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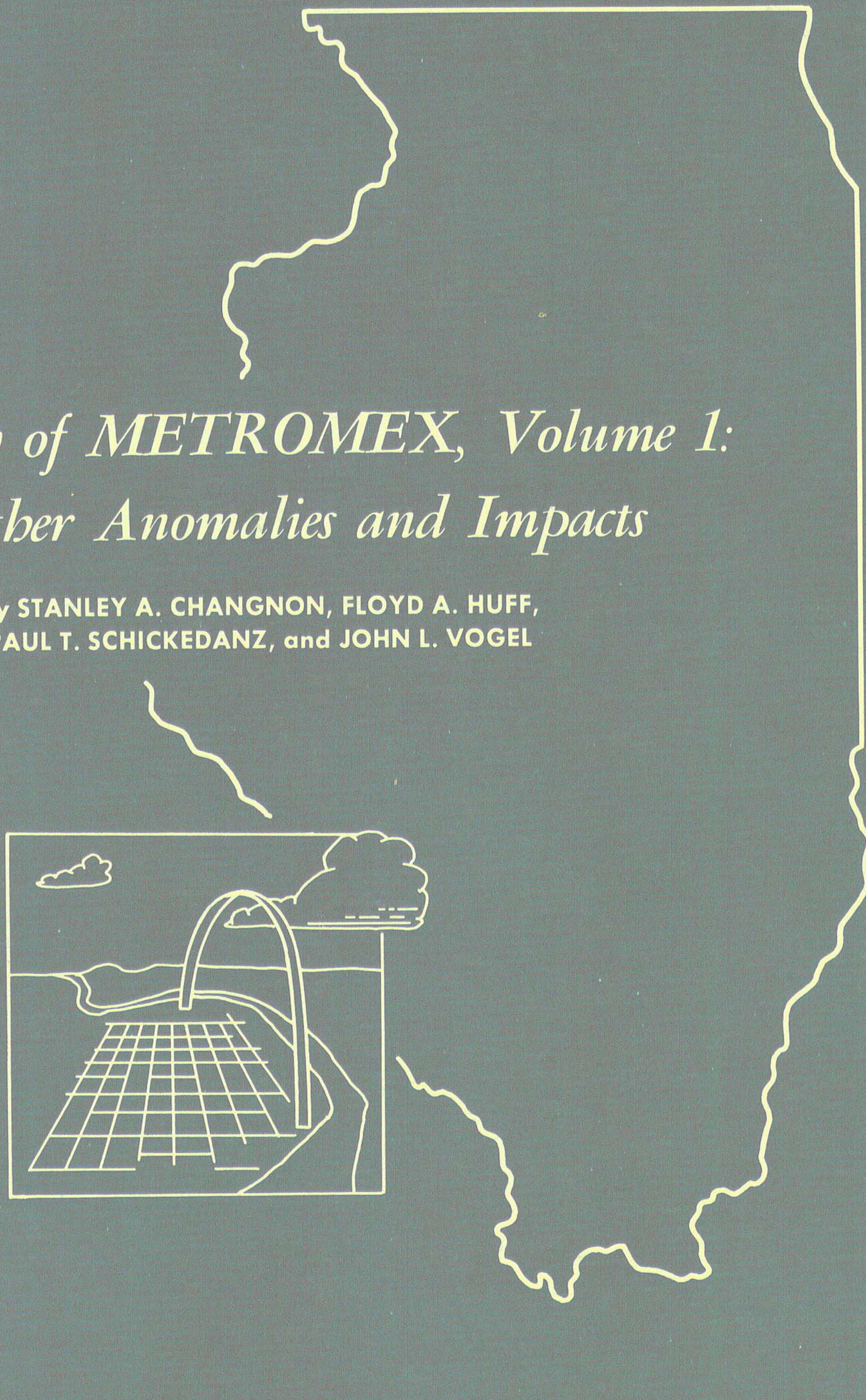

