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TEMPORAL AND SPATIAL VARIATIONS OF CLOUD-TO-GROUND LIGHTNING IN THE GREAT LAKES REGION

By

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ABSTRACT

TEMPORAL AND SPATIAL VARIATIONS OF CLOUD-TO-GROUND LIGHTNING IN THE GREAT LAKES REGION

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An initial analysis of lightning data for the southern Great Lakes Area was conducted for the period of 1 January, 1989 through 25 October, 1990. Emphasis was placed on (1) the temporal variations in characteristics of cloud-to-ground flashes with respect to frequency, strength, polarity, and number of return-strokes and (2) the spatial variations in the timing of lightning activity across the study region. An inverse relationship between flash frequency and the percentage of positive strikes was observed both on a monthly and diurnal scale. A higher flash total in 1990 coincided with a higher percentage of nighttime strikes. Considerable monthly and diurnal differences in lightning activity were observed for the eastern and western portions of the study area. A southwest-northeast axis of highest lightning activity could frequently be observed. Little correspondence between areas of high total flash receipts and number of days with lightning activity was evident.

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CHAPTER I

INTRODUCTION

Background of the Study

Lightning strikes have been termed "the nation's number one weather killer." According to Mogil et al. (1977), lightning was responsible for the deaths of almost 7,500 Americans between 1939 and 1976. Over 20,000 lightning-related injuries occurred during the same time period. Also, lightning strikes are the cause of approximately 10,000 wild-land fires each year (Krider et al. 1980). The advent of networks of magnetic lightning direction finders in the early 1980s has triggered a series of research projects aimed at a better understanding of lightning-producing storms. Lightning observations have been complemented by data obtained by radar, airborne balloons, field mills, and other field observations to acquire information about rainfall amounts, ground-flash rates, peak currents, numbers of return strokes, and orographic and synoptic controls of thunderstorms. The long-term goal of these studies is to improve the predictability of thunderstorms and their associated hazards.

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Lightning Detection Networks

In 1983, a network of magnetic direction finders (DFs) for observing cloud-to-ground lightning (CG) along the East Coast was established by SUNY-Albany with support from the Electrical Power Institute. Ten DFs covered an area from Maine to North Carolina and as far west as Ohio (Orville et al. 1983). The area of coverage of the Lightning Detection Network was extended farther west in 1989 when the commercial National Lightning Detection Network was created from three regional networks. The eastern network run by the State University of New York at Albany (SUNYA) was joined by the western network managed by the Bureau of Land Management (BLM) and a midwestern branch operated by the National Severe Storms Laboratory (NSSL). The National Network now covers three million square miles and employs approximately 115 magnetic direction finders (Orville et al. 1990).

The DFs have a detection rate of 80 percent within a nominal range of 400 km. The time, angle, signal amplitude, polarity of the first return-stroke, and number of return strokes of each detected cloud-to-ground flash are stored in digital form. After two or more DFs detect the same strike, the location of the ground-flash is interpolated and the information about the lightning strike is archived at a central facility (Orville et al. 1990). The principle of wideband magnetic direction finders has been previously described in detail (e.g. Krider et al. 1980).

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Diurnal and Seasonal Characteristics of Thunderstorms

In their fairly comprehensive study of the diurnal variations of thunderstorms, Easterling and Robinson (1985) identified nine thunderstorm regions for the conterminous United States. They based their classification upon both the "time of maximum storm occurrence and the concentration of activity around this time." They suggested that similar diurnal characteristics of thunderstorms are caused by "common causal mechanisms operating in each area." Throughout the nation they detected a clear trend for regions and seasons with an afternoon maximum in thunderstorm frequency to have a high amplitude diurnal frequency curve, whereas regions with nocturnal maxima were seen as having a tendency for lower amplitude hourly frequency distributions. Of interest for this study are only four of the identified thunderstorm regions, the Central United States, the Great Lakes Region, the Northeast, and the Southeast. In the Central United States, Easterling and Robinson identified an area of mainly nocturnal storms with a low normalized amplitude in all seasons except winter. The Great Lakes Region sets itself apart from the Central States through a significant number of winter storms. It is characterized by nocturnal low amplitude maxima in all seasons. In the Northeast, winter storms are less frequent and the timing of thunderstorms shifts to the afternoon hours. The amplitude of the afternoon maximum increases to medium. The Southeast has afternoon storms in all seasons except winter, when nocturnal storms are dominant. In this regic

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region, the amplitude of the frequency distribution is lowest during winter; it reaches a maximum during summer.

Analysis of satellite and lightning observations have further clarified the diurnal and seasonal variations of thunderstorm activity across the conterminous United States. In agreement with Easterling and Robinson's (1985) study, Orville's (1981) analysis of satellite imagery for September through November 1977 revealed a midnight maximum in thunderstorm frequency over the Midwest for autumn with a general decrease in lightning activity from September to November.

Speheger et al. (1990) examined the climatology of severe thunderstorm events in Indiana during a 31-year period (1959-1989). Speheger's findings for Indiana are in agreement with the findings of Easterling and Robinson (1985). Except for the extreme northern portion of the state, Indiana falls within the Southeastern region as classified by Easterling and Robinson. Typical of the Southeastern region, the onset of lightning activity in Indiana most commonly occurred between 2 and 7 p.m. Eastern Standard Time (1900-2400 GMT), and lightning activity was most frequent in June.

Several studies have contrasted the duration, spatial patterns, and seasonality of thunderstorms for different parts of the US. with those for Florida, the state with the most frequent thunderstorm activity. Maier and Krider (1982), using lightning observations, noted considerable differences between the characteristics of three severe thunderstorms that occurred in north Texas and Oklahoma during April

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and May 1979 and 268 "nonsevere air-mass thunderstorms" in Florida for the summer of 1978. The severe storms of the Great Plains were found to possess "well-defined lightning location clusters which would exist for long periods of time, traveling at moderate to high rates, thus affecting large areas." The average duration ranged from two to eight hours and the affected area for two of the storms was 1800 km^2 and 5000 km^2, respectively. The mean rates of cloud-to-ground lightning ranged from about two to six strikes per minute with peak rates approaching twenty ground flashes per minute. The Florida air-mass storms, on the other hand, were described as going through their life cycles quickly, affecting smaller areas and possessing lower flash rates. Storm duration rarely exceeded one to two hours with mean rates of cloud-to-ground (CG) lightning of about one strike per minute and peak rates of twelve strikes per minute. The total area affected was found to average about 450 km^2. On a typical summertime afternoon, however, ten to fifty airmass storms would form. Thus, the total storm duration, area, and the number of CG-flashes would be similar to that of severe storms in the Great Plains.

Piepgrass et al.'s (1982) results from an analysis of lightning activity in a 625 km^2 area of central Florida during the summers of 1976-1980 are in general agreement with the findings of Maier and Krider (1982). Seventy-nine storms with ten or more strikes produced a total of 27,494 discharges during the examined summers. Storm duration averaged

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107 minutes, and the average flash rate was 2.4 strikes per minute with maximum short-term discharge rates of 30.6 strikes per minute.

Summer lightning in Florida was also the focus of Maier et al.'s (1984) study. They found the peak in lightning activity in coastal areas of south Florida to occur between 2000 and 2100 GMT. In addition, the diurnal variation in lightning activity was smaller over the Atlantic and the Gulf of Mexico than over land.

Diurnal and spatial variability of lightning activity in Colorado and Florida was the focus of Lopez and Holle's study (1986). Topography and resulting diurnal circulations were found to exert strong influences on the time and place of lightning ground strike occurrences. For Colorado, they found the daily flash rate to be highly variable with a maximum around the first part of August. The diurnal cycle revealed a pronounced maximum between 4 and 5 p.m. MST (2300 and 2400 GMT) and a minimum between 7 and 8 a.m. MST (1400 and 1500 GMT). Orographic and thermal influences resulted in the frequent development of a cyclonic convergence-vorticity zone from the Denver area north-northeastward in the summer. The resulting circulations and confluence zones were found to have a "decided impact on the preferred formation and propagation patterns of the convective systems forming in the area."

For Florida, the annual maximum of lightning frequency also fell in the summer months of June, July, and August.

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Compared to Maier et al.'s (1984) previous study, Lopez and Holle identified a maximum in the diurnal cycle of lightning frequency between 2 and 3 p.m. EST. Three preferred times for the occurrence of first flashes were identified: around sunrise, around noon, and after midnight. Lopez and Holle related these relative maxima to the "varying influences of the sea breeze, the land breeze, or nocturnal cooling." As in the case of Colorado, Florida's lightning distribution was found to reflect topographical characteristics of the region.

The Diurnal Variations of Precipitation

The close association between rainfall and cloud-to-ground lightning characteristics has been noted by Goodman and MacGorman (1986) and Nielsen et al. (1990). Of special interest for this study is the occurrence of summertime nocturnal maxima in lightning and convective activity for the central part of the United States and an afternoon maximum for the eastern parts of the country. These maxima and minima are also evident in the diurnal frequency distribution of hourly precipitation.

Previous publications on the diurnal variation in precipitation and thunderstorm frequency include a study by Wallace (1975) conducted for the conterminous United States. Wallace examined differences in the timing of frequency maxima for various precipitation levels and for thunderstorms. Harmonic analysis of hourly frequencies revealed an earlier maximum in summertime thunderstorm activity as compared to

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summertime heavy precipitation (>0.25 cm h^{-1}) for the central part of the country. A difference of over six hours was noted for parts of Illinois, Indiana, and Ohio. These areas lie in the transition zone between regions experiencing a nocturnal maximum of precipitation and those experiencing a daytime maximum. Trace precipitation also showed a tendency to be out of phase with thunderstorm activity in the central United States, particularly in a triangular shaped area extending from Oklahoma to Michigan to North Dakota. In this region, thunderstorm activity was found to possess a midnight maximum and trace precipitation a morning maximum. During the winter months, weak nocturnal maxima in convective activity were evident for the temperate latitudes of both the central and eastern United States.

Balling (1985) also examined the summertime nocturnal maximum of hourly precipitation for different precipitation levels. He found that 60 percent of all warm season precipitation ≥0.25 mm h^{-1} in southern Nebraska, central Kansas, western Oklahoma and northern Texas occurred at night. The area of nighttime maxima was centered on southeastern Nebraska. In western Nebraska, Kansas, and Oklahoma an east-west gradient of about 1h per 100 km in the timing of maximum frequency was evident. Balling detected a much stronger modulation of the diurnal cycle for the ≥2.54 mm h^{-1} events compared to the lighter precipitation amounts. Also, larger precipitation levels displayed a frequency maximum that occurred one to two hours earlier than the maximum for the lighte

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In agreement with Wallace (1975), Winkler (1987) also identified a nocturnal regime of summertime very heavy precipitation (>6 mm h^{-1}) for the Central Plains and an afternoon maximum for the eastern United States. An area extending from central Texas to Indiana was seen as the transition zone between the two rainfall regimes. In this transition region, very heavy precipitation is likely to occur throughout the day, although two slight maxima at approximately 0600 LST (1200 GMT) and 1500 LST (2100 GMT) can be identified. The time of summertime very heavy precipitation was found to generally correspond with the time of thunderstorm activity. As previously identified by Wallace (1975), an exception was found in the Central Plains where the maximum thunderstorm activity occurred before the time of maximum frequency of very heavy rainfall. The two authors slightly diverged on the time lag between maximum thunderstorm and maximum rainfall activity. Winkler stated a difference of two to three hours for very heavy rainfall amounts.

In a later study, Winkler et al. (1988) examined the diurnal characteristics of heavy hourly precipitation (>2.5 mm h^{-1}) for all four seasons. Harmonic analysis revealed a nocturnal maximum across much of the eastern and central United States in winter and spring that gave way to an afternoon maximum across the southern and eastern states in the summer. Toward autumn the area of nighttime maxima increased again. It remained smaller than in winter and spring, however. With increa

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increasing intensity, rainfall was confined to increasingly shorter periods of the day. At the same time, more intense precipitation occurred considerably later in the day than light precipitation events. The only exception to this rule was found in the central United States "where during all seasons precipitation occurs earlier in the evening as rainfall intensity increases."

Electrical Properties of Thunderstorms

The electrical properties of lightning-producing thunderstorms have been found to vary with season and with particular phases in the life cycle of a storm. Orville et al. (1987) examined the characteristics of lightning strikes in the northeastern United States for twelve continuous months, from June 1984 through May 1985. The median amplitude for 720,284 first return strokes lowering negative charge to ground was 30 kA. Only a small percentage of negative flashes had first return strokes with "peak currents estimated to exceed 100 kA." The distribution of the peak current values for the recorded 17,694 positive cloud-to-ground flashes around the median value of 45 kA was significantly broader than for the negative strikes. In addition, a few positive strikes had peak currents exceeding 200 kA. The median strength of both negative and positive ground flashes was found to increase in the winter season. The average peak current in February, for example, was approximately 65 kA for negative strikes and 90 kA for positive flashes. An inverse

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relationship between the rate of negative cloud-to-ground lightning and mean peak current strength has frequently been identified (personal comment by Orville (1987) in Stolzenburg, 1990). Orville et al. (1987) also found that flash polarity varied with season. The percentage of positive strikes increased from less than 5 percent of the total number of strikes in the summer (May through September) to a maximum in February of slightly over 80 percent. In spring, the percentage decreased again to less than 10 percent in April. The number of return strokes associated with ground flashes also described an annual curve with increasing values in the warm months, although only signals for up to fourteen return strokes were processed by the direction finder microcomputer. Throughout the year, approximately 90 percent of the positive flashes had only one return stroke. The percentage of negative flashes with one return stroke increased from approximately 40 percent in June to over 80 percent in January and decreased again to less than 50 percent in April.

The different seasonal characteristics of lightning-producing storms were also at the heart of studies by Fuquay (1982), Orville et al. (1983) and Brook et al. (1982). During the summer thunderstorm seasons of 1965-67, Fuquay documented 75 ground flashes, an average of 3 percent of the total number of strikes, that lowered positive charge to ground over an area of about 2830 km^2 in the northern Rockies, . Each of these positive ground flashes was found to have one single return stroke. However, not all storms

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possessed positive lighting strikes. On storm days with the occurrence of positive ground flashes, positive strikes were recorded throughout the storms with the highest percentage occurring during the final stages of the storm. Within a 30-km radius centered on Missoula, Montana, storms that lowered positive charge to the ground ranged from 72 to 286 minutes . The positive flashes averaged 6 percent of all flashes. The strike density per season was found to approximate 0.01 positive and 0.3 negative ground flashes per square kilometer.

Orville et al.'s (1983) case study of an autumn storm with 11,000 ground flashes over southeastern New York and New England revealed a symmetrical increase and decrease in lightning frequency over the duration of the storm. While all strikes combined showed a parabolic frequency curve, the percentage of positive strikes increased toward the end of the storm to 37 percent of the total number of flashes. Averaged over the duration of the storm, the positive flashes amounted to 4 percent of the total number of strikes.

Brook et al. (1982) focused on the winter season of 1977-78 in their study of winter thunderstorms along the Hokuriku coast. They found that "positive currents peak about one order of magnitude greater than negative currents" and that the magnitude of the current for the positive return strokes occurring during the examined winter storms was comparable to large negative currents in summer storms. Also, the positive and negative charge centers within thunderclouds were found to occupy different heights. The center of posit

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positive charge was approximately 6.3 km above the surface, "while the highest negative charge was measured at 5.1 km." This "dipole" of different charge centers was attributed to vertical wind shear. Brook et al. speculated that positive ground flashes in summer storms might be accompanied by "significant shear in the cloud layer." They concluded that one "may indeed expect that the severe storms in the midwestern United States would exhibit a higher number of positive strokes than do the smaller orographic storms."

The different characteristics of positive cloud-to-ground strikes (+CGs) as compared to negative strikes (-CGs) have been commented upon by several additional authors. Rust et al. (1981) reported in their study on severe storms that most of the recorded positive strikes only had one return stroke. The average duration of positive strikes was about twice as long as that of negative flashes. Rust et al. attributed the longer duration of +CG to the "time taken for discharge processes prior to the first return stroke and for the apparent continuing current afterwards." Positive strikes were "observed to emanate from several regions of severe storms: high on the back of the main storm tower, through the wall cloud, and from the downshear anvil."

A spectacular lightning event was recorded by Idone et al. (1984). The authors were called to the scene where a positive cloud-to-ground flash had hit a residential home. Recordings from the lightning detection network revealed that the recorded +CG had been the only ground flash in a storm that

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that produced only a few total flashes. The positive strike possessed an estimated peak current of 70 kA.

The processes generating positive cloud-to-ground lightning have not yet been completely clarified. Takagi et al. (1986) supported the hypothesis of a tilted vertical dipole being a prerequisite for positive cloud-to-ground lightning. A thundercloud is generally assumed to be composed of a vertical dipole with net positive charge located above net negative charge. Initiating positive streamers progress downward into the negatively charged regions of the cloud. In the case of a tilted dipole with horizontal displacement between the positive and negative charge centers, a number of positive flashes can reach the ground instead of the negatively charged regions within the cloud. Takagi et al. used an electric dipole model to calculate the necessary horizontal displacement between the charge centers for the occurrence of +CG flashes. Winter thunderstorms in Norway and spring thunderstorms in Japan were examined to determine the height of the $-10^{\circ}C$ isotherm which is believed to be near the center of charge separation. The temperature difference between the positive and negative charge centers was assumed to be $20^{\circ}C$, which can be translated into a vertical distance of approximately 3 km. Different heights for the negative charge centers were tested with respect to the necessary horizontal distance between the positive and negative charge centers. Summer thunderclouds with a 5 km height of the negative charge center were found to generate positive ground flashes

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only if the horizontal distance between the charge centers was greater than 2.3 km. In Norwegian winter storms with negative charge centers at 1 km height, the fraction of positive CGs was high even in the absence of horizontal displacement between the positive and negative charge centers. Tagaki et al. concluded from their study that it was "easy to produce positive ground flashes when the height of the charge is low and the wind shear is strong."

The discussion about the origin and location of positive flashes is still continuing. Orville et al. (1988), Stolzenburg (1990), and Engholm et al. (1990) examined more closely the phenomenon of a bipolar pattern in the distribution of +CGs and -CGs generated by mesoscale storm systems. Orville et al. (1988) and Stolzenburg's (1990) findings differed with respect to the seasonal occurrence of bipolar patterns. Orville suggested a higher frequency for autumn and winter; Stolzenburg, on the other hand, maintained that summer is the season of higher frequency of this charge structure. She, however, shared Orville's opinion that in the winter months the percentage of storms with this pattern is higher and the bipolar pattern is better defined. In a February 1987 storm system along the Gulf coast, Orville found the ratio of positive to negative flash density to be 0.1 and the approximate length of the bipolar pattern to be 100 km, clearly longer than the cloud extend of the mesoscale system.

Engholm et al. (1990) found support for the "tilted dipole hypothesis" in case studies of winter and summer stor

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storms. Common features of the lightning bipoles included (1) the alignment of the bipole with the vertical wind shear, and (2) predominance of negative strikes in proximity to the deepest convection and a mixture of positive and negative locations displaced downshear from the deepest convection. Engholm et al. (1990) and Stolzenburg (1990) did not affirm Orville's hypothesis of a surface boundary typically separating the positive contoured flash center from the negative contoured flash center. Engholm et al. (1990) in addition expanded on Orville et al.'s findings suggesting seasonal variations in the alignment of bipoles. They suggested that "lightning 'bipole' orientations are aligned with the geostrophic wind in winter storms and with the vertical wind shear (which may be highly ageostrophic) in summer storms, with positive locations downwind (downshear) from negative locations."

Engholm et al. (1990) and Stolzenburg (1990) also hold different views on the generation of positive flashes. According to Stolzenburg the two main theories for positive charge build-up are: (1) the transfer of negative charge to the cloud-base by large precipitation particles and transfer of positive charge to the higher cloud regions by temperature-related cloud processes of small particles, and (2) convection of positive space charge into a growing cloud, whereby positive charges are carried to the upper portions of the cloud, and negative charges are carried down by convective motions at the outside of the cloud. While Stolzenburg adhe

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adheres to the theory of a large-scale advection of positive charge downwind, Engholm et al. (1990) favor the idea of an interplay of several mechanisms in the occurrence of positive lightning. Lightning bipoles are seen as the result of "active charge separation in convective clouds distributed over the entire area of the observed bipoles and not just in the deepest convection." In agreement with other studies (e.g. Rutledge and MacGorman 1988), the authors proposed that stratiform precipitation regions "may produce lightning independently of the deeper convection with which they are associated." Engholm et al. (1990) found lightning rates to increase dramatically with cloud depth. While negative strikes were prevalent in deeper clouds, positive lightning was more prevalent in shallow clouds located downwind from the deeper convection.

Return stroke characteristics have also been found to vary with different stages in convective systems. Goodman and MacGorman (1986) pointed out the relationship between different stages of Mesoscale Convective Complexes and the number of return strokes. They found that the most active electrical period (±2 h of the peak ground discharge rate) was characterized by "the greatest average number of discrete strokes (3-4 component strokes to ground) per flash and largest fraction of multiple stroke discharges." The first hour in the development of a mesoscale complex, on the other hand, contained a greater fraction of single stroke discharges.

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The Data Set

The lightning-strike data set utilized in this research project was obtained from the eastern branch of the national lightning detection network operated by the State University of New York at Albany (SUNYA). The data set is comprised of observations for 22 months, January 1, 1989 to October 25, 1990. The short length of the data set is due to the fact that no data were available for the time-period before January 1989, when the network was established in its entirety. The data were purchased in November 1990, which explains the abrupt ending in October 1990.

The area of observations extends from 78.9° to 96.7° W. and from 38.3° to 47.1° N. (Figure 1).

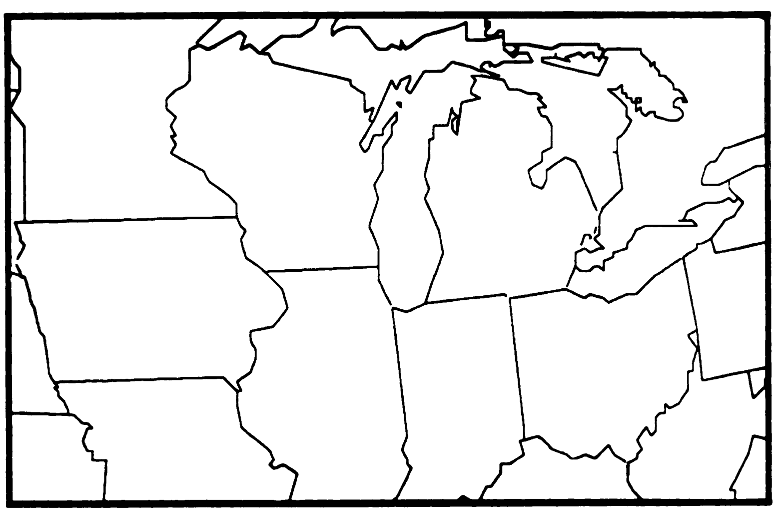

Fig. 1. Area of Coverage of the SUNYA data set.

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It thus includes portions of both areas of interest for this study; namely, the region of nocturnal maxima of precipitation and thunderstorm activity in the central US. and the region of afternoon maxima in the eastern US. The recorded components for each lightning event were time, location, number of return strokes, polarity, and amplitude.

Objectives of the Study

This study is a preliminary assessment of the climatology of cloud-to-ground lightning activity in the southern Great Lakes region. It is being conducted in connection with a larger, ongoing research project at Michigan State University's Department of Geography concerned with the climatology of convection in this region. The southern Great Lakes region was chosen as the study area because, as noted above, it lies astride the boundary between the nocturnal thunderstorm and precipitation regime in the central United States and the afternoon regime found in the eastern and southern United States. Consequently, this region is ideal for a systematic comparison of the characteristics of nocturnal and daytime convection.

As discussed above, a number of previous authors have identified temporal variations in the frequency and characteristics of lightning activity (i.e. Fuquay, Brook et al., Orville, and Orville et al.). In the first part of the study, the diurnal and seasonal variations of lightning activity with respect to the frequency of ground strikes, number of return strokes, peak amplitude, and polarity, are investigated for the entire southern Great Lakes region. This analysis expands on that of the previous authors in that it provides valuable climatological information for an additional part of the United States and more systematically compares, for each month of the study period with recorded lightning activity, lightning characteristics for daytime (1200-0000 GMT) and nighttime (0000-1200 GMT) periods.

In the second part of the study, the focus is on the spatial variations across the study region in the characteristics of lightning activity. In particular, spatial variations in the timing of lightning activity are emphasized. As noted above, previous authors have identified the southern Great Lakes region as a transition zone between nocturnal and afternoon convective regimes based on the frequency of thunderstorms and precipitation events. An objective was to determine whether lightning activity also displays similar spatial and diurnal variations.

One final objective of this thesis is the development and/or assessment of computer software suitable for spatial and temporal analysis of lightning observations. This software will be used for future studies encompassing broader regions and utilizing longer periods of observations.

PART I

TEMPORAL ANALYSIS

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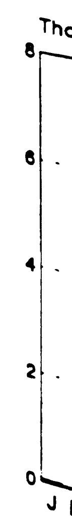

Fig.

CHAPTER 2

FREQUENCY OF LIGHTNING EVENTS

Annual Distribution

As noted previously, the data set used in this analysis spanned almost 22 months, January 1, 1989 until October 25, 1990. Lightning activity was reported during only twenty months. In both February 1989 and December 1989 no strikes were recorded for the study area. Despite the fact that in 1990 data were only available until October, the total number of strikes was considerably higher in 1990 (25,549 strikes) than in 1989 (22,168 strikes) (Figure 2).

