Summertime Cloud-to-Ground Lightning Activity around Major Midwestern Urban Areas

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ABSTRACT

Cloud-to-ground lightning flash data collected by the National Lightning Detection Network were analyzed in and around 16 central U.S. cities for the period 1989–92. Lightning data are well suited to study storm activity in and around large urban areas since their continuity and coverage in space and time is superior to historical, spatially limited records of thunderstorm activity. Frequency of cloud-to-ground lightning flashes (of negative and positive polarity) in the area immediately upwind, within, and immediately downwind of the cities were compared. An enhancement of lightning frequency on the order of 40%–85% was found over and downwind of many of these cities.

A number of possible urban-related causal factors were examined including effects of increased urban concentrations of cloud condensation nuclei, urban population and size, and the presence of distinct topographic features in and around the cities. Various factors, physical and anthropogenic, appeared to interact in diverse ways to account for changes in lightning flash frequency. The enhancement of lightning activity was largest during the afternoon hours when the urban–rural temperature differences are usually smallest, but when the atmosphere is generally the most unstable and when there is often a maximum in convective activity. The spatial distribution of the first 50 lightning flashes from each storm suggested that the urban area did not initiate new lightning storms. Thus, the overall results suggested that existing thunderstorms were the most strongly affected.

1. Introduction

Cloud-to-ground (CG) lightning data were used to examine regional differences in convective activity in and around 16 urban areas in the central United States. Cities were selected to span a range of sizes, populations, pollution characteristics, and topographic features. A unique new dataset from a network of lightning sensors developed in the 1980s was drawn upon for this study. The data were CG lightning flash observations from the National Lightning Detection Network (NLDN), and the data coverage was continuous in time and space. Many problems (poor station density, recording errors, calibration errors, hourly or daily values) limiting the results of studies based on surface observations were therefore minimized. Thus, a more definitive examination of storm activity was permitted than from historical records of thunder events at widely distributed weather stations. The spatial coverage was especially important for urban areas adjacent to a large body of water. This study investigated the frequency of CG lightning flashes (of negative and positive polarity) in three areas: immediately upwind of the cities, within the cities themselves, and immediately downwind of the cities. Differences in CG activity may have been due to enhanced storm activity, local features (water bodies, topography, urban influences on clouds), or structural differences (lightning "targets") between urban and rural areas. These factors that may have influenced the presence or absence of apparent localized differences were examined.

2. Data analysis

Lightning data for the years 1989 to 1992 were obtained from the archives of the NLDN. In the Midwest, this network utilizes data from lightning detectors (wideband, magnetic direction-finder antennas) operated by GeoMet Data Services, Inc., Tucson, Arizona, and the National Severe Storms Laboratory. The detection efficiency of individual lightning flashes is about 70%, and the CG flash location accuracy is usually within 10 km, but could be as large as 16 km. Location accuracy is related to azimuthal errors, the largest of which are associated with local site anomalies that have been evaluated annually and should have contributed minimally to location errors (Orville 1994). Azimuthal errors also depend on the direction-finder network configuration and flash location within the network, and thus in part to the number of direction finders sensing an individual lightning flash. In an attempt to minimize azimuthal errors, at least six direction finders had to be located within 400 km of the urban center for a city to be selected for this study.

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TABLE 1. The size and 1988 population of cities examined for possible urban effects on lightning frequency.

City	Metropolitan population	Urban population	Urban area (km^2)
Chicago	8 180 900	2 977 520	2298
Detroit	4 620 200	1 035 920	2224
Dallas–Fort Worth	3 766 100	1 671 430	1248
Minn.–St. Paul	2 387 500	603 780	960
St. Louis	2 466 700	403 700	864
Cincinnati	1 728 500	370 480	752
Milwaukee	1 571 700	599 380	736
Kansas City	1 575 400	438 950	704
Indianapolis	1 236 600	727 130	592
Columbus	1 344 300	569 570	544
Louisville	967 000	281 880	544
Wichita	483 100	295 320	432
Oklahoma City	936 800	434 380	400
Tulsa	727 600	368 300	336
Omaha	621 600	353 170	320
Toledo	616 500	340 760	288

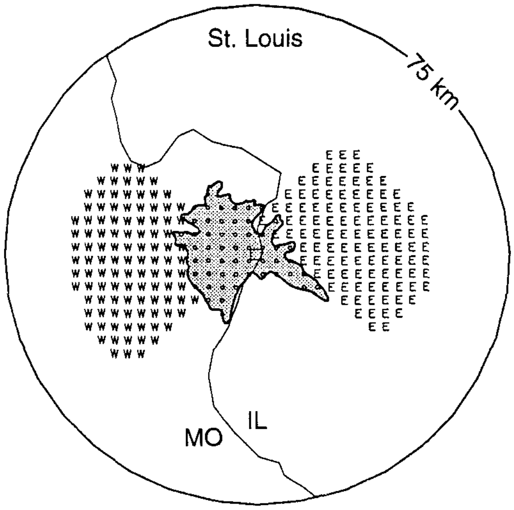

FIG. 1. Grid points selected for the upwind west (W), downwind east (E), and urban area (O), superimposed on an outline of St. Louis. A 75-km-radius circle and the Illinois–Missouri border are plotted.

