Urban Effects on Severe Local Storms at St. Louis

STANLEY A. CHANGNON, JR.

Illinois State Water Survey, Urbana 61801

(Manuscript received 24 August 1977, in final form 3 February 1978)

ABSTRACT

As part of METROMEX, a five-year study of how St. Louis affects summer weather, studies were made of possible urban effects on severe local storm phenomena. Localized (within 40 km of the city) increases were found in various thunderstorm characteristics (about +10 to +115%), in hailstorm conditions (+3 to +330%), in various heavy rainfall characteristics (+35 to +100%) and strong gusts (+90 to +100%). No indication of effects on tornado activity was found. The more substantial percentage increases were found in the expressions of storm intensity (very frequent thunder, hailfall impact energy and high rainfall rates). Urban-related increases in severe local storm conditions appeared at midday, were greatest in the evening and ended by midnight. Urban-induced increases occurred with all synoptic weather types but were most frequent and intense with squall lines and cold fronts. Results suggest that urban-induced factors alter the microphysical and dynamic properties of clouds and storms.

1. Introduction

One aspect of the METROMEX studies of urban effects on summer weather conditions included an investigation of characteristics of severe local storms (Changnon *et al.*, 1977). Data from the five summers (June–August) in the 1971–75 period were used to examine for local changes in thunderstorms, hail, heavy rainfalls, winds and tornadoes. This included all possible information about their frequencies in time and space, their intensities and durations. The primary goals were to discern whether there were any local area anomalies and to ascertain those weather conditions when they occurred, as input into the complex studies of how the urban area affected precipitation processes.

Climatic studies of eight urban areas presented evidence of localized increases in thunderstorm and hailstorm frequencies at the six largest cities (Huff and Changnon, 1973). An extensive climatic investigation of St. Louis data for 1941–70 revealed urban-related localized increases in thunderstorms of 25% and increases in hail days of 35% (Huff and Changnon, 1972). However, these studies could not define well the spatial patterns or reality of the apparent urban influences.

Prior research of the METROMEX detailed storm-day data (Changnon *et al.*, 1976; Boatman and Auer, 1974) sought explanations about how the city acts to influence the atmospheric processes that in turn lead to precipitation changes. Both studies offered hypotheses that indicated how urban effects lead to heavier rains and to more storm activity over and just beyond the city. The urban effects leading to altered precipitation are generally thermodynamic in nature, as opposed to microphysical changes. The increased merging of storms due to urban influences is seen as a key factor (Changnon, 1976) and prior research has established that merging of storm elements is conducive to increases in heavy rains and severe storm activity (Simpson *et al.*, 1971).

Data on thunderstorm activity came from two sources. Weather station observations taken at seven sites in the area were one source, and the other was records from six sites where the Illinois State Water Survey had built and installed remote recording audio devices to record lightning and thunder (Gardner, 1976). These 13 sites (Fig. 1) were used to sample an area of 10 000 km^2. The data from the six recording sites allowed very detailed temporal studies of the intensity of thunderstorm activity.

Data on rainfall came from 220 recording raingages evenly distributed throughout a circular network of diameter 80 km centered on St. Louis (Fig. 1). All rainfall data were digitized as 5 min totals, and then various analyses of heavy rainfall occurrences were performed for various durations and storm periods. Hailpads (929 cm^2 surfaces of aluminum foil on styrofoam) were located at each raingage site and used to obtain measures of hailstone frequencies and sizes, and impact energy of hail for each storm. Times of hail occurrence and its duration were derived from the 220 weighing-bucket recording raingages which had been modified to allow recording temporal information on hailfalls.

Wind data were collected at eight sites distributed around the circumference of a circle with a radius of about 32 km from the center of St. Louis. These were

0021-8952/78/0578-0586$05.00

cup and vane anemometers on 4.6 m masts, and a study was made of the maximum gusts recorded during each hour. Data on tornadoes and funnels aloft were derived from published records of the Environmental Data Service. More extensive information on the various METROMEX networks and resulting data are given by Changnon (1975).

2. Thunderstorms

The summer average pattern of thunder days (1971–75) is shown on Fig. 1. The major features include 1) generally low values to the south and northwest of St. Louis; 2) high values beginning over the city and fanning out eastward for about 30 km with an extension to the northeast (perhaps related to the separate urban-industrial area located north of St. Louis); and 3) a diminishing of the high urban-related frequencies 48–56 km to the east. The averages of the two easternmost stations are of the same general magnitude as those found to the west and considered to be unaffected by urban influences. The pattern of Fig. 1 strongly suggests local urban influences on thunderstorm frequencies with the maximum value being 29 days in St. Louis. The values of the four stations in the apparent urban maximum (29.0, 28.0, 25.3 and 25.0) have a mean value of 26.8 thunder days as compared with a rural mean of 18.5 days (based on the five rural stations with averages of 20.4, 19.3, 18.6, 18.4 and 16.0). This urban-rural difference is 8.3 days, and when compared to the rural mean (18.5), this difference represents a regional increase of 45% in thunder days. All urban values exceed the highest rural value, and values at stations farther east were 17.0 days at 80 km beyond St. Louis, 21.3 days at 100 km, and 19.0 thunder days at stations at 140 and 200 km east of St. Louis.

