Mesoscale Features of Urban Rainfall Enhancement

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ABSTRACT. Analyses of data from the first 4 years of a 5-year research project at St. Louis indicate a substantial enhancement of summer rainfall downwind of the urban-industrial complex. This anomaly appears to be caused primarily by the intensification of naturally occurring storm systems through the addition of heat and raindrop nuclei from the urban area. Most of the enhancement is associated with organized storm systems and is most pronounced during and after the period of maximum diurnal heating.

SINCE 1971, AN EXTENSIVE field and analysis program (METROMEX) has been under way in the St. Louis region to investigate the causes and effects of urban enhancement of precipitation in and downwind of large urban-industrial complexes *(Changnon et al. 1971)*. Huff and Changnon *(1972)*, in a study of eight major cities in the United States, found that the urban environment tends to enhance total precipitation, heavy rainstorms, and severe weather (hail, thunderstorms) in the vicinity.

The St. Louis program involves various types of surface and low-level atmospheric measurements of meteorological parameters. However, this paper is concerned only with findings for the summers of 1971-74 that have been obtained from analyses of data from a dense network of 225 recording rain gages in a circular area of 5,200 km^2 (fig. 1) and a 10-cm PPI radar (FPS-18). These two data sources have provided much information on the differential time and space characteristics of summer precipitation exposed to (1) the urban environment, (2) regional topographical influences, and (3) flat rural areas that serve as a control in evaluating urban and topographical effects on the regional rainfall distribution. Summer is emphasized because the earlier climatic studies *(Huff and Changnon 1972)* showed that the urban effect is most pronounced at that time in the Midwest.

In the METROMEX analyses, four potential sources of localized weather effects were evaluated: the major urban-industrial area of St. Louis, a major industrial area located 10 to 15 km north of St. Louis at Alton-Wood River, and two orographic features (fig. 1). The first of these topographic features is the Ozark Hills, which begin a few kilometers southwest of St. Louis, and the second is the bottomlands of the Missouri River, northwest of St. Louis and west of Alton-Wood River. The roughness of the hills can accelerate both the development and intensification of convective clouds, and the bottomlands are a heat-moisture source conducive to development of convective clouds.

SUMMER RAINFALL PATTERN

In the Edwardsville area the total summer rainfall for 1971-74 (fig. 1) indicates a peak that is frequently downwind of both urban-industrial areas, since westerly winds prevail. The Edwardsville high (120 cm) represents a 30 percent positive deviation from the network mean of 91.3 cm, or more than two standard deviations above the mean. The location of this peak and its large departure from the network mean are considered strong supporting evidence of an urban enhancement of precipitation. The lightest rainfall in the

