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SPATIAL AND TEMPORAL VARIATIONS OF CLOUD-TO-GROUND LIGHTNING IN SOUTHERN MICHIGAN

by

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Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
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Secondly, my gratitude goes out to my advisor, Dr. Elen Cutrim. Her guidance and support were fundamental in the successful completion of this study. I thank my thesis committee, Dr. Hans Stolle and Dr. Rolland Fraser, for their suggestions and guidance in polishing the final product presented here. I also thank my family and the staff at Kieser and Associates for their constant support and encouragement.

Lastly, I would like to thank my new wife Theresa for her help and support from the beginning of this project. I hope to help you with your thesis as much as you have helped me.

Michael A. Crimmins
SPATIAL AND TEMPORAL VARIATIONS OF CLOUD-TO-GROUND LIGHTNING IN SOUTHERN MICHIGAN

Michael A. Crimmins, M.A.

Western Michigan University, 1998

Lightning has a profound impact on many aspects of modern day society. Understanding its temporal and spatial distributions is fundamental in learning to coexist with its destructive power. This study surveyed the spatial and temporal distribution of cloud-to-ground lightning over southern Michigan using data provided by the Detroit Edison Company. 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 down to the diurnal scale.

The spatial analysis indicates both deficiencies in the dataset and true climatological patterns. High inter-annual variability and a well defined diurnal cycle are presented in the temporal analysis.
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CHAPTER I

INTRODUCTION

Statement of the Problem

Lightning is a very transient and random phenomenon. Over 100 lightning strikes occur each second across the globe, but little is known about their exact distribution ("Media Page" 1998). The questions of where and what lightning strikes are only now being answered with the new technology of lightning positioning systems. Before the advent of that technology, lightning observations were based on Thunderstorm Days which are defined as any day where thunder was heard at a particular location, usually a weather station (World Meteorological Organization 1953). This fixed location, human observation of thunder produced by lightning was the only possible data source to determine lightning distributions. For obvious reasons, these data are subject to human error and lack spatial resolution. Despite these known shortcomings, the thunderstorm day data were used in lieu of lightning records until lightning location technology was developed and tested in the 1970's (Court and Griffiths 1986).

The impact of lightning on human affairs has always been high. Hundreds of people each year are killed by direct or indirect strikes. A study of National Weather Service storm data from 1940 – 1981 indicated that 7,741 people had been killed by lightning, which was higher than tornadoes, floods, and hurricanes ("Number of
deaths by natural hazard: 1940-1981” 1998). Michigan ranked number two in both injuries and death by lightning per state in a recent study conducted by the National Oceanic and Atmospheric Administration ("35 years of lightning deaths and injuries” 1998).

Lightning indirectly impacts society by killing livestock, disrupting power service, endangering air traffic, damaging property, and igniting forest fires. These effects and the direct danger posed by lightning strikes warrant the need for a better understanding of the phenomenon. Lightning location technology, in the form of direction finding equipment, allows for accurate monitoring of cloud-to-ground lightning strikes and a consistent lightning data source. Power companies in particular have benefited from these systems. Detroit Edison Corporation, an electricity provider to over 2 million customers in Southeast Michigan, has been using a lightning location system since the early 1980’s. The primary use of the lightning detection system has been to monitor lightning activity in real time across the service area for efficient deployment of crews and to provide a data source for the study of lightning distributions for lightning protection. The impact of lightning on Detroit Edison was illustrated in 1983 when 31% of service outages were traced to lightning (Desmond and Whitney 1984). The Lightning Location and Protection (LLP) system operated by Detroit Edison from 1981 to the present, has helped in the understanding of the impact of lightning on the service area and in the developing of a lightning protection strategy.
Research Objectives

This study is the first spatial and temporal analysis of the data collected by the Detroit Edison LLP. It represents an analysis of the lightning data collected by the LLP between the years of 1985 through 1995. This 12-year period provides a considerable size sample to survey the long term spatial and temporal distributions of cloud-to-ground lightning across the service area and beyond. This analysis will help to characterize areas of higher lightning activity and establish temporal trends, from inter-annual periods down to diurnal.
CHAPTER II

REVIEW OF RELATED LITERATURE

Characterizing the spatial and temporal distributions of lightning is fundamental in understanding the phenomenon and in mitigating its negative impacts on human life. Technological developments over the last 30 years have made the remote sensing of cloud-to-ground lightning, a possibility. Data available from this new technology has allowed researchers to study the distribution of thunderstorms on many different scales and better understand the risk that accompanying lightning imposes on the society.

