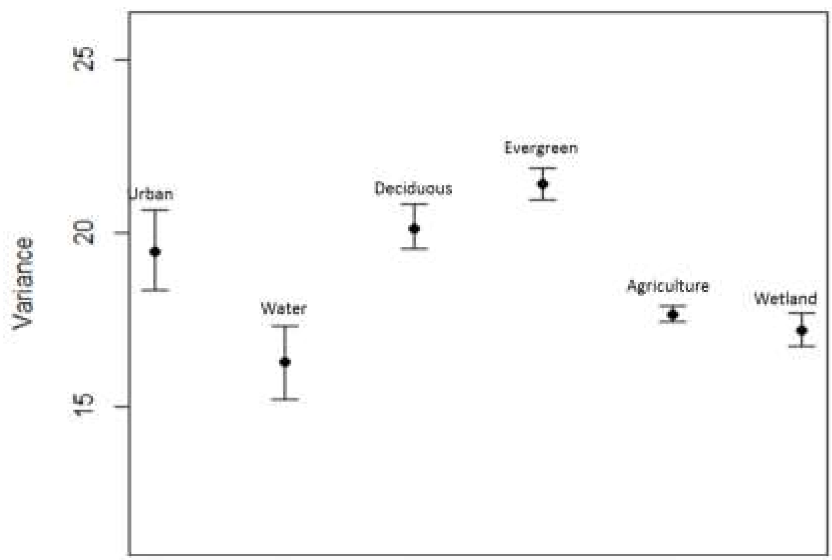

Figure 20 Bootstrap variance confidence interval plots for 4-km grid cells

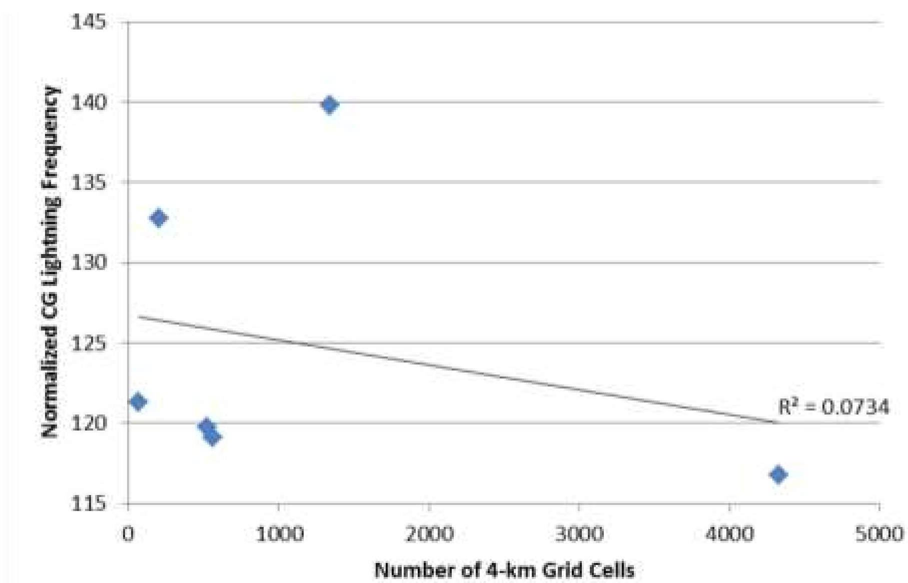

Figure 21 Number of grid cells for each LULC type vs. CG lightning frequency

1-km Grid Layer

Using the 1-km grid layer provides the best distinction of LULC types and can, therefore, more realistically represent the impacts of LULC on CG lightning activity (Figure 22 – 23). In the LULC map, the smaller rivers and lakes are easily discernible. Because LULC variations exist on such a small spatial scale, thunderstorm activity and therefore, CG lightning activity may respond on relatively small spatial scales as well. Using the 1-km grid layer most adequately represents this relationship while still taking into account the ~500-m accuracy of the NLDN.