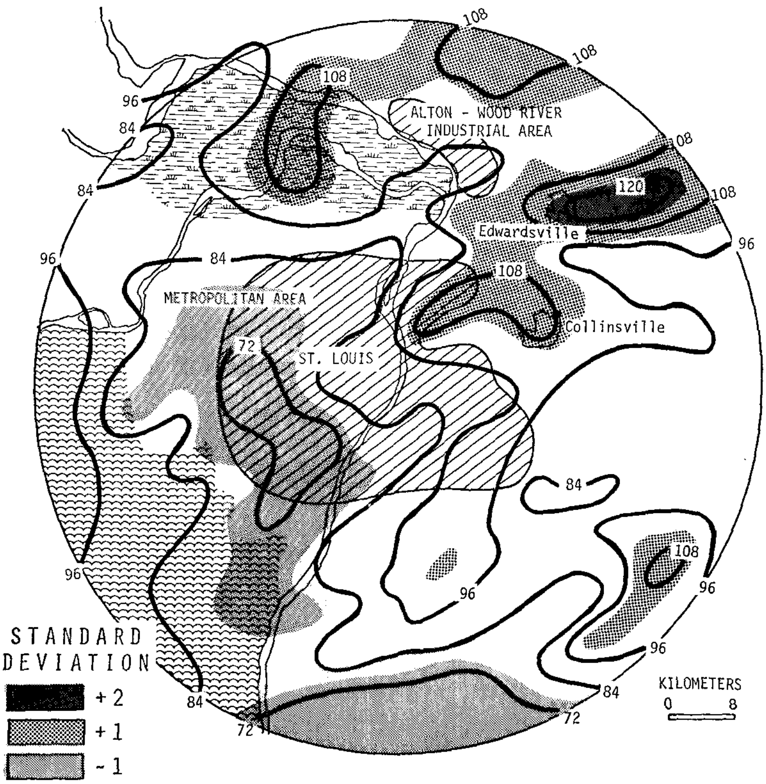


Figure 1.—Total summer rainfall, 1971-74.

four-summer period occurred west and southwest of the major industrial area, which is located along the east of the river. The low region is usually upwind of the industrial region. Thus, the four-summer pattern (fig. 1) shows highs in regions most frequently downwind of the major urban-industrial areas (northeast, east, and southeast of the river) and lows in areas upwind of the urban-industrial complexes.

SYNOPTIC WEATHER RELATIONS

An important consideration in evaluating the causes of urban rain enhancement is the distribution of the precipitation by synopic weather types. In the METROMEX research, efforts have been made to determine what weather processes are active in all rain periods, with special emphasis on the early stages of each rain period, when the urban heat island should exert its maximum effect. In so doing, storms have been classified into five basic synoptic types *(Vogel and Huff 1975)*. These include fronts (cold, warm, stationary), squall lines or squall areas, prefrontal and postfrontal rains, low-pressure center passages, and nonfrontal air-mass storms.

Results to date indicate that more than 75 percent of the summer rainfall in the St. Louis region is associated with organized squall lines and squall areas. These and cold fronts have accounted for nearly 90 percent of the total rainfall on the rain-gage network. Although air-mass storms have accounted for more than one-third of the summer storm occurrences, they produced less than 3 percent of the total network rainfall in 1971-73. This has led to the tentative conclusion that the more active and intense the synoptic situation, the greater are the chances that the city will effectively enhance the precipitation. The air-mass storms, which are unorganized, spatially scattered and usually short-lived, have contributed very little to the rainfall highs easterly of the urban-industrial complexes (fig. 1.)

WIND-RAIN RELATIONSHIPS

Another useful analysis in evaluating the urban effect is to determine the association between surface or low-level winds before rainstorms and the pattern of the resulting rainfall. Both storm movement and the ingestion of heat and particulates (source of rain drops nuclei) into storm systems are related to the low-level wind field. Therefore surface winds have been grouped according to the quadrant from which they blow and averaged for 1 to 3 hours before rainfall, depending upon wind speed. With an active urban enhancement mechanism, the rainfall would be expected to maximize in the quadrant downwind of the city with a given wind movement.

Results to date indicate that, in general, the expected distribution occurs. For example, in 1973 (table 1) the above hypothesis held for all wind movements. That is, with winds blowing from the northeast quadrant (0°-89°) the maximum rainfall with these surface winds (1.40 cm) was in the southwest quadrant. Similarly, the heaviest seasonal rainfall with southeast winds was in the northwest quadrant (15.00 cm), the maximum with southwest winds in the northeast quadrant, and the peak with northwest winds in the southeast quadrant. That is, in each case the highest percentage in each quadrant occurred when the prevailing wind prior to rainfall was blowing across the urban-industrial area. The wind-rainfall relations provide additional evidence of the reality of the observed tendency for the urban environment to enhance the naturally-occurring rainfall downwind of the city.