The best determination of thunderstorm distributions prior to the lightning detection network was done using the ‘thunderstorm day’. This by definition of the World Meteorological Organization is the number of calendar days per year on which thunder is heard. A study conducted by Court and Griffiths (1986) produced a thunderstorm day climatology covering the years of 1951 to 1970. The thunderstorm day data were gathered from weather service offices sparsely located throughout the United States. Data were collected by direct observations and not automated in any way. Study results provide a coarse, if not unrealistic, portrayal of thunderstorm distribution for the study period. The authors themselves question the quality of the data in the introduction to the research, pointing out the void in quality thunderstorm data and the absence of realistic national to local thunderstorm climatologies.
In the late 70's and early 80's, many researchers recognized the utility of lightning data for meteorological investigations. Orville et al. (1987) analyzed data from the beginnings of the National Lightning Detection Network (NLDN). At that time the NLDN consisted of nine direction finding antennas along the East Coast of the United States. The study used lightning data for the time period of June 1984 to May 1985 and analyzed lightning characteristics like peak current values and flash polarity as a function of season yet it did not attempt any analysis of the spatial distribution of lightning.

Orville continued his investigations with the NLDN through 1997, analyzing the annual distribution of lightning across the continental United States (Orville 1991, 1997). These studies marked the first observations of inter-annual variation in the spatial and temporal characteristics of cloud-to-ground lightning for the United States. National lightning distributions were displayed in graphic summaries showing flash densities. Orville stated that the flash density measurement was very important in the design and planning of lightning protection systems. A flash density analysis provided a much higher resolution determination of thunderstorm distributions than the ‘thunderstorm day’ method or the use of flash counters which were the only methods used to record thunderstorm distributions prior to lightning detection.

The work that Orville has done marks a milestone in understanding lightning on a national scale. The shortcomings of these studies are their application to the local scale. The national analysis provides an idea of general lightning distributions but lacks the resolution to identify local-scale patterns (Orville 1994). Orville’s analyses were done using a grid system with a cell resolution of 90 kilometers by 65
kilometers. Due to the huge amount of data implicit in a national lightning study, sixty five by ninety kilometers was the finest resolution possible using the available analysis software, according to Orville (1991). An analysis at this resolution is not useful for local applications, such as planning for utility operations or assessing lightning risk. Several applied studies recognized the need for a finer grid and implemented a ten by ten kilometer grid for flash density determinations (Lopez et al. 1997, Watson and Holle 1996). These studies found that a finer grid allowed for a much more realistic visualization of local scale lightning distributions which was important when being used in risk assessments. Livingston et al. (1996) used an even finer grid of 2.6 km by 2.6 km to produce highly detailed flash density maps of the Atlanta, Georgia area for the 1996 Summer Olympics.

Many regional scale studies have recognized the importance of high spatial resolution as well as high temporal resolution analyses. A regional study of cloud-to-ground lightning was performed by Clodman and Chisholm (1994) for Southern Ontario and the adjacent Great Lakes. The intention of this study was not to develop a lightning climatology for the area, but to investigate the development and evolution of thunderstorms in proximity to the Great Lakes. A temporal analysis of the lightning activity within these storms along with the flash density analysis helped shed insight on the dynamics of these storm events and proving the use of lightning data in local thunderstorm research. Other recent studies, (Lopez and Holle 1986, Reap 1986, Reap and MacGorman 1989) also indicated the importance of understanding the relationships between the spatial and temporal aspects of lightning by exploring the influence of geography on its timing and place.
Some studies have focused primarily on the temporal distributions of lightning with less emphasis on the spatial. A high-temporal resolution analysis of lightning data was performed by Krider and Maier in 1984. The study was able to determine 10-minute flash rates for days during the summer seasons of 1976-1978 and 1980 for the state of Florida. Results showed a substantial difference between human observations and detected lightning and characterized the extreme diurnal variability of lightning in the region.