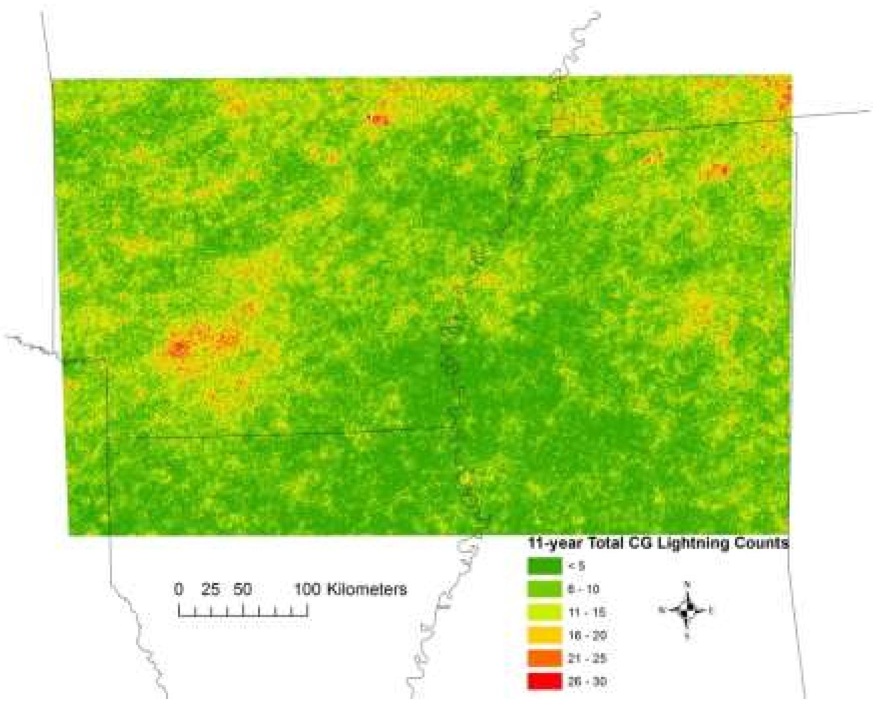

Figure 22 CG lightning counts in each 1-km grid cell

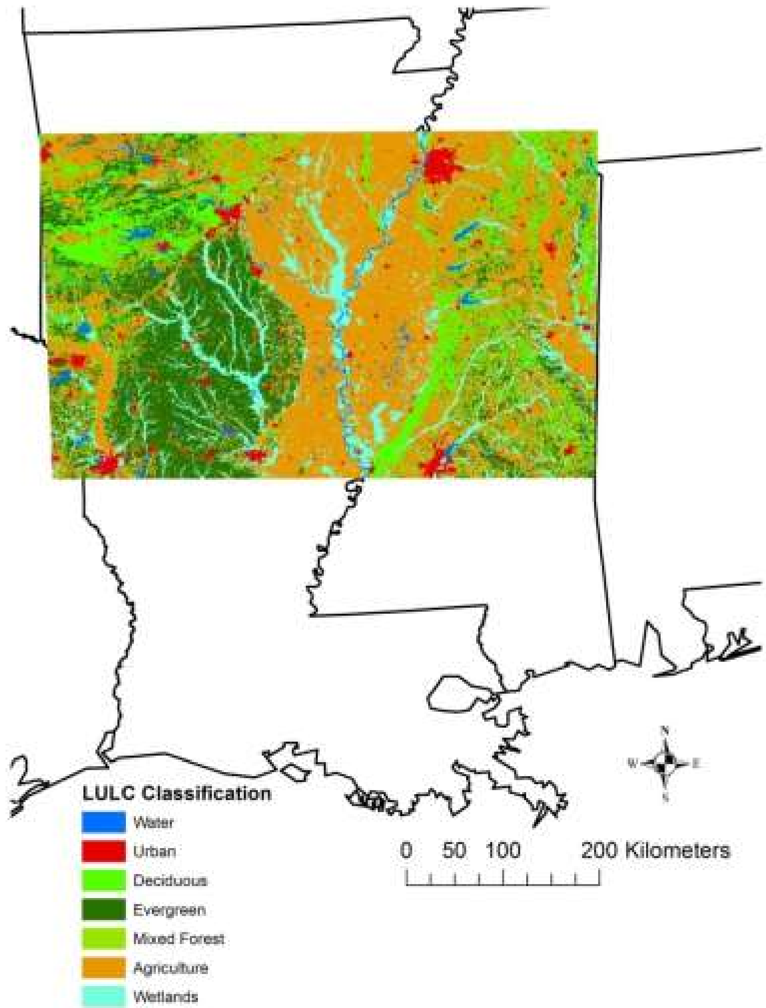

Figure 23 LULC classification for each 1-km grid cell across study area

The results of the bootstrap mean using the 1-km grid layer show detailed differences in the impacts of LULC on CG lightning counts (Figure 24). Evergreen forests, similar to the 16-km and 4-km grid layers, show statistically higher CG lightning counts than the other LULC types. However, on the 1-km grid layer, deciduous forests are shown to have the second-highest CG lightning counts, followed by urban LULC areas. Water bodies have the lowest CG lightning activity, which is supported in the previous literature. The results of the bootstrap variance show similar rankings among the

LULC types as the bootstrap mean using the 1-km grid layer (Figure 25). Similar to the other grid layer sizes, the number of grid cells used in the statistical analysis is not statistically related to the number of CG lightning strikes (Figure 26). Spearman correlation tests were also performed on each of the grid scales and also show that no significant correlation exists between the number of grid cells used in the bootstrap analysis and the values for the means from bootstrap analysis (Table 4).