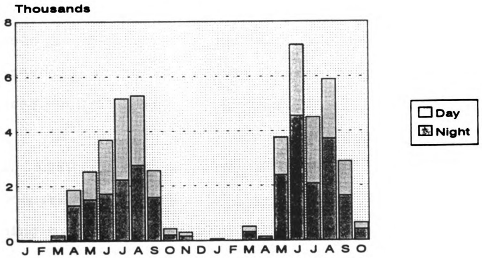

Fig. 2. Total Number of Nighttime and Daytime Flashes.

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The annual distribution of lightning strikes is in general agreement with other studies (e.g. Orville et al. 1987). As expected, a summer maximum in lightning frequency is evident, followed by a rapid decrease during autumn and a frequency minimum in the winter months (Figure 2). Bear in mind, that no information was available for November and December 1990.

Significant variations in lightning frequency are evident between 1989 and 1990. While the period of enhanced lightning activity ends abruptly in September in both years, the start of the enhanced lightning period varies considerably. In 1989, the period of increased lightning activity lasts from April through September; a steady increase in lightning activity is evident from April to August followed by a marked decrease toward September. Compared to 1989, 1990 has a shorter period of increased lightning activity starting in May and continuing until September. The frequency of lightning activity in 1990 does not increase steadily at the beginning of the period; rather, lightning frequency decreases in April after higher March values.

In addition, the monthly occurrences of lightning events in 1990 do not display as smooth a frequency curve as compared to 1989. Note the increase in the number of lightning events[1] in May 1990 after considerably lower April values. In fact, the number of occurrences in May 1990 exceeds

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1 Lightning event is used synonymously with cloud-to-ground flash or strike throughout the thesis.

those reported in June 1989. Two pronounced peaks in the 1990 frequency distribution, evident in June and August, are separated by July values that were lower than those recorded the previous year.

The higher number of strikes and the uneven distribution of occurrences in 1990 cannot be explained by differences in the number of days with lightning occurrences between the two years (Table 1).

Table 1.--Annual Distribution of Lightning Events and Lightning Days

	1989			1990		
Month	Lightning Events	Lightning Days	Events per Lightning Day	Lightning Events	Lightning Days	Events per lightning Day
Jan	37	6	6.17	62	8	7.75
Feb	--	--	--	4	3	1.34
Mar	211	12	17.58	513	10	51.30
Apr	1869	17	109.94	143	14	10.21
May	2539	24	105.79	3764	29	129.79
Jun	3688	29	127.17	7148	30	238.26
Jul	5192	31	167.48	4500	30	150.00
Aug	5303	30	176.77	5888	28	210.29
Sep	2575	18	143.06	2882	28	102.93
Oct	445	17	26.18	645	12	53.75
Nov	309	9	34.34			
Dec	--	--	--			

The total number of lightning days is almost identical in both years with 193 lightning days in 1989 and 192 days with lightning occurrences in 1990. However, the comparable months of both years show remarkable differences in the number of lightning events per lightning day. The ratio of lightning events per lightning day is considerably higher in 1990. For example, April 1990, has almost the same number of lightning days as April 1989, but the lightning events of April 1989 amount to less than one tenth of the number of lightning strikes of April 1989. Also, June 1990 recorded only one more day of lightning activity than June 1989 but 3500 more occurrences of lightning strikes. In August 1990 a larger number of strikes was recorded on fewer days than in August 1989.

The higher number of strikes per lightning day in 1990 is likely a result of different characteristics of the lightning-producing storm systems. The difference in the total number of events may result from differences in the areal extent of storm systems in 1989 and 1990. Storms that cover larger areas and are long-lived most likely have considerably higher flash totals than small, short-lived storms. Maier and Krider (1982), for example, reported that severe thunderstorm systems in the Great Plains were slow moving, well-organized structures with fairly high flash-density rates. Therefore, a possible cause of the discrepancy between the two years is a higher flash-density rate[2] due to major storm events in 1990. A few major storm systems can produce a high percentage of the annual cloud-to-ground lightning receipts in an area. A future research goal in this context is to determine if the recorded ground flashes during seasons and

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[2] Flash-density rate shall here be defined as the receipt of ground flashes in a unit area per unit time.

years of greater activity result from a few major storm events or if they are caused by an increased number of smaller individual thunderstorm cells during those seasons.

Time of Day of Lightning Activity

To assist in the initial investigation of the diurnal variability of lightning activity, CG strikes were first assigned to one of two broad periods, 0000-1200 GMT (nighttime events) and 1200-2400 GMT (daytime events). Both 1989 and 1990 display a higher total number of nighttime events than daytime events for the entire study area (Figure 2).

While there is a general tendency for a larger ground flash occurrence at night, for some months the maximum lightning activity occurred during the day. The likelihood of a daytime maximum is greater during warm season months. July, for example, experienced a daytime maximum in lightning activity during both years (Table 2). In addition, more ground flashes during the day than at night were reported during June, 1989; October, 1989 and April, 1990.

Table 2.--Nighttime Events as Percentages of the Monthly CG Totals

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
1989	51	--	61	70	60	47	43	52	62	49	53
1990	77	50	62	38	64	64	46	63	57	65	--

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The larger number of lightning events in 1990 may be related to the time of day of lightning occurrence. Note that in 1989 53 percent of the total number of CGs occurred at night, whereas in 1990 60 percent of the recorded lightning strikes were nighttime events. Note also that the warm season months of May through August, 1990 (except for July) display pronounced nighttime frequency maxima. In contrast, the small number of events of April 1990 compared to April 1989, were associated with a daytime frequency maximum. One can speculate that nighttime events either have higher flash densities or larger areal extent or are longer duration events compared to daytime storms.

Summary

The annual and diurnal variation of lightning frequency during January, 1989 through October, 1990 was examined. Lightning activity was most common in the summer months with the monthly frequencies varying considerably between the two years. The number of lightning days did not show much variation between years although the number of days varied significantly between months. Lightning is more likely to occur on a particular day during May through September when lightning activity was reported somewhere in the study area on almost every day of the month. A relationship between the time of day of lightning events and the frequency of strikes was proposed. The larger frequency during 1990 is suspected to be a consequence of the different areal extent, per

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persistence, and flash density of nocturnal versus daytime convective systems.

CHAPTER 3
RETURN STROKES AND AMPLITUDE

Methodology

The previous chapter examined the frequency of lightning activity separately for each month of the study period in order to better illustrate the large monthly and annual variation in lightning activity. In this chapter, the return stroke and amplitude characteristics of Great Lakes lightning months are discussed by individual month and by each month of the two year period combined. This was done in the hope of better identifying variations in these two lightning properties. Due to the lack of data for November and December 1990, only those months for 1989 were used.

Return stroke and amplitude characteristics have previously been recognized to vary with different stages of storm systems. Orville (1987, personal comment in Stolzenburg, 1990), for example, had reported an inverse relationship between the rate of negative cloud-to-ground lightning and mean peak currents. For mesoscale systems, on the other hand, Goodman and MacGorman (1986) had noted the correspondence of the most active lightning period with the period of the highest number of return strokes per flash.

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For the analysis of any temporal trends in return stroke and amplitude characteristics, five-minute maxima were employed. Five-minute maximum values have previously been used by Lopez and Holle (1986) to examine flash density rates. The analysis of five-minute intervals has the advantage that a fairly high degree of diurnal variability is preserved. For this thesis, maximum values of return strokes and amplitude were of special interest since strong cloud-to-ground lightning flashes produced by major thunderstorms pose the greatest danger to both property and human life.

Each successive five minute period of a month (00:05-00:10, 00:10-00:15, etc.) was examined for (1) the strike with the maximum number of return strokes, (2) the positive and the negative strike with the strongest amplitude.

In the analysis of five-minute maxima for return strokes no distinction was made with respect to polarity. An initial check of the data set had shown that it was in agreement with the findings by Orville et al. (1987) and Fuquay (1982) who proposed that most positive flashes only contained one return stroke. The frequency distributions of five-minute maxima of return strokes therefore describe the characteristics of negative flashes.

Positive and negative strikes possess different characteristics with respect to amplitude, however. Positive strikes had been reported to possess higher median amplitudes than negative strikes (Orville et al. 1987). In addition, Brook et al. (1982) found that in winter storms positive flashes can have peak currents about one order of magnitude greater than negative currents, thus being comparable to negative peak currents in summer storms. The different amplitude characteristics of positive and negative flashes required a distinction by polarity. Therefore, five-minute maxima amplitudes for negative and positive flashes were calculated and plotted separately. The resulting maximum values of all three variables were grouped into seven categories each. The plots for all three variables, return strokes, positive and negative amplitude, are placed alongside each other in the following figures to facilitate better comparison. The temporal characteristics of the number of return strokes will be discussed first, the discussion of monthly variation in strike amplitude is delayed until the end of this chapter.

A comparison of the frequency distributions of five-minute maxima of return strokes and negative and positive amplitude did not reveal any corresponding temporal patterns. While diurnal patterns were not very pronounced, an annual curve was evident in the five-minute maxima values for all three parameters.

Return Strokes Associated with Positive and Negative Flashes

The different characteristics of positive and negative strikes with respect to the number of return strokes have been noted by several authors. Rust et. al. (1981) and

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Fuquay (1982) noted that most positive CGs only contained one return stroke. Orville et al. (1987) found that the percentage of negative strikes with only one return stroke increased from 40 percent in the summer to 80 percent in January and then decreased again to less than 50 percent in the spring. For positive strikes they reported approximately 90 percent possessing only one return stroke throughout the year.

As expected, the number of return strokes varies markedly for positive and negative flashes in the Great Lakes region during 1989-1990 (Table 3). February 1990 is not taken into account due to the scarcity of recorded strikes.

Table 3.--Percentages of -CGs and +CGs with only one Return Stroke

	1989		1990	
Month	Percent +CG with one Return Stroke	Percent -CG with one Return Stroke	Percent +CG with one Return Stroke	Percent -CG with one Return Stroke
Jan	84	47	82	31
Feb	--	--	--	--
Mar	70	42	77	35
Apr	75	35	70	48
May	77	34	71	33
Jun	75	35	75	34
Jul	81	34	83	35
Aug	82	32	76	29
Sep	71	29	75	35
Oct	79	38	80	34
Nov	72	39		

The percentages of positive strikes with only one return stroke, which range from 70 percent to 84 percent of the total number of flashes throughout the year, are somewhat lower than the percentages reported by Orville et al (1987).

Also, unlike Orville et al.'s findings, the percentages of negative CGs with one return stroke do not display an annual curve in this study. The percentages ranged from 29 to 47 throughout the year, with the percentages for most months falling between 32 and 35. These values approximate the lower percentages reported by Orville et al. for the summer months.

The higher percentage of +CGs with only one return stroke is also reflected in the mean number of return strokes per flash (Table 4). Again, February 1990 was excluded due to the scarcity of recorded flashes. The average number of return strokes for +CG flashes ranged between 1.14 and 1.48 whereas corresponding numbers for -CG flashes were 2.1 and 3.04.

Table 4.--Mean Number of Return Strokes for Positive and Negative CG Flashes

	1989		1990	
Month	Mean Number +CG Return Strokes	Mean Number -CG Return Strokes	Mean Number +CG Return Strokes	Mean Number -CG Return Strokes
Jan	1.14	2.47	1.18	2.49
Feb	--	--	--	--
Mar	1.35	2.32	1.35	2.39
Apr	1.41	2.59	1.39	2.10
May	1.37	2.75	1.43	2.73
Jun	1.35	2.65	1.37	2.71
Jul	1.24	2.71	1.25	2.67
Aug	1.27	2.83	1.37	2.97
Sep	1.48	3.04	1.33	2.67
Oct	1.24	2.51	1.33	2.68
Nov	1.28	2.28		

Orville et al. (1987) reported the highest number of return strokes to be fourteen. In this study, the highest rec

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recorded number of return strokes associated with one ground flash is twenty-six. While the mean number of return strokes per flash is similar throughout the year, the maximum values increase during the warm months (Table 5). As expected, the maximum number of return strokes associated with negative CG flashes greatly exceeds that for positive strikes.

Table 5.--Maximum Number of Return Strokes for +CGs and -CGs

	1989		1990	
Month	Max. Number of Return Strokes +CG	Max. Number of Return Strokes -CG	Max. Number of Return Strokes +CG	Max. Number of Return Strokes -CG
Jan	2	9	2	6
Feb	--	--	2	2
Mar	3	12	4	11
Apr	4	15	3	9
May	8	13	7	13
Jun	6	16	5	16
Jul	5	15	4	15
Aug	5	15	7	26
Sep	11	15	4	16
Oct	3	10	5	14
Nov	2	10		

Monthly Variations in the Maximum Number of Return Strokes

The return strokes for both +CG flashes and -CG flashes for both years were combined for the analysis of the monthly variations in the number of return strokes per flash. Since the number of return strokes associated with negative flashes is considerably higher than that for positive flashes, the frequency distributions of five-minute maximum return stroke values, presented below, can be considered to reflect the characteristics of negative rather than positive strikes.

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Each five-minute interval per month (00:00-00:05 of April 1989 and 1990, etc.) was searched for the maximum number of return strokes within that interval, and the maximum value was assigned to one of seven equally spaced categories.

The monthly distributions of the five-minute maxima reveal some seasonal variations (Table 6). As shown before, the winter months had comparatively fewer return strokes. Generally, the number of return strokes was largest in the summer months. The absolute maximum number of return strokes (26) occurred in August 1990. Flashes with 26 return strokes were recorded both during the day and at night.

November through March had the largest portion of nighttime (0000-1200 GMT) five-minute periods with maxima falling in category I (0-3 return strokes). A shift toward a higher percentage of five-minute periods with at least four return strokes is evident in April and May. From May through September, the maximum number of return strokes for most of the five-minute periods fell into category III (8-11 return strokes). Note that during these months at least four return strokes were reported as maximum values for all the five-minute periods from 0000 to 1200 GMT. June and August were the only months when nocturnal lightning events with 16 to 20 return strokes were recorded. The largest number of return strokes per lightning event was reported in August. Note that August was the only month when the maximum number of return strokes for a five-minute period exceeded 24. Also, the

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largest number of five-minute periods with 8-12 (category II) and 12-16 (category IV) return strokes occurred in August.

The distribution of the maximum number of return strokes for daytime (1200-2400 GMT) five-minute periods varies somewhat from that for the nighttime period. Note that in each month, the maximum number of return strokes for at least one five-minute period was less than four, although a smaller number of return strokes per event was still most common in the cool months, as was the case for the nighttime period. As for the nighttime periods, the maximum number of return strokes per daytime five-minute interval is likely to fall between four and eight strokes in April and May. The period with the highest percentage of five-minute maximum values of return strokes falling within category III was shortened considerably (June-July) compared to nighttime activity (June-September). Only in June, August, and September did the maximum number of return strokes fall within category V (16-20 return strokes) for daytime five-minute periods, and August is the only month where more than 24 return strokes were recorded. However, the majority of five-minute nighttime periods during August reported maximum rates in categories III, whereas the majority of the August daytime periods recorded only 4-8 return strokes (category II).

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Table 6.--Five-minute Maxima of Return Strokes, 1989 and 1990.[3]

Nighttime (0000-1200 GMT)

Category (N of R.S.)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
I (<4)	42	2	68	14	4	--	--	--	--	50	85
II (4-8)	12	--	62	106	64	34	56	27	59	79	15
III (8-12	2	--	8	20	63	96	80	100	75	14	3
IV (12-16)	--	--	1	2	13	13	8	14	10	1	--
V (16-20)	--	--	--	--	--	1	--	1	--	--	--
VI (20-24)	--	--	--	--	--	--	--	--	--	--	--
VII (>24)	--	--	--	--	--	--	--	2	--	--	--

Daytime (1200-2400 GMT)

Category (N of R.S)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
I (<4)	22	2	99	44	1	3	1	1	3	73	71
II (4-8)	3	--	35	86	87	57	47	89	78	62	20
III (8-12)	--	--	7	13	49	75	82	42	55	9	3
IV (12-16)	--	--	--	1	7	7	14	8	7	--	--
V (16-20)	--	--	--	--	--	2	--	2	1	--	--
VI (20-24)	--	--	--	--	--	--	--	--	--	--	--
VII (>24)	--	--	--	--	--	--	--	2	--	--	--

[3] The frequency values indicate the number of five-minute periods with maximum reported number of return strokes in the respective category. Data for November are for 1989 only.

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Diurnal Variations in the Maximum Number of Return Strokes

The diurnal distribution of the maximum number of return strokes recorded during five-minute periods for January shows an increase in the frequency of return strokes during the evening hours (Figure 3a). More specifically, within the time period of greater lightning activity from approximately 2200 to 0800 GMT (1600-2000 CST), the highest values of return strokes per flash were observed in the late afternoon/early evening hours (2300-0200 GMT).

The four recorded strikes in February[4] do not reveal any diurnal pattern in the number of return strokes (Figure 4a).

In Figure 5a, note the general increase in the maximum number of return strokes per flash during March. The period with the largest value (12) of return strokes per flash was 0550 to 0555 GMT, although this value is the result of one singular, extreme strike. In general, the maximum number of return strokes is larger in the nighttime period. The number of return strokes per flash declines sharply during the early morning hours (approximately 0900 GMT) but increase once again in the early afternoon. A secondary maximum is evident at 2110 to 2115 GMT.

In April, large (≥14) return stroke values were recorded around 0700 and 0900 GMT (Figure 6a). Again, these lightning events are singular, unique occurrences, as the maximum number of return strokes for all other nighttime five-minute

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[4] February 1990 only; no flashes were recorded in February 1989.

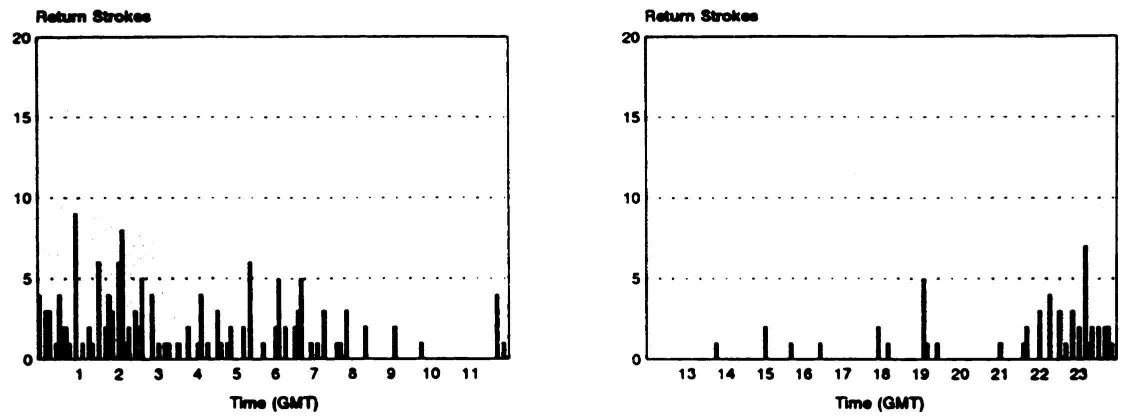

Fig. 3a. Five-minute Maxima of Return Strokes, January 1989 and 1990.

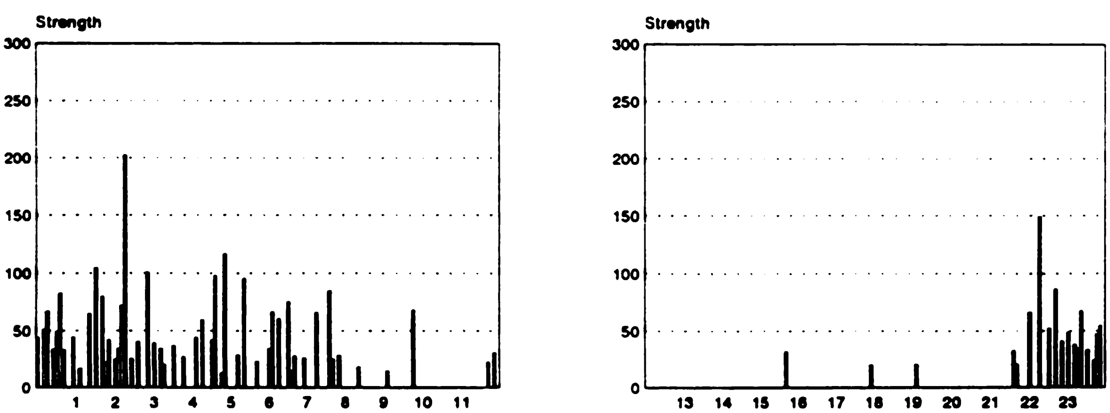

Fig. 3b. Five-minute Maxima of Amplitudes for Negative CG flashes, January 1989 and 1990.

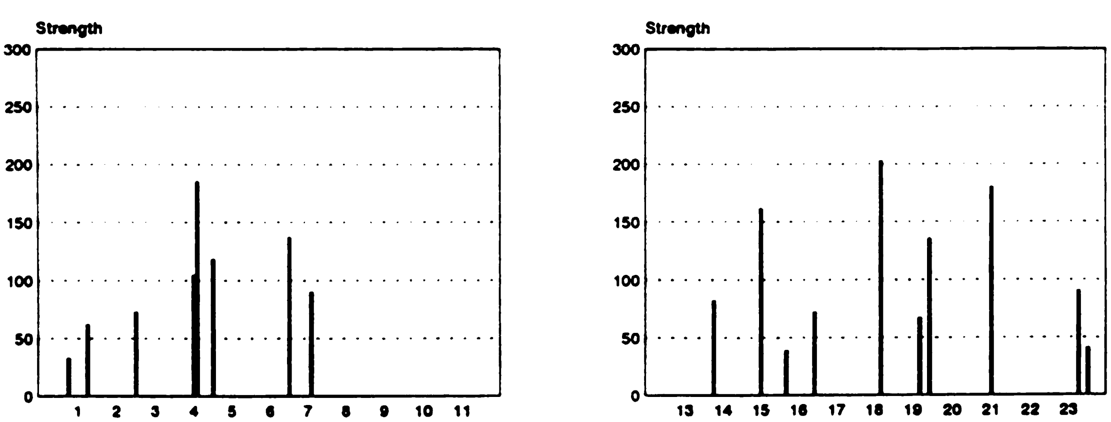

Fig. 3c. Five-minute Maxima of Amplitudes for Positive CG flashes, January 1989 and 1990.

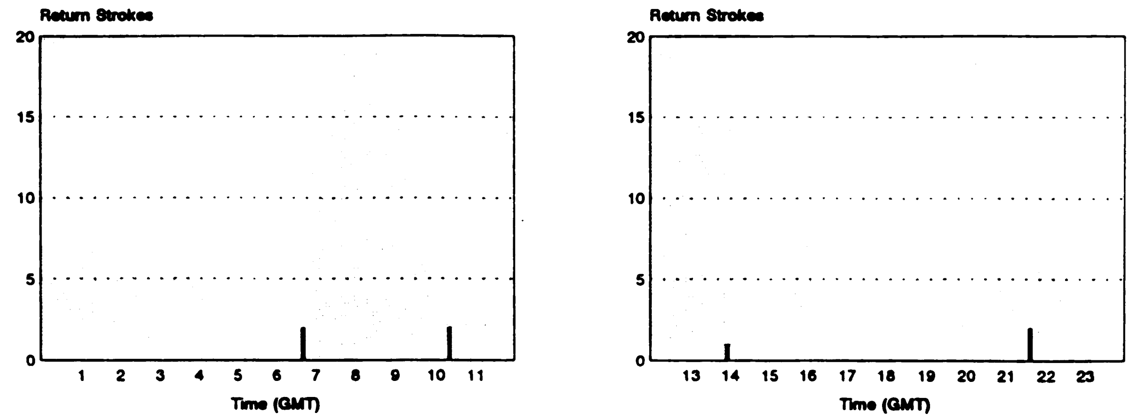

Fig. 4a. Five-minute Maxima of Return Strokes, February 1989 and 1990.

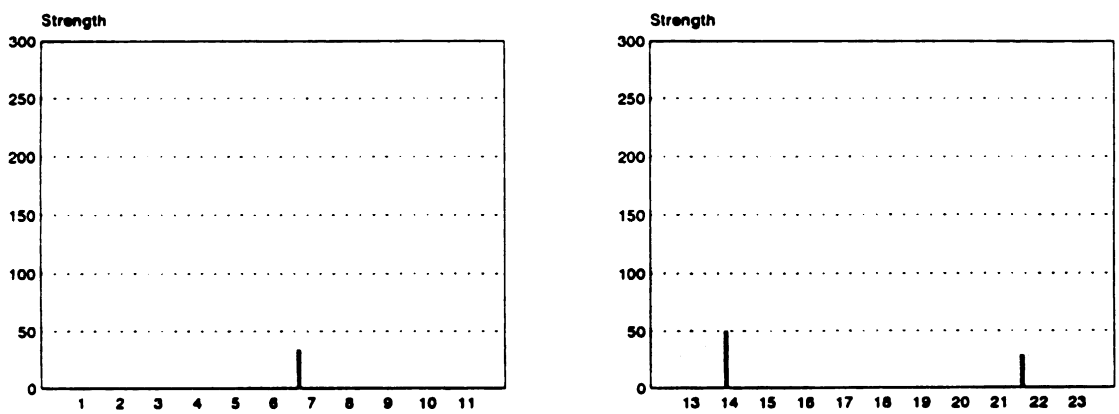

Fig. 4b. Five-minute Maxima of Amplitudes for Negative CG flashes, February 1989 and 1990.