Summary of METROMEX, Volume 1: Weather Anomalies and Impacts

by STANLEY A. CHANGNON, FLOYD A. HUFF,
PAUL T. SCHICKEDANZ, and JOHN L. VOGEL

ILLINOIS STATE WATER SURVEY
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by STANLEY A. CHANGNON, FLOYD A. HUFF,
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Abstract: This is the first of two volumes presenting the major findings from the 1971-1975 METROMEX field operations at St. Louis. It focuses on final interpretations and conclusions obtained primarily through climatological-statistical analyses of spatial and temporal distributions of surface precipitation and severe storms. It addresses also the impacts related to the urban-produced precipitation anomalies. Volume 2 concerns the causes of the anomalies. Key climatic effects are increased cloudiness (+10%), increased total summer rainfall (+30%), and increased severe storm activity (+100%). These increases occur over the city and 10 to 25 miles beyond (east) the urban-industrial areas. The urban-induced anomalies occur most often with squall lines and cold fronts; they maximize in the afternoon and again at night (2100-2400); they appear to be as active in dry periods as in wet periods. Impacts include more runoff, but also more local flooding, soil erosion, silting, and water pollution. The effect of altered weather leads to a 3 to 4% average increase in local crop yields. The urban-induced anomalies are generally disbeneficial in the floodplain area, and have mixed impacts in the rural uplands.

Reference: Changnon, Stanley A., Floyd A. Huff, Paul T. Schickedanz, and John L. Vogel. Summary of METROMEX, Volume 1: Weather Anomalies and Impacts. Illinois State Water Survey, Urbana, Bulletin 62, 1977.

Indexing Terms: Climatology, hydrology, impacts of altered weather, inadvertent weather and climate change, meteorology, rainfall, severe storms, water resources, weather modification.

STATE OF ILLINOIS
HON. JAMES R. THOMPSON, Governor

DEPARTMENT OF REGISTRATION AND EDUCATION
JOAN G. ANDERSON, B.S., Director

STATE WATER SURVEY DIVISION
WILLIAM C.ACKERMANN,D.Sc., Chief

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Part A. Introduction

Stanley A. Changnon, Jr.

Project Background

This report is the first of two volumes issued by the Illinois State Water Survey to summarize the METROMEX (Metropolitan Meteorological Experiment) activities and results obtained by the Survey staff during the 1971-1977 period. This first volume focuses on two of the major research areas of the Water Survey program in METROMEX: 1) the surface rainfall and severe local storms, and 2) impacts from the urban-altered precipitation phenomena.

Volume 1 also serves as a final report to the National Science Foundation on Grant ENV73-07796. This grant was the fourth in a series of NSF grants that began in March 1971. These grants and their periods include GA-28189X for March 1971 through February 1972; GA-33371 for March 1972 through February 1973; GI-38317 for March 1973 through February 1974, and the present grant which ran from March 1974 through September 1977. Some of the research under these NSF grants pertains more directly to the causative aspects of the anomaly and appears in volume 2 of this summary. The results from part of the ENV73-07796 support that appear in volume 2 include 1) the boundary layer and airflow studies, 2) the cloud initiation and cloud coverage results, 3) the radar echo results, 4) the major raincell results, and 5) the surface patterns of wind, temperature, and moisture.

The Water Survey projects for METROMEX had major support from three sources including the National Science Foundation, ERDA (Atomic Energy Commission during the early years of METROMEX), and the State of Illinois. Some supplementary EPA funding for a minor portion of the field effort was also obtained.

Most of the research reported here is a result of the 6½ years of funding from the National Science Foundation coupled with sizeable funding from the State of Illinois at a ratio of approximately 3:1. Research grants and contracts of other agencies supporting projects in METROMEX, particularly those of ERDA (AEC) to the Water Survey, contributed significantly to the collection of certain data used herein. Also, results of another NSF grant, GK-38329 from the Engineering Division of NSF, are summarized in this report, in addition to the two volumes of the final report of that project (Huff, 1975;,Schicht, 1977).

Volume 1 essentially focuses on two of the four broad major METROMEX goals: 1) the dimensionalizing of the surface precipitation and severe weather anomalies, and 2) the resulting impacts. Volume 2 of this 2-volume summarization of Water Survey METROMEX activities focuses on a third major goal: the delineation and definition of the causes of the METROMEX precipitation anomalies.