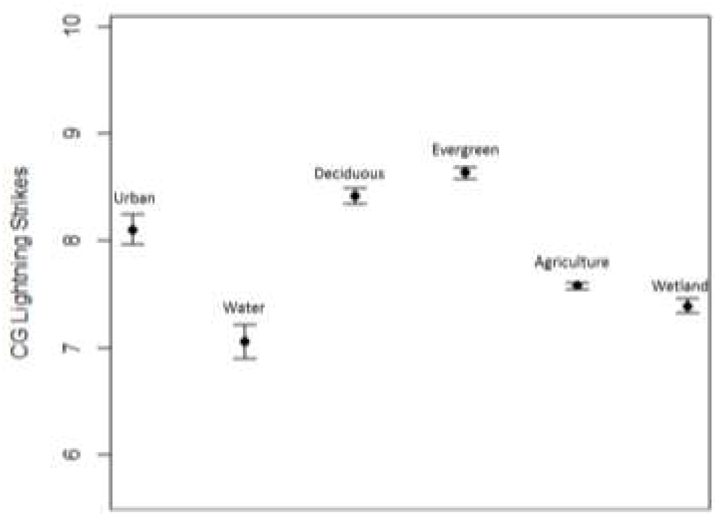

Figure 24 Bootstrap mean confidence interval plots for 1-km grid cells

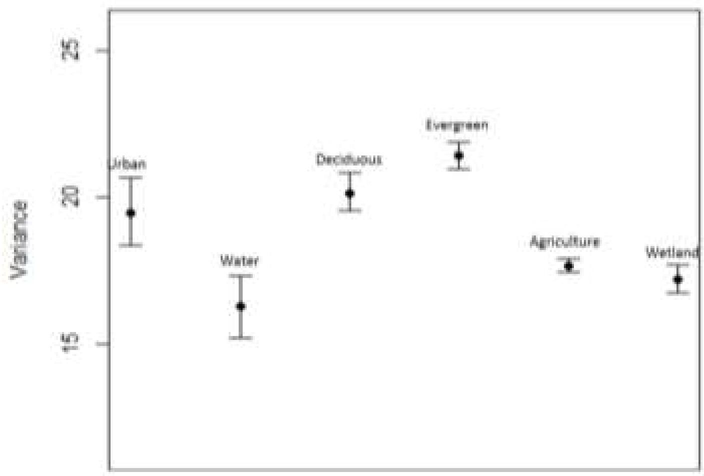

Figure 25 Bootstrap variance confidence interval plots for 1-km grid cells

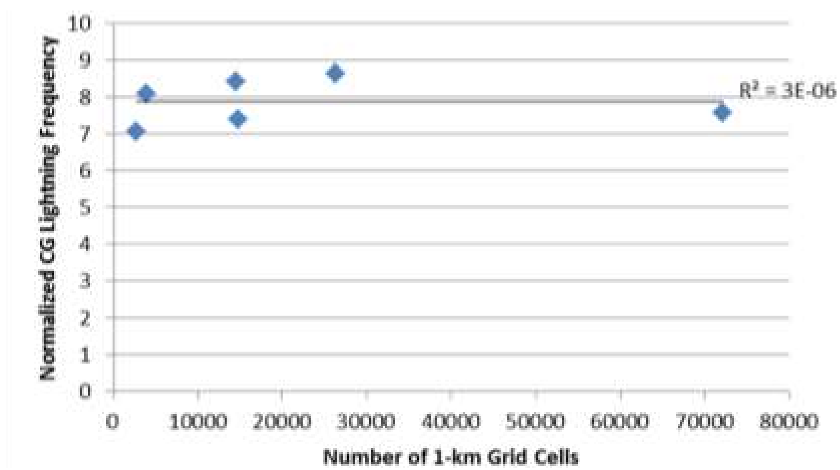

Figure 26 Number of grid cells for each LULC type vs. CG lightning frequency

Table 4 Spearman Correlation results for each grid scale

Grid Size	Spearman R value	P Value
16 km	0.0579	0.9131
4 km	-0.2000	0.7139
1 km	0.3714	0.4972

Individual City Insets

To investigate individual, chosen cities in the study area for evidence of urban-induced alterations to CG lightning counts, a 50-km zone was placed over each selected city to fully encompass the major urban areas while still allowing other LULC types surrounding the city to be included in the statistical analysis. The total area of each LULC in the 50-km zones around the cities was calculated using the 30-m resolution of the NLCD2006 (Table 5). The size of each city was ranked using the area of urban LULC in the each respective zone.