Lightning data were extracted for the region within 120 km of 16 Midwestern cities with metropolitan populations of greater than 500 000 (Table 1). The urban boundaries were delineated by the corporate limits of the cities, as of 1987 (Rand McNally Cosmopolitan World Atlas 1988). The urban areas ranged in size from 288 to 2928 km^2. While the smaller cities selected had a diameter larger than that of the worst estimate for location accuracy, it might be argued that more confidence should be placed in the results of the largest eight cities.

For ease in computation, each individual lightning event was assigned to a 4 km × 4 km grid square within the 120-km radius, and within each grid, the events were either summed (for the number of flashes and return strokes) or averaged (for the amplitude of the first return stroke). Grid boxes encompassed by the upwind and downwind areas were selected based on the strong westerly component of the prevailing storm motion for the Midwest. Hence, the upwind area was located to the west of the city and the downwind area to the east of the city. Both the upwind and downwind areas were defined to include twice the number of grid points of the urban area and to have widths comparable to the diameters of the cities. An illustration of the urban, downwind, and upwind grid point designation for St. Louis is presented in Fig. 1. The analysis was based on June, July, and August of the four years, the three peak months of thunderstorm activity.

Lightning flash events within 120 km of each city were grouped into storms. A storm was considered to consist of 5 or more CG flashes, with the flashes separated from all other flashes in the area by more than 1 h. No attempt was made to impose a spatial limit on the location of flashes within each storm. The storms ranged in flash occurrence, from 5 up to 42 000 flashes. The storms were analyzed by the frequency of flashes per storm, so that the very largest storms would not mask any possible urban effect upon the smaller storms. They were grouped into five classes: 5–50, 51–500, 501–5000, 5001–15 000, and greater than 15 000 flashes. Analysis also was done for all storms combined (Table 2). The results presented are for the storms or portions of storms that occurred within the upwind (west), downwind (east), and urban areas. Often storms were not completely contained within the upwind, downwind, and/or urban areas, so the statistics presented are for portions of the storms that entered into these three areas.

3. Results

For many cities, the total number of CG flashes were found to occur more frequently within and downwind of the urban area than for the western upwind area. For each city and storm class, regional differences in flash frequency were examined for statistical significance. Statistical significance for differences in the median and distribution of the change in flash frequency was determined using a two-sided Wilcoxon rank sum

TABLE 2. Number of lightning storms or partial lightning storms for 16 central U.S. cities, during June–August 1989–92.

Number of flashes	Mean	Std dev
A: 5–50	17	10
B: 51–500	41	10
C: 501–5000	63	10
D: 5001–15 000	16	6
E: >15 000	2	2
All storms	138	25

test (Bickel and Doksum 1977), and testing for differences in the mean number of flashes was done using the Student's t-test. In most instances, the results of the two tests were in agreement as to whether differences were significant at the 0.05% level.

In Table 3 (upwind versus urban) and in Table 4 (upwind vs downwind), pluses (+) indicate west-to-east increases in flash frequency and minuses (−) indicate decreases, both of which are significant at the 5% level. Consideration of all storms reveals 12 of the 16 urban areas showed statistically significant increases in CG frequency over the city (Table 3). Comparison of the downwind frequencies with the upwind frequencies revealed a higher frequency in the east downwind area at 13 of the 16 cities (Table 4). Conversely, at three cities (Detroit, Cincinnati, and Toledo) there were significant decreases in the downwind area. These three cities, except possibly Cincinnati, showed little significant change in lightning frequency over the urban area (Table 3).

The small storms ("A" in Tables 3 and 4) averaged only 0.3 flashes per 16 km^2 in the upwind area, and represent only a few events. While the large "D" and "E" storms averaged 45 and 26 flashes per 16 km^2, respectively, they also represented only a few events at each city. Caution should be taken in considering statistically significant values in these categories, and in considering significant values for all storms when only the D and E categories were significantly different. For the A storms, the total number of flashes sampled was very small and the total number of storms small; thus, the results may be skewed by the storms sampled. When only the D or E storms were significant—such as in Columbus, Indianapolis, and Louisville (Table 3)—the significant changes in lightning frequency may have been due to only a few events and again not as representative as categories with a larger sample of storms. The average number of flashes per 16 km^2, observed in the upwind area for the four summers of data, was 2.8 for the "B" storms, and 36 for the "C" storms. Thus, emphasis here is placed on the results for the C storms (501–5000 flashes) because they have both a moderately large flash density and a large sample of storms.

TABLE 3. Significant changes in CG flash frequency from the upwind to the urban area for storms grouped by flash frequencies of (A) 5–50, (B) 51–500, (C) 501–5000, (D) 5001–15 000, (E) > 15 000, and for all storms. Plus signs (+) refer to significant increases in the urban area and minus signs (−) to significant decreases. Circles denote no storms in the category.

City	A	B	C	D	E	All
Chicago		+	+	−	+*	+
Detroit				−**	○	
Dallas–Fort Worth		−	+		○	+
Minn.–St. Paul		−	+	**	○	+
St. Louis		+	+	+	−*	+
Cincinnati	−	−			−	
Milwaukee	**	−	+	−**	+*	+
Kansas City		+	+	+	−*	+
Indianapolis					+	+
Columbus	**			+	+	+
Louisville		+			+	+
Wichita				+	*	+
Oklahoma City					+*	+
Tulsa	+**	+			○	
Omaha	**		+	+	*	+
Toledo	*			**	*	

* Based on 1–3 storms.
** Based on ≤10 storms.