One of the potential impacts of added thunderstorm activity would be an increase in power outages due to surface lightning strikes. Data on all 1972–75 outages were used to develop a pattern based on township frequencies (Fig. 2). Also shown is the thunder day pattern from the METROMEX data. The outage pattern helps prove the validity of the thunderstorm anomaly with a concentration of outages just east of St. Louis. Outages are 5–10 times greater there than those in the eastern counties (Bond and Washington). When the county outages are adjusted to the number of miles of power line, the effect area counties of Madison and St. Clair have outage frequencies of 3.8 and 5.3 per 10 miles of wire, respectively. The frequencies in the three control counties were 1.0 (Washington), 2.6 (Bond) and 1.5 (Monroe), indicating 50–400% increases in the effect area.

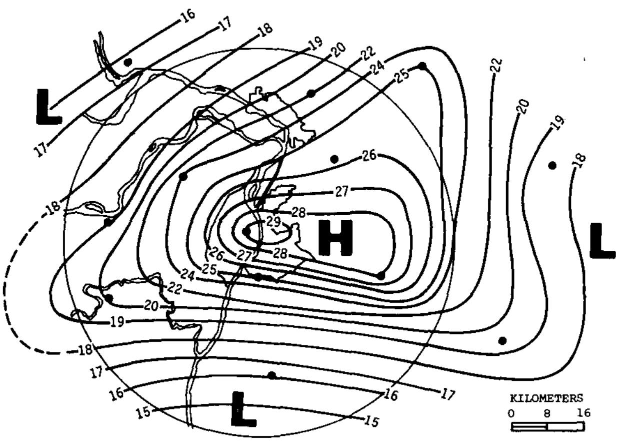

FIG. 1. Pattern of average summer thunder days (1971–75). St. Louis metropolitan area is shaded, and outline of circular raingage network is shown.

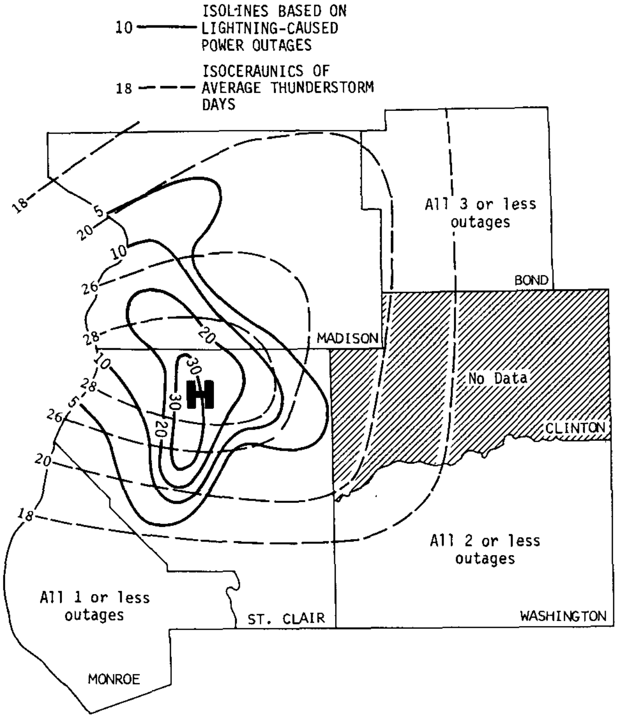

FIG. 2. The 1972–75 summer pattern of lightning-caused power outages, based on township frequencies, and the average thunder day pattern.

Results of various comparisons of urban and rural thunderstorm characteristics (Changnon *et al.*, 1977) are summarized in Table 1. The various urban-rural comparisons between summer thunder days, summer thunder periods, east-only versus west-only thunder day frequencies, the durations of the thunder periods and areal variations, with all primary synoptic weather types indicate *urban-related increases in all cases.* These increases range from a low of 11% for the very light thunder occurrence rates up to 116% for the urban versus rural differences in air mass related thunder periods. The lack of decreases (Table 1) in any of the urban-related thunderstorm characteristics strongly suggests that urban effects to increase thunderstorm activity were present and sizable.

TABLE 1. Urban-related increased in summer thunderstorm characteristics at St. Louis.