Table 5 Total area (km) of each LULC classification in the 50-km zones covering each city

LULC	Memphis	Little Rock	Jackson	Shreveport	Monroe	Texarkana
Water	107.978	126.432	145.093	136.158	114.149	163.821
Urban	1,034.733	546.506	543.201	478.141	297.072	285.070
Deciduous	262.966	685.189	303.394	178.735	106.242	301.820
Evergreen	44.427	245.420	240.506	484.286	438.823	484.859
Agriculture	882.480	748.613	906.584	673.181	824.684	985.329
Wetland	242.956	211.628	302.741	405.923	621.182	211.458

Jackson, Mississippi, has a large confidence interval range and therefore has no single LULC that stands out above the others (Figure 27). For Memphis, Tennessee, urban and water LULC have statistically higher CG lightning counts than the other LULC types. Water, in this case, might be over-represented in CG lightning counts because of the proximity of the Mississippi River to downtown Memphis. Nevertheless, urban LULC has shifted to exhibit more CG lightning strikes than evergreen and deciduous forests over the city of Memphis (Figure 27). Little Rock, Arkansas, shows a similar distribution of CG lightning across the different LULC types as the full study area results. However, in this example, agriculture shows up as having the highest CG lightning counts, statistically. The results for Monroe, Louisiana, show a significant increase in CG lightning over urban LULC compared to evergreen, agriculture, and wetland LULC types. However, it does not have statistically higher CG lightning counts than water or deciduous LULC. Shreveport, Louisiana, and Texarkana, Arkansas, both show urban LULC areas on the lower end of CG lightning counts compared to the other LULC types. This indicates that neither city significantly alters CG lightning activity. Shreveport, like Little Rock, AR, shows a similar pattern as the full study area, where evergreen forest areas have significantly higher CG lightning counts than the other LULC types. Texarkana is slightly different in that urban LULC has significantly lower CG lightning counts than water, evergreen, agriculture, and wetland LULC types, but does not have significant lower CG lightning counts than deciduous forests (Figure 27).

With the exception of Texarkana, there appears to be a downward trend in total CG strikes across all LULC types as the size of the city decreases (Figure 27). The results from each individual city inset can be found in Appendix I. This study indicates that CG lightning can be enhanced over large and/or sprawling urban LULC. Memphis, Tennessee, exhibits higher CG lightning counts than any of the other cities investigated in this study. Memphis also shows an enhancement of CG lightning over the urban LULC grid cells when compared to the nearby forested grid cells. This indicates an alteration to the expected pattern found across the entire study area. When the results of cities from this study are combined with those of Ashley et al. (2010), a better delineation of urban LULC size required to alter CG lightning/thunderstorm activity is apparent (Figure 28). The larger cities of Atlanta, Georgia; Memphis, Tennessee; and Birmingham, Alabama, show an enhancement of activity, while the smaller cities do not. There are a couple of proposed causes for this. First, the larger cities have more pronounced urban heat island effects, which lead to rising air over the cities as described by Findlay and Hirt (1969). Second, the increased presence of aerosols over the larger cities provides condensation nuclei that may lead to increased cloud formation as described by Van de Heever and Cotton (2006). Future research should focus on cities between Little Rock, Arkansas, and Birmingham, Alabama, in urban size to find a more precise urban extent required to alter CG lightning and thunderstorm activity.

