Cloud-to-Ground Lightning in Southern Michigan: 1985-1995

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Lightning has a profound impact on many aspects of modern day society. Understanding its spatial distributions is fundamental in learning to coexist with its tremendous power. This study examined the spatial distribution of cloud-to-ground lightning over southern Michigan using data provided by DTE Energy Corporation in Detroit, Michigan. Flash density and 'lightning day' maps were produced for every year of the 1985 to 1995 study period and then averaged to determine long-term trends. A temporal analysis determined the distribution of lightning from the inter-annual to the diurnal scale. The spatial analysis uncovered both climatological patterns in lightning strikes and limitations in the efficiency of the lightning detection system. High inter-annual variability and a well-defined diurnal cycle are presented in the temporal analysis. The mean flash density for southern Michigan was determined to be 1.99 flashes per year/km^2, while the mean days with lightning per year in each analysis grid cell was 3.46 days.

Keywords: Cloud-to-ground lightning, southern Michigan, lightning climatology

Lightning directly affects society by disrupting power service, periodically endangering outdoor recreation activities, and damaging property. Hundreds of people each year are injured or killed by direct or indirect strikes (Curran et al. 2000). Michigan is second only to Florida for lightning injuries (Curran and Holle 1997). The direct danger posed by lightning strikes warrants a better understanding of the phenomenon.

Characterizing the spatial and temporal distributions of lightning is fundamental to understanding the phenomena and mitigating its negative impacts on human life. Technological developments over the last 30 years have made remote sensing of cloud-to-ground lightning a possibility. Ground-based antennae detect the electromagnetic signals that lightning produce and determine location by triangulation and differential timing methods (Orville et al. 1987). This relatively new data source has improved the spatiaand temporal study of thunderstorm occurrence, increasing our ability to mitigate the risks posed by lightning.

Only recently have lightning studies been performed on a relatively small scale. Lopez et al. (1997) and Watson and Holle (1996) implemented a ten by ten kilometer grid to map cloud-to-ground lightning flash densities. Finer grids implemented in these studies allowed for realistic visualizations of local scale lightning distributions, important in risk assessments. Livingston et al. (1996) used a 2.6 km by 2.6 km grid to produce highly detailed flash density maps of the Atlanta, Georgia area for the 1996 Summer Olympics.Previous to these studies, coarse grid analyses (>10km) using data from the National Lightning Detection Network (NLDN) provided the best representation of annual lightning distribution across the continental United States (Orville et al. 1987; Orville 1991, 1997). Though Orville's works marked a milestone in understanding lightning on a national scale, they lacked utility for local applications such as planning for utility operations or assessing lightning risk.

Other regional lightning studies have made use of high spatial and temporal resolution analyses. Clodman and Chisholm (1994) studied cloud-to-ground lightning over Southern Ontario and the adjacent Great Lakes to investigate the development and evolution of thunderstorms in proximity to the Great Lakes. A temporal analysis of the lightning activity combined with a flash density analysis shed insight into the dynamics of storm events in this region and supported the utility of lightning data in local thunderstorm research. Lopez and Holle (1986), Reap (1986) and Reap and MacGorman (1989) also explored the influence of geography on lightning distributions.

Walters et al. (1995) emphasized temporal analysis in work involving the analysis of NLDN lightning data for the Great Lakes region. The study involved an in-depth investigation of the diurnal variations of summer cloud-to-ground lightning in association to other meteorological parameters, such as radar echoes and rawinsonde data. Interesting variations in peak lightning frequency timing are seen across the study area extending from Minneapolis, MN to Pittsburgh, PA. The data suggested a transition from nocturnal thunderstorm activity in Minneapolis to an afternoon maximum in activity for Pittsburgh. An extremely generalized spatial analysis is provided in the study and does little to explain the local or even regional spatial distributions of lightning across the Great Lakes. It was suggested in the conclusion of this study that more work be done to better quantify the spatial and temporal variations of lightning in the Great Lakes region.

Methods

Lightning data for this study were collected by DTE Energy's Lightning Location and Protection system, consisting of three direction-finding antennas located throughout southeast Michigan (Figure 1). Strike locations were determined by triangulation. Baseline strikes, recorded by two or less sensors, were not used in the analysis.

The spatial analyses were performed using ESRI ArcView 3.2 Geographic Information System (GIS) software. Data were aggregated by displaying long-term lightning data in flashes per square kilometer based on grids superimposed on the study area (Reap et al. 1986; Orville 1991). The optimal grid size for this dataset was determined to be five kilometers on a side. This grid size accounts for the decreasing spatial accuracy of the detection system away from the center of the network, but is fine enough to identify local-scale spatial patterns.

'Lightning day' maps were created to show the day frequency of lightning events across the study area for each year of the study. The 'lightning day' is similar to the traditional National Weather Service 'thunderstorm day', defined as the number of days that thunder is heard at a weather observing station. The thunderstorm day is logged by observers and is prone to human error. The 'lightning day' is derived from an automatic lightning detection system and can provide a high-resolution spatial depiction of convective weather frequencies.

