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FURTHER STUDIES OF URBAN EFFECTS ON PRECIPITATION AT ST. LOUIS

by

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A. INTRODUCTION

METROMEX was a definitive study of how a major urban area affects all aspects of the atmosphere, with particular emphasis on precipitation (Changnon et al., 1981). METROMEX focused largely on summer season (June-August) conditions. This single season focus occurred for various reasons including funding limitations and availability of staffing and equipment. Even with a summer focus, unresolved scientific questions remained relating to the precipitation findings from the 1971-75 summer sample. The monograph on METROMEX delineates these key remaining questions from the summer season (Changnon et al., 1981). Major questions also remained as to possible urban influences on precipitation in off season (September-May) periods.

Objectives

The inadvertent weather modification research described herein addressed two objectives. The first concerned an investigation, using historical and METROMEX data, of precipitation conditions in the other (non-summer) seasons: the transition seasons (spring and fall), and the winter season. The focus was to investigate possible urban-related anomalies in the precipitation, and to discern physical causes for anomalous conditions.

The second objective addressed the question of possible urban influences on a late (2100-0400 CST) nocturnal maximum of summer precipitation found NE of St. Louis. Detection of this maximum occurred late in the METROMEX studies and time did not permit its investigation (Changnon et al., 1981).

The data used to address these questions came from the METROMEX years (1971-75), and from other historical data bases (satellite and surface climatological data). The research has substantially defined the extent of urban influences on cold season (September-May) precipitation and has helped identify the likely causes of the changes noted. The research of the summer late night maximum of rainfall east of St. Louis helped indicate that this too was urban related. This project concluded with identification of some future research issues. We believe the research has increased knowledge of when and how much a mid-latitude large urban area affects precipitation.

This report is organized around five sections. One addresses the studies of storm, monthly, and seasonal precipitation in the fall, winter, and spring of 1971-75 using METROMEX data. A second focuses on these three seasons using NWS data for 1941-80. The third section addresses the summer nocturnal maximum in rainfall, and the fourth section treats the probing studies involving the use of satellite data to measure snow cover. The final section summarizes the main findings and lists future research questions.

B. STUDIES OF WINTER AND TRANSITION SEASON PRECIPITATION

Background Information

There have been limited studies indicating precipitation alterations in fall (Sep.-Nov.), winter (Dec.-Feb.), and spring (Mar.-May) at St. Louis and elsewhere (Changnon, 1976). For example, Dettwiller and Changnon (1976) analyzed the maximum daily precipitation during the cold season at St. Louis over an 84-year period and found a weak uptrend of +6%. A preliminary analysis of the monthly and seasonal patterns in fall, winter, and spring, using 1949-68 climatological data in the St. Louis region showed distinct but very localized areas of increased precipitation within 25 km east of the city (Huff and Changnon, 1972). The winter average precipitation had a very localized high of about 25 mm suggesting a 10% increase. Fall and spring data suggest similar anomalies.

These findings were supported by results of a limited analysis of fall, winter, and spring precipitation on the METROMEX network (Huff, 1977a). Evidence was found of a possible urban effect east and northeast of St. Louis (Fig. 1), particularly in winter and spring. The data indicated that an urban effect, if present, is less pronounced from fall to spring than during the summer, and this agrees with findings in the study of climatic data for 1948-1969 in the St. Louis area. However, it should be noted that it is not easy to discern these small changes in the St. Louis region, due to the natural climatic gradient from low to high in the general direction one would expect urban influences to exist (Huff and Changnon, 1972). Therefore, more refined studies of the METROMEX and historical data were undertaken to adjust for the climatic gradient and to determine more accurately the location and magnitude of any urban effect.

Monthly and Seasonal Analyses for Winter on METROMEX Network

For the four winters combined (1971-72 through 1974-75), the network mean was 95.40 cm (37.56 in.). The isohyetal map (Fig. 2) shows the heaviest precipitation NE, E, and SE of the St. Louis urban area. The maximum of 107.62 cm (42.37 in.) was recorded at Gage 103 about 27 km east of the urban-industrial area. The winter maximum was about 16 km south of the 1971-1975 summer maximum (Huff, 1977b). In general, the pattern of winter highs east of the Mississippi River, extending from the Edwardsville (EDW) area SSW to the Belleville (BLV) area, is very similar to the summer pattern. Other similarities between the winter and summer patterns include a secondary high area located W-NW of Alton-Wood River (ALN-WR) and a low extending W and WSW from the western part of the St. Louis (STL) urban area. The isohyetal pattern of Fig. 2 and other isohyetal presentations that follow have not been adjusted for the small-scale climatic gradient across the network.

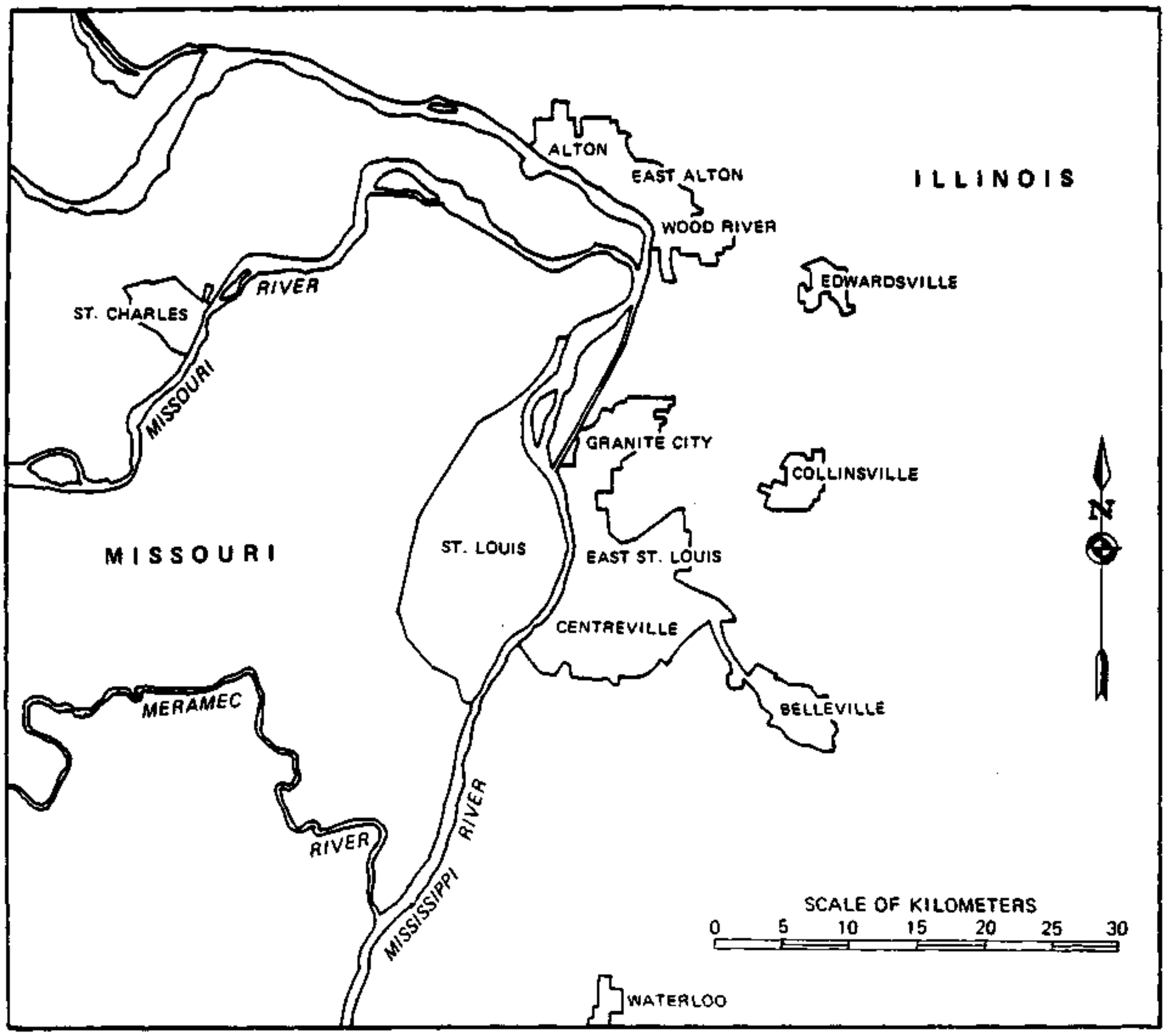


Figure 1. Location of METROMEX Research Project During 1971-1975.

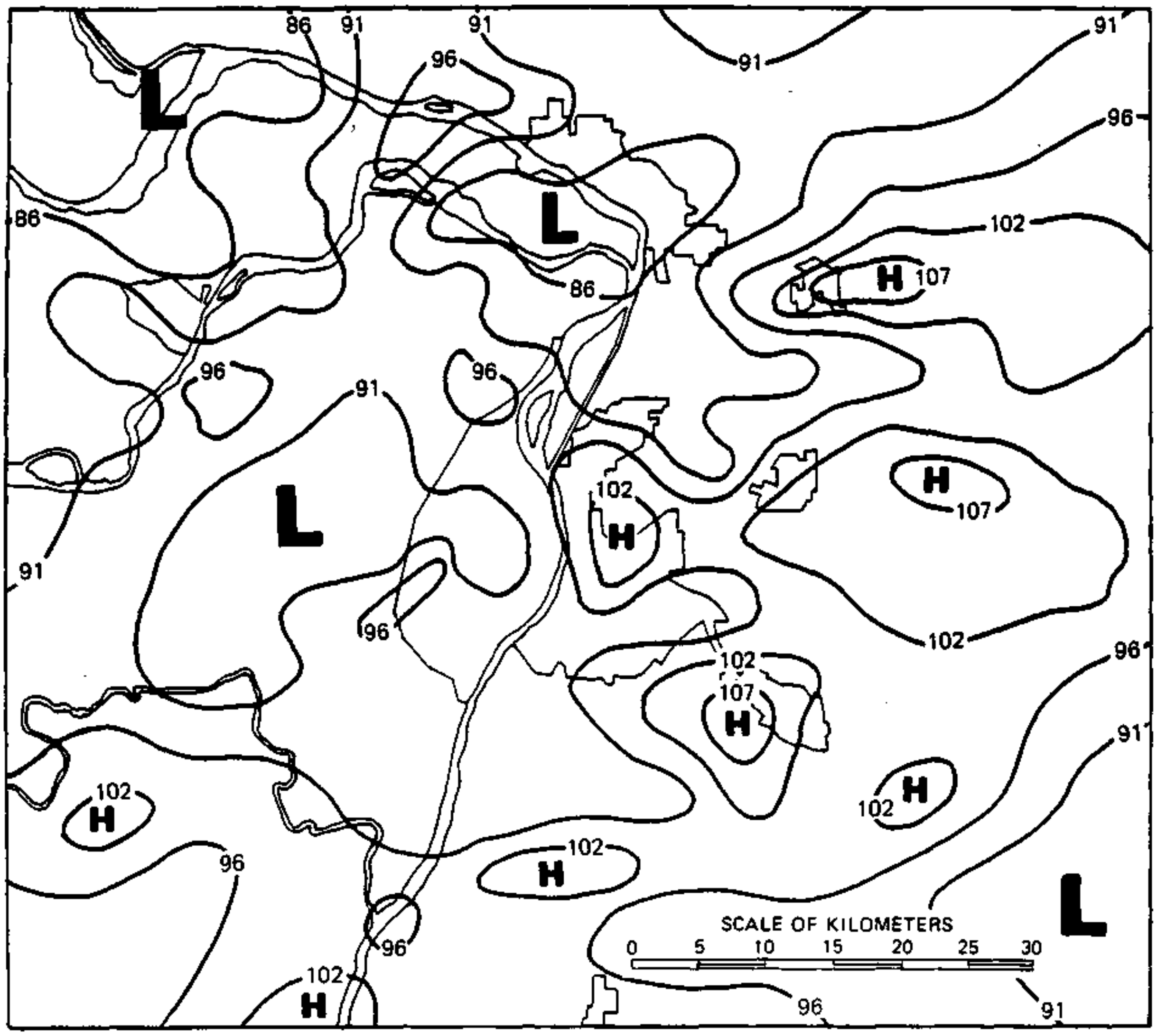


Figure 2. Total Winter Precipitation, 1971-72 Through 1974-75.

The standard deviation of the network 4-winter total was 5.69 cm. The easterly high was over twice the standard deviation and, therefore, appears to be significant. Other areas in the vicinity of EDW and BLV (Fig. 2) had 4-year totals that also exceeded two standard deviations.

In the next step of the winter analyses, the months were divided into three equivalent groups depending upon the network mean precipitation; that is, the four months of heaviest precipitation were designated "heavy", ranks 5-8 were called "moderate", and ranks 9-12 were designated "light". The purpose was to determine if the relatively heavy precipitation pattern in the region NE-E-SE of STL was strongly related to monthly precipitation intensity.

The heavy precipitation pattern (Fig. 3) was very similar to the 4-season total, with the maximum precipitation located east of Collinsville (COL). Although the general pattern was disrupted in the moderate group of months (not shown), a high center was maintained in the EDW area and relatively heavy precipitation occurred in the COL area. Neither the COL or EDW high center was present in the months classified as light precipitation. Thus, the strongest evidence of an urban-induced increase in winter precipitation, with respect to the isohyetal patterns, occurred in months of relatively heavy precipitation. In general, the months of relatively heavy precipitation were the largest contributor to the anomalies east of the Mississippi River, but the moderate months were also a major contributor, especially E and SE of the STL urban-industrial area.

For the entire network, the heavy months accounted for 55% of the total 4-winter precipitation. In the EDW and COL subareas, the heavy months accounted for 54% and 55%, respectively, of the total precipitation. For both the entire network and the two subareas, heavy plus moderate months produced 88% of the total winter precipitation. The light months produced only 12% of the total precipitation in the network and in those subareas which are downwind of the city in most storms. Of the precipitation surplus (deviation from network mean) in the heavy areas lying NE, E, and SE of STL in Fig. 2, 85% to 100% occurred in the months having moderate to heavy precipitation.

Subarea Analyses. In the earlier METROMEX research on inadvertent weather modification during summer in the St. Louis region, Huff and Vogel (1977) selected 17 areas for rainfall comparisons within the dense raingage network. These were selected to represent various degrees of urban, topographical, and combined urban-topographical effects on the rainfall spatial distribution. This procedure was followed in the winter analyses also. A total of 14 comparison areas and two control areas were used. These are shown in Fig. 4 and briefly described in Table 1.

For comparison purposes, the ratio of subarea to network and control area means were computed, after adjustment of the areal mean rainfall values for the climatic gradient across the network. Results for the four winters combined are summarized in Table 2. Values in Table 2 and all tables that follow have been adjusted for the small-scale climatic gradient. All except one area (SE Downwind) were the same as used in the earlier summer research.

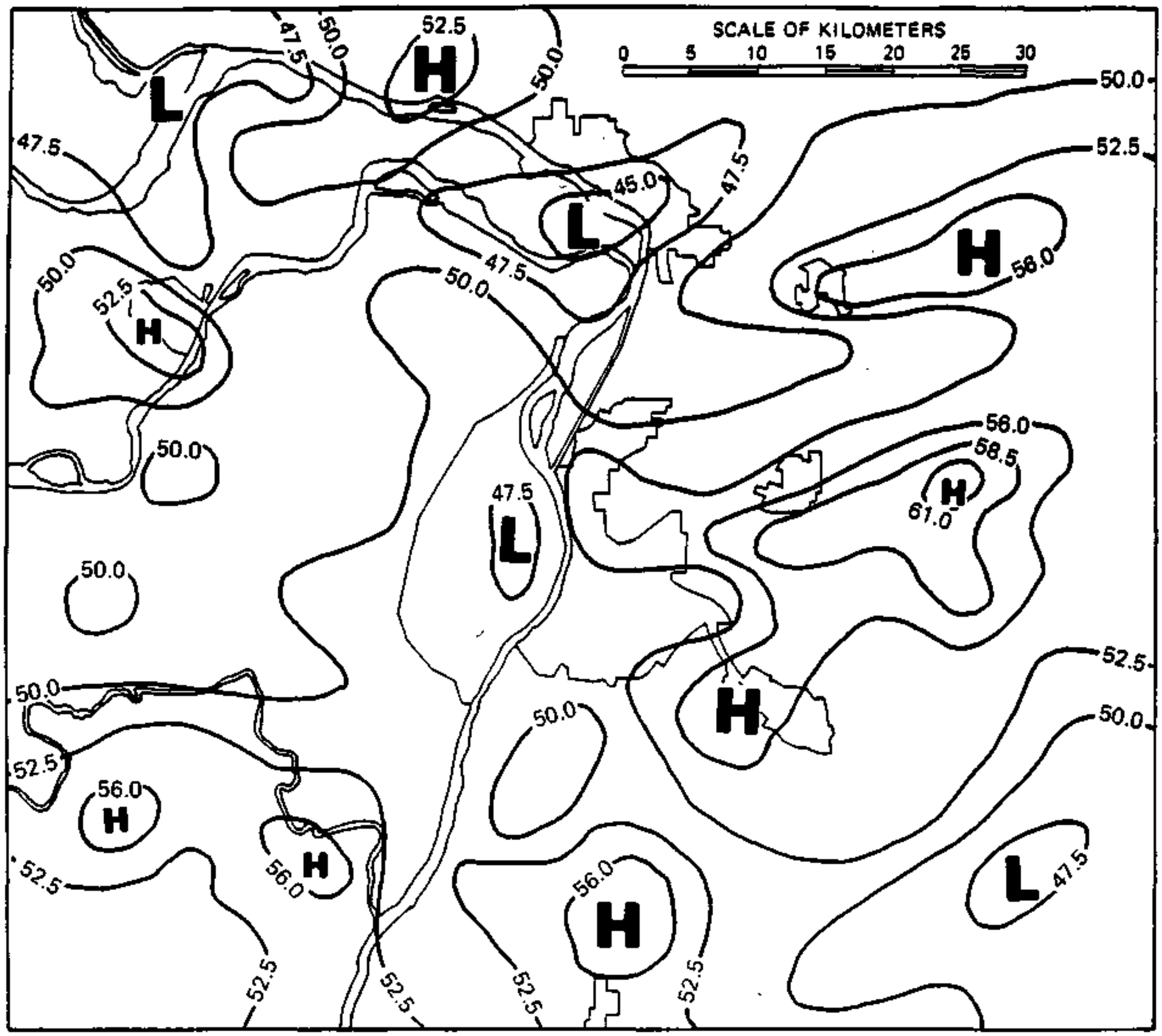


Figure 3. Total Winter Precipitation in Heavy Precipitation Months, 1971-72 Through 1974-75.

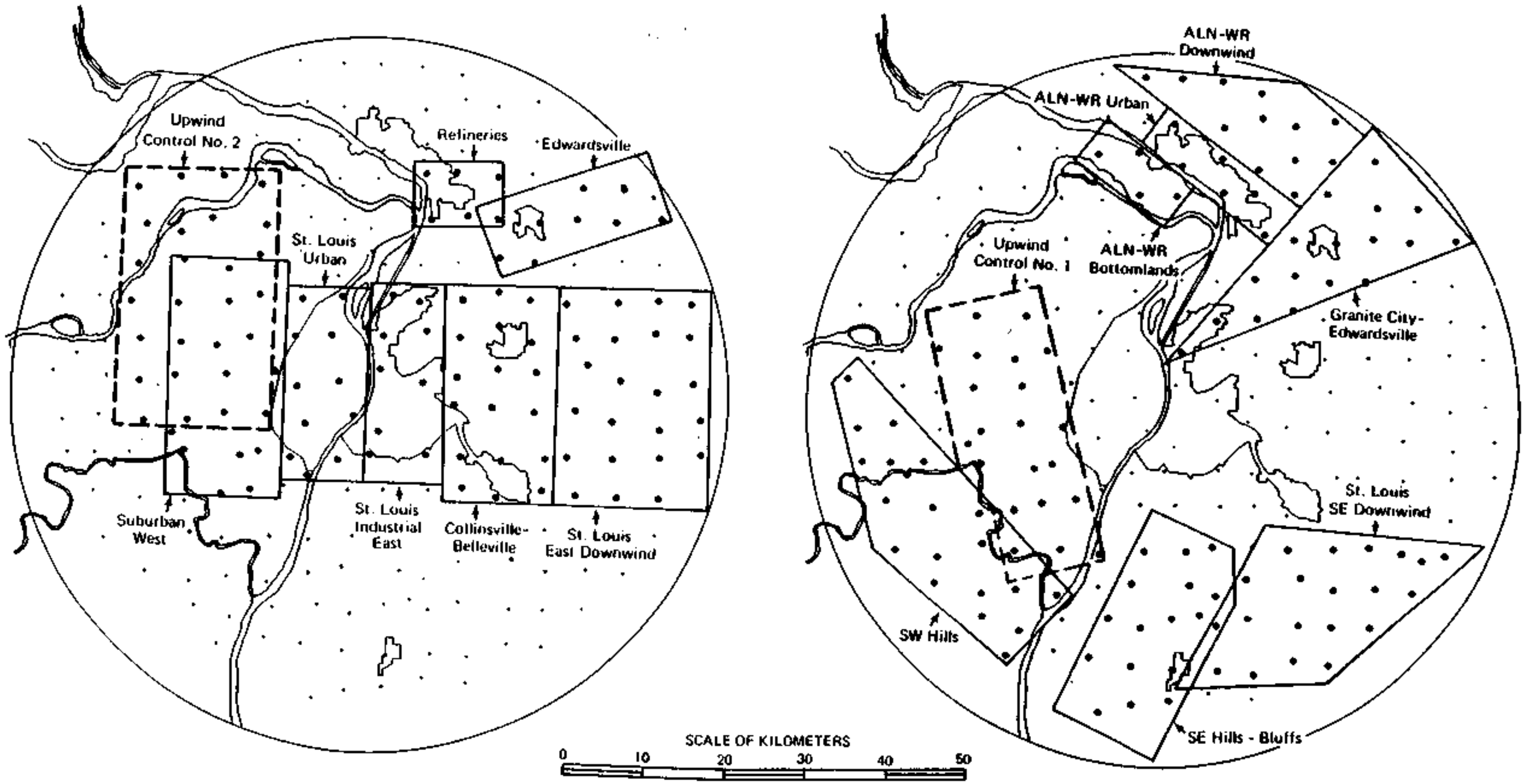


Figure 4. Subareas Used in Evaluating Inadvertent Effects.

Table 1. Description of Comparison Areas.

Nonenclature	Area (km^2)	Area Type	Description
Suburban West	443	Suburban	Largely residential
St. Louis Urban	256	Urban	Commercial and Industrial
St. Louis Industrial-East	210	Industrial	Major industrial area, much heavy industry
Edwardsville	210	Downwind (urban)	Heavy rainfall center-frequently downwind of urban-industrial areas
Granite City-Edwardsville	373	Downwind (urban)	Potentially strong urban and weak bluff enhancement
Collinsville-Belleville	420	Downwind (urban, bluffs)	Downwind of St. Louis-partial overlap by bluffs - potential urban plus bluffs effects
St. Louis East Downwind	536	Downwind	Near limit of expected urban effect and downwind of bluffs
St. Louis SE Downwind	395	Downwind	Similar to East Downwind
Southeast Hills-Bluffs	373	Topographic-urban	Primarily subject to downwind effect from SW hills and bluffs - occasionally downwind of St. Louis
Southwest Hills	466	Hilly	Most rugged hills in network, rarely urban-effected
Alton-Wood River Urban	140	Urban-industrial	Primarily industrial center, moderate commercial and residential
Alton-Wood River Downwind	303	Downwind	Subject to urban effects and possibly river bottomlands influences
Wood River Refineries	140	Industrial	Oil refineries, potentially strong nuclei and moisture source
Alton-Wood River Bottomlands	93	Topographic	Heat-moisture source for development upwind of ALN-WR
Upwind Control-1	490	No-effect	Mostly rural with potential for small hill or urban effect, if any
Upwind Control-2	650	No-effect	Mostly rural with potential for small river valley effects, if any

Table 2. Estimated Inadvertent Effect on Precipitation During Winter 1971-1975 in the METROMEX Network.

Area	Subarea Mean (in.)	Ratio, Subarea to Control Area Mean Network	Upwind-1	Upwind-2	Upwind Average
EDW	9.88	1.06	1.10	1.09	1.10
GRC-EDW	9.67	1.04	1.08	1.07	1.08
WR Refineries	8.88	0.98	1.01	0.99	1.00
STL Urban	9.18	0.98	1.01	0.99	1.00
STL Industrial East	9.58	1.02	1.05	1.04	1.05
COL-BLV	9.59	1.01	1.06	1.04	1.05
STL East Downwind	10.06	1.06	1.10	1.08	1.09
STL SE Downwind	9.47	0.97	1.00	0.99	1.00
SE Hills-Bluffs	9.51	0.97	1.00	0.99	1.00
STL Suburban West	8.96	0.96	0.99	1.00	1.00
ALN-WR Urban	9.97	1.00	1.03	1.02	1.03
ALN-WR Downwind	8.86	1.00	1.03	1.01	1.02
ALN-WR Bottomlands	8.54	0.96	0.99	0.97	0.98
SW Hills	9.49	1.00	1.03	1.02	1.02
Upwind Control-1	9.09	0.97			
Upwind Control-2	8.96	1.01			

Above ratios have been adjusted for variation in normal precipitation across the METROMEX network. Except for SE Downwind, the subareas are those used in the original METROMEX research.

The estimated urban effect is approximately 9%-10% in the EDW area, based on the subarea/control ratios in Table 2. Approximately the same ratios were obtained in the East Downwind area (STL ED) located E of COL. These are substantial increases, but small compared to the summer value of 49% in the EDW area, obtained by Huff and Vogel (1977) from comparison with the control designated Upwind-1 in Table 2. The summer increase was 19% in STL ED. Table 2 does show a gradual increase from no-effect in the St. Louis urban area to 4-5% in the industrial area just east of the urban area and then to the maximum of 9-10% in the EDW area. This is the same trend observed in the summer analyses. In the other comparison areas of Table 2 the ratios are close to 1.00 which would be expected with no effect. The ALN-WR downwind and bottomlands areas, which had relatively large departures from the control mean in the summer rainfall, show no indication of a significant effect in winter. For comparison, percentage differences in precipitation between Upwind Control-1 and potential urban and topographic effect areas are shown for winter and summer in Table 3.

Next, the consistency of the winter ratios between years was examined. The averages obtained from the two controls showed that the EDW/Control average exceeded 1.00 in all four winters. It varied from 1.02 in 1973-74 to 1.26 in 1972-73. The ratio for STL ED was greater than 1.00 in 3 of the 4 winters, and ranged from 0.94 to 1.26. The ratio for GRC-EDW also exceeded 1.00 in all four winters, and varied from 1.02 to 1.18. Thus, the EDW high was persistent throughout the 4-year sampling period, as was the extension of this high from EDW towards STL (GRC-EDW area). As indicated in Table 3, this was also the region where the summer urban effect was greatest.

Subarea ratios were determined next for months classified as having light, moderate, or heavy precipitation. Ratios of subarea to upwind control precipitation are shown in Table 4. The control precipitation was obtained from averaging values for the two upwind controls utilized in the various subarea analyses.

Ratios exceeded 1.00 in all three intensity classifications in the region lying NE, E, and SE of STL. Thus, all intensities made some contribution to the anomalies in this region which is usually located downwind of the urban-industrial areas of STL and/or ALN-WR. The highest percentages in the potential urban-effect subareas occurred with months having moderate precipitation and the lowest percentages with light monthly precipitation. The differences in total precipitation (subarea-control) were greatest in the moderate months for EDW, GRC-EDW, and STL Industrial East. Differences were greatest in the heavy months for STL ED, SE Hills-Bluffs, and STL Southeast Downwind (STL-SED). COL-BLV had the same difference for both moderate and heavy months. These computations indicate a trend for the inadvertent effect to shift from the moderate to heavy months in progressing E and SE from the STL urban-industrial area.

<u>Monthly Analyses</u>. Subarea analyses were performed for each individual month and the results summarized in Tables 5-7. The subarea-control ratios for the four Decembers combined in Table 5 are similar to those for winter. The highest ratios were obtained in the EDW, GRC-EDW, and STL ED

Table 3. Comparison of Winter-Summer Precipitation Differences Between Upwind Control-1 and Various Subareas Subject to Urban or Topographic Effects

Subarea	Winter	Summer
EDW	+10	+49
GRC-EDW	+8	+44
STL Urban	+1	+10
STL Industrial-East	+5	+22
COL-BLV	+6	+28
STL East Downwind	+10	+19
STL Suburban West	-1	-1
SE Hills-Bluffs	0	+24
SE Hills	+3	+9
ALN-WR Urban	+3	+34
ALN-WR Downwind	+3	+38
ALN-WR Refineries	+1	+38
ALN-WR Bottomlands	-1	+34

Table 4. Estimated Inadvertent Effect on Precipitation During Months of Relatively Light, Moderate, and Heavy Winter Precipitation on 1971-1975 METROMEX Network.

	Ratio, Subarea to Control Area Mean		
Subarea	Light	Moderate	Heavy
EDW	1.03	1.16	1.08
GRC-EDW	0.99	1.13	1.05
WR Refineries	0.92	1.06	1.00
STL Urban	0.99	1.01	1.00
STL Industrial East	1.03	1.10	1.04
COL-BLV	1.05	1.10	1.05
STL East Downwind	1.09	1.11	1.08
STL SE Downwind	1.06	1.02	0.98
SE Hills-Bluffs	0.95	1.04	1.01
STL Suburban West	1.00	0.99	1.00
ALN-WR Urban	0.94	1.10	1.02
ALN-WR Downwind	0.93	1.07	1.01
ALN-WR Bottomlands	0.87	1.06	0.98
SW Hills	1.07	1.00	1.03

Table 5. Estimated Inadvertent Effect on Precipitation During December 1971-1974 in the METROMEX Network.

Subarea	Ratio, Subarea to Control Area Mean			Upwind
	Network	Upwind-1	Upwind-2	Average
EDW	1.09	1.11	1.14	1.13
GRC-EDW	1.05	1.08	1.10	1.09
WR Refineries	0.96	0.99	1.00	1.00
STL Urban	0.98	1.00	1.03	1.02
STL Industrial	1.04	1.07	1.09	1.08
COL-BLV	1.03	1.06	1.08	1.07
STL East Downwind	1.07	1.09	1.13	1.11
STL SE Downwind	0.96	0.98	1.01	1.00
SE Hills-Bluffs	0.99	1.00	1.03	1.02
STL Suburban West	0.98	1.01	1.03	1.02
ALN-WR Urban	0.97	1.00	1.02	1.01
ALN-WR Downwind	0.98	1.00	1.03	1.02
ALN-WR Bottomlands	0.93	0.95	0.97	0.96
SW Hills	0.97	1.05	1.08	1.06

Above ratios have been adjusted for variation in normal precipitation across the METROMEX network. Except for SE Downwind, the subareas are those used in the original METROMEX research.

Table 6. Estimated Inadvertent Effect on Precipitation During January 1972-1975 in the METROMEX Network.

Subarea	Ratio, Subarea to Control Area Mean Network	Upwind-1	Upwind-2	Upwind Average
EDW	1.07	1.18	1.07	1.13
GRC-EDW	1.07	1.18	1.05	1.12
WR Refineries	1.02	1.13	1.01	1.07
STL Urban	0.97	1.05	0.95	1.00
STL Industrial	1.01	1.09	0.99	1.04
COL-BLV	1.05	1.14	1.02	1.08
STL East Downwind	1.04	1.13	1.02	1.08
STL SE Downwind	0.99	1.07	0.97	1.02
SE Hills-Bluffs	0.93	1.03	0.91	0.97
STL Suburban West	0.92	1.00	0.89	0.95
ALN-WR Urban	1.07	1.16	1.03	1.10
ALN-WR Downwind	1.08	1.18	1.05	1.12
ALN-WR Bottomlands	0.99	1.08	0.97	1.03
SW Hills	0.95	1.03	0.93	0.98

Above ratios have been adjusted for variation in normal precipitation across the METROMEX network. Except for SE Downwind, the subareas are those used in the original METROMEX research.

Table 7. Estimated Inadvertent Effect on Precipitation During February 1972-1975 in the METROMEX Network.

Subarea	Ratio, Subarea to Control Area Mean: Network	Upwind-1	Upwind-2	Upwind Average
EDW	1.01	1.04	1.02	1.03
GRC-EDW	1.01	1.04	1.02	1.03
WR Refineries	0.96	0.99	0.98	0.99
STL Urban	0.99	1.02	1.00	1.01
STL Industrial	1.01	1.04	1.02	1.03
COL-BLV	1.02	1.04	1.03	1.04
STL East Downwind	1.02	1.04	1.03	1.04
STL SE Downwind	0.99	1.01	1.00	1.00
SE Hills-Bluffs	1.01	1.04	1.02	1.01
STL Suburban West	0.99	1.00	0.99	0.99
ALN-WR Urban	0.99	1.01	1.00	1.01
ALN-WR Downwind	0.95	0.96	0.95	0.96
ALN-WR Bottomlands	0.98	1.01	1.00	1.01
SW Hills	1.02	1.05	1.04	1.04

Above ratios have been adjusted for variation in normal precipitation across the METROMEX network. Except for SE Downwind, the subareas are those used in the original METROMEX research.

areas and were slightly larger than the winter ratios. In January, the highest ratio was again in the EDW area, followed closely by GRC-EDW (Table 6). However, relatively high ratios occurred in January in the ALN-WR urban and STL ED areas. Assuming an urban effect is present, this suggests it may be approximately equivalent to the EDW anomaly in mid-winter. The February ratios (Table 7) were close to 1.00 throughout the various subareas, and, therefore, provide little evidence of an urban effect.

The consistency of the monthly subarea/control ratios were examined for the 12 individual months in the sample. The ratio for the EDW area exceeded 1.00 in 9 of the 12 months, and exceeded 1.10 in 5 months. The GRC-EDW ratio also exceeded 1.00 in 9 months and 1.10 in 4 months. Although the STL ED ratio only exceeded 1.00 in 7 of the 12 months, it exceeded 1.10 in 6 months. In general, the subareas lying east and NE of the STL urban area had monthly ratios that predominately exceeded 1.00. Other network areas tended to be more evenly divided between ratios less than and greater than 1.00, and exceeded 1.10 in only 2-3 months. In February, the ratios were predominately between 0.9 and 1.1 throughout the network.

Comparison of METROMEX and Earlier Winter Findings. The foregoing analyses of potential urban effects in winter on the densely-gaged METROMEX network were compared with those obtained in an earlier study which utilized only climatic network data in the St. Louis area (Huff and Changnon, 1972). In the earlier, less detailed study, a major effect area was designated which extended NE, E, and SE of the St. Louis urban area for a distance of approximately 40 km (Fig. 5). An upwind control extended W, SW, and NW of the city. For the 20-year period, 1949-1968, the mean precipitation ratio in December for the Major Effect/Control area was 1.06. Among the METROMEX subareas that are part of the earlier Major Effect area, the mean precipitation ratio ranged from 1.00 to 1.14 with an average of approximately 1.07. Thus, the two studies compare very closely.

The mean January ratio from the Huff-Changnon study was 1.05. Table 6 shows a range from near 1.00 to 1.18 for the METROMEX subarea ratio to the two upwind controls. The average for those subareas lying in the earlier Major Effect area is approximately 1.08, compared to 1.05 in the earlier study, but still a close comparison and a helpful confirmation of findings in both studies. The 1972 study shows a mean ratio of 1.01 for February in the Major Effect area. The METROMEX February ratios in Table 7 show a maximum ratio of 1.04 in the EDW and GRC-EDW areas, but the average for the subareas that are part of the earlier Major Effect area is approximately 1.02, very close to the 1972 result, and again confirming the findings in both studies. Furthermore, these comparisons between the two studies indicate that the climatic network data in the St. Louis area are adequate to obtain generalized estimates of the urban effect. This is an important finding with regard to evaluation of urban effects in other large cities and regions of the country.

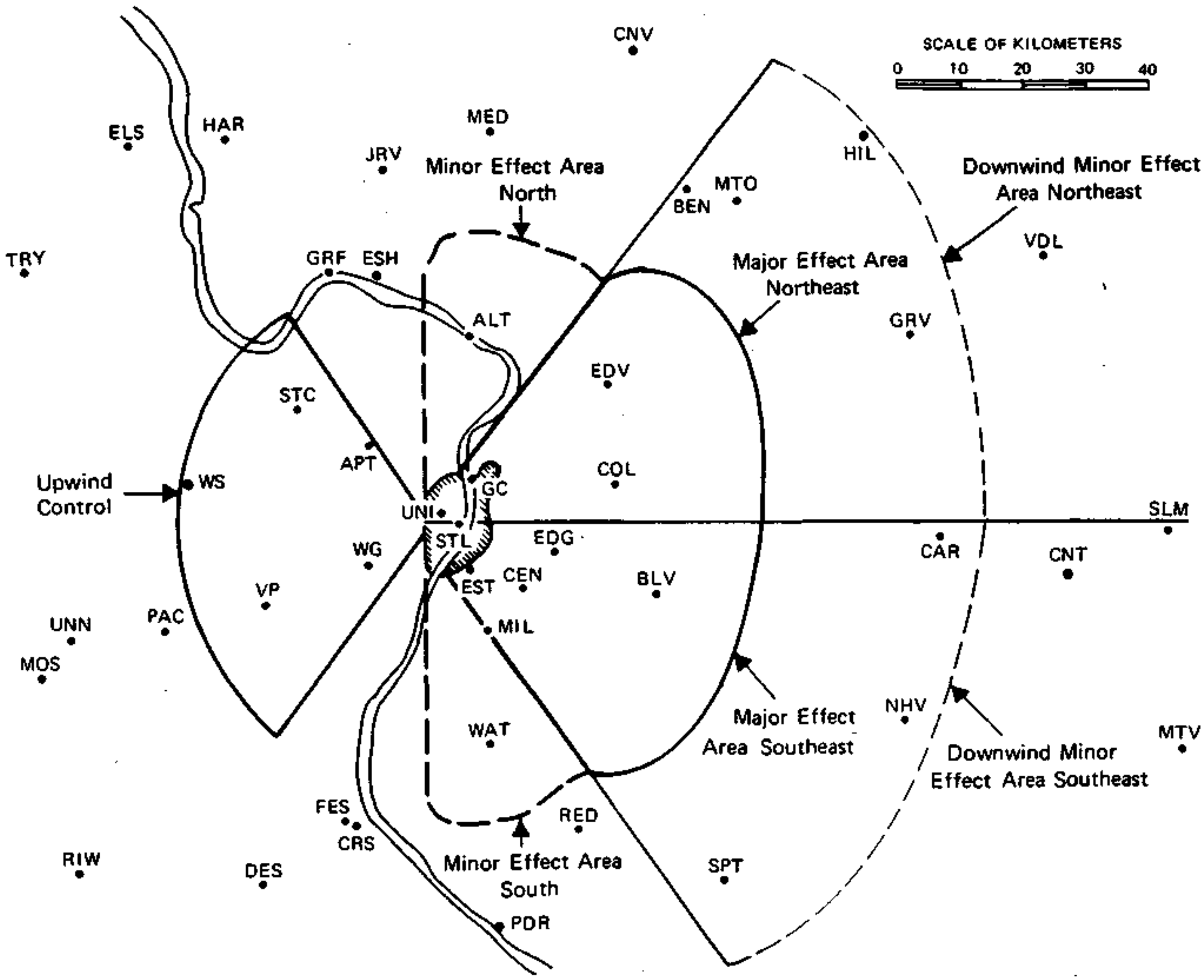


Figure 5. Stations and Subareas Used in Earlier Study of Urban Effects in St. Louis Area, Based on 1941-68 Climatic Data.

Winter Storm Analyses on METROMEX Network

The foregoing monthly and seasonal analyses provided evidence of an urban-induced increase in winter precipitation east of the Mississippi River. The effect was most evident in the EDW and STL ED areas. In the METROMEX summer study (Huff, 1977b), it was found that the urban effect was produced mostly in a relatively small percentage of the storms. This was determined by ranking the differences in mean rainfall between various subareas and the entire network. The positive deviations of subarea-network mean contribute to the anomalies in a given subarea, and the negative deviations modulate the anomaly produced by the positive deviations.

Winter Deviation Analyses. The above analytical technique was applied to the winter storms. Results indicated that the major anomalies in the EDW and STL ED areas were produced largely by a relatively small portion of the winter storms. In the network, there was a total of 136 storms with measurable precipitation. Of these, 63 had positive deviations in the EDW area, 36 showed negative differences between the subarea (A) and the network (N), and there was no difference in 37 storms.

From the deviation rankings, it was determined that 17 storms accounted for 75% of the EDW positive deviations. This represents only 12.5% of all winter storms and 27% of those having positive deviations. Figure 6a shows the isohyetal map for the 17 storms that were largely responsible for the EDW anomaly. These storms were responsible for 39% of the total 4-season precipitation on the METROMEX network and 44% of the EDW area total. This is reflected in many similar features of the 17-storm isohyetal map and total 4-season precipitation shown in Fig. 2. Both illustrations show a major high extending southwestward from the EDW area through the STL urban area, and low areas in the SE, W, and NW parts of the network. Maximum point amounts in the EDW area were 20%-25% greater than the network mean, as shown in the ratio map of Fig. 6b. This map was obtained from calculations of the ratio of point (raingage) amounts to network mean precipitation for the 17-storm total.

In the STL ED area in which the 4-season precipitation maximized (Fig. 2), there was a total of 41 storms with positive deviations, 49 with negative differences, and 46 in which the network and subarea means were the same. However, 12 storms accounted for 75% of the positive deviations. Thus, 9% of the total storms and 29% of those with positive deviations were largely responsible for the major anomaly east of the STL urban-industrial area. Figure 7 shows the isohyetal map for the 12 storms. The easterly high has a NNE-SSW orientation with its center located approximately 25 km (16 mi.) east of the STL industrial area on the east side of the Mississippi River. Point amounts in the center of this high were 25-30% greater than the network mean precipitation in the 12 selected storms.

The storms primarily responsible for the anomalies discussed above were moderate to heavy with respect to network precipitation. The median of the network means for the 136 storms during the four winters was only 1.25 mm (0.05 in.). Of the 17 storms producing 75% of the positive

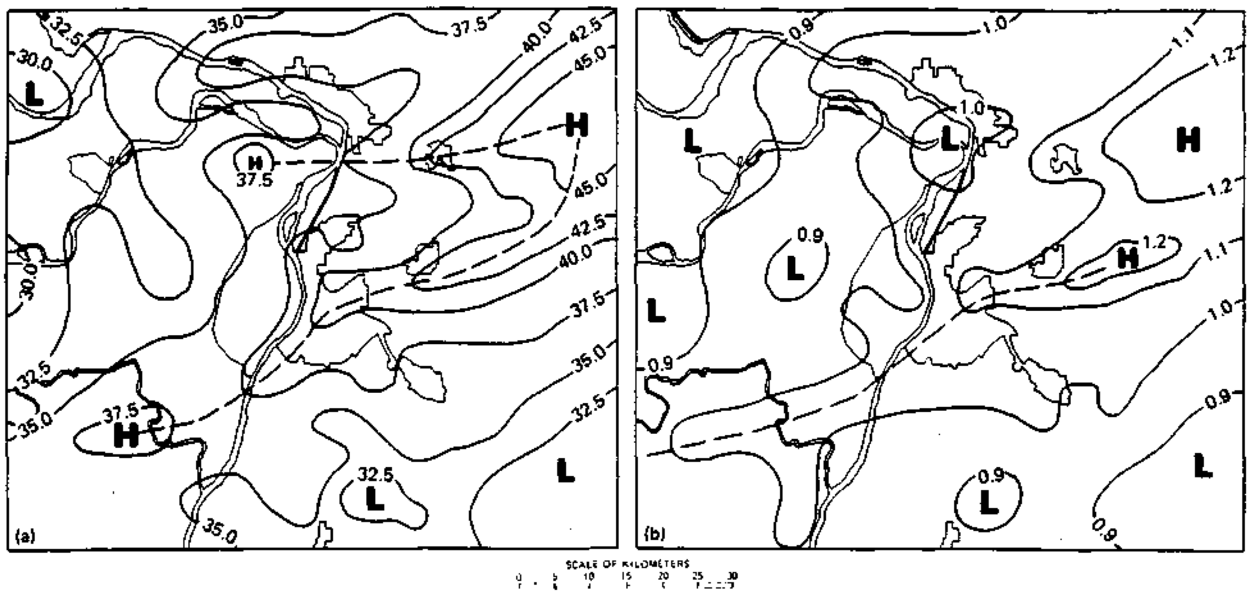


Figure 6. Distribution of Precipitation in 17 Storms Largely Responsible for the EDW Winter Anomaly.

a. Total Precipitation in the 17 Storms

b. Ratio of Gage/Network Precipitation in the 17 Storms

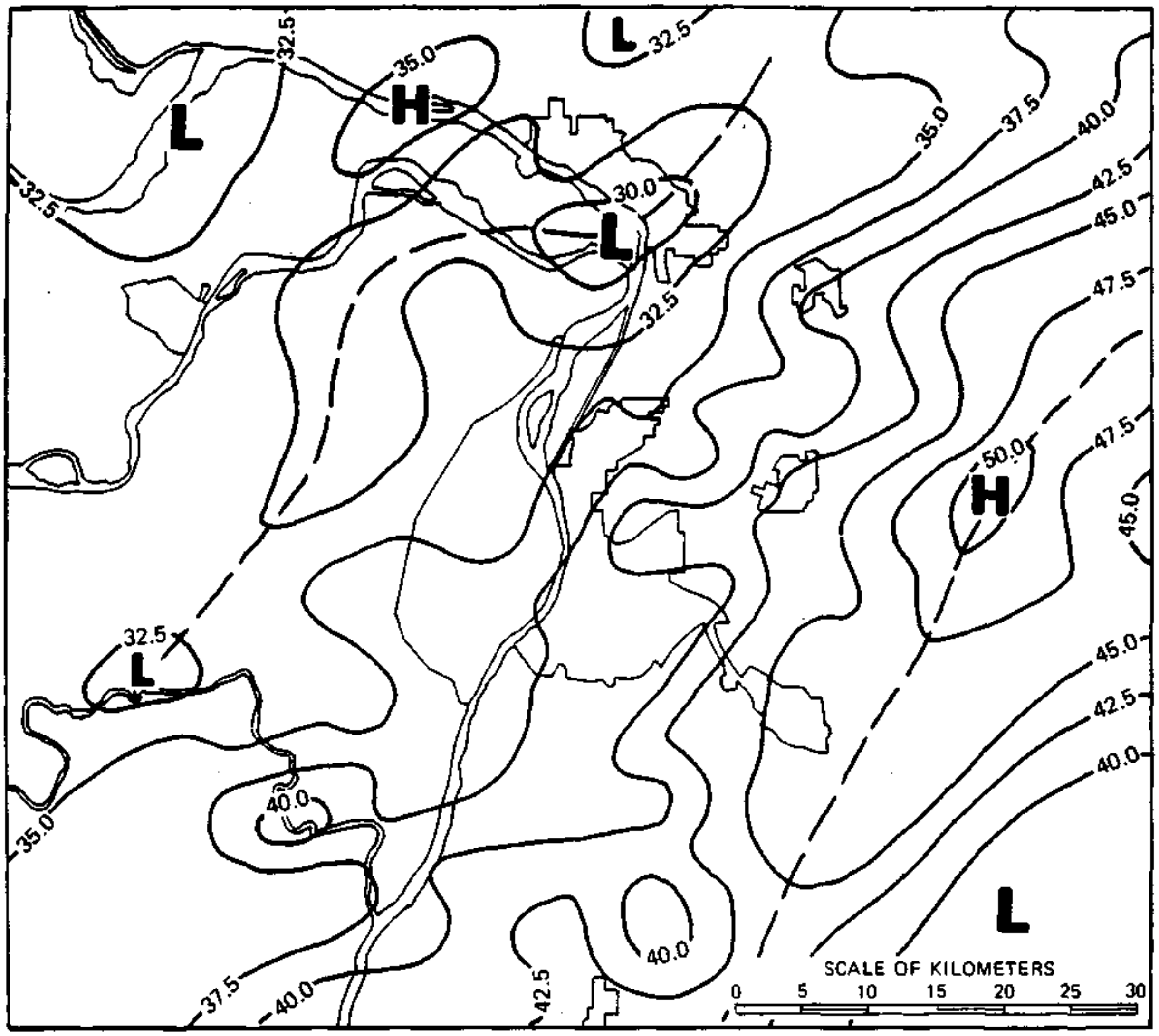


Figure 7. Distribution of Total Precipitation in 12 Winter Storms Largely Responsible for STL Downwind Anomaly.

deviations in the EDW area, the network mean exceeded 25 mm in 5 storms and 2.5 mm in all 17 storms. Similarly, among the 12 outstanding storms in STL ED, network means exceeded 25 mm (1.0 in.) in 6 storms and 4.5 mm (0.18 in.) all 12 storms.