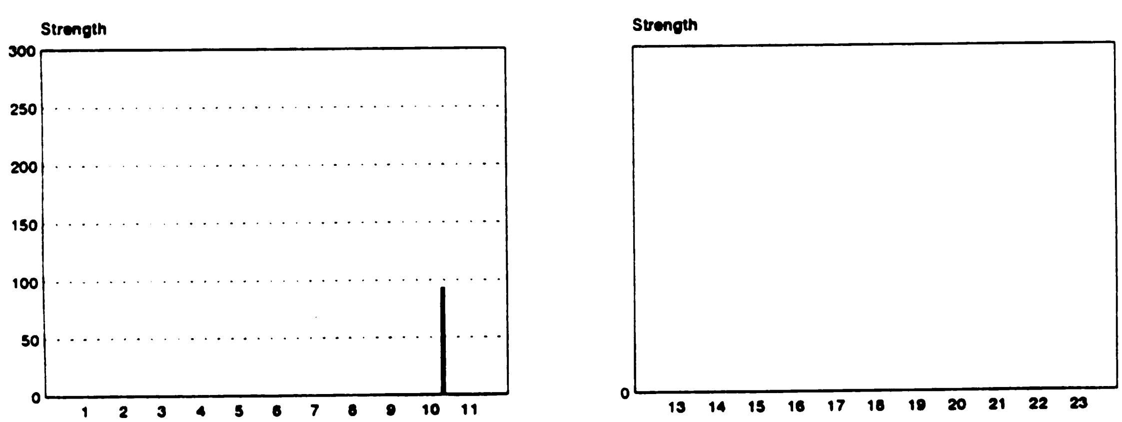

Fig. 4c. Five-minute Maxima of Amplitudes for Positive CG flashes, February 1989 and 1990.

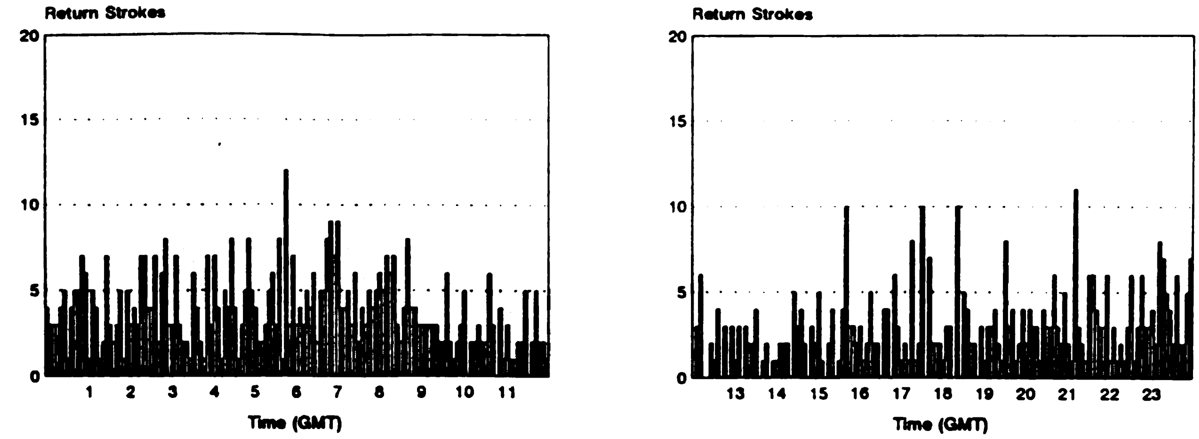

Fig. 5a. Five-minute Maxima of Return Strokes, March 1989 and 1990.

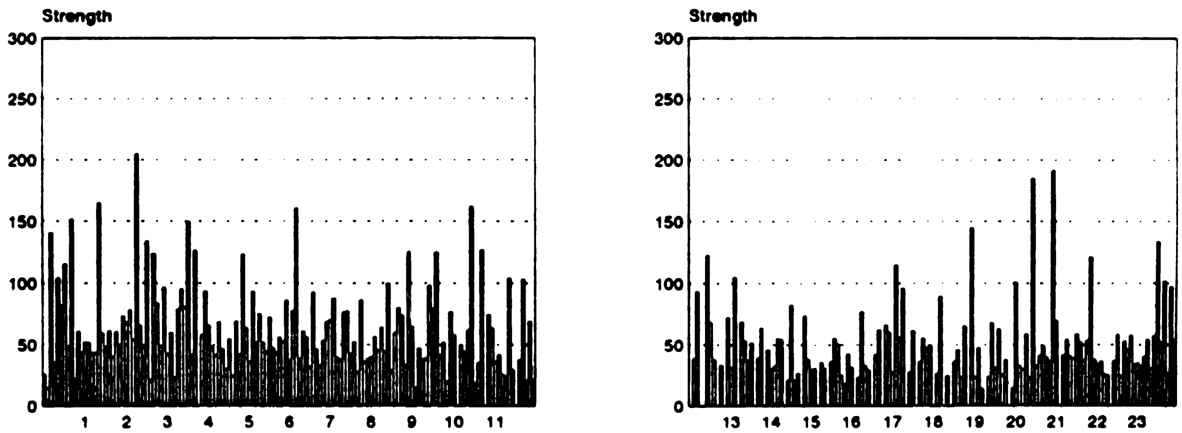

Fig. 5b. Five-minute Maxima of Amplitudes for Negative CG flashes, March 1989 and 1990.

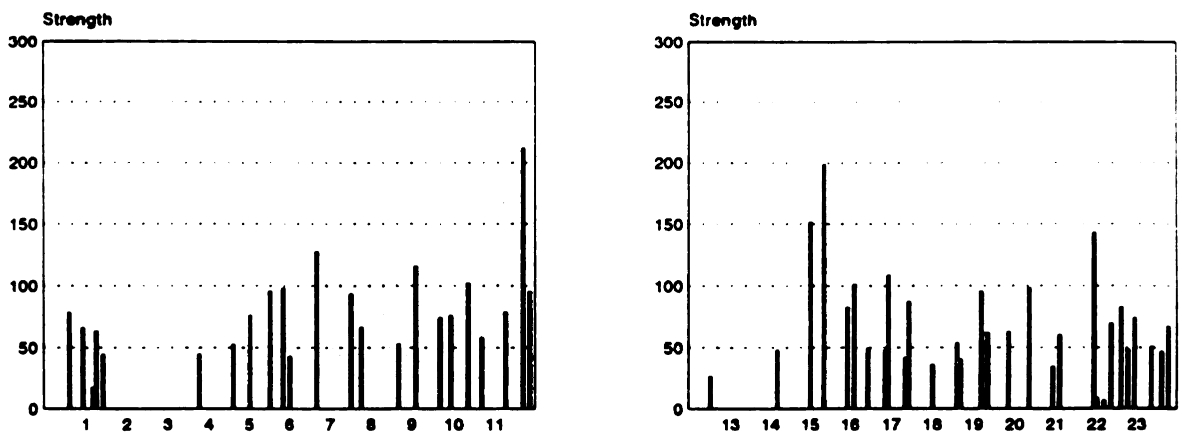

Fig. 5c. Five-minute Maxima of Amplitudes for Positive CG flashes, March 1989 and 1990.

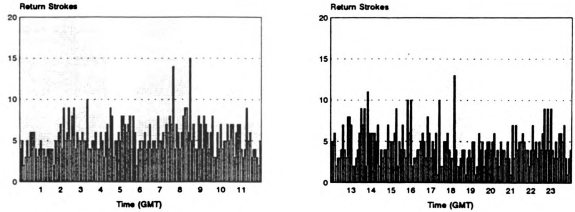

Fig. 6a. Five-minute Maxima of Return Strokes, April 1989 and 1990.

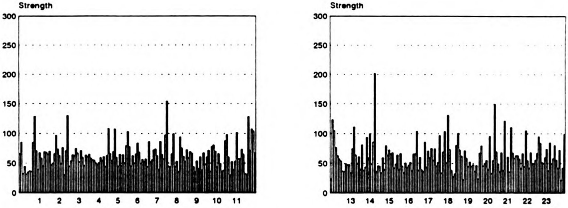

Fig. 6b. Five-minute Maxima of Amplitudes for Negative CG flashes, April 1989 and 1990.

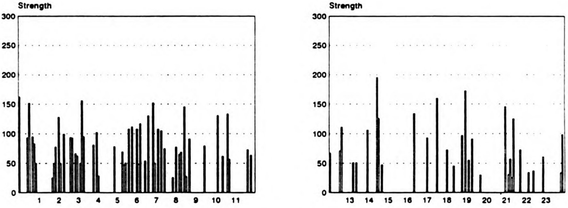

Fig. 6c. Five-minute Maxima of Amplitudes for Positive CG flashes, April 1989 and 1990.

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intervals falls well below 10 return strokes. For almost all five-minute periods at night between 0200 and 1100 GMT more than 5 return strokes per flash were reported, whereas 5 or fewer return strokes typically occurred from approximately 1830 to 2200 GMT (afternoon), and from 2300 to 0200 GMT (evening). In the morning hours (1300 to 1800 GMT) the number of return strokes for neighboring five-minute periods varied considerably.

Generally, the maximum number of return strokes per flash is larger in May compared to the previous months (Figure 7a). The maximum values differ little between nighttime five-minute intervals; the typical return stroke maxima fall between 6 and 10 strokes. Somewhat more variation is evident during the daytime hours. Daytime flashes are generally also associated with fewer return strokes.

During June, the maximum number of return strokes for nighttime periods varies little (Figure 8a); for most periods the maximum value was approximately 9 return strokes. As with May, more variation in the maximum number of return strokes is evident during the daytime hours with a number of periods reporting maximum values less than 5 strokes.

More variation between five-minute periods in the maximum number of return strokes per flash is evident in July (Figure 9a) compared to the two preceding months. The maximum number of return strokes for the majority of nighttime five-minute periods falls between 6 and 10 return strokes, whereas during the daytime the number of return strokes first

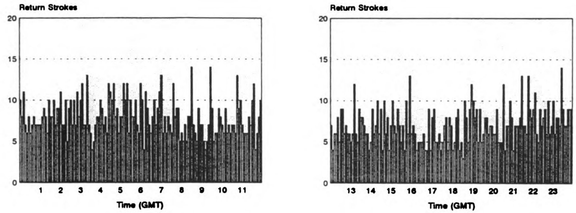

Fig. 7a. Five-minute Maxima of Return Strokes, May 1989 and 1990.

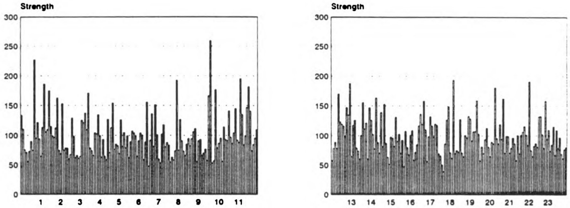

Fig. 7b. Five-minute Maxima of Amplitudes for Negative CG flashes, May 1989 and 1990.

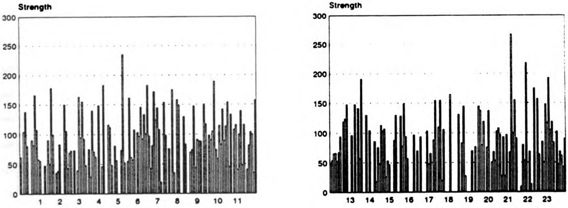

Fig. 7c. Five-minute Maxima of Amplitudes for Positive CG flashes, May 1989 and 1990.

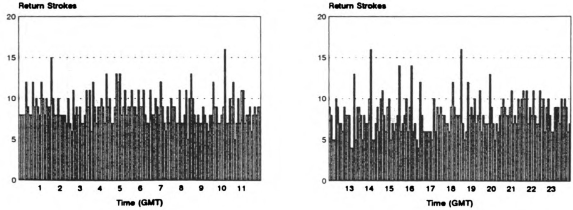

Fig. 8a. Five-minute Maxima of Return Strokes, June 1989 and 1990.

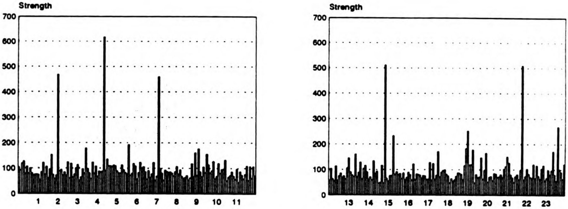

Fig. 8b. Five-minute Maxima of Amplitudes for Negative CG flashes, June 1989 and 1990.

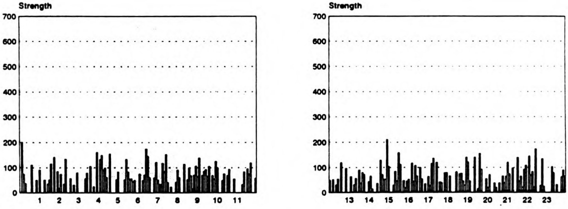

Fig. 8c. Five-minute Maxima of Amplitudes for Positive CG flashes, June 1989 and 1990.

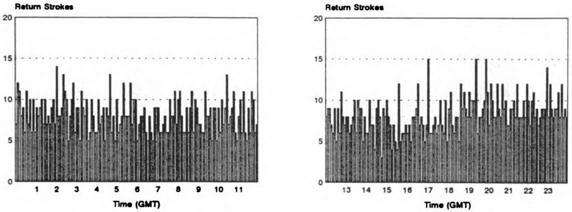

Fig. 9a. Five-minute Maxima of Return Strokes, July 1989 and 1990.

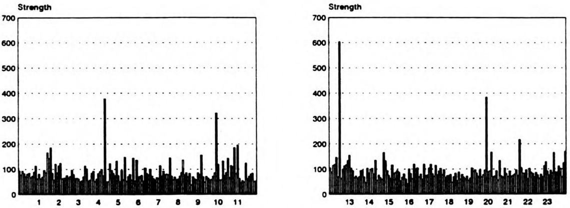

Fig. 9b. Five-minute Maxima of Amplitudes for Negative CG flashes, July 1989 and 1990.

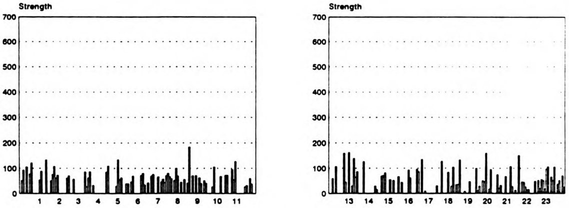

Fig. 9c. Five-minute Maxima of Amplitudes for Positive CG flashes, July 1989 and 1990.

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declines between 1400 and 1530 GMT and then increases from 1530 to 1930 GMT. At this time, the maximum number of return strokes is greater or equal 8 for most five-minute periods. The maximum number (15) of return strokes for the month of July was recorded three times between 1655 and 2000 GMT, and again was recorded in five-minute intervals with no equally high values preceding or following it.

August is the month with the highest number of return strokes recorded (Figure 10a; note the change in scale). Four five-minute periods during August 1989 and 1990 contained flashes with 26 return strokes. In general, the number of return strokes is higher for the nighttime compared to daytime flashes. From the early morning hours until the early afternoon (0900-2000 GMT), the maximum number of return strokes is lower than at other times of the day except for the five-minute maxima of 26 return strokes at around 2000 GMT. An interesting feature of the flashes with 26 return strokes is that the maximum number of return strokes for the preceding five-minute intervals is larger than the number of return strokes for other five-minute periods in that hour. This suggests that the storms or cells associated with these unusual flashes produced a number of flashes with exceptionally large numbers of return strokes. It remains to be tested if the flashes with 26 return strokes are singular features or if several flashes with extraordinarily high return stroke rates occurred in the same five-minute period.

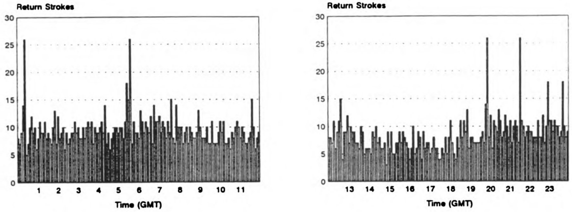

Fig. 10a. Five-minute Maxima of Return Strokes, August 1989 and 1990.

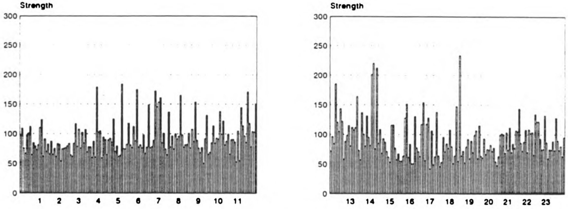

Fig. 10b. Five-minute Maxima of Amplitudes for Negative CG flashes, August 1989 and 1990.

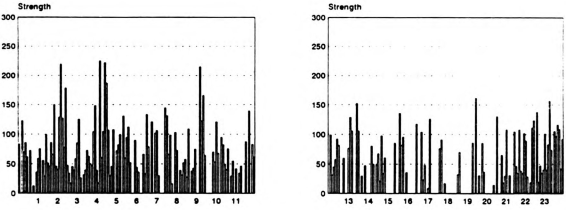

Fig. 10c. Five-minute Maxima of Amplitudes for Positive CG flashes, August 1989 and 1990.

In September, the maximum number of return strokes for nighttime flashes is generally higher than that for daytime flashes, despite the fact that the flash with the highest number of return strokes was recorded during the day (Figure 11a).

In October, a general drop in the number of return strokes as compared to the preceding months is apparent (Figure 12a). As for September, the nighttime five-minute maxima of return strokes are somewhat larger than those for the daytime periods. From slightly larger values between 0300 and 0900 GMT, the maximum number of return strokes decreases beginning at 0900 GMT and extending throughout the day until 2400 GMT. Note also that the number of return strokes varies considerably from period to period, particularly during the daytime hours.

In November, the maximum number of return strokes per flash generally is largest between 1100 and 1600 GMT, although the largest number of strokes was recorded for an individual strike during the night between 0215 and 0220 GMT (Figure 13a).

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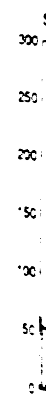

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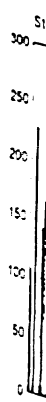

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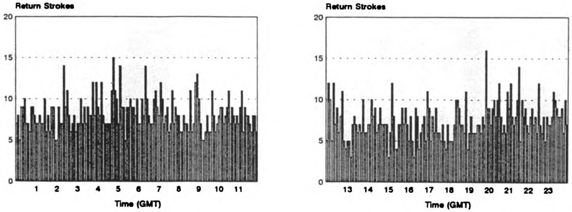

Fig. 11a. Five-minute Maxima of Return Strokes, September 1989 and 1990.

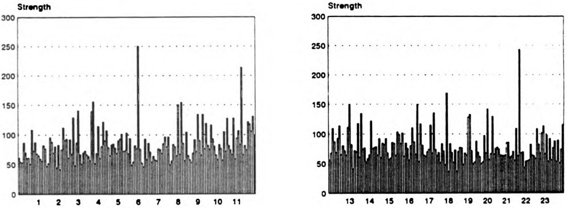

Fig. 11b. Five-minute Maxima of Amplitudes for Negative CG flashes, September 1989 and 1990.

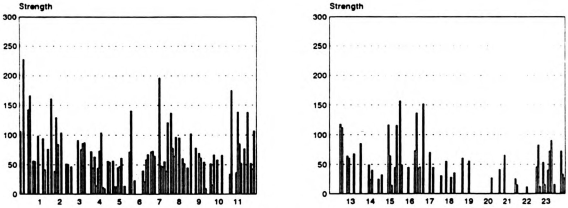

Fig. 11c. Five-minute Maxima of Amplitudes for Positive CG flashes, September 1989 and 1990.

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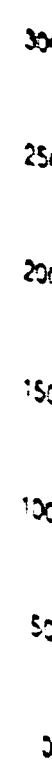

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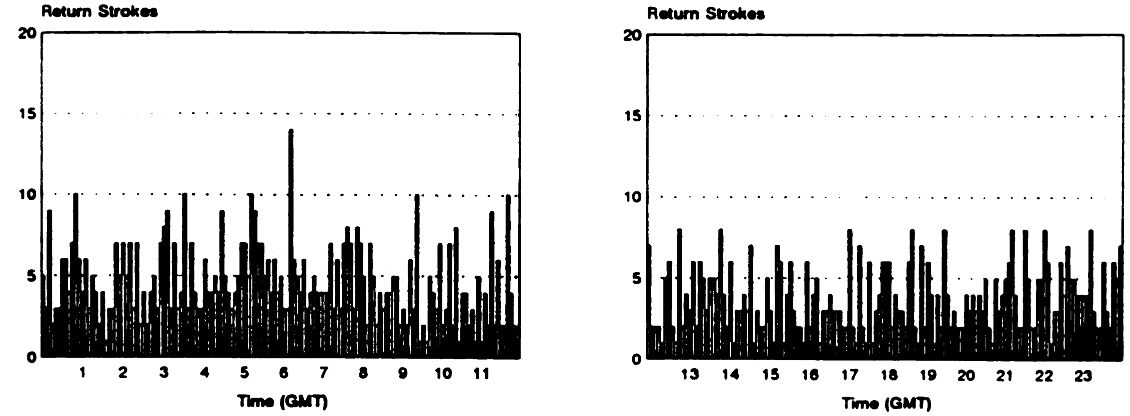

Fig. 12a. Five-minute Maxima of Return Strokes, October 1989 and 1990.

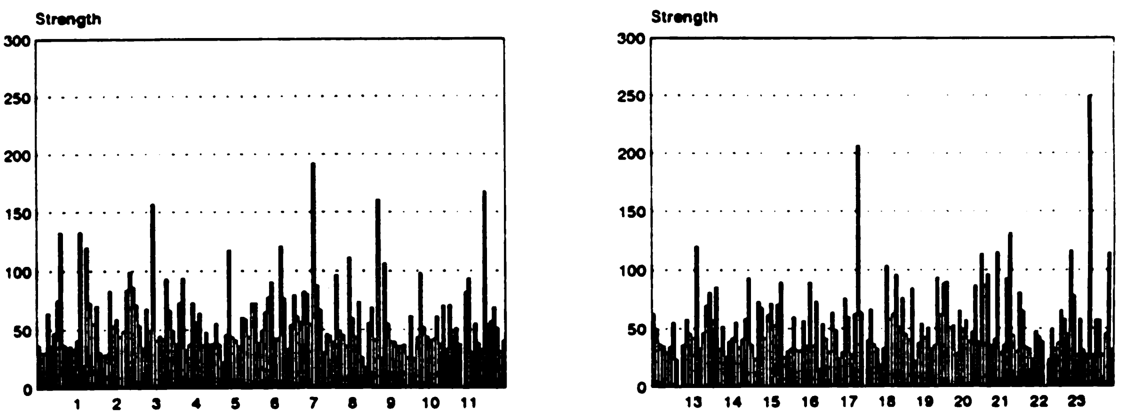

Fig. 12b. Five-minute Maxima of Amplitudes for Negative CG flashes, October 1989 and 1990.

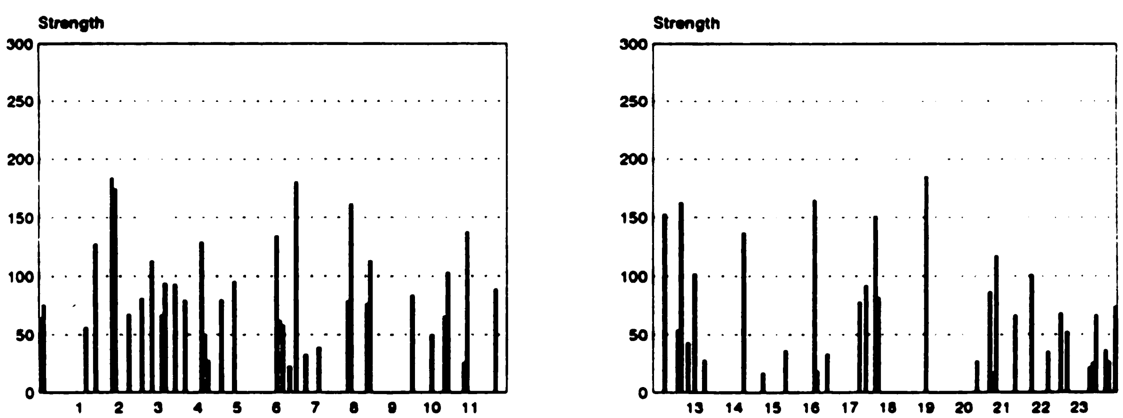

Fig. 12c. Five-minute Maxima of Amplitudes for Positive CG flashes, October 1989 and 1990.

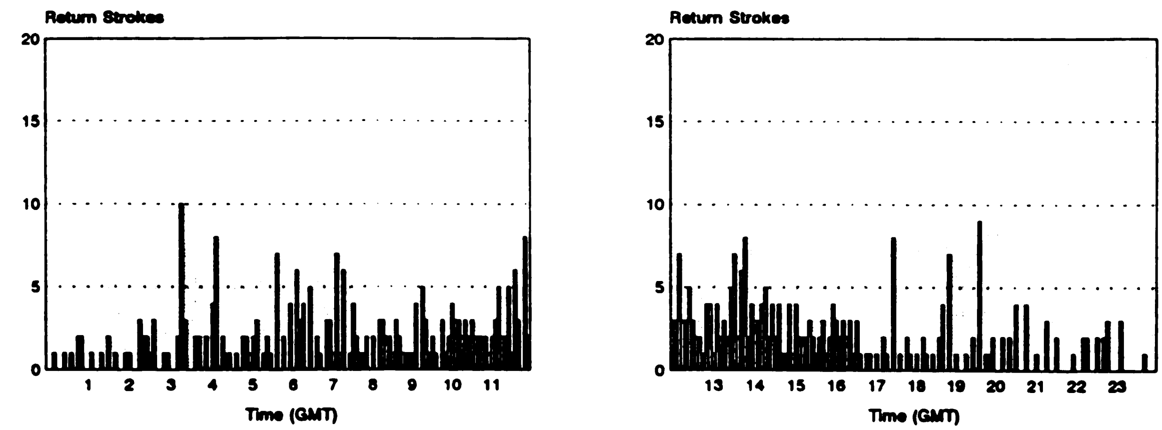

Fig. 13a. Five-minute Maxima of Return Strokes, November 1989 and 1990.

