The Urban-related Nocturnal Rainfall Anomaly at St. Louis

STANLEY A. CHANGNON, JR. AND FLOYD A. HUFF

Climate and Meteorology Section, Illinois State Water Survey, Champaign, IL 61820

(Manuscript received 9 November 1985, in final form 19 July 1986)

ABSTRACT

Studies during the Metropolitan Meteorological Experiment (METROMEX) sought to define influences of St. Louis on the summer atmosphere that led to alterations in rainfall. These studies defined how city influences caused an afternoon maximum of rainfall east of the city. Rain data indicated a second rain maximum northeast of the city during the 2000–2400 CDT period. Study of this nocturnal maximum revealed a 58% localized rain increase, relative to the mean rainfall in the 5200 km^2 network. The anomaly was present in all summers from 1971–1975. The northeast rain maximum is preceded by a local increase beginning 2 h earlier and 30 km west over the urban-industrial area. Most northeast anomaly-related storms were found to move either from the southwest (from over the urban area) or from the west-northwest (from a major industrial area), and to produce heavy rainfall rates; 19 storms moved from St. Louis between 2100–2400 and these produced 69% of the rainfall in the maximum rainfall area. The afternoon and nocturnal maximums both occurred when the entire area was receiving relatively heavy rainfall indicating that urban influences are most effective during relatively heavy rainfall conditions. All of the nocturnal anomaly rainfall occurred with well-organized convective systems. The individual convective raincells which led to heavy rainfall in the anomaly typically began over the urban industrial area and ended in the anomaly area. The raincell areas, volumes, and intensities were much greater than rural raincells. Collectively, the results strongly suggest that the nocturnal anomaly is a result of urban influences that affect a few of the heavier rain events.

1. Introduction and background

Previous rainfall studies based on 1971–1975 METROMEX data showed an urban effect on summer rainfall (Changnon et al., 1981). The most singular rain feature was an area of heavy rainfall located 30 km northeast of St. Louis and centered in the Edwardsville (EDW) area (Fig. 1). A distinct peak in the rainfall distribution occurred during the 3-h period ending between 1700 and 1800 CDT over most of the METROMEX dense raingage network including EDW (Huff and Vogel, 1978). All times are local, central daylight time, and to the nearest hour if given in periods. At EDW 23% of the total rainfall occurred in the 1400–1700 period (12.5% would be expected if rain were evenly distributed). Many of the METROMEX studies focused on the causes of this afternoon maximum, and they explained a chain of events that logically related the EDW area rain maximum during 1400–1700 to urban influences on the atmosphere (Braham, 1981).

However, a secondary rainfall high of nearly equivalent proportions, producing 21% of the total five-summer rainfall, occurred in the EDW area in the 3 h ending at 2400. Furthermore, other areas within the same general area of the 5200-km^2, 225-gage network exhibited strong rain maxima in the late evening. For example, in the Alton-Wood River (ALN-WR) industrial (refinery) area in the northern part of the network (Fig. 1), the heaviest rainfall diurnally was associated with a 2000–2300 rainfall maximum which accounted for 23% of the total rainfall. In the adjacent river bottomlands (ALN-WR bottomlands shown in Fig. 1), an early evening high was the most pronounced diurnal occurrence and produced 21% of the total five-summer precipitation.

The possible relation between these nocturnal highs and urban environmental factors was identified as one of the major issues unresolved in the earlier METROMEX research (Changnon et al., 1981). The carefully studied afternoon weather sequences leading to late afternoon rain maxima in the urban-effect regions located northeast, east, and southeast of the city do not explain the nocturnal maxima; i.e., the meteorological and environmental factors leading to the nocturnal heavy rainfalls appear to be different from those causing the afternoon maxima. Braham and Wilson (1978) noted that after 2100, the urban area experienced an increase in midsized echoes (10 000 to 12 000 m tall) but not in taller storms which had increased in the afternoon. Furthermore, the afternoon rain maximum had been associated with local increases in thunderstorms and hail but no such increase in these results of big storms was evident at night. Results from climatic research of historical (1949–68) data also provide evidence of a late evening maximum in the St. Louis area (Huff and Changnon, 1972). Hence, the nocturnal

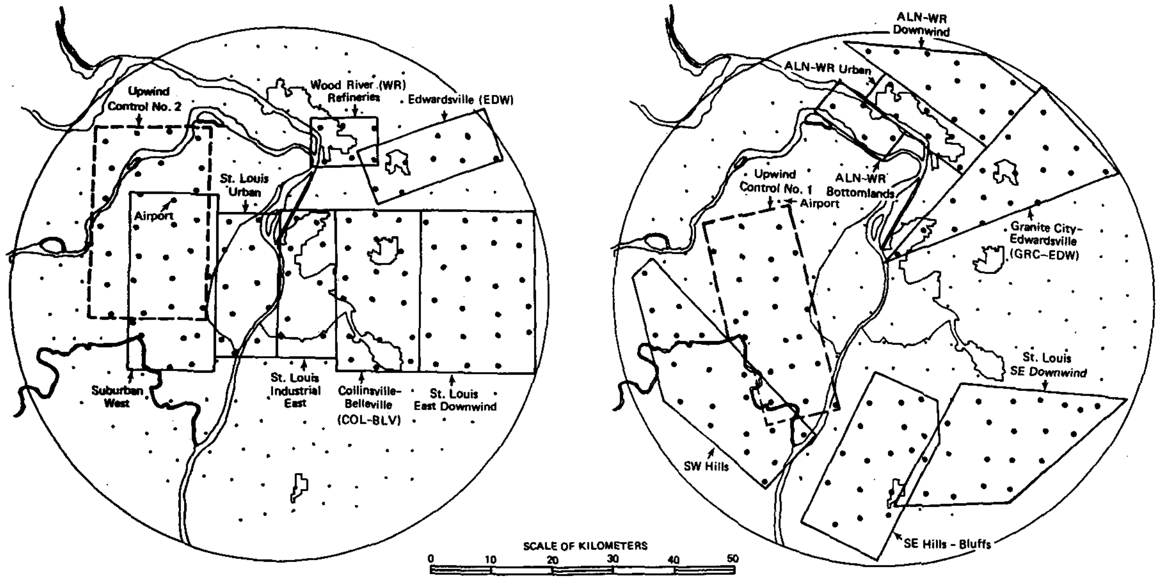

FIG. 1. METROMEX raingage network and 16 subareas used for rainfall studies, 1971–75. (Each dot is a recording raingage.)

rainfall high appeared to be a real phenomenon and not merely a sampling aberration of the 1971–75 METROMEX study period.