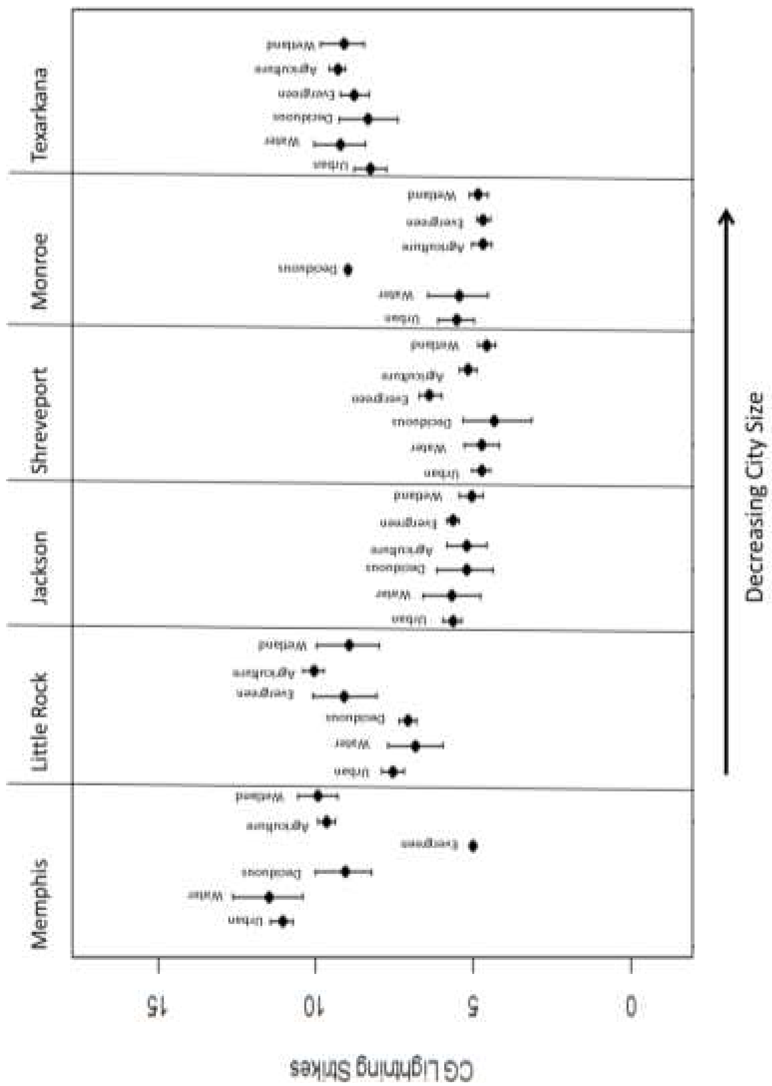

Figure 27 Confidence interval ranges of bootstrap means of each LULC type for each selected city

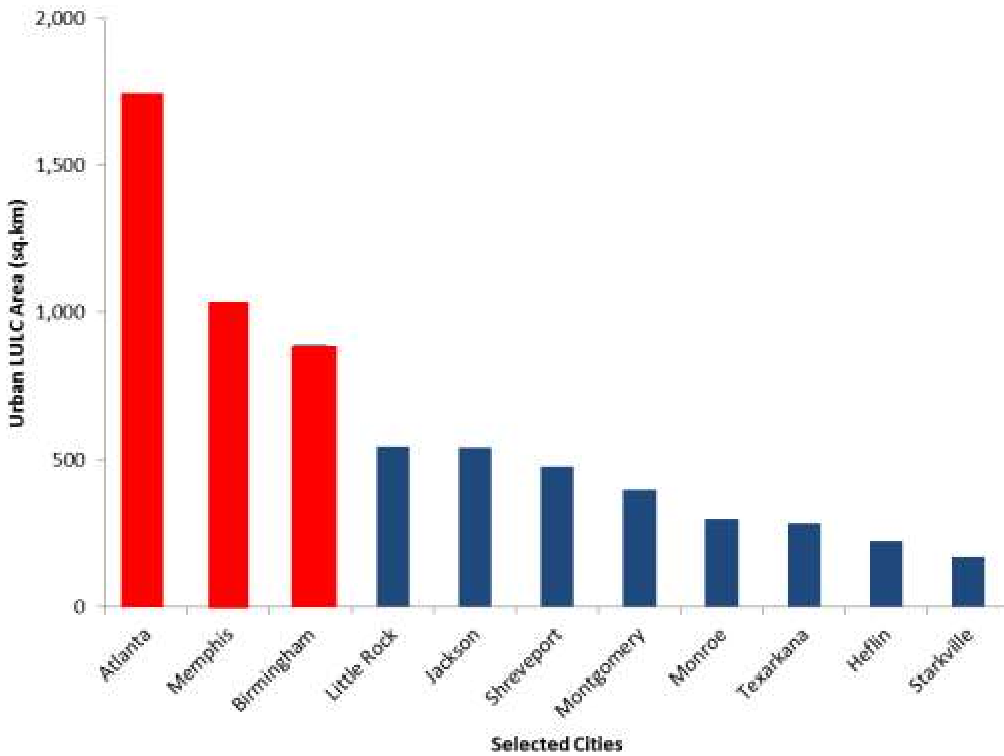

Figure 28 Area (km^2) of cities used

Red bars indicate cities that alter CG lightning/thunderstorms

CHAPTER IV

DISCUSSION AND CONCLUSIONS

According to results in this study, forested regions have the highest CG lightning frequencies of any other LULC classification. This is in agreement with Lopes et al. (2011), which found, using NDVI, that forested regions in Portugal experienced higher CG lightning frequencies. However, Rabin et al. (1990) found that convection was diminished over forests and lakes. The results of this study support the theory of diminished convection over lakes, but do not support the theory of diminished convection over densely forested regions when compared to agricultural regions. The source of conflicting results between this research and Rabin et al. (1990) is in the variables studied. Rabin et al. (1990) studied primarily convective cloud cover, using visible satellite imagery. This study, alternatively, focused on CG lightning, which requires deep convection and the presence of ice and liquid water. This reveals that while convective cloud cover may appear more readily over agricultural land, the thermodynamic characteristics of forested regions more readily support deep convection on synoptically weak days. This is supported by the results of numerical models performed by Clark and Arritt (1994). Also, this study found that evergreen forests supported higher CG lightning counts than deciduous forests. This could be due to the slightly higher albedo associated with evergreen forests. Another explanation could be the water stress that occurs often in the summers through the study area. Givnish (2002) found that deciduous trees often reduce transpiration rates when experiencing water stress (drought). This may lead to comparatively less moisture above deciduous forests than in evergreen forests during the summers in the study area. Next, this study suggests that water bodies reduce CG lightning activity, which is supported by the research of CG lightning over the Great Lakes (Clodman and Chisholm, 1994). This is likely due to the higher heat capacity of water, moderating the instability directly above the water body.