	Frequencies			Percent increase $\left(\frac{U-R}{R}\times 100\right)$		
	Urban (U)	Rural (R)	U−R			
Thunder days[4]	26.8	18.5	8.3	+45		
Thunder periods[1,4]	33.6	23.1	10.5	+45		
East-only verus west-only days[2,5]	39.0	22.0	17.0	+77		
Duration of thunder (all values in minutes)						
Thunder periods[4]	145	93	52	+56		
Very light thunder rates[3,4]	49	44	5	+11		
Light thunder rates[3,4]	64	48	16	+31		
Moderate thunder rates[3,4]	56	46	10	+22		
Intense thunder rates[3,4]	86	47	39	+83		
Synoptic weather conditions and thunder						
Thunder periods for cold fronts[6]	12.3	9.0	3.3	+33		
Thunder periods for warm-stationary fronts[6]	8.7	5.0	3.7	+74		
Thunder periods for air mass[6]	9.3	4.3	5.0	+116		
Thunder periods for squall areas and lines[6]	53.3	40.4	12.9	+32		
Monthly differences (U−R)				June	July	August
Average point thunder periods[1]				+66%	+43%	+34%
East-only versus west-only days[2]				+129%	+71%	+38%

[1] Discrete periods of thunder separated by $\geqslant 1$ h from other periods.

[2] Based on comparisons of days when there were only thunderstorms to the east of St. Louis (at one or all of four stations), or only to the west (four stations).

[3] Thunder rates were defined on peals per hour basis: very light $\leqslant 5\ \mathrm{h}^{-1}$, light 6–11 h^{-1}, moderate 12–60 h^{-1} and intense $>60\ \mathrm{h}^{-1}$.

[4] Point summer average values, 1973–75.

[5] Area total values, 1971–75.

[6] Point average totals, 1973–75.

An analysis of variance was used to compare and test the urban and rural values for various thunderstorm characteristics. The probability that the assertion, "the urban-rural values are different and that there is an increase in the urban values," is wrong, is very low for most characteristics. This probability (of a significant difference) was 0.1% for the thunder day differences and 0.2% for the thunder period difference, as based on comparison of the monthly values of the three urban effect stations and those of the three no-effect rural stations. A test of the urban versus rural values for duration of thunder periods showed a difference with a probability of 0.3%, and the significance of the greater intense thunder periods at urban stations was 0.1%. In essence, the urban-related thunderstorm values were all statistically significantly different (greater) than the rural values.

Thunderstorms appear to be affected by the St. Louis urban-industrial areas in a variety of ways. In the urban area, and to the east and northeast of it, there were more days with thunder, more periods of thunder, longer periods of thunder when storms occurred, and more frequent and longer periods of intense thunderstorm activity. These increases in thunderstorm activity occurred in all three summer months, but were greatest in June and least in August (Table 1).

The diurnal distributions of the urban thunderstorm conditions suggested that the urban effects existed at all hours, but were relatively greatest in the period of 1000–1400 CDT, indicating urban influences help to get thunderstorm activity started relatively early. Over and just east of the city, urban effects also lead to greater thunderstorm activity in the late afternoon and at night. Frequencies of intense thunder (with a rate at a point >60 peals per hour) and urban areas were less than rural values during the period 0600–1200 CDT, suggesting an urban decrease at that time. In all other hours, the intense thunder activity in the urban area greatly exceeded that in the rural area.

Synoptic weather analyses indicated that the conditions most favorable for urban-related thunderstorm increases were warm front and air mass types (Table 1). The point thunder period results also suggested the presence of the urban effects during cold front, squall line and squall area conditions. The considerable difference in the urban point values and the rural station values during 1973-75 is revealed in Table 2. None of the rural values are greater than any of the three urban values in the air mass, cold front and squall classes. Urban influences on the atmosphere affected thunderstorm activity with all precipitation-producing weather types.

3. Hail

The number of point hailfalls (discrete periods of hail produced by hailstorms) in the network at each site were plotted and the resulting pattern (Fig. 3) reveals an area of relatively low frequencies in the southwest. This is an area where the summer total rainfall was also lowest (Changnon *et al.*, 1977). The network mean for the five-year period was 4.9 hailfall occurrences, and most of the area west and south of St. Louis was below this mean. Long-term values for St. Louis indicate a five-year period average of four summer hail days.

The most notable hailstone area is that enveloped by six or more occurrences located to the northeast, east and southeast of St. Louis. Within this arc-shaped area of ⩾6 occurrences are three separate areas of ⩾10 occurrences (more than twice the network mean) to the east of St. Louis. A second area of high hail incidence is located northwest of the city, in and just east of the floodplain of the Mississippi and Missouri Rivers where a local rainfall high also was found (Changnon *et al.*, 1977).