Walters et al. (1995) also emphasized the temporal over the spatial in work on an ongoing study involving the analysis of NLDN lightning data for the Great Lakes region. The study involves 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 that extends from Minneapolis, MN to Pittsburgh, PA. The data suggest 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 nothing 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.
CHAPTER III

METHODS AND METHODOLOGY

Data

Lightning data for this study were collected by Detroit Edison’s Lightning Location and Protection system. Detroit Edison Corporation purchased the system from Global Atmospherics of Tuscon, Arizona in 1980 (Desmond and Whitney 1984). It consists of three direction-finding antennas located throughout southeast Michigan (Figure 1) to provide coverage of the entire Detroit Edison service area (Desmond and Whitney 1984). Incoming electromagnetic fields generated by lightning are detected by the antennas and converted to azimuth and time data. This information is then sent by modem to a position analyzer located in the Detroit Edison General Office Building in Detroit, Michigan. Flash locations are determined by using information from all direction finders that record any given flash. If all three sensors record the same flash, an optimization procedure is performed on the flash data to minimize the angle errors and provide a triangulated flash coordinate. Some strikes, known as baseline strikes, occur along the baseline of two direction finders and are only recorded by those two sensors, which creates a problem in flash coordinate location. Such flashes cannot be triangulated but can be resolved, with limitations, using a complicated algorithm, and with lower confidence in the coordinates. Baseline strikes were noted in the raw dataset provided by Detroit
Figure 1. Study Area With Five Kilometer Grid.
Edison, but were marked with a baseline indicator in the flash data code. Baseline strikes were not used in the analysis. The position analyzer compares incoming direction finding information with the known signal waveform for a cloud-to-ground lightning strike, eliminating the ambiguity of incoming signals generated by cloud-to-cloud and intra-cloud lightning. Strike locations are determined by a triangulation method using three sets of direction finder information for each strike.

The dataset was obtained from Detroit Edison as 180 Mb ASCII text file provided on CD-ROM. The set contained all recorded strikes from 1982 to the present. Each line of raw data is an individual strike event with time, date, state-plane coordinates, flash amplitude, and multiplicity recorded.

Data Processing

The data were selected and checked for errors before analysis by an in-house program designed to perform these specific tasks. A DOS executable program was created using a FORTRAN 77 compiler. The program reads in the Detroit Edison data file line by line, skipping all data prior to 1985, and writes to an output file. Errors are determined if the line does not fit a specific format or has a baseline indicator and are not written to the output file. A filter line within the program, insures that only strikes within the study area are used.

The output from the FORTRAN program consisted of 11 individual year files containing all flash information for the years 1985 to 1995, each year file a comma delimited text file approximately 15 megabytes in size. Microsoft Access database was used to manage all data files, which were imported directly and stored as tables.
within a single database. Spatial and temporal analyses were done with ESRI ArcView software on a 133 MHz personal computer using the Windows 95 operating system. Using the Access database allowed for the use of a connectivity standard used in Windows 95 called Open Database Connectivity, allowing for direct query from the Access database using ArcView, Microsoft Excel, and SPSS (Figure 2).

Figure 2. Software Used in Data Processing.

Spatial Analysis

The spatial analysis was done with ESRI ArcView geographic information system software. Plotting several million lightning flashes on a map produces an indiscernible representation of flash locations. A method used by Orville (1991) and
Reap, et al. (1986) consisted of displaying long term lightning data in flashes per square kilometer, based on grids superimposed on their study area.

The grid overlay was used in this project with flash density maps created in ArcView. Grid cells were created using a custom Avenue script that would create a grid theme with exactly square cells. The cell size was specified within the code and several different cell sizes were experimented. The optimal grid size was determined to be five kilometers on a side, providing interpretable maps for the study area and an adequate resolution to identify spatial patterns.

The grid was a vector theme overlaid with the flash data. The process was to join the grid theme to the flash data, producing a dataset including every flash point with a grid cell label attached to it. The flash data were then summarized by grid cell label and displayed as grid theme with flash count values. Summarizing the flash data made ArcView count the number of flashes reported in each grid cell and create a new grid theme of raw flash counts. A vector theme cannot be mathematically manipulated in ArcView, so it was rasterized to gain that functionality. Once a raster theme, the grid could be divided by the area of each grid cell (25 km²) to obtain the flash density in flashes per square kilometer. This process was repeated for all maps by linking to the Access database and acquiring the desired data to be analyzed.