The extensive METROMEX data base offered an opportunity to investigate key unresolved questions concerning the precise space–time distribution characteristics of this meteorological event, the synoptic weather conditions under which it occurs, and, most important, whether the urban environment appeared to be related to the development, intensification, and sustaining characteristics of the storms responsible for the nocturnal anomaly. This paper describes important results pertaining to a study of this problem (Changnon, et al., 1985).

2. Research approach

This study focused first on the METROMEX 3-h precipitation patterns for the 330 rain periods (storms) with measurable rainfall somewhere in the network during 1971–75. Earlier METROMEX studies showed that 3-h moving averages eliminated many of the spurious aberrations in the distribution that made comparative analyses very difficult (Huff, 1977).

Analyses were concentrated on rainfall in specific areas in which the nocturnal maxima appear most important. Huff and Vogel (1978) selected 16 discrete areas within the METROMEX network for comparative rainfall analyses (Fig. 1). These were selected to represent two upwind control areas where no urban influences were expected and 14 areas with various degrees of urban, topographic, and combined urban-topographic effects on the rainfall spatial distribution. Of the 16 areas, five had nocturnal maxima in which 20% or more of the total five-summer rainfall occurred in 3-h periods ending between 2100 and 2400. These five areas, plus one with a 1800–2100 maximum (ALN-WR bottomlands), were selected for the nocturnal study. The other five were designated (Fig. 1) as Edwardsville (EDW), Granite City-Edwardsville (GRC-EDW), Alton-Wood River urban (ALN-WR Urban), Alton-Wood River downwind (ALN-WR DW), and refinery area (WR Refineries). All were adjacent, some boundaries overlapped and were located where urban air and other influences could have frequently altered cloud and precipitation processes.

Various analyses were performed on a seasonal, monthly, and storm basis to help define the rainfall space–time distribution characteristics and the impact of the urban environment on rainfall intensity, duration, area extent, and other properties. In assessing urban effects on the anomalies, storms were stratified according to associated synoptic weather type and storm motion. Differences between subarea and network means in each storm were calculated to determine individual storm contributions to the nocturnal highs. Convective raincells (Changnon, 1981) in the storms largely responsible for the nocturnal high were defined and studied to ascertain the possible relationship of urban-exposed cells and the anomalies.

Groups of storms were selected for special analyses to help infer the reality and nature of urban influences at night. In one instance we identified, for each of the six subareas with nocturnal maxima (listed in Table 1), the ten nocturnal storms having the largest positive deviations from the network mean in order to analyze their motion, average rainfall in 3-h periods (2000–2300, 2100–2400), their raincells, and the synoptic weather conditions associated with each. Since some storms qualified in more than one area, this selection

TABLE 1. Major 3-h nocturnal anomalies among six test areas during summers of 1971–75. (A = subarea mean rainfall; N = network mean rainfall.)

Subareas	Time (CDT)	A (cm)	A − N (cm)	A/N	A/UC-1	A/UC-2	A/UC
EDW	2100–2400	29.11	10.72	1.58	2.04	1.84	1.94
GRC-EDW	2100–2400	27.36	8.99	1.49	1.92	1.73	1.83
WR refineries	2000–2300	28.96	8.89	1.44	1.92	1.61	1.71
ALN-WR downwind	2000–2300	29.74	9.68	1.48	1.97	1.65	1.81
ALN-WR urban	2000–2300	26.70	6.58	1.33	1.77	1.48	1.63
ALN-WR bottomlands	1800–2100	26.52	8.81	1.50	2.16	1.70	1.93

of the top ten in the six areas yielded a total of 27 storms out of the 330 total number in the 5 yr of METROMEX. Another group of storms investigated were those moving from west-southwest or southwest across St. Louis (STL) during the 2100–2400 period, which produced much of the 3-h rainfall. Nineteen storms which produced 69% of the total 2100–2400 rainfall fell into this movement category. A third group of storms analyzed, as part of the raincell investigations, were 13 nocturnal storms which accounted for 80–95% of the positive rainfall deviations in the six anomaly subareas, and these were labeled the anomaly causing storms.

3. Seasonal and monthly analyses

a. Delineating the nocturnal anomalies

Seasonal analyses of the 1971–75 rainfall data provided strong evidence of a nocturnal anomaly in subareas located north and northeast of St. Louis. Results are briefly summarized in Table 1, which shows the 3-h period in which the nocturnal anomaly maximized in each subarea, the average five-summer rainfall in each subarea (A), the difference between subarea and network mean rainfall (A − N), the ratio of subarea to the total network mean rainfall (A/N), and similar ratios of subarea to rainfall in two upwind control areas (A/UC-1, A/UC-2 as labeled in Fig. 1).

Table 1 shows that the anomaly in EDW occurs at 2100–2400 and is the largest (based on A/N values) with a subarea five-summer average that was 58% greater than the network average. Edwardsville was 104% more than UC-1, 84% greater than UC-2, and 94% greater than the average of the two upwind controls. The control area UC-2 was selected especially for the nocturnal evaluation, since the high rainfall areas occurred in the north and northeast portions of the network. Furthermore, UC-2 is located in the northwest quadrant of the network, lies to the southwest, west-southwest, or west of the anomalous areas, is not exposed to any substantial topographic effects, and is seldom downwind of summer storms or cells crossing the urban-industrial areas of STL or ALN-WR. It is considered a slightly more appropriate control for the nocturnal study than UC-1 which lies west and southwest of STL (Fig. 1) where rains approaching St. Louis also have had little or no opportunity to be urban influenced.

Figure 2 shows the average five-summer rainfall distribution for the 3-h period, 2100–2400. The maximum exceeded 35 cm near EDW and this was nearly double the network average of 18.4 cm. The EDW maximum was more than four standard deviations greater than the network mean. The foregoing findings indicate a very substantial and real anomaly in the EDW vicinity, approximately 30 km northeast of the center of St. Louis (STL).