The five-year hail pattern indicates area mean values east of St. Louis, as compared to those west of the city, reflect increases on the scale of 30%. Certain small areas of high incidence indicate 200% or greater increases in the number of hailfalls potentially related to urban effects. The area of urban increased hail is relatively small, as defined by the frequencies ⩾6, and the area of increased hail is roughly 10–30 km beyond the city (Fig. 3).

Various comparisons of hailfall and hailstreak (pattern of hail from a storm) characteristics for the five-year period were made on the basis of values in the potential urban-effect areas and the no-effect area. Hail from storms that developed or passed over the urban areas was classed as potentially urban effect hail, whereas that from all other storms in the area was classed as no-effect hail. Results of several comparisons appear in Table 3.

The difference in the frequency of hail periods when only (urban) effect hail occurred and that when only no-effect hail occurred indicated an urban-related increase of 31% greater in the frequency of hail periods. Comparison of the 53 network hail periods when both effect and no-effect hailstorms existed reveals the number of times that the impact energy of effect storms exceeded that of the no-effect storms. As shown in Table 3, the effect frequency was 192% greater than the no-effect frequency. A test of the effect and no-effect energy values shows their difference has a one-tail probability of 0.005. Thus, there is less than one chance in a hundred that the greater effect values are due to chance. In four out of five years the effect area mean energy values exceeded the no-effect area mean energy values. For the five-year sampling period, the mean energy value in the effect areas was 96% greater than that in the no-effect areas.

Table 2. The number of thunder periods in 1973–75 associated with major synoptic weather types.

Weather	Totals of three urban stations	Totals of three rural stations
Cold front	10, 13, 14	8, 9, 10
Warm and stationary front	5, 9, 12	3, 6, 6
Air mass	8, 8, 12	3, 4, 6
Squall line and area	47, 54, 59	38, 42, 42

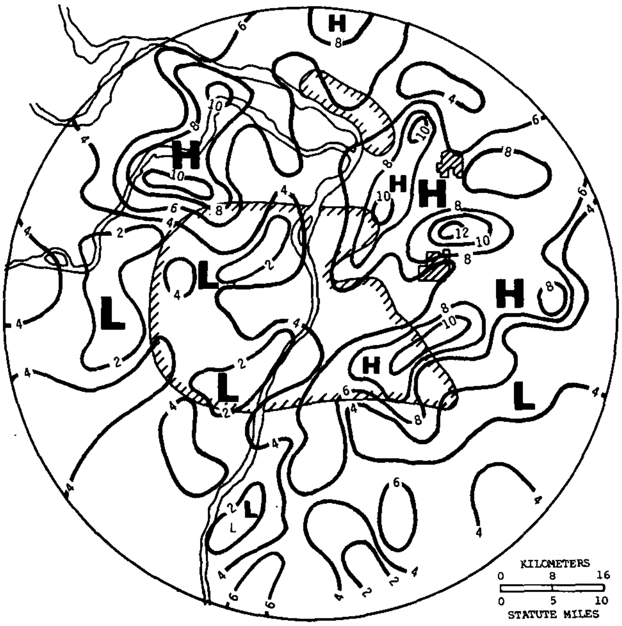

Fig. 3. Pattern of point hailfall frequencies (1971–75).

Various other hailfall values (frequencies, stone size and number of stones) shown next in Table 3 all exhibit moderate (28–44%) increases from storms potentially urban affected. Comparison of frequency of hail in the effect versus no-effect areas on a diurnal basis reveals a moderate increase from 1200–1800 CDT with the major increase occurring between 1800 and 2400. No difference is shown in the morning hours.

Other comparisons shown in Table 3 are based on hailstreak characteristics when both effect and no-effect hailstreaks occurred during 53 network hail periods. Very small differences are shown for areas of hailstreaks and for their duration, but sizable increases are shown for the other hailstreak characteristics, including point duration (+40%), the maximum hailstone diameter (+22%) and the point number of hailstones (+36%). These last three hailfall values effectively combine to produce a much greater difference in energy (+100%). Even the mean rainfall in the effect hailstreaks was 22% greater than that in the no-effect hailstreaks.

Several of the effect (E) hail values were compared and tested statistically against the no-effect (NE) values. An analysis of variance of the annual frequencies of hail periods when energy values of E>NE and those

TABLE 3. Comparison of effect and no-effect hail for 1971–1975.