It should be noted that, at this time, the research of the METROMEX data cannot totally delineate the causative mechanisms and that added research is being launched by the Water Survey under NSF sponsorship in 1977 for further studies of the METROMEX data. It should also be noted that a fourth major METROMEX goal, the translation and prediction of anomalies in other areas, has not been satisfied in existing Water Survey METROMEX research projects. Cloud modeling under NSF ENV73-07882, a 3-year grant, will be useful in the eventual translation process. However, a new research project being launched by the Water Survey is focusing on study of the past data in the Chicago area to develop comparisons with findings at St. Louis. This will test the transferability of the findings at St. Louis to another city with a different physical setting.

Goals of the Water Survey Projects

The general goals of the Illinois State Water Survey projects of METROMEX consisted of: 1) the delineation of any anomalies in the precipitation (quantity and quality) and in the severe weather frequencies in St. Louis and environs; 2) the definition of the causes for such anomalies; 3) investigations of the impacts of the weather anomalies on the local area and other urban-agricultural areas of Illinois; and 4) the transmission of all findings to potential users in the scientific community, the government, and the public.

These four broad goals of the Water Survey projects in METROMEX actually consisted of 14 specific objectives involving field operations, data collection, analyses, and research. These objectives also included the application and transmission of the results to various user groups. The 14 specific objectives and activity areas of the Water Survey's METROMEX program appear in table A-1.

A flow chart depicting the 14 areas involved in the Survey's projects and how they interrelated appears in figure A-l. The means of information exchange and transmission of results indicated on this chart reflect how our METROMEX data and findings have been exchanged both with internal (other METROMEX groups) users and with external users.

The goals and activities addressed specifically by the NSF support coupled with state support can be followed by examining table A-l and figure A-l. This support addressed 11 of the 14 goal-activity areas:

- 1 — Identification of rainfall and severe weather anomalies
- 2 — Mapping of surface weather conditions
- 3 — Study of the low-level airflow
- 6 — Synoptic weather analyses
- 7 — Identification of the causes for anomalies
- 8 — Measurements for prediction
- 9 — Local weather impacts
- 10 — Planning information
- 11 — Weather forecasting
- 12 - Applications to planned weather modification
- 14— Transfer of knowledge

General Analytical Approach

Two basic approaches to the analyses of the METROMEX data were employed. The first of these is typified by the results presented here in volume 1. This approach is basically one that treats *all the data* from a particular source in a climatic-type evaluation. That is, total or very large data samples of a given event, say daily rainfall amounts, are treated for all months, seasons, or years of the METROMEX operations. The other basic research approach that has been employed, but not used in this report, has consisted of intensive meteorological analyses of individual periods, usually individual days, exhibiting various precipitation conditions (Changnon and Semonin, 1975). This "case study" approach has been pursued as part of the NSF and related state support throughout METROMEX. Most of these results have appeared in separate publications (Changnon and Semonin, 1975) and also are treated in volume 2 which addresses the causative analyses within the Survey's METROMEX effort.