Winter Storms Grouped by Mean Precipitation. Storm data were grouped according to network mean precipitation. The groupings were the same as those used for summer rainfall in the earlier METROMEX research. These included mean precipitation less than 2.5 mm, 2.5-5.9 mm, 6.0-12.4 mm, 12.5-25.0 mm, and over 25 mm. The purpose was to determine whether the apparent urban-induced anomalies varied in strength with increasing storm magnitude. It was necessary to eliminate several storms from the analyses which occurred in a 11-day period in December 1973. Freezing rain and sleet made the raingage clock inoperable so that storms could not be separated. This causes a discrepancy between the storm, monthly, and seasonal totals appearing in this report. The network mean for the 11 days was 3.7 cm.

Results of this analysis are summarized in Table 8 which shows the subarea/upwind control ratios for selected subareas in which an apparent urban effect appears to be strongest. The control precipitation is an average for the two upwind controls described previously. Also shown in Table 8 is the percentage distribution of total precipitation by storm group.

The ratios in Table 8 show a weak trend for the subarea/control ratio to decrease with increasing mean storm precipitation in the EDW and GRC-EDW areas. However, this trend is not indicated in the STL ED area. Table 8 does show that storms producing precipitation having a network mean exceeding 25 mm (1 in.) dominate the winter precipitation distribution. These storms produced 58% of the total precipitation on the network and, therefore, exert a strong control on the magnitude of the subarea/control ratios for total monthly and seasonal precipitation. Figure 8 shows the isohyetal pattern for this storm group. The pattern is very similar to the area distribution pattern of total winter precipitation in Fig. 2.

Synoptic Weather Relations. The winter deviation analyses showed that 23 storms accounted for approximately 75% of the anomalies in the EDW and STL ED subareas where the urban effect apparently maximizes. Some of these storms were major contributors to the anomalies in both subareas. Synoptic weather relations were investigated in the 23 storms to determine whether certain conditions dominated, as they do in summer (Vogel and Huff, 1978).

Analyses of synoptic types were made, based on the method employed by (Vogel and Huff, 1978). Results indicated that 70% of the storms were approaching warm fronts or the approach and passage of major low pressure centers through or very close to the research area. Cold fronts were the major precipitation producer in 22% and stationary fronts in the remaining 8% of the selected storm sample. The foregoing analyses do not indicate anything unique with respect to the relationship between the anomalies and

Table 8. Relation Between Subarea Anomalies and Network Mean Precipitation in Winter Storms.

Storm	Percent of Total Precipitation			Subarea/Control Precipitation		
Mean (mm)	EDW	GRC-EDW	STL ED	EDW	GRC-EDW	STL ED
2.5	6	6	5	1.13	1.10	1.04
2.5-5.9	11	11	10	1.13	1.09	0.95
6.0-12.4	14	14	16	1.16	1.13	1.28
12.5-25.0	12	12	11	1.11	1.08	1.06
25.0	57	57	58	1.07	1.05	1.08

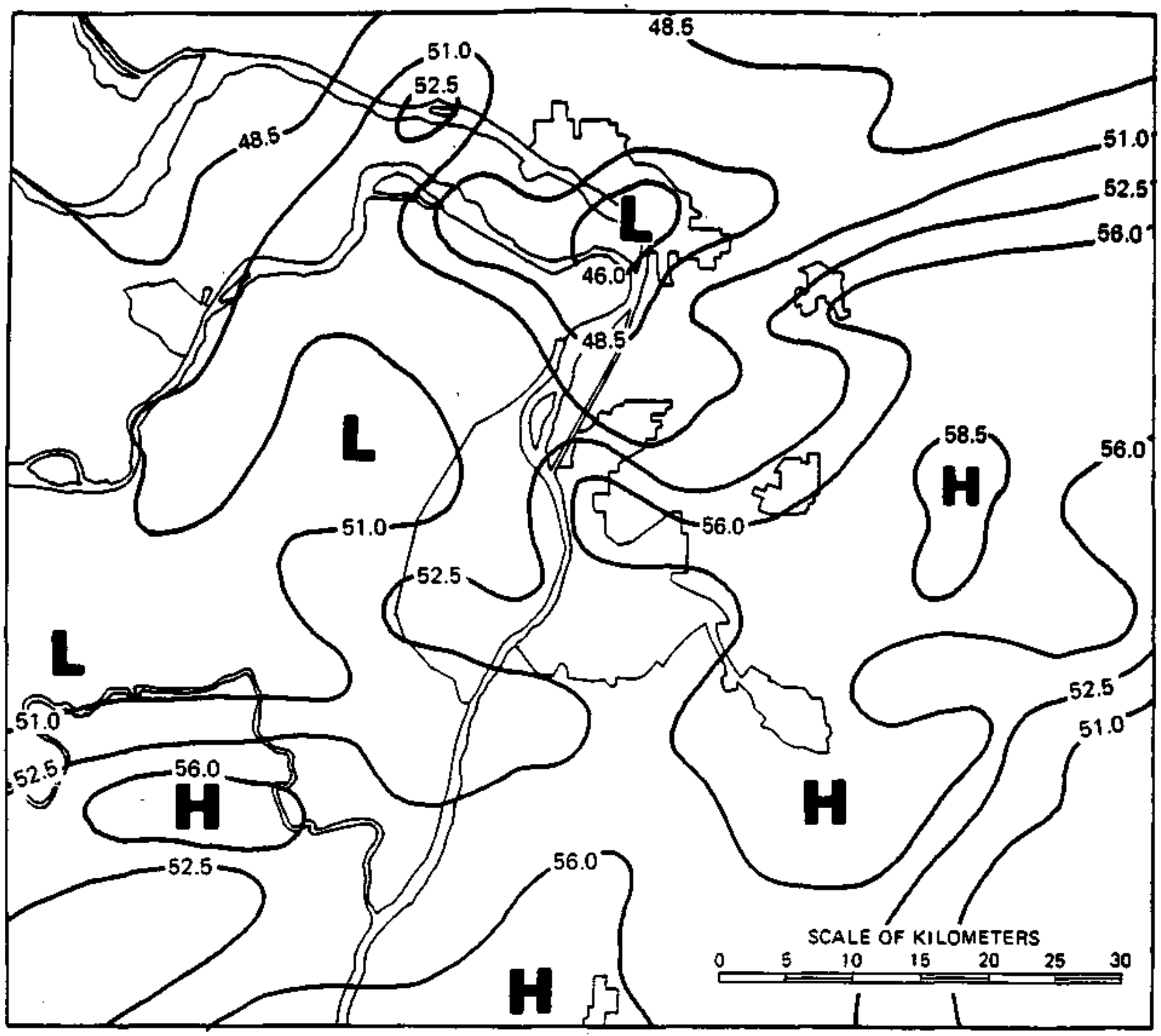


Figure 8. Total Precipitation in Winter Storms Having Network Means > 25 mm.

synoptic storm types. The major producers of winter precipitation in the Midwest are low pressure systems with much of the rain or snow occurring in advance of the associated warm front.

Analyses of storm motions in the 23 storms indicated that 48% moved from the SW, 35% from the WSW, and 9% from the WNW. Thus, 92% moved from directions that would expose them to the urban-industrial areas of St. Louis and/or Alton-Wood River before reaching the EDW and/or STL ED areas. This is a strong bias toward the most favorable storm movements for urban-induced effects on winter precipitation. For example, in the earlier METROMEX research on summer influences it was determined that only 59% of a 330-storm sample had movements from the SW, WSW, and WNW. Other priorities prevented a thorough climatological study of winter storm movements, such as performed for summer in the 1971-1975 METROMEX research.

Investigation of Urban Effects on Snowfall

Snowfall is not a major contributor to the total winter or cold season precipitation in the St. Louis area. On the METROMEX Network, approximately 98% of the average annual snowfall occurs during the November-March period. Based on long-term records of the National Weather Service (NWS), the average November-March snowfall on the METROMEX Network is 40 cm (15.8 in.). This amounts to only 12% of the total precipitation from November through March. Considering the small contribution of snowfall to the cold season precipitation at St. Louis and the natural interannual variability in both snowfall and total precipitation, the METROMEX 4-winter sample is inadequate to determine urban effects on snowfall with a high degree of reliability.

However, there is indication that the urban environment does influence snowfall distribution. Changnon (1976) points out that results of studies by several investigators indicate approximately a 10% shift in average snowfall patterns from urban effects. For example, studies of snowfall patterns at Toronto and Montreal (Potter, 1961) and at Washington, D.C. (Woollum and Canfield, 1968) showed decreases in snowfall in the urban centers. Our studies of urban effects on precipitation (mostly rainfall) on a storm, monthly, and seasonal basis have indicated that the urban effect is most evident during periods of relatively heavy rainfall. In all four seasons, the major portion of the urban-induced precipitation anomalies occurred in a small portion of the total storms.

Therefore, it was decided to examine the precipitation distribution during major snowstorms in the St. Louis area recorded during 1971-1975 . oh the densely-gaged METROMEX Network. It was hypothesized that if any substantial effect was present, it should be most evident in the heavy storms, based upon our other network analyses. For this heavy storm study, we first identified the "snow only" cases on the network from observations of the NWS at St. Louis and other regional stations. Most of these snowstorms were light with respect to production of precipitation (melted snowfall). As a result, if was decided to limit detailed analyses to those storms that produced 12.5 mm (0.5 in.) or more of snowfall at St. Louis. This selection process resulted in maximum network amounts of 25 mm at one or more of the METROMEX Network stations in each storm. The selection criteria yielded a sample of 13 major storms during the 4-season observational period.

Isohyetal Analyses. Both recording raingage data from the METROMEX Network and snow measurements from NWS stations were used in developing isohyetal patterns for each storm, month, and season, and for the four seasons (Nov.-Mar.) combined. The isohyetal pattern of the 13 storms combined is shown in Fig. 9. These consisted of two storms each in November, December, and March; three in January; and, four in February.

In the 13-storm pattern, there is a general decrease in snowfall from W-E across the network. This decrease is most evident in an area extending NE from the southern part of the city to EDW and then ENE to the network boundary. The relatively high area located W and SW of the city is maintained in the BLV area. The 13-storm pattern is substantially different than the normal November-March pattern (Fig. 10) derived from NWS records. The normal pattern shows a flat high E of the city rather than a low. Also, the normal indicates a N-S oriented low W of the city, whereas this is essentially a high in the 13-storm pattern. The 13-storm pattern indicates a possibility of an urban-induced decrease in the natural snowfall in heavy storms crossing the city. There is also some evidence that the snowfall may have been increased in the SW Hills and SE Hills-Bluffs (subareas of the network).

In Fig. 11, one storm (12/18-20/73) has been omitted from the 13-storm sample of major snowfalls. This outlier produced approximately 28% of the 13-storm total snowfall. However, the 12-storm pattern maintains the general features of the 13-storm map. Examination of the storm isohyetal map for the December 1973 storm (Fig. 12) showed that it conformed closely to the general pattern of the 13-storm total. Thus, it showed relatively heavy snowfall W, S, and SE of St. Louis and a low extending from south St. Louis NE to the EDW area. Therefore, it was decided to develop further statistics on the total 13-storm sample in an effort to identify potential urban effects in heavy snowstorms.

Subarea Analyses. No adjustment for the normal climatic gradient of snowfall has been made in the illustrations. This was then done following the procedures described earlier for winter precipitation. Table 9 summarizes the results through comparison of adjusted means for various network subareas described earlier. The subareas include those considered susceptible to urban effects and/or topographic influences., plus two control subareas located climatically upwind of the city (NW, W, SW of STL).

In Table 9, the subarea total snowfall for the 13 storms has been compared with three control areas. These are: the total snowfall average on the entire network for the 13 storms; the average for the two upwind control areas combined; and the average total snowfall for the St. Louis urban and industrial areas combined. The subarea/control ratios for the various subareas are listed in the table. There is no significant

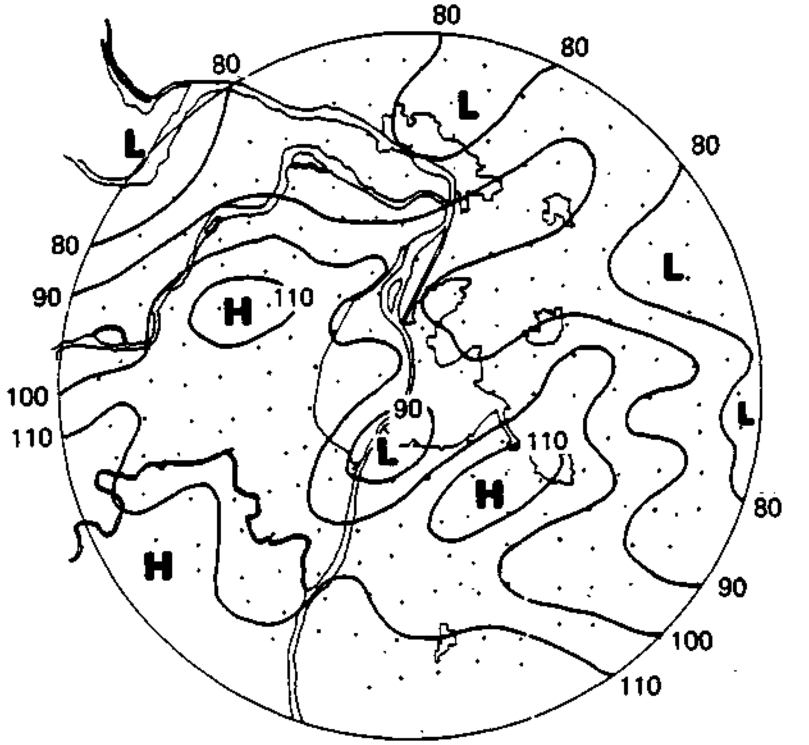


Figure 9. Total Snowfall (cm) in 13 Major Snowstorms on METROMEX Network During Nov-March 1971-75.

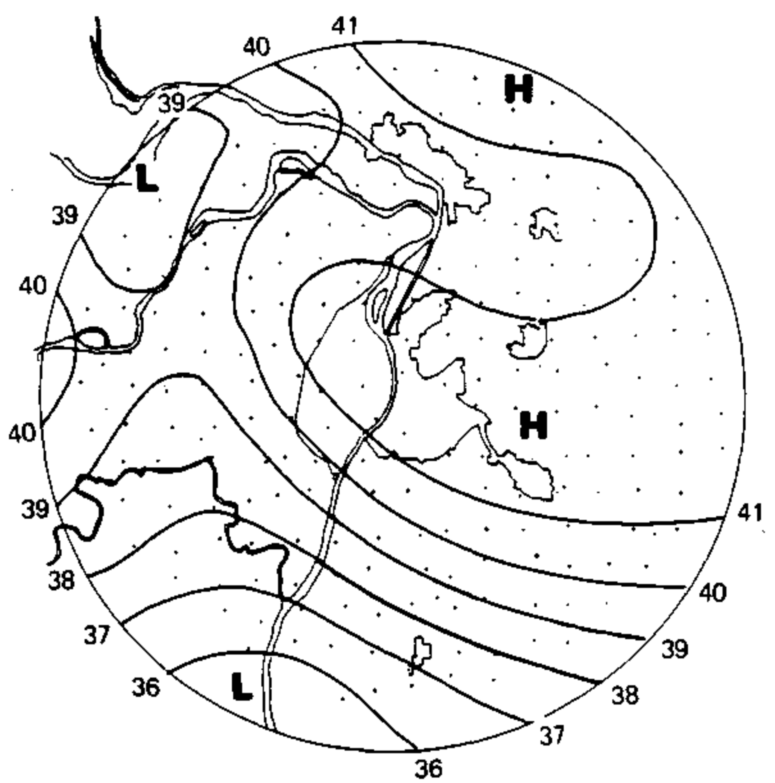


Figure 10. November-March Normal Snowfall (cm).

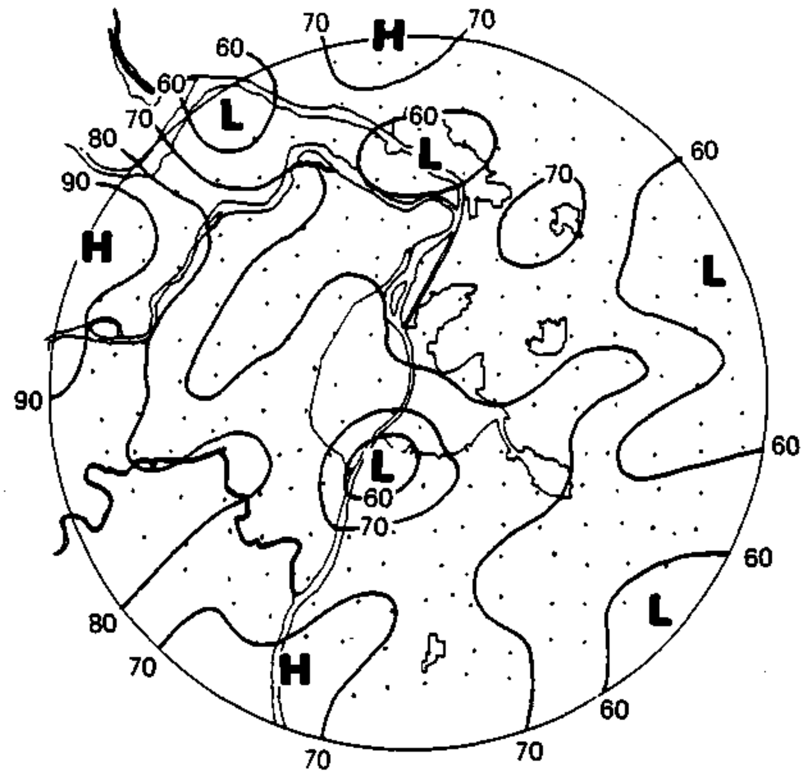


Figure 11. Total Snowfall (cm) in 12 Major Snowstorms During Nov-March 1971-75 (Omitting Dec. 18-20 1973 Storm).

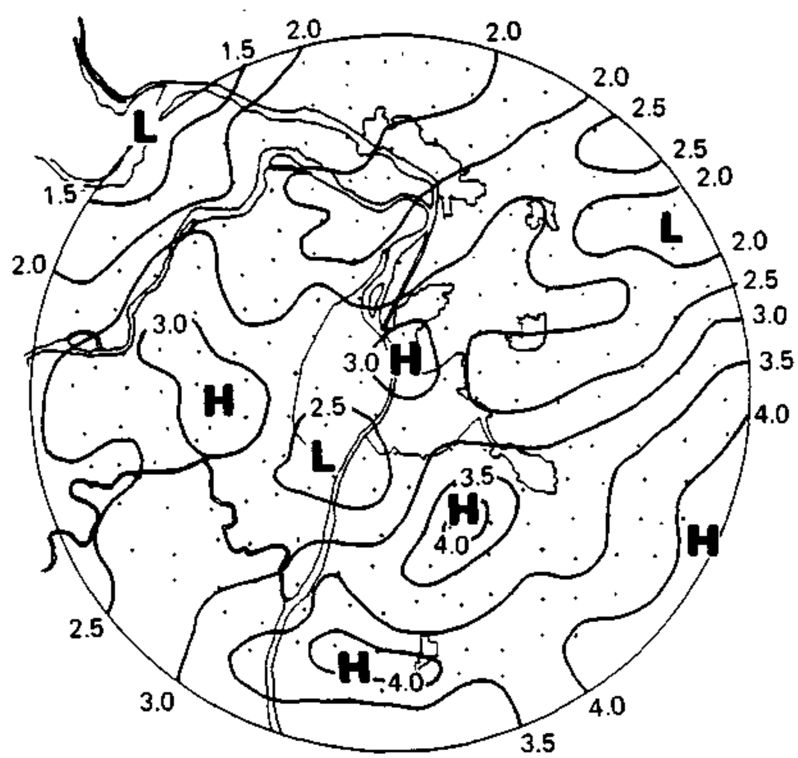


Figure 12. Snowstorm of December 18-20 1973.

Table 9. Computed Inadvertent Effect on Snowfall in 13 Major Storms During Nov.-March 1971-1975 on METROMEX Network.

Subarea	Subarea Total (cm)	Ratio, Subarea to Control Area: Network	Ratio, Subarea to Control Area: Upwind Controls 1 and 2 Ave.	Ratio, Subarea to Control Area: STL Urban-Industrial
EDW	87	0.88	0.84	0.85
GRC-EDW	91	0.93	0.90	0.89
WR Refineries	89	0.94	0.92	0.91
STL Urban	101	1.07	1.04	1 .04
STL Industrial	97	1.02	0.99	0.99
COL-BLV	95	0.98	0.98	0.95
STL East Downwind	87	0.88	0.85	0.84
STL SE Downwind	100	1.09	1.06	1.04
SE Hills-Bluffs	108	1.25	1.21	1.20
STL Suburban West	105	1.10	1.06	1.06
ALN-WR Urban	89	0.96	0.93	0.92
ALN-WR Downwind	82	0.86	0.83	0.82
ALN-WR Bottomlands	81	0.86	0.84	0.82
Southwest Hills	109	1.18	1.14	1.14
Upwind Control - 1	108	1.14	1.10	1.10
Upwind Control - 2	88	0.93	0.90	0.89
Entire Network	95	1.00	0.97	0.96

Above ratios adjusted for variation in normal snowfall across METROMEX Network.

difference in the ratios obtained with the combined upwind controls and the combined urban-industrial region. The network ratios are a little greater, but are only 3% to 4% greater than obtained with the other two comparison areas.

Table 9 shows some support for an urban effect, but the possibility that natural variability and gage exposure differences may have influenced the 13-storm ratios significantly can not be eliminated. As discussed elsewhere in this report, the urban effect on total precipitation in all seasons shows a tendency to maximize in the EDW area. After adjusting for the climatic gradient of snowfall across the network, Table 9 indicates a possible decrease in snowfall in the EDW region of approximately 12% to 16% (ratios of 0.84 to 0.88 among the three controls). This possible urban-induced decrease in snowfall agrees with the findings of others, as mentioned earlier (Changnon, 1976).

Table 9 indicates a small increase of snowfall within the STL urban area based on ratios of 1.07 and 1.04 obtained with the network and upwind controls. However, STL Suburban West which should not often be subjected to urban effects on precipitation, had even higher ratios of 1.10 and 1.06, which suggests a general decrease in snowfall occurs as the city becomes exposed to a heavy snowstorm. Based on past METR0MEX research, this effect, if present, would most likely maximize NE to E of the city. The largest decreases (lowest ratios) did occur in the EDW area NE of the city, and in the STL East Downwind and ALN-WR Downwind areas. The latter area may have been influenced by the industrial complex located in the ALN-WR urban area.

The largest ratios occurred in the SE Hills-Bluffs and the Southwest Hills. This suggests possible enhancement of the natural snowfall distribution by topographic effects. The SE Downwind subarea also had relatively high subarea/control ratios. This subarea lies east of the SE Hills and may have been affected by this topographic feature.

Thus, from this 13-storm study, some support was obtained for the findings of past investigators that large urban areas tend to decrease the amount of snowfall. This finding is based upon an observational network of over 100 raingages on 5200-km^2 operated for 5 years during the November-March period. It is recognized that the raingage is an inadequate recorder of snowfall because of eddy effects about the gage and these tend to be most troublesome in snowfall. However, all gages had approximately equivalent exposures, and while raingages tend to underestimate the snowfall, the error factor should be similar throughout the network. Therefore, it is believed that the network snowfall patterns do provide an acceptable portrayal of distribution differences, although measured amounts are likely to underestimate the true snowfall amounts. The underestimate problem would be suppressed somewhat in the heavy snowstorms studied here in which the snow is often relatively wet.

Monthly and Seasonal Analyses for Fall on METROMEX Network

The four fall seasons combined (1971-1974) had a network mean rainfall of 95.76 cm (37.70 in.) and a standard deviation of 5.87 (2.31 in.).

The isohyetal map of total precipitation in Fig. 13 does not exhibit strong indications of an urban-induced increase in precipitation. There is a high in the EDW region where the urban effect appears to maximize in summer and winter, but this high is of less intensity than others lying S and SW of the city. Only in the extreme southern and southwestern part of the network did raingage amounts exceed two standard deviations. Thus, the highs lying NE and SE of STL in Fig. 13 are not highly significant from a statistical standpoint.

Fall Relations Based on Intensity of Monthly Precipitation. Analyses were made also of the fall data divided into three groups of months having relatively light, moderate, and heavy precipitation, similar to the winter study. There was no stations in any of the three groups in which amounts NE, E, or SE of St. Louis equalled or exceeded three standard deviations. Thus, there were no strong indications of an urban effect portrayed by this statistical analysis. In the light group, amounts east of the river were below the network average. The moderate group (Fig. 14) showed small highs in the immediate vicinity of EDW and COL, and the COL high exceeded two standard deviations of the network mean for this group of months. The four fall months in the heavy category recorded the heaviest amounts south of the urban area near the network boundary. There were weak highs in the EDW area, the ALN-WR Bottomlands, and the SE quadrant of the network, but none of these exceeded two standard deviations. Thus, only the isohyetal pattern of moderate monthly precipitation indicated any real statistical support for an urban enhancement of fall precipitation. An area in the vicinity of COL and another extending E and SE of EDW did show ratios of gage/network mean precipitation exceeding 1.10 in the moderate group. From available information, it is not possible to determine whether the moderate pattern is a consequence of natural variability or an urban-induced effect.

Subarea Analyses in Fall. Subarea analyses were applied in the fall study using the same subareas and analytical techniques described in the winter study. Results for the four falls combined, adjusted for climatic gradient, are summarized in Table 10. The subarea/network ratios range from 0.95 to 1.06 with a median of 1.00. The highest ratio (1.06) occurred in the SW Hills which seldom lies downwind of the urban area. Comparison of the subareas with the two upwind controls shows an average ratio of 1.11 for the SW Hills compared with 1.07 in the EDW area where the urban effect would be likely to maximize. Furthermore, other areas lying NE and E of urban St. Louis also show ratios of 1.00 to 1.05. Thus, the map and ratio analyses provide little evidence of any strong urban effect in fall downwind of the city.

Table 11 shows the ratio of subarea to control area mean for the three groups of months classified light, moderate, and heavy. The control area mean is an average for the two upwind controls. As pointed out earlier in discussing the fall isohyetal analyses, the best evidence of a possible urban-induced effect is in the moderate group in the subareas lying NE, E, and SE of STL. This includes EDW, GRC-EDW, STL Industrial-East, COL-BLV, and STL ED. The ratios exceed 1.10 in these subareas which frequently lie in the path of storms crossing the STL urban area. However, SW Hills also shows a ratio of 1.10 in the moderate group, and this subarea seldom lies in the path of storms traversing STL.

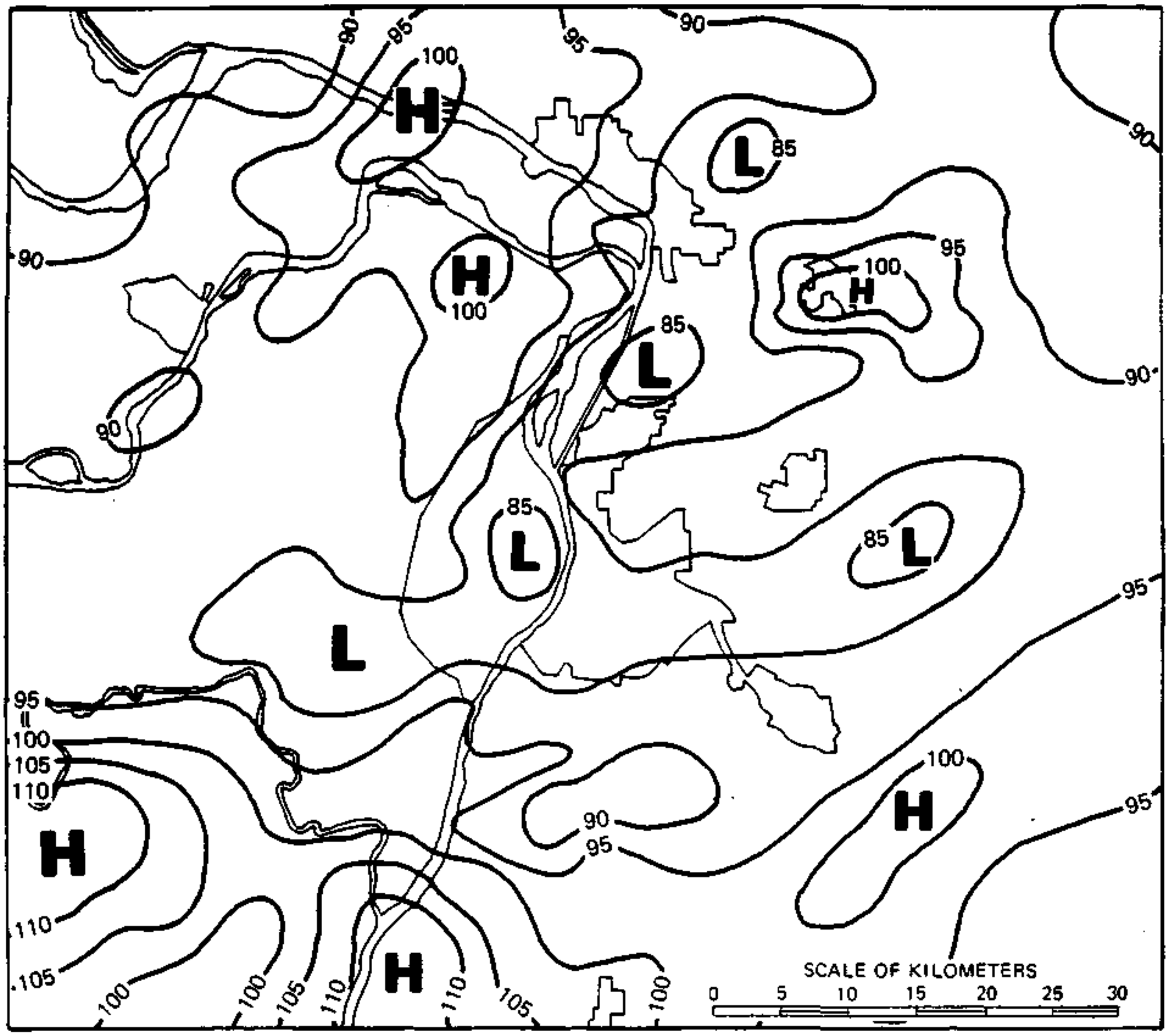


Figure 13. Total Fall Precipitation 1971 Through 1971.

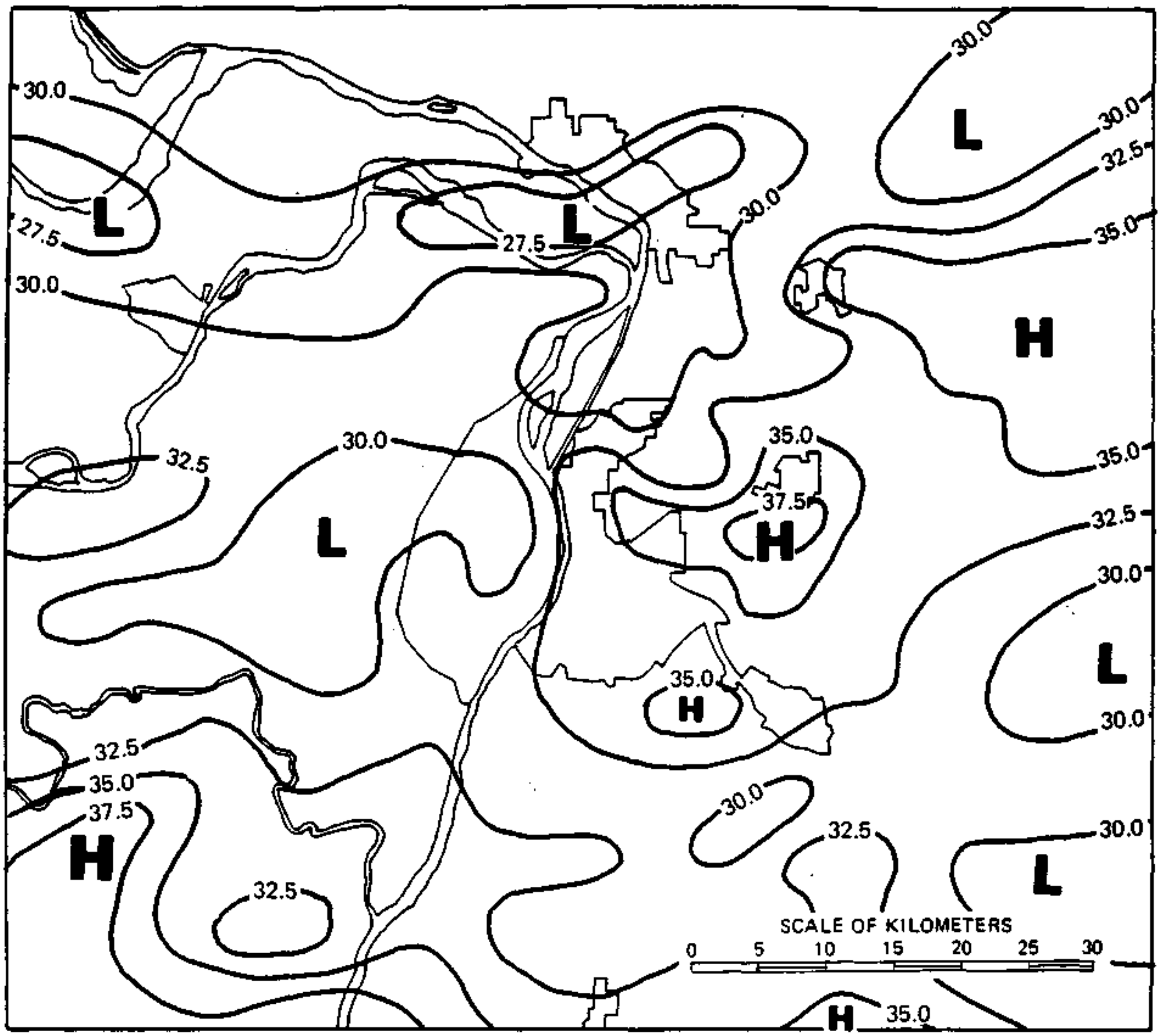


Figure 14. Total Fall Precipitation in Months Having Moderate Precipitation.

Table 10. Estimated Inadvertent Effect on Precipitation During Fall 1971-1974 in the METROMEX Network.

Subarea	Ratio, Subarea to Control Area Mean: Network	Upwind-1	Upwind-2	Upwind Average
EDW	1.02	1.08	1.05	1.07
GRC-EDW	1.00	1.06	1.03	1.05
WR Refineries	0.97	1.02	0.99	1.01
STL Urban	0.95	1.01	0.97	0.99
STL Industrial	0.98	1.04	1.01	1.03
COL-BLV	1.00	1.06	1.03	1.05
STL East Downwind	1.02	1.08	1.05	1.07
STL SE Downwind	1.05	1.12	1.08	1.10
SE Hills-Bluffs	1.06	1.12	1.08	1.10
STL Suburban West	0.96	1.02	0.99	1.01
ALN-WR Urban	1.00	1.05	1.02	1.04
ALN-WR Downwind	0.97	1.02	1.00	1.01
ALN-WR Bottomlands	1.00	1.06	1.03	1.05
SW Hills	1.06	1.13	1.08	1.11

Above ratios have been adjusted for variation in normal precipitation across the METROMEX network.

Table 11. Estimated Inadvertent Effect on Precipitation During Months of Relatively Light, Moderate, and Heavy Precipitation in Fall on the METROMEX Network.

Subarea	Ratio, Subarea to Control Area Mean Light	Moderate	Heavy
EDW	0.90	1.12	1.06
GRC-EDW	0.91	1.11	1.02
WR REfineries	0.89	0.98	1.03
STL Urban	1.02	1.03	1.02
STL Industrial	0.90	1.13	0.98
COL-BLV	0.86	1.18	0.99
STL East Downwind	0.93	1.13	1.04
STL SE Downwind	0.94	1.08	1.14
SE Hills-Bluffs	0.94	1.07	1.10
STL Suburban West	0.99	0.99	1.00
ALN-WR River Urban	0.91	1.01	1.06
ALN-WR Downwind	0.89	1.01	1.01
ALN-WR Bottomlands	0.89	0.95	1.14
SW Hills	1.08	1.10	1.08

In the heavy group of months, only STL SED and ALN-WR Bottomlands exceed 1.10, and only STL SED is in the climatic downwind area of STL with respect to storm movement. In the light category, most ratios are less than 1.00; thus, the upwind control region had more precipitation than the potential urban-effect and topographic effect regions, with the exception of the SW Hills.

The consistency of the subarea/control ratios was examined by determining the ratio relationships for each of the four fall seasons. Ratios in EDW, GRC-EDW, ED and STL SED exceeded 1.00 in 3 of the 4 years, based on average precipitation in the two upwind controls. These area are subject to potential urban effects. However, SW Hills also had ratios exceeding 1.00 in 3 of the 4 falls, and this subarea is unlikely to have any substantial exposure to urban effects on precipitation. The consistency analysis provides evidence of an urban-induced increase in precipitation NE, E, and SE of STL, but the support can not be considered strong. Of more significance is the consistency of a possible urban effect in the EDW and GRC-EDW subareas in all seasons.

Fall Monthly Relations. Next, the ratio relationships in individual months were examined. In September (Table 12), the highest ratio occurred in the ALN-WR Bottomlands, followed by the ALN-WR Urban and EDW areas. These areas conceivably could have been affected by inadvertent weather processes initiated in the STL and ALN-WR areas. In the earlier climatic study (Huff and Changnon, 1972), the September mean ratio of the Major Effect to No-effect rainfall during 1949-1968 was 1.12. For METR0MEX subareas lying in the Major Effect area, the average ratio of subarea to upwind controls ranged from 1.02 to 1.09 with an average of 1.04. This is much lower than the 1972 value, and may indicate our 4-year METR0MEX September sample is not representative of average conditions.

For October, the 1972 study indicated a mean ratio of 0.96, which would imply no urban effect or a negative effect on the rainfall. In the METR0MEX study, the subareas within the 1972 Major Effect area had ratios that varied widely from 1.02 to 1.47 with an average of 1.17 (Table 13). These statistics in Table 13 suggest a potential urban effect SE of the city with the maximum in the STL SE Downwind area. This finding does not agree very well with the results from the 1972 study.

Further study of the October data showed that one storm in 1972 accounted for over 40% of the network rainfall, and was most intense in STL ED, STL SED, and SE Hills-Bluffs. These are the subareas with the largest average ratios of subarea to control area precipitation in Table 13. For example, in STL SED, this rare storm event, which produced a network mean of 12.80 cm (5.04 in.), accounted for 56% of the 4-season precipitation. In the last column of Table 13, the average upwind ratios are shown when this storm is eliminated from the October sample. This results in a large decrease in the ratios E and SE of STL, and these appear more realistic when compared with other months during fall, winter, and spring. With elimination of the extreme event, the average ratio of the 1972 Major Effect area to the upwind control in the METR0MEX study lowers from 1.17 to 1.10.

Table 12. Estimated Inadvertent Effect on Precipitation During September 1971-1974 in the METROMEX Network.

Subarea	Ratio, Subarea to Control Area Mean Network	Upwind-1	Upwind-2	Upwind Average
EDW	1.04	1.12	1.06	1.09
GRC-EDW	1.02	1.07	1.03	1.05
WR Refineries	0.99	1.06	0.99	1.03
STL Urban	0.96	1.02	1.02	1.02
STL Industrial	0.99	1.05	0.99	1.02
COL-BLV	1.01	1.07	1.01	1.04
STL East Downwind	0.97	1.03	1.02	1.03
STL SE Downwind	1.02	1.02	0.98	1.00
SE Hills-Bluffs	1.00	1.08	1.02	1.05
STL Suburban West	0.96	1.01	0.97	0.99
ALN-WR Urban	1.06	1.11	1.07	1.09
ALN-WR Downwind	1.00	1.06	1.02	1.04
ALN-WR Bottomlands	1.09	1.16	1.11	1.14
SW Hills	1.04	1.11	1.01	1.06

Above ratios have been adjusted for variation in normal precipitation across the METROMEX network.

Table 13. Estimated Inadvertent Effect on Precipitation During October 1971-1974 in the METROMEX Network.

Subarea	Ratio, Subarea to Control Area Mean: Network	Upwind-1	Upwind-2	Upwind Average	Adjusted Upwind Average[1]
EDW	0.94	1.04	1.07	1.06	1.09
GRC-EDW	0.96	1.07	1.08	1.08	1.13
WR Refineries	0.92	1.02	1.03	1.03	1.11
STL Urban	1.04	1.13	1.15	1.14	1.10
STL Industrial	1.01	1.14	1.14	1.14	1.08
COL-BLV	1.00	1.13	1.13	1.13	1.01
STL East Downwind	1.17	1.30	1.32	1.31	1.14
STL SE Downwind	1.31	1.47	1.47	1.47	1.15
SE Hills-Bluffs	1.15	1.27	1.29	1.28	1.05
STL Suburban West	0.90	1.01	1.02	1.02	1.00
ALN-WR Urban	0.86	0.96	0.96	0.96	1.05
ALN-WR Downwind	0.83	0.93	0.93	0.93	1.02
ALN-WR Bottomlands	0.81	0.91	0.91	0.91	1.00
SW Hills	1.06	1.18	1.19	1.19	1.16

Above ratios have been adjusted for variation in normal precipitation across the METROMEX network.

(1)Rare storm event of 10/31/72 withdrawn from sample..

The METROMEX subarea ratios for November do not provide any strong indication of an "urban effect. Except for ratios of 1.04 and 1.03 for the EDW and GRC-EDW areas, none of the subareas lying NE, E, and SE of the St. Louis urban-industrial areas and subarea/network ratios exceeding 1.00 (Table 14). The highest subarea/network ratio of 1.11 occurred in the SW Hills. Ratios of METROMEX subarea precipitation to that for the two upwind controls showed an average of 0.99 in the 1972 Major Effect area, compared with an 1.08 ratio in the earlier study.

Overall, the 1972 study indicated a fall mean ratio of 1.05 in the Major Effect area. The METROMEX study also indicates a fall mean of 1.05. This is an excellent verification of the magnitude of the fall anomaly, except that difference among the individual months were relatively large between the two studies. This may result from sampling problems. For example, we are comparing a 4-year study employing very detailed precipitation data (METROMEX) with one that included 20 years of sampling with widely spaced raingaging stations (1972 study). The natural variability factor is likely to exert a stronger influence on the spatial distribution patterns in short-term sampling, and accurate definitions of spatial patterns is difficult with the NWS climatic network.