Detailed analyses were made of the urban causes for the major diurnal maximum which occurs in mid- to late afternoon on the METROMEX network (Changnon et al., 1976). The afternoon anomaly occurred throughout the network but maximized in the EDW area (northeast quadrant of network) as a result of urban induced effects on the precipitation process superimposed on the natural diurnal heating effect. The late evening anomaly also represents a magnification of the natural tendency for a maximum in the diurnal distribution throughout the network.

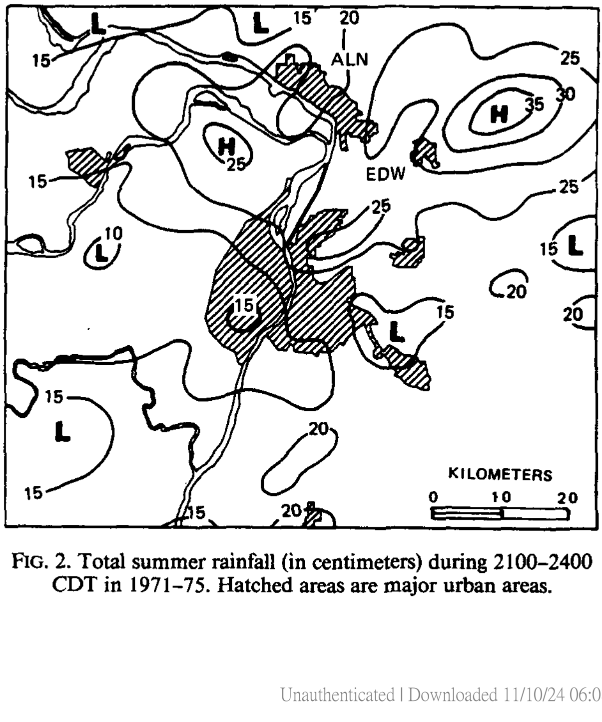

FIG. 2. Total summer rainfall (in centimeters) during 2100–2400 CDT in 1971–75. Hatched areas are major urban areas.

Two other minor diurnal peaks occurred in the METROMEX diurnal rain distribution (Changnon et al., 1985). One was at 0200–0500 and was recognizable but minor over most of the network. A large-scale study of the diurnal distribution of rainfall across Illinois revealed that the METROMEX network was in an area where a pronounced summer rainfall maximum existed at 0200–0500 (Huff, 1971). This maximum is apparently related to the midwestern nocturnal thunderstorm mechanism (U.S. Weather Bureau, 1947). The early morning METROMEX peak is part of a broad-scale climate feature west and east of STL, and has either little or no dependency on urban-influenced atmospheric factors.

A second minor peak in the diurnal distribution is recognizable in some portions of the METROMEX network at 0500–0800, and this peak is also apparently a climatic and nonurban anomaly. In the Huff (1971) study, an anomaly at this time was present at stations across southern Illinois and close to the southeast Hills-Bluffs subarea (Fig. 1) where the 0500–0800 peak was most pronounced in the METROMEX network. More information on these morning peaks can be found in Changnon et al. (1985).

Hereafter, in the text, reference to the nocturnal maximum is to those peaks during the 1800–2400 period that were suspected of being strongly related to urban influences on the atmosphere.

Over most of the network, the afternoon diurnal peak was the most pronounced of the day. However, the late evening peak (2000–2300 or 2100–2400) was approximately equal in strength in the EDW and GRC-EDW subareas, and more pronounced than the afternoon maximum in the ALN-WR region. The early evening maximum at 1800–2100 in ALN-WR bottomlands was not evident in other regions of the network; it could represent a delayed afternoon maximum related to storms developing over the Ozark Hills and river valleys to the southwest during middle to late afternoon, or could represent the initiation or passage of heavier rains that preceded the nocturnal (2000–2400) maximum 20 to 40 km east (EDW).

Table 2 shows a comparison of the five-summer rainfall anomalies (diurnal peaks) among the METROMEX subareas experiencing the most pronounced 3-h peaks during 1971–75. The maximum afternoon and evening anomalies both occurred in EDW, and were of the same magnitude. The early morning peaks were widespread areally and that at 0500–0800 much smaller in absolute magnitude than the other peaks. The anomaly at 0200–0500 was sizable percentagewise but the area of large difference was very localized to ALN-WR. It may suggest further local effects related to the industrial complex in this area.

b. *Persistence of nocturnal anomaly*

An obvious question in evaluating the potential urban involvement in the rain anomalies is whether they exhibit temporal consistency, or whether they may have resulted from 1 or 2 yr of unusually large differences between A and N, and between A and the upwind controls. Table 3 shows the range in the S annual values and mean, plus the number of years in which A/N exceeded 1.00; i.e., when the subarea mean exceeded the network mean. The ratio at EDW exceeded 1.00 in all of the five-summer sampling periods in the late evening anomalies. (Annual values in the sequence of 1971–75 were 2.19, 1.73, 1.03, 1.28 and 1.67.) This consistency provides support for the reality of the anomalies.

c. *Sample size*

Table 4 shows how A/N varied with increasing sample size; i.e., as the sampling period increased gradually from one to five summers, A/N exceeded 1.00 in all cases. Overall, the ratios indicate a decrease with increasing length of sampling period, but with little change from the four- to five-summer ratios. This is also considered supportive of the reality of the nocturnal anomalies.

d. *Monthly contributions to anomalies*

Monthly differences between A and N were investigated to help determine how the anomalies were produced during summer. In the earlier METROMEX research on total summer rainfall (Vogel and Huff, 1977), it was determined that the urban effect leading to increased rainfall was greatest in EDW and GRC-

TABLE 2. The most pronounced 3-h rainfall anomalies in any of the 18 subareas during 1971–75 on METROMEX network. (A = subarea mean rainfall; N = network mean rainfall.)

Time (CDT)	Location and maximum five-summer values (in parentheses) A (cm)	A − N (cm)	A/N
1400–1700	EDW (32.89)	EDW (11.81)	EDW (1.60)
2100–2400	EDW (29.11)	EDW (10.72)	EDW (1.58)
0200–0500	ALN-WR bottoms (17.78)	ALN-WR bottoms (5.97)	ALN-WR bottoms (1.51)
0500–0800	SE hills (12.57)	SE hills (1.02)	SE hills (1.09)

TABLE 3. Year-to-year persistence of A/N during 1971–75.