Total lightning day maps were created for each year of the study. Mean flash density values and mean lightning day values were calculated at varying distances from the center of the detection network. The detection efficiency decreases radially from the center of the network due to signal attenuation. Mean values were calculated within areas representing seventy, sixty, and fifty percent detection efficiency regions as set forth in network specifications (Figure 1).

Temporal analyses were performed using Microsoft Access and Microsoft Excel. The number of flashes per year was obtained directly from the number of records in each table of annual lightning data in the project database. From these data, descriptive statistics and summary graphics were generated.

Flash frequencies were aggregated by hour of the day to identify diurnal variations. This was performed for all flashes in the period of record to construct an annual average flash

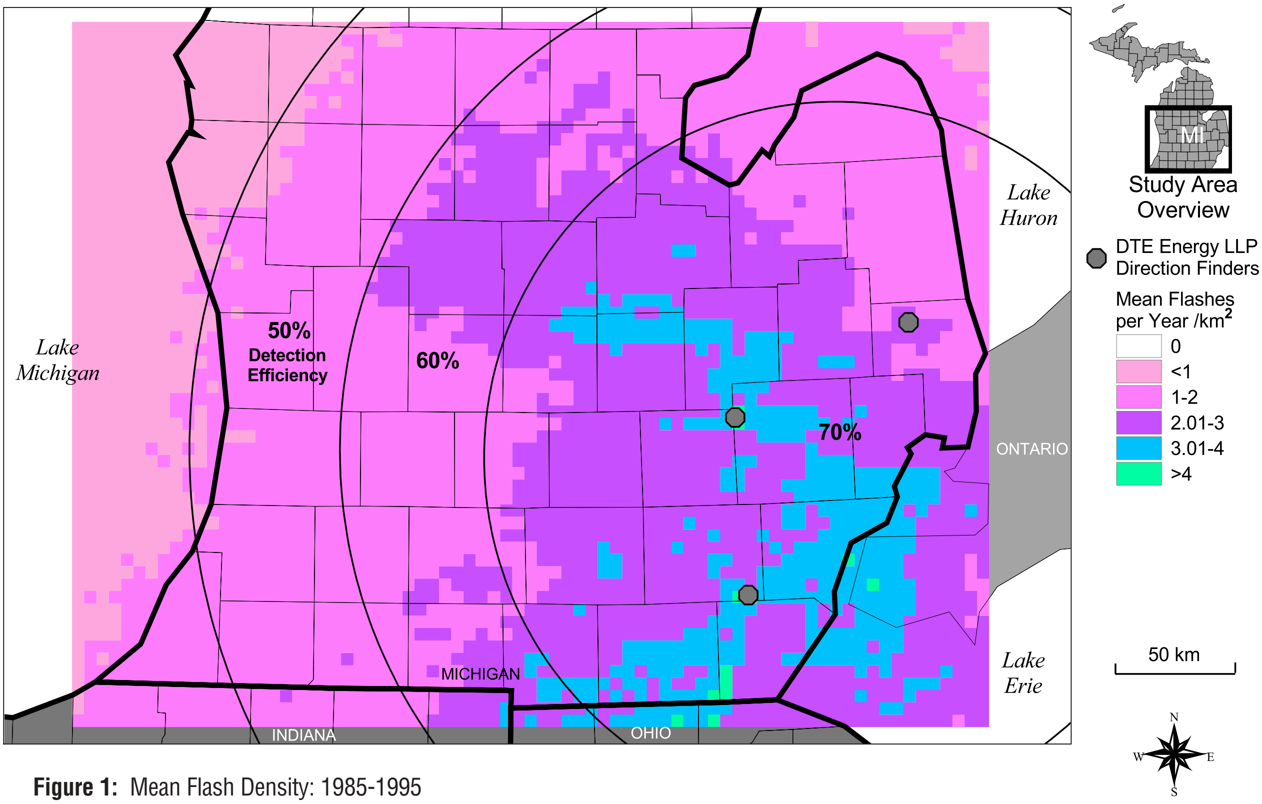

Figure 1: Mean Flash Density: 1985-1995

frequency chart and was also completed for each season (SON: Fall, DJF: Winter, MAM: Spring, and JJA: Summer).

Results

Spatial Analysis

The principal product of the spatial analysis was a mean flash density map (Figure 1) for the entire study period. It depicts the long-term spatial patterns created by cloud-to-ground lightning across the study area. A distinct pattern is evident in the northwestern quadrant of the study area where flash density values decrease across lines of constant detection efficiency. A similar pattern is observed in the southwestern quadrant of the study area. Flash densities decrease rapidly towards the extreme northeastern portion of the study area, but not necessarily across a line of constant detection efficiency.