	Frequencies			
	Urban effect value (E)	No urban effect value (NE)	Difference	Percent increase $\left(\frac{E-NE}{NE}\times 100\right)$
Frequency of hail periods with (urban) effect *only* versus no-effect *only* hail periods	17	13	4	+31%
Frequency of hail periods (with both effect and no-effect hail) when effect area mean energy > no-effect mean	38	13	25	+19%
Mean energy (J per 0.1 m^3) in effect area versus that in no-effect area	1.45	0.74	0.71	+96%
Average frequency of point hailfalls, effect area versus no-effect area	5.5	4.3	1.2	+28%
Median hailstone diameter (cm) in effect area versus that in no-effect area	1.27	0.97	0.3	+32%
Average hailstones per 929 cm^2, effect hail area versus no-effect hail area	372	259	113	+44%
Effect area hailfall frequency versus no-effect area frequency, differences for 6-hour periods				
0000–0600 CDT	0.6	0.6	0	0
0600–1200 CDT	0.3	0.3	0	0
1200–1800 CDT	1.2	1.0	0.2	+20%
1800–2400 CDT	1.7	1.0	0.7	+70%
Comparison of hailstreak characteristics (E vs NE) for 53 hail periods when both effect and no-effect hailstreaks occurred				
Hail streak durations (min)	14.9	14.2	0.7	+5%
Areas of hailstreak (km^2)	37.4	36.4	1.0	+3%
Average point duration (min)	2.9	2.1	0.8	+40%
Maximum hailstone diameter	1.41	1.15	0.26	+22%
Point (929 cm^2) number of hailstones	74	54	20	+36%
Energy (J per 0.1 m^{-3})	1.35	0.67	0.58	+100%
Mean rainfall in hailstreaks (cm)	2.05	1.69	0.36	22%
Comparison of effect and no-effect hailstreak energies (J per 0.1 m^{-3}) *with various synoptic weather conditions*				
Cold fronts	1.75	0.40	1.35	+333%
Squall lines	1.20	0.54	0.66	+125%
Squall areas	1.20	0.80	0.40	+50%
Stationary fronts	2.40	1.62	0.78	+50%
Air Mass	0.94	0.27	0.67	+250%

periods when energy of NE>E (the five-year total difference was 25 periods or a 192% increase, see Table 3) revealed a probability of 0.05%. Thus, there is less than one chance in 1000 that the claim that the effect hail exhibits decidedly greater hail energy is wrong. All hail characteristics were tested and a significance of 1% or less was found in most instances. The many E and NE hailstreak values (Table 3) were compared, and the probabilities of the significance of their differences were developed using the Wilcoxon non-parametric test and the paired t test. The results are shown in Table 4. The effect hailstreak values for point duration, hailstone size, number of hailstones and energy are significantly larger than those for the no-effect hailstreaks in both tests, and the area and streak duration values were not significantly different.

The final set of hail comparisons shown in Table 3 is based on the characteristics of all the effect hailstreaks and all the no-effect hailstreaks sorted according to various major synoptic weather conditions associated with the hailstorms. Increases apparently related to urban effects exist in all conditions, but the greatest percentage shifts are with cold front, squall line and air mass conditions.

The characteristics of effect and no-effect hailstreaks were compared and tested using the paired t test for each synoptic weather type. Differences with probabilities of less than 10% were found in 1) point hailfall durations in squall area streaks (9.4%) and cold fronts (1.3%); 2) maximum hailstone size in squall line streaks (0.4%) and squall areas (1.9%); 3) hailstone frequencies in squall lines (0.3%), cold fronts (3.6%) and squall areas (1.2%); and 4) energy values in squall line streaks (1.2%) and squall lines (2.2%).

4. Heavy rainfall

Considerable information on the apparent substantial effect of St. Louis to increase heavier, short-duration rain rates and the frequency of rainstorms has already been published (Changnon *et al.*, 1976; Huff, 1975). Summer frequencies of short-duration heavy rainfall rates and moderate to heavy rainstorms are increased in a fan-shaped area of 4000 km^2 east of St. Louis. Dettwiller and Changnon (1976) found a 37% increase in annual maximum daily rainfall values at St. Louis, and Huff (1976) used METROMEX data to show that in the area 20 km northeast of St. Louis the number of heavy rainstorms ($\geqslant$25 mm) is 93% greater than anywhere else within 40 km of St. Louis. Huff also showed that the maximum 5 min rainfall rates in urban-affected storms were 43% higher than the rates in no urban effect storms. Point occurrences of 5 min rain amounts $\geqslant$12 mm (a two-year recurrence interval) for the 1971–75 period reveal an 83% increase in the effect area as compared to the no-effect area (Changnon *et al.*, 1977). A similar analysis of the 1 h point values $\geqslant$30 mm (a two-year recurrence interval) indicated a 37% increase in the effect area. The various heavy rain increases noted vary from 37% up to 93% depending on the area and type of rain event under comparison.