The frequency distribution of subarea/control area ratios for individual months showed 8 of the 12 months with ratios exceeding 1.00 in the EDW and GRC-EDW areas, and ratios exceeded 1.10 in 6 months. However, the ratio exceeded 1.00 in 10 of the 12 months in the SW Hills, and in 9 months in STL Suburban West and the ALN-WR Bottomlands. Thus, relatively large ratios in the fall precipitation occurred in areas that are generally upwind of the urban-industrial areas of St. Louis, but consistently exceeded 1.00 also NE of St. Louis where the summer anomaly maximized.

Fall Deviation Analyses. Similar to other seasons, the network precipitation anomalies (heavy precipitation centers) were largely produced in a relatively small portion of the fall storms. For example in STL SED which had a subarea/control ratio of 1.10, there were 42 storms that had positive deviations from the network mean, 67 had negative deviations, and 44 showed no deviation. However, 11 storms accounted for 75% of the positive-deviation total, and this represents only 1% of all fall storms; that is, 1% of the storms were largely responsible for the anomaly in STL SED. Similarly, in the SE Hills-Bluffs and SW Hills, which had relatively large subarea/control ratios, less than 14% of the storms produced 15% of the positive deviations.

Figure 15 shows the total precipitation pattern in the 11 storms that produced 75% of the positive deviations (subarea mean - network mean) during the four falls. From the location of STL SED, SE Hills-Bluffs, and SW Hills (Fig. 4), all of which had relatively large subarea control ratios, it appears likely that topographic influences or natural temporal variability may have been the major cause(s) of the relatively heavy fall precipitation in these subareas. The ratios ranging from 1.05-1.07 in the subareas NE and E of STL (Table 10) more likely reflect an urban effect, since topography is not a major factor in this region of the METROMEX Network.

Table 14. Computed Urban Effect on Precipitation During November 1971-1974 in the METROMEX Network.

Subarea	Ratio, Subarea to Control Area Mean Network	Upwind-1	Upwind-2	Upwind Average
EDW	1.04	1.09	1.00	1.05
GRC-EDW	1.03	1.07	0.98	1.03
WR Refineries	1.02	1.03	0.94	0.99
STL Urban	0.93	0.97	0.90	0.94
STL Industrial	0.96	1.01	0.93	0.97
COL-BLV	0.99	1.04	0.94	0.99
STL East Downwind	0.93	0.98	0.90	0.94
STL SE Downwind	0.95	0.99	0.91	0.95
SE Hills-Bluffs	1.01	1.06	0.96	1.01
STL Suburban West	0.98	1.03	0.94	0.99
ALN-WR Urban	1.04	1.08	0.89	1.04
ALN-WR Downwind	1.04	1.09	0.94	1.05
ALN-WR Bottomlands	1.03	1.07	1.00	1.03
SW Hills	1.10	1.15	1.00	1.11

Above ratios have been adjusted for variation in normal precipitation across the METROMEX network.

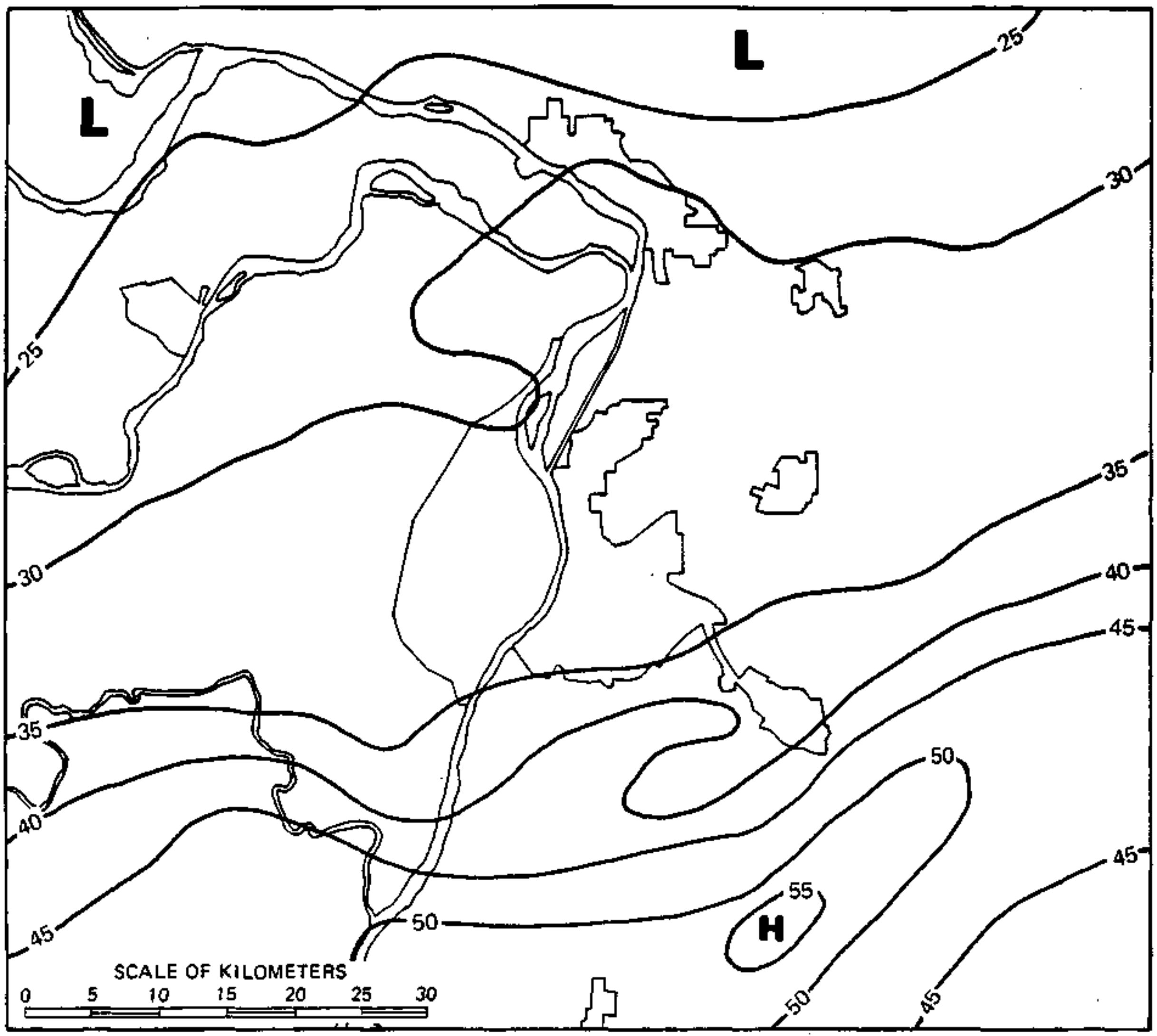


Figure 15. Total Precipitation in 11 Fall Storms Largely Responsible for the Network Anomalies.

Fall Storm Relations on METROMEX Network

The fall statistics in Table 15 show less relationship than winter (Table 8) between storm mean precipitation and subarea anomalies. The EDW and GRC-EDW ratios for total fall precipitation were 1.07 and 1.05, respectively (Table 10). Table 14 indicates these resulted largely from storms in the group ranging from 12.5-25.0 mm (moderate intensity); otherwise, there was no substantial effect indicated. In STL SED, the subarea/control ratio for total fall precipitation (1.10) was derived almost entirely from the group of heavy storms (> 25.0 mm). Overall, no strong trend is indicated between the subarea/control ratios and storm magnitude.

Figure 16 shows the isohyetal pattern of total precipitation for the storm group with network means of 12.5 to 25.0 mm. An area of relatively heavy amounts extends from the NE part of the network near EDW, SSW through the COL area to STL Industrial-East. Amounts in the region were 10% to 30% greater than the network average. However, similar departures from the network average occurred in the NW and extreme SW parts of the network that are seldom exposed to storms developing over or traversing the urban-industrial areas of STL and ALN-WR. Thus, Fig. 16 does not provide strong evidence of an urban-induced increase in fall precipitation. The isohyetal pattern for storms having means exceeding 25 mm, which accounted for 35% of the total fall precipitation, showed the heaviest rainfall SE of STL and provides some support for urban-induced increases. This storm group was largely responsible for the strong urban effect in summer identified in earlier METROMEX research (Huff, 1977b).

Synoptic Weather Relations. Table 10 shows that the inadvertent weather effect (urban and/or topographic) of approximately 10% was greatest in subareas designated SE Downwind and SE Hills-Bluffs which lie SE and SSE, repsectively, of St. Louis (Fig. 4). Analyses showed that 12 storms accounted for 75% of the precipitation anomaly in these two subareas. Cold fronts were predominant among the synoptic storm types, and accounted for 7(58%) of the 12 storms. All of the 12 storms moved from the SW or WSW. These storms do not appear to be urban-related, since their motion would not result in storm elements crossing the city to later cross either of these two subareas. Apparently, the anomalies in these subareas are related to topographic effects from hills and bluffs located to the W and SW, or are merely a natural fluctuation in the 4-year fall precipitation.

The smaller anomalies in the subareas designated EDW, GRC-EDW, and COL-BLV (+5% to +7%) are not subjected to nearby topographic influences, and may be related to urban effects largely imposed on storms moving from SW-WSW, the most common storm motions. In the EDW subarea, five storms produce 75% of the anomaly, as measured by the total positive deviation in these storms in which subarea mean rainfall exceeded the total network mean rainfall. Of the 5 storms, 3 moved from the SW, 1 from the WSW and the other from WNW-NW which would provide a trajectory across the ALN-WR industrial area.

Table 15. Relation Between Subarea Anomalies and Network Mean Precipitation in Fall Storms.

Storm Mean (mm)	Percent of Total Precipitation EDW	GRC-EDW	STL SEP	Subarea/Control Precipitation EDW	GRC-EDW	STL SEP
> 2.5	7	7	7	0.91	0.89	0.94
2.5-5.9	11	12	12	0.95	0.95	1.07
6.0-12.4	18	18	15	0.97	1.01	0.85
12.5-25.0	31	31	23	1.22	1.18	0.89
> 25.0	33	32	43	1.04	1.02	1.45

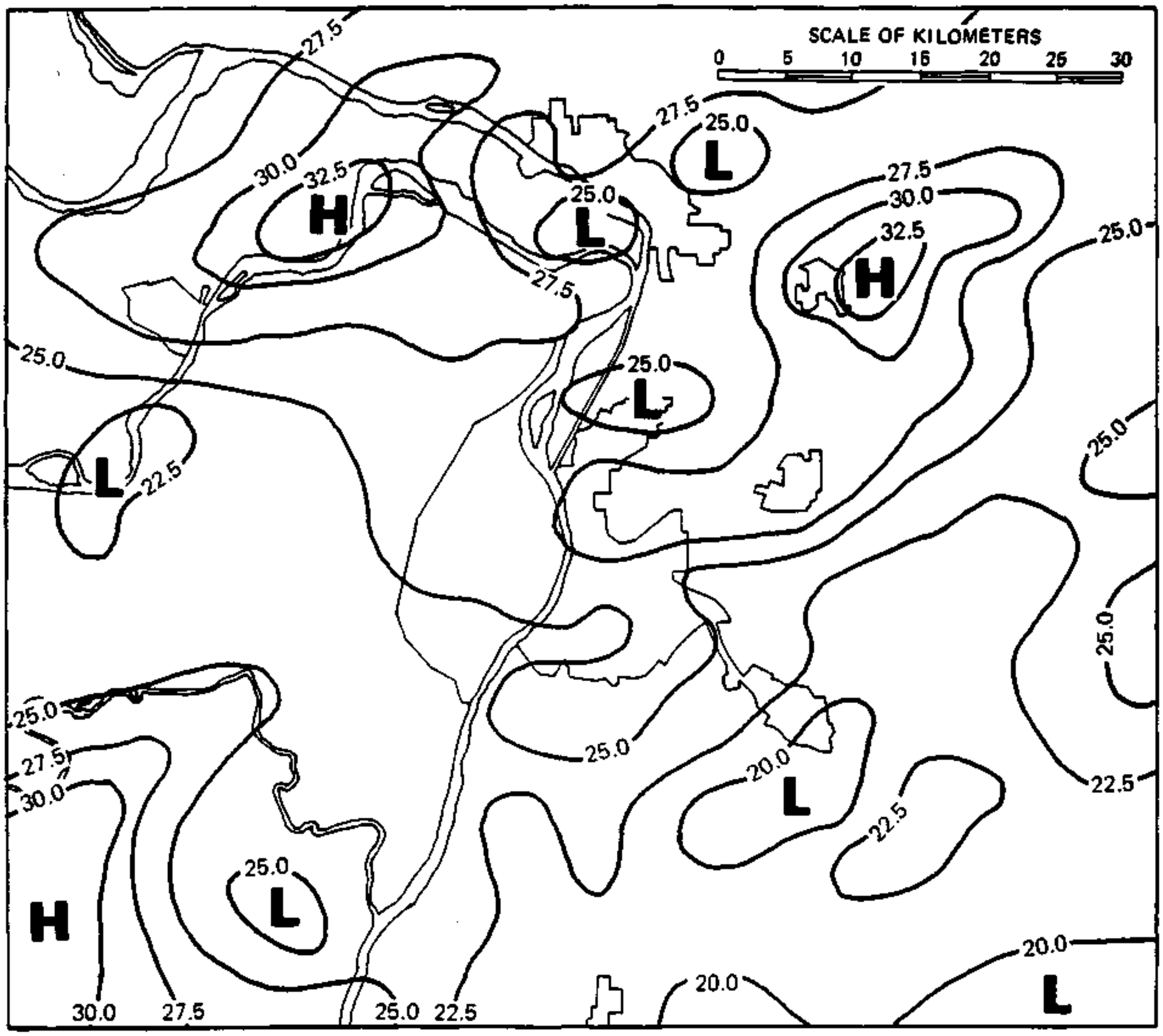


Figure 16. . Total Fall Precipitation from Storms Having Network Means of 12.5-25.0 mm.

Monthly and Seasonal Analyses for Spring on METROMEX Network

An isohyetal map for all four springs combined (1972-1975) is presented in Fig. 17a. The network mean was 130.58 cm (51.41 in.) and the standard deviation was 8.33 cm (3.28 in.). This map indicates relatively heavy precipitation ENE to NE of STL. Raingage amounts exceeded 2 standard deviations over much of this region. However, smaller areas of equal intensity were located S of the city. Figure 17b shows the A/N ratio pattern which provides a quantitative measure of the strength of the high and low centers in the precipitation pattern. A region in which the spring precipitation was 10%—15% above the network mean extends from NE of STL southwestward to the Ozark Hills in the SW portion of the network. Overall, the rainfall and ratio patterns for spring suggest a possible urban effect E-NE of STL, but one which is much weaker than the summer effect identified in the earlier METROMEX studies. The location of the highs and the magnitude of the inadvertent effect are similar to those for winter (Fig. 2).

Table 16 shows the relationship between various subareas and control areas for spring mean precipitation, after adjustment for the normal climatic gradient across the network. Based on the A/N and A/UC ratios in Table 16, the inadvertent effect is greatest in the NE and E parts of the network, which are frequently downwind of the urban-industrial areas in storms traversing the network. The average ratio of A/UC varied from 1.11 to 1.14 in EDW, GRC-EDW, STL Industrial-East, COL-BLV, and STL ED.

When the spring months were divided according to relatively light, moderate, and heavy rainfall it was found that the urban effect was strongest in those months having relatively heavy rainfall. Based on the average ratio of subarea means to those for the two upwind controls (A/UC), values of 1.26 for ALN-WR Urban, 1.22 for EDW, and 1.20 for GRC-EDW in the heavy months were obtained (Table 17). Relatively high ratios existed for all subareas located E and NE of St. Louis and in the ALN-WR region.

For comparison, A/UC was only 1.07 for EDW and GRC-EDW in the moderate months, and was less than 1.00 in the ALN-WR region. In the light months which accounted for only 20% of the network precipitation during the 4-year observational program, EDW and GRC-EDW had ratios of 1.05 and 1.09, respectively.

Figure 18 shows the isohyetal pattern of total precipitation for the relatively heavy precipitation months of spring. The pattern is similar to the total precipitation pattern for spring (Fig. 17), except for the pronounced high in the ALN-WR area in Fig. 18. The heavy months accounted for approximately 47% of the spring precipitation, compared with 33% in the moderate months, and 20% in the light months.

Monthly Analyses. Examination of adjusted subarea/control ratios for March precipitation indicate an inadvertent increase in precipitation of approximately 9% in the COL-BLV subarea east of STL (Table 18). Similarly, the effect appears to be about 5%-7% in several other subareas,

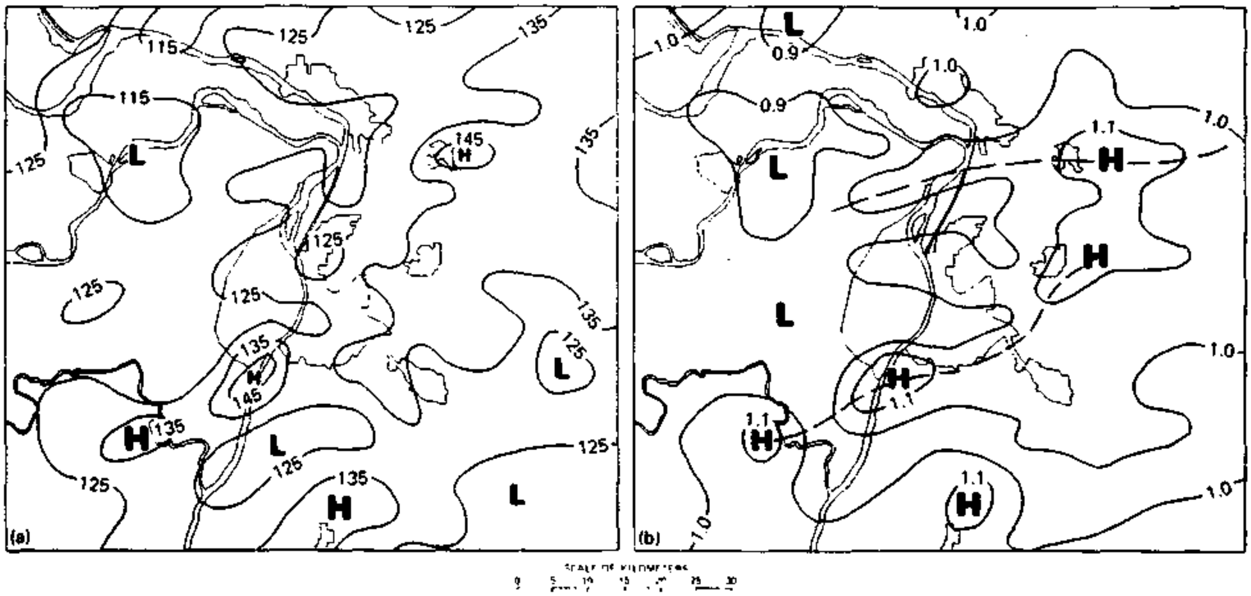


Figure 17. Distribution of Spring Precipitation 1972 Through 1975.

a. Four-Season Total Precipitation

b. Ratio of Gage/Network Precipitation
During 1972-1975

Table 16. Estimated Inadvertent Effect on Precipitation During Spring in the METROMEX Network.

Subarea	Subarea Total (in.)	Ratio*, Subarea to Control Area Mean: Network	Upwind-1	Upwind-2	Upwind Mean
EDW	54.83	1.09	1.11	1.17	1.14
GRC-EDW	54.03	1.08	1.11	1.16	1.13
WR Refineries	50.72	1.02	1.04	1.09	1.07
STL Urban	52.04	1.03	1.06	1.11	1.08
STL Industrial	53.19	1.09	1.09	1.13	1.11
STL Industrial-East	53.19	1.06	1.09	1.13	1.11
COL-BLV	54.24	1.07	1.10	1.15	1.12
STL East Downwind	54.03	1.06	1.09	1.14	1.11
STL SE Downwind	51.61	0.97	1.00	1.04	1.02
SE Hills-Bluffs	52.56	0.97	1.00	1.04	1.02
STL Suburban West	48.03	0.94	0.97	1.01	0.99
ALN-WR Urban	51.96	1.04	1.07	1.11	1.09
ALN-WR River Downwind	51.06	1.02	1.05	1.10	1.07
ALN-WR River Bottomlands	49.76	1.00	1.02	1.07	1.04
SW Hills	51.34	0.97	0.99	1.04	1.01

*Above ratios have been adjusted for variation in normal precipitation across the METROMEX Network.

Table 17. Estimated Inadvertent Effect in Spring Months of Relatively Heavy Rainfall.

Subarea	A/N	A/UC
EDW	1.15	1.22
GRC-EDW	1.13	1.20
ALN-WR Urban	1.18	1.26
ALN-WR Downwind	1.11	1.18
ALN-WR Bottomlands	1.07	1.14
WR Refineries	1.12	1.19
STL Suburban West	0.99	1.05
STL Urban	1.06	1.13
STL Industrial-East	1.07	1.14
COL-BLV	1.08	1.15
STL East Downwind	1.04	1.11
STL SE Downwind	0.95	1.01
SW Hills	0.91	0.97
SE Hills-Bluffs	0.93	0.99

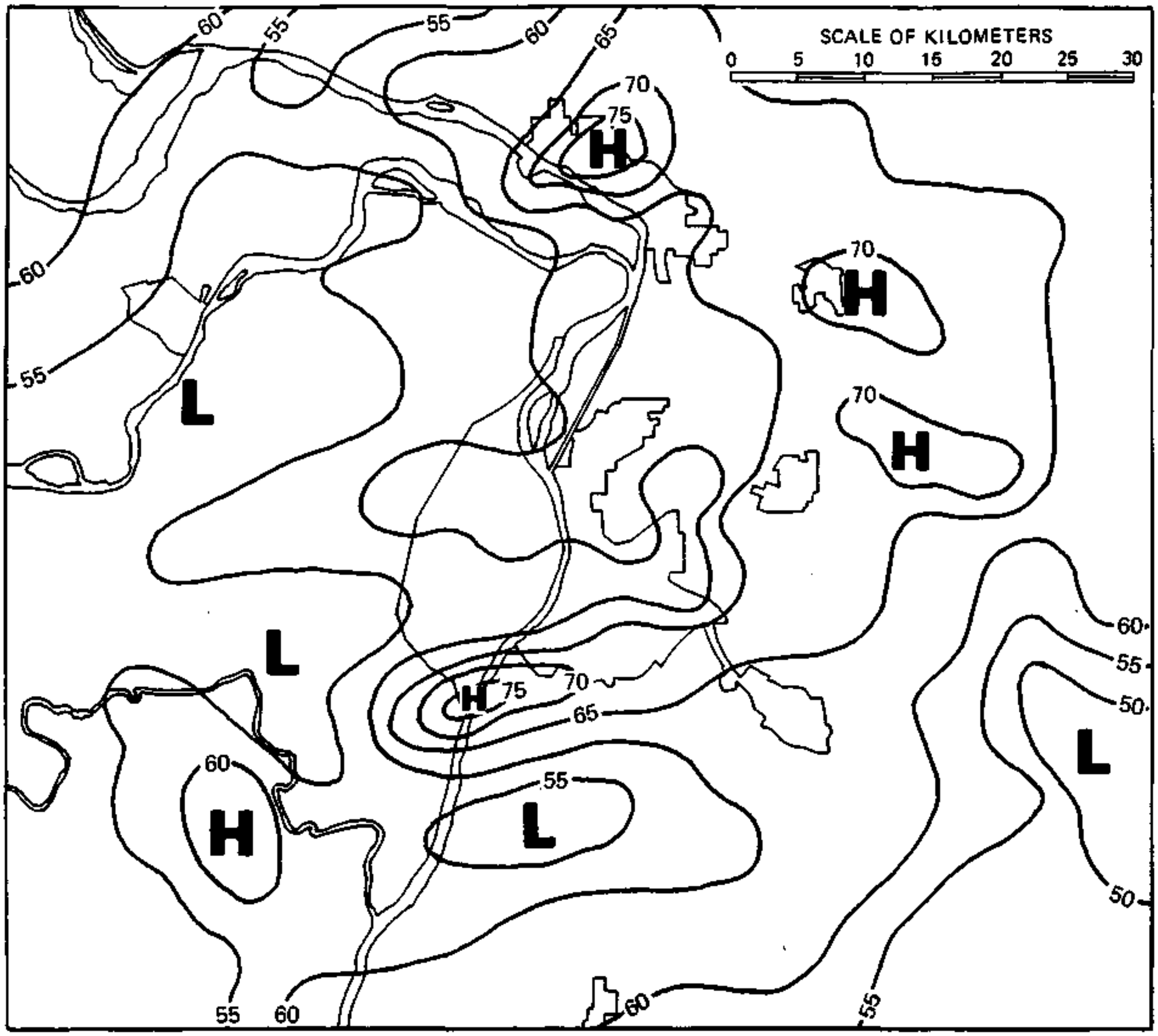


Figure 18. Total Spring Precipitation in Months of Relatively Heavy-Precipitation, 1972-1975.

Table 18. Estimated Inadvertent Effect on Precipitation During March in the METROMEX Network.

Subarea	Ratio, Subarea to Control Area Mean Network	Upwind-1	Upwind-2	Upwind Mean
EDW	1.04	1.05	1.08	1.07
GRC-EDW	1.04	1.03	1.07	1.05
WR Refineries	0.95	0.95	0.97	0.96
STL Urban	1.04	1.04	1.07	1.05
STL Industrial	1.02	1.03	1.05	1.04
COL-BLV	1.11	1.07	1.11	1.09
STL East Dowwind	0.93	1.04	1.07	1.06
STL SE Downwind	1.00	1.00	1.03	1.02
SE Hills-Bluffs	0.96	0.96	0.99	0.98
STL Suburban West	0.99	0.99	1.01	1.00
ALN-WR River Urban	0.98	0.99	1.01	1.00
ALN-WR Downwind	0.97	0.98	1.00	0.99
ALN-WR Bottomlands	0.99	0.89	1.01	1.00
SW Hills	1.02	1.03	1.07	1.05

Above ratios have been adjusted for variation in normal precipitation across the METROMEX Network.

including EDW, GRC-EDW, STL ED, and the STL urban area based on the average control values. No urban-induced increase in precipitation is indicated in the ALN-WR region.

The April ratios (Table 19) indicate anomalies of approximately 16%-18% in the region lying NE and E of STL. This includes the subareas of EDW, GRC-EDW, STL Industrial-East, COL-BLV, and STL ED. Again, there is no evidence of an urban effect in the ALN-WR region.

The May data (Table 20) indicate peak values in the ALN-WR urban and downwind areas. The subarea/control ranged from 1.22 (22% increase) using the entire network as a control area to 1.28 when the two upwind controls were used to measure the anomaly. The subarea/control ratios also exceeded 1.15 in the EDW and GRC-EDW areas where the summer urban effect maximized (Huff, 1977b).

Overall, the monthly and seasonal ratios indicate a modest urban-induced increase in precipitation during spring that gradually increases from March to May. A major increase then occurs in the June-August period.

Monthly and seasonal ratios of subarea/control precipitation were examined to determine the temporal consistency of the various subarea anomalies. Average precipitation in the two upwind control subareas was used in the A/UC computations. Results indicated a relatively high degree of temporal consistency, particularly in the subareas lying east of STL (STL Industrial-East, COL-BLV, and STL ED). In these three subareas, the ratio exceeded 1.00 in all four springs. Of the 12 months involved, the ratio exceeded 1.00 in 11 months in COL-BLV, and 10 months in STL Industrial-East and STL ED. The consistency was not as pronounced NE of STL in the EDW and GRC-EDW subareas. Both had A/UC ratios exceeding 1.00 in three springs, and in 9 of the 12 months in the data sample.

Spring Storm Analyses on METROMEX Network

The same methods employed in the winter and fall studies was used to investigate relations between the precipitation anomalies and certain storm parameters. As before, storm deviations from the network mean and storm intensity (mean precipitation) on the network were studied, along with synoptic storm type and storm movement in those storms largely responsible for the anomalies.

Spring Deviation Analyses. When the subarea deviations from the network mean were ranked, it was again found that a relatively small percentage of the spring storms were primarily responsible for the anomalies located NE and E of the STL urban-industrial complex. Thus, in the EDW area, 20 of the 207 spring storms (11%) produced 75% of the positive-deviation total in this subarea where the anomaly maximized. That is, 75% of the A - N positive differences (precipitation excesses) occurred in 20 storms. Similarly, 10% of the storms contributed 75% of the storm rainfall excess in GRC-EDW, and 13% of the storms produced 75% of the positive-deviation total in STL Industrial East, COL-BLV, and STL ED.

Table 19. Estimated Inadvertent Effect on Precipitation During April in the METROMEX Network.

Subarea	Ratio, Subarea to Control Area Mean Network	Upwind-1	Upwind-2	Upwind Mean
EDW	1.11	1.12	1.24	1.18
GRC-EDW	1.09	1.09	1.23	1.16
WR Refineries	1.03	1.04	1.17	1.11
STL Urban	1.05	1.06	1.18	1.12
STL Industrial	1.10	1.10	1.23	1.17
COL-BLV	1.10	1.10	1.23	1.17
STL East Downwind	1.11	1.11	1.25	1.18
STL SE Downwind	1.03	1.04	1.17	1.11
SE Hills-Bluffs	1.04	1.04	1.04	1.04
STL Suburban West	0.93	0.93	1.04	0.99
ALN-WR River Urban	0.97	0.97	1.09	1.03
ALN-WR Downwind	0.94	0.92	1.03	0.98
ALN-WR Bottomlands	0.94	0.94	1.06	1.00
SW Hills	0.95	0.95	1.06	1.00

Above ratios have been adjusted for variation in normal precipitation across the METROMEX Network.

Table 20. Estimated Inadvertent Effect on Precipitation During May in the METROMEX Network.

Subarea	Ratio, Subarea to Control Area Mean Network	Upwind-1	Upwind-2	Upwind Mean
EDW	1.09	1.18	1.14	1.16
GRC-EDW	1.10	1.18	1.15	1.17
WR Refineries	1.06	1.13	1.10	1.12
STL Urban	1.01	1.07	1.05	1.06
STL Industrial	1.05	1.12	1.10	1.11
COL-BLV	1.04	1.10	1.08	1.09
STL East Downwind	1.03	1.05	1.07	1.06
STL SE Downwind	0.87	0.93	0.90	0.92
SE Hills-Bluffs	0.93	0.99	0.96	0.98
STL Suburban West	0.93	0.99	0.97	0.98
ALN-WR River Urban	1.22	1.29	1.27	1.28
ALN-WR Downwind	1.22	1.29	1.27	1.28
ALN-WR Bottomlands	1.09	1.15	1.30	1.22
SW Hills	0.95	1.02	1.00	1.01

Above ratios have been adjusted for variation in normal precipitation across the METROMEX Network.

Figure 19 shows the total rainfall distribution for the 20 storms primarily responsible for the EDW anomaly. Approximately 28% of the total spring precipitation was recorded in these storms. Network mean rainfall exceeded 12.5 mm (0.50 in.) in 13 of the storms, and it exceeded 25 mm (1.00 in.) in 5 storms. Thus, a majority of the storms produced moderate to heavy storm means on the network. Within the EDW subarea, means ranged from 6 mm to 62 mm in the 20 storms, of which 17 had means exceeding 12.5 mm and 9 storms had subarea averages exceeding 25 mm. Thus, the large positive deviations tended to be associated with storms of moderate to heavy intensity.

Spring Storms Grouped by Mean Precipitation. Spring storms were grouped according to network mean precipitation, as was done in the other seasons. Results of this analysis are summarized in Table 21, which shows the ratio of precipitation in selected subareas to the average precipitation for the two upwind controls (A/UC). The subareas are those most likely to experience an urban effect. Overall, the A/UC ratios in Table 21 do not show any pronounced effect for the ratio to increase or decrease with increasing storm precipitation, which suggests little, if any, dependency of the anomalies observed E-NE of STL on storm magnitude. However, if one just considers the storms producing network means of 6 mm or more, which were responsible for 84% of the total precipitation, there is a trend for the A/UC ratios to increase with storm intensity. This trend was very strong in summer rainfall, but not in fall precipitation.

Figure 20 shows the isohyetal pattern resulting from summing rainfall from all storms in which the network mean exceeded 25 mm (1 in.). The pattern has considerable similarity to those for total spring precipitation and total precipitation in months with relatively heavy amounts (Figs. 17 and 18). All three maps show highs in the region NE and E of STL, where any urban effect would be expected to be most pronounced. Similarly, lows are found in the SE part of the network, and in the regions lying W and NW of STL. Weaker highs are indicated in the SW and SSE parts of the network in the SW Hills and SE Hills-Bluffs, regions in which a topographic-induced increase in rainfall was identified in the METR0MEX summer research. This topographic high, which was much weaker than the urban-induced highs in the summer pattern, appears to be present also in the spring precipitation distribution. Thus, Figs. 17, 18, and 20 provide some evidence and support for inadvertent precipitation effects in the METROMEX Network during spring, and these anomalies relate well spatially to the summer distribution in which they were much more pronounced.

Synoptic Weather Relations. The largest spring anomaly was in the EDW subarea (Table 16). Analyses indicated that 75% of the anomaly (approximately +14%) was produced by 20 storms among 207 storms recorded during the METROMEX research program. Squall areas were the strongest contributor among the storm types. They accounted for 6 (30%) of the 20 storms, and along with squall lines included 45% of this selected storm group. Storm movements from the SW dominated. Of the 20 storms, 10 moved from SW, 4 from WSW, 5 from WNW, and 1 from NW. All moved from directions that could have subjected storm elements to the St. Louis or Alton-Wood River urban-industrial regions prior to reaching the EDW subarea. Thus,

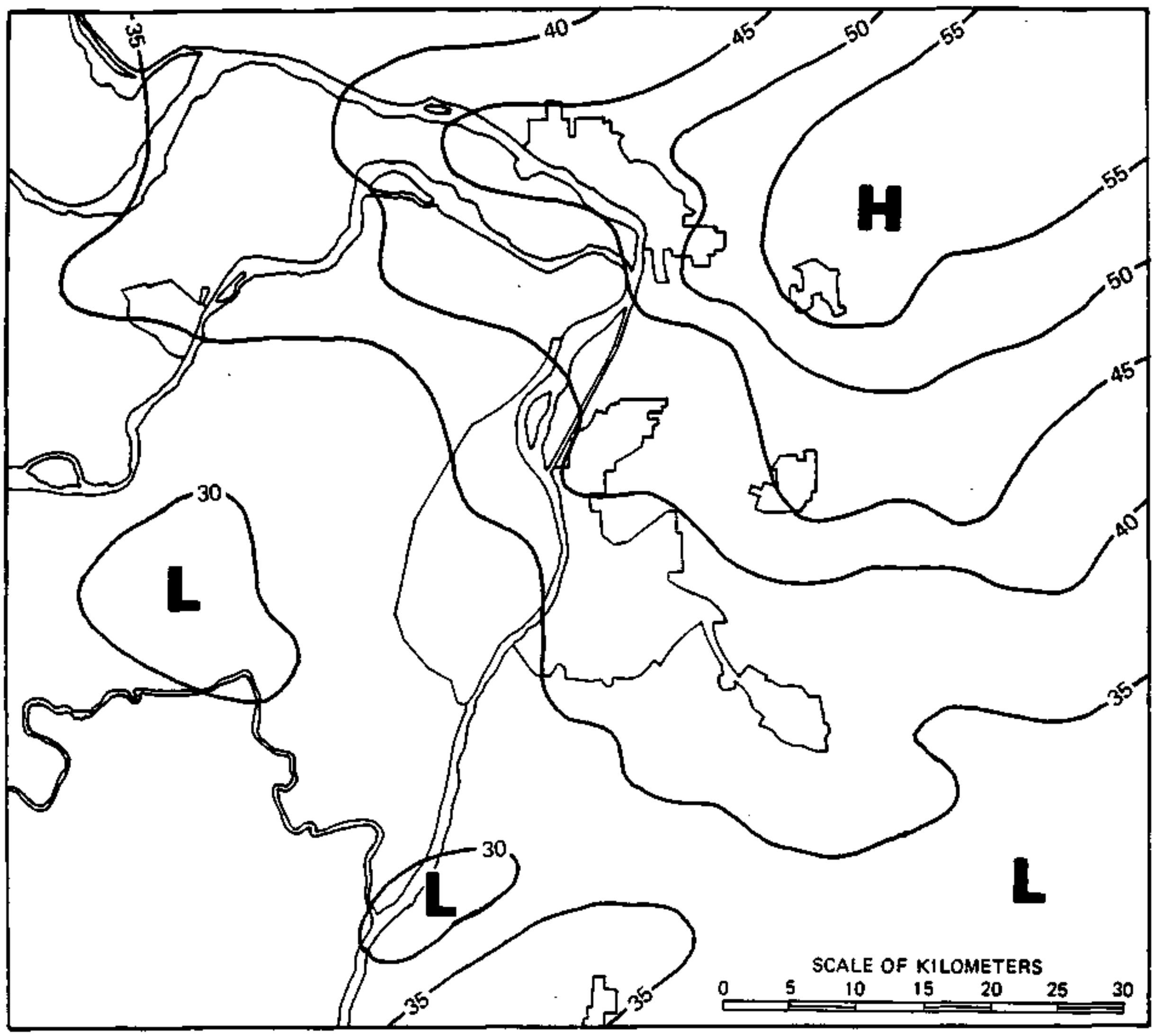


Figure 19. Total Precipitation in 20 Spring Storms Primarily Responsible for the EDW Anomaly.

Table 21. Relation Between Subarea Anomalies and Network Mean Precipitation in Spring Storms.

Storm Mean (mm)	Percent of Total Precipitation	Average Ratio, Subarea/Control Precipitation				
		EDW	GRC-EDW	STL I-E	COL-BLV	STL ED
< 2.5	5	1.10	1.05	1.04	1.18	1.44
2.5-5.9	11	1.21	1.26	1.10	1.19	1.09
6.0-12.4	27	1.01	1.03	1.11	1.10	1.02
12.5-25.0	31	1.16	1.14	1.08	1.07	1.12
> 25.0	26	1.23	1.18	1.14	1.15	1.15

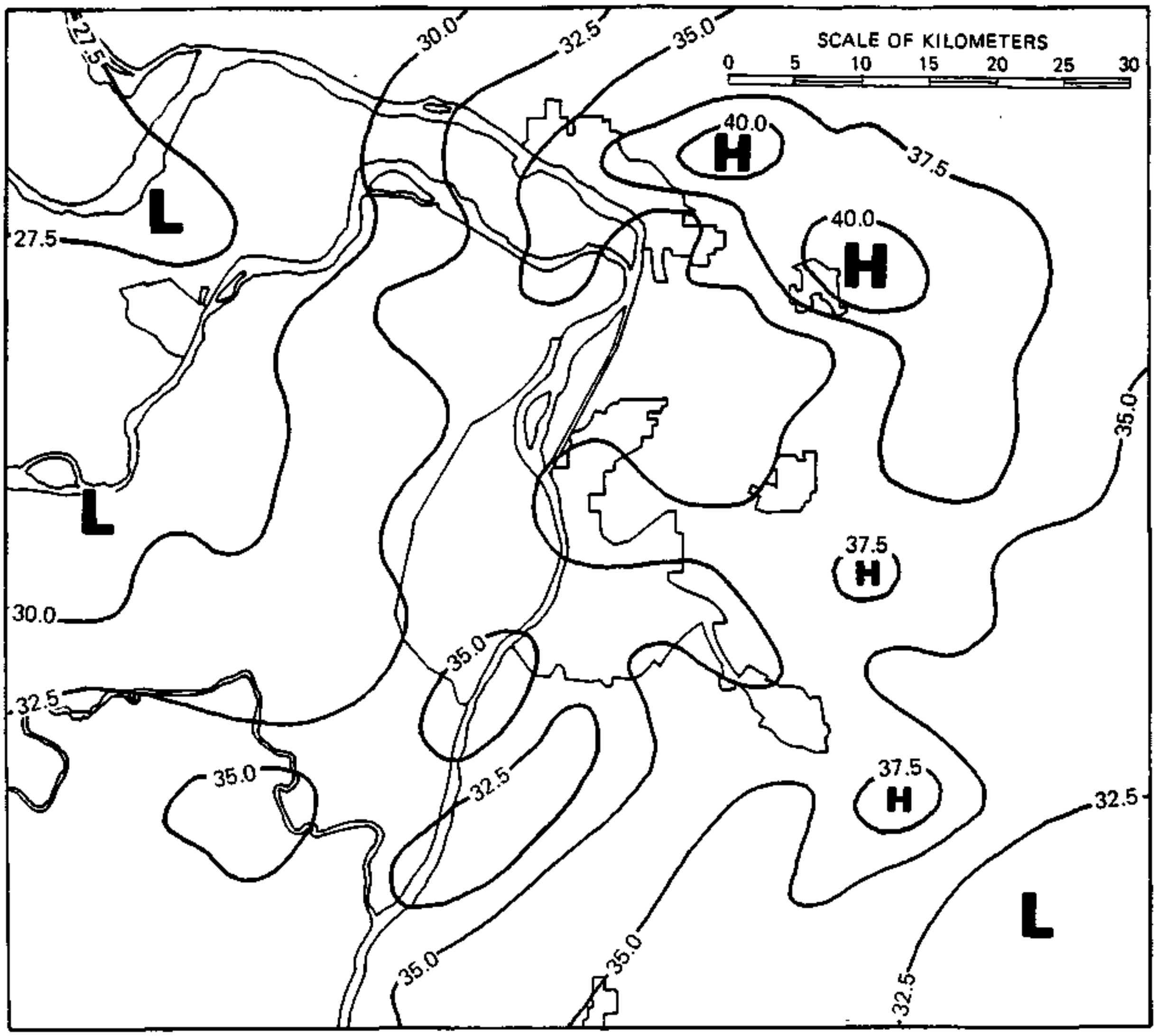


Figure 20. Precipitation Distribution in Spring Storms Having Network Means > 25 mm.

the storm movement analysis provides support for an urban-related cause of the EDW spring anomaly. The EDW spring anomaly exceeds those indicated for all and winter, but is much less than the summer anomaly identified in the earlier METROMEX research (Huff and Vogel, 1978).

Comparison of METROMEX and Earlier Spring Findings

Comparisons were made between results of the present findings for spring and those obtained earlier by Huff and Changnon (1972) in the 8-city climatic study. Results of the comparisons are summarized in Table 22. Similar to the winter and fall comparisons, all subareas lying in the 1972 "Major Effect" area were combined. The two upwind controls in the METROMEX study were also combined to conform approximately with the control area used in the 1972 study. In Table 22, the METROMEX-1 values were obtained using the combined subarea mean and the two upwind controls averaged. METROMEX-2 values are the ratio of the combined subarea mean to the entire network mean.

Table 22 indicates very close estimates of the urban effect when the METROMEX-1 results are compared with the 1972 values for spring. That is, the 1972 study indicated a spring increase of 10%, from urban-induced precipitation, and the present METROMEX results indicate a 9% increase. For individual months which involve small samples of rainfall data, the differences are larger, but sill comparable considering all the possible sources of error and natural variability involved between the two studies.

Larger differences are indicated with the METROMEX-2 control (entire network) than with the upwind control computations. The upwind control results are considered a better measure of the urban effect, since using the entire network as a control incorporates subareas which are part of the effect that is being evaluated. The upwind controls incorporate a region which would rarely be in the path of storms moving across the urban area of St. Louis, particularly those storms of moderate to strong intensity that contribute most of the areal rainfall.

Summary of Cold and Transition Season Studies on METROMEX Network

Winter. Combining the four winters (1971-72 through 1974-75), a pattern of precipitation highs was found east of the Mississippi River. These extended SSW from EDW located NE of STL to BLV situated SE of the city. This pattern is very similar to the summer pattern identified in the original METROMEX research. Other similarities in the winter and summer patterns include a secondary high located W to WNW of ALN-WR, and a low extending W and WSW from the western part of the STL urban area. However, the winter anomalies were not nearly as strong as those found in summer, but did exceed two standard deviations of the network mean NE and E of STL.

The winter months were divided into three groups having relatively light, moderate, and heavy precipitation. The heavy pattern was very similar to the 4-season total precipitation pattern with maximum amounts

Table 22. Comparison of Urban Effect Obtained from Two Studies.

	Ratio of Effect/No-Effect Mean Rainfall		
	1971-1972	METR0MEX-*1	METROMEX-2
March	1.10	1.04	1.03
April	1.10	1.15	1.09
May	1.11	1.08	1.02
March-May	1.10	1.09	1.05

*Based on METROMEX gages in 1971-1972 "Major Effect" area; UC-1 and UC-2 averaged for control in METROMEX-1; METROMEX-2 = effect/network means.

recorded east of STL near COL and a secondary maximum in the EDW area. The heavy precipitation months accounted for 55% of the network total precipitation. In the moderate months, the general pattern was disrupted, but a high center was maintained in the EDW area and relatively high amounts occurred in the COL area.

Within the METROMEX Network, 14 subareas were selected which were considered potentially susceptible to urban and/or topographic influences. Two control areas were selected for evaluating possible inadvertent precipitation effects in the 14 subareas. In comparing the subarea and control area precipitation, adjustments were made for the natural climatic gradient across the network. Ratios of subarea to control area mean precipitation were then computed to help evaluate potential inadvertent modification of the natural precipitation distribution.