Table A-1. Specific Goals of METROMEX Program of the Illinois State Water Survey

Goals–Activity Areas	*Duration*	*Milestones**	*Application of findings and users*
FIELD ORIENTED PROJECTS			
1. Study of surface rainfall and severe weather at St. Louis to define their time-space distributions and the presence of any anomalies.	5 Years (±1)	A	Goals 6, 7, 9, 11
2. Study of surface weather conditions (temperature, humidity, and winds) at St. Louis to define their time-space patterns.	5 Years(±1)	A	Goals 6, 7, 9, 11
3. Study of the airflow, circulation, and turbulence over St. Louis.	5 Years(±1)	A	Goals 6, 7, 9, 10, 11
4. Study of aerosols including their general sources, their transport using airflow measurements to clouds, and their deposition, both wet and dry, on the ground in the St. Louis area.	5 Years(±1)	A	Goals 5, 6, 7, 9, 10
5. Study of changes in surface and groundwater quality downwind of St. Louis.	2 Years(±1)	B	Goal 9
INTERNAL APPLICATIONS - ANALYTICAL PROJECT			
6. Mesoscale analyses of the synoptic weather conditions and atmospheric structure with precipitation events to classify events and relate surface conditions to precipitation processes.	5 Years	C	Goals 7 and 12
7. Identification and quantitative definition of the causes for the precipitation anomalies.	Last 4 Years	C	Goals 8 and 13, and other METROMEX groups
8. Definition of the measurements critical to define urban anomalies and their causes in METROMEX and at other cities.	5 Years	C	Goals 1–4, 7 and 11, and other METROMEX groups
EXTERNAL APPLICATIONS			
9. Identification of scientific and business concerns in local St. Louis area where anomalies have relevance.	Last 4 Years	D	City engineers, consulting engineers, water supply superintendents, local farmers and farm associations, ecologists, and weather insurance companies; goal 13.
10. Utilization of pollution data derived from any deposition studies.	Last 3 Years	D	Illinois and federal EPA officials, air pollution studies (RAPS), and local pollution agencies.
11. Definitive information on weather-climatic changes, due to an urban-industrial area, available for local and regional planning.	Last 2 Years	D	City planners, engineers, and zoning boards.
12. Improvements in urban area forecasting of precipitation.	Last 3 Years	D	Meteorologists (forecasters) in government and private practice.
13. Planning for purposeful weather modification experiments in Illinois.	Last 3 Years	D	Water Survey scientists, other meteorologists contemplating rain and severe storm modification projects, and Illinois Advisory Board on Weather Modification Statute.
14. Transfer of knowledge gained and new technologies developed to other scientists and other disciplines.	5 Years	D	The scientific and engineering communities.

* *Milestones*

A. Goal-Activity Areas 1-4 are basically 5-year ongoing projects. They have annual (spring) milestones after data processing and initial analysis sufficient to detect measurement gaps. The final milestone involves summary, interpretation, and presentation of results to users.

B. Has an annual milestone involving review of first year results and re-design (if needed) of second year measurements. Final milestone is completion, summary, and translation of information to users.

C. These studies have 1-year milestones, each aimed at summarizing and reviewing all past results, and the final milestone is the summarization and conclusion of the studies.

D. These activities are basically continuous efforts largely related to user identification, communication of initial results to users, feedback of suggestions from users, and then final communication of findings and results. The only milestone is their completion.