The spatial analysis also included the creation of ‘lightning day’ maps. These maps were created to show the day frequency of lightning events across the study area. The ‘lightning day’ is similar to a thunderstorm day in that it is a useful data source in quantifying convection across an area. The thunderstorm day data are logged by personnel at National Weather Service offices across the country.
thunder or lightning observed at the station makes the given day a thunderstorm day. The fact that the thunderstorm day is determined and logged by humans introduces large amounts of error into the dataset. The ‘lightning day’ is derived from a much more reliable data source and can provide a high resolution spatial depiction of convective weather frequencies.

The lightning day maps were created by interfacing features of Microsoft Access and ArcView to show only the number of flashes occurring on different days within each grid cell. Although flash density maps used all lightning data to derive the annual flash density per grid cell, only the filtered dataset showing flashes of different days per grid cell were used. Filtering was done in Microsoft Access.

Each flash was a record with a grid cell identifier in the Access database. To filter out all strikes of like days within each grid cell utilized the delete duplicates command in Access. This deleted all records that had other records with the same entries in the grid cell identifier and date. The resulting table was then linked to ArcView to create the lightning day maps in the same fashion as the flash density maps.

Spatial statistics were calculated with the ArcView Spatial Analyst extension, allowing for raster value operations to be performed. 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, so mean values were calculated within areas representing seventy, sixty, and fifty percent detection efficiency regions as set forth in network specifications.
Temporal Analysis

Temporal analysis was done using both Microsoft Access and Microsoft Excel. The number of flashes per year was obtained directly from the number of records in each year table of the database. The frequency of positive flashes per year was acquired by querying each year table for all records that had a positive amplitude value. All of these frequency values were stored in an Excel spreadsheet where they could be analyzed with descriptive statistics and summary graphics.

The data for the diurnal analysis were gathered by querying the ‘total’ table containing all flashes for the entire study period by whole hours 00 through 24. This provided the flash frequency for each hour of the day to be displayed in a histogram table showing the diurnal variations. This was also done by seasonal groupings. The ‘total’ table was split up into four different season tables grouped as follows: (1) Fall: September, October, November; (2) Winter: December, January, February; (3) Spring: March, April, May; and (4) Summer: June, July, August.

Each season table was then queried by hour to obtain the diurnal variation by season. All of the frequency data were stored in an Excel spreadsheet where histograms could easily be constructed. Descriptive statistics of the frequency data were also performed in Excel.
CHAPTER IV

RESULTS

Spatial Analysis

The principal result of the spatial analysis was a mean flash density map (Figure 3) 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 along 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 along a line of constant detection efficiency.

A broad area of flash densities above two flashes/km$^2$ is oriented from northwest to southeast across the southeast quadrant of the study area. The highest flash densities calculated in this study occur in this area which is within the 70% detection efficiency area of the network.

Yearly means and other flash density information are displayed in Table 1. The overall period mean within the 70% detection 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.
Figure 3. Mean Flash Density: 1985-1995.
### Table 1

Flash Density Statistics for the 70% Detection Efficiency Area

<table>
<thead>
<tr>
<th>Year</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Coeff. of Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1985</td>
<td>1.82</td>
<td>1.07</td>
<td>0.59</td>
</tr>
<tr>
<td>1986</td>
<td>0.94</td>
<td>0.85</td>
<td>0.90</td>
</tr>
<tr>
<td>1987</td>
<td>2.00</td>
<td>1.24</td>
<td>0.62</td>
</tr>
<tr>
<td>1988</td>
<td>2.13</td>
<td>1.14</td>
<td>0.54</td>
</tr>
<tr>
<td>1989</td>
<td>2.68</td>
<td>1.42</td>
<td>0.53</td>
</tr>
<tr>
<td>1990</td>
<td>1.38</td>
<td>0.83</td>
<td>0.60</td>
</tr>
<tr>
<td>1991</td>
<td>1.88</td>
<td>0.92</td>
<td>0.49</td>
</tr>
<tr>
<td>1992</td>
<td>1.48</td>
<td>1.06</td>
<td>0.72</td>
</tr>
<tr>
<td>1993</td>
<td>1.55</td>
<td>0.87</td>
<td>0.56</td>
</tr>
<tr>
<td>1994</td>
<td>3.05</td>
<td>1.40</td>
<td>0.46</td>
</tr>
<tr>
<td>1995</td>
<td>3.00</td>
<td>0.96</td>
<td>0.32</td>
</tr>
<tr>
<td>Mean</td>
<td>1.99</td>
<td>1.07</td>
<td>0.54</td>
</tr>
</tbody>
</table>