Area	Time (CDT)	Number of years (A/N > 1.0)	Range of annual A/N values	Mean A/N
EDW	2100–2400	5	1.03–2.19	1.58
GRC-EDW	2100–2400	5	1.03–1.97	1.49
WR refineries	2000–2300	4	0.94–2.51	1.50
ALN-WR downwind	2000–2300	5	1.06–2.03	1.36
ALN-WR urban	2000–2300	4	0.78–1.73	1.22
ALN-WR bottomlands	1800–2100	3	0.76–2.21	1.15

EDW in June, decreasing gradually throughout July and August. In the ALN-WR region, the anomaly was largest in July.

Table 5 shows close agreement between the nocturnal and these total rainfall anomalies. Most of the rain contributing to the EDW and GRC-EDW anomalies was produced in June, whereas the July contribution was greatest in the Alton area. The August contribution was slight in all six subareas. Since storm studies (section 4) indicated that urban-related increases were associated with vigorous and well-organized convective systems, a decrease in urban effects from June–July to August is logical since the number of vigorous systems decreases after June. The average number of rain-producing cold frontal passages and squall lines decreases from five to six in June, to three to four in July, and two in August (Hiser, 1956).

4. Storm rainfall studies

The study of individual rain periods in the network (labeled as storms) and how these related to the nocturnal rainfall maximum, focused on investigations of those storms that peaked in rainfall in the anomaly areas. Hence, a basic analysis used in the storm selection involved the deviation of the test area (subarea) mean rainfall from the network mean. These deviations (A − N) provided a measure of the rainfall excess (positive deviations) or deficiency (negative deviations) in each summer storm. The ranked positive deviations were used to select those ten storms primarily responsible for the nocturnal anomaly in each of the six subareas. For example, in the EDW subarea, 39 storms in 1971–75 produced measurable rainfall during 2100–2400, and 23 of these had positive deviations; we selected the top 10 ranked of these 23 for study. These selected storms were then subjected to various analyses, such as synoptic weather type with the storm, storm movement, and raincell morphology.

It was found that 13 storms accounted for 80–95% of the positive rainfall deviations in the six anomaly subareas; i.e., most of the nocturnal anomaly was produced by a small percentage of the 330 network storms. The annual frequency of these 13 storms was 4 in 1971; 2 in 1972, 1973, and 1974; and 3 in 1975.

a. Storm movement

Vogel and Huff (1977) found that storms moving from the west-southwest were a strong contributor to the urban rainfall anomaly that maximizes northeast of St. Louis in the EDW area. These storms accounted for 23% of the 330 storms studied, but produced 42% of the total network rainfall.

The strongest nocturnal anomaly occurred in the EDW area (Table 1) where the 5-yr total rainfall anomaly was identified in the earlier METROMEX research (Changnon et al., 1981). The EDW nocturnal anomaly maximized in the 2100–2400 period, but was of nearly equivalent strength from 2000 to 2300. In both these overlapping nocturnal periods, storms moving from the west-southwest accounted for over 50% of the total rainfall, a frequency much greater than 23% based on all storms during the day. Storms moving from the west-southwest, southwest and west-northwest are most likely to have crossed either the urban-industrial regions of St. Louis, or those of Alton-Wood River which is located north of St. Louis and west-northwest of EDW (Fig. 1). These three storm move-

TABLE 4. A/N variations with increasing sample size and for various subareas. (Time CDT)

Period	EDW 2100–2400	GRC-EDW 2100–2400	ALN-WR downwind 2000–2300	ALN-WR urban 2000–2300	WR refineries 2000–2300	ALN-WR bottomlands 1800–2100
1971	2.19	1.78	2.03	1.73	2.51	1.56
1971–72	2.04	1.90	1.47	1.17	1.74	1.09
1971–73	1.65	1.61	1.62	1.39	1.52	1.71
1971–74	1.55	1.52	1.49	1.32	1.39	1.47
1971–75	1.58	1.49	1.48	1.33	1.44	1.50

TABLE 5. Monthly contributions to nocturnal anomalies.

Subarea	Time (CDT)	Percent of total subarea rainfall June	July	August
EDW	2100–2400	71	25	4
GRC-EDW	2100–2400	59	30	11
ALN-WR downwind	2000–2300	13	76	11
ALN-WR urban	2000–2300	26	71	3
WR refineries	2000–2300	42	47	11
ALN-WR bottomlands	1800–2100	50	40	10

ments accounted for 93% of the rainfall in the EDW area during 2000–2300, and 83% of it from 2100–2400 CDT (Table 6).

With regard to frequency of storm movements, 32% of the storms moved from west-southwest at 2000–2300, and 33% at 2100–2400. Thus, movements from the west-southwest were most frequent, but the preponderance was not as pronounced as with the total rainfall yield and related percentages. The frequency-intensity statistics (Table 6) show that storms moving from the west-southwest were larger rainfall producers (55%), on the average, than those moving from the other directions. The average 3-h rainfall in storms moving from the west-southwest during 2000–2300 was 12.4 mm, compared to 7.4 mm for southwest to northeast storms, and 5.8 mm for west-northwest to east-southeast storms. For 2100–2400, the average amounts were 10.2, 10.2, and 4. 6 mm for west-southwest–east-northeast, southwest–northeast, and west-northwest–east-southeast moving storms, respectively. Among the ten storms having the largest positive deviations from the network mean for each subarea and 3-h period, approximately two-thirds moved from the southwest or west-southwest. The foregoing findings relative to nocturnal storm movements lend credence and additional evidence that the nocturnal anomalies are related to urban-induced influences on the development and/or intensification of summer convective storm systems moving through the St. Louis area.