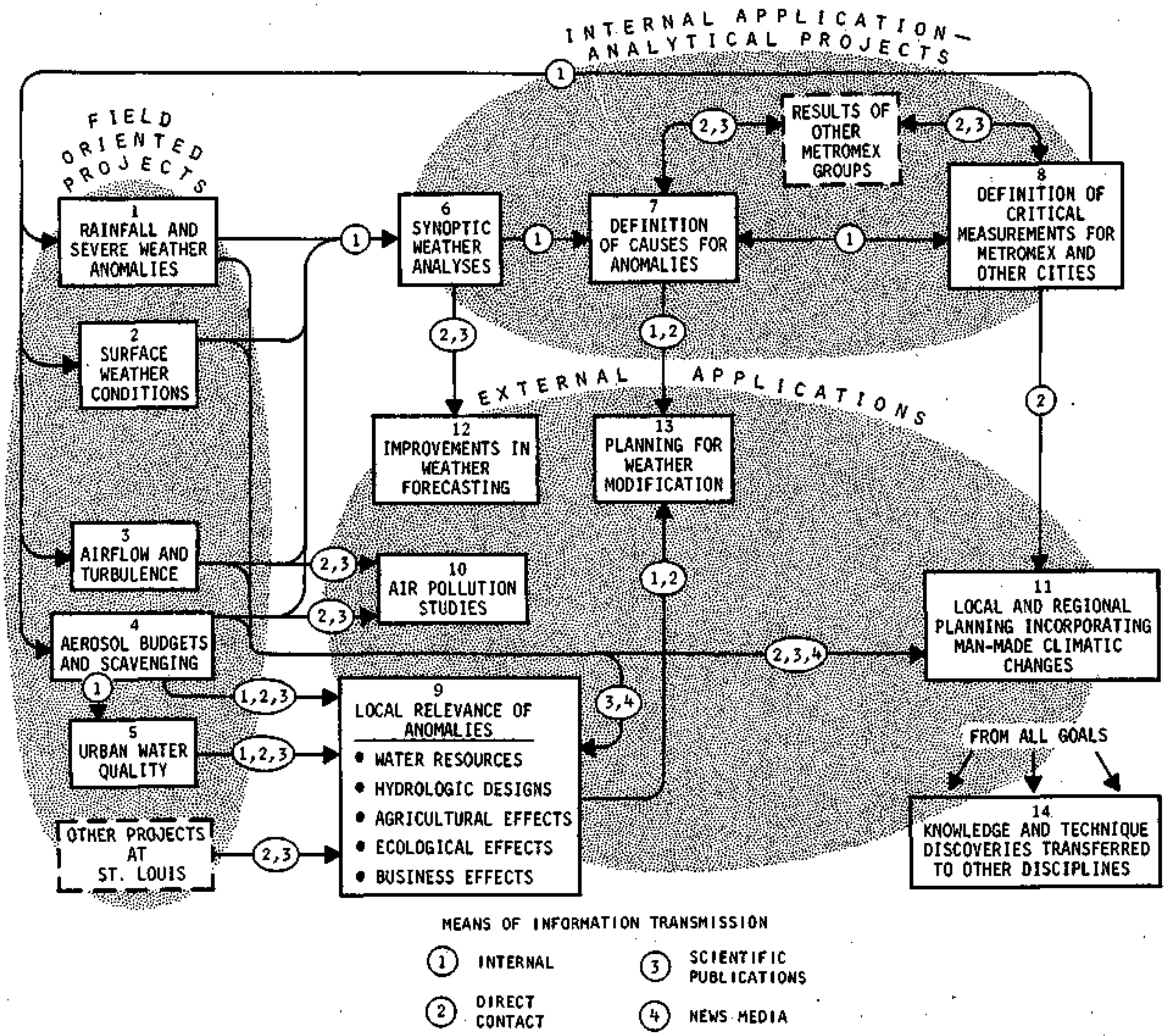

Figure A-1. Interaction of Water Survey METROMEX goal-oriented projects with their internal and external applications

Background and Adjustment to Emerging Findings

The major focus of the METROMEX effort was on summer (June-August) weather conditions. This focus was based on climatic research (Huff and Changnon, 1972) which had indicated the presence of major urban-related precipitation anomalies in this season. Much of the operational effort involving specialized field measurements was conducted during the summer months of the 1971-1975 period. However, half of all the network raingages (every other gage) was kept operating during the other 9 months (September through May) between 1971 and 1975 to gather precipitation information for the transition seasons (fall and spring) and winter (December through February). These data were collected to examine for potential precipitation anomalies in the other seasons.

Other facets of this 5-year field program featured rapid data processing and a quick initial analysis to inspect the results of each summer. A primary reason for this approach was to continually refocus the field operations and analyses as new findings of interest developed. In other words, the experiment over five years was kept as flexible as possible to adapt data collection to new findings. Several major shifts in research and operational emphasis resulted from this approach, as described below.

After the analyses of 1971-1972 data, it became apparent that a localized anomaly . might be produced by the Alton-Wood River industrial area, as well as by the separate St. Louis area. Because of this finding, some 22 recording raingages were installed to the northeast and east (beyond the basic study circle shown in figure B-1) to study in detail the rainfall patterns extending downwind (E and NE) from Alton-Wood River. The Alton-Wood River area field operations also included added cloud photography. This area is essentially an industrial point source with a concentrated petroleum refinery area. It offered a test site to compare effects against those of the industrial area at St. Louis that was separated (south) by several miles.

A second change in focus resulting from the analyses of the early data of 1971-1972 concerned the rainfall findings. The climatological studies had suggested that the urban effect was related only to an intensification of existing precipitation systems, but the METROMEX findings from the radar and the raingage network indicated that the urban areas also led to the initiation of precipitation under certain circumstances. Hence, radar operations beginning in 1973, and the ensuing analyses of radar and raingage data, focused on the initiation of precipitation as well as on its intensification.

Another finding emerging from both the "all-data" analyses and from early case studies was an indication that local rainfall initiation and intensification was related to warm, moist local surface areas. This finding, partially verified in the 1971 field data, led to an increase in the number of surface weather stations so as to better define the warm and humid areas.

A fourth revision of the operations and analyses related to the early cloud findings. The cloud camera operated at St. Louis University indicated that there were favored local areas of cloud formation over the northern portions of St. Louis. This finding led to the installation of two more cloud cameras and the accumulation of GOES satellite data for 1974-1975, all leading to a more intensive effort to study cloud initiation and cloud coverage throughout the METROMEX area.