These effects are illustrated in Fig. 4, based on the occurrence of heavy summer storms, defined as those producing $\geqslant$51 mm of rain. The five-year maximum frequency closely coincides with the placement of the thunderstorm maximum (Fig. 1). The central area frequency of six occurrences of $\geqslant$51 mm events is double the network point mean of 2.6 storms, and is over two standard deviations greater than the network mean. Most of the high occurrences are in and east of the city. The pattern of Fig. 4 provides strong evidence of an urban effect on storm rainfall, and studies of local water resource systems reveal the resulting impacts and problems and the need to consider this effect in urban hydrologic design problems (Changnon *et al.*, 1977). Climatic studies of data at Chicago, Cleveland and Washington suggest the presence of urban-induced increases in the number of days with heavy rain (Huff and Changnon, 1973).

The rainfall from the heavier rainstorms ($\geqslant$25 mm) are important contributions to the local urban rain anomaly (Huff, 1976). In the center of the urban rainfall high east of St. Louis, 45–55% of the total summer rainfall occurred with these heavier storms.

FIG. 4. Pattern of point frequencies of rainfalls $\geqslant$51 mm (1971–75).

Various METROMEX analyses indicate that intensification of existing storm systems is the most likely cause of the observed highs in the summer rain pattern (Changnon *et al.*, 1976). This intensification is apparently most pronounced in augmenting rainfall volume from moderate to relatively intense storms arising from natural causes unrelated to the urban effect. An abnormal number of 25 mm or heavier rains occur east of the city as storms cross the urban area and mature downwind.

Another method of evaluating the urban effect on rainfall has been the comparison of urban-affected and rural (non-urban affected) raincells, a raincell being defined by a closed isohyet (within an overall enveloping isohyet) lasting for 5 min or more. Raincells are the basic unit within convective storms (thunderstorms and rainshowers) responsible for most of the heavy warm-season rainfalls in the Midwest. The 365 heaviest cells, which produced mean rainfalls $\geqslant$6 mm during 1971–74, were examined. These represented about 9% of the four-summer sample, and included 138 defined as urban, 174 rural flatlands, 17 in rural hill areas, 21 in rural river bottomlands and 15 cells having exposure to more than one of these land types. A cell was considered urban-effected if it developed over or passed through any part of the urban-industrial area.

Raincell water volume was selected as the primary comparison parameter to evaluate the urban effect. Volume reflects the combined effects of rain rate, cell area, rain duration and storm movement. Comparison of total water volume between the urban and rural cells

TABLE 4. Probabilities from statistical testing of differences of the hailstreak characteristics of effect (E) and those classed as experiencing no urban effect (NE).

Characteristic	Wilcoxon non-parametric	Paired *t* test
Area of hailstreak	43.7%	92.6%
Point duration	0.05%	0.1%
Duration of hailstreak	55.5%	19.8%
Point rainfall	92.6%	83.8%
Maximum hailstone size	0.2%	0.04%
Number of hailstones	0.1%	0.06%
Point impact energy	0.04%	0.05%

TABLE 5. Comparison of water yield between urban effect (U) and rural (R) raincells among heaviest cells during 1971–1974.

Cumulative percent of raincells	Urban effect volume (m^3)	U−R (m^3)	Percent difference
10	3.43×10^6	1.69×10^6	97
20	2.06×10^6	8.63×10^5	72
30	1.48×10^6	5.61×10^5	61
40	1.17×10^6	4.31×10^5	59
50	9.25×10^5	3.27×10^5	55
60	7.34×10^5	2.53×10^5	53
70	5.73×10^5	1.85×10^5	48
80	4.25×10^5	1.23×10^5	41
90	2.84×10^5	7.40×10^4	35

is summarized in Table 5. The results indicate that the urban effect appears to be more prominent when natural rainfall processes are operating efficiently; that is, when moderate to heavy rainfall is occurring (Changnon *et al.*, 1977). The percentage difference between the urban and rural cells is greatest (97%) with the heaviest 10% of the raincells. The percentage difference gradually decreased to 55% at the median level, and to 35% when 90% of all the cells are included. The median percentage (55%) indicates that the urban effect is frequently quite pronounced in the heavier cells.

Synoptic weather conditions associated with those storms having patterns with distinct highs (with falls ⩾25 mm) east of St. Louis and resulting from raincells that developed or passed over the city were studied. The 38 rainstorms fulfilling this definition of possible urban effects were largely associated with squall lines and cold fronts, but heavy rain enhancement occurred to some extent in all synoptic weather types (Changnon *et al.*, 1977).