Results of the above computations provided an estimated urban effect of approximately 9%-10% NE and E of STL in the vicinity of EDW and COL. A gradual increase occurred from no effect in the STL urban area to about 5% in the industrial area on the eastern edge of the city and to the maximum of 9%-10% near EDW and COL. The ALN-WR area which had relatively large departures from the control means in summer showed no indication of a significant effect in winter.

Analyses of the consistency of the subarea/control ratios showed that the ratio exceed 1.00 in all four winters at EDW and in 3 of the 4 winters in the COL area. Analyses of the light, moderate, and heavy groups of monthly precipitation showed the ratios exceeding 1.00 in all three intensity classifications in the region lying NE, E, and SE of STL.

Monthly computations of subarea/control ratios were also made. For the four Decembers combined, the ratios were similar to those found for the winter season. The highest ratios were obtained in the EDW, GRC-EDW, and STL ED areas, and were slightly larger than the winter ratios. The highest January ratios were again in the EDW area, followed closely by GRC-EDW. The 4-year February ratios were close to 1.00 throughout the various subareas, and, therefore, provide little evidence of an urban effect. For the 12-month sample (4 winters), the subareas lying NE and E of STL had individual monthly ratios that predominately exceeded 1 .00. For example, the EDW ratio exceeded 1.00 in 9 months and 1.10 in 5 months. Similarly, GRC-EDW ratios also exceeded 1.00 in 9 months and 1.10 in 4 months. The relatively high degree of year-to-year consistency in the subarea/control ratios in the region lying NE and E of STL lend support to the existence of an urban effect suggested by the 4-winter precipitation pattern in Fig. 2.

Analyses of potential urban effects in winter on the densely-gaged METROMEX Network were compared with those obtained in an earlier study which utilized only climatic data in the STL area during 1949-68 (Huff and Changnon, 1972). This was done by combining various subareas in the 4-year METROMEX study to conform to the larger major effect and upwind control areas used in the 20-year climatic study. When this was done, results were very similar. Thus, for December the indicated ratio of effect/control mean precipitation was 1.07 in the METROMEX study and 1.06

in the climatic study. Similarly the January ratio was 1.05 in the climatic study and 1.08 in the METROMEX study. For February, the ratios were 1.01 in the 1982 study and 1.02 in the METROMEX computations. These two studies indicate that the climatic network data in the St. Louis area are adequate to obtain generalized estimates of the urban effect, but that a much denser precipitation network is needed to define the location and intensity of the maximum effect. This is an important finding with regard to evaluation of urban effects in other large cities in the United States.

Winter storm analyses showed that the precipitation anomalies were produced by a relatively few storms. Thus, in the EDW area, 17 storms (12.5% of all winter storms) were largely responsible for the EDW anomaly. In the high located east of STL (East Downwind area), only 9% of the winter storms were largely responsible for this major anomaly.

The winter storms were grouped according to network mean precipitation and subarea/control ratios computed for each group. It was determined that storms producing network means exceeding 25 mm (1 inch) dominate the winter precipitation distribution. These storms produced 58% of the total network precipitation during the four winters. The isohyetal pattern of this storm group (Fig. 8) is very similar to that for total winter precipitation (Fig. 2). This heavy storm group was also found to exert a strong control on the total rainfall distribution characteristics in the earlier METROMEX research on urban effects in summer.

Analyses of 13 major snowstorms indicated a possible urban-induced decrease in the natural snowfall in heavy storms crossing the urban-industrial areas of St. Louis. This is in agreement with other findings relating to urban effects on snowfall in large metropolitan areas. There was also indication that snowfall may have been increased by topographic influence's in the hilly regions of the METROMEX Network.

Fall. The isohyetal pattern for the four falls combined did not provide strong evidence of an urban effect. Although a high existed in the EDW area NE of STL, stronger highs were situated S and SW of the city. Similarly, the grouping of months into relatively light, moderate, and heavy precipitation did not provide strong evidence of an urban effect. Only the 4-month moderate group showed a relatively strong high downwind of the city.

Subarea analyses for the four falls combined showed subarea/control ratios of 1.07 and 1.10, respectively, in the EDW and STL ED subareas, but a ratio of 1.11 occurred in the SW Hills, SW of STL in a region seldom downwind of the city in storms. Ratios for the groupings of months with light, moderate, and heavy precipitation showed the best evidence of an urban effect in the moderate category. Subareas lying NE and E of the city had ratios exceeding 1.10, but SW Hills also had a ratio of 1.10. Monthly analyses produced the same results as the seasonal computations. Thus, EDW had monthly ratios of subarea/control ranging from 1.05-1.09 during September, October, and November. However, the SW Hills had ratios ranging from 1.06 to 1.16 in these three months. Except for the offsetting SW Hills anomaly, there is some evidence of an urban-induced increase NE, E, and SE of STL during the fall season. Possibly, the SW Hills anomaly in the fall distribution is related to topographic influences which would likely be greater in this subarea than other regions of the network.

Analyses of individual storms during the four falls indicated the various network anomalies were produced in a small portion of the storms, in agreement with the winter findings. Thus, in STL SED which had a subarea/control ratio of 1.10, 7% of the storms were primarily responsible for the precipitation excess. In the SW Hills, where topography may be related to the apparent anomaly, less than 14% of the storms produced 75% of the precipitation excess (subarea-control precipitation difference).

Overall, the fall studies provide some evidence of an urban-related anomaly NE, E, and SE of STL, but the evidence is not as strong as in winter, because of precipitation maxima in the S and Sw portions of the network. These may be related to topographic influences from the Ozark Hills to the SW and the hills and river bluffs in the SSE part of the network (SE Hills-Bluffs)

Spring. The isohyetal pattern for the four springs combined shows a region in which the spring precipitation was 10%–15% above the network mean extending from NE of STL southwestward to the Ozark Hills in the SW part of the network. Overall, the precipitation distribution pattern suggests a possible urban effect located E to NE of STL, but one which is much weaker than the summer effect identified in the earlier METROMEX research. The location of the highs and magnitude of the inadvertent effect are similar to those for winter.

The subarea/control ratios further define the apparent inadvertent effect NE and E of STL in regions that are frequently downwind of the STL and ALN-WR industrial areas in storms crossing the network. The average spring ratio varied from 1.11 to 1.14 in EDW, GRC-EDW, STL Industrial-East, COL-BLV, and STL ED.

When the spring months were divided according to relatively light, moderate, and heavy rainfall, it was found that the apparent urban effect was strongest in those months having relatively heavy precipitation. The isohyetal pattern derived from the heavy months is similar to the distribution for total spring precipitation. These months accounted for 47% of the total spring rainfall.

Monthly analyses indicated an inadvertent increase of 5% to 9% in March precipitation in those subareas lying NE and E of STL. The April ratios of subarea/control mean precipitation indicate anomalies of approximately 16%-18% NE and E of STL. The May data show peak values in the ALN-WR region, where the ratios exceeded 1.20. However, ratios also exceeded 1.15 in the EDW and GRC-EDW subareas. Overall, the monthly and seasonal ratios indicate a modest urban-induced increase in spring that gradually increases from March to May. A major increase then occurs in the June-August period.

Analyses showed strong year-to-year consistency in the ratios of the subareas, particularly in those lying E of STL (STL Industrial-East, COL-BLV, and STL ED). In these three subareas, the ratio exceeded 1.00 in all four springs. Of the 12 months involved, the ratio exceeded 1.00 in 11 months in COL-BLV, and 10 months in STL Industrial-East and STL ED.

Similar to fall and winter, a relatively small percentage of the spring storms were primarily responsible for the anomalies located NE and E of STL. Thus in the EDW subarea, 11% of the spring storms produced 75% of the positive-deviation total (subarea-network difference) in this subarea where the anomaly maximized. Similarly, 10% of the storms contributed 75% of the storm rainfall excess in GRC-EDW, and 13% produced 75% of the positive-deviation total in STL Industrial-East, COL-BLV, and STL ED. Other analyses showed that the large subarea excesses tended to be associated with storms of moderate to heavy intensity on the network.

The isohyetal patterns of total spring rainfall, months with relatively heavy precipitation, and total rainfall from storms producing network means exceeding 25 mm all show similar features. All three show highs in the regions NE and E of STL, where any urban effect would be expected to be most pronounced. Similarly, lows are found in the SE part of the network and in the region lying W and NW of STL. Weaker highs are indicated in the SW Hills and SE Hills-Bluffs, which are regions in which a topographic-induced increase was identified in the summer METROMEX research. The spring anomalies relate well spatially with the summer distribution in which they were much more pronounced.

Spring comparisons between the 1972 climatic study and the present METROMEX network study support each other, similar to the findings for fall and winter. The 1972 study indicate an urban-induced increase in spring of 10% over its relatively large "major effect" area. The present study indicates a 9% increase when subareas are combined to conform to the earlier major effect area.

Table 23 summarizes the subarea/control ratios throughout the METROMEX Network during each of the four seasons, based on 1971-75 data. Upwind Control-1 was used in the computations in Table 22. Upwind Control-2 was not used in the summer studies made in the original METROMEX research program. Table 23 indicates a much stronger inadvertent effect in summer than in any of the other seasons. In most subareas, the effect is similar in fall, winter, and spring.

Table 23. Computed Inadvertent Effect on Precipitation in the METROMEX Network During the Four Seasons of 1971-1975.

Subarea	Ratio, Subarea to Control Area Mean* Summer	Fall	Winter	Spring
Edwardsville	1.49	1.08	1.10	1.11
Granite City-Edwardsville	1.44	1.06	1.08	1.11
Wood River Refineries	1.38	1.02	1.01	1.04
St. Louis Urban	1.01	1.01	1.01	1.06
St. Louis Industrial-East	1.22	1.04	1.05	1.09
Collinsville-Belleville	1.28	1.06	1.06	1.10
St. Louis East Downwind	1.19	1.08	1.10	1.09
St. Louis SE Downwind**	-	1.12	1.00	1.00
St. Louis Suburban West	0.99	1.02	0.99	0.97
ALN-WR Urban	1.34	1.05	1.03	1.07
ALN-WR Downwind	1.38	1.02	1.03	1.05
ALN-WR Bottomlands	1.34	1.06	0.99	1.02
SW Hills	1.09	1.13	1.03	0.99
SE Hills-Bluffs	1.24	1.12	1.00	1.00

*Based on use of Upwind Control-1 for evaluating subarea effect.
**SE Downwind not used in original summer study.

C. STUDIES OF SEASONAL PRECIPITATION BASED ON 1941-1980 CLIMATIC RECORDS

Introduction

Historical precipitation data from the National Weather Service (NWS) and other sources were used to investigate the presence of an urban effect in the St. Louis area and to determine whether upward or downward trends occurred in this inadvertent weather phenomenon (if present). Data for the 40-year period, 1941-1980, were used. An earlier study by Huff and Changnon (1972) provided some evidence of an urban effect in the 1941-1968 period. However, except for summer there is an appreciable climatic gradient in normal rainfall across the circular experimental area having a radius of 80 km (50 mi) about the center of St. Louis and this may have distorted the earlier results. In the present study, adjustment was made for the climatic gradient in fall, winter, and spring, based on the normal precipitation distribution in southwestern Illinois and eastern Missouri. Furthermore, the present study includes 12 years (43%) of additional data to establish more firmly the existence, location, magnitude, and temporal variation of any urban-induced changes in the precipitation distribution that have occurred.

Of course, the climatic data can not locate urban effects with the accuracy of a dense raingage network, such as that employed in the METROMEX research (Changnon *et al*., 1977), but earlier research on potential urban effects at eight major cities in the United States indicated that such effects can be identified, if substantial, from climatic records (Huff and Changnon, 1972). The present research was limited to a 80-km radius about St. Louis. The METROMEX research using a very dense raingage network indicated that an apparent urban effect was largely contained within 40 km of the city with a much smaller effect in some months in the 40- to 80-km range.

Approach to Problem

The 1941-1980 experimental area is shown in Fig. 4 of the previous section, and is essentially the same as that used in the earlier Huff and Changnon study. Two hypothesized areas of major urban effect and two areas of minor effect are indicated, along with an upwind control area to assist in evaluating potential urban effects. The upwind control includes most of the two upwind controls used in evaluating the urban effects in the 1971-1975 METROMEX research. The two areas denoted as downwind controls in the earlier research (Fig. 5), are designated minor effect areas in the present research in view of the METROMEX findings. Stations having observations for all. or most of the 40 years are also indicated on Fig. 5.

Analyses for each season were performed for independent periods of 5, 10, and 20 years, in addition to the total 40-year sampling periods. This constituted 15 separate analyses for each season. The sub-period analyses provide pertinent information on trends, persistence, and temporal variability of the precipitation distributions. For example, assume an apparent urban effect is identified in the 40-year data sample. Immediate questions then include the persistence of this effect throughout the 40 years, its temporal variation within the sampling period, temporal trends in its intensity, possible shifts in location, and the natural variability and its possible influence on the location and magnitude of the apparent urban effect from time to time. For example, in a given 5-year period, will variations in departure from normal within the hypothesized effect and control areas distort the true location and intensity of the effect.

Analyses of 1941-1980 Spring Precipitation

Mean precipitation was determined for each station in each sub-period and for the total 40-year sampling period. From these computations, isohyetal maps were plotted and analyzed. Interpolated isohyetal values were determined for key stations having missing data in any 5-year period, and these estimates were used in other analyses. Areal mean precipitation was computed from the isohyetal maps for each of the effect and control areas indicated in Fig. 5. Also, means for selected station combinations lying within the major effect areas were calculated. These included Edwardsville (EDW) + Collinsville (COL), COL + BLV (Belleville), Centerville (CEN) + Edgmont (EDG), and the urban area, STL + UNI, in Fig. 5. Mean precipitation for the entire area within 40 km of central St. Louis (STL) was also computed for comparison purposes. The primary measure of potential urban effect was the ratio of point or areal mean precipitation in each effect area to the mean in the upwind control region. The upwind control mean (Upwind Control #1) was the average for the four stations shown in Fig. 4; that is, St. Louis Airport (APT), Webster Grove (WG), St. Charles (STC), and Valley Park (VP) .

Selected isohyetal patterns for spring are shown in Figs. 21a to 21d. These include the distribution of average spring precipitation in the first and second 20-year periods (1941-1960, 1961-1980), the 40-year sampling period (1941-1980), and the 1971-1975 period, which includes the four years (1972-1975) when the METR0MEX research network was in operation. The isohyetal values are shown in cm and are spring averages (not totals) for each time period involved.

Major features from the dense METROMEX network were detected by the 1971-1975 climatic network, but in much less detail, of course. Both isohyetal patterns (see Fig. 12 of previous section) show a major high in the vicinity of EDW and a distinct low extending W and WNW of the STL urban area. Figures 21b and 21c show distinct differences between the two 20-year periods. During 1941-1960, a relatively strong high in the precipitation pattern occurred in the EDW region, and a major low extended westward from the STL urban area. During 1961-1980, the EDW high was missing, and a distinct low was present SE of St. Louis in the BLV area, one of the hypothesized major effect areas. The EDW high was displaced

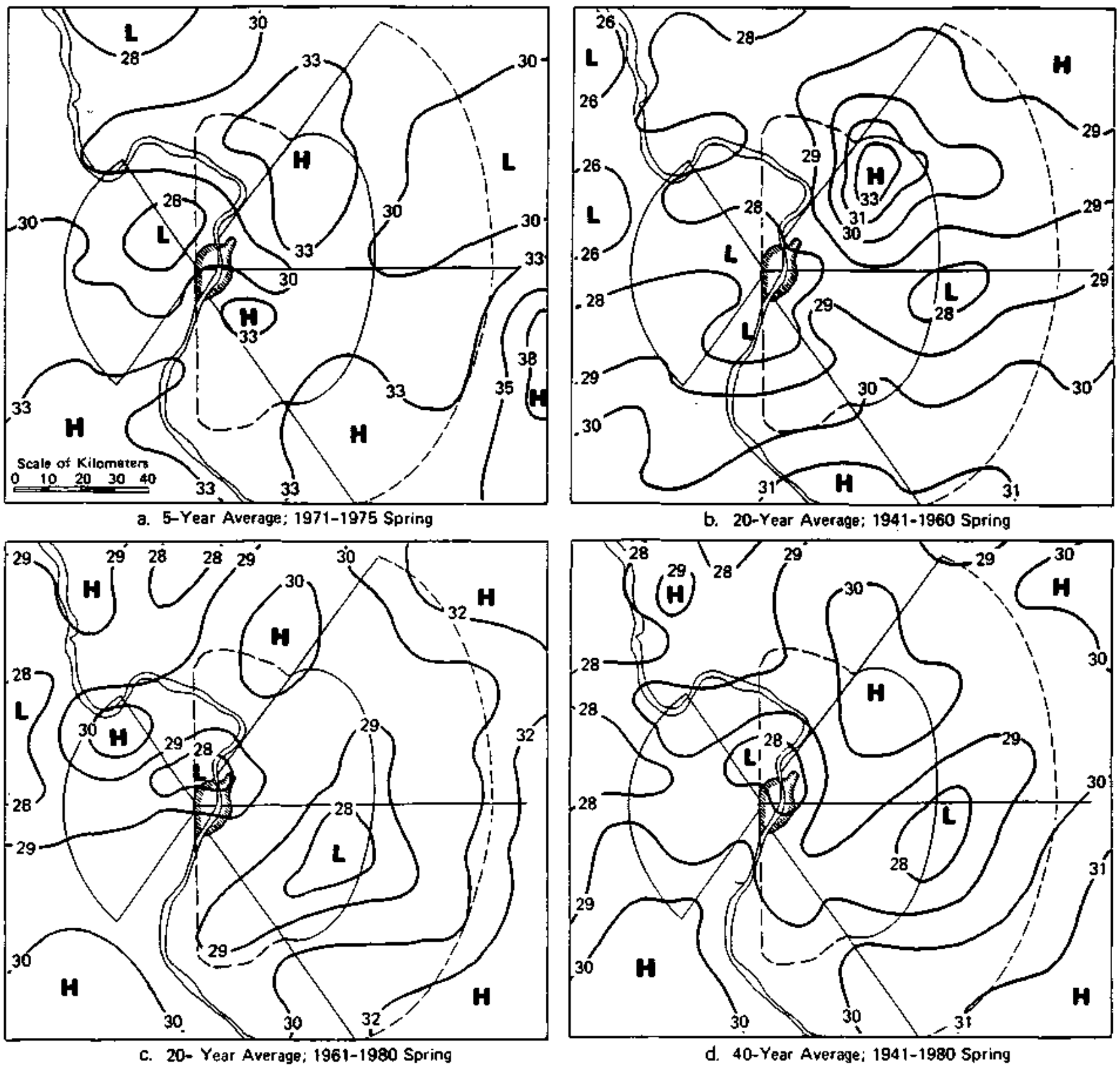


Figure 21. Selected Isohyetal Patterns for Spring, 1941-1980.

northward and located NE of ALT and NNE of the STL urban area. The 1941-1980 isohyetal pattern shows a high in the EDW area that extends S and SSW to COL and the EDG-CEN area. All the time periods covered in Fig. 21 show relatively high precipitation in the SW-S-SE extremities of the sampling region, which reflects the south-north climatic gradient in spring.

Table 24 shows effect/control ratios using Upwind Control #1 (4-station mean) for selected points and areas for which our hypothesis and the spring analyses indicated potential urban effects might exist. Only those points and areas where the potential effect appeared strongest are shown in this table. Adjustments have been made for climatic gradient.

In general, Table 24 indicates that the urban effect, as measured by the effect/control ratios, was most pronounced in the first 20 years, and was strongest in the EDW area. However, it was relatively strong in the EDW-COL area and in the NE Major Effect area, both of which are strongly related to the EDW observations. There was evidence of a weak effect in the SE Major Effect area and the Minor Effect area (N), but was insignificant in the Minor Effect area (NE) lying 40 to 80 km from central St. Louis. The 5-year ratios for 1961-1980 show ratios of only 1.05 and 1.04 for EDW and the Major Effect area (NE) where the urban effect would be expected to maximize considering the location of the urban area and prevailing storm movements (Vogel and Huff, 1978).

Table 25 shows the percentage deviation from the 40-year mean precipitation experienced at key locations during the 1941-1980 period. Comparing EDW and Upwind Control #1 , it is seen that EDW was more above average or closer to average (when both were below average) in the four 5-year periods from 1941 to 1960. Except for 1956-1960, this was also true for EDW + COL and for the NE Major Effect area. Except for 1971-1975, the opposite effects occurred in 1961-1980. Mathematically, this changing relation between effect and control areas largely explains the downward trend in spring effect/control ratios. Whether this is a sampling vagary (natural variability) or a climatic change, possibly related to urban influences, can not be determined from the existing climatic data.

Computations of the yearly coefficient of variation of spring precipitation showed that it decreased from 35% in 1941-1960 to 19% in 1961-1980 at EDW where the apparent urban effect maximized. At APT in the upwind control region WNW of STL, the coefficient of variation decreased from 32% to 20% between the two 20-year periods. At BLV, located ESE of STL, the change was not pronounced, decreasing from 28% to 25% between the two periods. The major decrease in relative variability between the area of maximum urban effect (EDW) and the upwind control area may have contributed to suppression of differences between the upwind and downwind areas during the two 20-year periods. With smaller deviations about the mean in the second 20 years, differences between the two areas due to natural rainfall variability would tend to be less also.

In Fig. 22, spring time trends for 1941-1980 are shown for a key station (EDW) in the Major Effect area and another in the Upwind Control (APT). Both stations have complete records for the 40-year sampling

Table 24. Ratio of Spring Rainfall in Potential Urban Effect Regions to Rainfall in Upwind Control No. 1 During Various Time Periods.

Period	EDW	COL	EDW & COL	Major (NE)	Major (SE)	Minor (N)	Minor (NE)
1941-45	1.25	1.10	1.17	1.14	0.98	1.09	1.23
1946-50	1.20	1.08	1.14	1.10	0.99	1.00	0.99
1951-55	1.31	1.15	1.23	1.16	1.10	1.10	0.81
1956-60	1.12	0.98	1.05	1.03	1.06	1.00	0.99
1961-65	1.00	1.10	1.05	1.04	1.05	1.02	1.02
1966-70	0.98	1.01	1.00	1.00	0.96	1.05	0.96
1971-75	1.20	1.14	1.17	1.10	1.09	1.06	1.04
1976-80	1.01	0.96	0.99	0.99	0.94	1.07	0.95
1941-50	1.23	1.09	1.16	1.12	0.99	1.04	1.11
1951-60	1.22	1.07	1.14	1.10	1.08	1.05	0.90
1961-70	0.99	1.06	1.03	1.02	1.01	1.03	0.99
1971-80	1.11	1.05	1.08	1.05	1.01	1.07	1.00
1941-60	1.23	1.08	1.15	1.11	1.04	1.04	1.01
1961-80	1.05	1.05	1.05	1.04	1.01	1.05	1.00
1941-80	1.14	1.07	1.10	1.07	1.03	1.04	1.00

Table 25. Percent Deviation of 5-Year Mean Precipitation from the 40-Year Mean for Spring 1941-1980.

	Percent Deviation from 40-Year Mean for 5 Years Ending at							
	1945	1950	1955	1960	1965	1970	1975	1980
Major Effect (NE)	+28	+1	-18	+2	+4	-6	+7	-11
EDW	+34	+5	-12	+7	-5	-12	+11	-14
EDW & COL	+29	+3	-15	+3	+3	-18	+12	-14
Upwind Control #1	+18	-3	-25	+5	+6	0	+3	-4

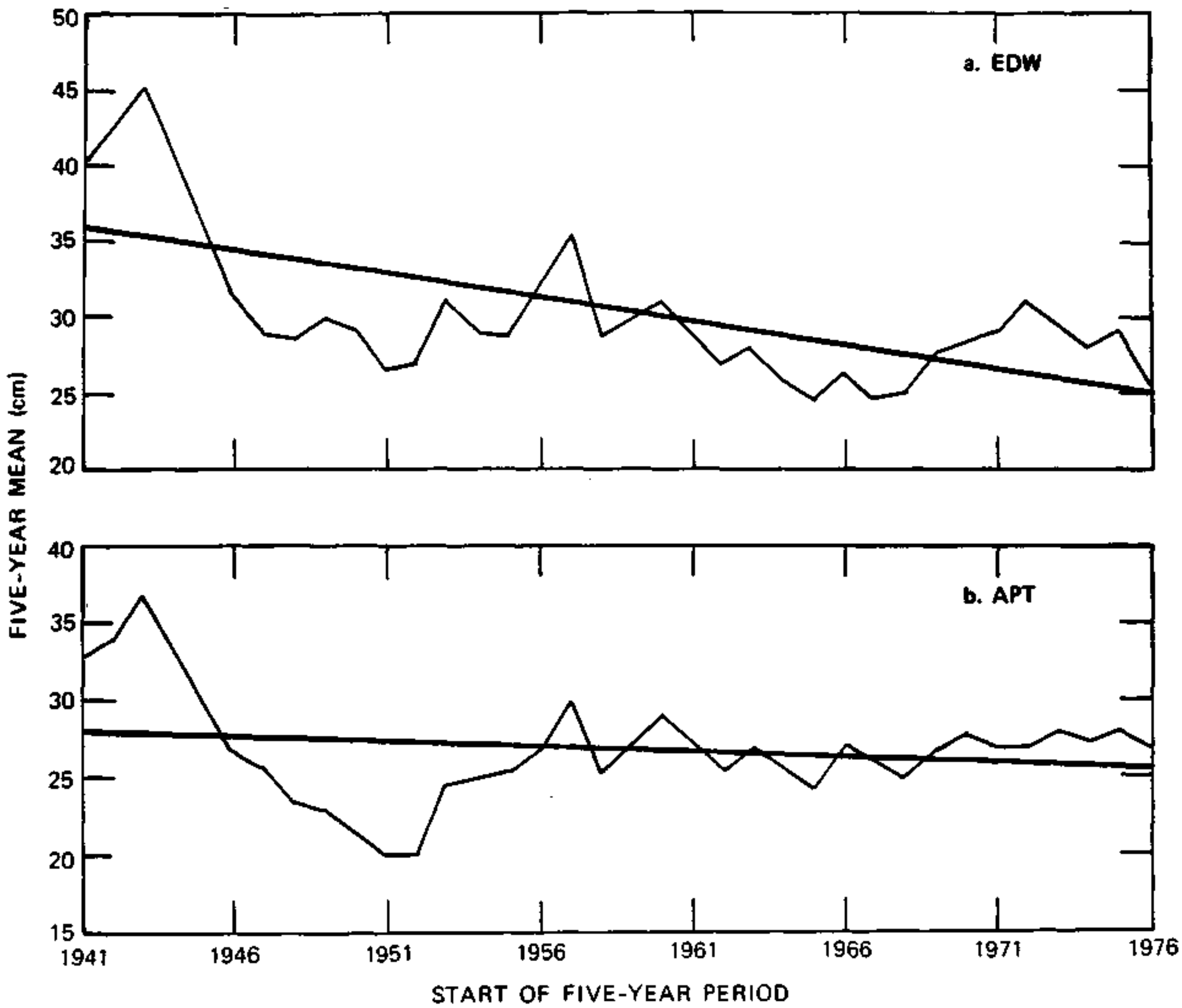


Figure 22. 1941-1980 Time Trend of Spring Precipitation at Key Stations.

period, and investigation showed no station changes of significance during the 40 years. Five-year moving averages of precipitation are shown for each station, along with the time-trend regression line derived from the data. Both show negative time trends, but the EDW decrease is much greater. Most of the downward trend occurred in the first 15 years. During the last 20 years, no significant trend existed at either station. Trend analyses for 1961-1980 indicated a -2% change for EDW and +4% at APT.

Much of the spring precipitation excess downwind of STL occurred in the first 15 years. Thus, at EDW the effect/control ratio was 1.25 for the first 15 years compared with 1.06 in the last 25 years. Similar values for EDW + COL were 1.18 and 1.05. For the NE Major Effect' area they were 1.13 and 1.03. Thus, the spring analyses of climatic data indicate a major decrease in any urban effect during the last 25 years of the 40-year sampling period.

Persistence of the apparent urban effect in spring was determined from the frequency with which the effect/control ratio exceeded 1.00 in the eight 5-year periods for selected points and areas. Using Upwind Control #1 (APT, WG, STC, VP), the ratio exceeded 1.00 in 6 of the 8 periods at EDW, COL, NE Major Effect area, and the North Minor Effect area (see Table 24). The area encompassed by this persistence pattern includes that within the NE quadrant of a 40-km radius circle centered in central STL. This area is located in the most frequent path of storms exposed to the STL urban area. The highest ratios were recorded at EDW which is located about 30 km NE of STL. Ratios varied from a low of 0.98 to a high of 1.31, and the 40-year mean was 1.14. This indicates an average urban-induced increase of 14% for the 40-year sampling period.

When the mean precipitation for the 40-km circle centered at STL is used as a "control", the effect/control ratios exceeded 1.00 in all 8 periods in the NE Major Effect area and in 6 seasons at EDW and COL. The 40-year mean ratio is smaller when the 40-km circular area is used as a control, because the urban-effect areas are included in the averaging process. This provides a conservative (but biased) estimate of the urban effect. The 40-year mean ratio for EDW was 1.11 compared with 1.14 using the Upwind Control #1. For the NE Major Effect area, the ratio was 1.05 compared with 1.07 when using Upwind Control #1. As shown above, both methods of calculating the effect/control ratio show a persistent precipitation excess in the region in which meteorological-climatological considerations would indicate an urban effect on precipitation would maximize.

A comparison of 40-year control/effect ratios, utilizing several control areas, is provided in Table 26. Upwind Control No. 1 (Fig. 5) is based on data for APT, WG, STC, and VP. This is considered the most applicable control, and is the one most of our stated implications are based upon. Upwind Control No. 2 is based on data for APT and WG, and is indicative of the precipitation distribution immediately upwind of urban St. Louis. Urban St. Louis is also used as a control in Table 26, since any downwind urban effect would be initiated in this region and the industrial area just east of the Mississippi River. This area was used also by Huff and Changnon (1972) as a control in their 8-city study. The

Table 26. 1941-1980 Effect/Control Ratios for Spring, Based on Several Controls.

Effect Location	Upwind No. 1	Upwind No. 2	Urban St. Louis	40-km Areal Mean
	Ratio for Given Control Area			
EDW	1.14	1.14	1.15	1.11
COL	1.07	1.08	1.08	1.04
EDW & COL	1.10	1.11	1.11	1.07
Major Effect (NE)	1.07	1.08	1.08	1.05
Major Effect (SE)	1.03	1.03	1.03	1.00
Minor Effect (N)	1.04	1.05	1.06	1.02
Minor Effect (NE)	1.04	1.05	1.06	1.02

other control shown in Table 26 is the average rainfall for the area within 40-km around St. Louis. As indicated above, this provides a conservative, but biased, measurement of any downwind urban effect.

Essentially the same results were obtained when Upwind Control No. 1, Upwind Control No. 2, and urban St. Louis were used as controls to evaluate the potential urban effect NE, E, and SE of St. Louis. As expected, the areal mean control produced smaller ratios for reasons discussed earlier. Overall, Table 26 indicates an urban effect that increases the natural spring rainfall by 14%-15% in the vicinity of EDW where the apparent effect maximizes. It is interesting to note that using the dense raingage network of the 1971-1975 METROMEX research project, the ratio for the EDW subarea was 1.15, nearly identical with the long-term average ratio derived from the climatic data. For 1971-1975, the climatic data indicated a ratio of 1.20 between the EDW station and Upwind Control No. 1. For this period, the METROMEX data indicated a maximum control/effect ratio of 1.21 in the EDW vicinity. For spring, at least, the short-term, highly detailed METROMEX data and the long-term, relatively sparse climatic area are in excellent agreement.

Analyses of 1941-1980 Summer Precipitation

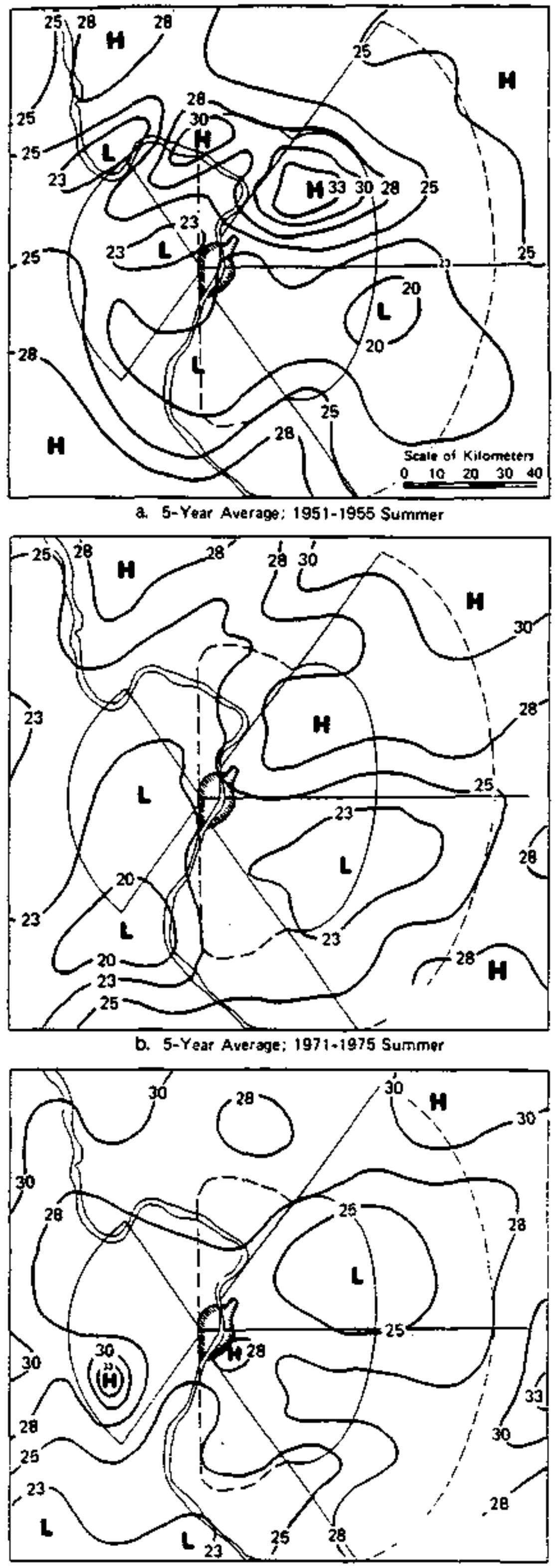
The same analytical procedure was followed as described in the preceding section on spring precipitation. Table 27 shows effect/control ratios for selected points and areas which were hypothesized to be susceptible to urban effects. Ratios are shown for the eight independent 5-summer periods, along with those for the four 10-year, two 20-year, and the total 40-year sampling period. The spring trend for the ratios to decrease greatly between the two 20-year periods was not shown in the summer data. A slight decrease occurred for 1961-1980 in the region E and NE of STL, but the 5-year ratios show no stable trend.

Table 27 shows that the effect/control ratios maximized in the 1951-55 and 1971-1975 periods. The latter period was that in which the METROMEX research was carried out in the St. Louis region. Isohyetal maps for these two periods are shown in Figs. 23a and 23b. Figure 23c shows the 5-year pattern for 1966-70 when the area E and NE of STL was in a low rather than the usual high. Upwind Control No. 1 had precipitation that was approximately 2% above the 40-year mean, whereas EDW, COL, and the NE major effect area were 10% to 20% below the 40-year average. This reversal in pattern is apparently due to vagaries in the natural distribution that were strong enough to block out any modest urban effect that may have been operating in the major effect areas.

Table 27 shows that points and areas lying E to NE of STL consistently experienced rainfall greater than the upwind control region. At COL, the effect/control ratio exceeded 1.00 in seven of eight 5-year periods. At EDW and in the designated major effect areas (NE and SE), the ratios exceeded 1.00 in six of the eight 5-summer periods. Similarly, the ratios exceeded 1.00 in three of the four 10-year periods and in both 20-year periods within the hypothesized effect areas.

Table 27. Ratio of Summer Rainfall in Potential Urban Effect Regions to Rainfall in Upwind Control Area during Various Time Periods.

Period	EDW	COL	EDW & COL	Major Effect (NE)	Major Effect (SE)	Minor Effect (N)	Minor Effect (NE)
1941-45	1.07	1.15	1.11	1.08	1.03	1.10	1.00
1946-50	1.10	1.25	1.17	1.17	1.12	1.09	1.00
1951-55	1.43	1.02	1.23	1.14	0.93	1.03	1.04
1956-60	0.92	1.04	0.98	0.99	1.03	0.93	0.95
1961-65	1.05	1.12	1.09	1.06	1.14	1.05	0.94
1966-70	0.88	0.91	0.90	0.90	0.98	0.97	0.94
1971-75	1.33	1.18	1.25	1.22	1.05	1.18	1.21
1976-80	1.15	1.08	1.12	1.05	1.01	0.93	0.99
1941-50	1.09	1.20	1.15	1.13	1.08	1.09	1.00
1951-60	1.13	1.04	1.08	1.05	0.99	0.98	0.99
1961-70	0.96	1.01	0.99	0.98	1.05	1.00	0.94
1971-80	1.24	1.13	1.18	1.13	1.03	1.04	1.10
1941-60	1.11	1.12	1.12	1.09	1.04	1.04	1.00
1961-80	1.10	1.07	1.09	1.06	1.04	1.02	1.02
1941-80	1.11	1.10	1.10	1.07	1.04	1.02	1.01



a. 5-Year Average; 1951-1955 Summer

b. 5-Year Average; 1971-1975 Summer

c. 5-Year Average; 1966-1970 Summer

Figure 23. Comparison of 5 Year Summer Precipitation Patterns at Selected Intervals.

Comparisons of the effect/control ratios during the 40-year period for spring and summer (Tables 24 and 27) shows values of very similar magnitude. However, the time distribution of the ratios with respect to magnitude was much more consistent for summer, since the large unexplained downward trend for spring was absent, or nearly so. Figure 24a and 24b show the summer isohyetal patterns for the two 20-year periods. Both show consistency in the critical areas; thus, both patterns have distinct highs in the EDW-COL region, and both show lows west of St. Louis. As a result of this consistency, the 40-year pattern (Fig. 24c) also shows a distinct high in the EDW-COL area that extends over the hypothesized NE Major Effect area. A major low exists W of STL, climatically upwind of the hypothesized urban-induced increase in precipitation.

Table 28 shows a comparison of effect/control ratios for selected potential effect areas using several control areas. These are the same controls described previously in discussing the spring analyses. The ratios are based on 40-year averages of summer precipitation. Table 28 shows only slight differences between the ratios obtained with the two upwind controls which are considered most representative of areas having little or no urban effect on precipitation. These ratios suggest an urban-induced increase of 10%—11% ENE to NE of the city (EDW, COL) and about an 8% average over the hypothesized NE Major Effect. These are very similar to the spring ratios. The ratios obtained with the STL urban area, likely subject to slight urban influences on its precipitation, are only a little smaller than the upwind ratios. As expected the areal mean ratios are the smallest.

Since the METROMEX dense raingage network was in operation over a 40-km radius about St. Louis in the summer of 1971-1975, it is interesting to compare the network and climatic findings for that period. The peak ratio in the climatic analyses was 1.33 for EDW, using Upwind Control No. 1. Using Upwind Control No. 2 it was 1.34. The ratio for the EDW subarea in the METROMEX analyses was 1.49, which is considerably greater than the climatic-derived value for EDW. However, most of the EDW subarea of METROMEX lies ENE of the city (Huff and Vogel, 1978), and this is where the rainfall maximized in the 1971-1975 period, based on the network observations. This probably accounts for the difference — not unexpected, since dense networks will normally record larger values than a relatively sparse climatic network. Although the climatic network apparently underestimated the urban effect for 1971-1975, it did identify the approximate location of the downwind high center and the approximate location of other highs and lows shown in the METROMEX isohyetal analysis (Changnon et al., 1977).

Figure 25 shows 5-year moving averages and the regression time trend line for summers 1941-1980 at EDW and APT. Similar to spring, both show negative trends. However, both trend lines show a nearly equal rate of decrease with time, whereas in spring the EDW decrease was much greater than experienced by APT. During the last 20 years (1961-1980), the downward trend was reversed at EDW. Calculations of 1961-1980 time trends indicated an 11% increase from start to end of the period. At the same time, the APT decrease is nearly eliminated.

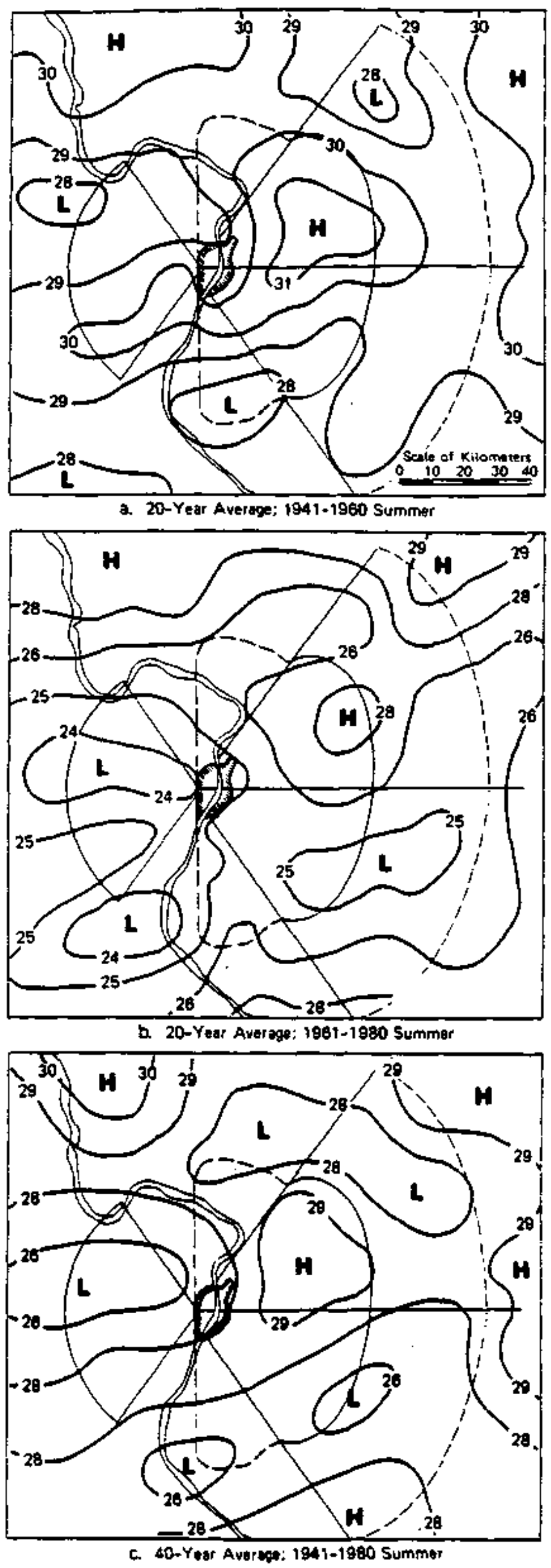


Figure 24. Comparison of Summer Precipitation Patterns for 20 Year Plus 40 Year Periods.

Table 28. 1941-1980 Effect/Control Rates for Summer Based on Several Controls.

Effect Location	Upwind No. 1	Upwind No. 2	Urban St. Louis	40-km Areal Mean
	Ratio for Given Control Area			
EDW	1.11	1.11	1.09	1.07
COL	1.10	1.11	1.09	1.07
EDW & COL	1.10	1.11	1.09	1.07
Major Effect (NE)	1.07	1.08	1.07	1.05
Major Effect (SE)	1.04	1.05	1.03	1.01
Minor Effect (N)	1.02	1.04	1.03	1.00+
Minor Effect (NE)	1.01	1.02	1.00	1.00

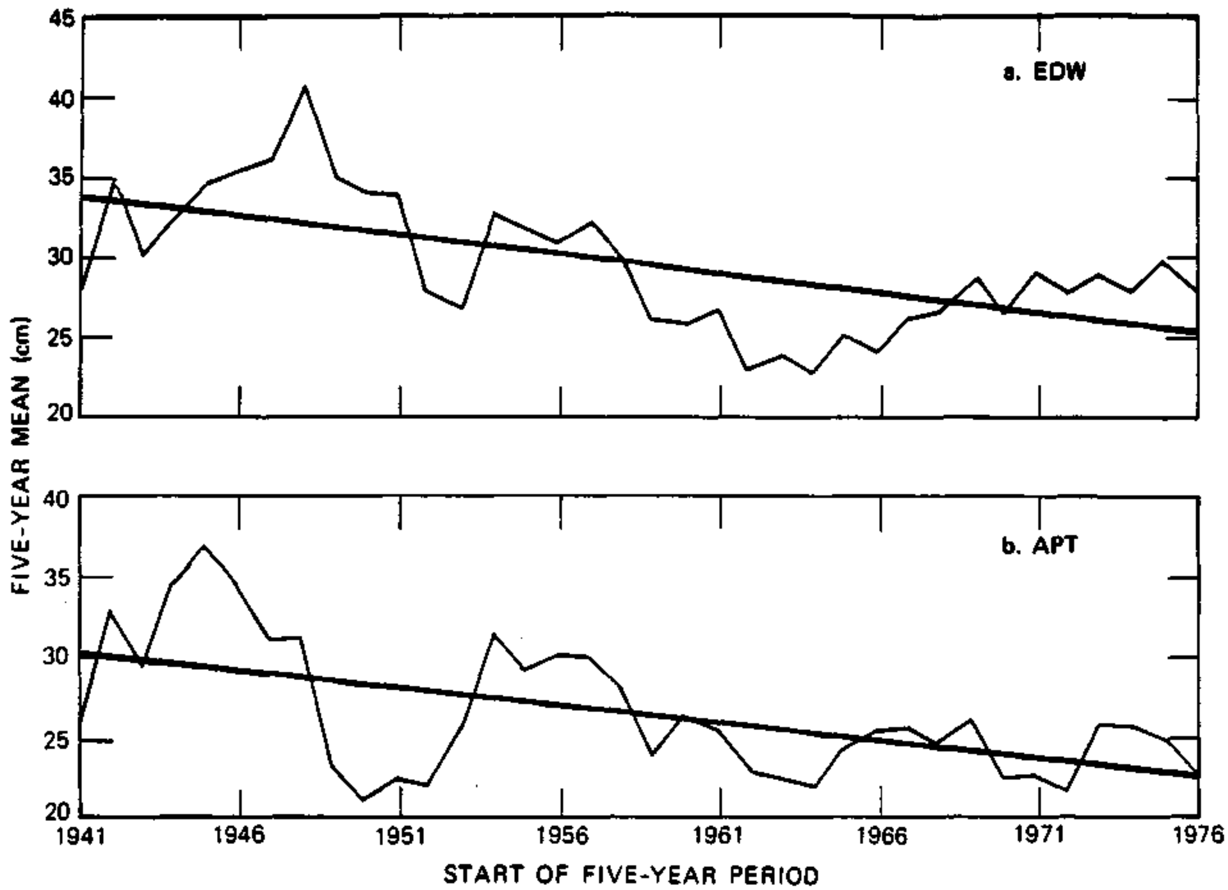


Figure 25. 1941-1980 Time Trend of Summer Rainfall at Key Stations.