Yearly means and other flash density information are displayed in Table 1. The overall period mean within the 70% detection efficiency (DE) is 1.99 flashes/km^2 with a standard deviation of 1.07. Mean values ranged from 0.94 flashes/km^2 in 1986 to 3.05 flashes/km^2 in 1994. A broad area of flash densities above the long term mean of 1.99 flashes/km^2 is oriented from northwest to southeast across the southeast quadrant of the study area (Figure 1). The highest flash densities calculated in this study occur in this area, which is within the 70% DE area of the network.

The mean lightning day analysis for the entire study period shows a spatial distribution of lightning days that is very similar to the mean flash density analysis (Figure 2). The drop-off in detection efficiency is still noted past the 70% DE area. The same general decrease in values towards the northeastern quadrant of the study area is noted again in the lightning day analysis. Values are one to two lightning days a year on average for grid cells along the Lake Huron shoreline.

The year with the highest flash frequency was 1994, with 237,790 flashes. This year, in turn, also had the highest mean

Table 1: Flash Density (flashes per year/km²) Statistics for the 70% Detection Efficiency Area

Year	Mean	Standard Deviation
1985	1.82	1.07
1986	0.94	0.85
1987	2.00	1.24
1988	2.13	1.14
1989	2.68	1.42
1990	1.38	0.83
1991	1.88	0.92
1992	1.48	1.06
1993	1.55	0.87
1994	3.05	1.40
1995	3.00	0.96
Mean	1.99	1.07

flash density within the 70% DE area at 3.05 flashes/km^2. A decrease in flash density towards the extreme northeastern portion of the study area is present in 1994 (Figure 3). The flash density values decrease to less than 0.5 flashes/km^2 along the Lake Huron shoreline.

The highest annual total of cloud-to-ground flashes within the study area occurred in 1994. This year had the highest mean flash density value within the 70% detection area, but did not have the highest incidence of lightning days. The mean number of lightning days (Figure 4) within the 70% detection area was 3.59 per grid cell for 1994. This was only slightly above the study period mean of 3.46 days shown in Table 2.

An interesting, yet subtle, pattern in flash densities is the area of high values along the Ontario-Lake Erie shore in the extreme southeast portion of the study area. The high values were persistent in almost every year through the study period. Lightning day values for this area range from three to four lightning days per year per grid cell on average.

Temporal Analysis

The total lightning days within the entire study area for each year were plotted with total flashes per year in Figure 5. The highest lightning day value occurred in 1987 but was a below normal year in total flashes. The lowest number of flashes and lightning days for the study period were seen in 1992.

Annual flash frequency by hour is shown in Figure 6. The hour of maximum flash frequency occurs at 1800 EST. This maximum primarily corresponds to the area within the 70% DE area because of the efficiency of the network. Most flashes used in the hourly determinations were located within the 70% DE area. The hourly percentage rises rapidly past noon into the evening hours, but decreases more gradually past the maximum at 1900 EST

The seasonal plots of flash frequency, shown in Figure 7, all indicate similar distributions to the annual plot. A late afternoon maximum, ranging from 1700 EST to 2000 EST, in hourly flash frequency is present in all seasons. Spring (March, April, and May) and summer (June, July, and August) both show a secondary maximum in early morning hours from 0300 EST to 0500 EST. A late afternoon maximum slowly decreases throughout the night into the early morning hours in the fall season (September, October, and November). A sharp increase and gradual decrease in the late afternoon flash frequency is seen in the winter season (December, January, and February).

The seasonal breakdown of flash frequencies shows 70.2% of the total flashesfor the study period occur in the summer season. Fall has the next highest share at 15.4% of the total. Spring follows closely at 14.1%, while the winter season only contributes 0.3% to the total number of flashes.