The aforementioned revisions and shifts of operations and research that occurred during METROMEX were reflected in the equipment utilized under this project. Table A-2 lists the numbers and types of major project equipment employed during the first operational summer, 1971, and in the last operational summer, 1975. In every instance, there was an increase either

Table A-2. Shifts in Major Project Field Equipment during METROMEX Supported by NSF Grants and State' Funding

	1971 *(First summer)*	*1975* *(Last summer)*
Number of recording raingages	220	252
Number of non-recording raingages	0	22
Number of hailpads	220	252
Number of thunder recorders	3	6
Number of cloud cameras	1	3
Radar	Fixed antenna tilt scanning and photographic data	2-3-dimensional antenna scan computer controlled, and digital data
Number of surface temperature-humidity stations	7	25
Number of surface wind stations	6	8

in the frequency or the quality of the projectequipment. All of these shifts were made in relation to findings revealed by the rapid data processing and early study of the results emerging from each summer. For example, the thunder data from 1971-1972 indicated a high in thunderstorm frequency at the stations located 10 to 20 miles (16 to 32 km) east of St. Louis. A major question raised was whether this increase extended beyond the basic METROMEX research circle (see figure B-1). Therefore, three additional thunder recorders were built and put into operation east of the circle.

Other shifts in equipment were made. In 1972, state funds were used to purchase 20 additional recording raingages to replace gages of the U.S. Corps of Engineers in the western half of the network. The Corps gages had proved inadequate for this project because of their intermittent performance during 1971. Also, 21 recording raingages belonging to the University of Chicago were obtained and installed in the "extended area" of 1700 square miles (4403 km^2) to the east of the circle (see figure B-29). These gageswere located oh a 9-mile (14.4 km) spacing to sample precipitation over this large downwind area. This was done because the local high in the Edwardsville area found in 1971 appeared to extend to the NE beyond the circle. This brought the network total recording raingages to 246 in 1972, as opposed to 220 in 1970. Also in 1972, 18 more surface weather stations consisting of standard weather shelters and recording hygrothermographs were purchased with state funds and installed to better describe the surface patterns of moisture and temperature throughout the network circle.

In 1973, the three additional thunder recorders were built and installed. Because of the limitation of the radar antenna in use with the 10-cm radar on this project (an antenna system on loan from NCAR), a proposal was written to NSF in 1973 for a new facility, a new 20-foot diameter antenna, pedestal, and drive system. This antenna and drive system were obtained during 1974 and put into operation in 1975 to furnish 3-diniensional radar data. In addition, a computer was built in 1973-1974 for the 10-cm radar system. This computer permitted remote control operations of the radar and digital recording of the radar data.

In 1974 more equipment revisions occurred. First, the 21 recording raingages in the large extended area were removed and relocated to the northeast of Alton-Wood River with a spacing comparable to that within the METROMEX circle (1 gage per 9 mi^2 or 23 km^2). Hailpads were also installed at these raingages. At the sites where these 21 gages had been in the downwind area, 21 non-recording raingages were installed to maintain daily rainfall records for the summers of 1974 and 1975.

Development of Equipment and Analytical Techniques

Another important aspect of these NSF and state supported projects within METROMEX concerned major developments of equipment and/or analytical techniques. These were important accomplishments needed to ensure the success of the projects.

The first of these was the design and development of remote automatic thunderstorm recorders. These were designed and developed by project engineers and graduate students to operate in remote locales to detect lightning activity which in turn automatically initiated the listening devices for the recording of thunder. These were also designed so the direction that thunder came from could be determined (Gardner, 1976). A second, less complicated and less expensive version of the thunder detector was designed and developed during 1972.

A second major development of this project was a means to analyze the extensive thunder and lightning data. A technique of searching the audio data tapes so as to separate the thunder signal from other noises was developed so that the data could be processed easily.

A third major development in this project was a technique for objective delineation of raincells (Schickedanz, 1973). An important part of this project was to outline and map the rainfall pattern of each individual convective cell (shower or storm) that occurred in the METROMEX network, and with about 1200 cells in each summer, this became a formidable manual (and subjective) task. To remove the time-consuming and uncertain subjective analyses, an objective technique utilizing the digital 5-minute rainfall data was developed so that all raincells could be identified and mapped by computer.