Analyses of 1941-1980 Fall Precipitation

Following the same analysis procedures used for spring and summer, investigations was made of potential urban effects in fall (Sept.-Nov.). Table 29 shows effect/control ratios for selected points and areas considered exposed to any urban-induced increases in precipitation. Overall, an urban effect, if present, appears to be relatively weak and of about equal strength in the two hypothesized major effort areas designated NE and SE in Fig. 5. Two changes have been made from similar tables for spring and summer discussed previously. Minor Effect (SE) was substituted for Minor Effect (N), because ratios tended to be larger in this region. Also, the SE Minor Effect area has been added for comparison with the Major Effect (SE) and Minor Effect (S) areas, which appear more important in fall than in spring and summer.

Table 29 indicates that the urban effect, if present, was more pronounced in the first 20 years than in the last 20 years of the 40-year sampling period. This is the same trend shown by the spring data. There is a slight trend also for the effect/control ratios to shift from maximization NE of STL in 1941-1960 to the region SE of the city in the last 20 years of the study period. Combining all 40 years, the average effect/control ratios NE of the city were more pronounced in spring than in fall (Tables 24 and 29).

Reference to the 5-year departures from the 40-year average ratios for fall showed the same characteristics found for spring. Thus, during the first 20 years, the 5-year ratios for EDW, near where the maximum urban effect would be expected, always showed a greater positive deviation from the mean or a lesser negative deviation than Upwind Control No. 1. During the last 20 years, this situation reversed. Regardless of the cause, this occurrence would result in the effect/control ratios being greater in the first than in the second 20 years — the same situation that occurred in spring between the area E and NE of the city and the region W of the urban area.

Figure 26a to 26c shows the fall isohyetal patterns for the two 20-year periods and the 40 years, 1941-1980. During 1961-1980, the EDW high of 1941-1960 collapsed, and the entire area lying NE, E, and SE of the city became part of a relatively flat low in the precipitation pattern. Precipitation gradients are weak in the 1961-1980 period. As a result of the first 20-year occurrences, a high in the EDW area is indicated during 1941-1980 and a low extends W and WNW of the city.

Figure 26d shows the 5-year pattern for 1971-1975. During the four years, 1971-1974, the METR0MEX dense network was in operation within a 40-km radius of STL. The 4-year METR0MEX isohyetal pattern (Fig. 8, previous section) shows a small high in the EDW area, and a low extending W-E across the STL urban area. The 5-year pattern from the climatic network (Fig. 26d) detected the low, but not the small high extending E from EDW. Both isohyetal maps show heavier precipitation SW of the city than in the area NE, E, and SE of the urban area.

Table 29. Ratio of Fall Precipitation in Potential Urban Effect Regions to Precipitation in Upwind Control Area During Various Time Periods.

Period	EDW	COL	EDW & COL	Major Effect (NE)	Major Effect (SE)	Minor Effect (NE)	Minor Effect (SE)	Minor Effect (S)
1941-45	1.18	1.11	1.14	1.09	1.03	1.08.	1.07	1.03
1946-50	1.13	1.01	1.07	1.04	0.92	1.08	1.03	1.03
1951-55	1.12	1.11	1.12	1.07	1.14	1.02	1.14	1.08
1956-60	1.16	1.14	1.15	1.09	1.18	1.02	1.08	1.19
1961-65	0.95	1.02	0.98	0.98	1.03	0.98	0.96	1.01
1966-70	1.00	0.95	0.97	0.95	0.95	0.95	0.94	0.98
1971-75	0.98	0.98	0.98	0.97	0.99	1.03	1.01	0.98
1976-80	0.97	1.08	1.03	1.02	1.09	1.01	0.96	1.12
1941-50	1.16	1.06	1.11	1.07	0.98	1.08	1.05	1.03
1951-60	1.14	1.13	1.14	1.08	1.16	1.02	1.11	1.13
1961-70	0.98	0.99	0.98	0.97	0.99	0.96	0.95	1.00
1971-80	0.98	1.03	1.00	1.00	1.04	1.02	0.98	1.06
1941-60	1.15	1.10	1.12	1.08	1.07	1.05	1.08	1.08
1961-80	0.98	1.01	0.99	0.98	1.02	0.99	0.97	1.03
1941-80	1.07	1.05	1.06	1.03	1.04	1.02	1.02	1.05

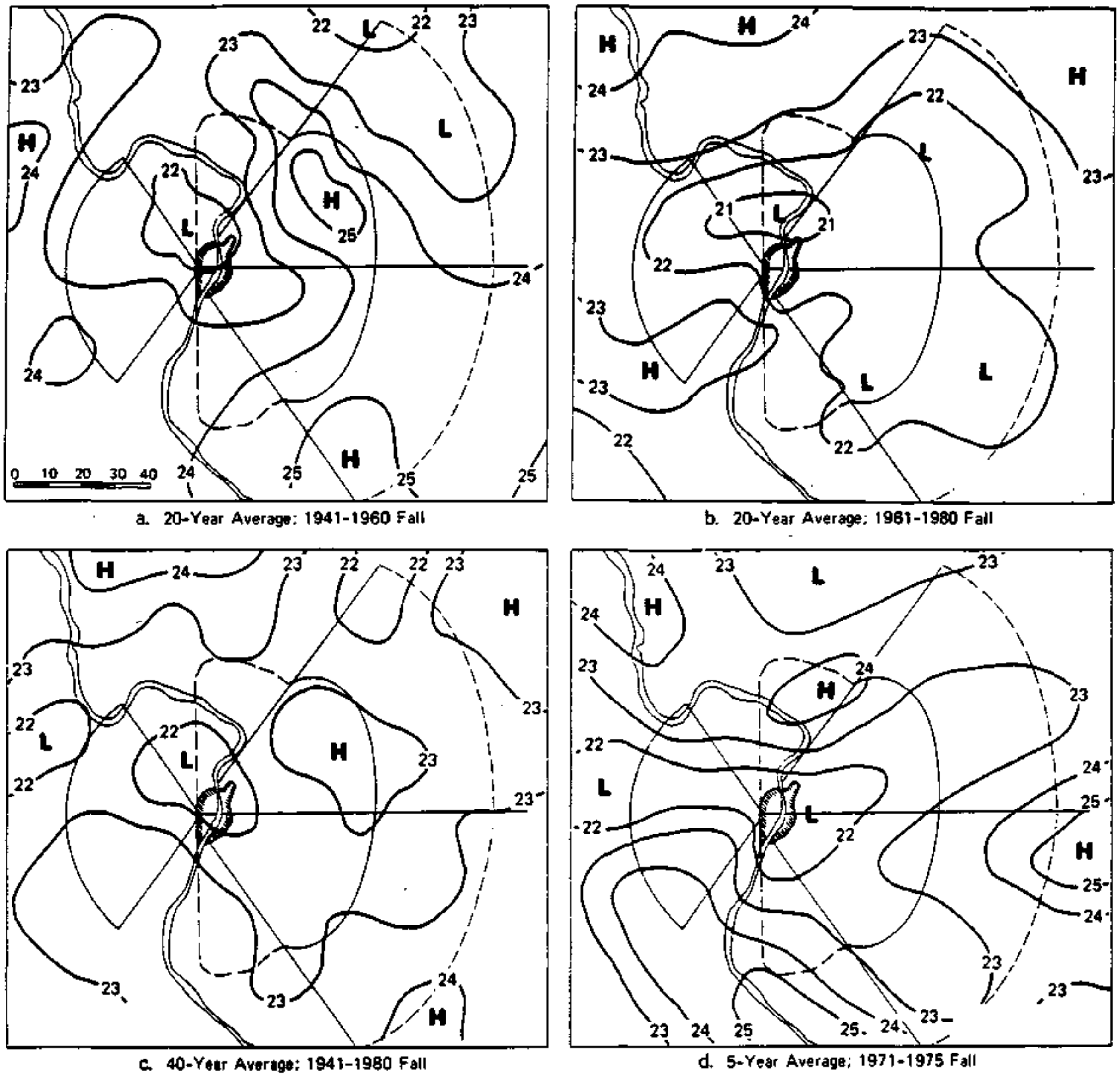


Figure 26. Selected Isohyetal Patterns for Fall, 1941-1980.

Table 30 shows a comparison of the 1941-1980 effect/control ratios for selected potential effect areas using the different control areas described previously in discussions of spring and summer analyses. Table 30 shows only small differences generated among the four controls. The last column shows average ratios combining the controls. For the 40 years, the ratios suggest a possible urban-induced precipitation increase of approximately 4% to 6% among the hypothesized major and minor effect areas, and a maximum increase of about 9% in the EDW area. These are substantially smaller than the ratios obtained for EDW, COL, and the NE Major Effect area for spring and summer. However, the ratios did not vary much among the three seasons in the SE Major Effect area.

Figure 27 shows 1941-1980 time trend relations for fall, based on 5-year moving averages and time-trend regression analysis. The time distribution characteristics are similar to those for spring (Fig. 22). Thus, both EDW and APT show negative time trends, but the EDW rate of decrease is considerably greater than that for APT. Other calculations showed that both stations experienced an upward trend in precipitation during the last 20 years of the sampling period.

Analyses of 1941-1980 Winter Precipitation

Tables 31 and 32 show the same type of relations described for the other seasons. Table 31 indicates relatively low winter ratios for points located E to NE of the city, compared with those found in the spring-summer analyses. Differences between fall and winter are very small. The relatively strong downward trend in the ratio from the first to the second 20-year period for spring and fall did not occur in winter.

Table 31, adjusted for climatic variations across the study area, indicates an urban-induced increase of 3% to 4% in the hypothesized Major Effect area lying E to NE of the St. Louis urban-industrial area, based on analyses of 10-, 20-, and 40-year periods. In an earlier study employing 1949-1968 data, Huff and Changnon (1972) found an average winter increase of approximately 4% in this area. Thus, for periods of 10 to 40 years, there is strong consistency in the results.

It is interesting to compare results of analyses for the 1971-1975 winters in Table 31 with those derived from the dense raingage network operated in conjunction with the METR0MEX research. The network was in operation during four winters starting in '1971. Averaging those ratios in Table 2 listed under "Upwind Average" which are a part of the Major Effect (NE) in Table 31, a winter ratio of 1.07 is obtained. This compares closely with the ratio (1.09) obtained from the NWS climatic network data for the 5 winters beginning in 1971. Similarly, Table 31 shows a ratio of 0.98 for the hypothesized area designated Major Effect (SE). The value derived from Table 2 is 1.00; again, very close correlation between results from the dense research network data and those derived from isohyetal analyses of the NWS climatic network data.

Figure 28a shows the isohyetal pattern for the 1971-1975 winters derived from the climatic data. This pattern, uncorrected for climatic gradient, indicates a weak high extending E and then NE of the St. Louis

Table 30. 1941-1980 Effect/Control Ratios for Fall, Based on Several Controls.

	Ratio for Given Control Area				
Effect Location	Upwind No. 1	Upwind No. 2	Urban St. Louis	40-km Areal Mean	4-Control Average
EDW	1.07	1.08	1.10	1.09	1.09
COL	1.05	1.06	1.08	1.06	1.06
EDW & COL	1.06	1.07	1.09	1.07	1.07
Major Effect (NE)	1.03	1.04	1.06	1.04	1.04
Major Effect (SE)	1.04	1.05	1.06	1.04	1.05
Minor Effect (S)	1.05	1.06	1.08	1.07	1.06
Minor Effect (NE)	1.02	1.04	1.06	1.04	1.04
Minor Effect (SE)	1.02	1.04	1.05	1.04	1.04

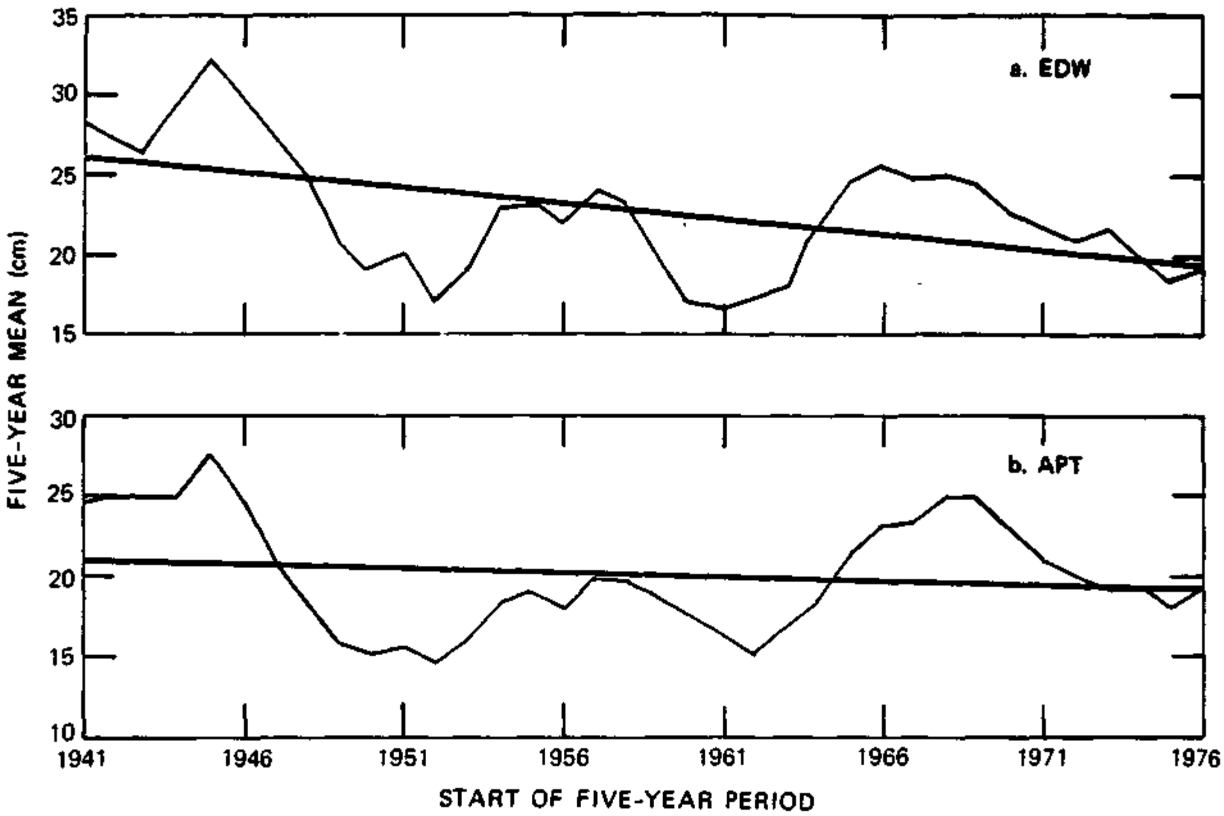


Figure 27. 1941-1980 Time Trend of Fall Precipitation at Key Stations.

Table 31 Ratio of Winter Precipitation in Potential Urban Effect Regions to Precipitation in Upwind Control Area During Various Time Periods.

Period	EDW	COL	EDW & COL	Major Effect (NE)	Major Effect (SE)	Minor Effect (N)	Minor Effect (NE)
1941-45	1.01	1.00	1.01	1.02	1.08	0.98	1.04
1946-50	1.08	1.04	1.06	1.05	1.02	0.96	1.06
1951-55	1.05	1.05	1.05	1.06	1.02	1.07	0.96
1956-60	1.05	0.99	1.02	1.01	1.08	0.96	1.00
1961-65	1.01	1.07	1.04	1.02	1.11	0.96	1.00
1966-70	1.06	1.05	1.06	1.02	0.99	1.08	1.04
1971-75	1.14	1.08	1.11	1.09	0.98	1.08	0.99
1976-80	1.01	0.96	0.99	0.99	0.94	0.94	0.95
1941-50	1.05	1.02	1.03	1.04	1.05	0.97	1.05
1951-60	1.05	1.02	1.03	1.04	1.05	1.01	1.01
1961-70	1.04	1.06	1.05	1.02	1.05	1.02	1.02
1971-80	1.08	1.02	1.05	1.04	0.96	1.01	0.97
1941-60	1.05	1.02	1.03	1.04	1.05	0.99	1.03
1961-80	1.06	1.04	1.05	1.03	1.01	1.01	1.00
1941-80	1.05	1.03	1.04	1.03	1.03	1.00	1.01

Table 32. 1941-1980 Effect/Control Ratios for Winter, Based on Several Controls.

Effect Location	Upwind No. 1	Upwind No. 2	Urban St. Louis	40-km Areal Mean
	Ratio for Given Control Area			
EDW	1.05	1.03	1.01	1.01
COL	1.03	1.03	1.01	1.01
EDW & COL	1.04	1.03	1.01	1.01
Major Effect (NE)	1.03	1.02	1.00	1.00
Major Effect (SE)	1.03	1.01	1.00	1.00
Minor Effect (N)	1.00	0.99	0.99	0.99
Minor Effect (NE)	1.01	1.00	0.99	0.99

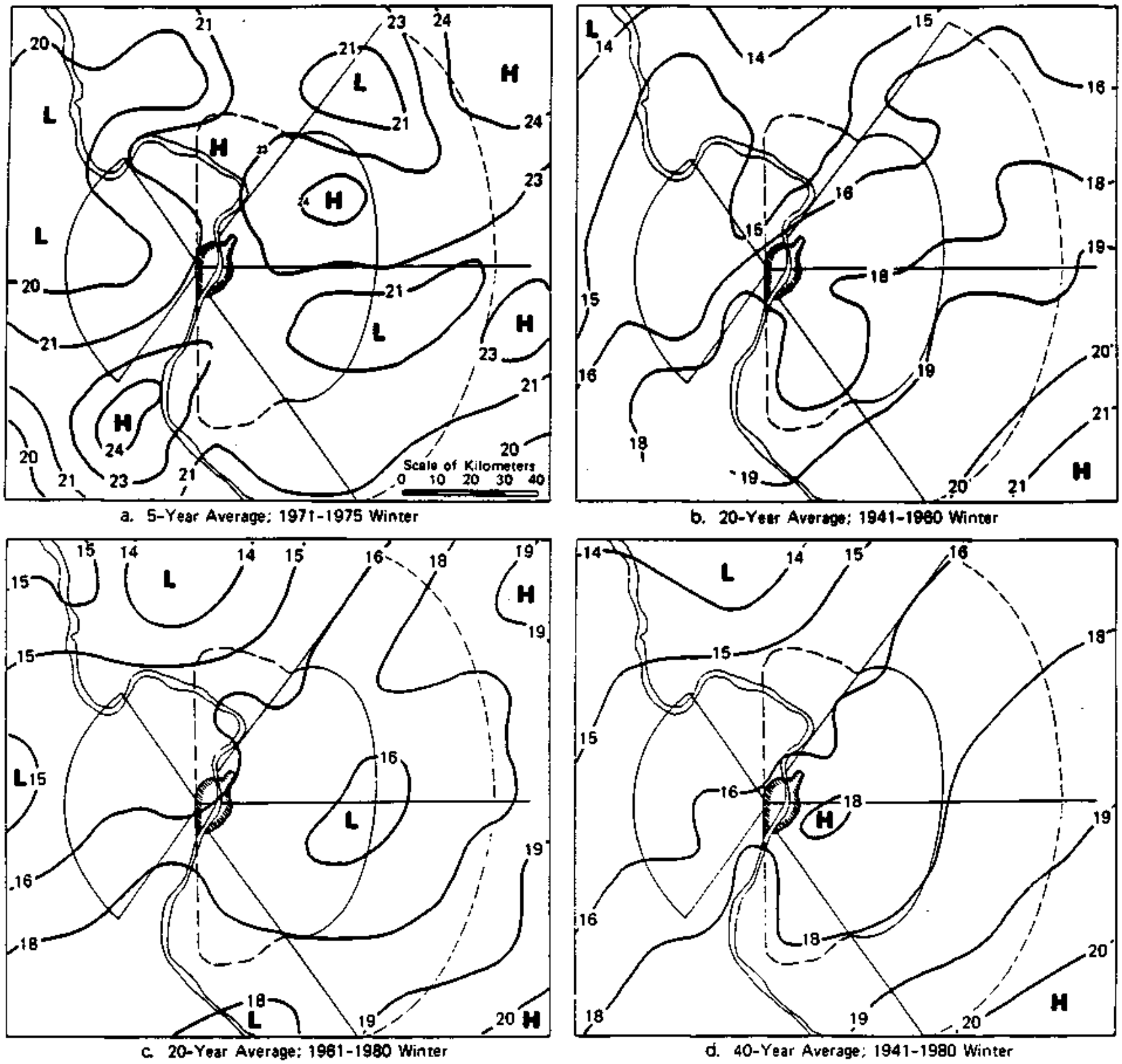


Figure 28. Selected Isohyetal Patterns for Winter, 1941-1980.

urban-industrial area. However, a high of equivalent magnitude is located SSW of the city in an area that is seldom downwind of the urban-industrial area in winter storms. This high may be associated with topographic influences from the Ozark foothills that protrude into the SW portion of the study area. The METROMEX isohyetal pattern (Fig. 2) shows much greater detail because of the dense network of gages, but the major highs and lows are in the same general areas, except that the climatic low indicated ESE of St. Louis is not verified by the dense network.

Figures 28b to 28d show the isohyetal patterns derived from the climatic network data for 1941-1960, 1961-1980, and 1941-1980. These do not provide significant evidence of an urban effect. However, the maps have not been adjusted for the climatic gradient, and the winter effect, as shown in Table 31, is small.

Table 32 shows the effect of using different controls in calculating the effect/control ratios. Only small differences are indicated in the table. As stated previously, the upwind controls are considered the most appropriate for evaluating a potential urban effect from the St. Louis and/or Alton-Wood River urban-industrial areas.

Figure 29 shows time trend relations for winter, 1941-1980. The time trend regression showed no significant trend for EDW or APT. The EDW trend indicated a small decreasing trend which was only -4% for the 40 years. APT had a 2% increase indicated for the sampling period. Both stations showed an upward trend during the last 20 years.

Comparison of Urban Effect Between Seasons

Table 33 shows effect/control ratios for the 40-year period for each of the four seasons and selected areas of potential effect. In all seasons, the effect maximized in the EDW-COL region located E-NE of the city. The NE Major Effect area had the largest ratios in spring and summer among the several potential effect areas. In fall and winter, the NE and SE Major Effect ratios were equivalent, but both were too small to distinguish an urban effect with a high degree of reliability. In general, the E/C ratios in Table 33 are very similar to those found in an earlier study of the St. Louis region based on 1941-1968 data (Huff and Changnon, 1972).

Summary and Conclusions

An investigation of potential urban effects within 80 to 100 km of central St. Louis was made through use of climatic data collected by the National Weather Service during 1941-1980. This study extends an earlier investigation using 1941-1968 data, and supplements the comprehensive METROMEX research program of 1971-1975. Analyses were performed on monthly and seasonal precipitation, after adjusting for the normal climatic gradient across the study area. (This had not been done in the previous St. Louis studies.) Potential urban effects were studied for periods of 5, 10, 20, and 40 years to investigate the persistence and temporal variability in potential effects and to explore possible time

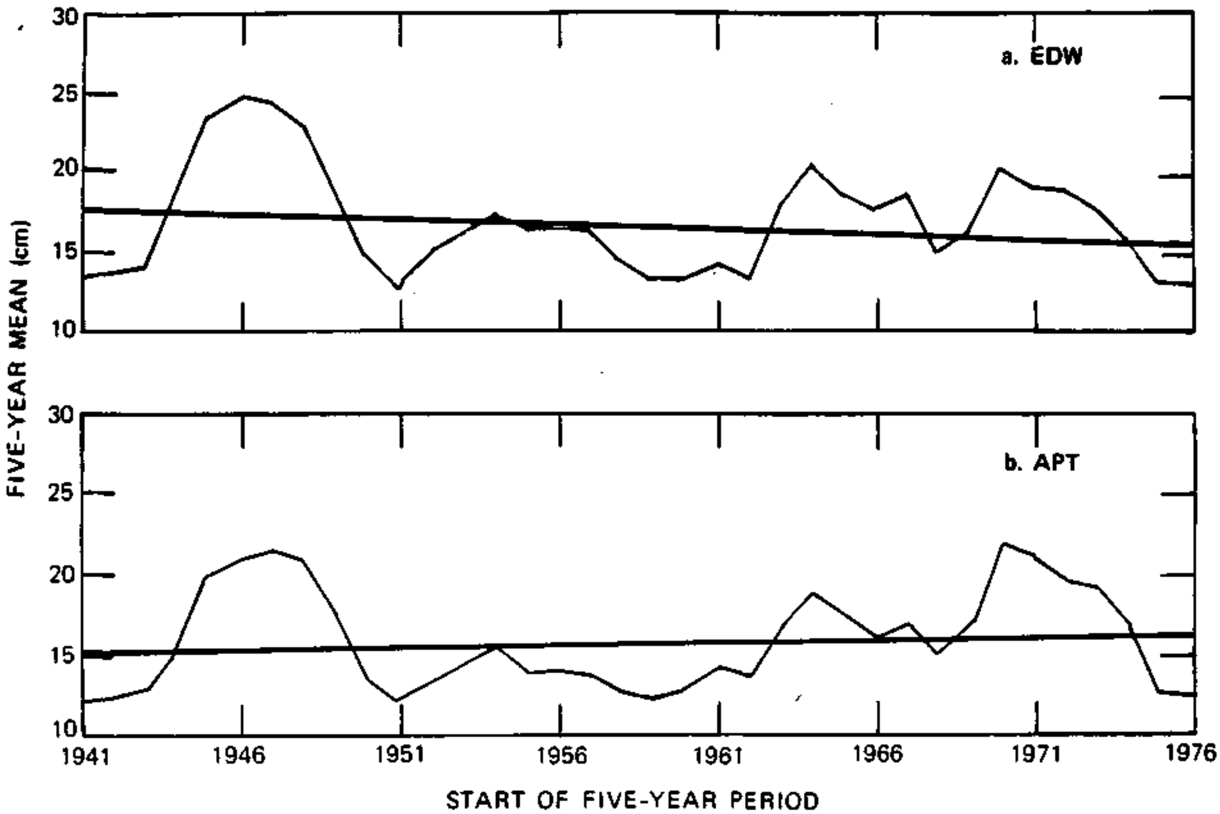


Figure 29. 1941-1980 Time Trend of Winter Precipitation at Key Stations.

Table 33. Seasonal Comparison of Effect/Control (E/C) Ratios During 1941-1980 for Selected Potential Urban Effect Locations and Upwind Control No. 1.

Effect Location	E/C for Given Season			
	Spring	Summer	Fall	Winter
EDW	1.14	1.11	1.07	1.05
COL	1.07	1.10	1.05	1.03
EDW & COL	1.10	1.10	1.06	1.04
Major Effect (NE)	1.07	1.07	1.03	1.03
Major Effect (SE)	1.03	1.04	1.04	1.03
Minor Effect (N)	1.02	1.02	0.98	1.00
Minor Effect (NE)	1.05	1.01	1.02	1.01
Minor Effect (SE)	1.00	1.00	1.02	1.00
Minor Effect (S)	1.00	1.02	1.05	0.99

trends in the precipitation distribution. For evaluating urban effects, the study area was divided into subareas hypothesized to be potentially major and minor effect areas. Several control areas were selected in regions that are seldom downwind of storms affecting metropolitan St. Louis and which are subjected to little or no topographic effects.

For the 40-year sampling period, 1941-1980, the spring precipitation distribution indicated the major urban effect was located in the Edwardsville (EDW) area, about 30 km NE of St. Louis, where the estimated urban effect was +14%. For the hypothesized major effect area lying E and NE of the city [Major Effect (NE)], the average urban-induced increase was 1%. A decrease from 11% to 5% was indicated in this area from the first to the second 20-year period, and this appears to have been related to natural variability in the temporal distribution, rather than a major change in the urban influence. Other hypothesized major and minor effect areas did not show this major change in the spring distribution. The effect/control ratio (E/C) exceeded 1.0 in six of eight 5-year periods in Major Effect (NE) using Upwind Control No. 1, and in all eight 5-year periods using the city as a control. This indicates strong persistence in this hypothesized region of major effect.

The summer data indicated an average 40-year increase of +7% in Major Effect (NE) and a maximum of +11% in the EDW area. Thus, spring and summer were in close agreement with respect to magnitude or urban-induced increases. However, the pronounced downward time trend found in the spring data did not occur in summer. A slight decrease from 1.09 to 1.06 occurred in E/C between the two 20-year periods in Major Effect (NE). No change occurred in Major Effect (SE) during the two periods. Actually trend analysis (Fig. 25) indicated reversal from a strong downward trend to a moderate upward trend in summer rainfall at EDW in the last 20 years. E/C exceeded 1.00 in six of eight 5-year periods at EDW, three of four 10-year periods, and both 20-year periods. Comparison of summer rainfall patterns for 1971-1975 derived separately from the climatic network and the dense METR0MEX raingage network showed that the climatic data network identified the approximate location of the downwind high (EDW area) and the approximate location of other highs and lows shown in the METR0MEX isohyetal analysis. However, the climatic network underestimated the magnitude of the urban effect (34% vs. 49%).

Fall analyses indicated that an urban effect, if present, is relatively weak and of about equal strength in the two hypothesized major effect areas of Fig. 5. For the 40 years, the E/C ratio was only 1.03 and 1.04, respectively, in Major Effect (NE) and Major Effect (SE). A substantial downward trend in precipitation, similar to spring, occurred over the 40-year period.

Similar to summer, winter did not show a substantial change in E/C between the two 20-year period. In Major Effect (NE) it varied from 1.04 to 1.03 between these two periods. E/C averaged 1.03 for 1941-1980 in both major effect areas. Thus, an urban-induced increase of small magnitude is indicated. Comparison of winter patterns from the climatic and METR0MEX networks for 1971-1975 showed an E/C of 1.09, based on climatic data, and 1.07 using the densely-gaged METR0MEX network for Major Effect (NE). This is even better agreement than obtained for summer, and is primarily due to the smaller spatial variability in winter precipitation.

D. RESULTS OF NOCTURNAL ANOMALY RESEARCH

Seasonal and Monthly Analyses

Analyses of seasonal and monthly rainfall data collected in the METROMEX Network during 1971-1975 provided strong evidence of a nocturnal anomaly in some subareas located in the N and NE regions of the densely-gaged network. An anomaly was identified in six subareas. These are EDW, GRC-EDW, ALN-WR Urban, ALN-WR Downwind, WR Refineries, and ALN-WR Bottomlands. Locations of these subareas and their description are provided in Fig. 1 and Table 1 of a previous section concerning the fall-winter-spring study. Except in the ALN-WR Bottomlands, the anomaly occurred in late evening and maximized at 2000-2300 or 2100-2400 CDT. The Bottomlands anomaly occurred at 1800-2100 CDT.

Results of the seasonal analyses are briefly summarized in Table 34 which shows the 3-hour period in which the anomaly maximized in each subarea, the subarea 5-year rainfall, the difference between subarea and network rainfall, the ratio of subarea to network rainfall, the ratio of subarea to upwind control rainfall (2 controls), and the average ratio of subarea to upwind control rainfall. In each case, the rainfall is the subarea and network average of total rainfall during the summers of 1971-1975. The network average is based on 225 gages in an area of 5200 km^2.

As shown in Table 34, the largest subarea-network differences and ratios occurred in the EDW area between 2100 and 2400 CDT. The ratios show that the subarea rainfall was 58% greater than the network average, 104% more than Upwind Control No. 1, 84% greater than Upwind Control No. 2, and 94% greater than the average of the two upwind control rainfalls. Upwind control #2 was selected especially for the nocturnal evaluation, since the anomalies occurred in the N and NE portions of the METROMEX Network. Upwind Control #2 is located in the NW quadrant of the network, lies to the SW, WSW, or W of the anomalous areas, is not exposed to any substantial topographic effects, and is seldom downwind of storms crossing the urban-industrial areas of STL or ALN-WR. It is considered a slightly more appropriate control for the nocturnal study than Upwind Control #1 lying W and SW of STL.

Figure 30 shows the total summer rainfall distribution for the 3-hour period, 2100-2400 CDT, during 1971-1975. The maximum exceeded 35 cm ENE of EDW and this was nearly double the network average of 18.3 cm. The EDW subarea (Fig. 30) averaged 58% more rainfall than the network in the 2100-2400 period. The maximum in the EDW area was more than four standard deviations greater than the network mean. The foregoing findings indicate a very substantial anomaly in the EDW vicinity, approximately 30-40 km NE of the STL urban center.

Table 34. Major 3-hour Nocturnal Anomalies Among Six Test Areas during Summers of 1971-1975.

Test Area	Time (CDT)	A(cm)	A-N(cm)	A/N	A/UC-1	A/UC-2	A/UC-Ave.
EDW	21-24	29.11	10.72	1.58	2.04	1.84	1.94
GRC-EDW	21-24	27.36	8.99	1.49	1.92	1.73	1.83
WR Refineries	20-23	28.96	8.89	1.44	1.92	1.61	1.71
ALN-WR Downwind	20-23	29.74	9.68	1.48	1.97	1.65	1.81
ALN-WR Urban	20-23	26.70	6.58	1.33	1.77	1.48	1.63
ALN-WR Bottomlands	18-21	26.52	8.81	1.50	2.16	1.70	1.93

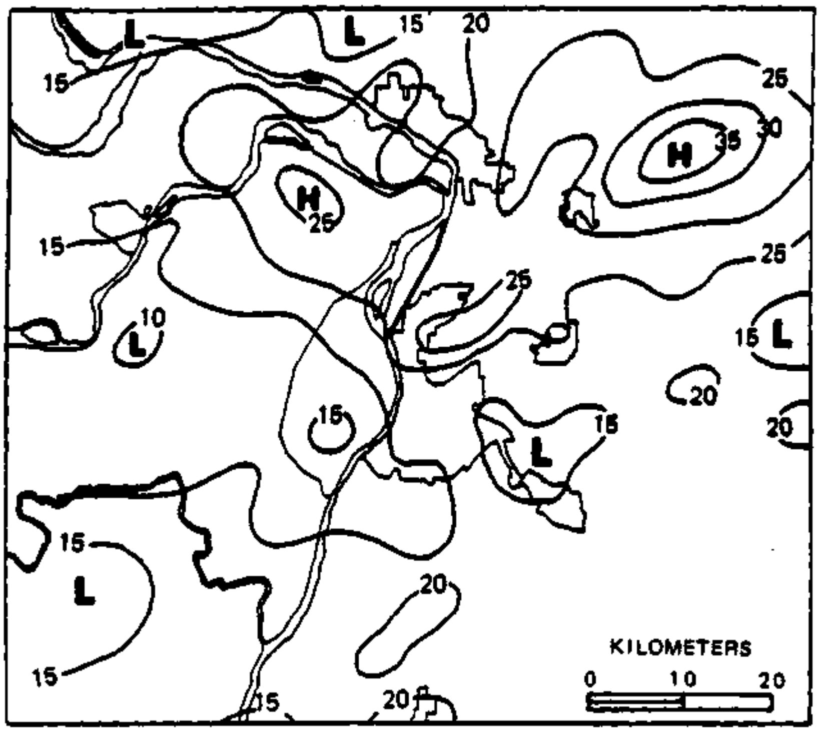


Figure 30. Total Summer Rainfall (cm) at 2100-2400 CDT During 1971-75.

In the earlier METROMEX research (Changnon _et al_., 1977), detailed analyses were made of the major diurnal maximum which occurs in mid- to late afternoon on the METROMEX Network. Analyses indicated a strong urban-induced increase in precipitation that maximized in the NE quadrant of the network in the EDW vicinity. The afternoon anomaly, related to diurnal heating mechanisms, occurred throughout the network, but maximized in the EDW area (NE quadrant of network), as a result of urban-induced effects superimposed on the natural diurnal heating effect. The late evening maximum in the diurnal distribution also represents a magnification of a natural climatic effect observed throughout the network and farther eastward in SW Illinois.

As part of the nocturnal study, analyses were made also of two minor diurnal peaks in the METROMEX diurnal distribution. One of these occurs in the early morning at 0100-0400 or 0200-0500 CDT. It is recognizable over most of the network and is most pronounced in the ALN-WR region (Urban, Downwind, and Bottomlands subareas). Otherwise, it is exceedingly weak and provides little evidence of urban involvement. Huff (1971) studied the diurnal distribution of rainfall at recording raingage stations in Illinois. The eastern part of the METROMEX Network lies in the "South Central Section" of Illinois, as defined by Huff. His study indicated a pronounced climatological maximum in this region at 0200-0500 during summer. This maximum is apparently related to the midwestern nocturnal thunderstorm mechanism which has been observed for many years. Therefore, it is concluded that the early morning METROMEX peak is climatically-related, and has no significant dependence on urban-induced atmospheric factors.

Similarly, a very weak peak in the diurnal distribution is recognizable in some portions of the METROMEX Network at 0500-0800 or 0600-0900 and is apparently a climatic anomaly. . In his 1977 study, Huff found this anomaly present at stations in southern Illinois, relatively close to the SE Hills-Bluffs subarea where the 0500-0800 peak was most pronounced in the METROMEX Network. The 0200-0500 anomaly was not found in the diurnal distribution for southern Illinois.

Over most of the network, the afternoon diurnal peak which occurs at 1400-1700 or 1500-1800 was the most pronounced. However, the late evening peak (2000-2300 or 2100-2400) was approximately equal in strength in the EDW and GRC-EDW subareas, and was more pronounced that 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, and may represent a delay in the afternoon maximum that could be related to storms developing over the Ozark Hills and river valleys to the SW during middle to late afternoon.

Table 35 shows a comparison of the 5-summer rainfall anomalies (diurnal peaks) among the METROMEX subareas experiencing the most pronounced 3-hour effects during 1971-1975. The upper portion of the table shows where the anomalies maximized and the magnitude of the peak values. Information is provided on the subarea 5-summer mean rainfall (A), the difference between the subarea and network means (A-N), and the ratio of

Table 35. Comparison of 5-Summer Rainfall Anomalies Among Subareas Experiencing Most Pronounced 3-Hour Effects during 1971-1975 on METROMEX Network.

Time (CDT)	A (cm)	A-N (cm)	A/N
	Location and Maximum 5-Summer Values		
1400-1700 1500-1800	EDW, 32.89	EDW, 11.81	EDW, 1.60
2000-2300 2100-2400	EDW, 29.72	EDW, 10.67	EDW, 1.58
0100-0400 0200-0500	ALN-WR B*, 17.78	ALN-WR B, 5.97	ALN-WR B, 1.51
0500-0800 0600-0900	SE Hills, 12.57	SE Hills, 1.02	SE Hills, 1.09
	Median Values of 5 Strongest Anomalies		
1400-1700 1500-1800	30.61	9.53	1.46
2000-2300 2100-2400	28.96	9.02	1.48
0100-0400 0200-0500	15.49	3.18	1.31
0500-0800 0600-0900	12.07	.0.51	1.04

*DW - downwind, B - bottomlands

the subarea to network mean rainfall (A/N). The lower portion of the table shows medians for the five subareas in which each anomaly was most pronounced.

As indicated in Table 35, the afternoon and evening anomalies both maximized in the EDW area, and were of approximately the same magnitude. The medians also indicate the two anomalies are of similar magnitude in the affected subareas. As shown by the A and A-N values, the morning climatic peaks were much smaller than the afternoon and evening peaks which are apparently affected by the urban environment.

Analyses of the frequency distribution of measurable rainfall showed diurnal distributions similar to those for total or mean rainfall. Over most of the network, the primary frequency peak occurred from 1500-1800. In the ALN-WR region, the primary peak was in late evening (2000-2300). A substantial peak in the frequency curves occurred from 0300-0600, and this was the second largest peak over the western half of the network (NW and SE quadrants). This region is in or near the eastern extremity of the nocturnal thunderstorm occurrences in the Midwest.

Persistence of Nocturnal Anomaly. An obvious question in evaluating the potential urban involvement in the anomalies is whether they are consistent from year-to-year, or whether they may have been produced by one or two years of unusually large differences. Table 36 shows the number of years in which A/N exceeded 1.00; that is, when the subarea mean exceeded the network mean. Values are shown for the primary and secondary nocturnal peaks in each test area, along with the range of ratios during the 5 summers. The ratios exceeded 1.00 all 5 years for the major peak (2100-2400) in the EDW and Granite City-Edwardsville (GRC-EDW) areas and in the Alton-Wood River (ALN-WR) Downwind area (2000-2300). The nocturnal anomaly persisted for 4 of the 5 years in the major peaks in the Wood River (WR) Refinery and ALN-WR Urban areas, and for the secondary peaks in the EDW and GRC-EDW areas. Thus, the nocturnal peaks at 2000-2300 and 2100-2400 show a strong degree of persistence especially in the NE quadrant of the METROMEX Network which frequently lies downwind of St. Louis and/or ALN-WR because most storms move out of the SW to W to NW.

Examination of the nocturnal data showed that rainfall in 1973 was much greater over the network, in general, than in any of the other four years. The A/N ratios were recalculated omitting 1973 to evaluate the effect of this abnormally heavy rainfall year. No consistent effect was found, since ratios for the peak period increased in three of the test areas and decreased in the other three, as shown in Table 37. The only major change was for the Bottomlands where the ratio decreased from 1.50 to 1.15. Furthermore, A exceeded N in only 3 of the 5 years. This raises some question regarding the veracity of this apparent anomaly.

Sample Size Affects. A further evaluation of the reality of the nocturnal anomalies was made by determining how A/N varied with increasing sample size. Table 38 shows how the ratios varied as the sample period was increased gradually from 1 to 5 years in each of the 3-hour peak periods. A/N exceeded 1.00 in all cases. The smallest ratio was 1.09 for the ALN-WR Bottomlands for the 1971-1972 period. This area also shows

Table 36. Year-To-Year Persistency of A/N.

Area	Time	Number of Years A/N > 1 .00	A/N Range
E D W	21-24	5	1.03-2.19
E D W	20-23	4	0.68-2.13
GRC-EDW	21-24	5	1.03-1.97
GRC-EDW	20-23	4	0.69-1.88
WR Refineries	20-23	4	0.94-2.51
ALN-WR Downwind	20-23	5	0.94-2.51
ALN-WR Urban	20-23	4	0.78-1.73
ALN-WR Bottomlands	18-21	3	0.76-2.21

Table 37. Ratio of Subareas for 1971-75 With and Without 1973 Data.

	1971-75	Omitting 1973
E D W	1.58	1.71
GRC-EDW	1.49	1.56
ALN-WR Downwind	1.48	1.36
ALN-WR Urban	1.33	1.22
ALN-WR Bottomlands	1.50	1.15
WR Refineries	1.44	1.50

Table 38. A/N Variation with Increasing Sample Size.

	EDW 21-24	GRC-EDW 20-23	ALN-WR Downwind 20-23	ALN-WR Urban 20-23	ALN-WR Refineries 20-23	ALN-WR Bottomlands 18-21
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

somewhat more of a random variation of ratios. Overall, the ratios indicate a decrease with increasing sampling period, but with little change from the 4-year (1971-74) to the 5-year (1971-75) ratios. The foregoing computations lend further support to the reality of the apparent anomalies.

Monthly Variations. The monthly differences between A and N were analyzed to determine whether the anomaly was produced largely in 1 to 2 months, or was rather uniformly distributed throughout the summer. In the earlier METROMEX research on total storm rainfall (Changnon et al., 1977), it was determined that the urban effect was greatest in the EDW and GRC-EDW area in June, and decreased gradually through July and August. In the ALN-WR area, the total rainfall anomaly was greatest in July.

Table 39 summarizes differences between A, N, and UC-2 among the three summer months in the 3-hour nocturnal anomalies. Thus at EDW, the major part of the test area deviation (A) from the network mean (N) occurred in the five Junes (71% to 77%), and there was no significant contribution in August. This same trend to a lesser degree is shown for GRC-EDW. Except for the Bottomlands, the major portion of the nocturnal anomaly occurred during the five Julys in the ALN-WR region. None of the test areas showed much of an August contribution, and, in several instances, N exceeded A in August. In general, the monthly trends found here agree with those obtained in the earlier total rainfall analyses.