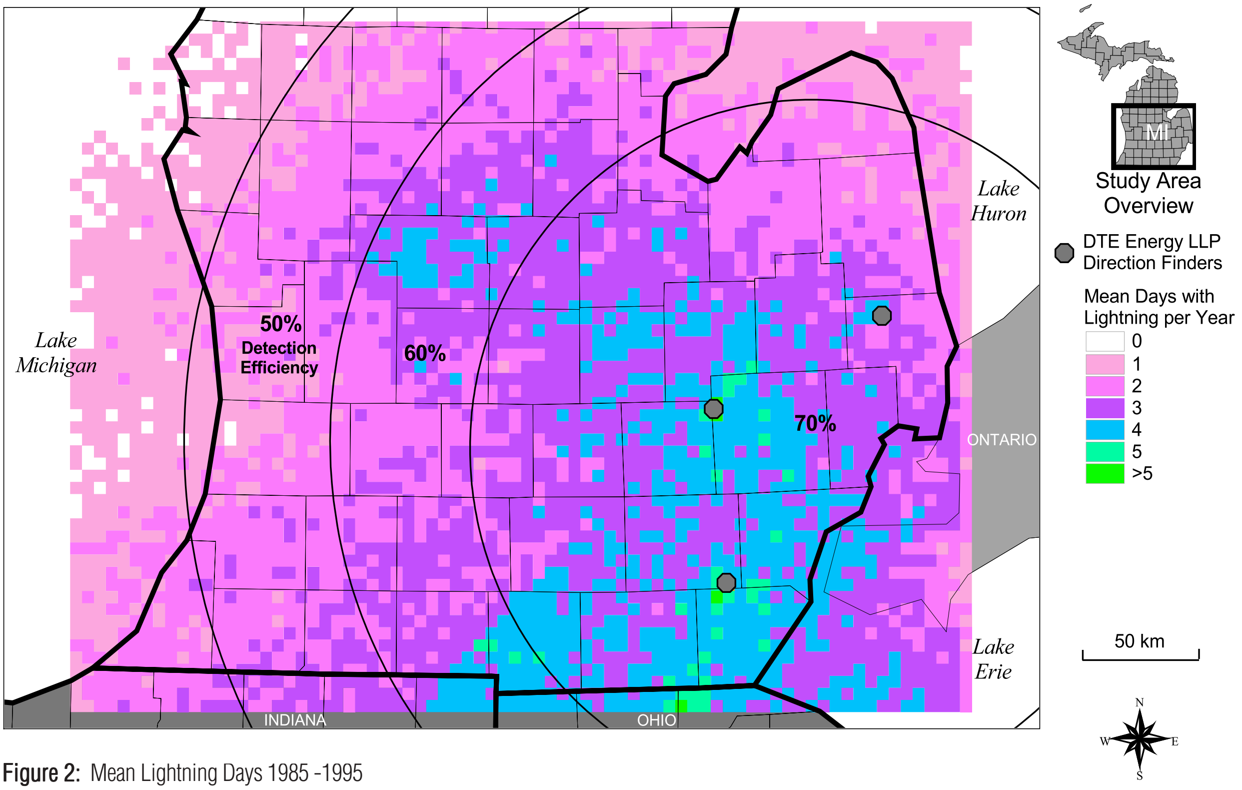

Figure 2: Mean Lightning Days 1985 -1995

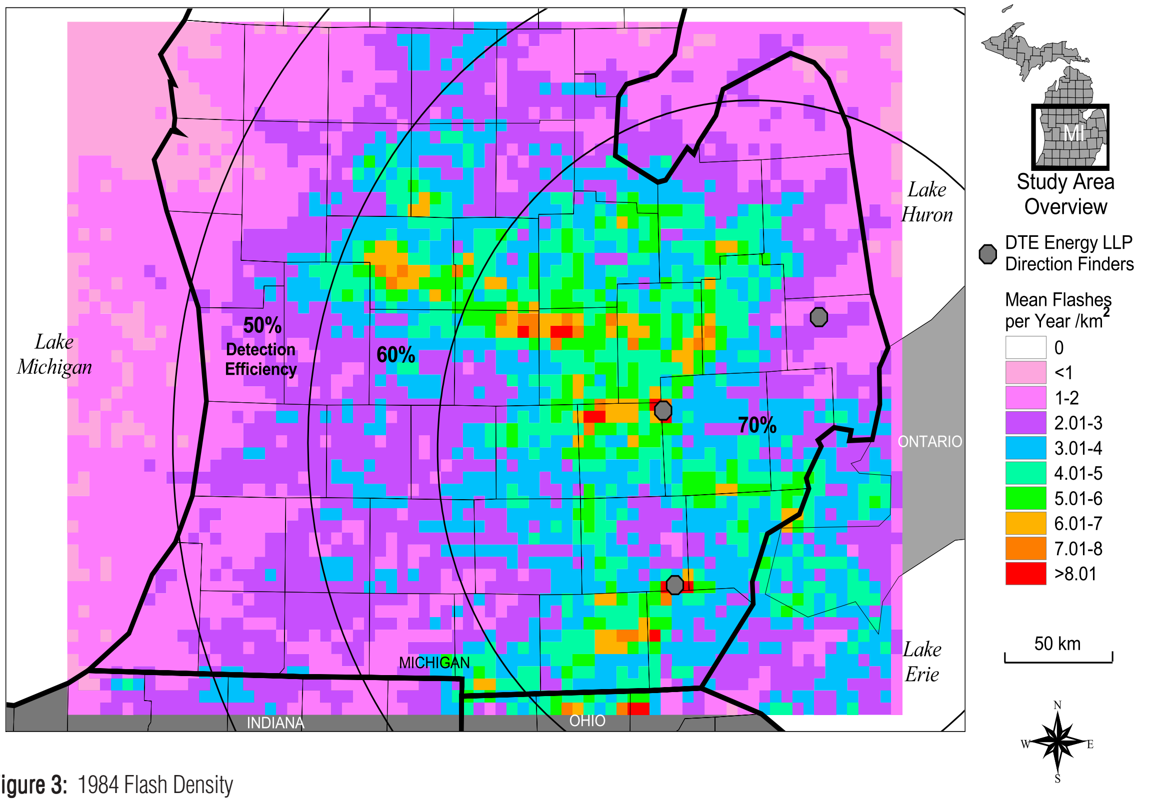

Figure 3: 1984 Flash Density

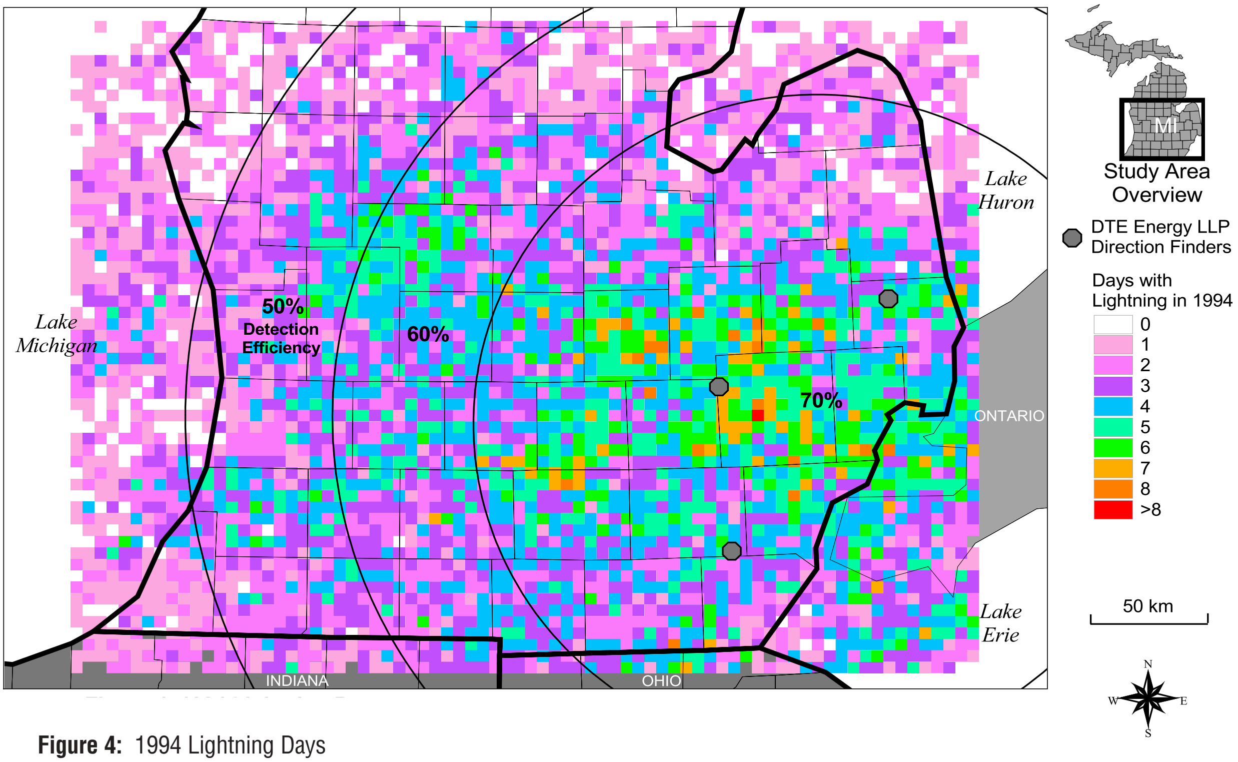

Figure 4: 1994 Lightning Days

Discussion

Spatial Analysis

The dominant pattern evident on the mean flash density map (Figure 1) is the decrease in flash density values with increasing distance away from the detection network. Network efficiency decreases with increasing distance away from the center of the network. The decrease in flash density to the western edge of the study area appears to be the result of this detection limitation.

Interesting patterns are evident within the 70% DE area, the most obvious being the distribution of flash density maxima. The pattern does not suggest any favored corridors of thunderstorm travel, but rather a decrease in flash activity towards the northeast quadrant of the study area. A study by the Illinois