This study used three different grid scales to study the relationship between CG lightning and LULC. Of these grid scales, the 16 km provided the least conclusive results. This larger spatial extent masked many of the water bodies in the study area and did not fully represent the small-scale variations in LULC that could influence atmospheric properties. The 4-km grid layer better represented the LULC variations, but still might not have fully represented the smaller water bodies and urbanization typical of small cities across study area. Therefore, the 1-km grid scale is likely the most accurate at representing the impacts of LULC on CG lightning. Thus, it is suggested that any future research on the impacts of LULC on atmospheric properties should not use grid scales that exceed 1 km. It is unknown whether grid scales smaller than 1 km would perform better in the analysis of LULC impacts on atmospheric phenomena.

The results from investigating cities individually in this study revealed interesting characteristics of the urban influence on CG lightning. The larger cities of Atlanta, Georgia; Memphis, Tennessee; and Birmingham, Alabama, show an enhancement of activity. Alternatively, cities that had smaller urban extents than Little Rock, Arkansas (~500 km^2) do not depict this enhancement of CG lightning. There are a couple of proposed causes for this. First, the larger cities have more pronounced urban heat island effects, which lead to rising air over the cities as described by Findlay and Hirt (1969). Second, the increased presence of aerosols over the larger cities provides condensation nuclei that may lead to increased cloud formation as described by Van de Heever and Cotton (2006). Future research should focus on cities between Little Rock, Arkansas, and Birmingham, Alabama, in urban size to find a more precise urban extent required to alter CG lightning and thunderstorm activity.

In summary, this research has shown that variations in LULC do impact CG lightning frequency. Humans are continuously altering LULC through urbanization, deforestation, and the creation of tree plantations. Urbanization to a certain limit can decrease CG lightning frequency; however, once a city becomes large enough, CG lightning frequency will increase. Deforestation to create agricultural land will lead to a decrease in CG lightning frequency. Alternatively, a common practice in the southeastern United States is to convert deciduous and mixed forests into evergreen forests for profitable tree plantations. This practice inadvertently leads to increased CG lightning frequencies. Overall, the results of this study are a step forward in the understanding of how human alterations to LULC can affect atmospheric properties.

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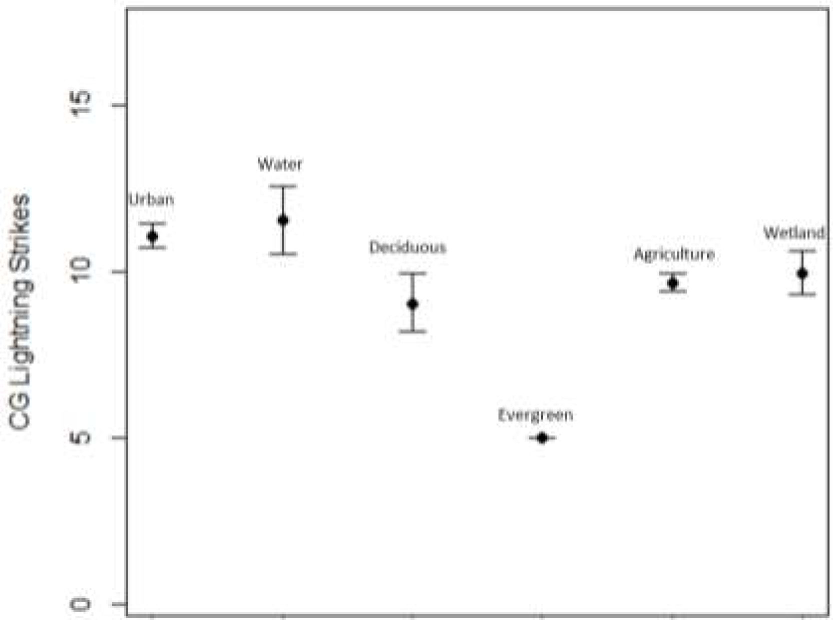
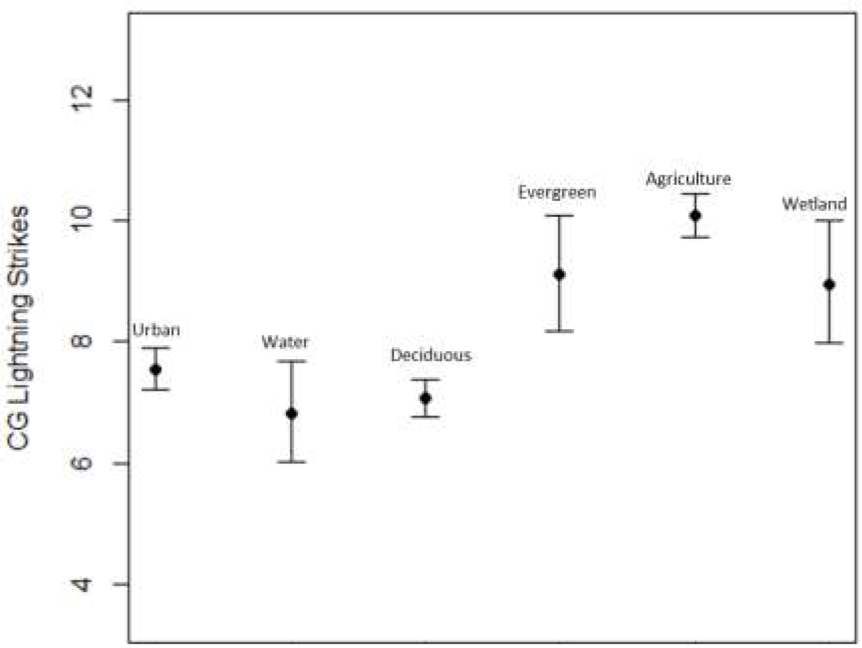
APPENDIX A