Table 39 also shows similar statistics using UC-2 for assessing the anomaly effect. UC-2 may be a more representative "control", since it is located largely in the NW quadrant of the METROMEX Network, and the anomalies are located near the northern boundary and in the NE quadrant of the network. The UC-2 values lead to the same general conclusions as the A-N values.

Thus, the anomalies are primarily a June-July phenonema. Combining all six areas, the August A-N difference is only 2% and the A-UC differences average less than 8%. The anomaly is most pronounced in the region from GRC to EDW in June, and in the ALN-WR region in July. No reason for this monthly variation can be identified.

Storm Rainfall Analyses. A major analysis has involved the deviation of test-area storm mean rainfall from the network mean during each 3-hour anomaly. These deviations represent the rainfall excess or deficiency in each storm. The deviations in each selected area and 3-hour period are then ranked. The ranked positive deviations determine those storms which are primarily responsible for the nocturnal anomaly in each test area.

Table 40 illustrates further how a few storms were largely responsible for the nocturnal anomalies. In this table, the distribution of the positive deviations from the network mean are shown for each area and each 3-hour anomaly. For example, in the EDW area, the sum of all positive deviations for 2100-2400 was 17.1 cm (6.75) inches. Of this, 15.9 cm (6.25 in.) or 93% of the total occurred in those storms having the 10 largest positive deviations. There were a total of 39 storms with measurable rainfall in this test area, and 23 storms (59%) had positive

Table 39. Monthly Comparisons of Differences Between Subarea (A), Network (N), and Upwind Control (UC-2) Means for 3-Hour Anomaly Periods During 1971-1975.

Area (A)	3-Hr Period	Percent of Total A-N June	July	August	Percent of Total A-UC 2 June	July	August
EDW	21-24	71	25	4	69	27	4
EDW	20-23	77	26	-3	65	34	1
GRC-EDW	21-24	59	30	11	58	32	10
GRC-EDW	20-23	66	33	1	55	40	5
ALN-WR Downwind	20-23	13	76	11	13	75	12
ALN-WR Downwind	19-22	40	44	16	39	46	15
ALN-WR Urban	20-23	29	74	-3	25	73	2
ALN-WR Urban	18-21	32	69	-1	21	65	14
WR Refineries	20-23	42	69	-11	49	58	-7
ALN-WR Bottomlands	18-21	50	40	10	38	43	19

Table 40. Distributions of Positive Deviations in 1971-75 Nocturnal Storm Periods.

	Time (CDT)	3-Hr* Dev. (cm)		Positive Deviation Rank 1	2	3	4	5	10	Total Positive Cases	Total Number Storms
EDW	21-24	17.1	A**	4.2	6.6	8.4	9.8	11.1	15.9	23	39
			P**	25	39	49	57	65	93		
GRC-EDW	21-24	12.5	A	2.8	4.7	6.0	7.0	7.9	11.0	28	41
			P	23	37	48	56	63	88		
EDW	20-23	13.6	A	4.0	6.2	7.8	8.8	9.7	12.7	24	41
			P	30	46	57	65	71	93		
GRC-EDW	20-23	11.0	A	2.6	4.4	5.7	6.6	7.3	10.0	26	45
			P	24	40	52	59	66	91		
ALN-WR Downwind	20-23	13.8	A	2.6	4.2	5.4	6.6	7.8	12.3	23	37
			P	19	30	39	48	56	89		
ALN-WR Urban	20-23	10.2	A	2.6	4.3	5.7	6.7	7.2	9.2	21	36
			P	25	42	56	66	71	91		
WR Refineries	20-23	15.2	A	3.4	5.4	6.6	7.8	8.8	12.4	23	38
			P	22	36	44	51	58	82		
ALN-WR Downwind	19-22	11.3	A	2.2	3.8	5.2	6.2	7.2	9.8	31	45
			P	20	34	46	55	64	87		
ALN-WR Bottomlands	18-21	14.3	A	2.6	4.6	6.2	7.3	8.2	11.6	28	47
			P	19	33	44	51	57	81		
ALN-WR Urban	18-21	12.1	A	3.2	4.4	5.6	6.6	7.5	10.2	28	47
			P	27	37	46	54	62	84		

* Sum of all Positive Deviation for subarea mean (A) minus network mean (N) for 3-hour storm period.

** A = Cumulative difference of A-N, P = Cumulative percent of total positive deviations.

deviations from the network mean. Overall, approximately 60% of the test area storms had positive deviations, but this varied from 58% to 69% among the various combinations of area and time periods.

Many of the storms among the top 10 contributors qualified in several areas and/or 3-hour anomaly periods. For example, the 10 storms for 2100-2400 were the same in both the Edwardsville and the Granite City-Edwardsville areas which overlap. Overall, 27 storms accounted for all of the top 10 selections among the 6 areas and four 3-hour time periods.

Antecedent Rainfall. The 10 storms with the maximum positive deviations were analyzed to determine the length of the rainfall period preceding the 3-hour anomaly in each area and time period. Antecedent periods ranged from 0 (started during 3-hour anomaly period) to 9 hours among individual storms. Medians and ranges are shown for the various areas and times in Table 41. Thus, in the EDW area at 2100-2400, the median antecedent rainfall period was 3 hours and the range was 0 to 6 hours. For the ALN-WR Bottomlands at 1800-2100, the median was 5 hours with a range of 1 to 7 hours. Median values for the late evening anomalies were 2-3 hours with a variation among storms mostly from 0 to 6 hours. Less than 10% of the various storm combinations (area-time groups in Table 41) had antecedent rainfall exceeding 6 hours.

Storm Movement Analyses. In the comprehensive study of summer rainfall distribution on the METROMEX Network during 1971-1975, Vogel and Huff (1978) found that storms moving from the WSW were a strong contributor to the urban rainfall anomaly that maximizes 30-40 km NE of central St. Louis in the Edwardsville area. These storms accounted for 23% of the 330 storms studied, but produced 42% of the network rainfall. In the nocturnal study, analyses were made to determine the relationship between storm movement and the strong rainfall anomalies occurring between 1800 and 2400 CDT.

The strongest nocturnal anomaly occurred in the EDW area where the 5-year total rainfall anomaly was identified in the earlier METROMEX research. The EDW nocturnal anomaly maximized in the 2100-2400 period, but was of nearly equivalent strength from 2000 to 2300 CDT. Analyses of storm movements showed an even stronger influence of storms moving from the WSW than observed for all summer storms combined during 1971-1975.

Table 42 shows the distribution of rainfall according to storm movement for the EDW area during 2000-2300 and 2100-2400 CDT. In both periods, storms moving from the WSW accounted for over 50% of the total rainfall. Storms moving from the WSW, SW, and WNW are most likely to have crossed the urban-industrial regions of St. Louis or Alton-Wood River, which is located N of St. Louis and WNW of the EDW area. These three storm movements (Table 42) accounted for 93% of the rainfall in the EDW area during 2000-2300 and 83% of it from 2100-2400 CDT.

With regard to frequency of storm movements, 32% of the storms moved from WSW at 2000-2300 and 33% at 2100-2400. Thus, movements from the WSW to ENE were most frequent, but the dominance was not as pronounced as with the total rainfall percentages. The frequency-intensity statistics show

Table 41. Length of Rain Period Prior to Start of 3-Hour Anomaly Period in 10 Storms Contributing Most to Subarea Anomalies.

Area	Time (CDT)	Median (Hours)	Range (Hours)
EDW	21-24	3	0-6
GRC-EDW	21-24	3	0-7
EDW	20-23	3	0-6
GRC-EDW	20-23	3	1-6
WR Refineries	20-23	3	0-6
ALN-WR Downwind	20-23	2	0-6
ALN-WR Downwind	19-22	2	0-5
ALN-WR Urban	20-23	3	0-7
ALN-WR Bottomlands	18-21	5	1-7

Table 42. Rainfall Distribution Grouped by Storm Movement in EDW Area During 3-Hour Anomaly Periods, 1971-75.

Storm Movement	Percent of Total Rainfall		Percent of Occurrences	
	2000-2300 CDT	2100-2400 CDT	2000-2300 CDT	2100-2400 CDT
NW-SE	6	16	19	20
WNW-ESE	18	14	22	22
WSW-ENE	55	50	32	33
SW-NE	20	19	20	18
SSW-NNE	1	1	7	7

that storms moving from the WSW were larger rainfall producers, on the average, than those moving from the other directions. Thus, for 2000-2300 the average 3-hour rainfall in storms moving from the WSW was 12.4 mm (0.49 inch), compared to 7.4 mm (0.29 inch) for SW-NE storms, and 5.8 mm (0.23 inch) for WNW-ESE storms. For 2100-2400, the average amounts were 10.2, 10.2, and 4.6 mm for WSW-ENE, SW-NE, and WNW-ESE storms, respectively.

Table 43 further defines the association between storm movement and the nocturnal anomalies. This table shows the distribution of storm movements in the 10 largest contributors to the 3-hour anomalies. These were the 10 storms having the largest positive departures from the network mean for each given subarea and 3-hour period. As shown in Table 43, approximately 2/3 of the storm movements were from the SW or WSW when all areas and time periods are combined. Except for ALN-WR Downwind at 1900-2200 and WR Refineries, storm movements from the SW and WSW dominated the distributions. As indicated earlier, these storms would have exposure to the urban area of St. Louis before reaching the EDW and GRC-EDW areas. They would also traverse ALN-WR Urban before reaching ALN-WR Downwind which had a pronounced anomaly from 2000-2300.

Thus, the same storm movements were largely responsible for the total rainfall anomalies determined in the original METR0MEX research (Changnon et al., 1977) and the nocturnal 3-hour anomalies investigated in the present research. These dominant storm movements would be conducive to urban-induced increases in rainfall, since the urban areas of St. Louis and/or Alton-Wood River would be upwind of the areas where the total rainfall and nocturnal anomalies were found. The present findings lend credence to the possibility that the nocturnal anomalies are related to urban-induced influences *on* the development and/or intensification of convective storm systems in summer. The storm movement findings are considered only one piece of evidence, but a very important one, in determining whether the nocturnal anomalies are urban-related.

Figure 31 shows the total rainfall pattern of WSW storms for 2100-2400 during the summers of 1971-1975 when a strong anomaly existed in the EDW area. A total of 14 storms contributed to the WSW pattern. The high exceeded 17.5 cm (ENE of EDW) which is over 3 times the network mean of 5.7 cm. The EDW subarea average was approximately 2.5 times the network average, and the EDW maximum exceeded three standard deviations of the network mean. As shown in Table 42, storms moving from the WSW accounted for 50% of the 5-summer total rainfall for 2100-2400 CDT.

Figure 32 shows the total rainfall pattern for 2100-2400 in storms moving from WSW or SW. This includes 19 storms which accounted for 69% of the total 3-hour rainfall in the 5-summer period. The heaviest rainfall occurred in the same area as the total rainfall maximum (Fig. 30) and the WSW storm maximum (Fig. 31). Amounts in the rainfall center ENE of EDW exceeded 27 cm which is nearly four times the network mean of 7.3 cm. The EDW subarea average as 19.3 cm, approximately 2.6 times the network mean. Amounts in the center of the EDW anomaly exceeded three standard deviations of the network mean.

Table 43. Distribution of Storm Movements in 10 Largest Storm Contributors to the 3-Hour Nocturnal Anomalies.

Test Area	Time (CDT)	SSW	SW	WSW	WNW	NW
EDW	21-24		5	3	1	1
GRC-EDW	21-24		5	3	1	1
EDW	20-23		2.5	4.5	2	1
GRC-EDW	20-23		2.5	4.5	2	1
WR Refineries	20-23		2	3	3	2
ALN-WR Downwind	20-23		5	2	1	2
AL-WR Downwind	19-22		3	1	4	2
ALN-WR Urban	20-23	0.5	3	3.5	1	2
ALN-WR Urban	18-21	1	3	5	1	
ALN-WR Bottomlands	18-21	2	4	2	2	
Percent of Total Cases		3.5	35.0	31.5	18.0	12.0

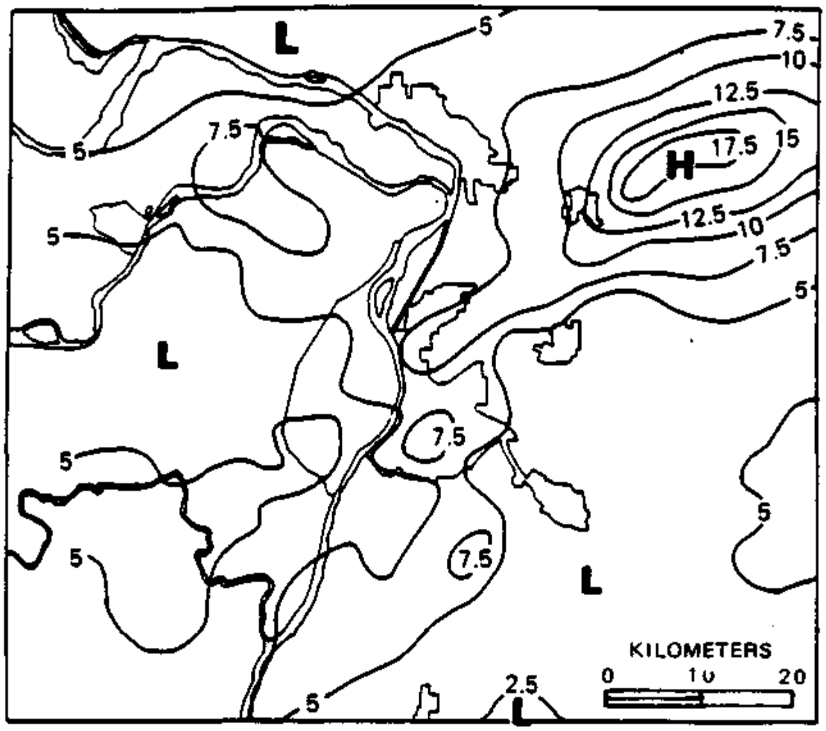


Figure 31. Total Summer Rainfall (cm) in Storms Moving from WSW at 2100-2400 CDT During 1971-75.

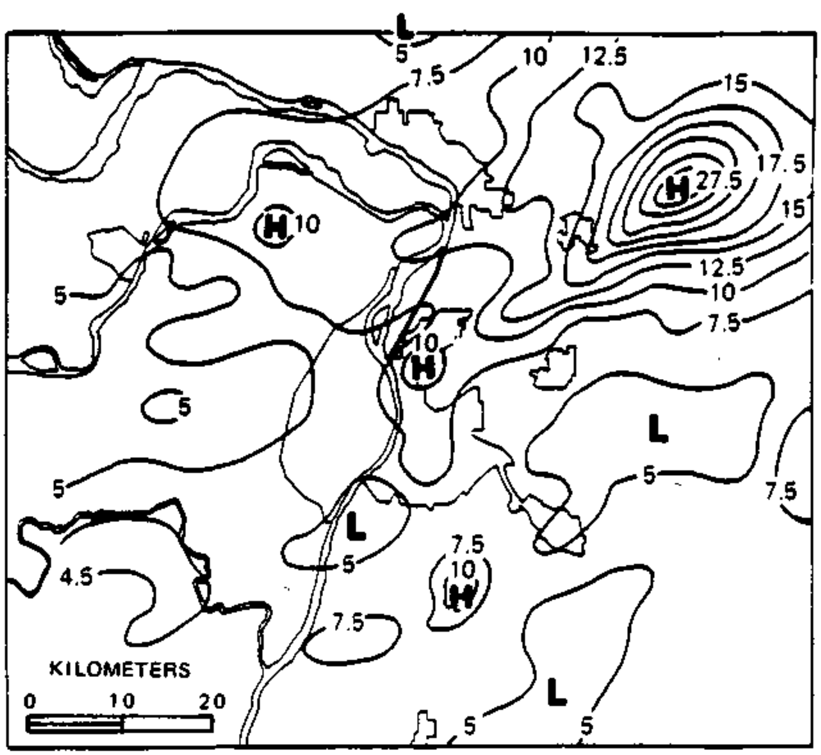


Figure 32. Total Summer Rainfall (cm) in Storms Moving from the WSW and SW at 2100-2400 CDT During 1971-75.

Figures 31 and 32, along with Tables 42 and 43 provide evidence of an urban effect involved in the EDW anomaly. The anomaly was produced largely in storms moving from the SW and WSW, and these would frequently traverse the STL urban-industrial areas 30-40 km upwind of the anomaly. That is, the urban-industrial area is located in a favorable position for development and/or intensification of convective entities, which would later cross the EDW region.

Synoptic Storm Analyses. Storms associated with the 3-hour anomalies were classified according to synoptic storm type. The same classification was used in the earlier METROMEX research on total storm rainfall (Changnon et al., 1977). In that research, it was determined that the urban effect was most commonly associated with organized convective activity, such as squall lines and cold fronts (Vogel and Huff, 1978).

Initially, the synoptic types were determined for the 10 storms with the greatest positive deviations in each subarea and for each 3-hour anomaly. As shown in Table 40, these accounted for over 80% of the total positive deviations in all storms.

In all areas, these major contributors to the nocturnal anomalies were most often squall lines and squall areas, as shown in Table 44. Thus, the largest 10 positive deviations in storms in the EDW area during the 2100-2400 anomaly were associated with 4 squall lines, 3 squall areas, a cold front, a stationary front, and a warm front. Similarly, the strong 2000-2300 anomaly in the ALN-WR Downwind area had 5 squall lines and 2 squall areas among the 10 largest contributors to the anomaly. Overall, squall lines and squall areas accounted for 82% of the cases among the various 3-hour anomalies shown in Table 44. In the earlier METROMEX research on total storm rainfall, it was found that about 76% of the network summer rainfall occurred with squall lines and squall areas. Thus, these two storm types are the most prolific rain producers in summer in the St. Louis region.

Analyses of the synoptic storm types in all storms involved in the 3-hour anomalies in each subarea of the network was then undertaken. Three analyses were performed for each anomaly in each subarea. These included grouping of those storms in which the subarea had positive deviations from the network mean, those in which negative deviations occurred, and all storms combined.

Combining all storms involved in the 3-hour anomalies, it was found that a total of 88% of the storms were associated with squall lines, squall areas, and cold fronts. Of the 88%, 35% were squall lines, 36% were squall areas, and 17% were cold fronts. The only other synoptic type of significance was stationary fronts which accounted for 1% of the storms associated with the various anomalies. Thus, organized convective systems, exemplified by these storm types, were responsible for producing the 3~hour nocturnal anomalies. This agrees with findings for the afternoon anomalies and total rainfall anomalies in the original METROMEX research. Among the various combinations of 3-hour periods and subareas, positive deviations occurred in 60% of the storms, on the average, with a range from 58% t0 69%. Thus, a majority of the storms were contributing to the 3-hour anomalies.

Table 44. Synoptic Storm Type Associated with 10 Largest Storm Contributors to the 3-Hour Nocturnal Anomalies.

Test Area	Time (CDT)	Cold Front	Squall Line	Squall Area	Static Front	Warm Front	Air Mass
EDW	21-24	1	5	3	1		
GRC-EDW	21-24	1	4	3	1	1	
EDW	20-23		7.5	2.5			
GRC-EDW	20-23		7.5	2.5			
WR Refineries	20-23		6	3	1		
ALN-WR Downwind	19-22	3	4	3			
ALN-WR Downwind	20-23	1	5	2	2		
ALN-WR Urban	20-23	2	5.5	1.5	1		
ALN-WR Urban	18-21	0.5	7	2	0.5		
ALN-WR Bottomlands	18-21	1	8				1
Percent of Total Cases		9.5	59.5	22.5	6.5	1	1

Analyses were made also of the percent of the total rainfall produced by the various storm types. Results for each of the 3-hour anomaly periods are summarized in Table 45, in which average values are shown for the number of subareas involved. Thus, the percentages for 2100-2400 are an average for the EDW and GRC-EDW areas, both of which experienced pronounced anomalies in this period. Table 45 indicates that squall lines were the largest producer of rainfall in all 3-hour periods. Squall areas ranked second in the late evening anomalies and cold fronts in the early evening anomalies.

For comparison purposes, percentages are shown for the 225-gage network in Table 46. Median values compare closely with those for the anomaly subareas. The major difference is for 1800-2100 in which squall lines dominated the distribution to a greater degree in the anomaly areas.

Other analyses showed that squall lines contributed more to the anomalies, on the average, than the other two major contributors, squall areas and cold fronts. Combining all 10 combinations of time and location, A-N had an average of 5.28 cm (2.08 in.) for squall lines, 2.95 cm (1.16 in.) for squall areas, and 1.32 cm (0.52 in.) for cold fronts. However, the greatest percentage difference occurred with squall areas for which the average A/N was 1.87 compared with 1.54 for squall lines, and 1.41 for cold fronts.

Table 47 shows the network-subarea relations for each of the 10 anomalies investigated. In each case, A was greater than N for squall lines and squall areas. However, for the 2000-2300 period in the GRC-EDW and EDW areas the network total rainfall with cold fronts was greater than in the anomaly areas. The cold front contribution was most pronounced in the 1900-2200 period in ALN-WR downwind.

Figures 33 and 34 illustrate typical distribution patterns of network rainfall and the ratio of gage to network mean rainfall. These illustrations are for 2100-2400 and include storms which were involved in establishing the 3-hour anomaly in the EDW area which is outlined on the maps. The maps are for squall-line and squall-area precipitation which were the largest contributors to the 2100-2400 anomaly.

Network mean rainfall was 10.13 cm (3.99 in.), compared with 13.89 cm (5.47 in.) in the EDW subarea during squall-line precipitation. The average ratio of subarea to network mean rainfall was 1.37; that is, the anomaly area experienced 37% more rainfall than the network average in squall lines during the summers of 1971-1975. The isohyetal map of squall-line rainfall (Fig. 33) shows relatively heavy rainfall throughout the EDW area and extending SW toward St. Louis. The EDW rainfall center is located in the same general area as those for total rainfall (Fig. 30), and storms moving from the SW and WSW.

The squall-area map (Fig. 34) indicates relatively heavy rainfall extending across the northern part of the METROMEX Network, but heaviest in the EDW area. Mean rainfall was 9.73 cm (3.83 in.) in the EDW subarea compared with 3.91 cm (1.54 in.) for the network, which results in a ratio of 2.49, or a 149% greater rainfall in the anomaly area than on the

3-hour period (CDT)	Number of areas involved	Subarea Percent of Total Rainfall for Given Storm Type			
		Squall line	Squall area	Cold front	Static front
2100-2400	2	50	32	10	3
2000-2300	5	53	24	16	4
1900-2200	1	50	13	36	0
1800-2100	2	70	12	16	0
Median		52	19	26	2

Table 46. Percent of Total Network Rainfall Associated with Major Synoptic Storm Types During 1971-1975.

3-hour period (CDT)	Percent for Given Storm Type			
	Squall line	Squall area	Cold front	Static front
2100-2400	59	23	9	5
2000-2300	56	12	18	2
1900-2200	50	13	36	0
1800-2100	54	14	32	0
Median	55	18	25	2

Table 47. Relations Between Synoptic Storm Type and 3-Hour Nocturnal Anomalies in Each Time Period and Subarea, 1971-1975

Synoptic type	Number of cases	Subarea (A) total (cm)	Network (N) total (cm)	A-N	A/N
		EDW, 2100-2400			
Squall Area	12	9.7	3.9	5.8	2.49
Squall Line	14	13.9	10.1	3.8	1.38
Cold Front	6	2.7	1.6	1.1	1.69
		GRC-EDW, 2100-2400			
Squall Area	14	8.9	4.0	4.9	2.22
Squall Line	14	13.4	10.1	3.3	1.33
Cold Front	6	2.6	1.6	0.9	1.62
		EDW, 2000-2300			
Squall Area	14	9.1	4.3	4.8	2.12
Squall Line	16	16.9	10.6	6.3	1.59
Cold Front	7	2.8	3.5	-0.6	0.80
		GRC-EDW, 2000-2300			
Squall Area	16	7.6	4.4	3.2	1.73
Squall Line	15	16.0	10.5	5.4	1.52
Cold Front	7	3.1	3.5	-0.3	0.89
		WR Refineries, 2000-2300			
Squall Area	12	9.0	2.9	6.0	3.10
Squall Line	14	15.8	10.4	5.4	1.52
Cold Front	7	4.5	3.5	1.1	1.29
		ALN-WR Urban, 2000-2300			
Squall Area	13	5.7	4.2	1.5	1.37
Squall Line	14	13.5	10.4	3.0	1.30
Cold Front	5	6.5	3.4	3.1	1.91
		ALN-WR Downwind, 2000-2300			
Squall Area	13	5.2	4.0	1.2	1.30
Squall Line	12	15.0	10.2	4.8	1.48
Cold Front	7	6.7	3.5	3.3	1.91

Table 47. Continued.

Synoptic type	Number of cases	Subarea (A) total (cm)	Network (N) total (cm)	A-N	A/N
		ALN-WR Downwind, 1900-2200			
Squall Area	18	3.0	2.0	1.0	1.50
Squall Line	16	12.0	8.0	4.0	1.50
Cold Front	9	8.7	4.9	3.9	1.78
		ALN-WR Urban, 1800-2100			
Squall Area	18	2.9	1.9	1.0	1.53
Squall Line	16	16.8	8.7	8.1	1.93
Cold Front	9	3.7	3.6	0.1	1.03
		ALN-WR Bottomlands, 1800-2100			
Squall Area	17	2.8	2.1	0.6	1.33
Squall Line	16	17.8	9.0	8.9	1.98
Cold Front	4	4.4	3.5	0.8	1.26

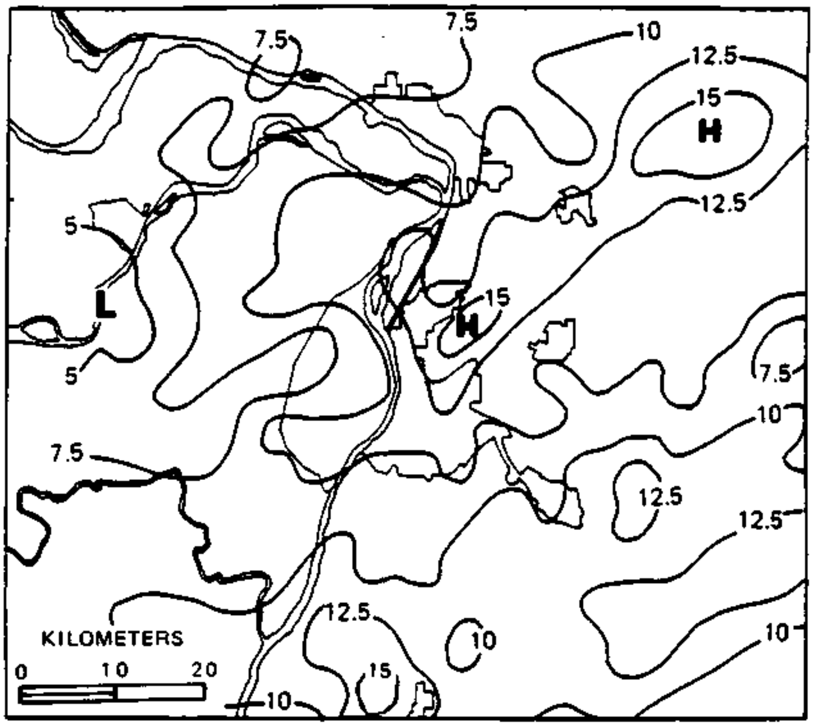


Figure 33. Total Summer Rainfall (cm) in Squall-Line Storms at 2100-2400 CDT During 1971-75.

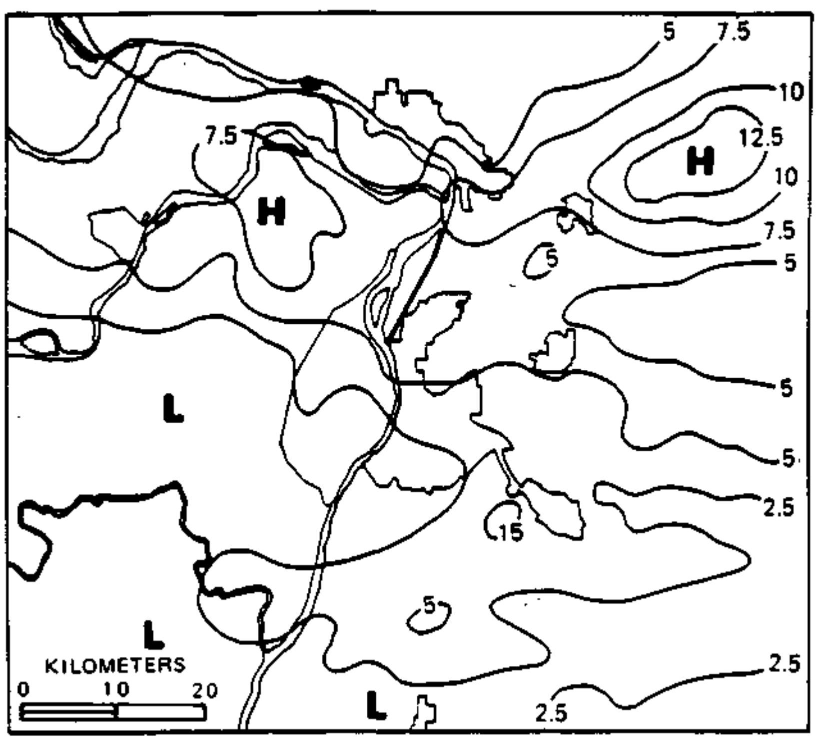


Figure 34. Total Summer Rainfall (cm) in Squall-Area Storms at 2100-2400 CDT During 1971-75.

225-gage network. Thus, both the squall-line and squall-area patterns indicate a strong 3-hour anomaly in the EDW area from 2100 to 2400 CDT. The rainfall centers corresponds closely with those in Figs. 30-32.

Figure 35 shows the isohyetal map for 2100-2400 CDT in the storm of 16 June 1975. This storm was the largest contributor to the EDW and GRC-EDW anomalies for 2100-2400 CDT. Most of the storm rainfall occurred from 2000-2400. This storm was also the largest contributor to the 2000-2300 anomaly in WR Refineries, EDW, GRC-EDW, and ranked second in ALN-WR Urban. The storm consisted of squall areas moving across the network. Predominant motion of these storm elements was from the WSW, and secondly from the SW and WNW. At 2100-2400, the EDW mean was 5.10 cm, compared with 0.83 cm for the network. Similarly, the GRC-EDW mean was 3.66 cm. Raincell analyses indicated that many of the heavy cells contributing to the heavy amounts in the EDW and GRC-EDW areas developed in the industrial regions of GRC and ALN-WR. This agrees with findings of a radar study of raincell initiations in earlier METROMEX research (Huff, 1978). The radar study indicated a maximum frequency of network raincell initiations just south of Wood River where oil refineries and other industries are located. Another region of above average frequency was identified in the St. Louis urban-industrial region extending northward from East St. Louis to Granite City.

Comparison of Synoptic Storm Types Associated with Nocturnal Anomalies and Total Storm Rainfall

A comparison of the frequency distribution of storms by synoptic type is shown in Table 48. Several major differences are apparent. Squall lines and squall areas were the major type associated with the nocturnal anomalies, whereas air mass storms were most frequent when all summer storms during 1971-75 are considered (Changnon et al., 1977). Squall lines accounted for 35% of the nocturnal storms compared with 15% for all storms. Air mass storms were of little consequence in the establishment of the nocturnal anomalies, accounting for only 3% of the storm occurrences compared with 27% when all times of the day are involved. The three major types of organized convection (squall lines, squall areas, and cold frontal) were associated with 88% of the nocturnal storms, compared with 54% for all storms combined.

Table 49 shows how the total rainfall was distributed during the nocturnal storm periods and in all storms combined during the summers of 1971-75. The largest difference in rainfall production was with cold fronts which accounted for 26% of the total rainfall during the 3-hour nocturnal periods compared with 12% for all storms combined. The three major storm types (squall lines, squall areas, and cold fronts) accounted for 97% of the total rainfall in the nocturnal storm periods and 88% of that for all storms combined.

Overall, the nocturnal anomalies were even more strongly related to organized convection than the general summer rainfall distribution during 1971-75. In both distributions, squall lines were the most prolific rain producer, accounting for over 50% of the total rainfall. Cold fronts were

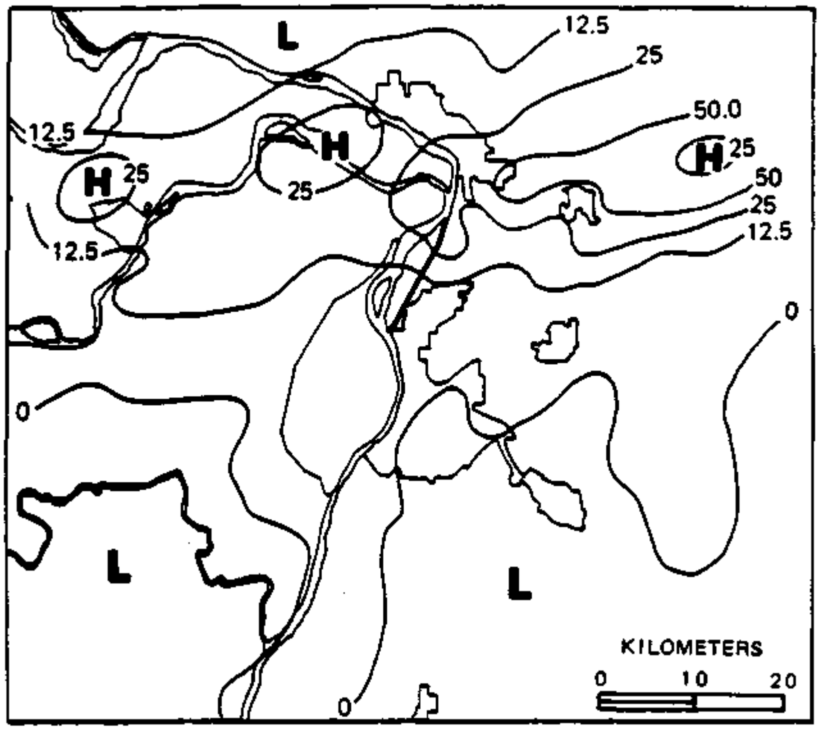


Figure 35. Network Rainfall Distribution (mm) at 2100-2400 CDT in Storm of June 16 1975.

Table 48. Frequency Distribution of Synoptic Storm Types During 1971-75 in all Summer Storms Combined and in the 3-Hour Nocturnal Anomalies.

	Percent of Occurrences	
Synoptic Type	All Storms	Nocturnal Storms
Squall Lines	15	35
Squall Areas	25	36
Cold Fronts	14	17
Static Fronts	6	7
Warm Fronts	4	2
Air Mass Storms	27	3
Others	9	0

Table 49. Percent of Total Rainfall Associated with Various Synoptic Storm Types in all Summer Storms and in 3-Hour Nocturnal Anomalies.

Synoptic Type	All Storms	Nocturnal Storms
Squall Lines	51	52
Squall Areas	25	19
Cold Fronts	12	26
Static Fronts	7	2
Warm Fronts	2	<1
Air Mass Storms	2	<1
Others	1	0

a stronger influence in the nocturnal storm periods than in all storms combined. Air mass storms were of little consequence as a rain producer in both distributions, but did occur frequently during the afternoon as indicated by their 27% frequency among all storms combined.

Squall lines and cold fronts accounted for 78% of the total rainfall associated with the nocturnal anomalies (Table 49). Table 39 (discussed previously) shows that over 95% of the anomaly in the EDW area occurred in June and July. In all areas, over 80% of the nocturnal anomaly resulted from June-July storms. Therefore, it was decided to investigate whether squall lines and cold fronts had a tendency to occur with greater frequency in the METROMEX Network during the evening hours in June and July than during other periods of the day. If so, this would help explain the existence of the nocturnal anomalies.

From synoptic weather and radar data, the time of squall line and cold frontal passages at St. Louis was tabulated. The number of passages were grouped by 3-hour and 6-hour periods. Fronts which produced no rainfall as they crossed the network were omitted from the statistical computations. If the squall line and frontal passages were evenly distributed throughout the day, 12.5% would occur in each 3 hours and 25% in each 6 hours.

Analyses showed that 50% of the rain-producing cold fronts occurred from 1800 to 2400 CDT during June-July, 1971-1975. Squall lines had 41% of their diurnal occurrences in this 6-hour period. When grouped by 3-hour periods, 29% of the cold fronts and squall lines passed St. Louis between 1800 and 2100, compared with an expectancy of 12.5 if no diurnal trend was present. From 2100 to 2400, 17% of the total number occurred; 13% were recorded in the 1500-1800 period; and, only 8% from 1200 to 1500.

Thus, the above statistics indicate a relatively strong peak in the diurnal distribution of cold fronts and squall lines at 1800-2100. This would be in the early portion of the ALN-WR anomalies (1900-2200, 2000-2300), and just prior (0 to 3 hours) to the EDW and GRC-EDW anomalies. The sequences of storm system passages and occurrences of rainfall anomalies is logical. The NWS first-order station (STL Airport) is located about 20 km NW of the central city, and systems moving from SW-W-NW would pass this point before reaching the ALN-WR and EDW areas. Thus, the foregoing analysis provides evidence that the nocturnal anomalies in the N and NE portions of the METROMEX Network may be partially explained by the above average frequency of storm system passages across the urban area during the evening hours.

Nocturnal Raincell Analyses

One of several approaches that was used successfully in the original METROMEX research to help understand and evaluate urban-industrial effects on precipitation was the analyses of surface raincells. The underlying assumption is that urban-induced changes in precipitating clouds that are generated over urban-industrial areas or cross these areas are reflected in the distribution characteristics of surface raincells produced by the urban-exposed clouds. Therefore, raincell analyses were employed in studying the nocturnal anomalies within limitations imposed by the financial constraints of the project.

Surface raincell analyses were performed in 13 storms which were the largest contributors to the several nocturnal anomalies. The contribution of a storm was determined from calculation of the deviation of subarea mean rainfall (A) from the network mean rainfall (N). Thus, the 13 storms were those in which the deviations (A-N) were among the largest for one or more subareas for one or more of the 3-hour anomaly periods. Most of these storms qualified as outstanding contributors in several time periods and/or subareas. For example, the storm of 16 June 1975 ranked first among all 1971-75 storms in producing the 2000-2400 anomalies in the EDW and GRC-EDW subareas. It also ranked first for 2000-2300 in the WR refinery area, and second in the ALN-WR urban and ALN-WR downwind areas. It ranked sixth among all storms in producing a 1900-2200 anomaly in the ALN-WR downwind area. Thus, this storm was a major contributor to the anomalies observed in 5 subareas and 3 time periods. Its isohyetal pattern for 2100-2400 is shown in Fig. 35.

Following the procedures established in the earlier METROMEX research (Changnon et al., 1977), raincells were determined from 5-minute 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; that is, it defines an area of significantly greater intensity than the system enveloping isohyet, and must last for more than 5 minutes to qualify as a cell. In the nocturnal study, major emphasis were placed upon those cells which developed or passed over the urban-industrial areas of St. Louis or Alton-Wood River and affected one or more of the anomalous subareas.

For each cell, the following parameters were determined: time and place (gage) where the cell was first observed (initiated), duration, direction and speed of movement, path length, duration, mean rainfall, cell area, cell water yield (volume), maximum point rainfall and its location, time and location of any cell mergers or splits, plus any pertinent comments about the cell's behavior. From the 13 storms, 450 surface raincells were identified. Of these 236 (52%) met the qualifying criteria of exposure to one of the urban-industrial areas and/or contributing to the 3-hour rainfall in one or more of the anomalous subareas.

Figure 36 shows the total raincell rainfall produced by urban-related cells in 9 storms which maximized in late evening (2000-2300, 2100-2400). The 15-cm isohyet outlines the area most affected by these cells. The area of maximum effect includes most of the EDW and WR Refineries and portions of GRC-EDW and ALN-WR Downwind. As indicated several times previously, this is a region that frequently lies downwind of the urban-industrial areas. The rainfall west of STL and ALN-WR (Fig. 36) is associated with cells that developed upwind of the potential effect areas, but later crossed STL or the ALN-WR area and proceeded downwind as an active rain producer.

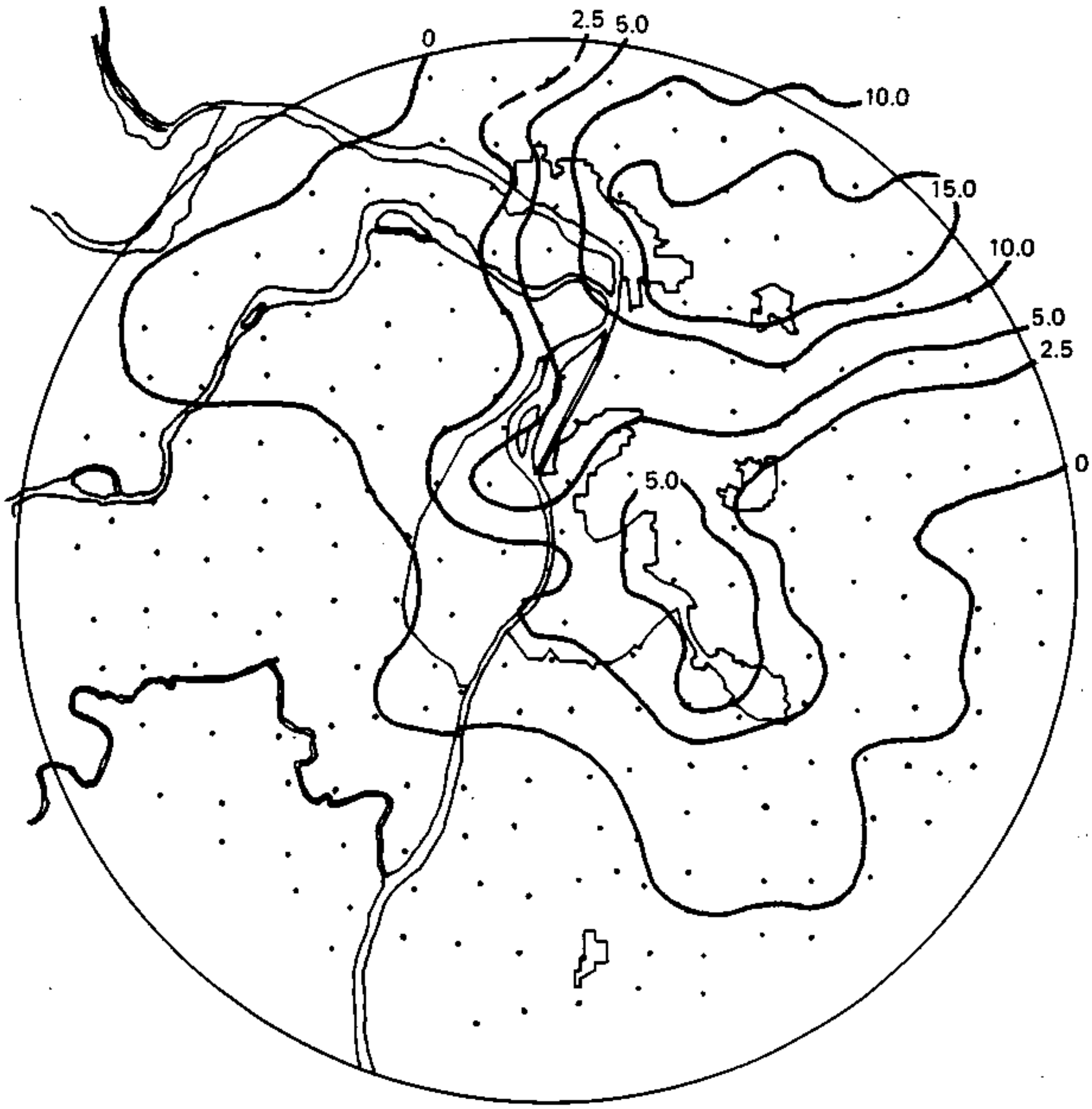


Figure 36. Urban-Related Raincell Rainfall, 9 Storms, 2000-2400 CDT.

In the EDW area, 77% of the total raincell rainfall during 2000-2400 (Fig. 30) 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. Much of the urban-effect rainfall was associated with cell mergers. In EDW, 46% of the total raincell rainfall of 16.94 cm was produced by merged cells. Similarly, 43% of the GRC-EDW cell rainfall occurred in merged cells. However, only 12% of the cells contributing to the rainfall in Fig. 37 were merged cells. Among merged cells, 90% occurred when one or more of the merging cells had been urban-exposed. Thus, the urban cells have a much greater tendency to merge than rural cells, and account for a disproportionate amount of the rainfall in the urban-effect subareas of the METROMEX Network. This is related to tendency for new cells to develop over and/or immediately downwind of the urban-industrial areas, and accelerated areal growth of existing cells exposed to the urban environment.

Table 50 summarizes the relationship between urban and rural cells for four major properties. The 13 storms were divided into two groups, those maximizing from 2000-2300 and 2100-2400 (2000-2400 CDT), and those peaking at 1800-2100 or 1900-2200 (1800-2200 CDT). 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 cells. Volume averaged 38% greater in the urban cells in late evening and 15% more in the earlier group. Combining all storms, the urban cell volume averaged 31% (1.31) more than the rural cells.

Overall, Table 50 indicates that the most pronounced urban effect is reflected in raincell areal growth, and secondly, from increased duration of cell rainfall. Rainfall intensity did not appear to be affected in the 13 selected storms, since mean rainfall (product of intensity x duration) did not change significantly in the 1800-2400 period.

Figure 37 shows the frequency distribution of raincell initiations in the 13 selected storms. The greatest frequency was along a line extending SSW from NE of ALN-WR to GRC and STL Industrial-East. If the STL and ALN-WR urban-industrial regions are influencing the development of rain-cells, the maximum frequency is in the expected location since storms move predominately from WSW to WNW in the METROMEX Network.