A fourth key technique development related to the 10-cm wavelength (FPS-18) radar system. The need to have continuous radar operations throughout the summer, 24 hours a day and 7 days a week, was a major and costly manpower item. To minimize this cost, a system for the control of the radar operations was developed with a mini-computer. Software was developed so that the movement of the radar antenna and the recording of the data could be done automatically, based on the presence of echoes, without the continuous presence of a radar operator.

Management

Another important aspect of the NSF projects represented by this report concerns the overall management of the METROMEX program, including all of the Water Survey projects as well as those of the nine other scientific groups that participated in METROMEX. The need for centralized project management was urged in 1972-1973 by NSF as the project became funded under the RANN program of NSF. To this end, the Principal Investigator, Stanley A. Changnon, of this series of four sequential NSF grants focusing on urban effects on precipitation and severe weather in St. Louis also served as the "Program Coordinator" for METROMEX in 1971. In this role, Changnon served as a focal point for all individual NSF projects and for communications with NSF and other federal agencies supporting METROMEX. In 1972, Richard G. Semonin of the Water Survey served as the Program Coordinator. At the insistence of NSF in 1972, the Water Survey prepared a proposal to NSF (that was subsequently funded) to provide a full-time research coordinating scientist for METROMEX. Dr. William P. Lowry was employed in this role and served during 1973.

Following 1973, the management of the METROMEX project was handled differently and a coordinating group composed of the Principal Investigators of each of the projects was established. Basically, the lightly controlled management of METROMEX was a major program asset. Each of the research groups had separately funded projects with very little redundancy between groups. Principal scientists of the various groups cooperated well and many joint operational efforts were conducted. An open and free exchange of data between the METROMEX participants has occurred. METROMEX represents a well-conducted large national program that did not have strong central federal control and management. The interest and cooperation of the various METROMEX scientists are apparent in the many jointly authored publications.

Transmission of Results to Users

A major endeavor of these NSF and allied state projects has been to transmit project results to a wide variety of users (see figure A-1). A variety of means were used to accomplish transmission including these two summary volumes. The interactions with users occurred through a variety of media including 1) publications in scientific and technical journals, 2) talks at scientific meetings and seminars, and 3) oral presentations on radio and TV. A reflection of this effort can be gained by inspecting the project publications listed at the end of this volume.

The extensive user interactions that have occurred over 6½ years of these projects are not reported in this volume though most of them, at least through 1976, have been reported in a variety of publications. Any one interested in user interactions of these projects should refer to the following publications. First is the *Interim Report of METROMEX Studies: 1971-1973,* edited by Floyd A. Huff (Huff, 1974). Another report itemizing user interactions is the *Study of Urban Effects on Precipitation and Severe Weather in St. Louis,* the Water Survey's annual report to the National Science Foundation (Changnon, 1973). A third source of information about the user aspects of the project is a publication entitled *RANN Utilization Experiment,* Case Study No. 37; METROMEX. This is an evaluation of METROMEX done by the Research Triangle Institute (1976). A major conclusion of that evaluation of the METROMEX utilization effort is as follows:

> The most immediate and direct, but not unexpected, utilization of METROMEX results has been by state and local agencies in and around metropolitan St. Louis. The application of the results by federal government agencies and the state governments, city governments, business, and industries has been indirect in the sense that the groups are aware of the METROMEX results, recognize their implications in other areas, and are concerned with translation of results into their area. Direct application of METROMEX results by these users will be reconciled to a degree when procedures for translation of results are explicit.
>
> The wide utilization of the results of METROMEX is due to two factors: the first is the significance of the results themselves and their importance to potential users. The second is the strong and very effective efforts made by Mr. Changnon to promote the distribution and utilization of the research results. Based on the utilization of METROMEX, the inclusion in other NSF/RANN-sponsored programs of a person who is specifically responsible for the promotion and dissemination of the results of that program could significantly and positively influence utilization.

An important indication of the attention to user aspects has been a special report for water research interests consisting of a catalog of all heavy rainfall data from the METROMEX Network (Huff and Vogel, 1977).