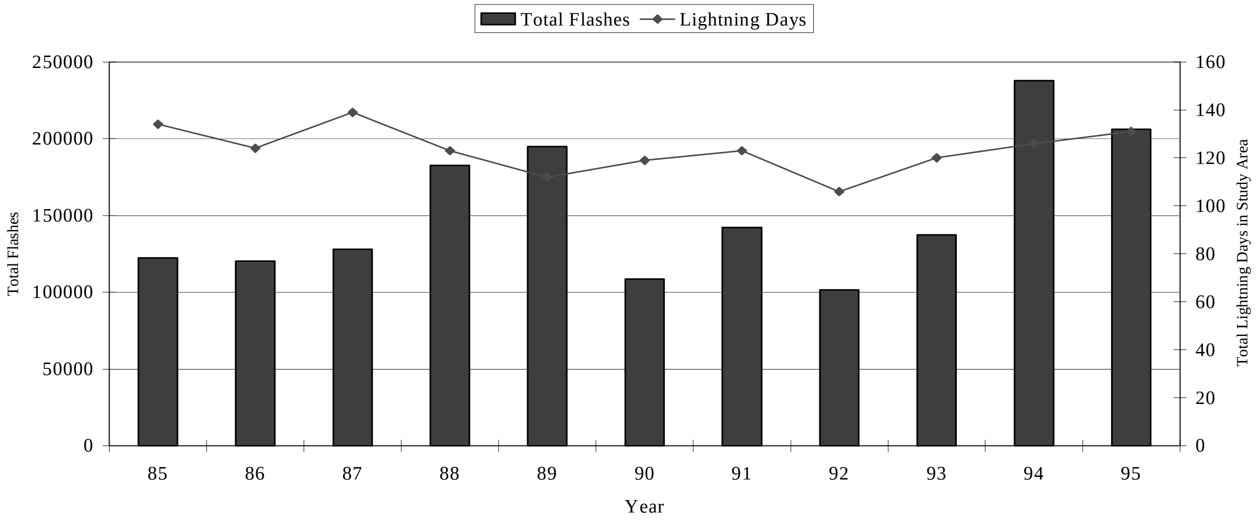

Figure 5: Total Lightning Days

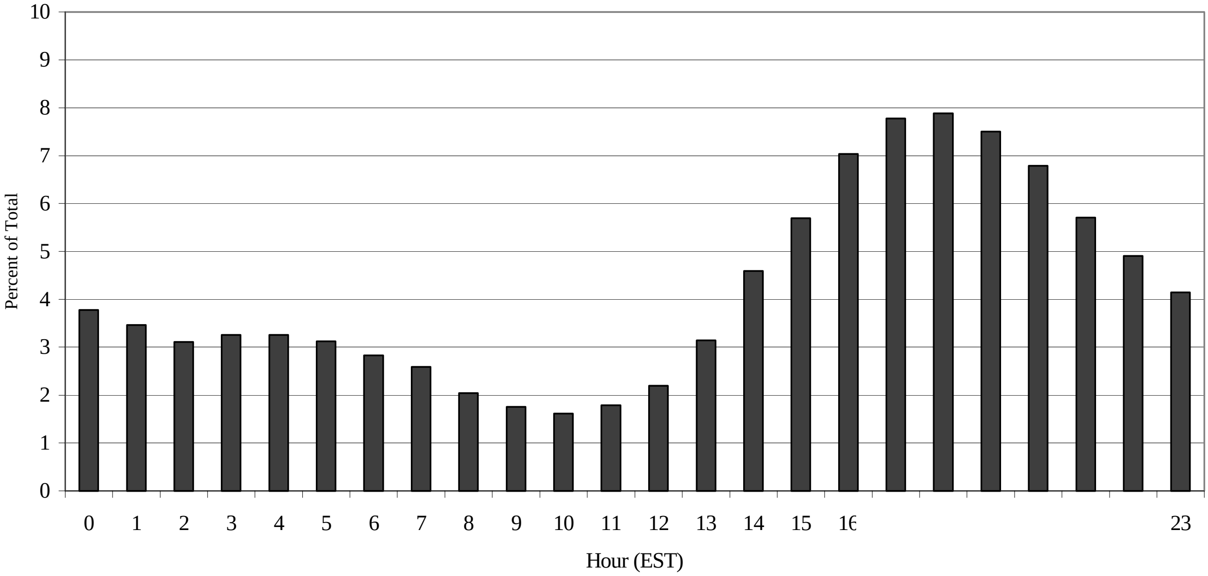

Figure 6: Annual Flash Frequency by Hour

Water Survey showed that thunderstorm activity was greatly reduced along the shores of the southern Great Lakes because of the stabilizing effect of their cool waters (Eichenlaub 1979). Lake Huron appears to be influencing the distribution of flash density in the northeast quadrant of the study area by stabilizing the nearshore atmosphere and limiting thunderstorm activity. The lowest flash density values within the 70% DE area are found along the Lake Huron shore in the extreme northeastern quadrant and are most likely due to this 'lake-effect' impact on convection.

A subtle feature on the mean flash density map (Figure 1) is a small maximum along the Ontario-Lake Erie shore in the extreme southeast quadrant of the study area. A study done by