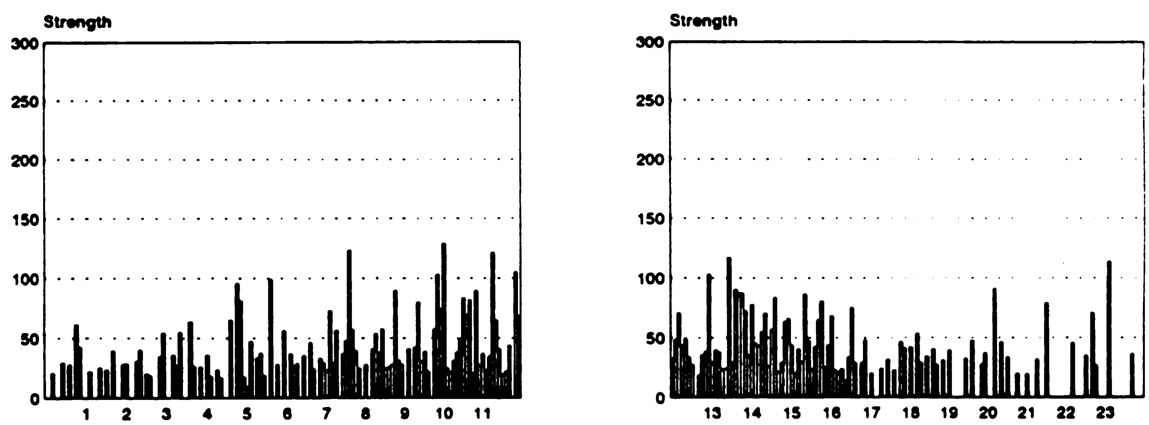

Fig. 13b. Five-minute Maxima of Amplitudes for Negative CG flashes, November 1989 and 1990.

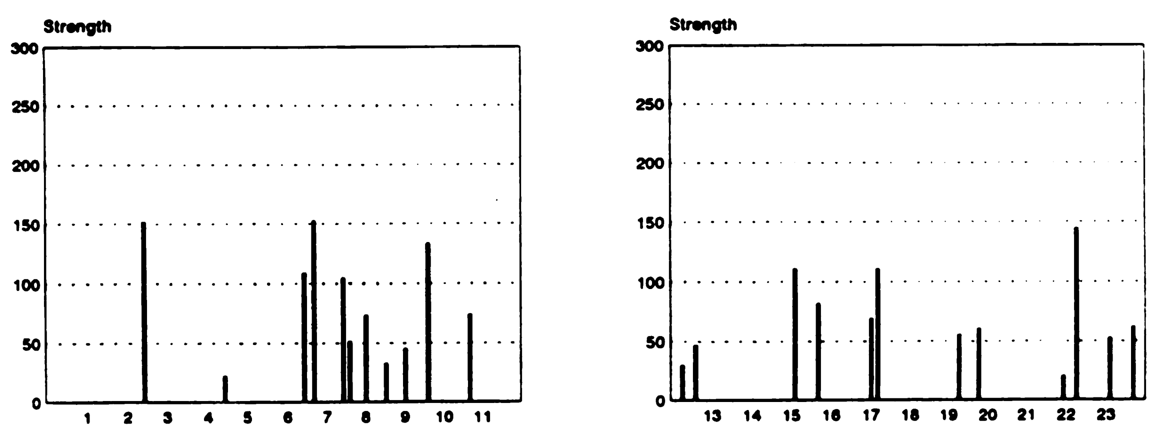

Fig. 13c. Five-minute Maxima of Amplitudes for Positive CG flashes, November 1989 and 1990.

Amplitude of Negative and Positive Strikes

The amplitude of lightning strikes has previously been examined with respect to polarity. Orville et al. (1987), for example, reported that the median peak current for positive strikes exceeded the median peak current for negative strikes. Amplitudes of >100 kA were observed with negative strikes, whereas amplitudes associated with positive strikes exceeded 200 kA. Also, the median peak current of both +CG and -CG increased in the winter season.

The results of this study are in general agreement with those of Orville et al. (1987). While the median values were not calculated, the mean values of amplitude for positive strikes are considerably higher than the mean values for negative strikes (Table 7).

Table 7.--Mean Amplitude of +CGs and -CGs

	1989		1990	
Month	Mean Amplitude +CG (in kA)	Mean Amplitude -CG (in kA)	Mean Amplitude +CG (in kA)	Mean Amplitude -CG (in kA)
Jan	100.4	45.5	106.2	47.4
Feb	--	--	93.0	37.0
Mar	79.9	45.4	67.6	39.9
Apr	83.1	35.1	76.7	41.6
May	77.8	36.1	84.7	40.5
Jun	68.4	35.2	64.9	33.4
Jul	63.3	35.7	56.5	33.0
Aug	60.4	35.8	65.6	34.1
Sep	57.5	36.4	66.7	34.3
Oct	81.1	38.1	73.3	36.0
Nov	75.7	39.4		

The largest mean amplitudes of both +CGs and -CGs occurred in January of both years. A slight decrease in amplitude toward summer was found for both positive and negative events followed by a slight increase toward autumn.

The previously described procedure for obtaining the five-minute maximum value of a variable was also employed in the analysis of the diurnal patterns of the amplitudes of ground flashes. A distinction, however, was made with respect to polarity. The occurrence of fewer positive strikes on one hand and the expected higher amplitude of positive strikes on the other hand required that the five-minute maximum values for amplitude be calculated separately for positive and negative strikes. In order to identify and compare the temporal characteristics of maximum amplitude, separate plots were made for negative and positive strikes. The same five-minute intervals employed for the analysis of the number of return strokes were used in the analysis of strike amplitude to allow for comparison of the diurnal properties of all three variables. Also, the distributions of maximum amplitude were summarized by grouping the five-minute periods into seven categories based on the maximum amplitude observed in that period. In the following discussion, February 1990 will not be included due to the scarcity of recorded flashes.

The distributions of the five-minute maxima of return strokes and negative and positive amplitude are not in agreement. Diurnal and monthly variations are much less pronounced for maximum amplitude compared to the number of return strokes. Nevertheless, some variations between negative and positive amplitude maxima are evident.

Monthly Variations in the Maximum Amplitudes for Positive and Negative Strikes

The distribution of five-minute maxima for negative and positive strikes reveals considerable variation between strikes of either polarity. While the largest amplitudes are associated with negative flashes, the likelihood of amplitudes exceeding 100 kA is greater for positive strikes than for negative strikes.

For the following discussion, the percentages of five-minute maxima for +CGs and -CGs (Table 9) were calculated for each category in addition to the number of five-minute intervals with maximum values in respective categories (Table 8) to facilitate comparison. Due to the limited length of the data set, not all five-minute periods contained lightning flashes. Also, comparatively fewer five-minute periods recorded positive than negative flashes. The conversion to percentages of five-minute periods helps detect annual trends in the maximum values of return strokes.

The maximum strength per five-minute period is generally higher during the warm months than during the cold months (Table 8). Amplitudes ≥250 kA during the night were only recorded for negative strikes. During the daytime hours one five-minute interval in May contained one or more positive flashes with amplitudes ≥250 kA in addition to six five-minute intervals in June and July with negative strike amplitudes ≥250 kA. Amplitudes exceeding 300 kA were observed only for negative flashes during both nighttime (0000-1200 GMT) and daytime hours (1200-2400 GMT) in June and July. These findings are somewhat surprising as positive flashes have generally been attributed larger amplitudes. Orville et al. (1987) for example only mention amplitudes in excess of 200 kA in relation to positive flashes.

During the nighttime hours, throughout the year, the majority of five-minute maxima reporting positive strikes fall into category II (50-100 kA) (Tables 8 and 9). In January, the maximum amplitudes for positive strikes are as likely to fall between 50-100 kA as between 100-150 kA (category III). In November, categories I, II, and III contain an equal number of five-minute intervals. The distribution of the maximum amplitude of negative strikes is somewhat different during the nighttime hours. From March to September, the highest percentage of five-minute intervals falls in category II. However, in the cold months (October through January), a higher percentage of five-minute periods are found in category I (<50 kA). Thus, for negative strikes peak amplitudes tend to be smaller during the cool season compared to the warm season.

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Table 8.--Five-minute Maxima of Amplitude for Positive and Negative Strikes, 1989 and 1990.[5]

Nighttime (0000-1200 GMT)

Category (in kA)		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
I	+	1		4	8	18	17	18	35	25	6	3
(<50)	-	32		60	39	1	1	4	--	7	73	71
II	+	3		15	28	44	47	43	45	44	19	3
(50-100)	-	15		62	95	89	99	110	104	109	59	24
III	+	3		3	12	32	18	8	23	12	7	3
(100-150)	-	3		13	9	39	35	23	30	23	7	5
IV	+	1		--	4	16	4	1	3	4	4	2
(150-200)	-	--		4	1	13	6	5	10	3	4	--
V	+	--		1	--	1	1	--	4	1	--	--
(200-250)	-	1		1	--	1	--	--	--	1	--	--
VI	+	--		--	--	--	--	--	--	--	--	--
(250-300)	-	--		--	--	1	--	--	--	1	--	--
VII	+	--		--	--	--	--	--	--	--	--	--
(>300)	-	--		--	--	--	3	2	--	--	--	--

Daytime (1200-2400 GMT)

Category (in kA)		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
I	+	2		12	8	13	32	30	32	27	13	3
(<50)	-	12		70	57	2	4	3	4	7	75	64
II	+	4		14	13	44	39	27	24	16	10	6
(50-100)	-	5		39	74	81	102	100	91	112	57	21
III	+	1		3	6	30	18	10	19	5	4	3
(100-150)	-	1		8	11	49	26	33	41	22	7	3
IV	+	2		2	3	8	3	4	3	2	5	--
(150-200)	-	--		2	--	12	7	5	4	2	0	--
V	+	1		--	--	1	1	--	--	--	--	--
(200-250)	-	--		--	1	--	1	1	4	1	2	--
VI	+	--		--	--	1	--	--	--	--	--	--
(250-300)	-	--		--	--	--	2	--	--	--	--	--
VII	+	--		--	--	--	--	--	--	--	--	--
(>300)	-	--		--	--	--	2	2	--	--	--	--

[5] Figures indicate the number of five-minute periods (out of 144) with positive/negative maxima in the respective categories.

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Table 9.--Percentages of Five-minute Maxima of Amplitude for +CGs and -CGs in each category, 1989 and 1990.[6]

Nighttime (0000-1200 GMT)

Category (in kA)		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
I	+	12		18	15	16	19	26	32	29	17	27
(<50)	-	63		43	27	1	1	3	--	5	51	71
II	+	38		65	54	40	54	61	41	51	53	27
(50-100)	-	29		44	66	61	69	76	72	75	41	24
III	+	38		13	23	29	21	11	21	14	19	27
(100-150)	-	6		9	6	27	24	16	21	16	5	5
IV	+	12		--	8	14	5	2	2	5	11	19
(150-200)	-	--		3	1	9	4	3	7	2	3	--
V	+	--		4	--	1	1	--	3	1	--	--
(200-250)	-	2		1	--	1	--	--	--	1	--	--
VI	+	--		--	--	--	--	--	--	--	--	--
(250-300)	-	--		--	--	1	--	--	--	1	--	--
VII	+	--		--	--	--	--	--	--	--	--	--
(>300)	-	--		--	--	--	2	2	--	--	--	--

Daytime (1200-2400 GMT)

Category (in kA)		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
I	+	20		39	27	14	35	42	41	54	41	25
(<50)	-	67		58	40	2	3	2	3	5	53	73
II	+	40		45	43	45	42	38	31	32	31	50
(50-100)	-	28		33	51	56	71	70	63	78	41	24
III	+	10		10	20	31	19	14	24	10	12	25
(100-150)	-	5		7	8	34	18	23	28	15	5	3
IV	+	20		6	10	8	3	6	4	4	16	--
(150-200)	-	--		2	--	8	5	3	3	1	0	--
V	+	10		--	--	1	1	--	--	--	--	--
(200-250)	-	--		--	1	--	1	1	3	1	1	--
VI	+	--		--	--	1	--	--	--	--	--	--
(250-300)	-	--		--	--	--	1	--	--	--	--	--
VII	+	--		--	--	--	--	--	--	--	--	--
(>300)	-	--		--	--	--	1	1	--	--	--	--

[6] Figures indicate the percentage of five-minute periods with positive/negative maxima in the respective categories.

During the daytime hours, a higher percentage of five-minute periods fall in category II than in any other category for lightning activity of either polarity during April-June. However, the maximum amplitude for five-minute intervals with positive strikes during July-October are more likely to be <50 kA. For negative strikes, March is the only month where the distribution of five-minute maximum amplitude values differs between the nighttime and daytime period. While during the night, the highest percentage of five-minute periods fall in category II, during the day the highest percentage of five-minute intervals fall in category I.

The distribution of the percentage of five-minute periods with maximum values ≥100 kA relative to the number of five-minute periods with recorded lightning activity reveals considerable differences of amplitude characteristics between positive and negative strikes (Table 10). During the night, between 13 and 50 percent of the five-minute periods with recorded lightning activity reported maximum amplitudes ≥100 kA for positive strikes whereas the comparable percentages for negative strikes lay between 5 and 38 percent. During the daytime period, between 14 and 41 percent of positive five-minute maximum amplitudes and between 3 and 42 percent of the negative five-minute maximum amplitudes were ≥100 kA.

The maximum amplitude values of negative strikes display an annual curve during both the nighttime and daytime hours. The percentage of five-minute intervals with maximum values exceeding 100 kA strongly increases in the warm months.

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These findings are contrary to Orville et al.'s (1987) who found the median amplitude to increase in the winter season. During the daytime, May through September is the season with a greater percentage of five-minute periods containing flashes ≥100 kA. There is no clear annual curve in the distribution of percentages of maximum amplitudes ≥100 kA for positive strikes. However, there seems to be a tendency for a greater likelihood for maximum values of positive strikes to exceed 100 kA in periods with positive lightning activity in the cold months (January and November). The maximum amplitude values for May are intriguing: Note that the likelihood of a five-minute period reporting maximum amplitudes ≥100 kA is considerably higher in May than in the surrounding months for both positive and negative strikes. The reasons for the seemingly stronger maximum amplitudes of lightning strikes in May remain to be clarified.

Table 10.--Percentages of Five-minute Periods with Maximum Amplitude ≥100 kA Relative to the Number of Five-minute Intervals with Recorded Lightning Activity for Positive and Negative Strikes.

	Nighttime +CGs	Nighttime -CGs	Daytime +CGs	Daytime -CGs
January	50%	8%	40%	5%
February	--	--	--	--
March	17%	13%	16%	9%
April	31%	7%	30%	9%
May	44%	38%	41%	42%
June	27%	30%	23%	26%
July	13%	21%	20%	28%
August	26%	28%	28%	34%
September	20%	20%	14%	17%
October	30%	8%	28%	6%
November	46%	5%	25%	3%

Diurnal Variations in the Maximum Amplitude of Positive and Negative Strikes

The diurnal variations of five-minute maxima of amplitude for negative and positive strikes are not as pronounced as for the number of return strokes. However, some differences between the distributions of negative and positive strikes can be detected.

The diurnal distribution of the maximum values of amplitude for negative (Figure 3b) and positive strikes (Figure 3c)[7] during January reveals diurnal characteristics for the strikes of different polarity. While negative cloud-to-ground lightning displays a strong temporal concentration between 2200 and 0800 GMT with peak activity at approximately 0200 GMT, positive CG flashes are spread out more evenly throughout the day and are considerably less frequent. However, the maximum amplitude of positive lightning strikes per five-minute period is considerably higher than for negative strikes. The difference in amplitude between positive and negative lightning strikes is especially pronounced during the day.

The February plot does not allow for extensive interpretation due to the scarcity of recorded strikes. Note the difference in amplitude between negative (Figure 4b) and positive strikes (Figure 4c), however.

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[7] Figures for maximum values of amplitude for negative and positive strikes are included previously in the section on maximum values of return strokes (pp. 39-52).

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Temporal preferences of negative and positive strikes are also evident in March. While negative lightning was recorded during almost all five-minute intervals during the night (0000-1200 GMT), some five-minute periods did not report negative CG strikes (Figure 5b). In general, the amplitude of negative lightning strikes is stronger during the night, especially between 0000 and 0600 GMT. Interestingly, the period with no positive lightning activity (0130-0330 GMT) occurs during the period of high amplitude negative strikes. Positive lightning (Figure 5c) is less frequent during the night than during the day. Maximum amplitudes of positive and negative flashes do not differ greatly between the daytime and nighttime period.

Generally, the five-minute maximum values of amplitude for negative CGs in April (Figure 6b) do not show as much diurnal variation as negative CGs in March. While the smallest maximum values in almost all five-minute periods are ≥50 kA, very few five-minute periods contain strikes that exceed 100 kA. Also, the highest values of maximum amplitude do not reach values for March. The number of five-minute periods with positive CGs during the nighttime period increases considerably from March to April (Figure 6c). Concentrations in activity are evident between 0000 and 0100 GMT, 0200 and 0400 GMT, and 0500 and 0900 GMT. During the day, fewer five-minute periods recorded positive lightning strikes in April than in March. The maximum amplitude per five-minute period for positive lightning is considerably

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larger in April than in March. Noteworthy is the absence of positive lightning between 1500 and 1600 GMT and 1930 and 2100 GMT.

Compared to April, the maximum amplitudes of both positive and negative strikes show a marked increase in May. The maximum amplitudes for negative strikes were somewhat larger during the nighttime period, especially between 0000 and 0200 GMT and between 1000 and 1100 GMT (Figure 7b). During both the nighttime (0000-1200 GMT) and daytime (1200-2400 GMT) periods, positive lightning flashes were recorded in almost all five-minute periods (Figure 7c). Positive lightning was most infrequent between 1500 and 1900 GMT. At the same time, the maximum amplitudes were generally lowest in the afternoon hours. Increased maximum amplitudes are evident between 2100 and 2400 GMT.

The June plots reveal surprisingly little diurnal variation in the maximum amplitude of negative strikes (Figure 8b; note the scale difference between May and June). Except for a few extraordinarily high values of amplitude, the five-minute maximum values are less than the May values. Slight increases in amplitude can be observed between 0900 and 1000 GMT, 1300 and 1500 GMT and around 1900 GMT. The diurnal variation is only slightly greater for positive strikes (Figure 8c).

The distribution of maximum amplitude per five-minute period for July is similar to that in June. There is very little diurnal variation in the maximum amplitude of negative strikes with only a few exceptionally large amplitudes

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(Figure 9b). During the night, periods of larger maximum amplitudes are evident between 0100-0200 GMT and 1000-1100 GMT. Positive strikes are more infrequent than in June and have smaller maximum amplitudes (Figure 9c). No diurnal variation in maximum amplitude of positive cloud-to-ground lightning can be detected.

In August some diurnal trends with respect to amplitudes of positive and negative CGs are evident. A period of higher maximum values of negative strikes is apparent between 0400 and 1400 GMT (Figure 10b). After 1400 GMT, there is an increase in the number of five-minute periods with maximum values of approximately 50 kA until 2100 GMT. An exception is the 1830-1835 GMT period when the highest amplitude for negative strikes in August was recorded. The maximum amplitudes for positive nighttime strikes are generally larger than those for negative strikes although positive strikes were not reported in all five-minute periods. Three time periods with strong positive amplitudes are evident: 0200-0230 GMT, 0400-0430 GMT, and 0900-0930 GMT. During the day, positive strikes were recorded in fewer five-minute periods. Positive lightning activity was especially infrequent between 1500 and 2100 GMT.

The tendency for positive lightning to be more infrequent during the day is continued in September. While no distinct diurnal distribution can be detected for negative strikes (Figure 11b), positive strikes are considerably more infrequent and of lower maximum amplitude during the day

(Figure 11c). Daytime positive lightning strikes occurred most frequently between 1200 and 1900 GMT with highest amplitudes being recorded between 1500 and 1700 GMT. The nighttime distribution reveals an absolute maximum in amplitude shortly after 0000 GMT. The maximum is succeeded by decreasing maximum amplitudes until 0500 GMT, after which five-minute maximum values of amplitude increase again until 0730 GMT. A drop in amplitude after 0730 is followed by higher values starting at approximately 1100 GMT.

October displays very little diurnal characteristics of amplitude. For negative strikes, the strongest amplitudes were observed during the daytime period (Figure 12b). Positive strikes were most frequent between 0100 and 0500 GMT (Figure 12c).

The negative flashes in November (Figure 13b) show a general increase in both the number of five-minute intervals with recorded lightning activity and the maximum values of amplitude from 0000-1200 GMT, after which the amplitude decreases again and lightning becomes increasingly less frequent. Contrary to that general picture, a few five-minute periods between 2000 and 2400 GMT stand out with relatively high amplitudes. The diurnal curve of negative amplitude values is not duplicated in the frequency distribution of five-minute maxima of positive CGs (Figure 13c). Apart from a slight concentration of positive lightning between 0600 and 1100 GMT, no diurnal trend is apparent. The amplitude of positive lightning during the day is generally lower than during the nig

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the night, although the number of occurrences of positive lightning strikes is small in November.

Summary

The data set was examined for annual and diurnal patterns of five-minute maximum values of amplitude and return strokes. No direct relationship between the peak current of flashes and the number of return strokes was detected. A systematic increase in the number of return strokes in summer, followed by a decrease in the cool season was identified. For maximum values of amplitude, an annual curve was evident as well. The strongest amplitudes were reported for negative flashes in June and July both during the day and at night. However, maximum amplitudes values of positive flashes were more likely to exceed 100 kA than those of negative flashes. With respect to amplitude, May takes on a special role. For both negative and positive strikes, the likelihood of maximum amplitudes to exceed 100 kA was higher than in the surrounding months.

CHAPTER 4

POLARITY

Monthly and Diurnal Variations

The total number of recorded positive lightning strikes during the study period amounted to 4 percent of the number of negative strikes. In general agreement with other studies (e.g. Orville et al. 1987), the percentage of positive strikes was higher in the winter months than in the summer months. Note in Table 11 the inverse relationship between the total number of events and the percentage of positive strikes. The smaller the total number of strikes per month, the higher the percentage of +CGs.

Table 11.--Total Number of Events and Percentages of +CGs 1989 and 1990

	1989		1990	
Month	Total Number of CGs	Positive Strikes (%)	Total Number of CGs	Positive Strikes (%)
January	37	18.92	62	17.74
February	--	--	4	25.00
March	211	8.06	513	8.38
April	1869	4.17	143	16.08
May	2539	4.41	3764	6.43
June	3688	2.14	7148	3.15
July	5192	1.75	4500	2.24
August	5303	3.43	5888	2.50
September	2575	4.16	2882	2.95
October	445	8.54	645	5.58
November	309	8.09		

Note especially the correspondence of a drop in lightning frequency from March to April 1990 with a considerable increase in the percentage of positive flashes (from 8.38 to 16.08 percent).

The inverse relationship between flash frequency and percent positive strikes holds up to a considerable degree on the diurnal scale as well (Table 12). With the exception of January 1989, August 1989, September 1989, and September 1990, the time of day of less lightning activity corresponds with higher percentages of positive strikes.

Table 12.--Nighttime/Daytime Total Number of Events and Percentage of Positive Flashes

	1989				1990			
	Nighttime		Daytime		Nighttime		Daytime	
Month	Total Events	+CGs (%)	Total Events	+CGs (%)	Total Events	+CGs (%)	Total Events	+CGs (%)
Jan	19	21%	18	17%	48	8%	14	17%
Feb	--	--	--	--	2	50%	2	50%
Mar	146	6%	65	12%	319	5%	194	14%
Apr	1304	4%	565	4%	54	20%	89	13%
May	1511	4%	1028	5%	2395	6%	1369	8%
Jun	1725	2%	1963	2%	4555	2%	2593	5%
Jul	2229	2%	2963	2%	2075	2%	2425	2%
Aug	2768	4%	2535	3%	3717	2%	2171	3%
Sep	1603	5%	972	3%	1633	3%	1249	2%
Oct	217	8%	228	9%	418	5%	227	6%
Nov	163	7%	146	9%				

The percentage of positive strikes in 1989 decreased from 21 percent at night and 17 percent during the day in January to 2 percent in the summer months for both nighttime and daytime period and then decreased again toward winter.

1990 also witnessed a general decrease in the percentage of positive strikes in the first half of the year with a subsequent increase in autumn. As mentioned previously, however, the percentage of positive strikes at night shows a considerable increase in April after lower values in March. The percentage decreased again in May and remained ≤5 percent into October. The percentages for January and February are unreliable due to the small number of events in those two months. A more systematic annual trend is evident for daytime positive strikes in 1990 with the lowest percentages evident in June through August. September shows a slight drop in the percentage of positive strikes. The inverse relationship between lightning frequency and positive strikes, especially in the summer months, still needs further clarification.

A possible reason for the relative increase in positive strikes in months with fewer events may be found in cloud characteristics. In the case of bipoles, negative strikes are believed to predominate in proximity to the deepest convection whereas positive strikes are likely found in stratiform precipitation regions (Engholm et al. 1990). Stolzenburg (1990) and Orville et al. (1988) found a higher occurrence of storms with bipolar patterns relative to the total number of storms in the winter months. In the winter months, the wind shear of storms is often sufficient to produce the necessary horizontal displacement between the center of positive charge and the negative charge center to generate a significant amount of positive ground flashes. A small scale investigation of the charge patterns during periods of increased numbers of positive strikes might provide some answers to the observed phenomenon.