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 4). The drop-off in detection efficiency is still noted past the 70% detection efficiency 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 1 to
Figure 4. Mean Lightning Days: 1985-1995.
2 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 flash density within the 70% detection efficiency 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 5). The flash density values drop-off to less than 0.5 flashes/km$^2$ along the Lake Huron shoreline.

1994 incurred the most cloud-to-ground flashes within the study area and 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 6) 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 not completely obvious pattern in flash densities, are the 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. This pattern is reflected in 1994 and in the overall mean. Lightning day values for this area range from 3 to 4 lightning days per year per grid cell on average.

Temporal Analysis

A plot of total flashes by month (Figure 7) shows a defined seasonal cycle with low frequencies in the winter months and higher frequencies regularly occurring in the summer months. Monthly flash counts range from zero in many winter months to 91,115 for July of 1994.
Figure 5. 1994 Flash Density.
Figure 6. 1994 Lightning Days.
Table 2
Lightning Day Statistics for the 70% Detection Efficiency Area

<table>
<thead>
<tr>
<th>Year</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Coeff. of Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1985</td>
<td>4.48</td>
<td>2.02</td>
<td>0.45</td>
</tr>
<tr>
<td>1986</td>
<td>3.67</td>
<td>1.95</td>
<td>0.53</td>
</tr>
<tr>
<td>1987</td>
<td>3.71</td>
<td>1.78</td>
<td>0.48</td>
</tr>
<tr>
<td>1988</td>
<td>3.04</td>
<td>1.56</td>
<td>0.51</td>
</tr>
<tr>
<td>1989</td>
<td>3.01</td>
<td>1.34</td>
<td>0.45</td>
</tr>
<tr>
<td>1990</td>
<td>3.26</td>
<td>1.58</td>
<td>0.48</td>
</tr>
<tr>
<td>1991</td>
<td>3.64</td>
<td>1.61</td>
<td>0.44</td>
</tr>
<tr>
<td>1992</td>
<td>3.81</td>
<td>1.87</td>
<td>0.49</td>
</tr>
<tr>
<td>1993</td>
<td>2.83</td>
<td>1.64</td>
<td>0.58</td>
</tr>
<tr>
<td>1994</td>
<td>3.59</td>
<td>1.68</td>
<td>0.47</td>
</tr>
<tr>
<td>1995</td>
<td>3.03</td>
<td>1.77</td>
<td>0.58</td>
</tr>
<tr>
<td>Mean</td>
<td>3.46</td>
<td>1.71</td>
<td>0.49</td>
</tr>
</tbody>
</table>

Figure 8, a plot of annual lightning distributions, shows the first three years of the study had the highest monthly flash counts occurring in September and October while the rest of the study period maintained highest counts in the summer months of June, July, and August. The variation in the amplitude of the annual cycle presents some periodicity even within this small study period. A qualitative analysis of the
Figure 7. Total Flashes by Month: 1985 - 1995.
Figure 8. Annual Flash Distribution by Month.
time series chart shows a peak in monthly frequencies in 1988 followed by a peak the next year, but with less amplitude.

The total lightning days within the study area for each year were plotted with total flashes per year in Figure 9. 1987 had the highest lightning day value but was a below normal year in total flashes. 1992 had both the lowest number of flashes and lightning days for the study period.

Annual flash frequency by hour is shown in Figure 10. The hour of maximum flash frequency occurs at 1900 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% 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 Figures 11 through 14, 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 flashes
Figure 9. Total Lightning Days and Total Flashses per Year.
Figure 10. Annual Flash Frequency by Hour.
Figure 11. Summer Flash Frequency by Hour.
Figure 12: Spring Flash Frequency by Hour.
Figure 13. Fall Flash Frequency by Hour.
Figure 14. Winter Flash Frequency by Hour.
for 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.
CHAPTER V

DISCUSSION OF RESULTS

Spatial Analysis

Flash Density

The most obvious pattern evident on the mean flash density map (Figure 3) is the radial decrease in flash density values away from the detection network. The network is most efficient at detecting lightning flashes that occur close to the direction finders. Detection efficiency figures were provided as product specifications by the direction finder manufacturer. 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. There the flash density values decrease slower with distance from the network. This is most likely the result of a combination of high flash frequencies and poor network detection.