Figure 3 shows the total summer rainfall pattern for 2100–2400 in storms moving from west-southwest and southwest from across St. Louis towards EDW. This includes 19 storms which accounted for 69% of the total 3-h rainfall in the five-summer period. The heaviest rainfall occurred in the same area where the total 2100–2400 rainfall maximum occurred (Fig. 2) revealing the significance of these storm movements. Amounts in the rainfall center east-northeast of EDW exceeded 27 cm which was 75% of the total and nearly four times the network mean of 7.3 cm. The EDW subarea average was 19.3 cm, approximately 2.6 times the network mean. Amounts in the center of the EDW anomaly (generally >15 cm) exceeded three standard deviations of the network mean.

b. *Synoptic weather conditions*

Storms associated with the 3-h nocturnal anomalies were classified according to synoptic weather type. The classification used was identical to that used in the earlier METROMEX research (Changnon et al., 1981). In the earlier research, it was determined that the urban effect was most commonly associated with well-organized convective activity, such as squall lines and cold fronts (Huff and Vogel, 1978).

Synoptic types were determined for the ten storms previously identified as having the greatest positive deviations in each of the six subareas and for each 3-h anomaly. These storms in the EDW area (during the 2100–2400 anomaly) were associated with four squall lines, three squall areas, a cold front, a stationary front, and a warm front. Overall, squall lines and squall areas accounted for 82% of the 27 storms causing the 3-h anomalies. This compares with 41% of all the other 303 network storms during 1971–75 with squall lines and squall areas. Ten percent of the nocturnal anomaly storms were with cold fronts and 8% with other conditions.

Thus, organized convective systems, exemplified by these storm types, were heavily responsible for producing the 3-h nocturnal anomalies. The nocturnal anomalies were more strongly related to organized convection than the total summer rainfall (Huff, 1977). Figures 4 and 5 show the five-summer isohyetal patterns of squall line and squall area rainfall at 2100–2400. Both patterns indicate a major anomaly in EDW, and the rainfall centers correspond closely with those

TABLE 6. Rainfall distribution grouped by storm movement in EDW area during 3-h anomaly periods, 1971–75. (Time CDT)

Direction from which storms moved	Percent of total rainfall 2000–2300	Percent of total rainfall 2100–2400	Percent of occurrences 2000–2300	Percent of occurrences 2100–2400
Northwest	6	16	19	20
West-northwest	18	14	22	22
West-southwest	55	50	32	33
Southwest	20	19	20	18
South-southwest	1	1	7	7

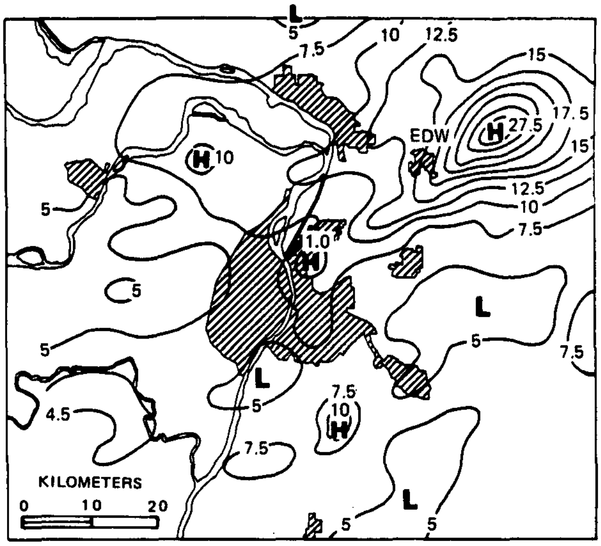

FIG. 3. As in Fig. 2 but in storms moving from the west-southwest and southwest at 2100–2400 CDT during 1971–75.

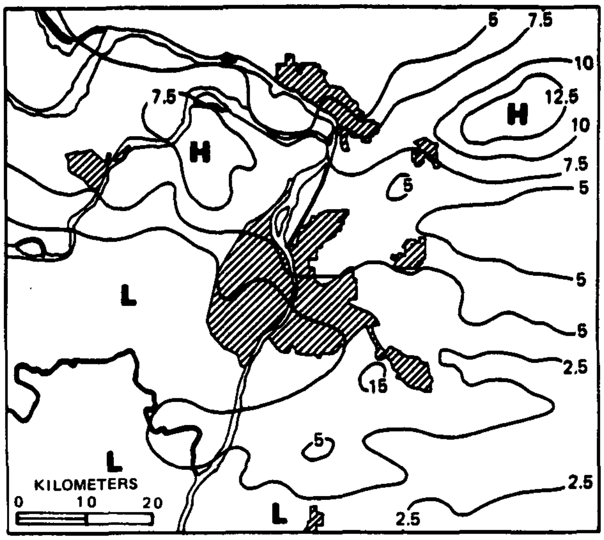

FIG. 5. As in Fig. 2 but in squall area storms at 2100–2400 CDT, 1971–75.

for storms moving from west-southwest and southwest in (Fig. 3).

Figure 6 shows the isohyetal map for 2100–2400 CDT on 16 June 1975. This storm was the largest contributor to the EDW and GRC-EDW anomalies, accounting for 25 and 23%, respectively, of all the positive deviations in the 40 storms crossing these subareas during 2100–2400 in the period 1971–1975. It was also the largest contributor to the 2000–2300 anomalies in WR refineries, EDW, and GRC-EDW. Predominant motion was from the west-southwest in this squall-area storm.

This storm exemplifies the typical urban-intensified storm identified by the METROMEX research; i.e., a relatively strong organized convection system moved across the urban-industrial region(s) of STL (and/or ALN-WR) from the southwest, west-southwest, (or west-northwest) with new raincells initiated or existing cells intensified by the urban environment, particularly in the heavy industrial region extending northward from East St. Louis to GRC and WR.

A study of the frequency of squall line and cold front passages at STL Airport (Fig. 1) was made for summers 1971–75 to help understand better the findings in the

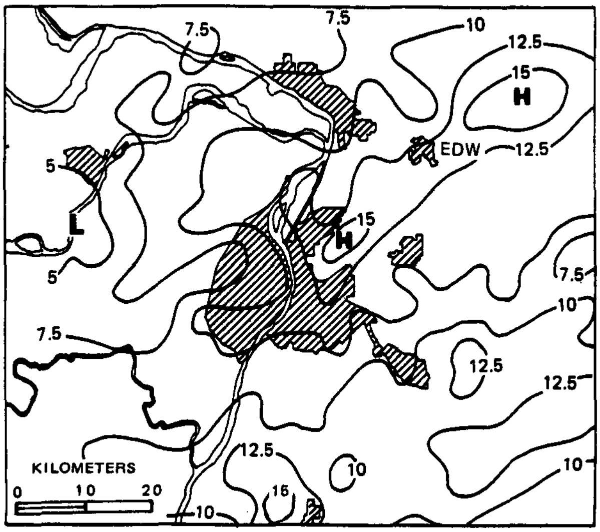

FIG. 4. As in Fig. 2 but in squall line storms at 2100–2400 CDT, 1971–75.