DIURNAL DISTRIBUTION OF THE URBAN EFFECT

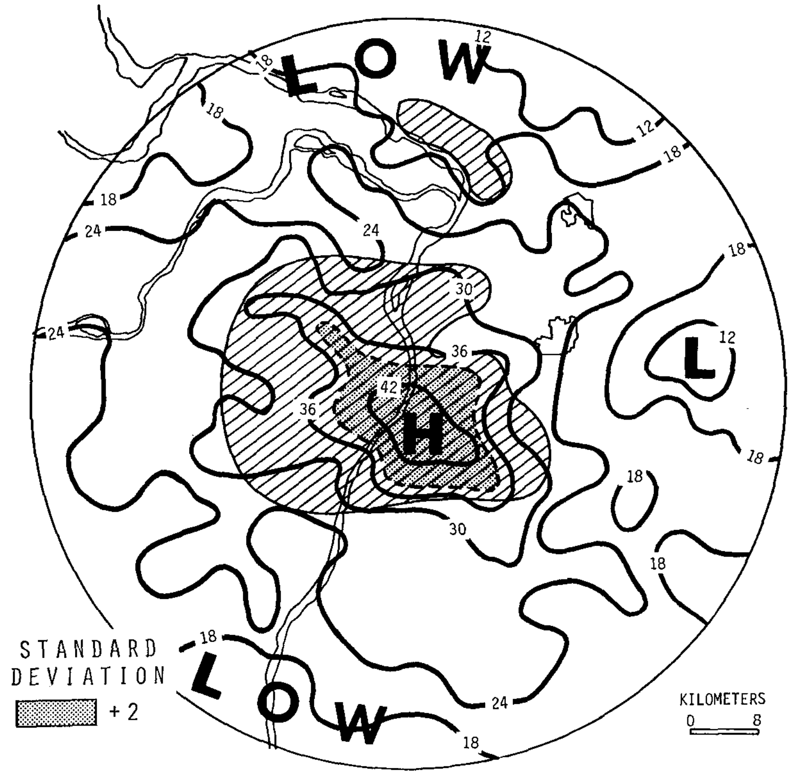
It was hypothesized that the urban effect would maximize diurnally during and immediately after the period of maximum solar heating. At that time, the urban heat discharge combined with the solar heating would tend to produce maximum destabilization in the lower layers of the atmosphere. Then convective growth or development would be favored by the increased thermodynamic instability and/or transferal of raindrop nuclei from stack discharges to cloud base, where they could stimulate the cloud-precipitation processes.

Analyses showed that rainfall tended to maximize over the immediate urban area (fig. 2) in the late afternoon. From 1500 to 1800 CDT, several rain gages in the southeastern part of St. Louis recorded more than 40 percent of their total rainfall for the three-summer period 1971-73. A considerable portion of the urban area (fig. 2) had percentages that exceeded two standard deviations above the network mean of 24

Table 1.—Relation between prevailing surface wind direction before start of rain and network rainfall during summer 1973

Prevailing wind direction	Mean rainfall (cm) for given network quadrant			
	NE	SE	SW	NW
N-E	0.15	0.51	1.40	0.69
E-S	12.20	12.97	12.50	15.00
S-W	11.58	10.00	3.08	2.47
W-N	.25	1.02	.25	.15

Figure 2.—Rainfall pattern for 1500-1800 CDT, 1971-73.