TABLE 4. Significant changes in CG flash frequency from the upwind to the downwind area for storms grouped by flash frequencies of (A) 5–50, (B) 51–500, (C) 501–5000, (D) 5001–15 000, (E) > 15 000, and for all storms. Plus signs (+) refer to significant increases in the urban area and minus signs (−) to significant decreases. Circles denote no storms in the category.

City	A	B	C	D	E	All
Chicago		−	+	−	+*	+
Detroit			−	**	○	−
Dallas–Fort Worth	−		+	+	○	+
Minn.–St. Paul	+	−		+**	○	+
St. Louis		+	+	−	−*	+
Cincinnati	−				−	−
Milwaukee	**	−	+	**	*	+
Kansas City		+	+	+	*	+
Indianapolis				+	+	+
Columbus	**		+	+	+	+
Louisville		+	+		+	+
Wichita		+	+	+	*	+
Oklahoma City		+		+	+*	+
Tulsa	**	−	+	+	○	+
Omaha	**	+	+	+	+*	+
Toledo	*	+		−**	−*	−

* Based on 1–3 storms.
** Based on ≤10 storms.

The results for the C storms in the Chicago and St. Louis areas generally agreed with those of past studies (Changnon 1980; Changnon et al. 1981). Overall, there were more convective storms over and downwind of the cities (Table 5). Increases in the number of flashes produced by C storms from the upwind to the urban area were 22% over Chicago and 36% over St. Louis. The C storms in the downwind area, as compared to those in the upwind area, were also greater at both cities, by 23% at Chicago and by 136% at St. Louis. A statistically significant enhancement of both urban and downwind lightning flash frequency for C storms also was found for Dallas–Fort Worth, Kansas City, Milwaukee, and Omaha.

For the C storms, all of the large cities except Detroit and Cincinnati showed some indication of increased lightning frequency within the urban area, and all but Minneapolis–St. Paul, Detroit, and Cincinnati showed increases downwind of the city. Except for Omaha, the eight smaller cities showed little change in lightning

TABLE 5. For C storms (501–5000 flashes), the mean number of CG flashes per 16 km^2 found in the upwind west areas, and significance of changes in frequency of CG flashes from the upwind to the urban area and from the upwind to the downwind area.

		(Urban − upwind/upwind)		(Downwind − upwind/upwind)	
City	Upwind flashes	Percent change	*P* value	Percent change	*P* value
Chicago	26	22.4	0.000	23.2	0.000
Detroit	35	3.2	0.491	−20.0	0.000
Dallas–Fort Worth	27	97.5	0.000	109.8	0.000
Minn.–St. Paul	30	26.3	0.000	7.1	0.488
St. Louis	23	35.6	0.000	136.3	0.000
Cincinnati	59	8.2	0.086	4.4	0.414
Milwaukee	20	40.8	0.000	26.6	0.001
Kansas City	29	46.7	0.000	57.7	0.000
Indianapolis	43	24.3	0.308	16.1	0.559
Columbus	34	−6.8	0.337	40.7	0.000
Louisville	41	18.0	0.282	53.8	0.000
Wichita	40	10.5	0.071	30.4	0.000
Oklahoma City	37	13.3	0.078	8.7	0.072
Tulsa	38	−9.4	0.436	13.8	0.014
Omaha	40	12.7	0.043	20.2	0.000
Toledo	37	−6.1	0.073	−24.1	0.126

frequency for the C storms within the urban area. Five of these smaller cities, however, showed increases in lightning immediately downwind of the city.

4. Possible factors relating to spatial changes in flash frequency

The spatial shifts in lightning frequency were examined with regard to possible factors that could cause such changes. These include effects of increased urban concentrations of cloud condensation nuclei, urban population and size, the presence of distinct topographic features in and around the cities, and possible structural differences that might lead to more CG lightning flashes. The data also were analyzed according to diurnal variations and by their downwind characteristics to help clarify causes for the spatial differences.

The influence of urban areas on the local climate has been a matter of interest for a number of decades. The existence of "urban heat islands" is well established. It also has been established that large cities affect convective processes, although the nature of this influence has been examined only in part because of differences in urban settings (building architecture, building density, and topography); in the chemical composition and concentration of pollutants; and in the local climate (prevailing winds and humidity). Technical limitations also make collection of certain microphysical, kinematic, and even precipitation measurements difficult (Oke 1982). Cities, however, are generally considered to be characterized by factors that could contribute to enhanced convection. They are a source of heat that can destabilize air flowing over the city, a source of cloud condensation nuclei (CCN) or ice nuclei that can alter precipitation formation processes, and a source of frictional lift that can promote convection (Oke 1979; Landsberg 1981; Changnon et al. 1981).