A check of this detection efficiency observation was performed through a correspondence with Dr. Richard Orville at Texas A&M University. Dr. Orville accessed data provided by the National Lightning Detection Network to check against the Detroit Edison network. His analysis of NLDN mean flash density for southern Michigan, 1989-1996, showed an increase in flash density values toward the southwest quadrant of the study area. The pattern within the 70% detection efficiency
area was very close to the one portrayed by the NLDN for southeastern Michigan, even with differing time periods. Flash density values calculated using the Detroit Edison data are not realistic outside of the 70% detection efficiency area when compared to the NLDN flash density analysis.

With an understanding of the limitations of the existing Detroit Edison Lightning Detection Network, careful interpretation of the mean flash density map can be made. Interesting patterns are evident within the 70% detection efficiency 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 (Figure 15). A study by

![Figure 15. Spatial Pattern of Mean Flash Density in Northeastern Quadrant of Study Area.](image-url)
the Illinois 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% detection efficiency area are found along the Lake Huron shore in the extreme northeastern quadrant and are most likely due to a ‘lake-effect’ on the local climate.

A mean flash density for the study area within the 70% detection efficiency was calculated for each year to obtain a study period mean (Table 1). This allows a quantitative examination of the overall variability of flash densities within the most efficient area of the detection network. A comparison of this number to other regional mean flash densities is difficult due to the rarity of other published values. A study done by Lopez et al. (1997) showed values ranging from 0.6 flashes/km$^2$ to 4 flashes/km$^2$ for the state of Arizona. These values were calculated using a twenty by twenty km grid and also corrected for detection efficiency limitations, cannot be directly compared due to the differences in climate, between Michigan and Arizona. Orville (1994) published a study calculating flash densities for the entire United States, 1989-91, on an extremely coarse scale. Results showed annual means in the Midwest ranging from two to four flashes/km$^2$. The highest values in the U.S. were over nine flashes/km$^2$ in the state of Florida. A correction factor of 1.4 was applied to these values to account for network detection efficiency limitations. This fact makes
direct comparison of flash density values difficult again, due to differences in study design.

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

A separate spatial analysis was performed in the calculation of lightning days. The discrete number of days that lightning occurred per year per grid cell was displayed in the lightning day maps. This analysis is very similar to the statistics provided in a thunderstorm day map. Lightning day maps are constructed using remotely sensed lightning data while thunderstorm day maps use data gathered by human observers.

A lightning day map provides a separate determination of lightning variability apart from the flash density analysis. Areas of above normal flash densities on an annual or long term mean map may be the result of either a high frequency of individual convective events passing over the area or a few events producing large amounts of cloud-to-ground lightning. Characterizing the cause of high flash
densities is important in the correct interpretation of lightning climatologies. High flash densities do not always indicate areas favored for cloud-to-ground lightning strikes.

It appears 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. The fact that the spatial patterns are similar between the flash density analysis and the lightning day analysis suggests that high flash density areas are the result of persistent convective patterns rather than random, high flash frequency events.

There are some deviations from this fact visible in comparing the two analyses. One area with a high mean flash density does not have a corresponding maximum in lightning days. These values are right around the mean number of lightning days within the 70% detection efficiency 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 study indicated that the persistent high flash densities from year to year in this area may be the result of unique lake breeze interactions with the synoptic environment. The mean lightning day analysis suggests that convective events in this area not necessarily more frequent than in other areas within the 70% detection efficiency area. The relationship between lightning days and flash densities in this area suggest that there is an average number storms producing an above average amount of lightning per event. This would be characteristic of a quasi-stationary storm feeding off of the low-level convergence provided by a lake breeze boundary interacting with the synoptic environment.
Discussion of 1994

The spatial patterns in the 1994 flash density analysis are very similar to the overall mean flash density analysis. High flash density values (> 4 flashes/km²) are much more prevalent 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 6) to the flash density analysis for the same year shows the relationship of flash density values to frequency of events. This again suggests that the highest flash density values are the result of large amounts of lightning produced by an average number 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.