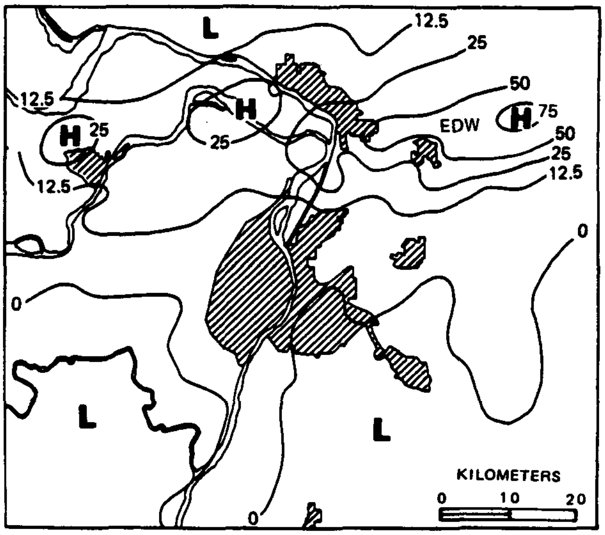

FIG. 6. Rainfall pattern (in millimeters) at 2100–2400 CDT in storm of 16 June 1973.

northeast anomaly storms. Passage was defined at the time the system reached the station. Results indicated that 29% of these convective systems passed between 1800 and 2100. If evenly distributed diurnally, only 12.5% would be expected in this period. The 1800–2100 peak matches the rain peak in the adjacent ALN-WR bottomlands (Fig. 1); it is in the early part of the nocturnal anomalies in the ALN-WR urban and downwind areas (2000–2300), and 0 to 3 hours prior to the EDW and GRC-EDW anomalies. The National Weather Service (NWS) airport station is located 40 km west-southwest (upstream) of Edwardsville. Rain systems with cold fronts or squall lines moving from the southwest, west, or northwest would pass this point 1 to 3 h before reaching the ALN-WR and EDW areas. For example, a squall line moving eastward at 20 km h^{-1} (a typical speed) would reach the center of the EDW subarea in about 2 h after arriving at the airport station. The foregoing study suggests the nocturnal anomalies may have occurred when they did because of the combination of 1) an ever present urban environment and its influences on convection, and 2) natural (climatic) diurnal distribution of convective systems susceptible to urban influences. The peak of squall line and cold frontal passages in the network during 1800 to 2100 in 1971–75 may be a sampling vagary or a real persistent feature of the regional climate.

5. Raincell analysis

Following the procedure in earlier METROMEX research (Changnon et al., 1977), raincells were determined from 5-min rainfall amounts in the 225-gage network. A raincell was defined as a closed isohyetal entity within the overall enveloping isohyet of a rainstorm system; i.e., it defined an area of significantly greater rainfall amount than the system-enveloping isohyet, and persisted >5 min (Changnon, 1981). Raincells which developed or passed over the urban industrial areas of St. Louis or Alton-Wood River and affected one or more of the six anomalous subareas were the focus of this analysis.

The raincell parameters determined were time and place (gage) where the raincell was first observed (initiated), duration, direction and speed of movement, maximum point rainfall and its location, time and location of any raincell mergers or splits (based on time analysis), plus any pertinent comments about the raincell's behavior. From the 13 storms that largely caused the anomaly, 450 surface raincells were identified. Of these, 236 (52%) met the qualifying criteria of exposure to (moving over) one of the urban industrial areas and/or contributing to the 3-h rainfall in one or more of the six anomalous subareas.

Figure 7 shows the total rainfall produced by urban

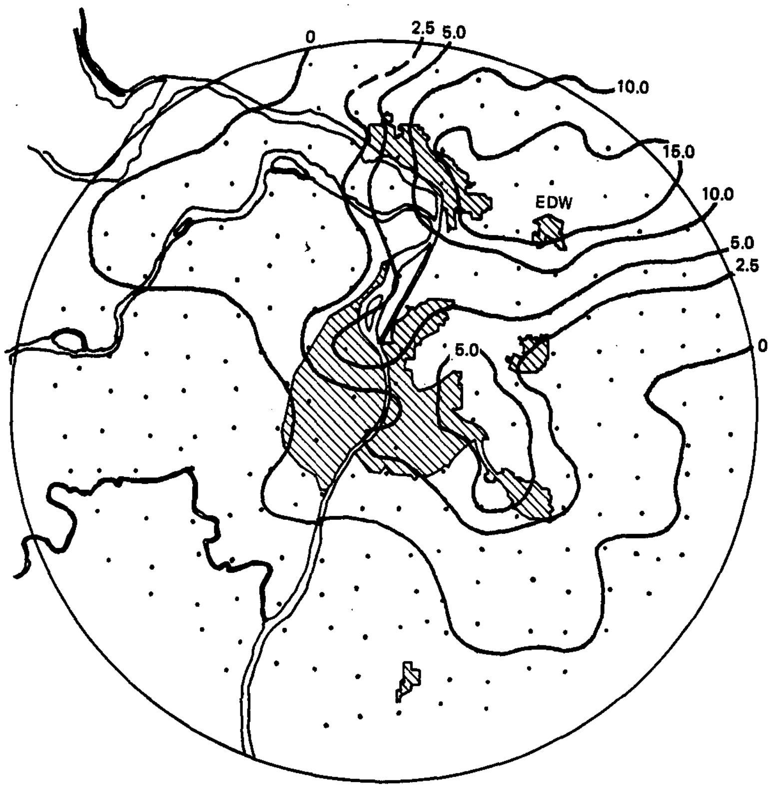

FIG. 7. Rainfall from urban-related raincells in nine storms that maximized in EDW subarea during 2100–2400 CDT.

related raincells in the nine of the ten storms which maximized in late evening between 2100 and 2400 at EDW subarea and with the largest positive deviations. Cells in one of the ten storms could not be accurately determined. The 15-cm isohyet outlines the area most affected by these raincells. The area of maximum effect includes most of EDW and WR refineries, and portions of the GRC-EDW and ALN-WR downwind areas (Fig. 1). The rainfall west of STL and ALN-WR (Fig. 7) is associated with raincells that developed upwind of the potential effect areas, but later crossed STL or the ALN-WR area and proceeded downwind as active rain producers.