Two major field experiments examined the effect of urban areas on the initiation and enhancement of summer rainfall, employing large, dense rain gauge networks, weather radars, and a wide array of other weather sensors. Observations made in the St. Louis area during project METROMEX (Metropolitan Meteorological Experiment, 1971–75) indicated that the warm and aerodynamically rough urban surface promoted increased mixing and convection within the boundary layer (Changnon et al. 1981). Observations of low-level convergence (Ackerman 1978) and numerical simulations of the St. Louis area (Hjelmfelt 1982) indicated that a combination of urban effects led to positive vertical velocities over and downwind of the urban area. A 15% increase in summer average precipitation was found over and downwind of St. Louis. This urban effect on rainfall was most apparent in larger, organized convective storms, about 25% of the total population of summer rain events. The five-year METROMEX project also employed data on thunderstorm occurrences from seven observer stations and from six thunder-sensing devices distributed in and around St. Louis to study possible local changes in storms (Semonin 1981). This analysis showed that summer thunderstorm activity was locally enhanced; the 5-yr average number of thunder days west of St. Louis was 18, while the average within the city and extending out 40 km east of the city was 25, an increase of 40%. A second field project, the three-year Chicago Area Project (CAP, 1976–78), corroborated the rainfall results of the St. Louis study. Summer rainfall over and downwind of Chicago was found to increase by 15%, and the increases again were most apparent in the larger storms (Changnon 1980).

A number of other studies have assessed warm season convective anomalies around cities in other regions. A climatological study of rainfall amounts, thunder events, and hail occurrences (Huff and Changnon 1973) indicated a localized increase in thunderstorm activity at seven of nine large U.S. cities investigated. The effect at times was found to extend 50 km downwind of the urban area. This study also suggested that city size may determine the amount of change in storm activity, with larger cities having the greatest increases in the occurrence of thunderstorm days.

In a study of 10 years of precipitation data from southeast England, Atkinson (1969) found that only a small percent of storms contributed to a statistically significant maximum in rainfall in central London. Atkinson (1971, 1975), in several case studies of storms passing over London, found evidence of urban effects and concluded, as did Changnon et al. (1981), that mechanical lifting established by the city was the primary cause of urban rainfall increases. Harnack and Landsberg (1975) showed that thermal effects were an important factor leading to a positive urban rainfall anomaly in Washington, D.C. A study of precipitation over the Judean Mountains in Israel indicated that a positive precipitation anomaly existed over Jerusalem (Shafir and Alpert 1990). Based on numerical modeling results, this rainfall enhancement was attributed to the effects of higher urban temperatures, humidity, and CCN concentrations. These studies, which are strongly suggestive of an urban influence on summertime convective activity, typically have taken a case study approach, or have been climatological studies limited by data with nonoptimal station spacing (Landsberg 1981).

To assess possible influences of urban particulate matter on storm activity, annual averages of PM10 (particulate matter with aerodynamic diameters smaller than 10 μm) and sulfur dioxide (SO_2) were used as gross indicators of CCN concentrations (U.S. Environmental Protection Agency, National Air Quality and Emissions Trends Report 1989, 1990). The 1988 urban and greater metropolitan populations were used as a measure of the size of the urban influence on the atmosphere. To investigate possible topographic effects, mean elevations were determined for 2 km × 2 km grid boxes within 120 km of the city center for the three largest cities, within 75 km for the next five largest cities, and within 60 km for the smallest eight cities. The geographical features considered were proximity to a large body of water that could act either to suppress or enhance summertime convection; the presence of a major river that could act as a source of moisture; and the general shape of the terrain features in the urban area. Assessment of possible differences due to structural differences between edifices in the urban and rural environs relied on past findings.

a. Anthropogenic nuclei

A number of studies have shown that convection can be enhanced downwind of particulate generating sources, such as pulp and paper mills (Hobbs et al. 1970; Mather 1991). Hobbs et al. (1970) found significant increases in rainfall, on the order of 30% immediately downwind of pulp and paper mills in Washington State. In the Mather (1991) study, the appearance of large (>4 mm) drops at $-10°C$ was found just downwind of a paper mill, which indicated an enhanced coalescence precipitation formation process, possibly the result of the observed broadening of the cloud droplet spectra at cloud base. The clouds downwind of the mill also were found to be taller, longer lasting, and to produce more rain than most other storms in the area.

While urban areas are generally sources of particulate matter, differences in the chemical composition, concentration, and size distribution of urban particulates may have differing effects on cloud and precipitation processes. Braham (1974) indicated that CCN levels in St. Louis were elevated and altered the cloud drop distribution by increasing the number of small drops. The possibility that increased numbers of CCN may reduce the efficiency of precipitation growth due to competition between particles, was suggested by the results of Warner and Twomey (1967) and Warner (1968) where precipitation downwind of sugar cane fields in Queensland was diminished. Eagleman et al. (1972) indicated a downward trend in New York City precipitation (1927–65) during a period of increased industrialization, also suggesting the negative effects of increased CCN. However, it also was found in St. Louis that radar first echoes developed at a lower elevation over the urban area. It was postulated that ultragiant CCN observed emanating in St. Louis were responsible for the more rapid growth of precipitation-sized drops. Further, it was suggested that the large CCN may have played an indirect role by enhancing the Hallet–Mossop (1974) ice multiplication processes, resulting in enhanced glaciation of clouds (Braham 1981). A direct physical link between anthropogenic nuclei and the urban precipitation anomaly, however, was not found in the St. Louis study.