Temporal Analysis

Inter-annual Variation

Figures 7 and 8 represent the temporal distribution of cloud-to-ground lightning frequencies by month for the entire study period. The flash frequency distribution generally has a similar pattern, but does vary slightly from year to year through the study period.
Monthly flash totals do not necessarily indicate an increase in the overall frequency of convective events. The increase in monthly flash totals from the winter to summer season is from a combination of more convective events and more lightning per convective event. The highest monthly flash totals for the study period are the result of one or two convective events producing large amounts of lightning rather than many events with equal amounts of lightning.

There does not appear to be a periodicity in the number of lightning days within the study area for the study period of 1985 through 1995. Visible periodicity in high monthly flash totals could be the result of a cycle in large convective events, but not in the number of events. Through visible inspection of Figure 9 there appears to be no relationship between the number of lightning days and the total flashes per year. The highest frequency of lightning days corresponds to a year with a below average number of annual total flashes. Years with the highest annual flash totals correspond to average total lightning day frequencies.

Diurnal Analysis

A well defined diurnal cycle is evident when looking at the histogram of total lightning frequency by hour (Figure 10). The histogram represents the percentage of total flashes occurring during that hour. A well known pattern of an afternoon maximum is evident. This pattern has been seen in other studies of precipitation and thunderstorm events 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 from the late evening into the early morning hours is seen in the average
hourly distribution for all seasons and may be the result of the influence of a nocturnal jet formation. The nocturnal jet is primarily a summer phenomena in Michigan and the summer season (June, July, August) hourly flash distribution histogram (Figure 11) shows a definite secondary maximum in the early morning hours indicating a probable nocturnal jet influence.

The summer event occurrences contributed most of the hourly flashes throughout the year. The summer histogram shows a maximum that is slightly earlier in the day than the annual histogram. The summer maximum occurs at 1800 EST, but extends into the next hour of 1900 EST. The slightly earlier maximum is probably the result of more intense solar heating earlier in the day during the summer months. This allows for the atmosphere to destabilize earlier in the day producing thunderstorms and lightning.

The spring histogram (Figure 12) is compiled from the flashes that occur during the months of March, April, and May. The smaller sample used in the spring analysis means that the hourly percentage value cannot be directly compared to the summer values, or any other seasonal hourly value. The timing of the maximum flash frequency per season is the important feature of the hourly analyses. The smaller number of flashes still indicates a diurnal cycle with an early evening maximum. Convective weather is an early evening-late afternoon phenomenon in the spring season, also. Destabilization of the atmosphere by solar forcing coupled with late afternoon frontal passages is the most likely cause of the spring afternoon maximum. A secondary maximum is also evident in the early morning hours (200 – 400 EST) indicating a slight increase in convective activity. The early morning rise in
convection could be influenced by the formation of a nocturnal low-level jet (Walters et al. 1995).

The fall histogram (Figure 13) 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. The lift provided to an unstable atmosphere by a frontal passage would produce the most vigorous convection and in turn the greatest amount of lightning.

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 14) 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.
CHAPTER VI

CONCLUSIONS

The results of the spatial analysis suggest that the Detroit Edison lightning detection network provides adequate coverage to only areas within the 70% detection area. Outside of this area, detection efficiency quickly falls off and fails 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 even with the large amount of variability in flash distribution do exist. 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’ on reducing convection in that portion of the study area. This result does seem to be an actual climatological finding.

Another persistent pattern was a maxima in flash densities along the Ontario-Lake Erie shoreline. This area appears to have another ‘lake-effect’ association with its flash distribution. In this case the lake seems to enhance the occurrence of quasi-
stationary thunderstorms which in turn produces large amounts of cloud-to-ground lightning in small areas.

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 lightning day analysis.

The temporal analysis proved interesting patterns on different scales ranging from inter-annual to diurnal. The temporal patterns shown in the inter-annual analysis show a great amount of variability from year to year. The number of cloud-to-ground lightning strikes per year deviated greatly suggesting an average yearly frequency is not realistic with this small sample. A longer term analysis would help alleviate the influence of climatic variations with time scales longer than the period of this study.