A closer look at the temporal distribution of positive strikes in Table 13 reveals high monthly and annual variability in terms of the time of day of occurrence. The percentages of nighttime events among the positive strikes range from 45 to 72 percent in 1989 and from 35 to 65 percent in 1990. Thus the percentages of positive strikes occurring at night were generally higher in 1989 than in 1990. In 1989, January through April had a relative nighttime maximum of positive ground flashes. After May, a transition month with an equally high occurrence of positive strikes during the day and at night, most positive strikes were recorded during the daytime period in June and July. The relative maximum then shifted to the night again where it remained from August through September. In October and November, more positive strikes were recorded during the day than at night. Unlike 1989, early 1990 witnessed a relative daytime maximum of positive strikes from January through April. It was followed by a nighttime maximum in May. Relative daytime maxima in June and July were followed by relative nighttime maxima in August and September. The daytime maximum evident during the cool months of 1989 was not present during 1990. October, for example, recorded a nighttime maximum. Due to lack of data, November 1990 could not be included in this comparison.

Table 13.--Nighttime (0000-1200 GMT) and Daytime (1200-2400 GMT) Occurrence of Positive Strikes.

	1989				1990			
Month	Nighttime		Daytime		Nighttime		Daytime	
Jan	4	(57%)	3	(43%)	4	(36%)	7	(64%)
Feb	-	--	--	--	1	(100%)	0	(0%)
Mar	9	(53%)	8	(47%)	15	(35%)	28	(65%)
Apr	54	(69%)	24	(31%)	11	(48%)	12	(52%)
May	56	(50%)	56	(50%)	139	(57%)	103	(43%)
Jun	39	(49%)	41	(51%)	105	(47%)	120	(53%)
Jul	44	(48%)	48	(52%)	46	(46%)	55	(54%)
Aug	112	(62%)	70	(38%)	82	(56%)	65	(44%)
Sep	77	(72%)	30	(28%)	55	(65%)	30	(35%)
Oct	17	(45%)	21	(55%)	22	(61%)	14	(39%)
Nov	12	(48%)	13	(52%)				

Polarity in Relation to Return Strokes and Amplitude

The average number of return strokes is higher for negative strikes than for positive strikes (Tables 3-4). Note also that the maximum number of return strokes of -CGs is considerably higher than that of +CGs. (Table 5). The maximum number of return strokes for both positive and negative flashes was larger for summertime lightning flashes compared to winter flashes. The percentage of events with only one return stroke is largest in winter for both -CG and +CG flashes.

The interrelationships reflected here between polarity and mean flash amplitude support Orville et al's (1987) findings. Orville et al. reported a median amplitude of 30 kA for negative strikes and 45kA for positive flashes. As shown in Table 7, the mean amplitude of +CG strikes is considerably higher than that of -CG flashes. However, while the mean amplitude values are highest in the winter months for both positive and negative flashes, the maximum values of amplitude per five-minute period occurred in June and July for negative flashes. Amplitudes >300kA were recorded for negative flashes during both the daytime and nighttime period in June and July (Tables 8 and 9). The maximum values for positive strikes are considerably lower. The highest values of amplitude (200-250kA) were recorded during the nighttime period in March, May, June, August and September and during the day in May and June. However, except during warm months (nighttime period in June and July and daytime period in July and August), the percentage of five-minute periods with maximum amplitude values ≥100kA was greater for positive strikes than for negative strikes (Table 10).

Summary

The data set was examined for temporal variations in the distribution of the frequency and characteristics of positive and negative strikes. Contrary to other studies, the largest amplitudes were reported in association with negative strikes in June and July. Also, positive strikes did not display a general increase in maximum values of amplitude in winter as expected. The percentage of five-minute periods with maximum amplitude values ≥100kA was greater for positive strikes than for negative flashes.

An additional interesting finding was the inverse relationship between the number of positive strikes and the total number of ground flashes on both a diurnal and annual scale. The relationship between cloud characteristics and flash polarity was suggested as a possible cause for the relative increase in positive strikes during periods with less lightning activity.

PART TWO

SPATIAL ANALYSIS

CHAPTER 5

SPATIAL ANALYSIS OF LIGHTNING ACTIVITY: PROCEDURES AND METHODOLOGY

Objectives

The major objective of the second part of the study was the analysis of the spatial distribution of lightning strikes with respect to time of day. A combination of spatial and temporal analyses was chosen to achieve this objective. Since this study was designed as a preliminary examination of a SUNYA lightning data set with the overall goal of interrelating the timing and locations of lightning activity to precipitation activity in the study region, the spatial component of the analysis was structured in a way to allow for the comparison of precipitation and lightning data. A grid system commonly used for radar data of precipitation was thus chosen for the analysis (MDR grid). The special location of the study area in the transition zone between nocturnal and afternoon regimes of precipitation and thunderstorm activity has previously been noted. To account for the different diurnal characteristics, the study area was divided into two equal halves and frequency curves of lightning activity were calculated separately for the eastern and western portions of the study area.

A second objective was incorporated in the spatial-temporal analysis: the distinction of lightning events by polarity. While the spatial discrimination of positive and negative cloud-to-ground lightning strikes were not undertaken in this thesis, a distinction with respect to polarity was made in the hourly frequency distributions.

A final objective was the development and testing of computer software for spatial analysis and graphic output of lightning observations.

The Analysis Grid

The data set for the previously-discussed temporal analysis of lightning activity in the first part of the study included all observations located in an area bounded by 38.3°N and 47.1°N and by 78.9°W and 96.7°W. However, for the spatial analysis of lightning activity, observations from only a subset of this area were utilized. The primary motivation for reducing the analysis area was to better coordinate this project with a second project concerning the spatial variations of convection in the Great Lakes region currently underway in the Department of Geography at Michigan State University.

This second study is employing manually digitized radar (MDR) intensities to characterize convection. MDR reports are for grid cells within a regular rectangular matrix superimposed on a polar stereographic projection. For the conterminous United States the matrix extends 113 cells in an east-west direction and runs 89 cells in a north-south. Grid spacing is 47.625 km at 60°N latitude. The principal investigators chose a 32x19 cell subgrid for the analysis of radar observations in the Great Lakes region. This subgrid is composed of east-west cells 57 through 88 and south cells 48 through 66 from the larger MDR grid. This same subgrid is used for the present study of lightning activity in order to share analysis and plotting software. A future goal, although not undertaken in this thesis, is the study of the relationship between lightning activity and radar echo strength in the Great Lakes region.

Lightning locations in latitude and longitude were translated to the MDR grid cells using software programs provided by the National Meteorological Center. All strikes that fell into a particular grid cell were assigned the X and Y coordinates for that cell. The center of the grid cell was taken as the reference point when assigning lightning observations rather than the grid intersection points.

The relative size of the data set used for the spatial analysis of lightning activity compared to the data set used for the first part of the study is shown for each month in Figure 14.

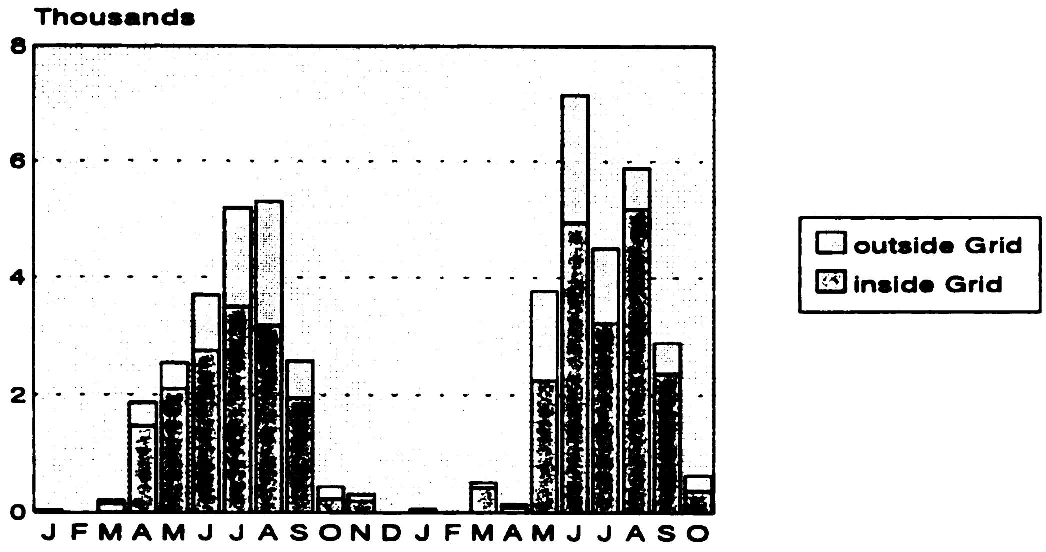

Fig. 14. Monthly Distribution of Strikes inside and outside the 32-by-19 MDR grid.

Calculation of Grid Cell Frequencies and Mapping

The calculation of lightning frequency and density per grid cell for subsequent display was performed using FORTRAN programs (see Appendix for example programs). Atlas Mapmaker was employed in the analysis of grid frequencies and to map grid cell values. The grid basemap and the state outlines for the following figures were entered as boundary files in Atlas Mapmaker, into which the frequency values for each cell were read. In order to make the following figures easily comparable, the numerical ranges for categories on each of the monthly maps were standardized.

Due to the low frequency of lightning strikes in the winter and several of the transitional months, only months with "increased lightning activity", as previously defined

(p. 23), were plotted. These months include April through September of 1989 and May through September 1990.

Temporal Component of the Spatial Analysis

To examine the diurnal characteristics of the region, daytime hours (1200-2400 GMT) and nighttime hours (0000-1200 GMT) were analyzed separately. In order to investigate any differences in the frequency and timing of lightning activity in the eastern and western parts of the study area, the study area was divided into two equal halves. Daytime and nighttime hourly frequencies were calculated separately for both regions with FORTRAN programs. For graphic output Harvard Graphics was employed. The wide range of frequency values over the course of the examined months required some adjustment of the vertical scale. Note that the vertical scale is 100 strikes per hour in April, 160 flashes in May and September; June through August have vertical scales of 300 strikes per hour.

CHAPTER 6

SPATIAL ANALYSIS OF LIGHTNING ACTIVITY: RESULTS

In general, lightning activity decreases from south to north across the MDR subgrid. Note in Figure 15 that all grid cells except for a few along the extreme edges of the analysis area reported lightning strikes from January 1989 to October 1990. The lack of data in the extreme corners of the analysis area may indicate that these MDR grid cells lie outside the effective range of the SUNYA lightning detection network.

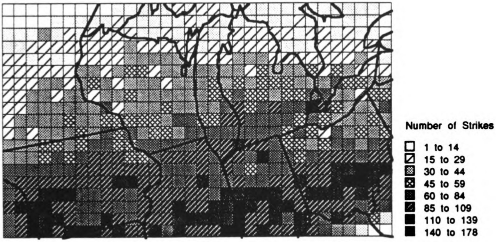

Fig. 15. Total Number of Cloud-to-Ground Strikes for the Study Period

Two axes of somewhat increased lightning activity can be observed. The first is oriented in southwest-northeast direction and extends from Iowa into lower Michigan. The second has a similar orientation and extends from southern Indiana into Ohio. The highest cumulative lightning frequencies with 140 strikes or more per cell during the study period are found in southwestern Iowa, along the Indiana-Illinois border, and in Ohio. The highest number of strikes that was reported for a single cell was 178.

Monthly Variations in Daytime and Nighttime Lightning Activity

The spatial analysis by month was conducted for nighttime (0000-1200 GMT) and daytime (1200-2400 GMT) hours separately. For each monthly nighttime/daytime period, the cumulative number of lightning events and the number of lightning days per grid cell were plotted. In addition, the spatial analysis is augmented by the calculation of hourly frequencies of ground strikes accumulated over the entire month for the eastern and western halves of the study region. Variations in the timing and frequency of lightning activity in the eastern and western portions of the study area are evident. These variations are presented in detail in the following discussion.

April 1989

In April 1989, a considerably higher number of strikes was recorded during the night (0000-1200 GMT) than during the day over the entire study area (1075 flashes compared to 396 strikes). Note in Figure 16a that the flash density during the night is also larger than the daytime equivalent (Figure 17a). During the night, a maximum of 34 CG strikes per grid cell is found along the Ohio/Indiana border embedded in a band of relatively high frequencies stretching from Illinois to Ohio (Figure 16a). A secondary frequency maximum can be identified from the southern portion of Lake Michigan through southern Michigan to Ohio.

In general, lightning activity was infrequent during all daytime periods of April 1989. Only 396 strikes were reported for the grid system and the maximum number of lightning events per individual grid cell was fourteen strikes. As Figure 17a shows, the area of maximum frequency extends from Ohio into West Virginia. A secondary frequency maximum can be observed in Iowa and Minnesota. Similar distinct maxima are not evident in the plot of lightning days in April 1989 (Figures 17b) suggesting that the patterns of daytime lightning events likely result from only one or two storm events with fairly large lightning densities. Or in other words, the poor correspondence between the number of strikes per grid cell and the number of lightning days suggests that centers of daytime lightning frequency in April 1989 probably

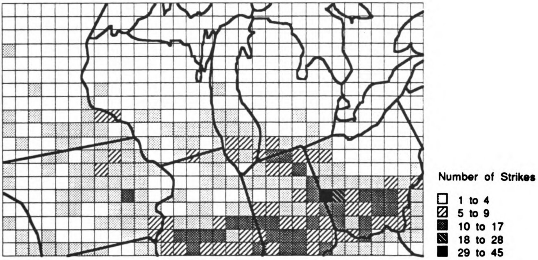

Fig. 16a. Nighttime (0000 - 1200 GMT) Lightning Strikes, April 1989.

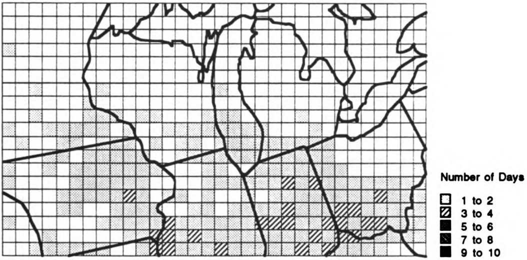

Fig. 16b. Number of Days with Nighttime Lightning Activity, April 1989.

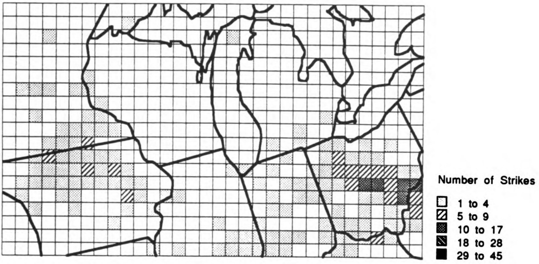

Fig. 17a. Daytime (1200 - 2400 GMT) Lightning Strikes, April 1989.

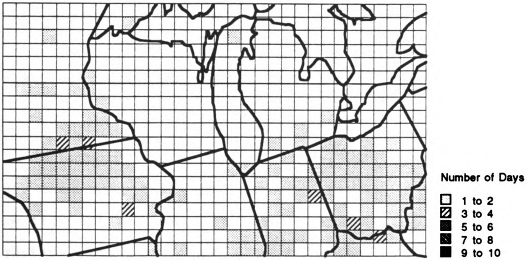

Fig. 17b. Number of Days with Daytime Lightning Activity, April 1989.

result from single events with relatively high lightning activity.

Differences in the diurnal phasing of convection during April 1989 are evident in the hourly frequency totals for the western and eastern portions of the study area. In the west (Figure 18a), lightning activity increased fairly steadily throughout the day and into the night. The frequency maximum was recorded at 0500 GMT, after which the curve shows a sharp decline in lightning frequency. The east (Figure 18b), on the other hand, shows decreasing lightning frequencies over the course of the day after fairly high frequencies during most hours of the night. The highest hourly values, also at 0500 GMT, are also preceded by an increase in lightning frequency.

An additional interesting, but as yet difficult to explain, observation is that during April 1989 positive lightning flashes were more common during the night, especially in the western portion of the study area.

May 1989

In comparison to April, the lightning events of May 1989, both nighttime and daytime (Figures 19a and 20a), are more frequent farther north in the study area. As for April, nighttime activity in May 1989 far exceeds daytime activity. Between 0000 and 1200 GMT, 1337 CG flashes were reported. High frequencies are found in a triangular region extending from Wisconsin through northeastern Ohio to the southern edge

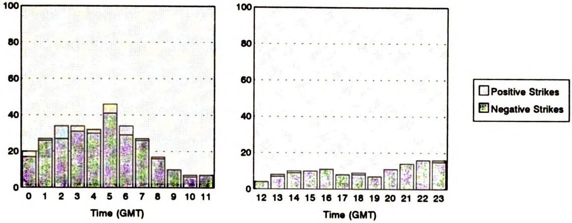

Fig. 18a. Hourly Flash Frequencies for the Western Portion of the Study Area, April 1989.

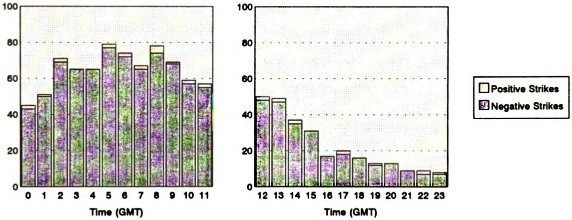

Fig. 18b. Hourly Flash Frequencies for the Eastern Portion of the Study Area, April 1989.

May 1989

In comparison to April, the lightning events of May 1989, both nighttime and daytime (Figures 19a and 20a), are more frequent farther north in the study area. As for April, nighttime activity in May 1989 far exceeds daytime activity. Between 0000 and 1200 GMT, 1337 CG flashes were reported. High frequencies are found in a triangular region extending from Wisconsin through northeastern Ohio to the southern edge of Indiana (Figure 19a). In addition, a few grid cells in northwestern Iowa reported higher values than the surrounding areas. Despite the fact that almost twice as many ground strikes were recorded during the night than during the day, the maximum frequency was only slightly higher with 18 CGs per cell as compared to 14 flashes per cell during the day. The different lightning density values suggest that nighttime activity extended over a broader area than daytime activity. There is only a small correspondence between the number of nighttime CG flashes per grid cell and the number of lightning days (Figure 19b). Within the above-described triangle of highest frequency, only a few cells from eastern Wisconsin and western Michigan reported lightning activity on three or more days. For the remaining grid cells, including northwestern Iowa where a comparatively high number of events was recorded, lightning occurred on only one or two days during the month. On the other hand, in southwestern Illinois and across Lake Erie, the number of lightning events was small in spite of a relatively larger number of lightning days.

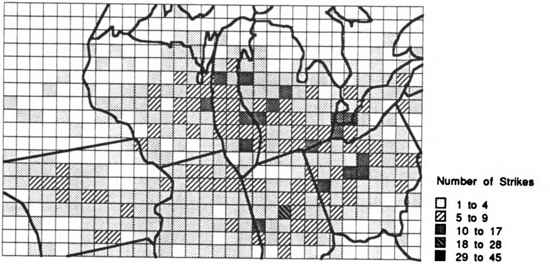

Fig. 19a. Nighttime (0000 - 1200 GMT) Lightning Strikes, May 1989.

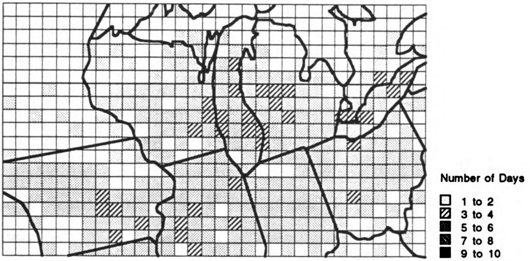

Fig. 19b. Number of Days with Nighttime Lightning Activity, May 1989.

As Figure 20a shows, the 766 recorded daytime ground flashes have their main concentration in a triangle extending from southern Lake Michigan through southern Michigan to Indiana. A secondary concentration is found in southeastern Minnesota and central Wisconsin. Overall, more grid cells reported daytime ground strikes in May than in April although the typical number of strikes per cell remains relatively low (1-4 CG flashes). Again, the distribution of lightning events is not reflected in the distribution of lightning days (Figure 20b). Most grid cells within the area of main concentration from Michigan to Indiana reported lightning on only one or two days in May except for one cell along the Michigan-Indiana border and another one in Indiana along Lake Michigan, where daytime lightning activity was recorded on more than three days. Some differences in daytime flash density are evident in the western and eastern portions of the study area. In the east, most grid cells recorded lightning on only one or two days, whereas cells in Wisconsin and along the Wisconsin-Minnesota border also had a larger number of lightning days (3 to 4).

As in April, the hourly frequency distributions vary considerably for the eastern and western portions of the study area. In the west (Figure 21a), the diurnal curve of lightning frequency shows similarities to the April 1989 curve, as lightning activity increases throughout the day to a peak at 0500 GMT. In contrast to the fairly steady increase in frequency during the afternoon hours evident in

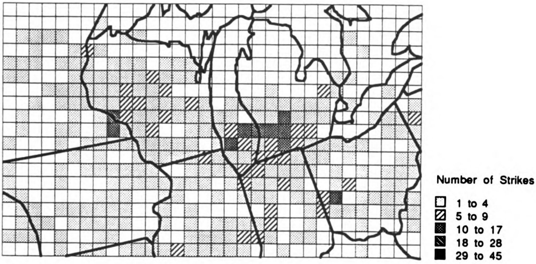

Fig. 20a. Daytime (1200 - 2400 GMT) Lightning Strikes, May 1989.

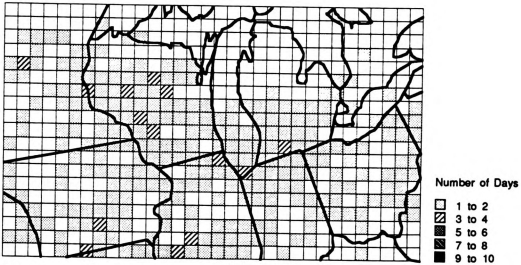

Fig. 20b. Number of Days with Daytime Lightning Activity, May 1989.

April, hourly frequency values in May decrease between 2100 and 0000 GMT. The sharp decline after 0500 GMT is even more pronounced than in April. In the east (Figure 21b), the curves for April and May are very different. While fairly high hourly values are evident throughout the nighttime period in April (note the difference in the vertical scale between April and May), a distinct frequency maximum in May at 0100 GMT is followed by a steady decline until 1800 GMT with very low (less than ten strikes) hourly frequencies between 1200 and 1700 GMT. After 1800 GMT the hourly frequencies increase sharply. The positive and negative lightning strikes frequencies do not reveal any regional or temporal preferences.

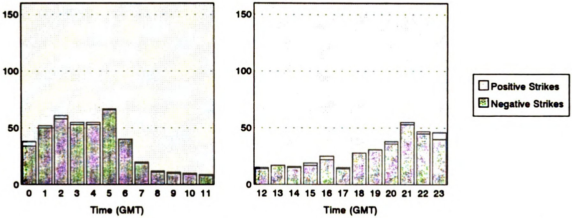

Fig. 21a. Hourly Flash Frequencies for the Western Portion of the Study Area, May 1989.

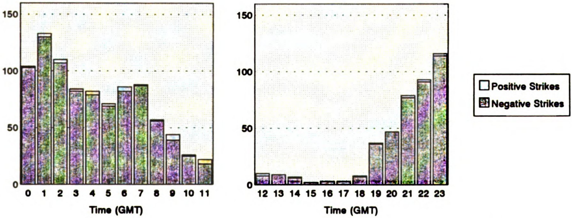

Fig. 21b. Hourly Flash Frequencies for the Eastern Portion of the Study Area, May 1989.

June 1989

Compared to April and May, lightning strikes for the entire study area during June 1989 were more frequent during the day than at night. The fewer nighttime strikes (1075 total events) are concentrated along the Iowa-Nebraska border and in a band stretching from the Iowa-Missouri border into southwest Ontario (Figure 22a). The maximum frequency per grid cell (34) is found in northern Missouri. This value is considerably higher than the daytime maximum value (21 strikes) despite the larger total number of strikes during the day. Except for small areas in Illinois and western Iowa, nighttime lightning activity occurred on only one or two days during June 1989 (Figure 22b). This suggests that the cumulative flash totals resulted from one or two major storm systems tracking through the area, as was also evident in April and May. Some correspondence between lightning frequencies and the number of lightning days per cell is evident in the southwest corner of the study area. However, while the maximum number of events is clustered in the center of that region, the maximum number of lightning days is located near the periphery. The southwest-northeast oriented axis of increased lightning activity from Iowa to Ontario is not mirrored in the spatial distribution of the number of lightning days.

In June 1989, the large increase in daytime lightning strikes (1541 total events) compared to April and May is accompanied by a distinct concentration of a higher number of

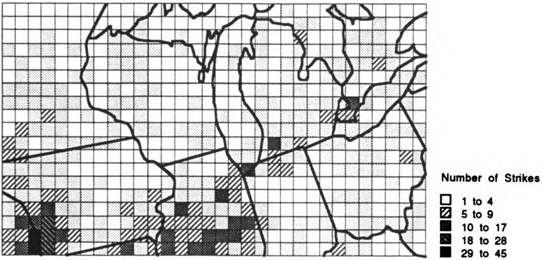

Fig. 22a. Nighttime (0000 - 1200 GMT) Lightning Strikes, June 1989.