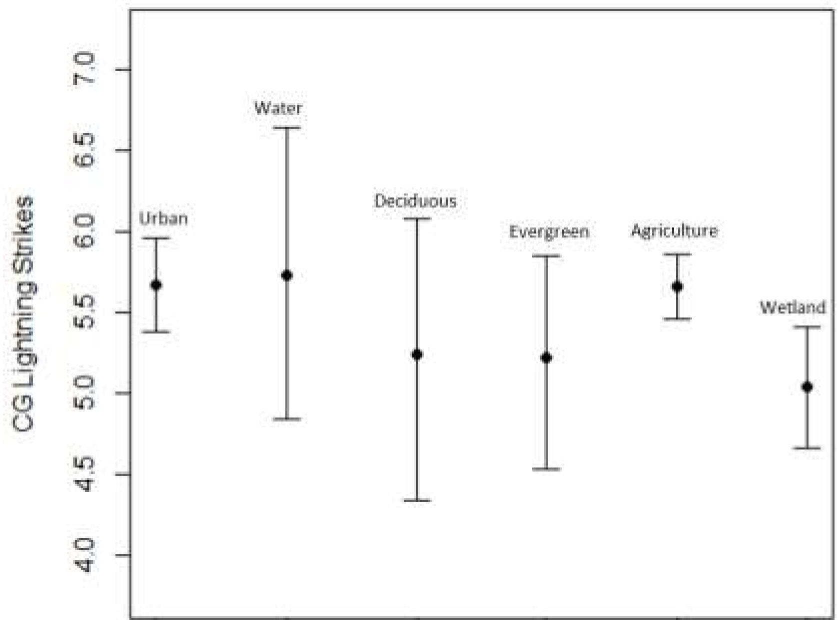
BOOTSTRAP MEAN RESULTS



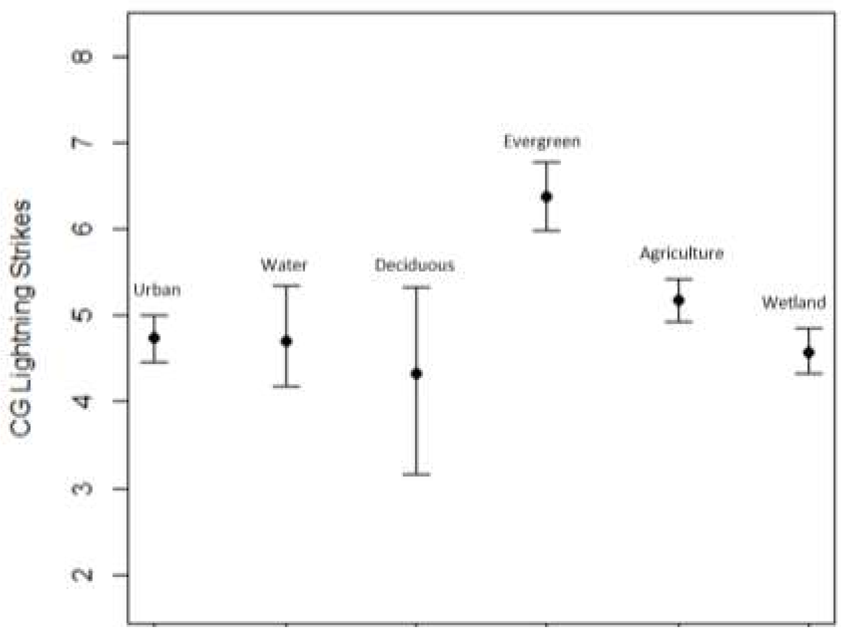
a. Bootstrap mean results from the Memphis, TN, 50-km inset