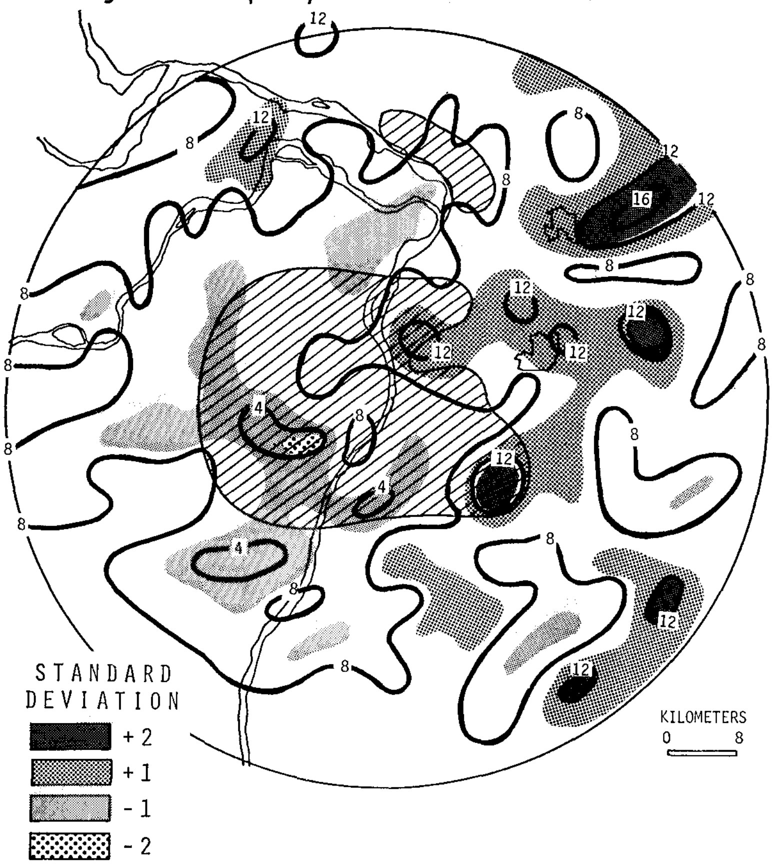
percent of the total rainfall for the three summers. During the following three hours, 1800-2100, the high in the diurnal pattern shifted eastward, as would be expected with raincell initiations in the urban area leading to raincell mergers and intensification of rainfall easterly of the urban-industrial areas. The later high was centered approximately 20 km east of the center at 1500-1800 (fig. 2) and had amounts exceeding two standard deviations above the network mean. Thus the diurnal patterns provide further evidence of an urban-induced enhancement of the natural rainfall downwind of the urban-industrial area.

URBAN EFFECTS ON HEAVY RAINFALL

Another finding from the eight-city climatic study *(Huff and Changnon 1972)* was that the urban effect was most active on days when atmospheric conditions were favorable for storm development from natural processes, and this resulted in a substantial increase in the number of heavy rainstorms downwind of large urban-industrial areas. The earlier finding has been supported by the METROMEX studies, in which the frequency of storm rainfalls of 25-mm or more and their contribution to the total seasonal rainfall have been determined. These storms are of an intensity to be of importance to the hydrologist concerned with the design and operation of urban storm and sanitary sewer systems.

Analyses of the frequency of 25-mm rainfalls at each rain gage during the four summers, 1971-1974, showed a maximum northeast of St. Louis in the Edwardsville area (fig. 3) where the total seasonal rainfall was highest (fig. 1). The low region of heavy rain occurrences was west and southwest of the

Figure 3.—Frequency of 25-mm storm rainfalls, 1971-74.



river (fig. 3) in the same region as the four-season rainfall low. The maxima of 14 to 16 occurrences in the Edwardsville high (fig. 3) were more than two standard deviations above the network mean of eight storms. Rainfall in these storms accounted for over 50 percent of the total rainfall in the Edwardsville high for the 1971-1974 summers; this emphasizes the importance of the heavy storms in defining the general rainfall pattern and controlling the location of high and low centers in the network pattern.

Our studies to date indicate that the maximization of heavy rainstorms in the Edwardsville region occurs from the enhancement of natural storm systems, particularly squall and cold-front systems, as they move across the St. Louis or Alton-Wood River areas. The urban environment acts to intensify existing raincells and to initiate new raincells within ongoing storm systems. This results frequently in maximum rain outputs near Edwardsville, which lies a few km east-southeast of Alton-Wood River and northeast of St. Louis.