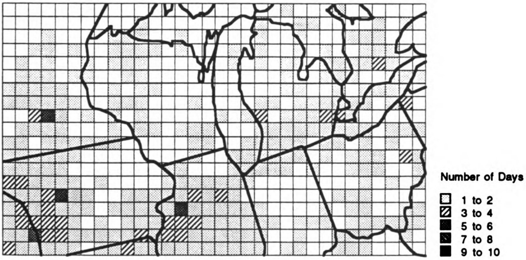

Fig. 22b. Number of Days with Nighttime Lightning Activity June, 1989.

strikes in the eastern half of the study area (Figure 23a). This concentration of ground flashes in the eastern half of the study area is in general agreement with studies by Wallace (1975) and Winkler (1987) who reported afternoon maxima of precipitation and thunderstorm activity for the eastern United States and a nocturnal maximum for the central part of the country. Compared to the two previous months, a better correlation between regions of increased daytime lightning activity and regions with higher number of lightning days (Figure 23b) is evident in June 1989. Note that both, the highest frequencies and number of lightning days, are found in the eastern part of the study area suggesting that the significantly higher frequency of lightning events in the eastern portion of the study area is a result of the larger number of days on which lightning occurred rather than the result of a few, larger convective systems with unusually high lightning activity.

The hourly flash frequencies for the western portion of the study region show an increase in lightning activity from 2000 GMT to a maximum at 0300 GMT (Figure 24a) after which the hourly frequencies decrease again (note the scale change between May and June). As in May, the eastern portion of the study region (Figure 24b) displays a strong increase in hourly frequencies in the early afternoon hours. Compared to May, however, the increase in hourly values starts two hours earlier in June (1700 GMT compared to 1900 GMT) and ends fairly abruptly at 2200 GMT, whereas the curve in May

Fig. 23a. Daytime (1200 - 2400 GMT) Lightning Strikes, June 1989.

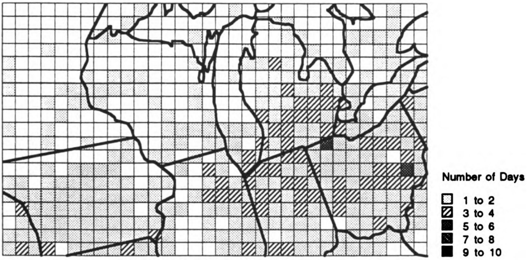

Fig. 23b. Number of Days with Daytime Lightning Activity, June 1989.

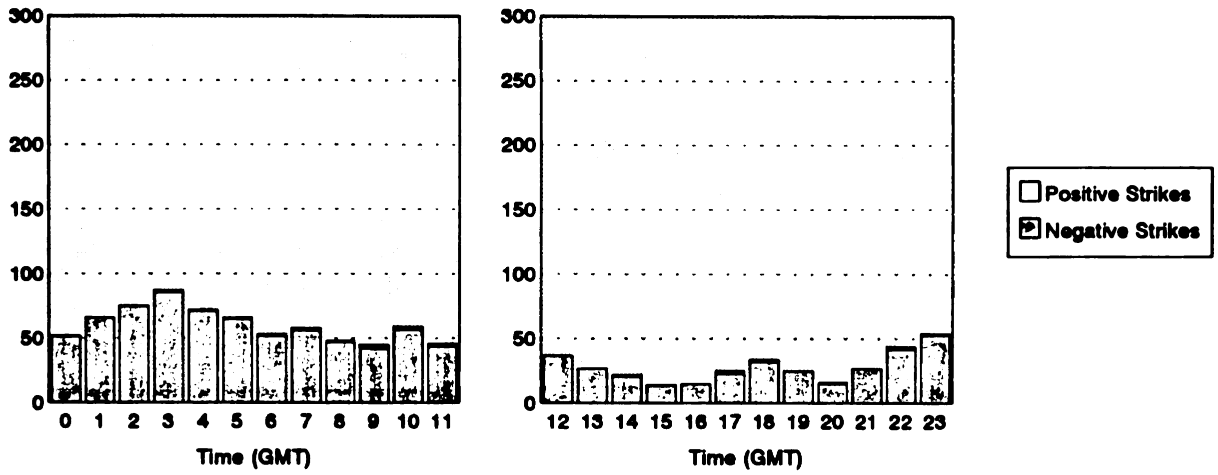

Fig. 24a. Hourly Flash Frequencies for the Western Portion of the Study Area, June 1989.

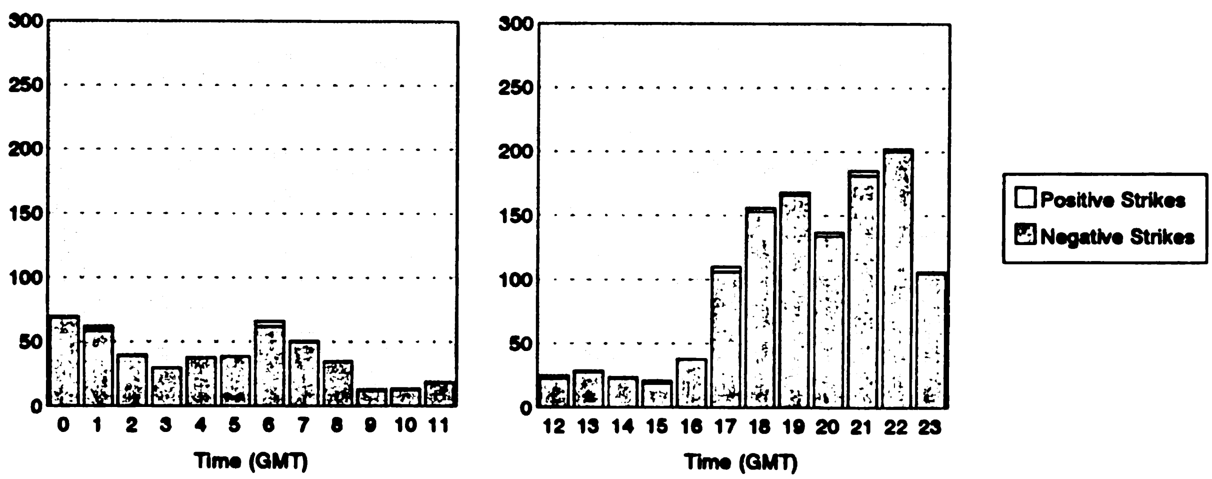

Fig. 24b. Hourly Flash Frequencies for the Eastern Portion of the Study Area, June 1989.

increases until a maximum at 0100 GMT and then gradually declines. No diurnal trend in the frequency of positive lightning flashes in either region is evident in Figures 24a and 24b.

July 1989

As for June, most ground flashes in July 1989 occurred during the day. During the nighttime period (0000-1200 GMT), the west received a slightly higher number of events (720 CGs) than the east (714 CGs). Three distinct clusters of increased lightning activity, western Iowa, southern Lake Michigan, and western Lake Erie, are evident in Figure 25a. Especially intriguing are the clusters over the lakes, as this activity is occurring over the summertime cooler lake waters. Although there was some indication of frequency maxima in these areas on the June plot, the maxima are more distinct and include a larger number of cells in July.

The recorded events during the daytime period in July 1989 also support the findings by Wallace (1975) and Winkler (1987). Note in Figure 26a the significantly higher number of lightning events in the eastern portion of the study area (1515 flashes) than in the west (543 events). However, elevated daytime lightning activity of 5-9 strikes per cell is also found in the western region from southern Iowa to eastern Illinois. In general, a west to east axis of maximum activity from eastern Iowa to southeast Ohio is evident. In Lower Michigan, fewer flashes were reported in July 1989

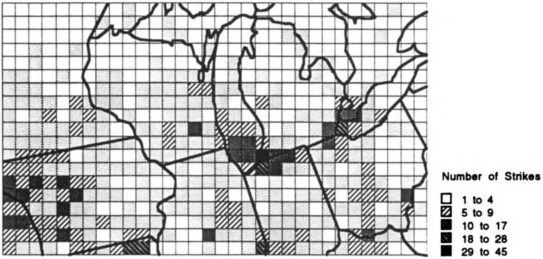

Fig. 25a. Nighttime (0000 - 1200 GMT) Lightning Strikes, July 1989.

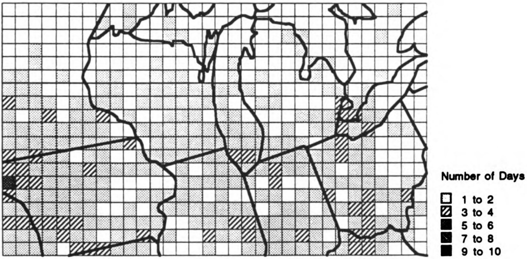

Fig. 25b. Number of Days with Nighttime Lightning Activity, July 1989.

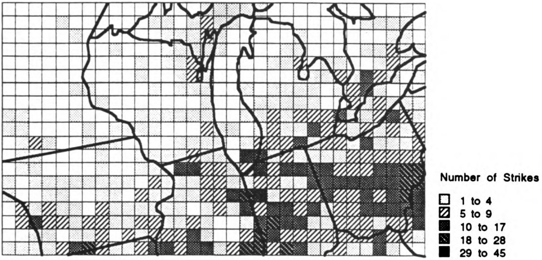

Fig. 26a. Daytime (1200 - 2400 GMT) Lightning Strikes, July 1989.

Fig. 26b. Number of Days with Daytime Lightning Activity, July 1989.

compared to June, suggesting a more southerly storm track for July 1989. As for June, daytime lightning activity was reported on a significantly larger number of days in the eastern portion of the study region, particularly in southeastern Ohio, compared to the western portion (Figure 26b).

The much larger number of events in the eastern region, and especially during the day, is clearly evident in Figures 27a and 27b. The hourly plots show a much smaller amplitude in the frequency curve for the western portion (Figure 27a) of the study region than for the east. Lower values in the morning hours (1300-1800 GMT) are followed by fairly steady frequencies in the afternoon and throughout the night (1900-1200 GMT). Despite the lower total number of strikes, the plot of positive lightning strikes reveals a slight preference for the western part of the study region.

In the east (Figure 27b), on the other hand, the tendency for a steep increase in hourly values in the afternoon hours, apparent in May and June, is continued in July. Starting at 1700 GMT, hourly frequencies sharply increase until 1900 GMT when they level off. The decrease is prolonged one hour compared to June, and is most pronounced between 2300 and 0200 GMT.

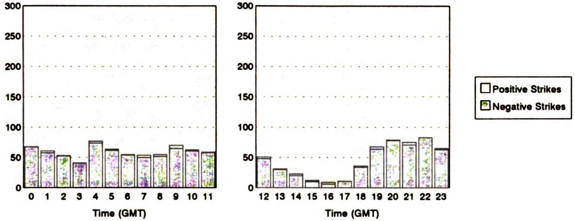

Fig. 27a. Hourly Flash Frequencies for the Western Portion of the Study Area, July 1989.

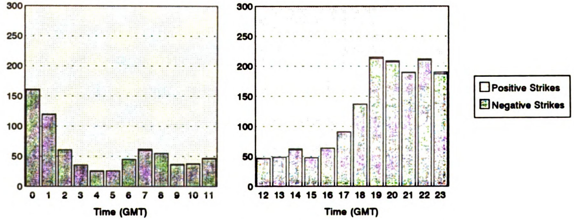

Fig. 27b. Hourly Flash Frequencies for the Eastern Portion of the Study Area, July 1989.

August 1989

Fewer nighttime (1358 CGs) than daytime strikes (1813 CGs) were also reported during August 1989. Little regional differentiation in the frequency of lighting activity is evident for the nighttime hours (Figure 28a). Note that several spatially dispersed clusters of maximum activity are evident, including southern Iowa, southeastern Ohio, and southern Lake Michigan. Missing are the clusters of enhanced activity in western Lake Erie and southwestern Iowa evident in the two previous months. The only cells with five or six nighttime lightning days in August 1989 are found in southern Iowa (Figure 28b). This area corresponds to a main cluster of lightning activity. The other clusters of higher nighttime lightning frequencies are not reflected in the distribution of lightning days.

During the daytime period, the spatial concentration of ground flashes shows a clear preference for the eastern half of the grid system (Figure 29a). As for July 1989, higher daytime lightning activity in August is concentrated along a southwest-northeast oriented axis, although this axis is located farther south (from southeastern Illinois to southern Ohio) compared to July. Both June and July had daytime maxima in lightning frequency, but the highest cumulative strike frequencies per grid cell were recorded during the nighttime period, whereas in August maximum frequencies per cell occurred during the daytime period. The maximum cell frequency value of 36 events exceeds those for June and July. It

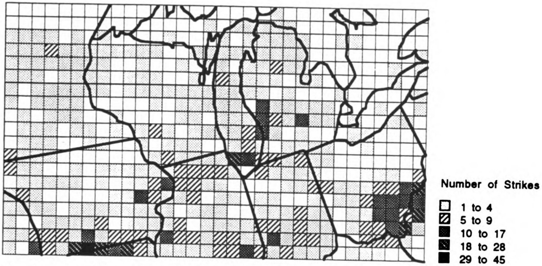

Fig. 28a. Nighttime (0000 - 1200 GMT) Lightning Strikes, August 1989.

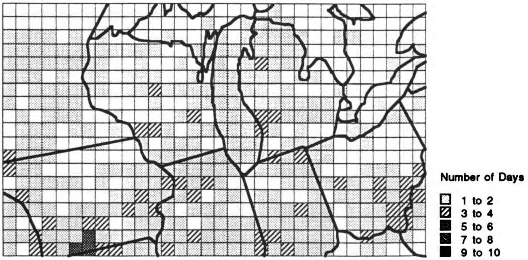

Fig. 28b. Number of Days with Nighttime Lightning Activity, August 1989.

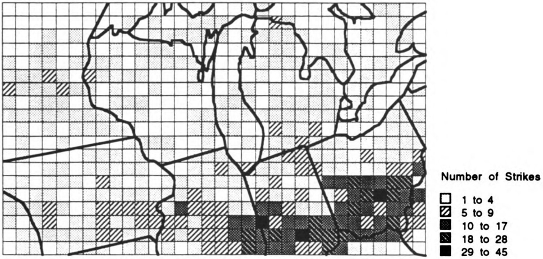

Fig. 29a. Daytime (1200 - 2400 GMT) Lightning Strikes, August 1989.

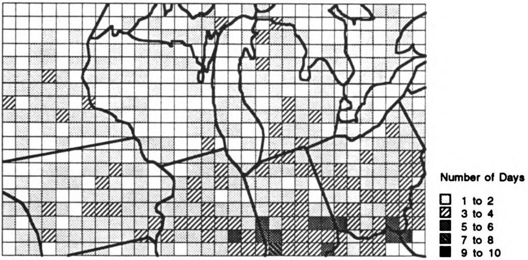

Fig. 29b. Number of Days with Daytime Lightning Activity, August 1989.

approximates the nighttime values for the preceding two months (36 and 37 flashes per cell, respectively). However, the increase in daytime lightning frequency in August as compared to July was not accompanied by a significant increase in the number of lightning days (Figure 29b). Most cells fall in category II (3-4 lightning days per cell), a few fall in category III (5-6 lightning days per cell), and one cell recorded lightning on seven or more days. Considerably more cells in July were assigned to category III. The axis of maximum daytime lightning frequency in the southern and southeastern portions of the study area generally experienced five to six lightning days in August 1989.

The hourly frequency curves for both the western and eastern portions of the study area resemble the June (Figures 24a and 24b) rather than the July (Figures 27a and 27b) distribution . Similar features in the western curve (Figure 30a) include a steady increase in hourly frequency toward a nocturnal peak that is followed by a decrease in hourly values to a minimum around noon. While the June maximum occurred at 0300 GMT, the August maximum was delayed by four hours. The hourly frequency distribution for the eastern portion of the study area (Figure 30b) again shows the strong increase in lightning activity in the afternoon hours that was observed in May through July. Hourly frequency decrease beginning at approximately 2300 GMT.

An interesting feature concerning the polarity of lightning strikes is evident in the west, especially in the

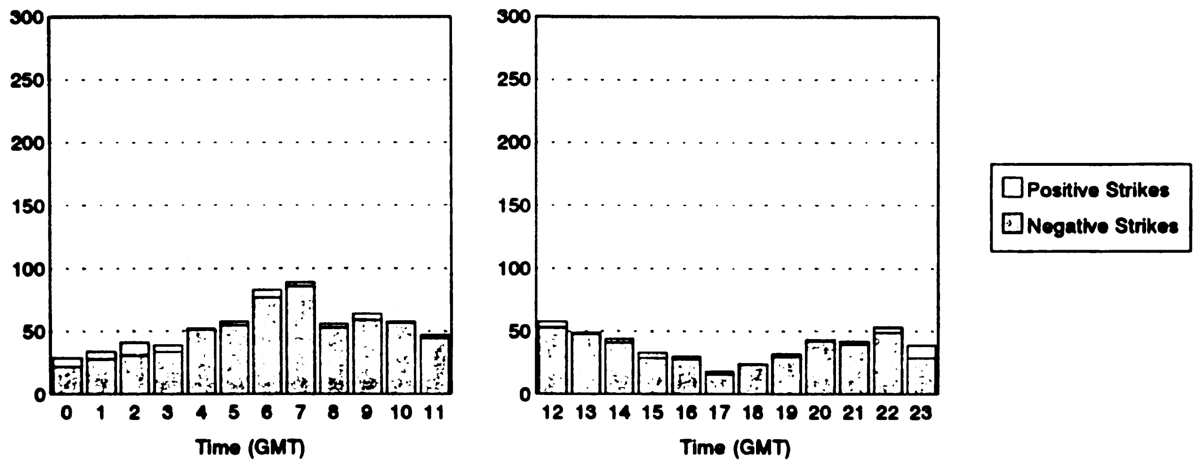

Fig. 30a. Hourly Flash Frequencies for the Western Portion of the Study Area, August 1989.

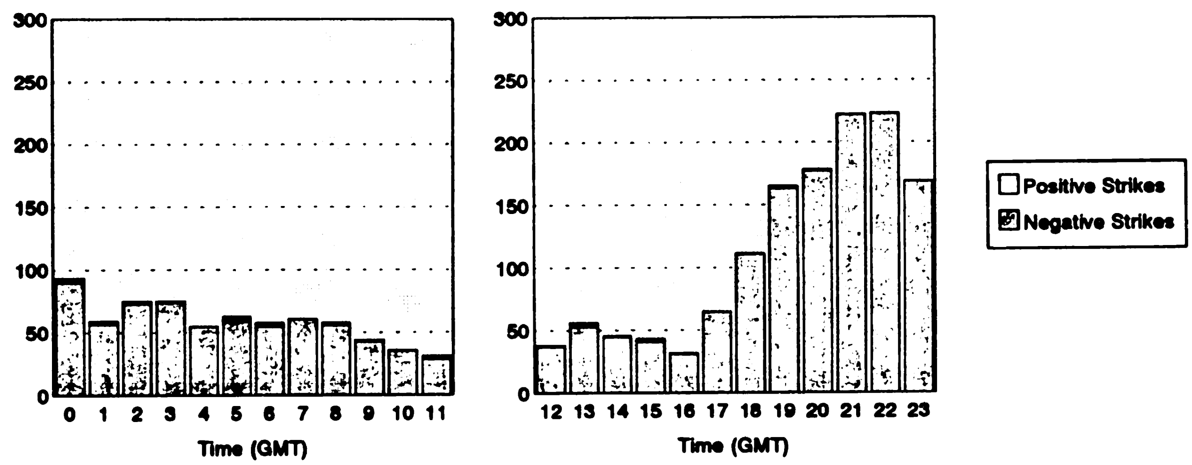

Fig. 30b. Hourly Flash Frequencies for the Eastern Portion of the Study Area, August 1989.

evening hours. Despite the lower hourly frequency values in the western portion of the study area as compared to the east, the percentage of positive strikes is considerably higher. Thus, the prevalence of positive strikes in the west that had already been observed in July is even more pronounced in August.

September 1989

After three months with daytime maxima in lightning activity, in September 1989 the nighttime lightning events (1305 total flashes) exceed the daytime events. This shift in temporal preference is a result of a sharp decline in the number of daytime events (645 compared to 1813 in August).

The higher nighttime totals are accompanied by a higher maximum frequencies per cell (Figure 31a). While a maximum of 33 CG strikes per cell was recorded for nighttime activity in September, the equivalent figure for daytime activity is 18 CG strikes per cell. Nighttime lightning activity shows a clear concentration in the western half of the study area (1032 strikes compared to 273 in the east). Clusters of higher lightning activity in the west can be identified along the Iowa-Nebraska border, in northeast Iowa, and in central Illinois. Two of these spatial clusters, Iowa-Nebraska and central Illinois, are also evident in the distribution of lightning days (Figure 31b). In Iowa, on the other hand, strikes were recorded on only two days during all the nighttime intervals in the month of September. Weaker frequency

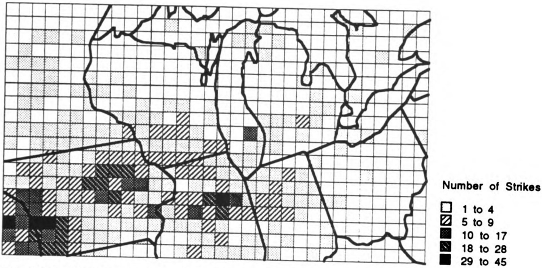

Fig. 31a. Nighttime (0000 - 1200 GMT) Lightning Strikes, September 1989.

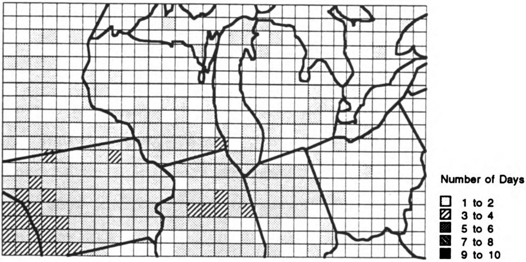

Fig.31b. Number of Days with Nighttime Lightning Activity, September 1989.

maxima in both, the number of lightning events and lightning days, are evident over southern Lake Michigan and eastern Lake Erie.

The dramatic decrease in the frequency of daytime events from August to September is accompanied by a more uniform distribution of lightning strikes across the study area compared to the previous months, although there is a slight preference for the eastern half of the study area. Apart from a slight concentration extending from Illinois into Indiana, the daytime spatial distribution does not reveal any trends (Figure 32a). In regards to the number of lightning days, the cluster in Illinois-Indiana is duplicated only by a fraction of the affected cells (Figure 32b). Four grid cells along the Illinois-Indiana border are the only cells that reported 5-9 CG strikes

The hourly frequency curves for the eastern and western portions of the study area differ substantially. While the hourly frequency of CG flashes was fairly uniformly distributed throughout the daytime hours in the western region with approximately 30 CGs per hour, lightning activity was almost three times more frequent in the nighttime period between 0300 and 0800 GMT (Figure 33a). In the eastern portion, maximum activity occurred in a limited period during the afternoon and early evening hours from 2000 GMT to 2300 GMT (Figure 33b). In both regions the shapes of the diurnal curves resemble those for August, in spite of the large difference in strike frequency (note the scale difference

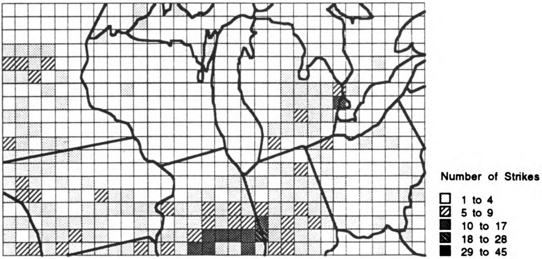

Fig. 32a. Daytime (1200 - 2400 GMT) Lightning Strikes, September 1989.

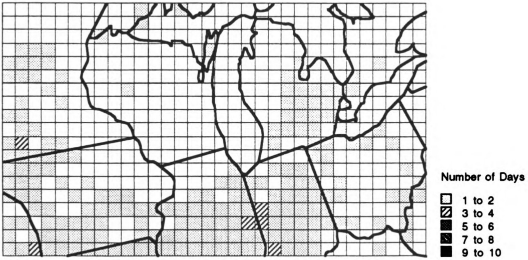

Fig. 32b. Number of Days with Daytime Lightning Activity, September 1989.

between August and September). While the daytime maximum in the eastern portion of the study area stands out in August, it is the nighttime maximum in the west that is more apparent in September. The nighttime lightning events in the west are also characterized by a relatively high percentage of positive strikes. Unlike the two previous months, the nighttime period is not the period of small lightning frequencies. Thus the previously proposed inverse relationship between the total number of strikes and the number of positive strikes is not evident in September. It rather seems that there may exist a temporal and spatial preference for positive lightning strikes. The tendency of the largest number of positive strikes to be recorded in western portion of the study area, mainly during the nighttime period, can also be observed in 1990 as will be seen in the following discussion.

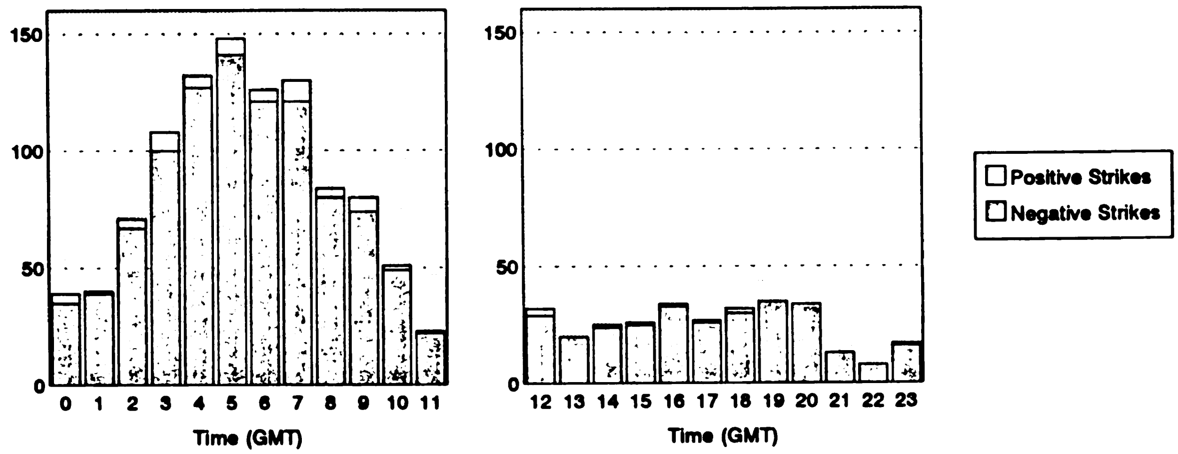

Fig. 33a. Hourly Flash Frequencies for the Western Portion of the Study Area, September 1989.