In the EDW area, 77% of the total raincell rainfall during 2000–2400 (Fig. 7) was associated with urban-exposed cells, and only 23% with rural cells (no urban exposure). In GRC-EDW, 81% of the raincell total was associated with urban related cells.

Studies of the daytime anomaly revealed that much of the urban-effect rainfall was associated with raincells that had merged (Changnon et al., 1981). However, only 12% of the raincells contributing to the EDW nocturnal rainfall anomaly (Fig. 7) were from merged raincells. However, among merged raincells, 90% occurred when one or more of the merging raincells had been over the urban area. Thus, the urban raincells had a greater tendency to merge than rural raincells; this is likely related to the tendency for the anomaly related raincells to initiate most frequently over and/or immediately downwind of the urban-industrial areas (Fig. 8), plus potentially accelerated areal growth of existing raincells that move over STL and become exposed to the urban environment.

Table 7 summarizes the relationship between urban and rural raincells for four major properties. The 13 northeast anomaly causing storms were divided into two groups: those maximizing later, at 2000–2300 and at 2100–2400; and those peaking earlier, at 1800–2100 or 1900–2200. Ratios of urban-to-rural values are shown for each group and for the 13 storms combined. Volume (total water output) shows the largest difference between urban and rural raincells. Volumes averaged 38% greater in the urban raincells in late evening and 15% more in the earlier group. Combining all storms, the urban raincell volumes averaged 31% (1.31) more than the rural cells. This suggests an urban mechanism that increases rain rates in storms over the city and/or industrial areas.

Figure 8 shows the areal distribution of initiations of raincells in the 13 northeast anomaly causing storms. The greatest frequency was along a line extending over the urban-industrial areas, south-southwest from the

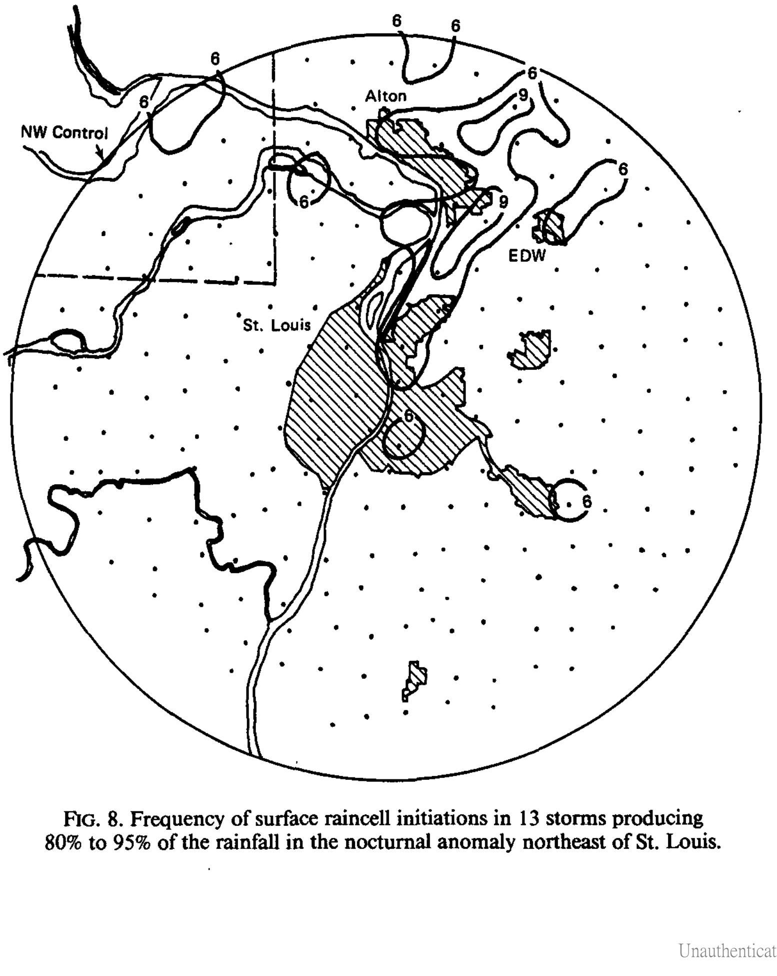

FIG. 8. Frequency of surface raincell initiations in 13 storms producing 80% to 95% of the rainfall in the nocturnal anomaly northeast of St. Louis.

TABLE 7. Comparison of urban (U) and rural (R) raincell characteristics in 13 selected storms. (Time CDT)

Raincell characteristics	Ratio of urban to rural mean value 2000–2400	1800–2200	1800–2400
Mean rainfall	1.03	0.93	0.98
Duration	1.06	1.15	1.09
Area	1.29	1.16	1.25
Volume	1.38	1.15	1.31
Number of storms	9	4	13

ALN-WR area to GRC and STL Industrial-East areas. If the STL and ALN-WR urban industrial regions are influencing the initiation of rainfall and raincells, the maximum frequency is in the expected location since the 13 storms moved predominately from west-southwest to west-northwest. Ratios of the average frequency of raincell initiations in selected subareas to the frequency in an upwind control area revealed the largest ratios (>2.0) occurred in subareas in and immediately downwind of the urban industrial areas, as implied by Fig. 8. A rapid decrease in the ratios occurred a few kilometers east of STL in the BLV-COL subarea (Fig. 1). Average frequencies in COL-BLV and STL East downwind areas were similar to that in the two upwind controls.

The preceding analyses indicate that nocturnal subarea anomalies were related both to enlargement of rain areas from ongoing storm entities and to the development of many new raincells in the St. Louis urban-industrial complex. The first analysis indicated that nocturnal urban-exposed raincells had larger areas and lasted longer than rural raincells, on the average. The raincell initiation analysis shows a strong tendency for new cells to develop much more frequently in and immediately downwind of the urban industrial complex than occurs upwind and short distances downwind of STL.