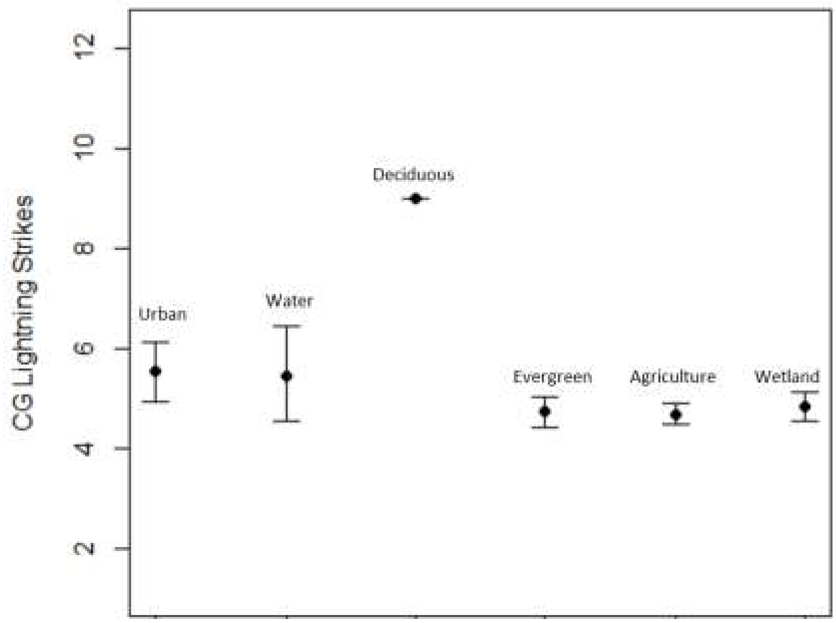
b. Bootstrap mean results from the Little Rock, AR, 50-km inset



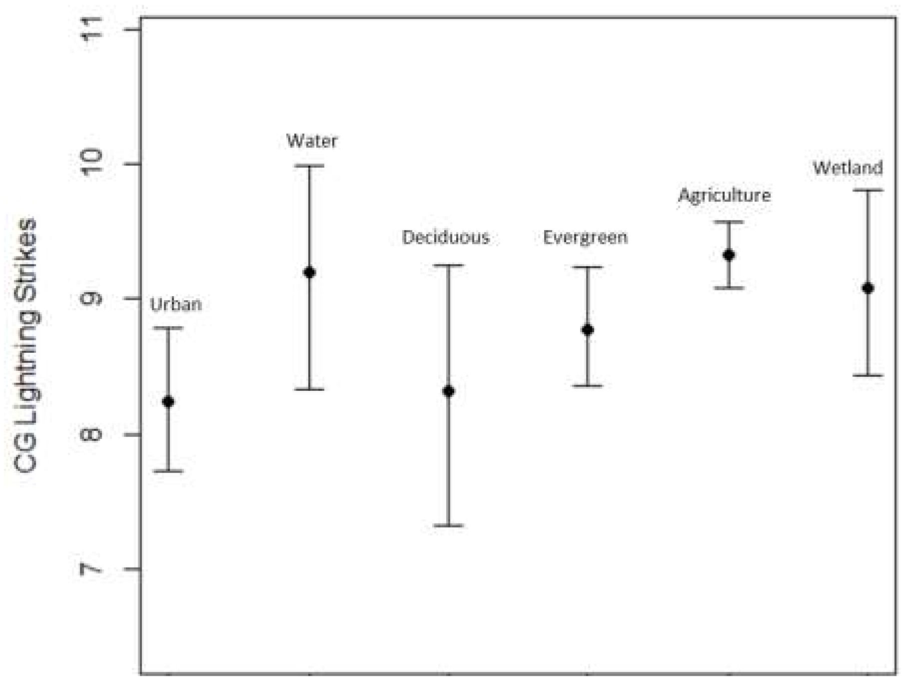
c. Bootstrap mean results from the Jackson, MS, 50-km inset



d. Bootstrap mean results from the Shreveport, LA, 50-km inset



e. Bootstrap mean results from the Monroe, LA, 50-km inset



f. Bootstrap mean results from the Texarkana, AR, 50-km inset