The annual distribution of lightning by year showed a marked peak of lightning activity in the summer months within the study area. This is expected with Michigan receiving its greatest amount of solar forcing in these months. Some deviations from this normal pattern were noted in the early years of this study with peaks in the early fall months. This could be the result of large storm occurrences in
the fall coincidentally for these years or the ending of an unusual shift in climatic patterns.

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. 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.

This study made an attempt to quantify the spatial and temporal variations of cloud-to-ground lightning in southern Michigan using data from a relatively new technology. A climatological view of these variations provides a greater understanding of the regional impact of lightning on southern Michigan. As with all climatologies continual reevaluations with newer datasets is necessary.

Further studies in regional lightning climatologies should aim to use datasets with greater spatial coverage. 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. Local lightning data could be analyzed for periodicity and correlations to other larger scale climatic variations. This would help define the impact of global teleconnections at the regional and local scale.
1985 Flash Density
1986 Flash Density

- Detroit Edison LLP
- Direction Finders

Flashes/km²
- <0.5
- 0.5 - 1
- 1 - 2
- 2 - 3
- 3 - 4
- 4 - 5
- 5 - 6
- 6 - 7
- 7 - 8
- 8≤
1989 Flash Density

- Detroit Edison LLP
- Direction Finders

Flashes/km²

- <0.5
- 0.5 - 1
- 1 - 2
- 2 - 3
- 3 - 4
- 4 - 5
- 5 - 6
- 6 - 7
- 7 - 8
- 8<

Detection Efficiency: 50%, 60%, 70%

Lake Michigan, MICHIGAN, Lake Huron, INDIANA, OHIO, Lake Erie

50 km scale
1995 Flash Density

Flashes/km²

- <0.5
- 0.5 - 1
- 1 - 2
- 2 - 3
- 3 - 4
- 4 - 5
- 5 - 6
- 6 - 7
- 7 - 8
- 8≤

Detection Efficiency
50%
60%
70%

Detroit Edison LLP
Direction Finders

Lake Michigan
MICHIGAN
Lake Huron

INDIANA
OHIO
Lake Erie

50 km
Appendix B

Lightning Day Maps
1986 Lightning Days

Detection Efficiency

Days with Lightning

Detection Eden LLP
Direction Finders

Lake Michigan
MICHIGAN
Lake Huron

INDIANA
OHIO
Lake Erie

50 km

N
S
E
W
1987 Lightning Days

Detroit Edison LLP
Direction Finders

Days with Lightning

Detection Efficiency
50%
60%
70%
1989 Lightning Days

Detroit Edison LLP
Direction Finders

Days with Lightning

Detection Efficiency

50%
60%
70%

Lake Michigan
MICHIGAN
Lake Huron

INDIANA
OHIO
Lake Erie

50 km

N
E
S
W
1990 Lightning Days

Detection Efficiency

50%

60%

70%

Detroit Edison LLP
Direction Finders

Days with Lightning

0
1
2
3
4
5
6
7
8
9
10
10<

Lake Michigan

MICHIGAN

Lake Huron

INDIANA

OHIO

Lake Erie

50 km

W

S

N

E
1991 Lightning Days

Lake Michigan
MICHIGAN
Lake Huron

Detection Efficiency 50%
60%
70%

Days with Lightning

0
1
2
3
4
5
6
7
8
9
10

Detroit Edison LLP Direction Finders

50 km

INDIANA
OHIO
Lake Erie
1992 Lightning Days

Detected Efficiency 50% 50% 50%

60% 70%

Days with Lightning

0 1 2 3 4 5 6 7 8 9 10 10<
1993 Lightning Days

Detection Efficiency

Days with Lightning

- Detroit Edison LLP
- Direction Finders

Lake Michigan

MICHIGAN

Lake Huron

INDIANA

OHIO

Lake Erie

50 km

0

1

2

3

4

5

6

7

8

9

10

10<
1995 Lightning Days

Detroit Edison LLP Direction Finders

Days with Lightning

- 0
- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 10
- 10<

50 km

Lake Michigan

MICHIGAN

Lake Huron

INDIANA

OHIO

Lake Erie

Detection Efficiency

50%

60%

70%
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