Examination of PM10 values (Table 6) revealed that only St. Louis exceeded the expected Environmental Protection Agency (EPA) annual mean criteria of 50 $\mu g\ m^{-3}$ for PM10 in both 1989 and 1990. Chicago, Kansas City, and Omaha had the next highest values of PM10 for these two years. None of the cities exceeded the annual mean criteria of 0.03 ppm for SO_2 in 1989 and 1990. As expected, the cities covering a wider area and with a larger population had larger annual values of PM10 and SO_2, and they also generally had larger urban and downwind values of CG flashes. Dallas–Fort Worth, Cincinnati, and Detroit were notable exceptions. While enhanced lightning activity over and

TABLE 6. Factors that might lead to changes in lightning flash frequency: cloud condensation nuclei (CCN) concentration estimated by the annual average (1989 and 1990) of PM10 and SO_2; slope (m m^{-1}) of a 10-km-wide west-to-east swath through the upwind, urban, and downwind areas (m m^{-1}).

City	PM10 ($\mu g\ m^{-3}$) 1989, 1990	SO_2 (ppm) 1989, 1990	Upwind fall (m m^{-1})	Downwind rise (m m^{-1})
Chicago	48, 45	0.011, 0.010	0.0009	0
Detroit	52, 35	0.015, 0.018	0.0021	0
Dallas–Fort Worth	36, 35	0.005, 0.006	0.0030	0.0005
Minn.–St. Paul	33, 34	0.010, 0.010	0.0060	0.0045
St. Louis	76, 82	0.018, 0.015	0.0026	0.0040
Cincinnati	45, 35	0.016, 0.017	0.0002	0.0020
Milwaukee	40, 35	0.007, 0.007	0.0020	0
Kansas City	47, 43	0.006, 0.004	0.0023	0.0015
Indianapolis	43, 38	0.014, 0.013	0.0100	0.0040
Columbus	40, 35	0.010, 0.008	0.0020	0.0035
Louisville	38, 36	0.012, 0.012	0.0033	0.0045
Wichita	31, 30	—, 0.009	0.0020	0.0010
Oklahoma City	27, 29	0.006, 0.004	0.0033	0
Tulsa	36, 27	0.007, 0.012	0.0020	0
Omaha	46, 44	0.002, 0.002	0.0020	0.0045
Toledo	—, 26	0.008, 0.007	0.0013	0

downwind of Dallas–Fort Worth was evident, the city was "cleaner" than the other large cities. Both Detroit and Cincinnati were relatively "dirty" but exhibited little effect on localized lightning activity. Sanderson and Gorski (1978) in a six-year study of the Detroit area (spring, summer, and fall 1970–75) found an increase in precipitation in the western regions of Detroit, but a downwind decrease in precipitation and in the number of rain days when traveling from west to east, from Detroit to either Lake St. Clair or to Windsor. They speculated that this decrease was related to urban production of large numbers of CCN, which compete for moisture and result in fewer precipitation-sized drops in the downwind regions of the city. Because of the prevailing wind direction (south-southwest) they felt the nearby Great Lakes had little impact on the precipitation pattern in the area.

While increased concentrations of CCN may have contributed to the increase or decrease in lightning flashes in some cities, without direct measurements of CCN and cloud drop size spectra it is not possible to draw firm conclusions regarding their impact on these cities. The CCN findings, in comparison with the lightning findings, indicate that other factors were likely influencing local convective activity.

b. Urban size and topographic features

The urban heat island, the difference in temperature between the urban area and the surrounding countryside, has been found to increase as a function of urban population (Oke 1973, 1982). The temperature difference is typically most obvious during the nighttime hours. The results of Huff and Changnon (1973) also indicated that the increase in the number of days with thunder in seven of nine large U.S. cities might be related to the size of the urban area. The intensity of the urban heat island was found by Oke (1982) to be strongly related to both population and to changes in the urban radiation budget resulting from differences in urban and rural building properties (size, density, construction materials) and geometry (the area of the overlying hemisphere open to the sky). The prevailing climate (winds, cloud type, and atmospheric stability) and season, and the land use distribution act to modulate the physical effects related to the urban environment (Oke 1982; Karl et al. 1988). A substantial observational and modeling effort for each city would be required to relate these factors to the urban heat island and to effects upon thunderstorm activity. Thus, urban size and population were employed as easily measured indices of the many urban factors that could influence cloud and precipitation processes.

The change in lightning flash frequency was examined with regard to urban population and size. Values of the mean percentage change in C storm lightning flash frequency from the upwind to the urban areas, and from the upwind to the downwind areas are presented for the 16 cities in Figs. 2 and 3, respectively. Examination of the data from all 16 cities does not suggest that the size or population of the city affected the magnitude of the flash frequency.