6. Summary and conclusions

This study focused on a maximum of summer precipitation north and northeast of St. Louis that occurred late in the day, between 2000 and 2400. Earlier extensive studies of the METROMEX summer rainfall data from 1971–75 (Changnon et al., 1981) focused on an afternoon anomaly in the same general area and established that it was statistically significant and related to a series of urban factors that influences the lower atmosphere, alters convective cell development, and enhances precipitation and storm development leading to a 30% increase in rainfall. These earlier METROMEX studies also detected a second maximum of rainfall northeast of STL but later in the day. However, these prior studies had not investigated its statistical or physical reality.

The primary nocturnal maximum occurred 30 km northeast of St. Louis between 2100–2400. That area received 58% more rainfall than the rest of the network during these 3 h.

This study established that the heavy nocturnal rainfall northeast of St. Louis at Edwardsville was a real anomaly. Its reality, regardless of causes, was reflected in several ways. It was present in each of the five summers of the METROMEX sample (1971–75). The maximum was in the correct locale for a sequence of movement of the rain increases which first developed between 1800 and 2100, west of Alton, peaked in the Alton-Wood River area between 2000–2300, and then moved eastward to Edwardsville area in the next hour. The nocturnal maximum in the area northeast of St. Louis also was statistically significant, being four standard deviations above the network mean.

The relationship of the anomaly to urban influences was established by the fact that most storms peaking in the anomalous area moved from the southwest and from over the urban industrial area to the Edwardsville area. The anomaly was due to the heavier rain events in the evening, a condition typical of the daytime summer findings. The 19 storms that moved from the west-southwest or southwest during the 2100–2400 period produced 69% of the rainfall anomaly in the Edwardsville region, and each of these 19 storms had several rain cells that developed over St. Louis.

The nocturnal anomaly also was similar to the afternoon maximum in that both maximums at Edwardsville occurred during periods of network-wide peaks in rainfall. In other words, when the atmosphere was capable of producing relatively heavy rainfall, the urban influences were most active. Another physical factor revealing when and how the urban influences occurred was that the nocturnal maximum was produced during the passage of organized convective systems.

The raincell analysis showed that 82% of all the raincells affecting the Edwardsville maximum developed and/or intensified over St. Louis and/or Alton-Wood River industrial areas. The average dimensions of these raincells indicated that they were larger, longer lasting, and yielded more water than the average rural raincells. Braham (1981) speculated that the evidence relating to a nocturnal increase in middle size storms over the urban area, coupled with a lack of corresponding increases in hail and thunderstorm activity, were indicative that the θ_e hypothesis, as postulated by Boatman (1974), was a possible explanation for the nocturnal maximum.

Results of this study showing larger, more intense raincells just east of St. Louis but with little merging of raincells appear to be partially supportive of the "θ_e hypothesis." Its rationale is that the injection of warm, dry air with relatively low θ_e, characteristic of urban areas and relatively more pronounced at night, causes a decrease in storm updraft buoyancy and its ability to carry previously condensed liquid water. This would result in a premature weakening of the nocturnal storms passing over the urban industrial area, and subsequent release of water stored in the storms, leading to an increase in rainfall rates which we found. One would predict that the surface rain maximum should lag the point of an initial injection of the lower θ_e air by 20 to 60 min, which is consistent with the findings of the placement of the increase in nocturnal raincells closest to STL-ALN—the area of six or more raincell initiations (Fig. 8). The occurrence of an apparent urban effect in so few storms at night may relate to the fact that many nocturnal thunderstorm systems are decoupled from the boundary layer. Unfortunately, the scope of this study did not allow assessment of sounding or radar data to investigate this hypothesis further. It would be an important possibility to investigate in future research.

Acknowledgments. This research was performed as part of a grant from the National Science Foundation, ATM83-05502. However, the findings herein do not reflect the views of the National Science Foundation. The assistance of Peter J. Lamb and J. Loreena Ivens in the review, and of John Brothers in preparing the figures is appreciated. Reviewers of this paper for JCAM provided very useful suggestions for improving the paper.

REFERENCES

Boatman, J. F., 1974: *Inadvertent Thunderstorm Modification by an Urban Area.* M.S. thesis, Dept. of Atmos. Sci., University of Wyoming, Laramie, 126 pp.

Braham, R. R., 1981: Urban precipitation processes. *METROMEX: A Review and Summary. Meteor. Monogr.* No. 18, Amer. Meteor. Soc., Boston, 75–116.

——, and D. Wilson, 1978: Effects of St. Louis on convective cloud heights. *J. Appl. Meteor.,* **17,** 587–592.

Changnon, S. A., 1981: Convective raincells. *J. Atmos. Sci.,* **38,** 1793–1797.

——, 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: *Summary of METROMEX, Volume 1: Weather Anomalies and Impacts.* Bull. 62, Illinois State Water Survey, 260 pp.

——, ——, S. Q. Kidder and H-T. Wu, 1985: *Further Studies of Urban Effects on Precipitation at St. Louis.* Contract Rep. 372, Illinois State Water Survey, 165 pp.

——, R. G. Semonin, A. A. Auer, R. R. Braham and J. Hales, 1981: *METROMEX: A Review and Summary. Meteor. Monogr.* 18, Amer. Meteor. Soc., Boston, 181 pp.

Hiser, H., 1956: Type distributions of precipitation at selected stations in Illinois. *Trans. Amer. Geophys. Union,* **32,** 421–424.

Huff, F. A., 1971: *Distribution of Hourly Precipitation in Illinois.* Circular 105, Illinois State Water Survey, 23 pp.

——, 1977: Diurnal distribution of summer rainfall. *Summary of METROMEX, Volume 1, Weather Anomalies and Impacts.* Illinois State Water Survey Bull. 62, 45–52.

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

——, and J. L. Vogel, 1978: Urban, topographic and diurnal effects on rainfall in the St. Louis region. *J. Appl. Meteor.,* **17,** 565–577.

U.S. Weather Bureau, 1947: *Thunderstorm Rainfall.* Hydromet. Rep. 5, New Orleans, 218 pp.

Vogel, J. L., and F. A. Huff, 1977: Relation between surface winds, storm movement, and rainfall. *Summary of METROMEX, Volume 1, Weather Anomalies and Impacts,* Illinois State Water Survey Bull. 62, 61–66.