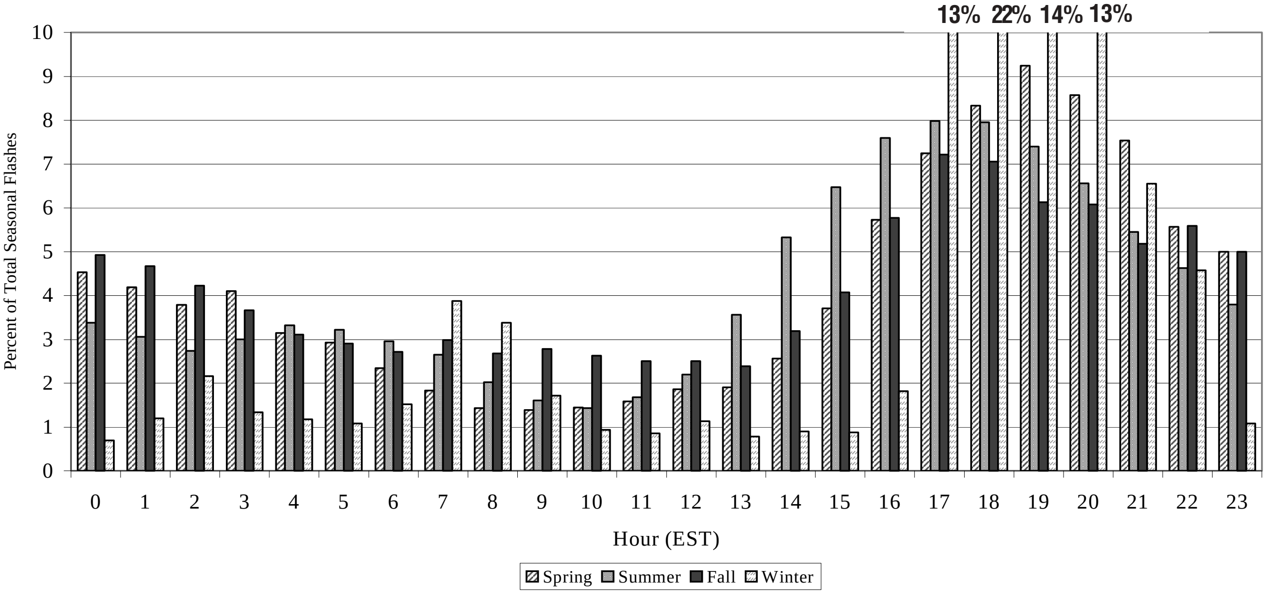

Figure 7: Seasonal Flash Frequency by Hour

Clodman and Chisholm (1994) showed that this area can enhance thunderstorm development under certain synoptic conditions because of the unique lake-land geography of the area. Several storms in 1989 and 1990 occurred over this area. The storms were thought to have formed off of lake-breeze convergence zones and remained nearly stationary, producing large amounts of rain and cloud-to-ground lightning.

Lightning Days

More detailed spatial patterns further away from the center of the network are present on the 1994 lightning day map (Figure 4) relative to the 1994 flash density maps (Figure 3). This would suggest that the network is much more efficient at detecting at least one strike from each convective event per day than the total strikes from each event. Overall the spatial patterns are similar between the mean flash density analysis (Figure 1) and the mean lightning day analysis (Figure 2). This observation implies that areas with high flash densities are most likely the result of persistent convective patterns rather than random, high flash frequency events.

There are some deviations from this fact visible when comparing maps of the two different analyses. The far southeastern portion of the study area in Lake Erie has an area of relatively high mean flash densities, but does not have a corresponding maximum in lightning days. These values are close to the mean number of lightning days within the 70% DE area as shown in Table 2. This suggests that the high flash density values are the result of more cloud-to-ground lightning per convective event. The earlier discussion of this area with the Clodman and Chisholm (1995) study indicated that the persistent high flash densities from year to year in this area might be the result of unique lake breeze interactions with the synoptic environment. The mean lightning day analysis suggests that convective events in this area are not necessarily more frequent than in other areas within the 70% DE area. The relationship between lightning days and flash densities in this area suggest that there is an average number of storms producing an above average amount of lightning per event. Lake breezes in this portion of the study area may help to develop thunderstorms in a weak synoptic environment where no other convective forcing is present. With no steering winds aloft, the storms could become quasi-stationary and stall in common areas producing long-lived convective events with high overall event lightning strike totals.

Analyses of 1994

The spatial patterns in the 1994 flash density analysis (Figure 3) are very similar to the overall mean flash density analysis. High flash density values (> 4 flashes / km^2) are much more prevalent in this year than in any other year of the study. The highest values are grouped in the center of the study area rather than in the southern portion as in the overall mean. This probably is the result of either stronger storms or more storms penetrating deeper towards the minimum in flash density along Lake Huron. A visible comparison of the lightning day analysis for 1994 (Figure 4) to the flash density analysis for the same year shows the relationship of flash density values to frequency of events. The spatial pattern of high flash densities relative to high lightning days does not match well in some areas. The highest flash densities in the southeastern quadrant of the study area do not have corresponding maximum in lightning days. This again suggests that the highest flash density values are the result of large amounts of lightning produced by an average number of events.

Temporal Analysis

The total number of lightning days for any given year in this study is not well correlated (r = 0.13) with the total number of flashes for the same year (Figure 5). This indicates that lightning strike annual totals cannot fully characterize a convective climatology. Increasing total flash amounts do not necessarily indicate a greater frequency of convective events.

A well-defined diurnal variation is evident when looking at the histogram of total lightning frequency by hour (Figure 6). A well-established pattern with an afternoon maximum is evident. This pattern has been observed in other studies of precipitation and thunderstorm activity in Michigan (Walters et al. 1995). Convective instability caused by afternoon solar heating is most likely the cause of the sharp afternoon peak. The gradual drop in lightning activity from the late evening into the early morning hours is seen in the average hourly distributions for all seasons. A local, secondary maximum in lightning activity is especially evident during the early morning hours for the summer season

(Figure 7). This early morning rise in convection could be influenced by the formation of a nocturnal low-level jet that aids in the transport of low level moisture (Walters et al. 1995).