However, if the four cities adjacent to the Great Lakes are ignored (Chicago, Detroit, Toledo, and Milwaukee), the relationship between urban population (or size) and changes in flash frequency improves greatly. The correlation between the percent change in total flash frequency and urban size increased from less than +0.2 to greater than +0.55 when the four lake cities were excluded. In both Chicago and Milwaukee, cities with large regions of urban area adjacent to the western shore of Lake Michigan, there was an increase

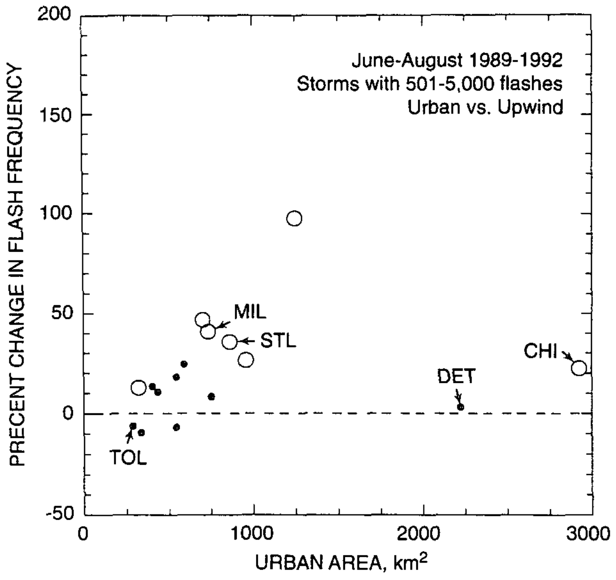

FIG. 2. Percent change in CG flash frequency from the upwind to the urban area for C storms (501–5000 flashes) in 16 Midwestern cities, June–August 1989–92. Open circles refer to cities with statistically significant changes, and closed circles to cities with insignificant changes.

in lightning frequency over and downwind of the city. In Chicago, many instances have been observed where a lake-breeze situation has enhanced convection over the city (e.g., Changnon 1980). However, the magnitude of the four-summer average increase in lightning frequency was not what might be expected for a city of its size. Also, for both Chicago and Milwaukee the increase was the same or smaller downwind than over the city. Detroit and Toledo have a smaller portion of their urban shore adjacent to a large lake and thus have fewer lake-breeze situations. Therefore, sufficient cooling and stabilization of the atmosphere may occur to create a localized decrease in convection. The results suggest that at these four cities, lake influences may overwhelm or diminish any possible urban enhancement of convection over and particularly downwind of the city.

Most of the 16 cities were located along a river or large body of water. Six cities were located along major river valleys of considerable size, either the Ohio, Missouri, or Mississippi River valleys. These cities included Omaha, Minneapolis–St. Paul, St. Louis, Louisville, Kansas City, and Cincinnati. A north–south orientation of the river was found in the first four of these cities. These same four cities had some of the largest cross-sectional elevation changes both upwind and downwind of the city, based on the west-to-east slope of a 10-km swath through the upwind, urban, and downwind areas (Table 6). All six cities except Cincinnati, which is characterized by an extremely complex terrain, showed an increase in lightning activity over or downwind of the city. The varied terrain in the Cincinnati area may act to diffuse local organized circulations and hence any notable urban influence on the atmosphere.

Indianapolis and Columbus also were characterized by relatively large slopes in the mean terrain of both the upwind and downwind areas. For the C storms, however, only the change in CG flash frequency from the upwind to downwind area in Columbus was statistically different (Table 5). Dallas–Fort Worth, Tulsa, and Wichita, which showed little terrain differences in the downwind area, showed statistically significant increases in lightning activity. Dallas–Fort Worth showed some of the largest increases for all 16 cities. Thus, for these six cities (Indianapolis, Columbus, Dallas–Fort Worth, Tulsa, and Wichita), topographic features do not appear to greatly impact urban effects. Numerical modeling studies such as those by Hjelmfelt (1982) are required to further explore the interaction of terrain features and major water bodies on convection in urban locations.

c. *Onset of lightning, diurnal differences, and downwind effects*

Results from the METROMEX project indicated that increased numbers of radar first echoes (first radar observation of clouds containing precipitation-sized drops) occurred over and downwind of St. Louis (Braham and Dungey 1978). To determine whether the onset of lightning within a thunderstorm was observed more often within the 16 cities, the locations of the first 50 flashes from all storms were examined. No indication was found of a greater number of thunder-

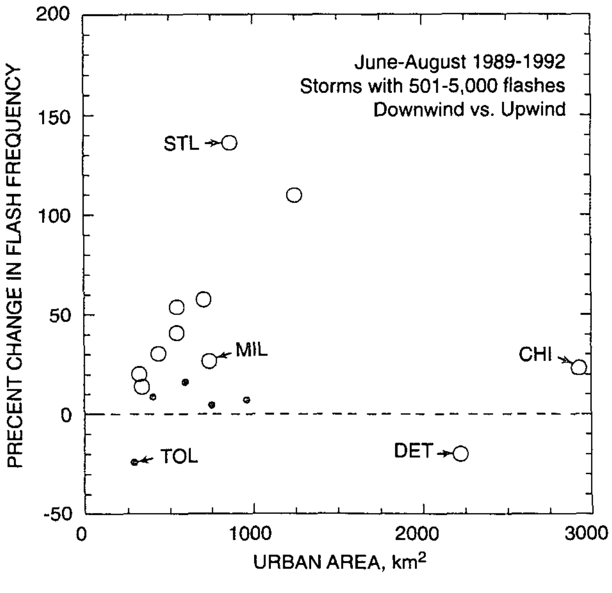

FIG. 3. As in Fig. 2 but for the percent change in CG frequency from the upwind to the downwind area for C storms.