A number of case studies have shown that quasistationary mesosystems, maintained by mergers with urban related convective cells, are a common cause of severe rainstorms of hydrologic significance in the urban region *(Vogel and Huff 1975)*. Mergers are frequently associated with storm intensification, and these are favored in the urban region where the environment stimulates new raincell formations and growth of existing convective entities. Other findings from the METROMEX studies show that raincell initiations are frequently associated with "hot spots" in the experimental area, and these occur more frequently within the urban region than in the surrounding rural regions. From aircraft measurements, there are also indications that large amounts of condensation nuclei of urban origin are commonly ingested into cloud systems in the vicinity, and this provides another potential mechanism for initiating rainfall and intensifying ongoing storm systems. In general, analyses to date indicate that excessive heat output from the urban region (a destabilizing force), and raindrop nuclei ingestion from the urban-industrial stack outputs, are probably the major causes of urban rainfall enhancement.

RAINCELL ANALYSES

A primary method of evaluating the urban effect in METROMEX studies has been through comparison of urban-affected and rural (non-affected) raincells. Only those cells that spent their entire life on the network (complete cells) are used. Comparisons have been made for various stratifications of the data, but in this paper I will discuss only analyses of heavy raincells that are of primary concern to the urban hydrologist. For this purpose, the 300 cells with the heaviest mean rainfall were separated from the 2,688 complete cells sampled in the 1971-73 summers. This included all cells with mean rainfall of 6 mm or more. A raincell is defined as a closed isohyetal entity within the overall enveloping isohyet of a rainstorm system; that is, it defines an isolated area of significantly greater intensity than the system enveloping isohyet, and must last more than 5 minutes to qualify as a cell *(Schickedanz 1972)*.

Comparison of the water yield (rainfall volume) from the heavy cells with all 2,688 cells showed that the 300 cells (11 percent of total) accounted for 63 percent of the total water yield. Similarly, the heaviest 100 cells (4 percent of total) produced 40 percent of the water output by all 2,688 cells, and the 50 heaviest cells (2 percent) accounted for 28 percent of the 2,688-cell rainfall. The weight that these cells exert in determining the network rainfall pattern and the magnitude of any urban effect is obvious from the above calculations.

A cell was considered to be potentially urban-effected if it developed over or passed through either of the two major urban-industrial areas. Of the 300 heavy cells, 118 were classified as urban-effected and 134 were included in the rural (no-effect) group. The remainder fell into the topographic-effected group. A comparison of percentage differences between the water yield of these two groups showed that the urban cells had a median output of 1.05 x $10^6 m^3$, which was 55 percent greater than the rural cell median (table 2). The difference was 97 percent or more for the heaviest 5 percent of the cells and was 29 percent or greater when 95 percent were included. The comparison of water outputs associated with the urban and rural cells (table 2) provides further evidence

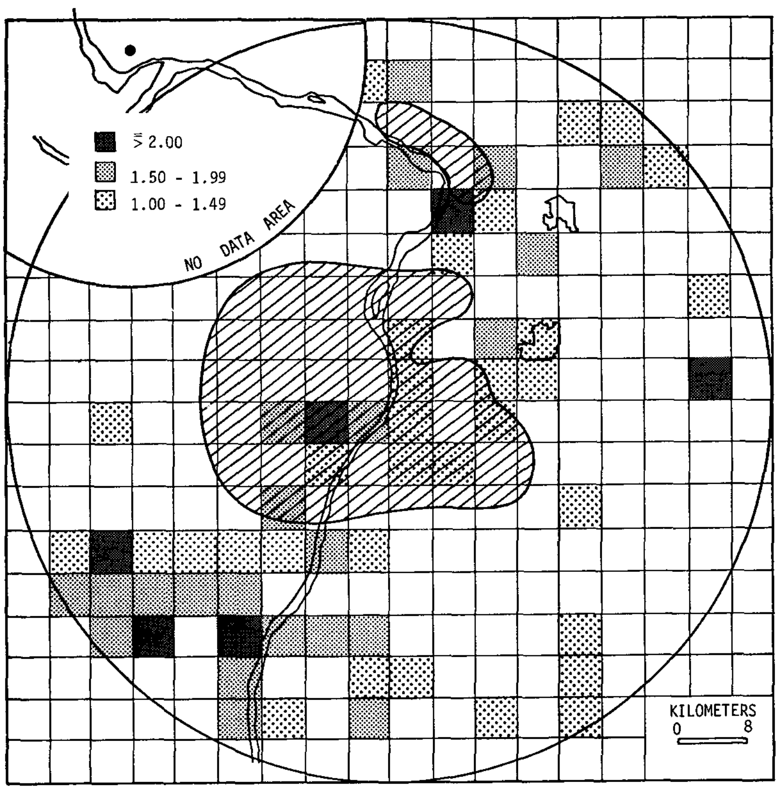
Table 2.—Comparison of water yield between urban-effect (U) and no-effect (C) raincells among 300 heaviest cells in 1971-73