Table 51 provides another measure of the urban-industrial influence on raincell initiation. In this table, ratios of the average frequency of cell initiations in selected subareas to the frequency in an upwind control area (Fig. 37) are shown. The largest ratios ($\geqq$ 2.00) occurred in subareas in and immediately downwind of the urban-industrial areas as implied in Fig. 37. These ratios indicate that increases of 100% or more in cell initiations were produced in the potential urban-effect areas. A rapid decrease occurred in the ratio a few kilometers east of STL in the BLV-COL subarea. Average frequency in COL-BLV and STL ED was similar to that in the upwind control.

The preceding analyses indicate the nocturnal subarea anomalies are related both to stimulation of ongoing storm entities and the development of new raincells by effects from the urban-industrial complex extending from STL to ALN-WR. The first analysis indicated that urban-exposed cells

Table 50. Comparison of Urban (U) and Rural (R) Raincell Characteristics in 13 Selected Storms.

Raincell Characteristic	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

Table 51. Effect of Urban-Industrial Environment on Raincell Development at 1800-2400 CDT.

Subarea	NW Upwind Control
EDW	1.36
GRC-EDW	1.32
WR Refineries	2.00
ALN-WR Urban	2.48
ALN-WR Downwind	2.20
ALN-WR Bottomlands	1.28
STL Urban	0.88
STL Ind.-East	1.72
Granite City	2.00
COL-BLV	0.80

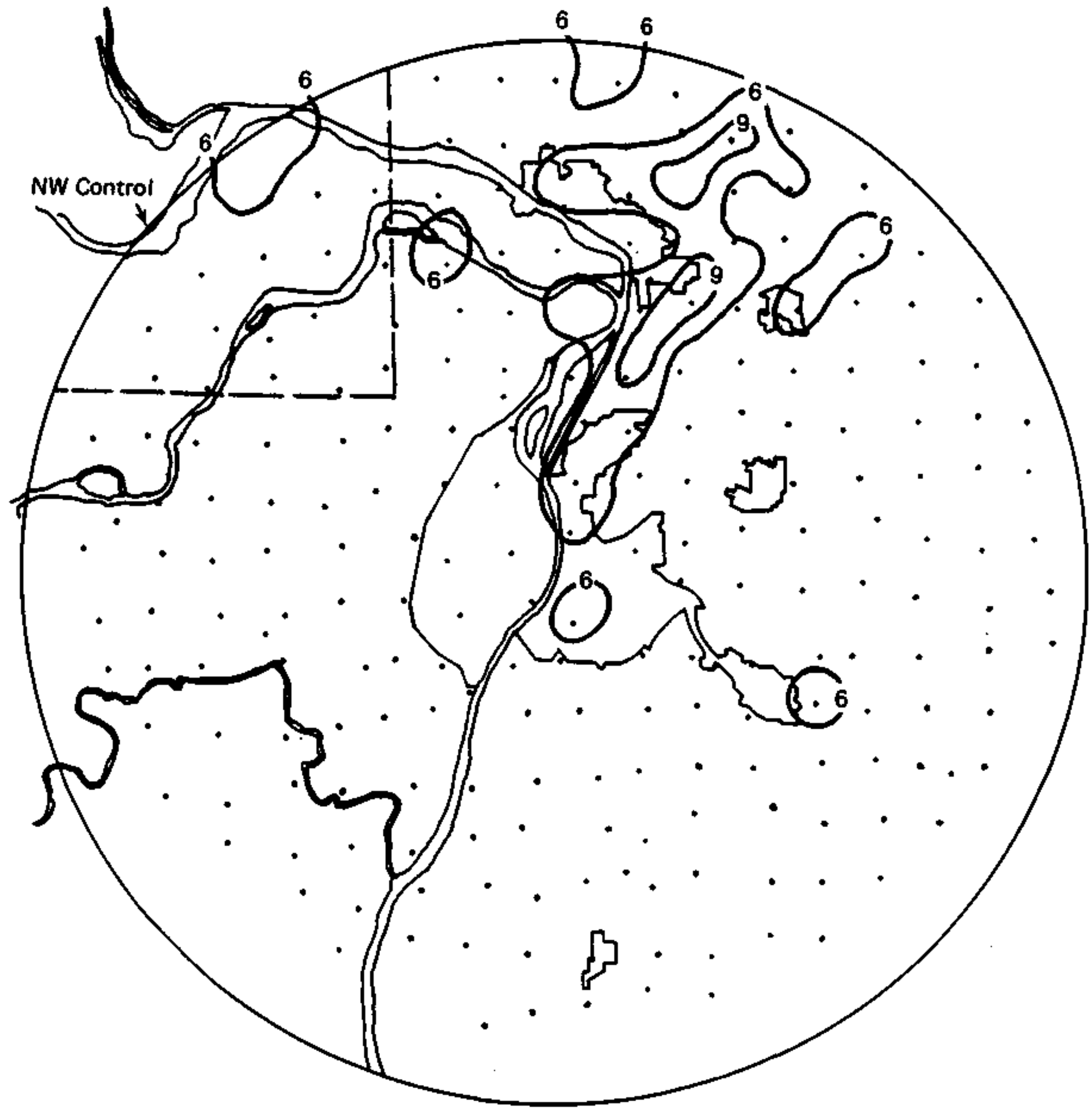


Figure 37. Frequency of Surface Raincell Initiations, 13 Storms.

have larger areas and last longer than rural cells, on the average. The cell 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.

Summary and Conclusions

The nocturnal anomaly on the METROMEX Network maximized at 2100-2400 CDT in the EDW area, approximately 30-40 km NE of the STL urban-industrial region. This was the same area in which the urban-related maximum of total summer rainfall and the afternoon diurnal maximum were identified in the original METROMEX research (Changnon et al., 1977). The EDW nocturnal maximum was of approximately the same magnitude as the afternoon anomaly in this area. Thus, the nocturnal maximum was 58% greater than the network mean, compared with 60% greater in the afternoon maximum, and approximately 25% greater than the total rainfall (all hours combined) anomaly. Ratios of EDW/Upwind Control rainfall were 1.84, 1.71, and 1.49, respectively, for the EDW nocturnal, afternoon, and total rainfall maxima.

The nocturnal anomaly was also pronounced in several other subareas in the N and NE part of the network. These included those in the ALN-WR region (urban and downwind areas) and GRC-EDW. The anomaly maximized at 2000-2300 in the ALN-WR region and at 2100-2400 in the NE part of the network. A pronounced peak occurred in early evening (1800-2100) in the ALN-WR Bottomlands, and may represent a delay in the afternoon maximum resulting from storms generated over the Ozark Hills and river valleys to W and SW during middle to late afternoon.

Climatic-related peaks in the diurnal distribution occurred during four periods of the day. Among the various METROMEX subareas, these included 0100-0400 or 0200-0500, 0500-0800 or 0600-0900, 1400-1700 or 1500-1800, and 2000-2300 or 2100-2400. The early morning and early forenoon peaks were weak, not discernible in some subareas, and provided no evidence of a significant input from the urban environment. Reference to a climatic study of the diurnal distribution of summer rainfall in south central and southern Illinois, which incorporates areas NE, E, and SE of the METROMEX Network, also indicated early morning and early forenoon peaks in the diurnal distribution of recording raingage stations (Huff, 1971). These are apparently caused by the nocturnal thunderstorm phenomena which encompasses much of the Midwest.

The afternoon and evening anomalies were pronounced in some subareas and identifiable throughout the network. The afternoon anomaly was most pronounced in the NE quadrant of the network in subareas which frequently are downwind of storms crossing the STL urban-industrial area and/or the ALN-WR industrial region. The nocturnal anomaly peaked in the N and NE parts of the network in subareas which were in the ALN-WR industrial region or frequently downwind of the STL and ALN-WR industrial regions. The primary peak in the diurnal distribution occurred over most of the network in the afternoon. The nocturnal and afternoon peaks were equivalent in parts of the NE quadrant of the network, and the nocturnal peak was the greatest in ALN-WR Urban and ALN-WR Downwind.

The afternoon and nocturnal peaks apparently incorporate local effects superimposed on the climatic factor. As shown in the original METROMEX research, the superimposed factor is primarily urban-induced increases in the natural rainfall distribution, plus (to a much smaller extent) topographic intensification in some areas of the METROMEX Network, such as the SE Hills-Bluffs and the SW Hills. The topographic factor has little or no influence on rainfall in the EDW area where the afternoon and nocturnal anomalies were the greatest.

The nocturnal anomalies in the N and NE parts of the network showed a strong degree of persistency throughout the 5-summer sampling period. For example, the EDW mean rainfall at 2100-2400 CDT exceeded the network mean during all five summers. Subarea means exceeded the network mean in either 4 or 5 summers among the other late evening anomalies.

The EDW anomaly was strongest in June. Of the 5-summer total rainfall difference between EDW and the network, 69% of the difference occurred in the five Junes compared with 27% in July and only 4% in August. The pronounced June maximum at 2100-2400 agrees with the findings for total summer rainfall in the earlier METROMEX research (Huff and Vogel, 1978). The anomaly was also strongest in June for GRC-EDW and in July for ALN-WR Urban, ALN-WR Downwind, and WR Refineries. Most of the anomaly was produced in June and July in all of the above subareas. This also agrees with the earlier findings for total summer rainfall.

Storm rainfall analyses showed that a relatively few storms were responsible for the nocturnal anomalies. In the EDW area, 10 of the 39 storms with measurable rainfall produced 93% of the total positive deviations (subarea - network mean rainfall). However, 59% of the storms had positive deviations and, therefore, contributed some to the EDW anomaly. Combining all subareas showing a pronounced nocturnal anomaly, approximately 60% of the storms contributed to the anomalies.

Antecedent rainfall was studied to ascertain whether there was a tendency for the nocturnal anomalies to be associated with long-duration storms which would produce a saturated surface prior to the nocturnal storm period. Results indicated a median of 2-3 hours for all the late evening anomalies. The range of antecedent rainfall durations among all storms was 0-7 hours. Thus, the tendency was for the anomalies to be associated with storms starting in late afternoon or early evening.

Analyses of storm movements showed that rainfall in the late evening anomalies occurred most frequently with storms moving from the WSW, followed by those moving from the SW and WNW. These three storm movements accounted for 93% of the total rainfall in the EDW area for 2000-2300 and 83% for 2100-2400. Storms moving from these directions are most likely to have crossed the urban-industrial regions of STL or ALN-WR. Among the 10 storms that were the largest contributor to the EDW anomaly, 5 moved from the SW, 3 from WSW, 1 from WNW, and 1 from NW. Thus, 9 of the 10 had movements favorable for interactions with the urban-industrial environment. Combining all affected subareas, 85% of the storms that were the largest contributors to the nocturnal anomalies moved from the SW, WSW, or WNW.

Synoptic analyses indicated that the late evening anomalies were associated with organized convective activity. Of the 10 largest contributors to the EDW anomaly at 2100-2400, 5 occurred with squall lines, 3 with squall areas, 1 with a cold front, and 1 with a warm front. Combining all subareas involved in the late evening anomalies, 82% occurred in conjunction with squall lines and squall areas. In the earlier METROMEX research on total summer rainfall, 76% of the precipitation was associated with squall lines and squall areas. Thus, these two storm types are the most prolific rain producers in summer in the STL region. Storms associated with these synoptic types are most likely to move from the SW, WSW, and WNW; that is, from the directions most conducive to integration of urban effects into the rainfall distribution. Squall lines were the largest producer of rainfall in all 3-hour anomaly periods. For all subareas combined, they accounted for over 50% of the total 3-hour rainfalls.

Other analyses indicated that a peak in the diurnal distribution of squall line and cold front passages occurs in the STL urban area in the 1800-2100 period. These are the two synoptic types largely associated with the nocturnal anomalies occurring between 1800 and 2400. The time distribution of the storm system passages and the nocturnal anomalies in the N and NE parts of the network provides a logical sequence of events, and suggests a link between the above average frequency of storm system passages in early evening and the strong nocturnal anomalies occurring from middle to late evening.

Raincell analyses in 13 storms that were major contributors to the nocturnal anomalies indicated that most of the cells in these storms moved from directions (SW, WSW, WNW) that are favorable for urban involvement before reaching the anomalous subareas. The raincell analyses provided strong evidence that initiation and/or stimulation of ongoing storm entities and development of new cells took place in the urban-industrial complex extending from STL to ALN-WR. This agrees with findings in the earlier METROMEX research that indicated these two processes were responsible for the afternoon diurnal peak in the NE quadrant of the raingage network and the total rainfall anomaly that maximized in the EDW area.

E. A SATELLITE-BASED STUDY OF THE ST. LOUIS AREA UNDER SNOW-COVERED CONDITIONS

Introduction

In the wake of the Metropolitan Meteorological Experiment (METROMEX, Changnon et al., 1981), it is natural to ask what urban effects might be observed in other seasons. Given that the collection of very high resolution data as in METROMEX is expensive, it is logical to ask what contribution meteorological satellites might make in this effort.

A review of the literature reveals that several studies of urban effects using satellite data have been undertaken: most used 10.5 to 12.5 μm infrared (IR) satellite measurements, most concentrated on the heat island effect, and most studied the Summer season. Rao (1972) first noted that the New York-Washington urban corridor could be detected with 7.4 km resolution IR data on 19 October 1970 from the Improved TIROS Operational Satellite (IT0S-1). Carlson et al. (1977) used 1 km resolution IR data from the N0AA-3 satellite to map surface temperature distribution over the Los Angeles area on 29 March 1975. Matson et al. (1978) located 50 heat islands in the Midwest and Northeast using 1 km resolution IR data from the NOAA-5 satellite on 28 July 1977. Maximum urban-rural temperature differences ranged from 2.6 to 6.5 K. Price (1979) used 0.5 km resolution IR data from the Heat Capacity Mapping Mission (HCMM) satellite (see the HCMM User's Guide, 1978) to estimate urban-rural ground temperature differences in New England near 1330 LT on 6 June 1978. HCMM was placed in a special orbit designed to observe near the times of maximum and minimum temperatures. As a result large urban-rural temperature differences were found: 17 K between New York City and the surrounding country. Carlson et al. (1981) used HCMM IR data in a boundary layer model to calculate surface energy balance, moisture availability, and thermal inertia in Los Angeles on 30-31 May 1978 and in St. Louis on 9-10 June 1978. They found a marked reduction of evaporation and moisture availability and. a corresponding increase of sensible heat flux over urban areas. They also found little difference in thermal inertia between urban and rural areas. Vukovich (1983) used both IR and visible (0.5-1.1 μm) data from the HCMM satellite to study the St. Louis area for six time periods in 1978: four during Summer, one during Winter, and one during Fall. He found daytime urban-rural temperature differences ranging from 2.4 K in the winter to 6.5 K in the summer and urban-rural reflectivity differences of -2 to -4% (urban areas darker).

The current study serves as a companion to the above studies. It differs in two respects. First, it is a case study of St. Louis during Winter when snow was on the ground, and second, it uses satellite data in five spectral intervals rather than one or two.

AVHRR Data and Data Processing

Instrument Description. The NOAA-7 satellite was launched on 23 June 1981 into a near-polar, sun-synchronous orbit with an altitude of approximately 850 km and equator crossing times near 0230 and 1430 LT. One of the instruments on board the satellite is the Advanced Very High Resolution Radiometer (AVHRR) which scans the earth from 55.4° right to 55.4° left of the subsatellite track in 2048 steps each 167 ms. The instantaneous field of view of each sensor is about 1.3 mrad (Schwalb, 1978), which results in a 1.1 km resolution at the subsatellite point.

The relative frequency response of the five AVHRR sensors is shown in Fig. 38. The AVHRR is similar to the Very High Resolution Radiometers (VHRR) carried on the NOAA-2 through -5 satellites, except that the VHRR had only two channels, one similar to AVHRR channel 1 and the other similar to a combination of AVHRR channels 4 and 5. NOAA-7 was the first satellite to carry the full complement of AVHRR sensors. The TIR0S-N and N0AA-6 satellites which preceded NOAA-7 did not have channel 5.

The infrared channels (3-5) are calibrated in flight using space and the instrument housing as temperature references. The noise equivalent temperature difference (NETD) is designed to be about 0.12 K for a 300 K scene (Schwalb, 1978). At other temperatures, however, NETD is different because of its dependence on the Planck function. At 250 K, which serves as a minimum temperature for the scenes we will examine, NETD is about 0.2 K for channels 4 and 5 and about 1 K for channel 3. The visible and near infrared channels (channels 1 and 2) are not calibrated in flight. The pre-launch calibration is specified to have at least a 3:1 signal to noise ratio at 0.5% reflectance[1] (Schwalb, 1978).

Data Conversion. Data for two consecutive passes of the satellite near St. Louis on 18 December 1981 at 0851 and 2017 GMT were obtained from the Satellite Data Services Division of the National Climatic Data Center[2]. The data are in the form of 10 bit (0-1023) digital counts which were converted to reflectances (channels 1 and 2) or radiances (channels 3, 4, and 5) using slope and intercept parameters supplied with the data. The reflectances were then converted to albedos by dividing by the cosine of the solar zenith angle (also supplied with the data). The radiances were converted to equivalent blackbody temperatures (T_{BB}) using the Planck function. The central wave numbers employed in this conversion were 2670.3, 926.8, and 840.5 cm^{-1} for channels 3, 4, and 5, respectively (Kidwell, 1983). The T_{BB}s were discretized in 0.5 K steps and the albedos were discretized in 1% steps for display and analysis.

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[1] Reflectance refers to the ratio of the radiometer-measured radiance of a scene to the radiance that would be recorded if the radiometer were pointed at a perfectly-reflecting Lambertian surface oriented perpendicular to the sun's rays. Albedo refers to reflectance divided by the cosine of the solar zenith angle of the scene. Albedo is a property only of the surface being viewed and the viewing geometry, whereas reflectance is also a function of the solar zenith angle.

[2] World Weather Building, Washington, D.C. 20233.

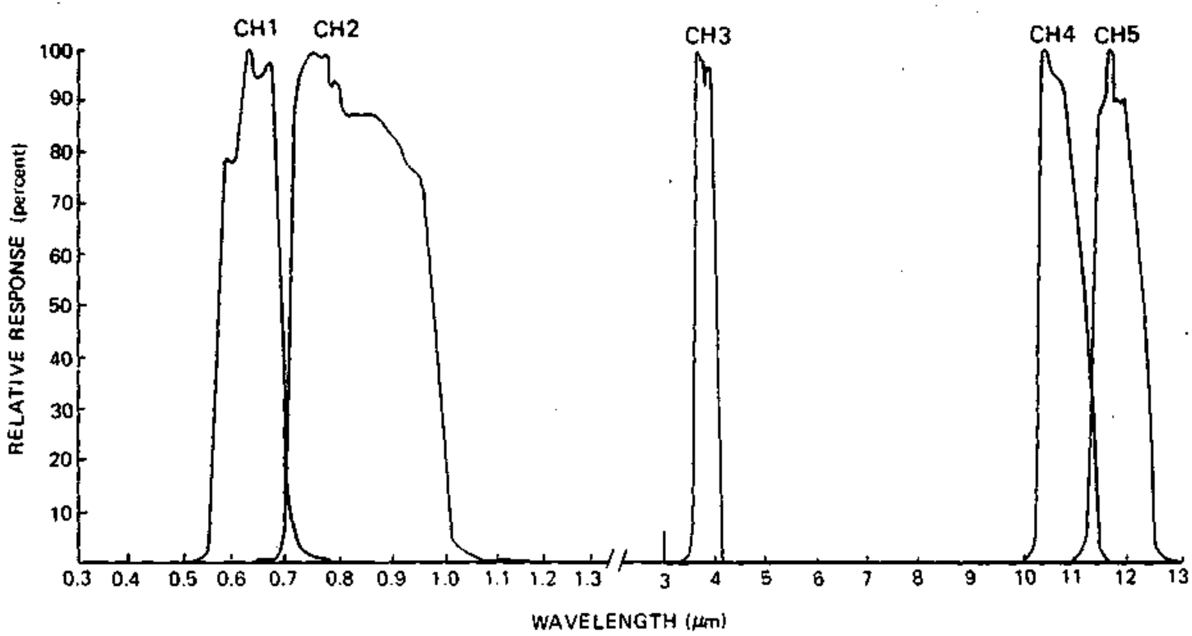

Figure 38. Relative Frequency Response of the AVHRR Sensors. (Adapted from Kidwell, 1983).

<u>Data Mapping</u>. Due to the varying geometry on the two passes, the data were remapped onto an azimuthal equidistant analysis map with a radius of 75 km centered on the St. Louis Gateway Arch (38.617°N, 90.183°W) by a process similar to that of Vukovich (1983). A transformation between points in the satellite image, specified by scan line L and element E, and points in the analysis map, specified by their Cartesian coordinates X and Y, is necessary. A linear transformation is desirable because it is simple and computationally fast. However, the satellite image is inherently nonlinear due to foreshortening as the radiometer scans away from nadir. To correct this problem, a new element number E' was calculated using the following formulas:

$$\alpha = \delta\,(1024.5 - E), \qquad (1a)$$

$$E' = R_e\,\{\sin^{-1}[(1+h/R_e)\,\sin\alpha] - \alpha\} \qquad (1b)$$

where R_e is the earth's radius, h is the height of the satellite (850 km), and 6 is the scan angle increment between elements (0.945 mrad). E' is approximately the distance from the subsatellite point in kilometers; it is positive if E is 1024 or less (right of track) and negative otherwise. Since the transformation does not depend on latitude or longitude, a lookup table can be constructed to eliminate repeated trigonometric calculations.

Latitudes and longitudes of selected points on each scan line are included in the data tapes. For 25 of these points in the analysis map area, the latitude and longitude were converted to (X,Y) by the map projection equations. The line and element (L,E) were converted to (L,E') by eq. (1). Two matrices were constructed:

$$U = \begin{pmatrix} X_1 & Y_1 & 1 \\ X_2 & Y_2 & 1 \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ X_{25} & Y_{25} & 1 \end{pmatrix}, \quad V = \begin{pmatrix} L_1 & E'_1 & 1 \\ L_2 & E'_2 & 1 \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ L_{25} & E'_{25} & 1 \end{pmatrix} \qquad (2)$$

The least squares best solution for the matrix A which transforms (X,Y) to (L,E') was then calculated as

$$A = (U^T U)^{-1}\, U^T V \qquad (3)$$

To fill the analysis map (512 x 512 pixels), the vector (X,Y,1) for each pixel was postmultiplied by A to produce the vector (L.E',1):

$$(L,\ E',\ 1) = (X,\ Y,\ 1)\ A \qquad (4)$$

The element number E was then calculated using the inverse of eq. (1). The value in the satellite image at point (L,E) was assigned to the analysis map at point (X,Y).

Because the navigation data (latitudes and longitudes) are not perfectly accurate, the analyzed images were not centered on St. Louis. The images were therefore shifted to center St. Louis. The daytime images were shifted 4.7 km west and 11.2 km south, while the nighttime images were shifted 6.3 km east and 2.3 km south. By comparing landmarks (lakes and rivers) in the images and on U.S. Geological Survey maps, final position errors of the analyzed maps were estimated to be less than 1.5 km.

The choice of 75 km as the distance from St. Louis to the edge of the image necessitated repeating pixels 10 to 12 times, which resulted in a "jagged" appearance. To alleviate this problem, a 3 x 3 point binomial smoother was applied to each image.

Description of the Study Area. St. Louis lies in a large, flat floodplain formed by the Missouri and Mississippi Rivers. Figure 39 shows the important lakes, rivers, and topography in the study area. The circle (radius 43 km) is the research circle used in METROMEX. Figure 40 shows the major urban areas and parks in the study area. These features will be further discussed in section 4.

On 17 December 1981, one day before the satellite passes, a surface low pressure system crossed southern Missouri and southern Illinois leaving a band of snow across the central plains (Fig. 41). It was the first snow of the winter in St. Louis. By 18 December the low pressure area had moved off the East Coast and had been replaced with a broad high pressure area (Fig. 42). Table 52 shows that on 18 December skies were clear, temperatures were cold, and dewpoints were low in St. Louis. The cold temperatures suggest that little of the snow could have melted. At Lambert Field the snow depth was 3 inches on 18 December. Figure 43 shows the 1200 GMT 18 December sounding from Salem, Illinois, (about 100 km east of St. Louis). An intense surface inversion, which is to be expected under high pressure and light winds, were present. The precipitable water at Salem was about 3 mm.

Results

Albedos. The albedo distribution from AVHRR channel 1 at 2017 GMT on 18 December 1981 is shown in Fig. 44. The image is contoured in 8% albedo steps. The most striking features of this image, and indeed of most of the images, are the rivers: the Mississippi, Missouri, and Illinois. Comparison of Fig. 44 and Fig. 39 reveals that other river systems can be observed in the image, especially the Kaskaskia River. Many of these rivers are too small to be observed directly by AVHRR, but the surrounding vegetation that protrudes through the snow causes a lowering of the albedo. Several small lakes, including Horseshoe Lake, Litchfield Lake, Coffeen Lake, Baldwin Reservoir, and a portion of Lake Carlyle can also be seen. Comparison of Fig. 44 and Fig. 40 shows that all the major urban areas near St. Louis can be observed in the albedo pattern as low albedo regions. This is probably due to a combination of vegetation, which distinguishes an urban area from the surrounding farmland (vegetation-free at this time of the year), and snow removal.

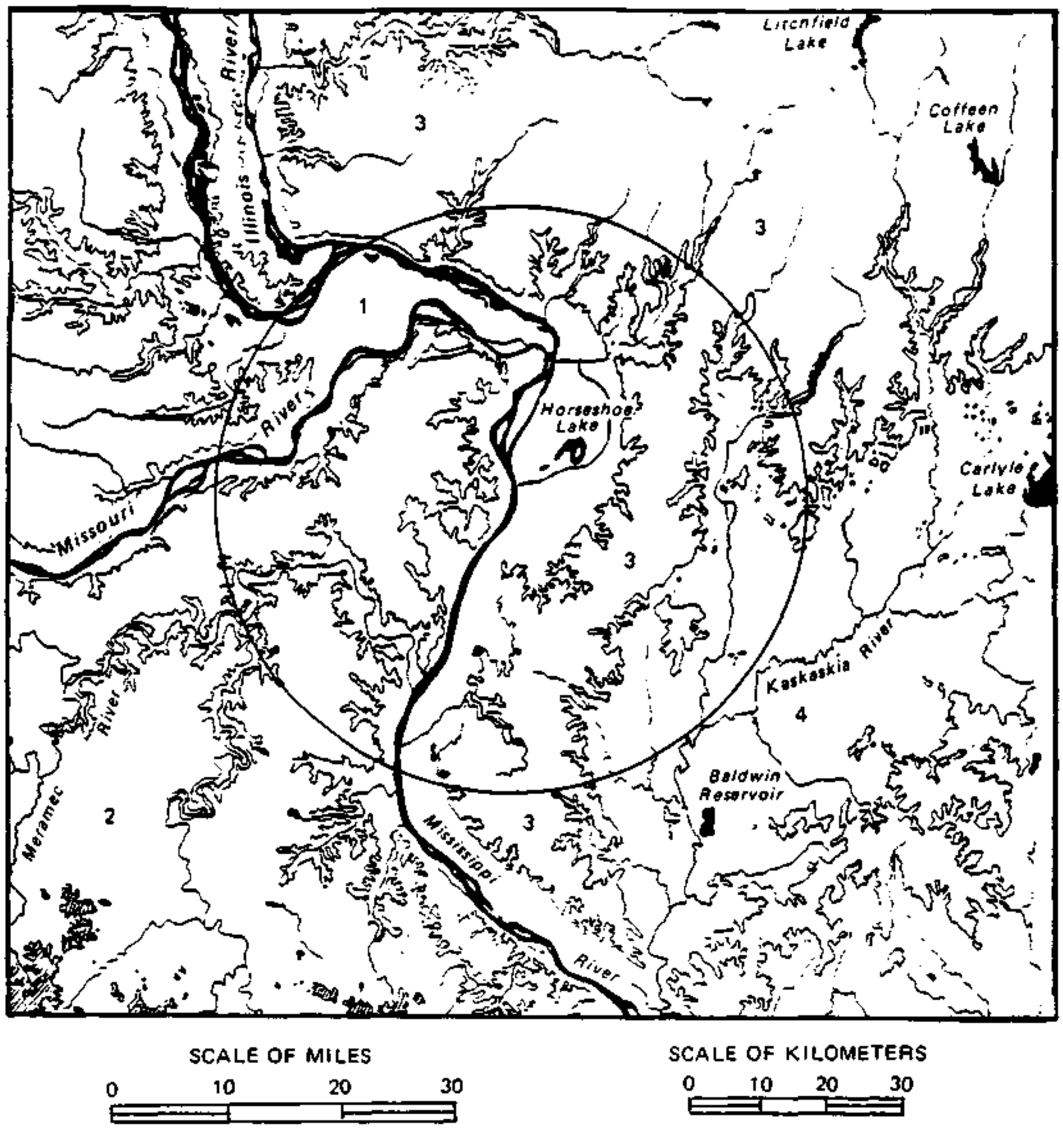

Figure 39. Topographic and Geographic Features of the Study Area. Contours are at 500 ft Intervals With Terrain Above 1000 ft Indicated by Hatching.

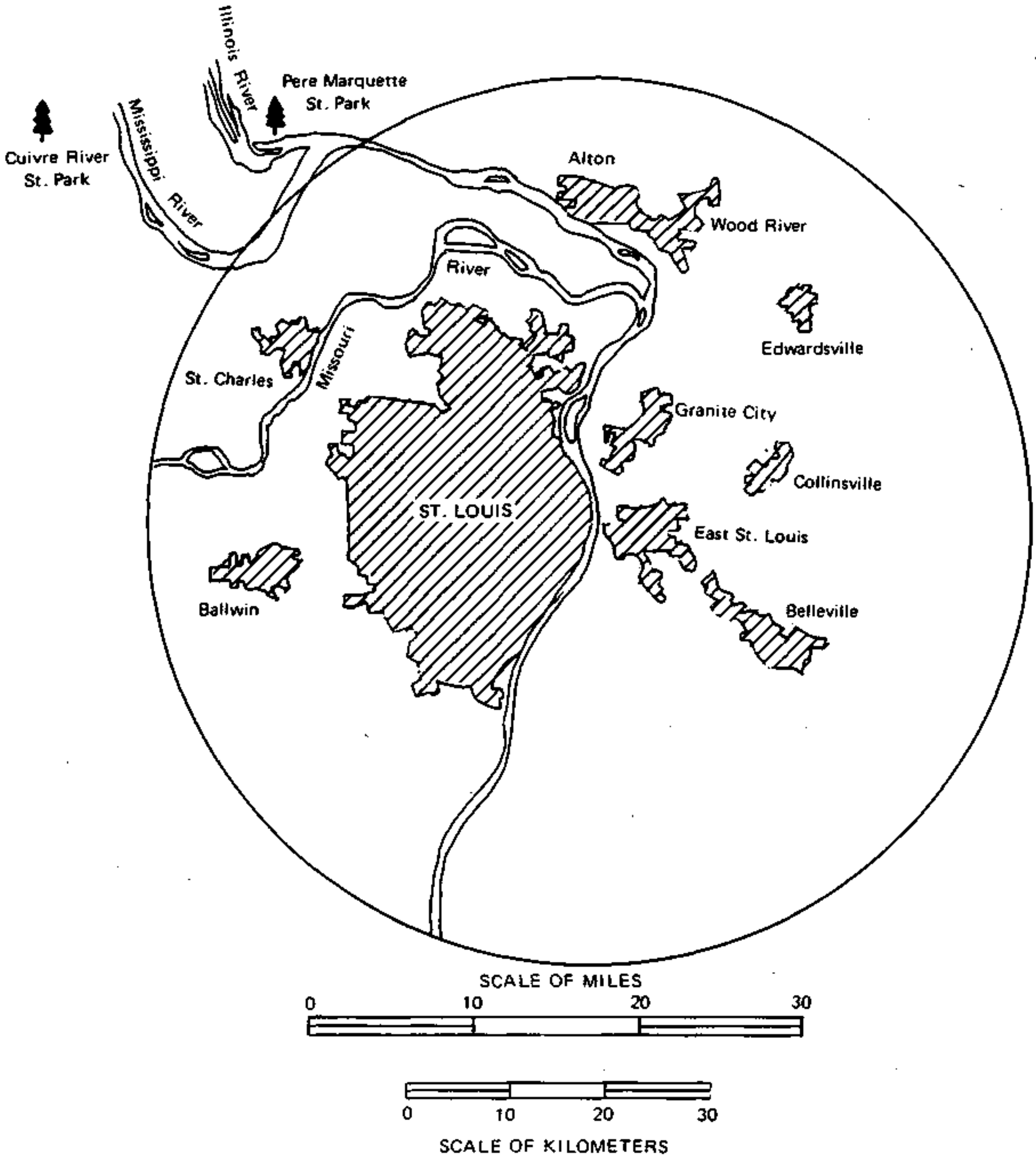

Figure 40. Urban Areas in the St. Louis Region.

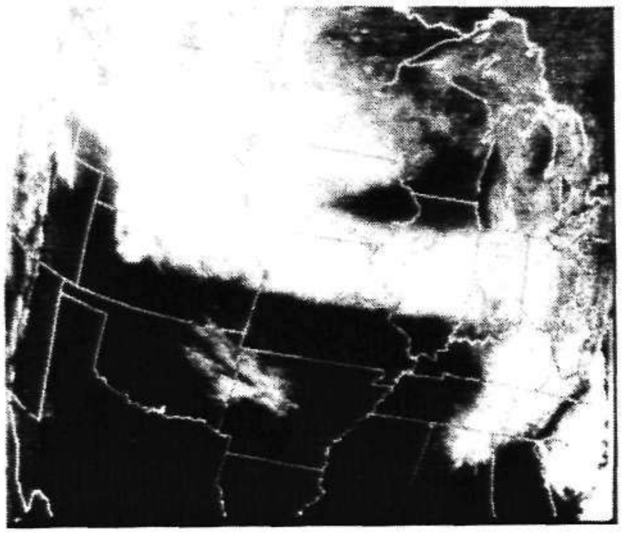

Figure 41. AVHRR Channel 1 (Visible) Image on 18 December 1981 at 2017 GMT. The Snow Band Across Missouri, Southern Iowa, and Illinois Fell on 17 December. The Bright Area in North-Central Kansas and Central Nebraska is Cloud, not Snow (Kidder and Wu, 1984). The Snow in Northwest Iowa, Southern Minnesota, and the Dakotas is Old Snow.

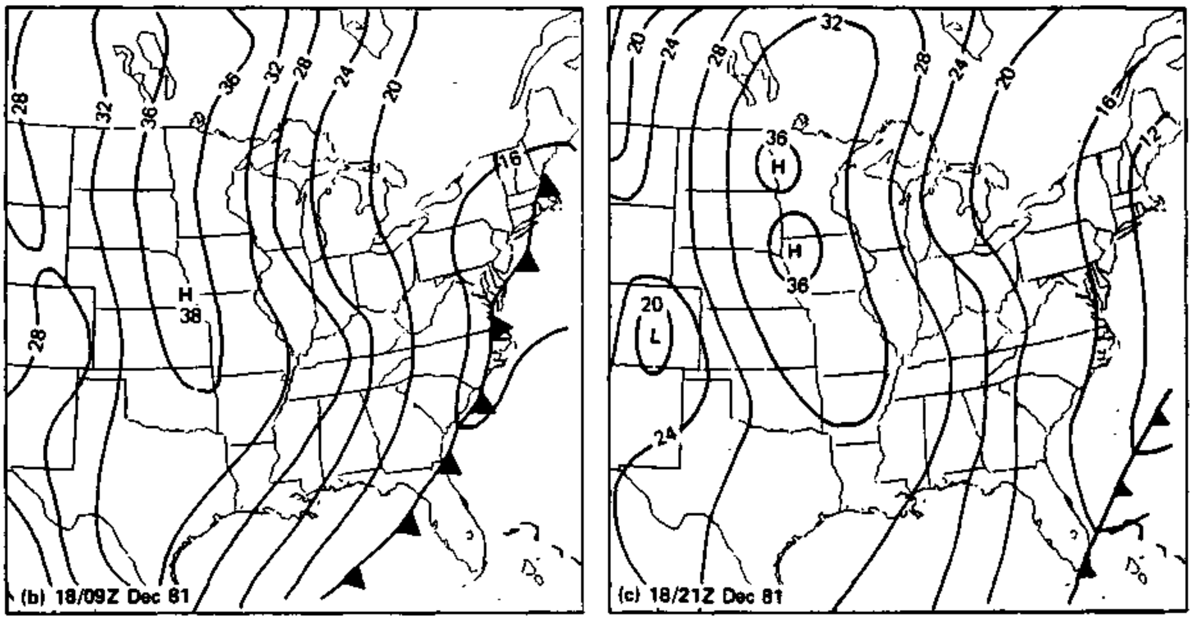

Figure 42. Surface Pressure Analyses for the Synoptic Times Nearest the Satellite Passes (a) 0900 GMT 18 December 1981, and (b) 2100 GMT 18 December 1981.

Table 52. National Weather Service Observations on 18 December 1981 at Lambert Field, St. Louis.

Time (GMT)	Temperature (°C)	Dewpoint (°C)	Wind Speed ($m\ s^{-1}$)	Wind Direction (degrees)	Cloud Cover (tenths)	Visibility km
0850	-16.7	-17.8	4.5	290	0	16
1947	-12.2	-18.3	4.0	300	0	24
2047	-11.7	-17.8	3.5	290	0	24

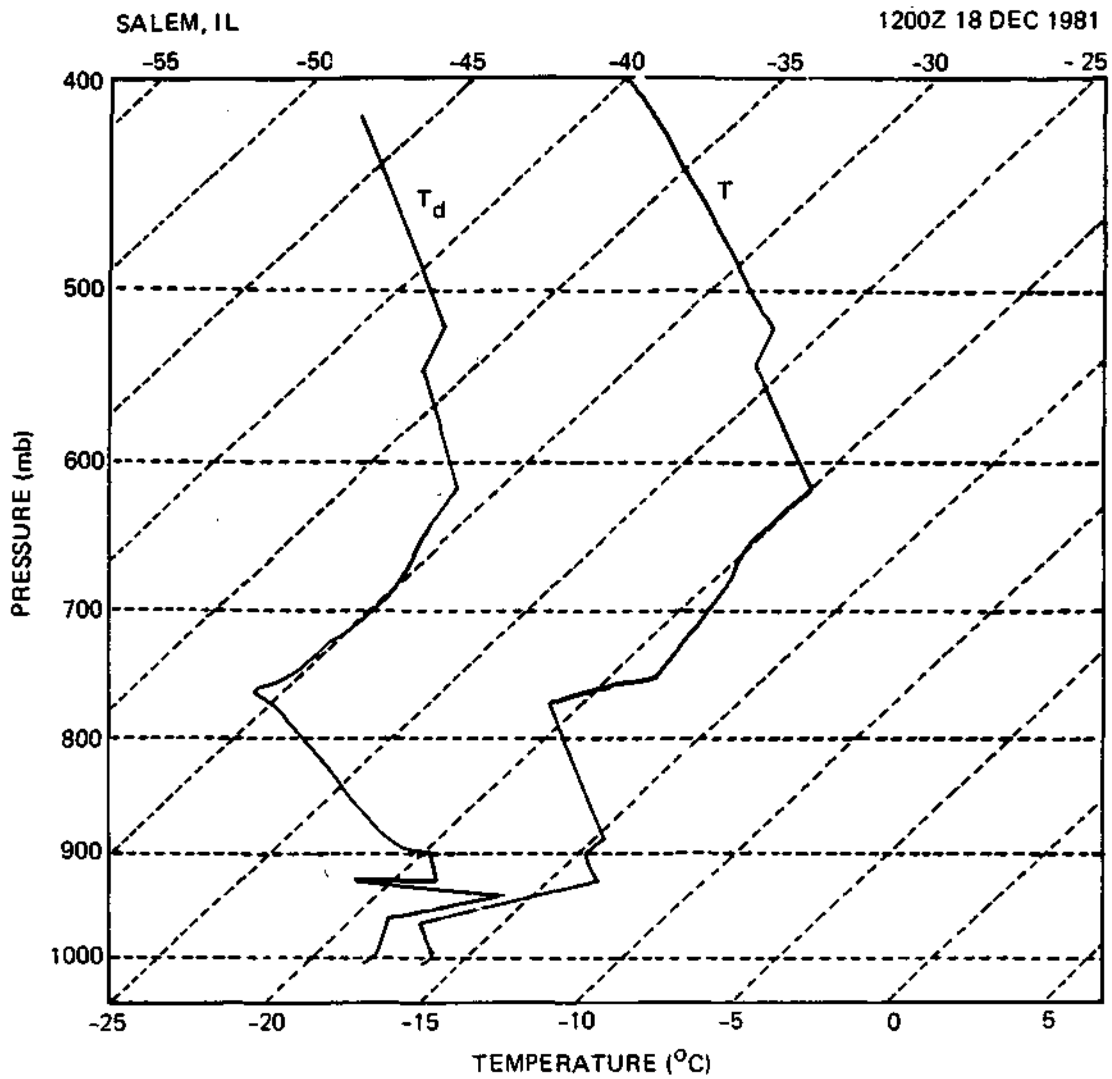

Figure 43. 1200 GMT 18 December 1981 Sounding from Salem, Illinois.

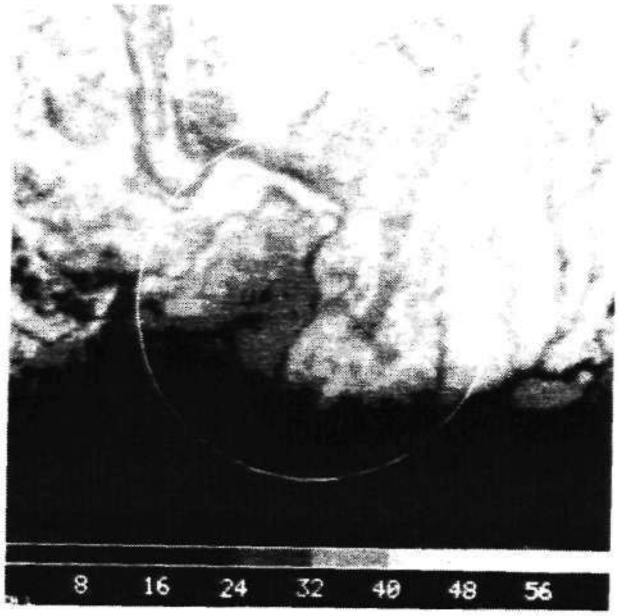

Figure 44. Channel 1 (Visible) Albedo (%) on 18 December 1981 at 2017 GMT.

Figure 45 shows an east-west cross section of channel 1 albedo through St. Louis. In the city of St. Louis, the albedo averages about 26%, while in the rural area between 30 and 60 km east of St. Louis, the albedo averages about 42%. This results in a -16% urban-rural albedo difference. Other urban-rural albedo differences in the snow-covered area are between -10 to -30%, depending on which urban area and on which rural location one chooses. Indeed, rural areas have substantial albedo variations under snow-covered conditions due to vegetation. Pere Marquette State Park, near the confluence of the Illinois and Mississippi Rivers, for example, appears much like a city due to low albedo trees protruding through the snow. Vukovich (1983) reported urban-rural reflectivity differences of -2 to -4% on 26 February 1978 in the St. Louis area. When converted to albedos, this amounts to albedo differences of -3 to -6%. In the snow-free area south of St. Louis, the albedo was 15 to 20%, which compares well with the 18% found by Vukovich on 26 February 1978 (again, after conversion from reflectance).

Albedos calculated for the channel 2 data (Fig. 46) appear similar to channel 1 albedos except that the albedo in the snow-free area is higher than for channel 1 data. Of more interest is the difference between channels 2 and 1 (Fig. 47). Because chlorophyll has a much higher albedo in the near-infrared than in the visible portion of the spectrum (Hoffer and Johannsen, 1969), areas covered with green vegetation appear brighter in channel 2 than in channel 1. This property has been exploited to produce maps showing the extent of vegetation over large land areas (e.g. Tucker et al., 1985; Tarpley et al., 1984).

Of particular interest in Fig. 47 is the sharp gradient that exists at the edge of the snowpack east of the Mississippi. Figure 48a shows a north-south cross section (A-B in Fig. 47) through the edge of the snowpack in the rural area. It appears that when the difference between the albedo in channels 1 and 2 falls below about 2%, the region is snow-covered. Schneider et al. (1981) also found a significant change in the difference between channel 2 and channel 1 in N0AA-6 AVHRR data at the edge of snowpacks in Colorado. They report, however, that the signature can be complicated by the presence of protruding, green vegetation (evergreen trees) in the snow-covered region. Figure 48b shows a northeast-southwest cross section (C-D in Fig. 47) across the snow boundary in St. Louis. Although the albedos change more slowly than in rural areas, the albedo difference is still sharp. Setting an albedo difference threshold may offer an accurate method of discriminating between snow-covered and snow-free areas.