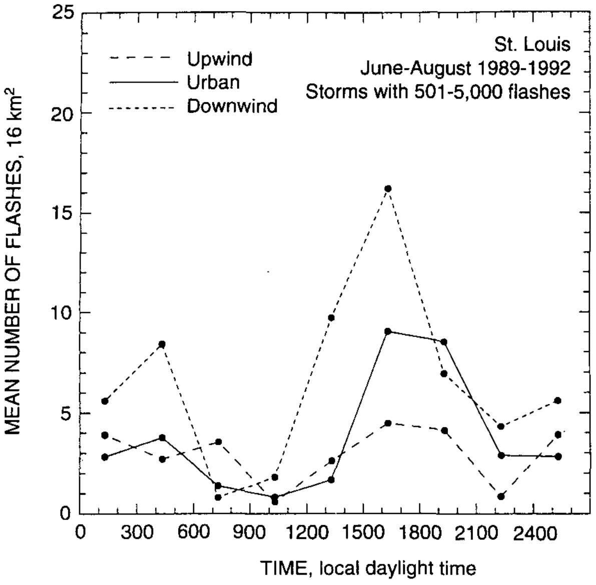

FIG. 4. Temporal plot of the mean number of CG flashes per 16 km^2 for the upwind, urban, and downwind areas for C storms (501–5000 flashes) in St. Louis, June–August 1989–92.

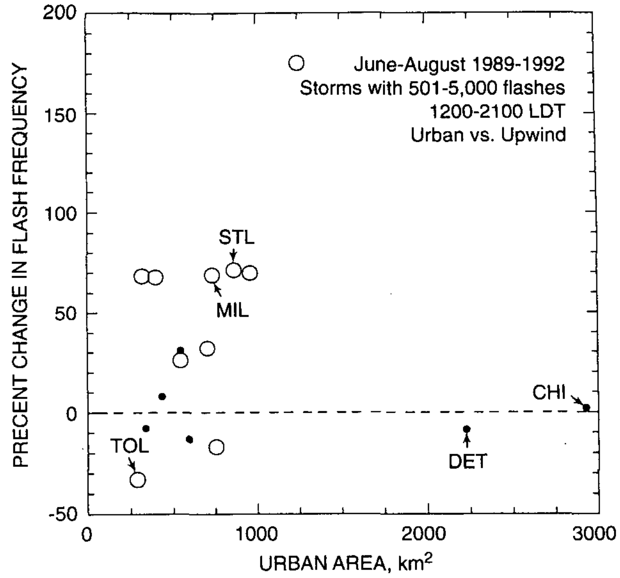

FIG. 5. As in Fig. 2 but for the percent change in CG frequency from the upwind to the urban area for C storms during the period 1200–2100 LDT.

storms producing lightning first over or downwind of the 16 urban areas. This suggests that although an urban area may initiate new cloud growth, the effects on thunderstorm activity may be realized most by enhancing CG activity in existing thunderstorms that pass over the city and beyond.

Prior St. Louis radar findings also indicated that echoes could grow to greater heights over and downwind of the urban area during the afternoon hours when the maximum interaction occurs between the urban heat island and the unstable air flowing across it (Braham and Wilson 1978). A temporal plot of the mean number of flashes per 16 km^2 within a 3-h period for the C storms in St. Louis (Fig. 4) shows an afternoon enhancement of lightning flash frequency in the urban and downwind areas. A similar examination of lightning frequency during the period of maximum convective activity, from 1200 to 2100 LDT, was made for all cities. During the afternoon and early evening hours, 8 of the 16 cities showed a statistically significant increase in lightning over the urban area (Fig. 5), and 10 cities showed an increase downwind of the urban area (Fig. 6). For the cities with a statistically significant increase in flash frequency, the percent change for C storms was considerably greater during the afternoon period: an average of 72% and 85% for urban and downwind areas, respectively, during the afternoon (Table 7), as opposed to increases of 40% and 51% over a 24-h period (Table 5).

When examining the afternoon results from the C storms, based on whether or not the city was in close proximity to the Great Lakes, it was found that 8 of the 12 "non-lake cities," and only 1 of the 4 "lake cities" had larger increases in lightning frequency over and downwind of the city. For the non-lake cities, the downwind–upwind differences usually were the same or larger than the urban-upwind differences. For the four lake cities, the downwind–upwind differences were the same or smaller than the urban-upwind differences. These results suggest again that, in some instances cool, stabilizing air over the lakes may have acted to suppress convection particularly downwind of the urban areas.

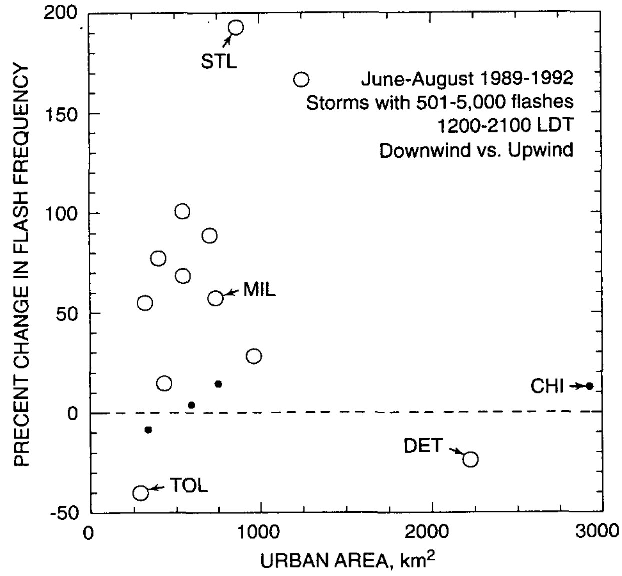

FIG. 6. As in Fig. 2 but for the percent change in CG frequency from the upwind to the downwind area for C storms during the period 1200–2100 LDT.