Cumulative percentage of raincells	Urban-effect volume (m^3)	U - C (m^3)	Percent difference
5	4.75 x 10^6	2.32 x 10^6	97
25	1.99 x 10^6	8.43 x 10^5	73
50	1.05 x 10^6	3.70 x 10^5	55
75	5.83 x 10^5	1.82 x 10^5	45
95	2.47 x 10^5	5.56 x 10^4	29

Table 3.—Comparison of percentage difference between urban-effect and no-effect rainfall parameters in 1971-1973 heavy raincells

Cumulative percentage of raincells	Percentage difference equalled or exceeded			
	Mean rainfall	Area	Path length	Duration
5	20	72	72	42
25	11	51	56	20
50	11	35	45	10
75	10	32	29	14
95	10	25	17	11

Figure 4.—Number of radar echo initiations per 25 mm of rainfall.



of the urban effect and its observed tendency to increase with increasing rainfall yield from natural causes. Statistical tests (u-test and t-test) showed the urban-rural differences to be significant at the 1 percent probability level.

Comparison of urban-rural raincell differences for various rainfall parameters showed the maximum difference associated with rainfall volume that integrates the effects of cell area, duration, intensity, and path length. However, other parameters did show larger values for the urban cells (table 3). For example, median percentage differences were 45, 35, 11, and 10 percent respectively for cell path length, area, mean rainfall, and duration (table 3) compared with 55 percent for rainfall volume (table 2). This consistency of positive differences between cell parameters adds to proof of the urban effect.

RADAR MEASUREMENTS OF URBAN EFFECT

Analyses were made of radar echo observations from 27 storms sampled with the 10-cm FPS-18 radar in 1972-74. Major emphasis was placed on preferred areas of echo initiation and echo mergers in the METROMEX network. Initiation counts were based upon the number per 23 km^2 (9 mi^2) and merger counts on the frequency per 92 km^2 (36 mi^2). Results of these analyses indicated a strong trend for echo initiations (rain entities) to occur most frequently in and downwind of the urban-industrial areas and in the Ozark foothills (fig. 4). The most frequent region of occurrence was in the vicinity of oil refineries at Wood River, where the normalized frequency (number/25-mm of rainfall) was 50 percent greater than for any other unit area in the network.

Raincell and radar echo mergers are frequently associated with intensification of ongoing storm rainfall. Therefore the radar data were examined for the distribution of echo mergers in the 27-storm sample. Results showed the most frequent area of mergers near the eastern and southeastern boundaries of the urban area of St. Louis, and a secondary maximum appeared in and downwind of the Ozark Hills, as well as downwind of the urban area. Thus, the radar analyses add support to validation of the urban enhancement mechanism by exhibiting a source of above-normal frequency of raincell development and intensification in the urban-industrial regions. The radar analyses also showed that the foothills are likely a region of topographic effect on convective development and rainstorm enhancement.

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