11-12 μm Window Temperatures. Figure 49 shows the day and night equivalent blackbody temperature from AVHRR channel 4. These temperatures most nearly represent ground temperature; however, they have not been corrected for atmospheric effects or surface emissivity. The chief absorber in the 10.5 to 12.5 μm region of the spectrum is water vapor. Because the precipitable water is only about 3 mm, the water vapor effect is small, perhaps 1-3 K (see below). Neglect of surface emissivity causes a larger error. The emissivity of snow is about 0.90 and that of water is about 0.99 at this wavelength (Wolfe and Zissis, 1978). The emissivity of snow-free land is in the range 0.95-0.99 (Taylor, 1979), with 0.97 being a

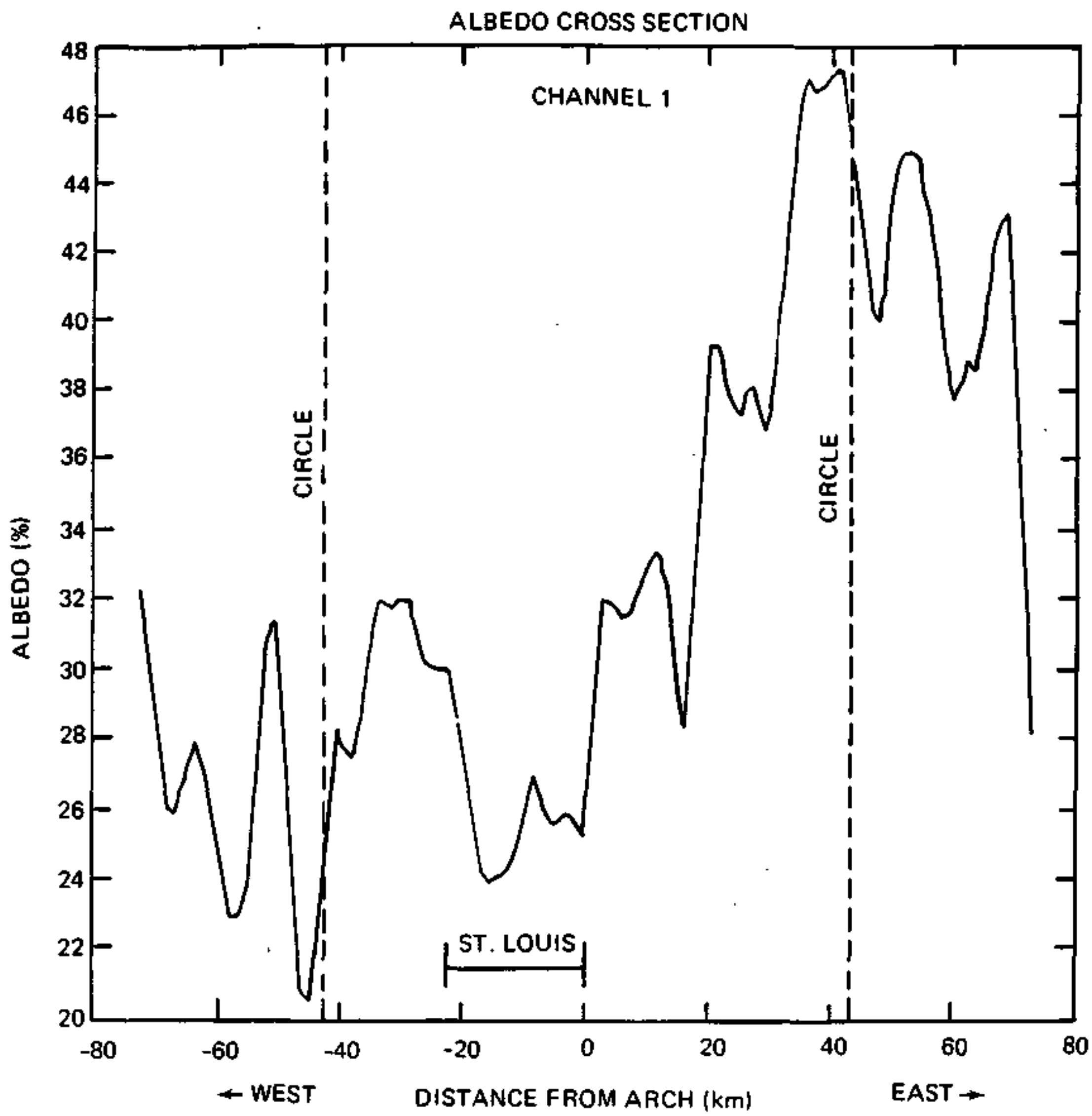

Figure 45. East-West Cross Section of Channel 1 Albedo Through St. Louis. The Data Have Been Averaged over a 10 km Wide Strip.

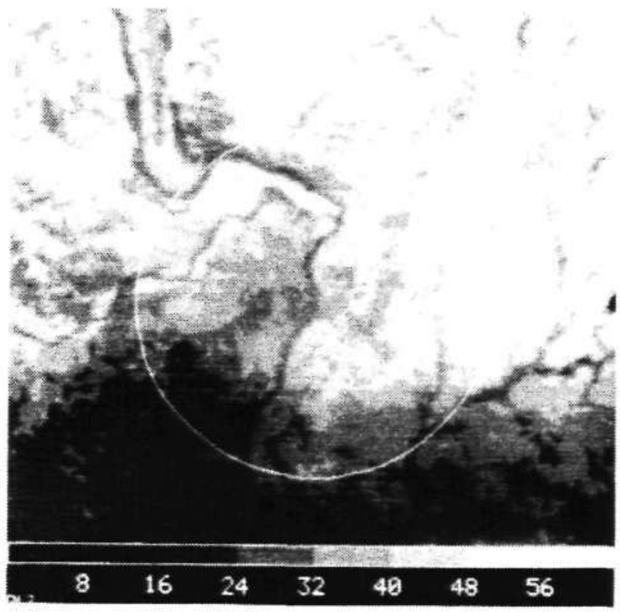

Figure 46. Channel 2 (Near-Infrared) Albedo (%) on 18 December 1981 at 2017 GMT.

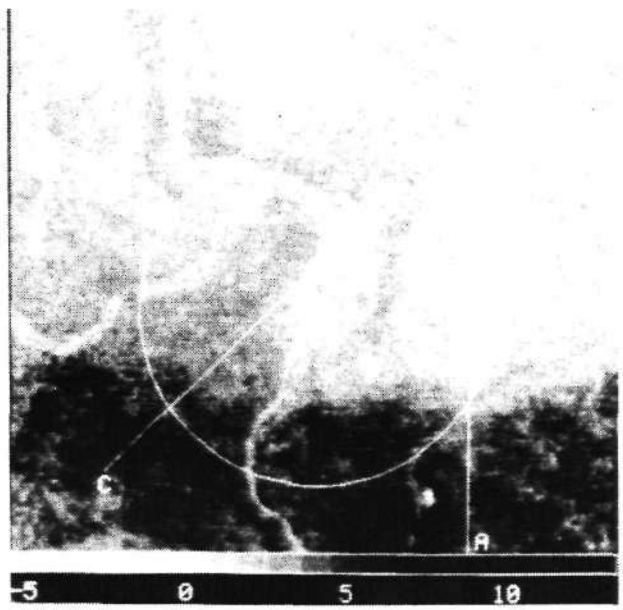

Figure 47. Channel 2 Albedo Minus Channel 1 Albedo (%).

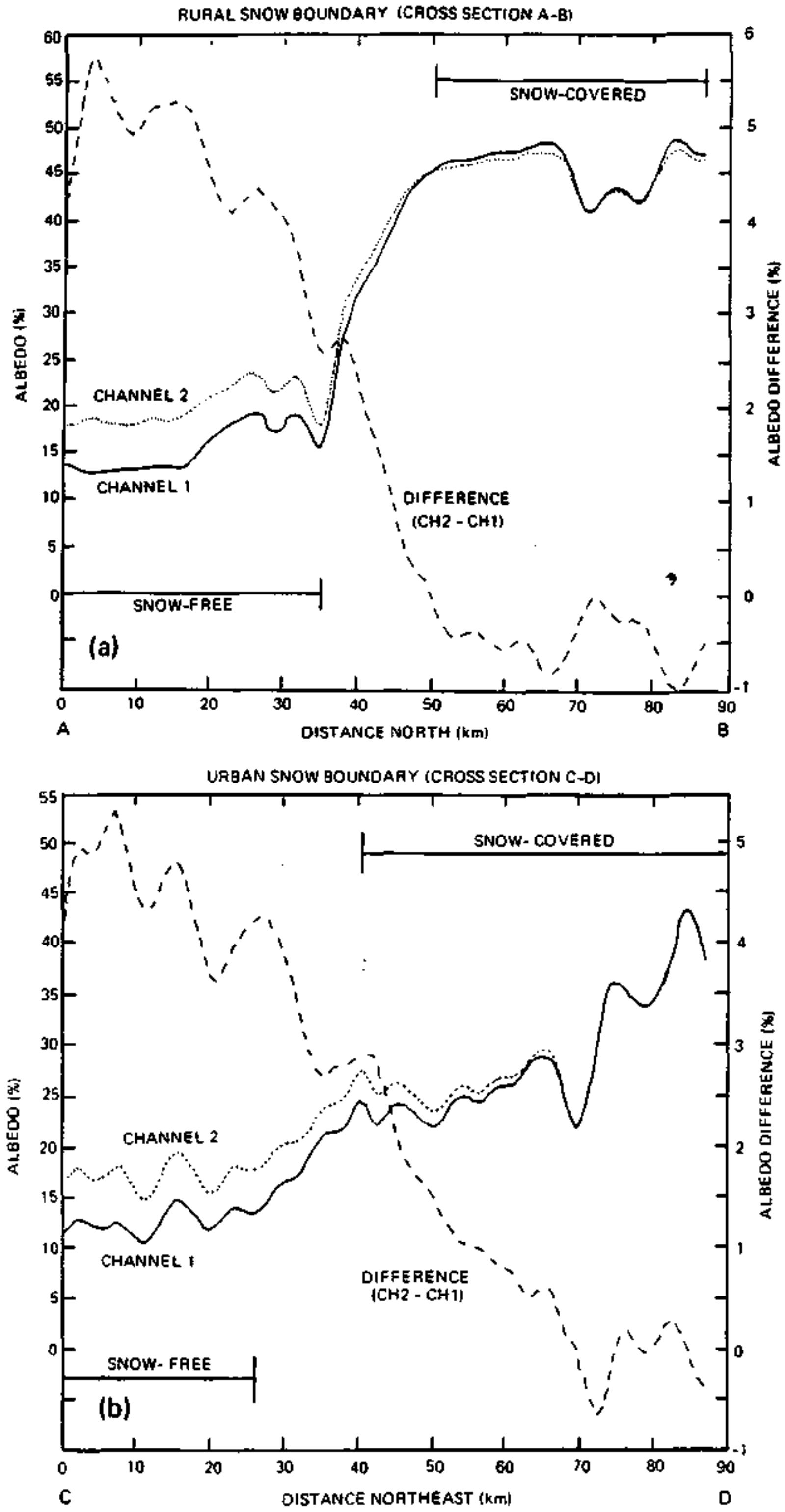

Figure 48. Cross Sections of Channels 1 and 2 Albedo and Their Difference Across the Snow Boundary. (a) Cross Section in a Rural Area (A-B in Fig. 10). (b) Cross Section in St. Louis (C-D in Fig. 10). The Scale for the Difference is 10 Times that for the Albedos.

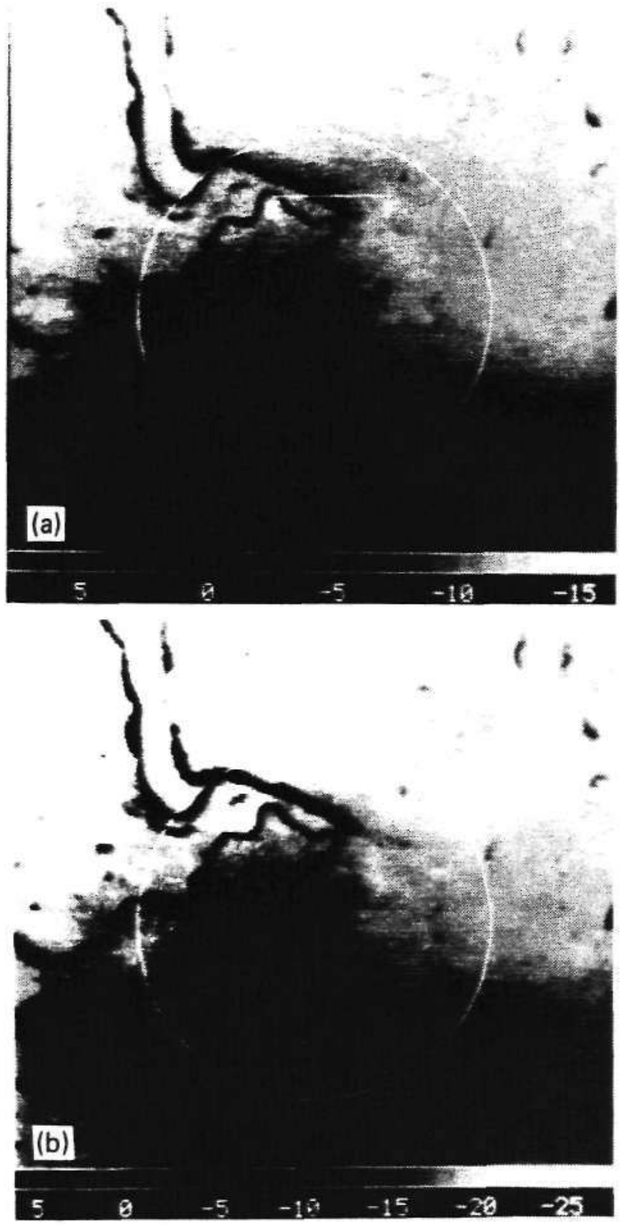

Figure 49. Channel 4 Equivalent Blackbody Temperature (°C) at (a) 2017 GMT and (b) 0851 GMT on 18 December 1981.

suitable average. Thus for a snow surface temperature of 260 K, the T_{BB} estimated by the satellite would be about 255 K or 5 K below the true surface temperature. Two places allow comparison. At Lambert Field, northwest of central St. Louis, the AVHRR channel 4 T_{BB}s were -18°C at 0851 GMT and -11°C at 2017 GMT, while the corresponding air temperatures were -17°C and -12°C, respectively. At Baldwin Reservoir, which is a cooling pond for an electrical power generating station, the water temperature at the intake for the power plant was 11°C on 18 December, while the AVHRR channel 4 T_{BB} was 6°C. This last comparison, however, is affected by water vapor evaporating from the reservoir. Because of the difficulty of determining accurate corrections, no corrections were made. Our purpose was not to accurately estimate ground temperatures, but to observe the influence of urban areas on satellite-observable parameters. Further work, however, will require these corrections to be applied.

The most apparent feature in Fig. 49 are, again, the rivers and lakes. Since this was the first cold weather of the season, water bodies are warm in comparison to air or land surface temperatures. Also of interest is the high temperature gradient at the snow boundary, although this is caused in part by the difference in emissivity between land and snow.

Urban heat islands are well defined both day and night. Figure 50 shows east-west cross sections through St. Louis of channel 4 T_{BB}. The warmest part of St. Louis is in the commercial-industrial zone west of the Mississippi River. The temperature falls further west until it approaches rural values. If the region from 30 to 60 km east of the Arch represents rural temperatures, and if the warmest part of St. Louis is used, urban-rural temperature differences are about 3 K during the day and about 2.5 K at night. Vukovich (1983) found a 2.4 K urban-rural difference in February 1978 under snow-free conditions using HCMM data.

The pattern of the urban heat island is interesting. In the daytime, the warmest temperatures in St. Louis are found in the commercial-industrial-residential zone (Auer, 1978) near the Mississippi. At night, the warmest zone expands to cover not only the commercial-industrial-residential zone, but also the compact residential zone (> 70% vegetation) that surrounds it.

Another interesting result is the difference between day and night temperatures shown in Fig. 51. The smallest day-night differences (0-5 K) are associated with major rivers and lakes because of their high thermal inertia. Comparison with U.S. Geological Survey topographic maps shows that the white regions, which have high day-night differences, are mostly associated with woods-brushwood areas[3].

Unlike the temperature patterns at a single time, Fig. 51 shows little indication of either the snow boundary or of urban influences. Figure 52 shows a cross section of day and night channel 4 T_{BB}s from the

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[3]Note that bright areas near water bodies (for example, the western edge of Baldwin Reservoir) are the result of slight navigation errors and are not real.

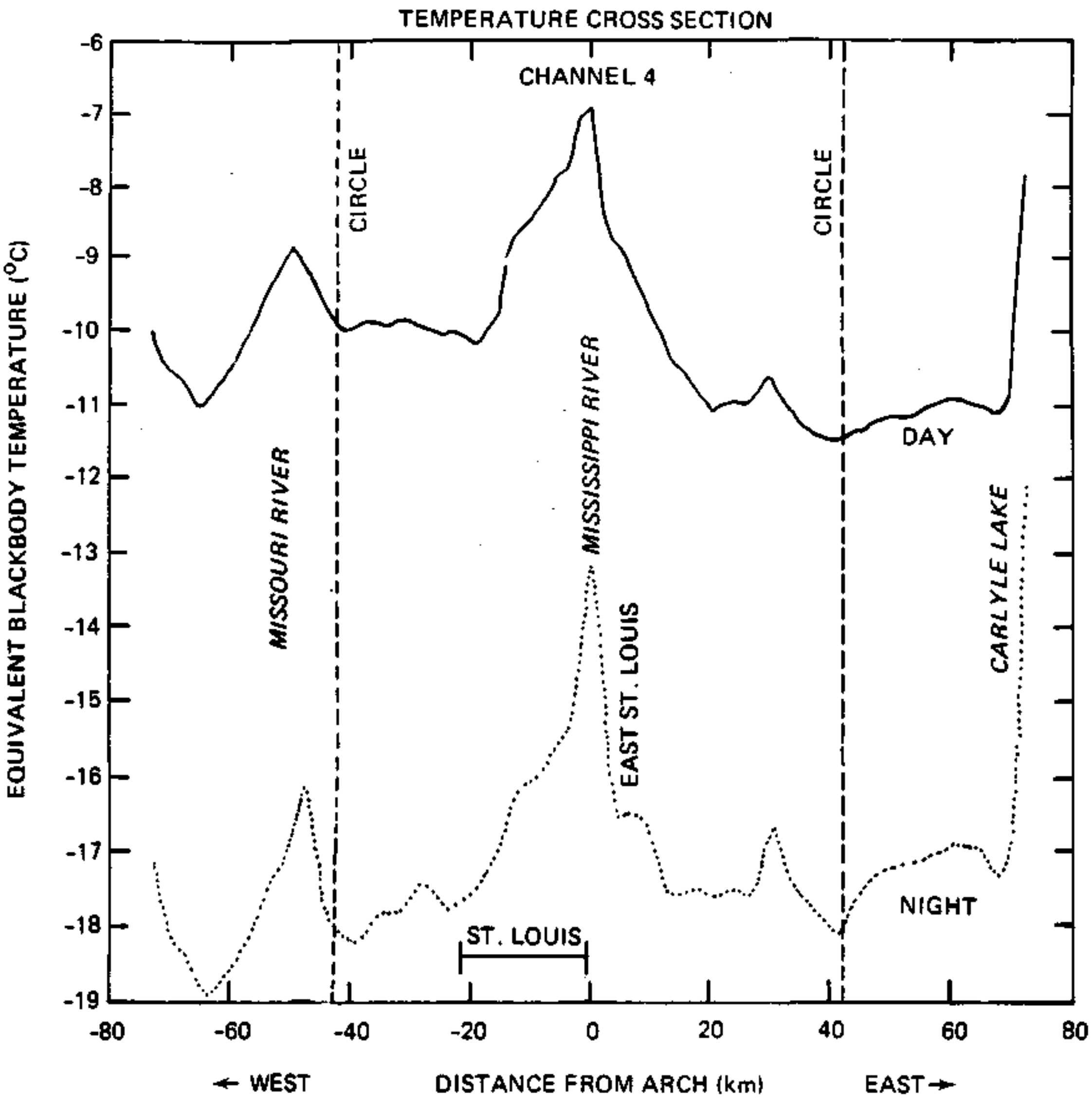

Figure 50. East-West Cross Sections of Channel 4 T_{BB} Through St. Louis. The Data Have Been Averaged Over a 10 km Wide Strip.

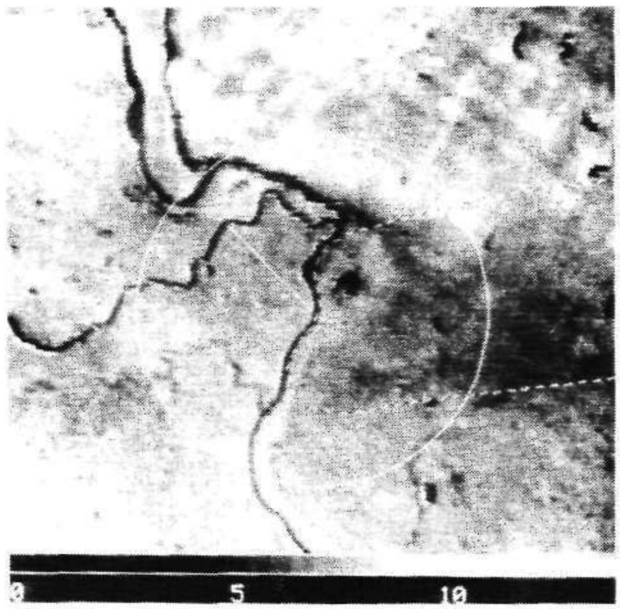

Figure 51. Difference Between Day and Night Channel 4 Equivalent Black-body Temperatures (K). This is the Increase in Temperature Between 0851 and 2017 GMT.

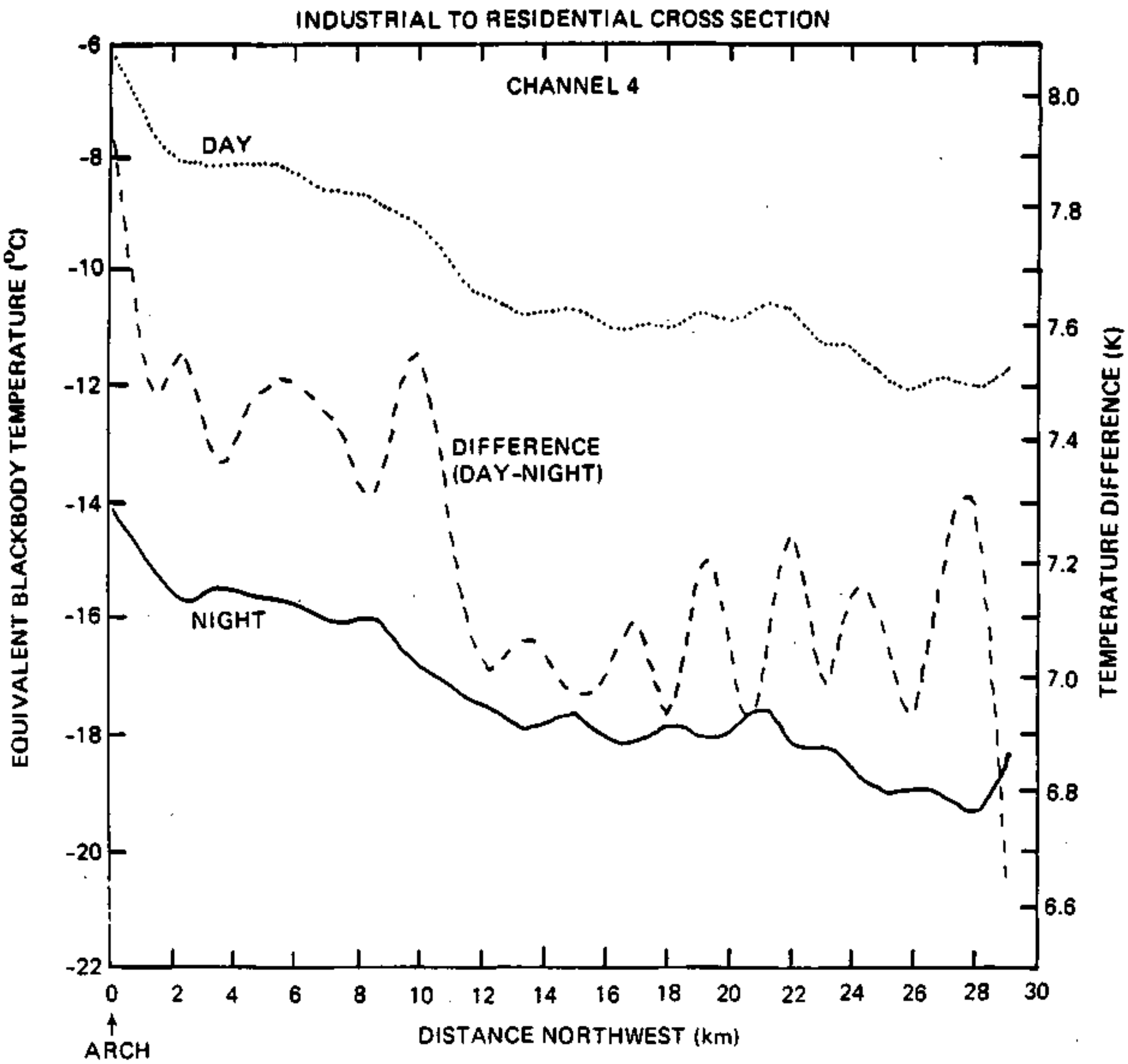

Figure 52. Cross Section of Channel 4 T_{BB}s From the Arch Northwest Toward the Residential Area (see Fig. 14). The Scale for the Temperature Difference is 10 Times the Scale for the Temperatures.

Arch northwest toward the residential area (see Fig. 51). There appears to be a slight tendency for the day-night difference to decrease away from the central city. Also, during the day, temperatures of the suburban regions to the northwest of central St. Louis have about the same temperature as the surrounding rural regions, but at night these suburbs are warmer than their surrounding rural regions by about 1 K. Both of these effects are thought to be a result of residential heating.

The primary difference between channels 4 and 5 is that channel 5 is more sensitive to water vapor than is channel 4. Differences between channels 4 and 5 have been used to correct sea surface temperature estimates (Strong and McClain, 1984) and land surface temperature estimates (Price, 1984). In both cases, the correction is approximately 3 times the difference in T_{BB} between the channels. Because the atmosphere was dry on 18 December, channel 5 images appear much the same as channel 4 images. The daytime difference between channel 4 and channel 5 is shown in Fig. 53. Over most of the image, the difference is between -1 and +1 K, which indicates that the true ground temperature is within about 3 K of the channel 4 T_{BB}. Near lakes and rivers, where moisture and heat are being input to the atmosphere, the differences are more extreme[4].

An interesting feature of Fig. 53 is the area east of St. Louis and north of the snow boundary (outlined with a dashed line) which has slightly higher differences than either the snow-free area to the south or the other snow-covered areas to the west and north. Unfortunately, one cannot interpret differences between channels 4 and 5 alone as water vapor differences (McMillin and Crosby, 1984). Either the area east of St. Louis has more water vapor, or the difference between the ground temperature and the near-surface air temperature is larger than elsewhere. An intriguing hypothesis is that heat and/or moisture input from the St. Louis urban area is the cause of the larger difference. However, the wind appears to have been from the northwest at all levels up to 850 mb at this time. Thus an easterly plume does not seem to be the explanation for the larger differences. This same area also has smaller day-night variation in channel 4 T_{BB} (Fig. 51).

<u>3.7 μm Temperatures</u>. Figure 54 shows the daytime and nighttime 3.7 μm images. Immediately apparent is the higher noise in channel 3 data as evidenced by a "patterning" of the images. The images appear much the same as the channel 4 images: water bodies stand out,' and there is a sharp gradient at the snow boundary. That no large dark areas appear on the daytime channel 3 image shows that the study area is cloud free, at least for the daytime case (Kidder and Wu, 1984).

In contrast to the channel 4 images, however, are the "hot spots" located at Alton, Wood River, and Granite City. Matson and Dozier (1981) point out that channel 3 is much more sensitive to sub-pixel size elevated temperature (industrial) targets than is channel 4. Figure 55 shows day and night cross sections through Alton (E-F in Fig. 49a) of channels 3 and 4 T_{BB}. The large spike in channel 3 is caused by cooling steel at Laclede

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[4]There may also be slight misalignment between the fields of view of the channels, which would contribute to the contrast seen at water bodies.

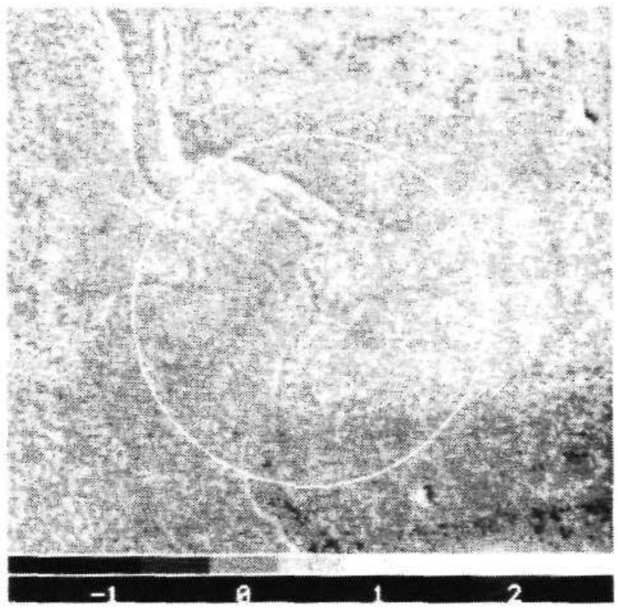
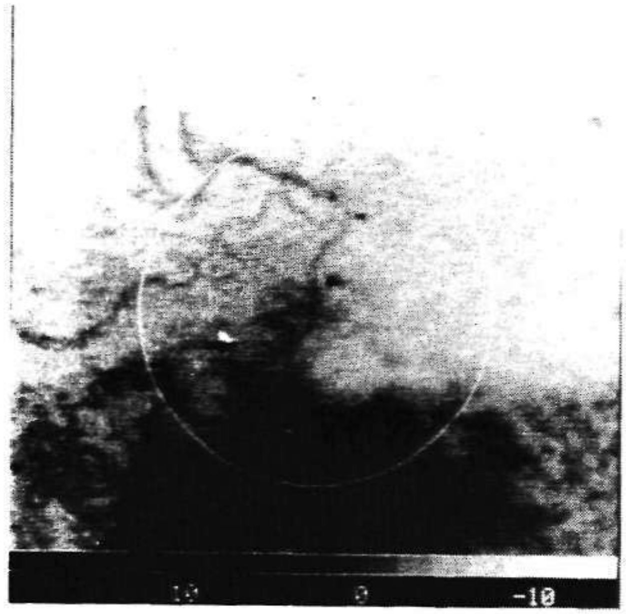


Figure 53. Difference Between Channel 4 and Channel 5 Equivalent Black-body Temperatures (K) at 2017 GMT on 18 December 1981.



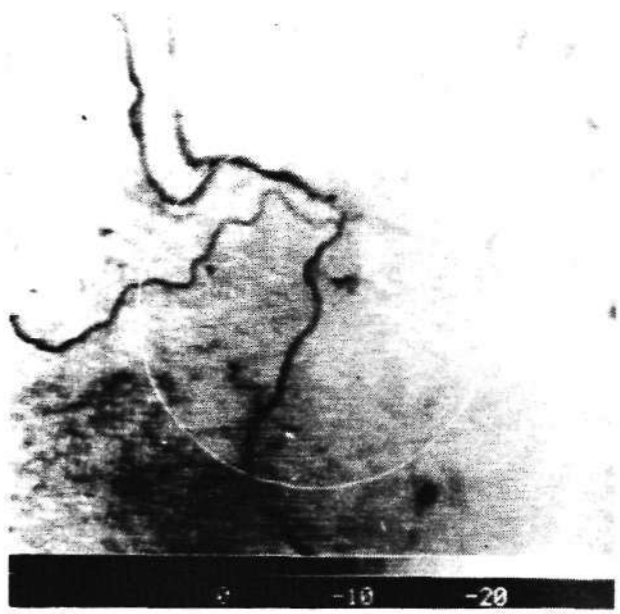


Figure 54. Channel 3 Equivalent Blackbody Temperatures (°C) at (a) 2017 GMT and (b) 0851 GMT on 18 December 1981.

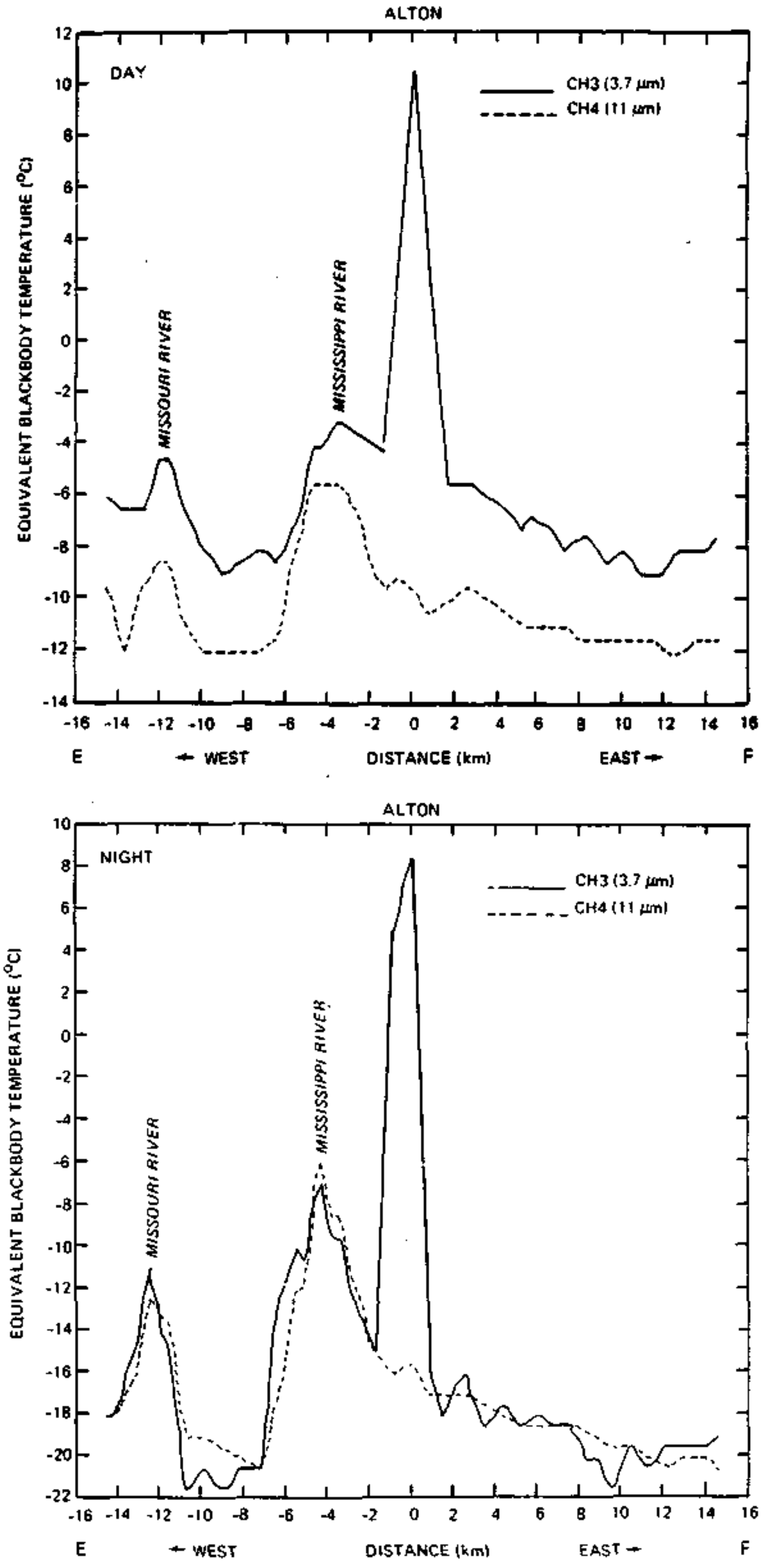


Figure 55. Cross Sections Through Alton (E-F in Fig. 12a) of T_{BB} for Channels 3 and 4 (a) Day and (b) Night. The Large Spike in Channel 3 is Laclede Steel Co.

Steel Co. The hot spot at Granite City is caused by slag pits at Granite City Steel Co., and the Wood River spot is caused by gas flares from an oil refinery complex. Gas flaring is an intermittent operation, which may explain why the Wood River hot spot diminishes at night. The 4 K offset between channel 3 and channel 4 during the day is explained by reflected sunlight. Snow has an albedo of 1% at 3.7 μm (Wiscombe and Warren, 1980).

Matson and Dozier (1981) attempted to estimate the temperature of the hot target and the fraction of the pixel area it covered by assuming that the radiance measured by the satellite in the hot pixel was a linear combination of the hot radiance and the background radiance, the proportionality constants being the fractional area covered by the target and the background. Using radiances from channels 3 and 4 for the hot pixel and for an adjacent background pixel, they could then calculate the temperature of the target and its fractional area. We modified the Matson-Dozier technique slightly to account for reflected sunlight by allowing different background temperatures in the two channels. Table 53 shows the estimated temperatures and areas for the hot spots. These numbers are consistent with estimates obtained from the engineering departments of the above-mentioned companies.

The channel 3 data could be useful for navigation of satellite images, if the locations of several constant hot spots were known (Matson and Dozier, 1981). Matson et al. (1984) are using the channel 3 data to detect fires.

Summary and Conclusions

Data for two consecutive passes of the 5-channel NOAA-7 AVHRR near St. Louis on 18 December 1981 have been examined. It was found that under snow-covered conditions, urban-rural albedo differences for channel 1 ranged from -10 to -30%. The difference between the albedo in St. Louis and in a typical rural region about 45 km east of St. Louis is about -16%. The difference between channel 1 (visible) albedo and channel 2 (near-IR) albedo appears to be a useful indicator of the snow boundary. Urban-rural equivalent blackbody temperature differences for channel 4 (11 μm) ranged from 2-4 K. The difference between the warmest part of St. Louis and a typical rural region about 45 km east of St. Louis was about 3 K during the day and about 2.5 K at night. Day-night temperature differences were nearly the same in urban as in rural areas, as well as in snow-covered and snow-free areas. Largest day-night differences were found in forested portions of the snow-covered area. Slightly larger (about 0.5 K) day-night differences were observed in the commercial-industrial area of St. Louis than in the residential area. Temperature patterns in channel 5 (12 μm) data were essentially the same as in channel 4 data. In particular, the difference between channel 4 and channel 5 equivalent blackbody temperatures were mostly between -1 and +1 K, indicating the ground temperature was close to the channel 4 temperature. Finally, analysis of channel 3 data (3.7 μm) revealed some interesting "hot spots" over the cities of Alton, Wood River, and Granite City, Illinois. These turned out to be industrial targets.

Table 53. Estimated Temperatures and Areas of Hot Targets in Channel 3 Images Using the Matson-Dozier (1981) Technique. All Temperatures are in Kelvin.

Location	Hot Spot		Background		Target	
	$T_{3.7}$	T_{11}	$T_{3.7}$	T_{11}	Temp	Area (m^2)
Alton (night)	281.5	257.5	257.0	256.0	472	2800
Alton (day)	283.5	263.5	267.5	263.0	570	580
Granite City (night)	271.0	258.5	255.0	256.5	388	8000
Granite City (day)	280.0	264.5	266.5	263.0	423	4600
Wood River (day)	281.5	265.5	265.0	261.0	362	20000

In conclusion, it appears that 1.1 km resolution AVHRR data are useful for the examination of (1) urban-rural differences in albedo and ground temperature, (2) day-night differences in ground temperature, (3) snow boundaries, and (4) industrial heat sources.

F. CONCLUSIONS

This research focused on two scientific topics: the existence of urban-altered precipitation in winter and the transition seasons, and in the reality and possible causes of a nocturnal summer maximum of rainfall east of St. Louis. First, let us address the winter and transition season results.

Two major questions were posed by this research: were there apparently real urban-related precipitation anomalies in the transition and winter seasons, and under what types of conditions did these occur? The results clearly indicated the reality of urban-induced increases in the fall, winter, and spring seasons. Persistence of the anomalies in 5-year periods in the hypothesized effect areas east of the city was strong. Of the three seasons, the spring urban effect appears to be both strongest and most substantiated. The winter effect, which is spread in the northeast, east, and southeast of the city, is less than in spring but also quite real and present in seven of the eight 5-year periods (1941—80). The urban effect on fall is the smallest of the three seasons and less persistent.

The magnitude of the urban precipitation changes in the three seasons is much less than summer. The peak of urban influences occurs near Edwardsville (northeast of St: Louis) and it shows a 49% increase in the summer, compared to 14% in spring, 10% in winter and 8% in fall. The study also revealed that urban effects and presumably the heat of the city, acts to decrease the quantity of snowfall occurring over the city. This supports prior findings.

Increases in the hilly areas southwest and southeast of the city were more pronounced particularly in fall and winter than in the summer and spring seasons. A confounding factor is that urban influences may also be greater in these areas south and southwest of the city in these cooler seasons due to N and NE inflow into larger cyclonic systems.

The analysis of synoptic weather conditions, and precipitation motion of the storms causing the precipitation peaks in each of the seasons revealed that the anomalies were caused by relatively few storms in any season, commonly about 10% of the total seasonal number. Most importantly, most effected storms revealed the presence of well organized convective elements. This agrees with the findings for summer season. The below normal fall rainfall during 1971-74 with fewer convective storm systems is believed to be a primary cause for a weak urban effect in the METROMEX data sample for fall.

An interesting unexpected finding related to the down trend in apparent urban effect precipitation. This relative decrease occurred largely during the 1941-60 period and in the two transition seasons. Although no analysis were performed to explain this, it may be related to the shift in the frequency of convective storms susceptible to urban influences during this period, or to a reduction in some urban influence on the atmosphere critical to precipitation development.

Another important finding relates to the close agreement of the 1971-75 METROMEX precipitation patterns with those based on the much less dense, National Weather Service climatic stations. The dense METROMEX network showed greater areal detail, but the NWS stations detected the main features in the precipitation patterns. This suggests that studies of urban effects in large metropolitan areas and focusing on transition and winter season conditions, can be adequately investigated with the normal density of National Weather Service stations which are usually located 30 to 50 km apart.

The second phase of this research project focused on a major maximum of precipitation north and northeast of St. Louis that occurred late in the day, between 2000 and 2400 hours. Earlier studies of the METROMEX summer rainfall data from 1971-1975 identified an afternoon anomaly in the same general area, and further established that the anomaly was statistically real and related to a series of urban factors that first influenced the lower atmosphere, then altered convective cell development, increased precipitation and storm development, and led to additional precipitation. The earlier METROMEX research identified a second rain maximum later in the day, but had not attempted to establish its reality nor to explain its occurrence.

The primary nocturnal maximum occurred 30 km northeast of St. Louis between 2100-2400 hours. The Edwardsville (EDW) area received 58% more rainfall than the rest of the network during these 3 hours. Later, more minor peaks in the network rainfall occurred between 0200 and 0500, and 0500 and 0900 but various climatological studies revealed these to be features of the general regional climate.

This research established that the heavy rainfall values N and NE of St. Louis were a true anomaly. Its reality was partially established by the fact that the EDW high was present in all 5 summers of the METROMEX sample (1971-75). A maximum in the EDW area was in the correct place for a logical sequence of local rain increases which first developed between 1800 and 2100 in and west of Alton, peaked in the Alton-Wood River area between 2000-2300, and moved eastward to EDW in the next hours. The NE nocturnal maximum values were so large so as to be statistically significant, being four standard deviations away from the network mean.

Its relationship to urban influences was partly indicated by the great preponderance of storm movements from the southwest and hence from over the urban industrial area, to the EDW area. The rains causing the anomaly occurred in the heaviest rain events of the evening, a condition which was typical of other findings on anomalous rain increases in the daytime. The 19 storms that moved from the west-southwest and during the 2100-2400 period produced 75% of the rainfall anomaly in the EDW region, and each of these 19 storms had storm elements passing over St. Louis.

Another key finding about the physical basis of the nocturnal anomaly was that it was a result of very few storms, 14 out of the 330 that occurred in the 5-summer sample. This was based on those storms that maximized in the NE anomaly. The nocturnal situation also was very similar to the afternoon maximum in that both maximums at EDW and reflecting urban effects, occurred when network-wide heavy rainfall occurred. In other words, when the atmosphere was providing conditions conducive to relatively heavy rainfall, the urban influences were most active. The physical factors relating to the urban influences at night were similar to the overall daytime findings in that the nocturnal maximum was produced by well-organized convective systems.

The study of raincells showed that 82% of all the raincells in the Edwardsville maximum at night developed and/or intensified over St. Louis and/or Alton-Wood River. The average dimensions of the potential urban-influenced cells indicated that they were larger, longer lasting and produced a much greater rain volume than the nocturnal rural raincells. Braham (1981) had speculated that the limited early evidence relating to a nocturnal increase in middle size storms (up to 12,000 m high) coupled with no increase in heavy storms, hail and thunderstorms, was indicative that the Theta θ hypothesis (postulated by Boatman, 1973) was active. That is, that storms moving over the urban area were injecting relatively low Theta θ air which, in turn, ended their growth and caused them to deposit their rainfall.

Results of this latest study showing the initiation of urban rain-cells close to St. Louis and their characteristics are supportive of the Theta 9 hypothesis. The rational is that the injection of warm, dry air with relatively low Theta 9, which is characteristic of urban areas at night, causes a decrease in updraft buoyancy and its ability to carry previously condensed liquid water. This would result in the premature weakening of the storm, and release of water stored in the storm, leading to an increase in rainfall rates. One would thus predict that the resulting surface rain maximum should lag the point of an initial injection of the lower Theta 9 air by 20 to 60 minutes (5 to 20 km dis-tance). This is in keeping with the findings on the raincells, storms, and locale of the nocturnal maximum.

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