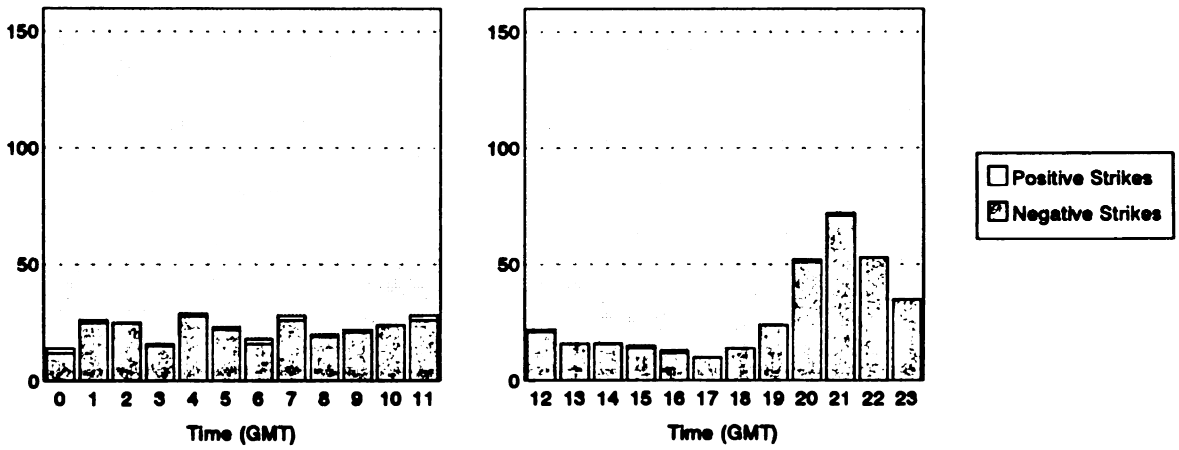

Fig. 33b. Hourly Flash Frequencies for the Eastern Portion of the Study Area, September 1989.

May 1990

The large amount of interannual variability in storm tracks and the possible impact of high activity from single systems on the frequency of lightning strikes are evident when comparing the May 1989 and May 1990 plots of nighttime and daytime activity. Both nighttime and daytime lightning frequencies for May 1990 (Figures 34 and 35) are concentrated along a southwest-northeast axis from Nebraska into southern Lake Michigan and Indiana, whereas in May 1989 (Figures 19 and 20) nighttime events were most frequent in Michigan and Indiana, and daytime events were most frequent in Wisconsin, southwest Michigan and northern Indiana.

Lightning activity in May 1990 was much more frequent at night (1530 occurrences) than during the day (723 events). Also, the largest strike frequency per cell is considerably higher for the nighttime period (29 strikes) than daytime period (10 strikes). This axis of lightning activity during the nighttime period is better observed in the distribution of lightning days (Figure 34b) than in the distribution of lightning events (Figure 34a). The larger number of nighttime lightning occurrences in May 1990 is accompanied by a larger number of lightning days. For example, the region of frequent nighttime lightning activity along the Nebraska-Iowa border reported ground flashes on up to eight days.

Two main concentrations of daytime lightning activity (Figure 35a) and lightning days (Figure 35b) in southwestern Iowa and in northwestern Illinois can be identified within

Fig. 34a. Nighttime (0000 - 1200 GMT) Lightning Strikes, May 1990.

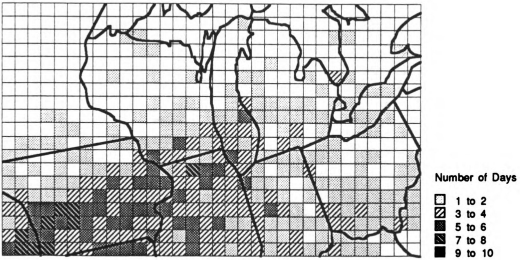

Fig. 34b. Number of Days with Nighttime Lightning Activity, May 1990.

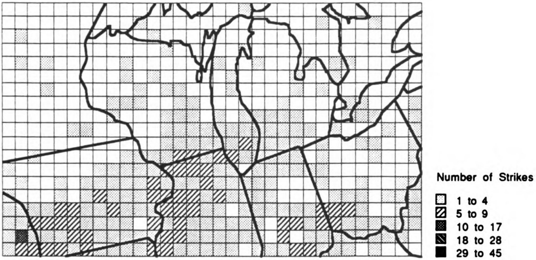

Fig. 35a. Daytime (1200 - 2400 GMT) Lightning Strikes, May 1990.

Fig. 35b. Number of Days with Daytime Lightning Activity, May 1990.

the band extending from Nebraska into southern Lake Michigan and Indiana. An additional area of frequent activity, apparent only on the plot of lightning events is found in southern Indiana and southwestern Ohio. Here CG strokes were reported on only one to two days, unlike the two other centers of lightning activity that reported daytime lightning activity on up to six days in May 1990.

The prevalence of nighttime events is particularly evident in the western portion of the study area where over 120 events were reported between 0400 and 0500 GMT (Figure 36a). The hourly frequency distribution in the west is characterized by a minimum in lightning activity between 1500 and 1800 GMT followed by a steady increase in activity until 0400 GMT and a subsequent decrease. In the eastern portion of the study area (Figure 36b) the number of events is fairly uniformly distributed throughout the daytime hours. The nighttime period, on the other hand, shows three peaks from 2300-0100 GMT, 0500-0700 GMT, and 1000-1100 GMT. Not only does the spatial distribution vary between May 1989 and May 1990, but also the diurnal curves vary significantly. The previously noted marked period of minimum activity from 1100 to 1800 GMT in May 1989 (Figure 21b) is not present in May 1990. Also, the late morning minimum evident in May 1989 for the eastern region is not as well defined in 1990. The curve for the western part of the study area resembles to some extent the April 1989 (Figure 21a) and September 1989 (Figure 33a) curves, however, in that all three curves display a

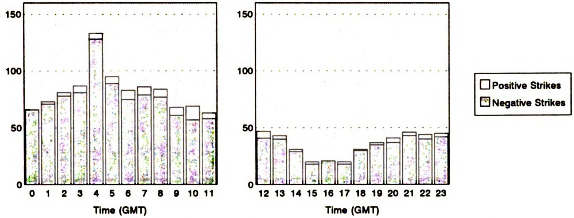

Fig. 36a. Hourly Flash Frequencies for the Western Portion of the Study Area, May 1990.

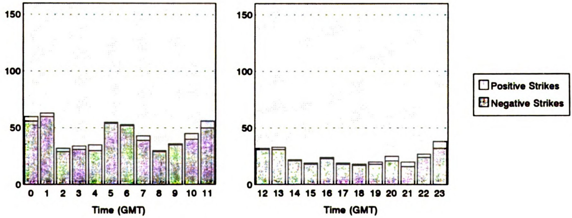

Fig. 36b. Hourly Flash Frequencies for the Eastern Portion of the Study Area, May 1990.

pronounced late night maximum (at 0400 GMT, respectively at 0500 GMT). With respect to the polarity of lightning events, a distinct preference of positive strikes for the western portion of the study area during the nighttime period is evident.

June 1990

Unlike June 1989, which had a daytime frequency maximum, June 1990 showed a pronounced nighttime maximum in lightning activity (3257 flashes compared to 1697). The distinct preference for nighttime events to occur in the western half of the study area and daytime events in the eastern half of the study area described in June 1989 (Figures 22a and 23a) is not evident in June 1990 (Figures 37a and 38a). In June 1990, lightning activity is most frequent in the western portion of the study area in both time periods, particularly in southern Iowa and western Illinois. Also, a secondary frequency maximum is evident in the eastern portion of the study area in central and southwestern Ohio.

The larger number of events is also reflected in the plot of lightning days (Figures 37b and 38b). In both daytime and nighttime periods, the number of days with lightning activity is larger in the western portion, in particular in central Iowa, where some grid cells experienced 9 to 10 lightning days.

The nighttime maximum in lightning activity is evident in the hourly frequency distributions, too. The June 1990

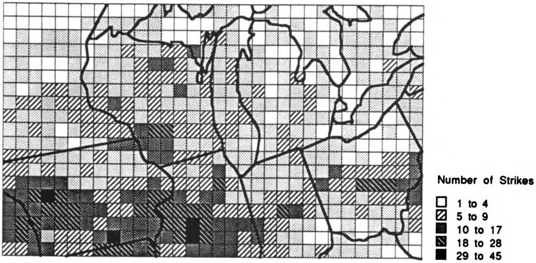

Fig. 37a. Nighttime (0000 - 1200 GMT) Lightning Strikes, June 1990.

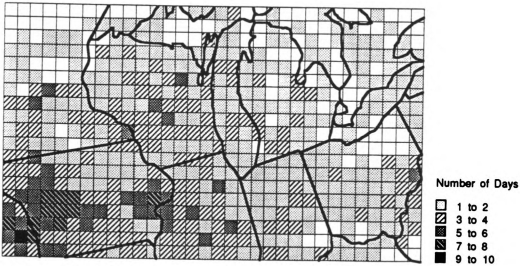

Fig. 37b. Number of Days with Nighttime Lightning Activity, June 1990.

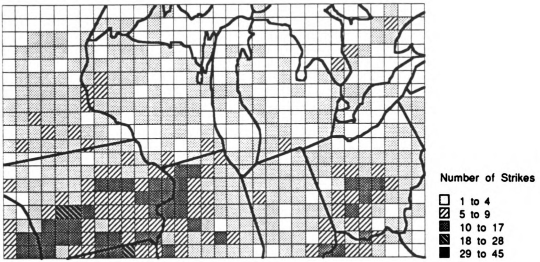

Fig. 38a. Daytime (1200 - 2400 GMT) Lightning Strikes, June 1990.

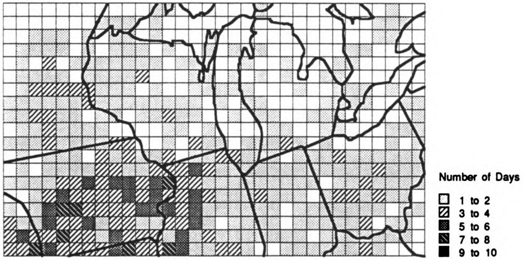

Fig. 38b. Number of Days with Daytime Lightning Activity, June 1990.

(Figure 39a) distribution for the western portion of the study area closely resembles the May 1990 distribution (Figure 36a). Both curves have considerably higher hourly values in the nighttime period with the time of maximum frequency occurring around 1-2 hours before local midnight (at 0400, respectively 0500 GMT). While May 1990 shows a drop in lightning frequencies between 1500 and 1800 GMT, the hourly values in June maintain a fairly steady level during the day (note the difference in scale between the May and June plots). The plots for the eastern portion of the study area for May (Figure 36b) and June (Figure 39b) do not display similarities.

Lightning activity in June 1990 shares some features with the June 1989 distribution. Despite the much larger amplitude in 1990, both curves display a nighttime maximum at 0300 GMT, respectively at 0400 GMT, for the western part of the study area. An additional consistent feature between June 1989 (Figure 24b) and 1990 (Figure 39b) is the distinct period of relatively infrequent lightning activity in the eastern portion of the study area from approximately 1200 to 1600 GMT (late morning and midday). In June 1990 this period is prolonged until 1900 GMT. For the eastern region, the increase in lightning activity in the afternoon hours that had been reported for May through September 1989 is evident again. Also apparent is the preference of positive lightning for the western portion of the study area (Figure 39b).

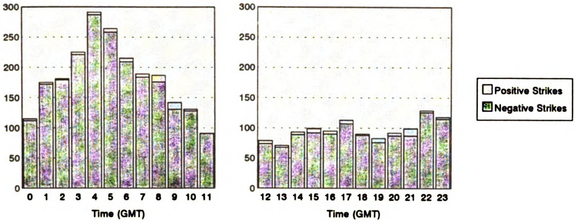

Fig. 39a. Hourly Flash Frequencies for the Western Portion of the Study Area, June 1990.

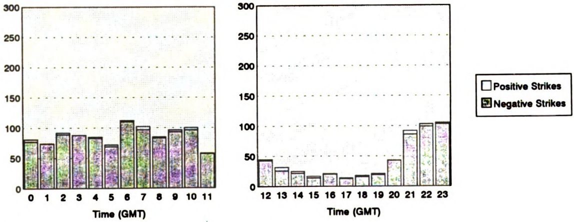

Fig. 39b. Hourly Flash Frequencies for the Eastern Portion of the Study Area, June 1990.

Unlike May, no clear temporal preference can be identified, however.

July 1990

In July 1990, lightning activity was more evenly distributed in the nighttime and daytime periods (1748 and 1467 strikes) compared to June 1990. However, the maximum number of strikes per cell was greater for the nighttime period. During the night, the cell with the highest strike totals reported 34 CGs; the highest daytime strike density, on the other hand, was 19 CGs per cell. The nighttime lightning flashes during July 1990 were more frequent in the western part of the study area than in the east (Figure 40a). The area of higher frequencies extends northward from Iowa into southern Minnesota and eastward into Illinois. The number of lightning days is also large for this area (Figure 40b). A major difference between the nighttime distribution for July 1989 (Figure 25a) and July 1990 is the relatively infrequent occurrence of flashes over southern Lake Michigan and western Lake Erie compared to July 1990.

As for July 1989, daytime lightning activity is more frequent in the eastern half of the study area although the number of strikes reported in 1989 (Figure 26a) was considerably larger than in 1990 (Figure 41a). The highest concentration of daytime lightning events is observed in Ohio. A slight southwest-northeast oriented axis of greater activity is evident from Indiana across Ohio into West

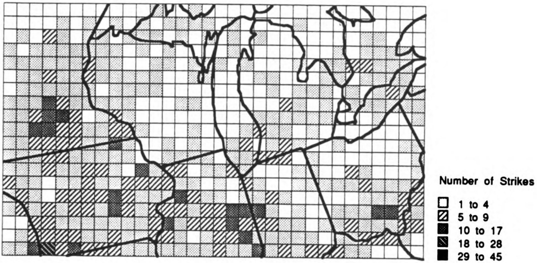

Fig. 40a. Nighttime (0000 - 1200 GMT) Lightning Strikes, July 1990.

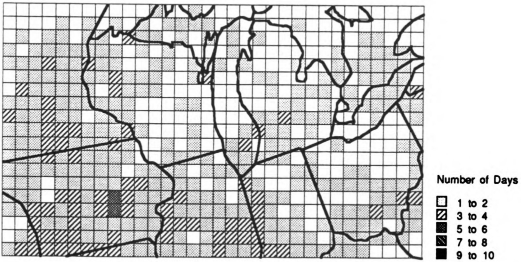

Fig. 40b. Number of Days with Nighttime Lightning Activity, July 1990.

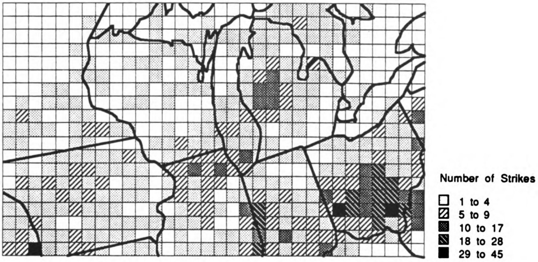

Fig. 41a. Daytime (1200 - 2400 GMT) Lightning Strikes, July 1990.

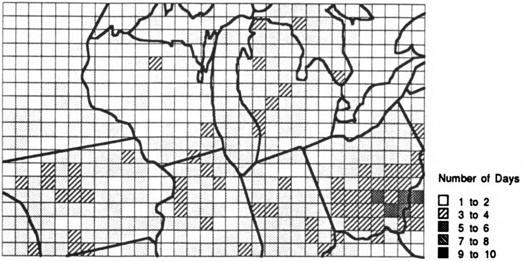

Fig. 41b. Number of Days with Daytime Lightning Activity, July 1990.

Virginia. The frequency maximum in Ohio also corresponds with the relative maximum in the number of lightning days per grid cell (Figure 41b). Grid cells with the highest number of lightning days recorded strikes on five or six days. A secondary axis of higher daytime ground flash frequencies in July 1990 extends from Indiana into central lower Michigan.

On the other hand, the diurnal distributions of lightning activity by hour are very similar for the July 1989 and 1990, particularly in the eastern portion of the study area. In both months, a period of elevated activity is evident from approximately 1900 to 0200 GMT (late afternoon and early evening) in the eastern portion (Figures 27b and 42b), whereas in the western portion (Figures 27a and 42a) lightning activity is frequent over a broader period (approximately 2100-1100 GMT). In July 1990, very few positive lightning strikes were recorded.

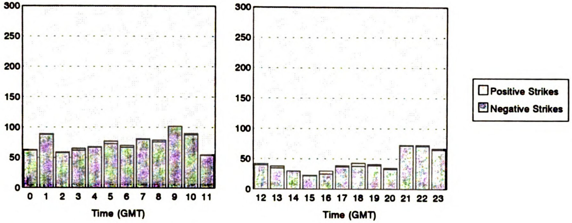

Fig. 42a. Hourly Flash Frequencies for the Western Portion of the Study Area, July 1990.

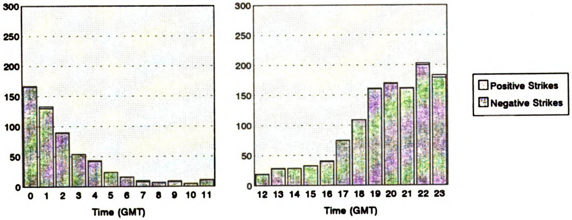

Fig. 42b. Hourly Flash Frequencies for the Eastern Portion of the Study Area, July 1990.

August 1990

Lightning activity was considerably more frequent in August 1990 compared to August 1989. Unlike August 1989, a clear nighttime maximum in lightning frequency was evident in August 1990. Areas of higher frequency extended further north during August 1990 than in the previous months of June and July. In the nighttime period, lightning activity was most frequent in northern Iowa, southwestern Wisconsin and in eastern Indiana (Figure 43a). These cores of high lightning frequencies, however, are surrounded by cells with fairly high strike frequencies. In fact, the nighttime period of August 1990 has the largest areal extent of grid cells with five or more strikes of all examined months.

For the daytime hours, two main areas of concentration can be identified in western Iowa and northern Indiana (Figure 44a). Apart from these two main centers of lightning activity with considerable areal extend, several smaller clusters can be located in Ohio, in southern Ontario, and in the central portion of Michigan. The highest cumulative strike frequency per cell was recorded in northern Indiana. This particular cell, however, was affected by CGs on a maximum of two days in the whole month. The number of lightning days for daytime activity (Figure 44b) is comparatively low with only two cells falling into category II (5-6 lightning days). The 3340 daytime ground strikes have a slightly higher maximum cell frequency (43 CG strikes per cell) than the 1835 nighttime events (41 CG strikes per cell).

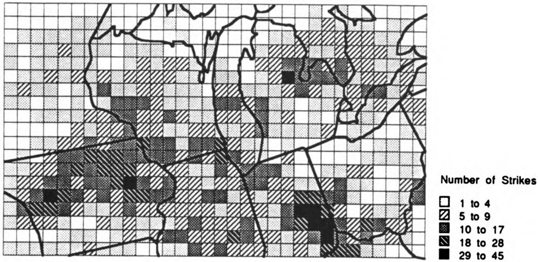

Fig. 43a. Nighttime (0000 - 1200 GMT) Lightning Strikes, August 1990.

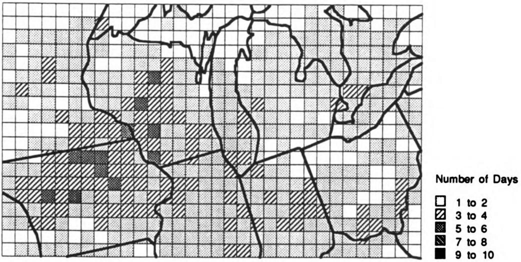

Fig. 43b. Number of Days with Nighttime Lightning Activity August 1990.

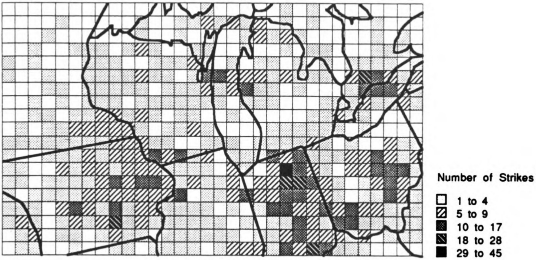

Fig. 44a. Daytime (1200 - 2400 GMT) Lightning Strikes, August 1990.

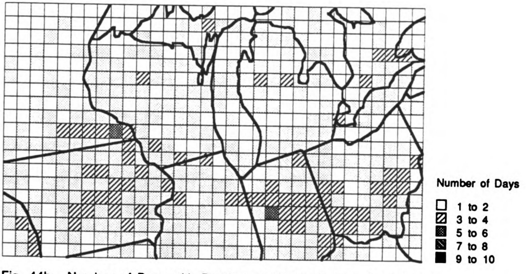

Fig. 44b. Number of Days with Daytime Lightning Activity, August 1990.

The shape of the diurnal curve for the western portion of the study area for August 1990 (Figure 45a) is similar to the one previously presented for August 1989 (Figure 30a) while the eastern curve (Figure 45b) more closely resembles the July 1990 (Figure 42b) curve. As for August 1989, the hourly frequency distribution for the west shows lightning activity to be least around noon local time. Both curves show a decline in lightning activity between 1500 and 1900 GMT. Lightning activity subsequently picks up and displays a peak shortly after midnight LST (0700 GMT), after which it drops off again. The amplitude of the diurnal curve in August 1990 is about double that of August 1989.

In the east, both July 1990 and August 1990 show a marked increase in hourly frequency values around noon LST. While the July curve peaks at 2300 GMT and subsequently decreases, however, the August curve maintains fairly high hourly values until 0300 GMT and drops off then. As in the previous months, a higher percentage of positive strikes was recorded in the west than in the east. With respect to temporal characteristics, a slight preference for the nighttime period can be detected in the record of positive strikes in the western portion of the study area.

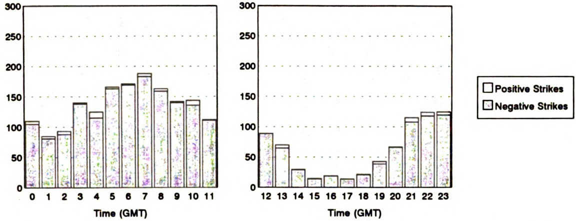

Fig. 45a. Hourly Flash Frequencies for the Western Portion of the Study Area, August 1990.

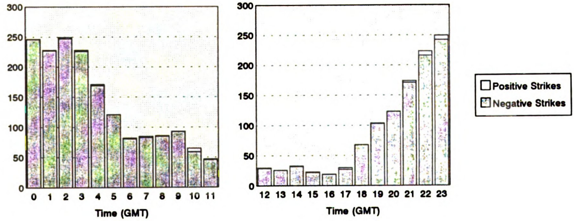

Fig. 45b. Hourly Flash Frequencies for the Eastern Portion of the Study Area, August 1990.

September 1990

Nighttime activity was more frequent in September 1990 than daytime events (1320 strikes compared to 1041). For the nighttime period, a northwest-southeast band of increased activity can be identified from northwestern Wisconsin into the northeast corner of Ohio (Figure 46a). A striking feature about the nighttime distribution of September 1990 is the occurrence of both higher lightning frequency and a higher number of lightning days (Figure 46b) along the northern border of the study region, an area with little activity in the previous months. Maximum nighttime strike frequency per cell was 25 CG flashes compared to 24 CG flashes for the daytime period.

During both, night and day, the eastern part of the study area received higher numbers of CG strikes. While there is a fairly good distinction between regions at night with 810 eastern strikes versus 510 strikes in the west, the preference for the eastern section of the study area is very distinct during the day with 865 strikes in the east versus 176 western events.

Daytime lightning flashes during September 1990 were concentrated in a triangle extending from southwest Michigan into Pennsylvania and into Ohio (Figure 47a). Generally, the plot of lightning days (Figure 47b) does not correspond well with the distribution of events, indicating that the band of higher lightning frequencies from southwest Michigan into Pennsylvania is most likely the result of one or two major

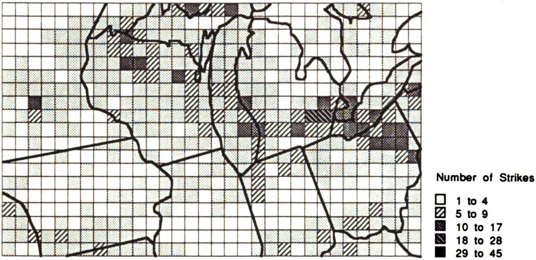

Fig. 46a. Nighttime (1200 - 2400 GMT) Lightning Strikes, September 1990.

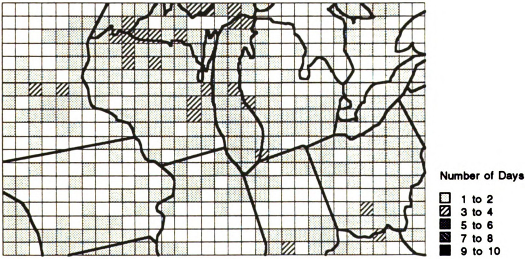

Fig. 46b. Number of Days with Nighttime Lightning Activity, September 1990.