TABLE 7. For C storms (501–5000 flashes), occurring during the period 1200–2100 LDT, the mean number of CG flashes per 16 km^2 found in the upwind west areas, significance of changes in frequency of CG flashes from the upwind to the urban area and from the upwind to the downwind area.

City	Upwind flashes	(Urban − upwind/upwind)		(Downwind − upwind/upwind)	
		Percent change	P value	Percent change	P value
Chicago	16	2.1	0.378	12.7	0.419
Detroit	18	−8.6	0.166	−23.8	0.000
Dallas–Fort Worth	11	175.2	0.000	166.5	0.000
Minn.–St. Paul	9	69.8	0.000	28.2	0.001
St. Louis	11	71.3	0.000	192.9	0.000
Cincinnati	41	−17.1	0.001	14.3	0.710
Milwaukee	10	68.7	0.000	57.3	0.000
Kansas City	11	32.0	0.010	88.8	0.000
Indianapolis	25	−13.2	0.242	4.0	0.742
Columbus	20	26.0	0.025	100.7	0.000
Louisville	28	31.0	0.072	68.5	0.000
Wichita	18	8.0	0.554	14.6	0.006
Oklahoma City	15	67.7	0.000	77.3	0.000
Tulsa	20	−7.8	0.861	−8.5	0.552
Omaha	10	68.2	0.000	55.0	0.000
Toledo	27	−33.1	0.046	−40.2	0.001

d. Urban–rural structural differences

Building density and construction materials differ in urban and rural areas. To investigate the impact of structural differences on lightning frequency, a survey of lightning damage and injuries based on land-use areas and building types was done as part of a 34-year climatological study (Changnon 1964). Overall, more buildings were damaged in rural areas while a greater frequency of lightning damage was found per square mile in urban areas. Most damage (82%) in rural area was done to farm buildings, 90% of which were barns. Because barns are typically the tallest structures within a group of rural buildings, and often are constructed of wood, they are the most susceptible to damage. As most property damage resulted from fires caused by lightning, it may be that more buildings are susceptible to damage in rural areas than in urban areas. A factor of 10 to 35 more buildings were damaged or destroyed in cities and towns per unit area, respectively, than in rural areas. Because there is often a factor of 10 more buildings per unit area in cities, the amount of lightning damage in an urban area may simply result from a greater density of buildings. As increases in CG flash frequency generally were present downwind of urban areas and often were greater in downwind areas than over cities (Tables 5 and 7), it therefore could be concluded that lightning frequency was not greatly affected by urban–rural structural differences.

5. Summary and conclusions

An examination of four years of summertime CG lightning flash frequency in and around 16 central U.S. cities, indicated that summertime CG lightning frequencies were greater within and downwind of most of the urban areas. When possible causal factors were examined, it was found that no single factor could explain the observed increase in lightning flash frequency over and downwind of the cities. A summary of the results follows.

1) In general, the larger cities had higher annual values of SO_2 and PM10 and had larger increases in lightning activity. There were notable exceptions, however. Dallas–Fort Worth was relatively clean but exhibited some of the largest changes in lightning flash frequency, and Detroit and Cincinnati, relatively dirty cities by this measure, had some of the smaller and even negative changes in flash frequency.

2) If the four cities located near one of the Great Lakes were disregarded, there was some evidence that the urban effect on lightning frequency increased with urban size. For the cities adjacent to a large lake, it appears that the local influence of the lakes on convection may have overwhelmed (Detroit and Toledo) or at least diminished (Chicago and Milwaukee) possible urban effects.

3) In some instances, a deep north–south-oriented river valley may have aided in focusing an increase in CG lightning activity (St. Louis, Minneapolis, Omaha, and Louisville). In other urban regions with a smaller downwind rise in elevation, however, a large urban effect also was observed over and downwind of the city (Dallas–Fort Worth, Milwaukee, and Kansas City).

4) The enhancement of lightning activity was largest during the afternoon hours when the urban–rural temperature differences may be smallest, but when the atmosphere is generally the most unstable and most apt to produce convective storms. There did not appear to be an increase in the number of lightning storms ini-

tiated over the city, and as found in previous studies, these results suggest that the urban area can strongly affect existing convective activity.

Some of the ambiguities found here regarding the effects of topography, the urban setting, atmospheric stability, and pollution sources upon the spatial distribution of CG lightning may be explained in part by examining the frequency of lightning flashes with respect to the speed and direction of motion of lightning storms and their path across the urban area, by further examination of diurnal effects and by evaluation of the ambient storm environment. Future work is planned that will address these issues and include several more years of data to more closely examine where and when spatial changes in CG frequency due to urban effects might be expected.

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