5. Strong surface gusts

Another possible indication of urban effects on severe storm phenomena is in the frequency of strong gusts during the summers of 1971–75. A study of this possibility was based on analyses of the strongest gusts recorded in each hour at six wind stations. The data were sorted and grouped according to two areas. The three rural wind stations located about 30 km to the southwest, west and northwest of St. Louis were classed as having no urban effects, and the three rural stations located about 30 km to the southeast, east and northeast of St. Louis were classed as possibly urban affected. They were either in or near to the areas of greater thunder (Fig. 1) and hail frequencies (Fig. 3).

The average point frequencies within the two areas of maximum hourly gusts $\geqslant 12$ and $\geqslant 17\ \mathrm{m\ s^{-1}}$ appear in Table 6. The effect area point frequency of hours with $\geqslant 12\ \mathrm{m\ s^{-1}}$ gusts is double the west no-effect area frequency. The difference in gusts $\geqslant 17\ \mathrm{m\ s^{-1}}$ reveals a 91% increase in the urban effect area. These are sizable but not unlike several of the urban-rural (effect versus no-effect) percentage differences obtained for certain characteristics of thunderstorms, hailfalls (energy in particular) and heaviest raincells.

The distribution of directions of the winds with these gusts in both areas showed no great regional differences. In both areas, about 70% of the gusts came from northerly directions. The urban effect area gusts did show more from the northwest (45%) than did the no-effect area gusts (26%). All gusts in both areas occurred with thunderstorm activity. The predominating synoptic weather types with these high gusts were squall lines and cold fronts. None occurred with stationary front or air mass conditions.

6. Tornadoes

Data on tornadoes and funnels aloft during the 1971–75 period and within a 100 km radius of St. Louis were examined for any evidence of urban effects. During this period there were only ten tornadoes and seven funnels aloft. It should be realized that summer is not a prime tornado period in this area. The low frequency of events in a five-year sample is expected but makes it difficult to derive any conclusions about urban effects on tornadoes.

The five-year pattern of the ten tornadoes is random and gives no suggestion of a concentration in or beyond St. Louis. However, six of the seven funnels aloft were observed in the potential urban effect area extending eastward 40 km from St. Louis in a fan-shaped area. However, the population density is higher in this urban effect area than elsewhere, and the statistics may be biased by the greater chances of sighting a funnel. The METROMEX sample of the tornadoes and funnels aloft give no indication of urban effects on summer tornado activity, although longer records indicate that the area just east of St. Louis has the highest tornado frequency in Illinois (Wilson and Changnon, 1971).

7. Conclusions

The findings establish the reality of anomalies in most severe storm phenomena over and just east of St. Louis. The fact that these phenomena result from many

TABLE 6. Comparison of summer maximum hourly gust frequencies in the urban effect area and rural no-effect around St. Louis (1971–75).

	Average number of gusts at a point	
	$\geqslant 12\ \mathrm{m\ s^{-1}}$	$\geqslant 17\ \mathrm{m\ s^{-1}}$
Urban (U) effect area	34 (27–45)*	6.3 (5–8)*
West (W) no-effect area	17 (10–25)	3.3 (2–5)
Difference (U−W)	17	3.0
(U−W)/W (percent)	100	91

* Range of point average values found in each area shown in parentheses.

convective elements that initiate or traverse over the metropolitan area strongly suggests that the increased localized frequency and intensity of thunderstorms, hail, heavy rains and winds are related to the urban influences on the atmosphere. This statistically focused study alone cannot delineate the causative mechanisms, those specific urban influences that affect the atmosphere and lead to more storminess. However, some findings suggest certain urban factors are important in modifying the weather. In general, urban factors affect severe storm conditions in all synoptic weather conditions, suggesting that the urban influence makes the precipitation process more efficient and more active in any kind of unstable condition conducive to natural precipitation production.

The fact that urban-rural differences are greater for measures of storm intensity (stone size, hail energy, high frequency, thunder, etc.) than for storm frequency (number of days and areal extent) indicates urban mechanisms tend to intensify more than to initiate convective activity.

The findings on the diurnal distributions of additional local thunder and hail activity suggest that thermodynamic and microphysical influences of the city on the atmosphere are both important. The urban-induced thunder activity begins earlier in the day with the greatest urban-rural difference between 1000 and 1400 CDT. This could result from greater and earlier urban-induced release of thermal energy to initiate or invigorate showers, or it could be related to earlier ice formation (which leads to electrification) resulting from either larger drops from urban CCN and/or more ice nuclei from urban sources. The urban-rural differences in hail activity occur between 1200 and 2200 CDT, suggesting local thermal intensification of convection during the normal period of greatest heating and convective activity.