The spring histogram (Figure 7) is compiled from the flashes that occur during the months of March, April, and May. The diurnal distribution of flashes shows a pattern very similar to the summer season, even though the spring total number of flashes is less. Destabilization of the atmosphere by solar forcing coupled with late afternoon frontal passages is the most likely cause of the spring afternoon maximum as it is in the summer season (Easterling and Robinson 1985; Walters and Winkler 1999). A secondary maximum is also evident in the early morning hours (200 – 400 EST) indicating a slight increase in convective activity possibly related to the development of a low-level jet.

The fall histogram (Figure 7) shows a sharp rise to a maximum value at 1700 EST with a very gradual decrease throughout the evening and early morning hours. This pattern again indicates a late afternoon maximum in lightning activity with lowest values in the morning hours. The afternoon maximum is again most likely related to the destabilization of the atmosphere due to solar forcing. The timing of frontal passages may explain the slight variations in time of maximum lightning frequency throughout the spring, summer, and fall seasons (Easterling and Robinson 1985).

The winter season histogram produces the most unusual distribution of flashes. This can be traced back to the extremely small number of flashes represented in this seasonal analysis. Most of the winter flashes represented here were the result of one or two convective events. The result is that the maximum of hourly flash counts (Figure 7) is the product of one or two winter storms producing relatively large amounts of lightning to other winter lightning events. The maximum at 2000 EST represents 21% of all flashes occurring in the winter season. Half of the flashes represented in this season were produced by an event on January 7, 1989. The event produced 2500 cloud-to-ground flashes across the study area between the hours of 1700 EST and 2200 EST. The distribution represented in the winter analysis does not necessarily show the long-term temporal behavior of wintertime lightning. Winter lightning is rare in Michigan and this fact is supported by this study. A much longer study period is needed to detect any long-term patterns in Michigan wintertime lightning events.

Conclusion

Flash density and lightning day maps indicate that the Detroit Edison lightning detection network is, indeed, most sensitive within the 70% detection area. Outside of this area, detection efficiency quickly decreases, failing to provide enough data to develop an accurate climatology of lightning flash distributions. This is clearly evident in the mean flash density analysis where flash densities evenly decrease with distance westward from the center of the detection network. The lower flash densities on the western periphery of the network, visible in each yearly flash density analysis, are the result of poor detection efficiency, not a climatological pattern.

Some persistent patterns do exist even with the large amount of variability in flash distribution. The most persistent pattern identified appears to be the decreasing flash density towards the northeastern corner of the study area. The lowest flash densities within the 70% detection area are in the extreme northeastern portion of the study area, along the Michigan-Lake Huron shoreline. This finding points to a possible 'lake-effect' induced impact on convection in that portion of the study area.

The spatial patterns in the flash density analysis were further explained with the use of the lightning day. The lightning day analysis helped to determine the cause of high flash density distributions and quantify the daily variability of lightning events. In many years, high flash density areas were not the result of the frequent passage of thunderstorms. Many high-density areas were the result of one or two 'extreme' storms producing above normal amounts of lightning over an area in just one day. There is no distinction of the temporal aspect of lightning distributions in a flash density analysis without the comparison to a lighting day analysis.

The temporal analysis displayed interesting patterns on different scales ranging from inter-annual to diurnal. The number of cloud-to-ground lightning strikes per year deviated greatly due to large storm events suggesting an average yearly frequency is not useful with respect to this relatively short study period. A longer study period would serve to capture a better sample of large and small convective events and produce a more realistic climatological mean of lightning activity.

The hourly analysis of lightning frequencies showed a well defined diurnal cycle that peaked in the late afternoon-early evening hours in all seasons. This late day peak is most likely due to the combination of an unstable atmosphere from solar forcing and the timing of frontal passages (Easterling and Robinson 1985; Walters and Winkler 1999). The fact that the timing of the diurnal peak was similar in all seasons suggests that the cause of the convection was similar regardless of the time of the year. Winter and fall lightning frequencies were very small relative to the summer and spring frequencies. The peaks of their hourly distributions come from very few events compared to spring and summer and are probably unusual events.

Further studies to develop regional lightning climatologies should aim to use datasets with greater spatial coverage and better detection efficiencies. A long-term dataset with accurate coverage of lightning from the Lake Michigan shore to the Lake Huron-Lake Erie shore would shed further insight into the true impact of a 'lake-effect' on convective patterns and lightning in southern Michigan.

The temporal aspect of lightning frequencies should also be further explored. The signature of lightning as a convective indicator allows for high resolution temporal analyses to be made. Time series of local lightning data could be analyzed for periodicity and correlations to other larger scale climatic variations. This would help define the impact of larger scale climatic changes on regional and local scale lightning activity.

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