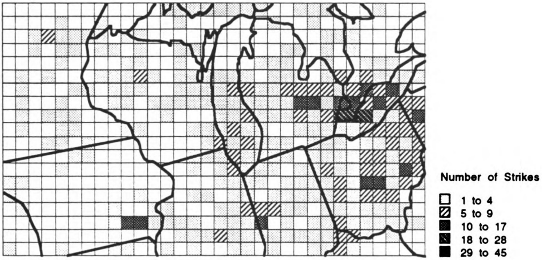

Fig. 47a. Daytime (1200 - 2400 GMT) Lightning Strikes, September 1990.

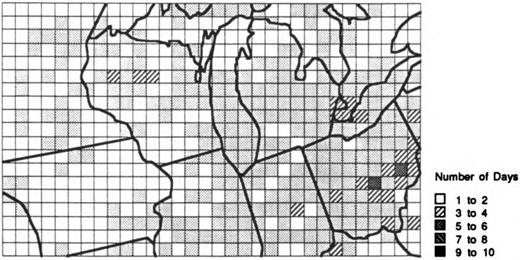

Fig. 47b. Number of Days with Daytime Lightning Activity, September 1990.

storm systems, while the grid cells in Ohio were affected by several thunderstorms. In Ohio lightning activity was recorded on up to 6 days.

While there are few similarities in the frequency distributions of September of both years, September 1990 has some resemblance with the August 1990 curve (Note the difference in scale between the two months). In the west (Figures 47a and 48a), little lightning activity occurred around noon and into the early afternoon in both August and September. The period of small lightning activity is even more extended in September (1500-2200 GMT unlike 1500-1900 in August). The largest lightning activity was recorded around local midnight. In September 1990, the period of strongest lightning activity extended from 0600 GMT to 1200 GMT.

As for August 1990 (Figure 47b), the frequency distribution for September in the east (Figure 48b) displays a strong increase in lightning activity starting at 1800 GMT and peaking at 2300 GMT. While the September curve subsequently decreases, August shows a prolonged period of elevated hourly frequencies until 0300 GMT. The period of weaker activity in both months extends from 0600 GMT through 1800 GMT. While September does not show much variation in this time interval, the hourly values in August decrease even further to a minimum between 1200 GMT and 1800 GMT. Consistent with September 1989, the nighttime interval in the west stands out as the time and place of preferred occurrence of positive lightning strikes.

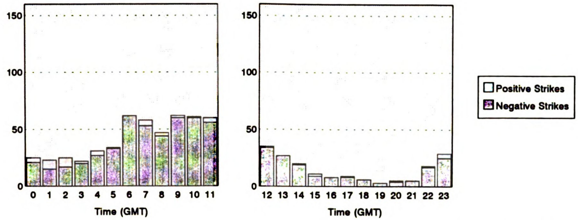

Fig. 48a. Hourly Flash Frequencies for the Western Portion of the Study Area, September 1990.

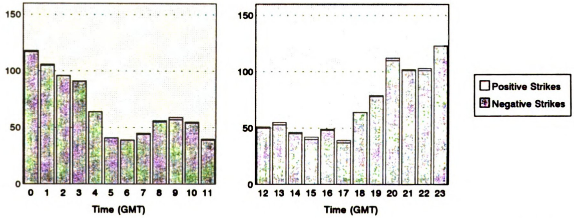

Fig. 48b. Hourly Flash Frequencies for the Eastern Portion of the Study Area, September 1990.

Summary

The eastern and western portions of the study area display different temporal preferences of lightning activity. While in 1989 the whole study area reported more daytime strikes than nighttime strikes in June, July, and August, in 1990 July was the only month with more daytime than nighttime flashes. Apart from August 1989 and July 1990 the maximum flash frequencies per cell were reported for the nighttime interval. Areal preferences of lightning activity vary by months. During the day, the east received more lightning strikes than the west in all months except May 1990 and June 1990. The nighttime distribution is not as clear cut. An equal number of months recorded an eastern maximum as a western maximum. Eastern maxima were recorded in April 1989, May 1989, August 1989, August 1990, and September 1990.

CHAPTER 7

SUMMARY AND CONCLUSION

This thesis was designed as a preliminary examination of cloud-to-ground lightning observations for the southern Great Lakes region. It was part of a larger, ongoing research project in the Geography Department at Michigan State University concerned with a climatology of convection in the southern Great Lakes region. The southern Great Lakes region lies astride the boundary between the nocturnal thunderstorm and precipitation regime in the central U.S. and the afternoon regime in the eastern U.S. Therefore, it is ideally suited for a systematic comparison of characteristics of nocturnal and daytime lightning activity and convection.

In the first part of the study, the diurnal and seasonal variations of lightning activity were examined with respect to frequency of ground strikes, number of return strokes, peak amplitude, and polarity. One objective was to investigate the timing of peaks in amplitude and return strokes and their interrelationship. Another objective was to examine temporal variations in the occurrence of positive and negative strikes.

The second part focused on spatial variations in lightning characteristics across the study region. One goal was to determine whether the eastern and western portions of the study area displayed differences in the timing and frequency of lightning events similar to previously identified spatial and diurnal variations of precipitation. Also of interest were temporal and spatial variations in the occurrence of positive lightning flashes. A final objective was the development and/or assessment of computer software suitable for spatial and temporal analysis of lightning observations.

Methodology

For the analysis of temporal trends in lightning characteristics both monthly totals and five-minute maxima of the number of return strokes and peak amplitudes were employed. Cloud-to-ground strike frequencies were calculated for the nighttime (0000-1200 GMT) and the daytime (1200-2400 GMT) period of each month separately.

Return stroke and amplitude characteristics were first analyzed separately and then examined for corresponding temporal trends by means of five-minute maxima. The choice of five-minute intervals was made because they preserve a fairly high degree of diurnal variability. The data for the respective months of both years were combined and each successive five-minute period (00:00-00:05, 00:05-00:10, etc.) was examined for (1) the strike with the highest number of return strokes and (2) the positive and the negative strike with the largest amplitude. In the calculation of the maximum number of return strokes per five-minute period, no distinction was made with respect to polarity since, as previously reported by other authors (e.g. Rust et al. , 1981), a high percentage of positive flashes have only one return stroke. The different amplitude characteristics of positive and negative flashes, however, required that a distinction by polarity be made in the analysis of five-minute maxima of amplitude.

A grid system commonly used for radar observations (MDR grid) was employed for the analysis of spatial variations in lightning characteristics. A 32x19 cell subgrid of the 113x89-cell MDR matrix extending over the conterminous United States was chosen as the analysis area for the southern Great Lakes region. Lightning locations in latitude and longitude were translated to the MDR grid cells (grid spacing is 47.625 km at 60°N) using software programs provided by the National Meteorological Center. Lightning frequencies and the number of lightning days per cell were calculated monthly for the nighttime (0000-1200 GMT) and daytime (1200-2400 GMT) periods. Atlas Mapmaker was employed in the analysis of grid frequencies and to map grid cell values. In addition, hourly flash frequencies for positive and negative flashes were calculated for the eastern and western halves of the study area for both times of day. The graphic output for hourly flash frequencies was produced using Harvard Graphics.

Major Findings: Temporal Analysis

The annual distribution of lightning strikes is in general agreement with other studies of cloud-to-ground lightning characteristics (e.g. Orville et al. 1987) with the most frequent lightning activity in the summer months and little activity in the winter. There is considerable variation in the frequency and distribution of lightning events between 1989 and 1990, although the number of days with lightning occurrences is comparable. In 1990, more lightning events (25,549 flashes) were reported than in 1989 (22,168 flashes) despite the fact that in 1990 data were only available until 25 October. The period of "increased lightning activity" in 1989 includes the months of April through September and in 1990 lasts from May through September. For the entire study area more lightning strikes were recorded during the nighttime (0000-1200 GMT) than during the daytime (1200-2400 GMT) period. In 1989, 53 percent of cloud-to-ground lightning strikes were reported during the night; in 1990, the comparable figure was 60 percent. While overall more strikes were recorded during the night, some months, typically occurring during the warm season (June 1989, July 1989, October 1989, April 1990, and July 1990), reported more strikes during the day.

The higher total number of events and the higher percentage of nighttime events in 1990 suggest different cloud characteristics for both years. One might speculate that nighttime storms are of larger areal extent and/or longer duration and/or generate higher flash-density rates.

A small scale investigation of areal extent, duration, and flash-density rates would be needed to determine whether differences in cloud systems, i.e. a few major storms or a number of smaller storms, are responsible for the differences in flash frequencies between the nighttime/daytime period and between the two years.

The characteristics of return strokes and flash amplitude did not display distinct seasonal differences, although some monthly variations were apparent. For example, the maximum number of return strokes per flash generally was largest in the warm months. The largest number of return strokes for negative flashes (26) was recorded in August 1990; for positive flashes the maximum value of 11 return strokes was recorded in September 1989.

The number of return strokes varied markedly for positive and negative flashes. In general agreement with previous studies (e.g. Rust et al., 1981), a high percentage (70-84 percent) of positive cloud-to-ground flashes had only one return stroke, although the percentage was lower than that reported by Orville et al (1987). Also unlike Orville et al's findings, the percentage of negative flashes with only one return stroke did not fluctuate seasonally but rather fell between 29 and 47 percent throughout the year.

The peak amplitude of lightning flashes also displayed little diurnal or monthly variation. Contrary to previous findings, the peak amplitudes for negative cloud-to-ground flashes tended to be smaller in the cool season. The highest amplitude values were recorded for negative flashes in the warm season; nine lightning flashes >300kA were recorded in June 1989 and July 1989. The strongest recorded amplitude was 617kA.

No direct relationship between the peak current of positive and negative flashes and the number of return strokes was detected in this climatological analysis. Due to the short length of the data set, undue influence by individual storms may overshadow temporal trends. Therefore, case studies of individual storms may be needed to further examine the temporal characteristics of flash densities, peak currents, and number of return strokes.

Major Findings: Spatial Analysis

Over the entire study area, cloud-to-ground lightning was more frequent during the nighttime period (0000-1200 GMT) than during the day (1200-2400 GMT) except for some warm months. However, the eastern and western portions of the study area displayed different diurnal characteristics. In 1989, the eastern half of the study area recorded more strikes than the west during all daytime periods. During the nighttime periods in 1989, only April, May, and August recorded a relative maximum in the east. In 1990, the beginning of the warm season (May and June) displayed a relative maximum in lightning frequency in the western portion of the study area for both the daytime and nighttime periods. After July, a transition month with a daytime maximum in the east and a nighttime maximum in the west, the later part of summer (August and September) showed relative maxima in the east for both times of day.

Little correspondence between the cells of greatest lightning frequencies and the number of days with recorded lightning activity in these cells indicated great differences in flash density for individual storms. Also, the time of day when the largest number of flashes for individual cells was recorded did not always correspond with the time of day of a higher total number of strikes. June and July 1989, for example, with a relative daytime maximum for the entire study area, reported higher maximum flash frequencies per cell during the night.

The axis of largest flash frequency differed considerably between months and the same months of different years indicating the impact of individual storm tracks. A slight tendency for a southwest-northeast axis of higher lightning frequency could be detected in both the plot of all lightning events for the period of "increased lightning activity" and in the plots for individual months (e.g. in the daytime plots for July 1989, August 1989, May 1990 and in the graphs for the nighttime period of April 1989, June 1989, September 1989, and May 1990). The southwest-northeast orientation of the area of highest lightning frequencies that could be observed both during the day and at night suggests that a different areal division for the analysis of daytime versus nighttime characteristics for the eastern and western halves of the study area might be appropriate.

The more frequent occurrence of positive lightning flashes in the western region, particularly at night, may again be indicative of different cloud systems. Positive lightning has previously been reported to occur more frequently in regions of stratiform precipitation as opposed to the convective regions of individual storm systems. Additional analyses of the spatial distribution of positive strikes on an individual storm scale are therefore warranted.

In some months slightly elevated lightning frequencies are apparent over southern Lake Michigan and western and central Lake Erie. The increased lightning activity is especially apparent in the plot of lightning days for the nighttime periods of May 1989, July 1989, and July 1990 and the daytime period of September 1990.

A Note on Software

For the analysis of the lightning observation data set, a number of FORTRAN programs were written by the author. Other software packages that were employed in the temporal and spatial analyses and graphic output included (1) Harvard Graphics for bar charts of five-minute maximum values of return strokes and peak amplitude values and (2) Atlas MapMaker for the analysis of grid cell frequencies and the mapping of flash frequencies and lightning days within the MDR subgrid.

Thirdly, Aldus Freehand was used in combination with Atlas Mapmaker to produce the map of the whole study area (Figure 1).

Limitations of the Study

The most constraining limitation of this climatological analysis was the short length (less than two years) of the data set, especially since the examined 22 months revealed considerable differences in lightning frequency and lightning characteristics between months and the same months of both years. Any seasonal and diurnal trends may be overshadowed by the influence of individual storms. Therefore, the results from the temporal analysis of lightning characteristics, especially the five-minute maximum values of the number of return strokes and peak amplitude, have to be treated with caution.

Different study regions were employed in the first and second part of the thesis. Due to the difference in areal size of the two study regions and the resulting smaller data set in part two (Figure 14), results from the first part of the study could not be incorporated in the discussion on spatial variations.

Recommendations for Further Research

The preliminary examination of the cloud-to-ground lightning observation data set has shown considerable differences in lightning frequencies between the two examined years. For a climatological study of convection the analysis of a longer data set is warranted.

Also, analyses of areal extent, duration, and flash frequency of storm systems for different times of day, by season, and for the eastern and western portions of the study area are needed to answer questions about the nature of lightning producing storms. Of special interest in this context is whether the cloud-to-ground strikes are produced by few major storms or a number of smaller systems.

To further the compatibility of cloud-to-ground lightning observations with observations of precipitation, detailed analyses of the relationships between flash-frequencies, number of return strokes, peak amplitudes, polarity, cloud characteristics, and precipitation amounts over the duration of individual storms are needed. Since this study has suggested different cloud and lightning characteristics for nighttime versus daytime lightning-producing storms, case studies of daytime and nighttime storm systems are strongly recommended.

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APPENDICES

APPENDIX A

FORTRAN Program Grid

```
      PROGRAM GRID
c     December 1991 - C. Gunreben
c        Program to take file of lightning strikes
c     with parameters month, day, year, hour, min,
c     sec, latitude, longitude, # of return strokes,
c     polarity, amplitude and put them into a
c     113x89 grid according to MDR standards.
c        The conversion program provided by the Nat.
c     Meteorol. Center is used to translate the coor-
c     dinates from latitude/longitude to the grid
c     coordinate system overlaid on a polar stereo-
c     graphic map projection true at 60 degrees.
c        The original record is read and the pro-
c     spective grid cell is determined.  The grid
c     cell is added at the end of each record as
c     variable of i and j.
c
c     Variables:
c
c     radpd
c     earthr                  earthradius
c     xmeshl                  meshlength of grid
c                             cells at 60 Degr. N
c     orient                  grid centered along
c                             105 Degr. W
c
c
      INTEGER I,J
      INTEGER MONTH,DAY,YEAR,HOUR,MIN,SEC,MULT
      REAL ELAT,ELONG,STRENGTH,RADPD,XMESHL,ORIENT,
      REAL EARTHR,RE,XI,XJ
      REAL WLONG,R,XLAT
      RADPD=0.01745329
      EARTHR=6371.2
      XMESHL=47.625
      ORIENT=105.0
10    READ (9,123,END=85) MONTH,DAY,YEAR,HOUR,MIN,
     *SEC,ELAT,ELONG,MULT,STRENGTH
123   FORMAT (6(I2,1X),1X,F6.3,2X,F7.3,1X,i2,2X,F6.1)
      ELONG=ABS(ELONG)
      RE=(EARTHR*1.86603)/XMESHL
```

```
      XLAT=ELAT*RADPD                                       GRI00420
      WLONG=(ELONG+180.0-ORIENT)*RADPD                      GRI00430
      R=(RE*COS(XLAT))/(1.0+SIN(XLAT))                      GRI00440
      XI=R*SIN(WLONG)                                       GRI00450
      XJ=R*COS(WLONG)                                       GRI00460
      XI=XI+41                                              GRI00470
      XJ=XJ+161                                             GRI00480
      I=XI                                                  GRI00490
      J=XJ                                                  GRI00500
      WRITE (10,124) MONTH,DAY,YEAR,HOUR,MIN,SEC,           GRI00510
     *ELAT,ELONG,MULT,STRENGTH,I,J                          GRI00520
124   FORMAT (6(I2,1X),1X,F6.3,2X,F7.3,1X,i2,2X,            GRI00530
     *F6.1,2X,I2,2X,I2)                                     GRI00540
      goto 10                                               GRI00550
85    WRITE (*,*) 'DONE'                                    GRI00560
      STOP                                                  GRI00570
      END                                                   GRI00580
```

APPENDIX B

FORTRAN Program Mmultmax

```
      PROGRAM MMULTMAX
c     program to read file of five-minute maxima of
C     the number of strikes (Fivemult) and create
C     files of five-minute maxima for the same
C     months of both years combined
      INTEGER MONTH,DAY,YEAR,HOUR,MIN,SEC,MULT
      INTEGER I,J,K,L,M,AMULT(12,0:23,12)
      REAL ELAT,ELONG,STRENGTH
      DO 15, I=1,12
        DO 25, J=0,23
          DO 35, K=1,12
            AMULT(I,J,K)=0
35        CONTINUE
25      CONTINUE
15    CONTINUE
10    READ (9,123,END=80) MONTH,DAY,YEAR,HOUR,MIN,
     *SEC,ELAT,ELONG,MULT,STRENGTH
123   FORMAT (6(I2,1X),1X,F6.3,2X,F7.3,1X,I2,2X,F6.1)
      DO 45, I=1,2
        DO 55, J=1,12
          DO 65, K=1,31
            DO 75, L=0,23
              DO 85, M=1,12
                IF (MONTH.EQ.J.AND.HOUR.EQ.L.AND.
     *          MIN.LT.(M*5)) THEN
                  IF (AMULT(J,L,M).LT.MULT) THEN
                    AMULT(J,L,M)=MULT
                  ENDIF
20                READ (9,123,END=80) MONTH,DAY,YEAR,
     *            HOUR,MIN,SEC,ELAT,ELONG,MULT,
     *            STRENGTH
                  IF (MONTH.EQ.J.AND.HOUR.EQ.L.AND.
     *            MIN.LT.(M*5)) THEN
                    GOTO 20
                  ENDIF
                ENDIF
85            CONTINUE
75          CONTINUE
65        CONTINUE
55      CONTINUE
45    CONTINUE
80    DO 95, I=1,12
```

```
      DO 105, J=0,23                                     MMU00430
        DO 115, K=1,12                                   MMU00440
          WRITE (I+10,124) I,J,K,AMULT(I,J,K)            MMU00450
124       FORMAT (I2,3X,I2,3X,I2,3X,I2)                  MMU00460
115     CONTINUE                                         MMU00470
105   CONTINUE                                           MMU00480
95  CONTINUE                                             MMU00490
    WRITE (*,*) 'DONE'                                   MMU00500
    STOP                                                 MMU00510
    END                                                  MMU00520
```

APPENDIX C

FORTRAN Program Days

```
      PROGRAM DAYS
C     December 1991 - C. Gunreben
C     program to calculate the number of lightning
C     days per grid cell (32x19 MDR grid) by day/
C     nighttime (0000-1200 GMT / 1200-2400 GMT) and
C     put them into monthly files; output adjusted
C     according to Atlas MapMaker data file require-
C     ments
      INTEGER MONTH,DAY,YEAR,HOUR,MIN,SEC,MULT
      INTEGER CYEAR,CMONTH,CDAY,TIME
      INTEGER I,J,K,L,N,P
      INTEGER COUNT(89:90,12,2,57:88,48:66)
      INTEGER FLAG(2,57:88,48:66)
      REAL ELAT,ELONG,STRENGTH
C
C     variables:
C     month,day,year,hour,min,sec = time variables
C     original data set
C     elat/elong = latitude/longitude original data
C                  set
C     mult       = number of return strokes original
C                  data set
C     strength   = amplitude original data set
C     i/j        = location within 113/89 MDR grid
C                  system calculated by Fortran
C                  Program GRId (C. Gunreben, 1991)
C     l          = variable to adjust output files
C     n/p        = variables to adjust location with-
C                  in 113/89 MDR grid to 32x19 grid
C     time       = variable for distinction daytime/
C                  nighttime in array
C                  1=0000-1200 GMT /2=1200-2400 GMT
C     count      = array to count number of lightning
C                  days per cell
C                  count(year,month,time,i,j)
c     flag       = marker to reject further strikes
C                  for one cell for the same day
c
c     set arrays to 0
      DO 5, CYEAR=89,90
        DO 10, CMONTH=1,12
```

```
          DO 20, TIME=1,2
              DO 30, I=57,88
                DO 40, J=48,66
                  COUNT(CYEAR,CMONTH,TIME,I,J)=0
                  FLAG(TIME,I,J)=0
40              CONTINUE
30            CONTINUE
20          CONTINUE
10        CONTINUE
5       CONTINUE
c       read first record
15      READ (9,123,END=85) MONTH,DAY,YEAR,HOUR,MIN,
       *SEC,ELAT,ELONG,MULT,STRENGTH,I,J
c       read next record if outside grid
        IF (I.GT.88.OR.I.LT.57.OR.J.GT.66.OR.J.LT.48)
       *THEN
          GOTO 15
        ENDIF
123     FORMAT (6(I2,1X),1X,F6.3,2X,F7.3,1X,i2,2X,
       *F6.1,2(2X,I2))
c       set array
        DO 50, CYEAR=89,90
          DO 60, CMONTH=1,12
            DO 65, CDAY=1,31
              DO 66, TIME=1,2
                DO 67, K=57,88
                  DO 68, L=48,66
                    FLAG(TIME,K,L)=0
68                CONTINUE
67              CONTINUE
66            CONTINUE
35            IF (YEAR.EQ.CYEAR.AND.MONTH.EQ.CMONTH.
       *      AND.DAY.EQ.CDAY) THEN
                IF (HOUR.LT.12) THEN
                  TIME=1
C                 check grid cell, if no strike has
C                 been recorded for that day for
C                 0000-1200 GMT - advance daycount for
C                 nightly hours by one
                  IF (FLAG(TIME,I,J).EQ.0) THEN
                    COUNT(CYEAR,CMONTH,TIME,I,J)=COUNT
        *            (CYEAR,CMONTH,TIME,I,J)+1
                    FLAG(TIME,I,J)=1
                  ENDIF
                ELSE
                  TIME=2
C                 check grid cell, if no strike has
C                 been recorded for that day for
C                 1200-2400 GMT, advance daycount for
C                 daytime hours by one
                  IF (FLAG(TIME,I,J).EQ.0) THEN
                    COUNT(CYEAR,CMONTH,TIME,I,J)=COUNT
       *             (CYEAR,CMONTH,TIME,I,J)+1
                    FLAG(TIME,I,J)=1
```

```
                ENDIF                                       DAY00960
              ENDIF                                         DAY00970
C             read next record                              DAY00980
25            READ (9,123,END=85) MONTH,DAY,YEAR,           DAY00990
     *        HOUR,MIN,SEC,ELAT,ELONG,MULT,STRENGTH,        DAY01000
     *        I,J                                           DAY01010
              IF (I.GT.88.OR.I.LT.57.OR.J.GT.66.OR.         DAY01020
     *          J.LT.48) THEN                               DAY01030
                GOTO 25                                     DAY01040
              ELSE                                          DAY01050
                goto 35                                     DAY01060
              ENDIF                                         DAY01070
            ENDIF                                           DAY01080
65        CONTINUE                                          DAY01090
60      CONTINUE                                            DAY01100
50    CONTINUE                                              DAY01110
85    DO 100, CYEAR=89,90                                   DAY01120
        DO 110, CMONTH=1,12                                 DAY01130
          IF (CYEAR.eq.90) THEN                             DAY01140
c           l adjusts output to 22 monthy files             DAY01150
            L=CMONTH+12                                     DAY01160
          ELSE                                              DAY01170
            L=CMONTH                                        DAY01180
          ENDIF                                             DAY01190
C         output adjusted so it can be read directly        DAY01200
C         into Atlas Mapmaker boundary file created         DAY01210
C         for this grid system by C. Gunreben (1991)        DAY01220
          WRITE (10+L,126) 'M','/','D',',','DAYAM',         DAY01230
     *    ',','DAYPM'                                       DAY01240
126       FORMAT (A1,A1,A1,A1,A5,A1,A5)                     DAY01250
          DO 80, I=57,88                                    DAY01260
            DO 90,J=48,66                                   DAY01270
              N=I-56                                        DAY01280
              P=J-47                                        DAY01290
              WRITE (10+L,127) N,'/',P,',',COUNT            DAY01300
     *        (CYEAR,CMONTH,1,I,J),                         DAY01310
     *        ',',COUNT(CYEAR,CMONTH,2,I,J)                 DAY01320
127           FORMAT (I2,A1,I2,A1,I4,A1,I4)                 DAY01330
90          CONTINUE                                        DAY01340
80        CONTINUE                                          DAY01350
          IF (L.EQ.22) THEN                                 DAY01360
            GOTO 150                                        DAY01370
          ENDIF                                             DAY01380
110     CONTINUE                                            DAY01390
100   CONTINUE                                              DAY01400
150   WRITE (*,*) 'DONE'                                    DAY01410
      STOP                                                  DAY01420
      END                                                   DAY01430
```