The findings showing hailstreak areas and durations from urban-affected storms are comparable to those of non-urban influenced hailstorms, coupled with the fact that the urban hailstreaks had more and larger hailstones, longer point durations and larger energy values than in rural ones are informative. Together they suggest that urban influences are acting in at least two ways. The lack of difference in the hailstreak areas and durations suggests urban thermodynamic factors do not lead to larger or more sustained updrafts in urban-affected storms. Downdrafts are still dominant in their effect on updrafts, and indeed the higher gusts produced by urban-area storms reflect the findings about greater volumes of rain and hail produced by urban-affected storms. However, greater point durations of hail, more rain and larger stones generated in urban hailstreaks suggest that urban factors of a dynamic nature induce stronger updrafts that bring more water rapidly into the storms. The greater number of hailstones produced by urban hailstreaks suggest urban additions of ice nuclei leading to the production of hail embryos. These various findings do not specify any one urban influence as dominant, but rather suggest that the urban area acts to alter both the dynamic and the microphysical processes, particularly by intensifying convective processes and hydrometeor growth during natural rain producing conditions.

The various urban effects collectively lead to increases in activity, intensity and/or duration of severe events at points in and just east of St. Louis. It is important that all thunderstorm and hailstorm characteristics examined and compared (urban vs rural) reveal an urban-induced increase, indicating internal consistency.

At points in the affected area, delineated as a fan-shaped area extending from St. Louis eastward out to 40 km and covering roughly 2600 km^2, there are 1) more thunderstorms and hailstorms, 2) more hail and lightning strokes per unit area when they occur, 3) longer lasting periods of thunder activity and hail and 4) more frequent high winds and damaging hail. Power company records of lightning-induced power outages and hail insurance records of crop-hail losses substantiate the thunder and hail anomalies (Changnon *et al.*, 1977; Changnon, 1976).

Various thunderstorm characteristics are increased within a range of +11 to +116%; hail characteristics increased in a range of +3 to +333%; heavy rain features by +35 to +97%; and strong gusts by +91 to +100%. The more substantial percentage changes found for thunderstorms, hail and rainfall were realized in their intensity expressions. One of the largest increases was 83% for the duration of very frequent thunder activity. The largest differences in the hail data were in the energy values (100% up to 192%) and the largest difference for the raincells (97%) came with the heaviest 10% of all cells.

Urban effects were greatest in June with a gradual decline in July and August. Urban effects occurred with all major rain-producing weather types, being enhanced most in periods of more organized convection.

Acknowledgments. This paper is based on research supported by NSF Grant ENV73-07796 and State of Illinois funds. The assistance of Paul T. Schickedanz, Floyd A. Huff and Neil G. Towery of the Illinois State Water Survey staff, plus many others too numerous to mention, is gratefully acknowledged. Thanks go to the Illinois Power Company for furnishing the lightning data.

REFERENCES

Boatman, J. F., and A. H. Auer, 1974: Inadvertent thunderstorm modification by an urban area. *Preprints 4th Conf. Wea. Mod.*, Ft. Lauderdale, Amer. Meteor. Soc. 366–373.

Changnon, S. A., Jr., 1975: Operations of mesoscale networks, illustrated by METROMEX. *Bull. Amer. Meteor. Soc.*, **56**, 971–977.

——, 1976: Inadvertent weather modification. *Water Resour. Bull.* **12**, 695–718.

——, R. G. Semonin and F. A. Huff, 1976: A hypothesis for urban rainfall anomalies. *J. Appl. Meteor.*, **15**, 544–560.

——, F. A. Huff, P. T. Schickedanz and J. L. Vogel, 1977: St. Louis Precipitation anomalies and their impact. Vol. 1, METROMEX Final Summary, Illinois State Water Survey, 196 pp.

Dettwiller, J., and S. A. Changnon, 1976: Possible urban effects on maximum daily rainfall at Paris, St. Louis and Chicago. *J. Appl. Meteor.*, **15**, 517–519.

Gardner, M. R., 1976: Instrumentation for the remote sensing of thunderstorm activity. *J. Appl. Meteor.*, **15**, 503–508.

Huff, F. A., 1975: Urban effects on the distribution of heavy convective rainfall. *Water Resourc. Res.*, **11**, 889–896.

——, and S. A. Changnon, 1972: Climatological assessment of urban effects on precipitation at St. Louis. *J. Appl. Meteor.*, **11**, 823–842.

——, and ——, 1973: Precipitation modification by major urban areas. *Bull. Amer. Meteor. Soc.*, **54**, 1220–1232.

Simpson, J., W. L. Woodley and A. H. Miller, 1971: Precipitation results of two randomized pyrotechnic cumulus seeding experiments. *J. Appl. Meteor.*, **10**, 526–544.

Wilson, J., and S. A. Changnon, 1971: Illinois tornadoes. Circ. 103, Illinois Water Survey, 58 pp.