Further information on user interactions of METROMEX can be found in two special reports prepared by the Water Survey at the request of NSF. Project results have appeared in a large variety of national magazines and on national TV. An estimated 70 million Americans had the opportunity to read about the METROMEX results by the end of 1973 (Changnon, 1974).

Scope of This Report

This report presents the major findings from analyses of data collected during the 1971-1975 METROMEX field operations supported by NSF grants and the State of Illinois. Information is provided on the various types of field measurements employed as well as on the analytical approaches used. A major focus is on the presentation of final interpretations and on the conclusions reached from the 5-year observational program. The report is restricted primarily to climatological-type statistical analyses of the spatial and temporal distribution characteristics of surface precipitation and severe storm events. Volume 2 of this 2-volume series covers analyses directed toward the causation of the METROMEX anomalies.

The text of this report has two major parts, each with several contributions from senior project researchers including Changnon, Huff, Schickedanz, and Vogel. Part B concerns studies of surface rainfall and severe local storms. Part C addresses the impacts defined as related to the urban-produced precipitation alterations. In this section, the primary focus is on impacts to water resources, agriculture, business and industry, the environment, human health and activities, the atmospheric sciences, and institutions. This second section is followed by a general summary with conclusions addressing all parts of this volume. Also included is a list of published papers and reports generated by the NSF-sponsored projects, a glossary of terms used throughout the report, and a listing of the abbreviations and acronyms found throughout the report.

Acknowledgments

The report was prepared under the general supervision of William C. Ackermann, Chief of the Illinois State Water Survey. The principal authors of this document were Stanley A. Changnon, Jr., Floyd A. Huff, Paul T. Schickedanz, and John L. Vogel.

This report has resulted from the cooperation of all staff members involved in the METROMEX program. Each contribution and section of this volume indicates the author of that section, but it should be recognized that numerous staff members materially contributed to the work in all cases. Other past and present staff members who made major contributions in the field operations and analyses reported on herein include Donald Staggs, Douglas Jones, John Wilson, Robert Beebe, Mark Gardner, David Brunkow, Bernice Ackerman, Richard Semonin, Douglas Green, Marion Busch, Elmer Schlessman, Neil G. Towery, and Griffith M. Morgan. The extensive graphic arts work was done under the supervision of J. W. Brothers, and the final manuscript was edited by J. L. Ivens. It should be recognized that in addition to the above named contributors to the work in this report, many other sub-professional and student employees numbering more than 100 have worked on the project since 1971. The entire effort of this large team was needed to bring the project to a successful conclusion.

This report is dedicated to Joe Coons, a friendly and very capable electronic technician who helped install the extensive field equipment and who died during METROMEX.

The advice and aid of the METROMEX advisory panel were of great help. These advisors included Horace R. Byers, Glenn Hilst, and James D. McQuigg.

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Part B. Anomalies in Precipitation and Severe Weather

I. RAINFALL STUDIES

1971-1975 RAINFALL PATTERN COMPARISONS

F. A. Huff

There are three basic levels of investigation needed to evaluate the urban rainfall effect for practical applications in agriculture, hydrology, and climatology. These include the urban effect on 1) monthly and seasonal rainfall patterns, 2) the characteristics of storm rainfall distributions, and 3) the small-scale, short-duration distribution of intense rainfall rates, as portrayed by raincell analyses. In this section, effects of the urban environment and certain topographic features on the monthly and seasonal rainfall patterns will be discussed. The monthly and seasonal patterns provide a measure of the net effect of the urban anomaly, that is, the excess water yield generated by the urban environment over a relatively long period.

Seasonal Rainfall

The 5-year pattern of total rainfall for summer (June-August) is shown in figure B-l. These totals are based on all rainfall recorded in the network, so that amounts are somewhat greater than the objective storm totals derived from 5-minute storm amounts which frequently did not include early June data. Thus, figure B-l and the monthly maps which follow depict the total rainfall distributions for the 5-year sampling period.

The heaviest rainfall was recorded in the Edwardsville area where maximum amounts at the center of the high were over 30% greater than the network mean of 121.00 cm (47.64 inches). The network mean was approximately 83% of normal, based upon long-term normals for the network region published by the National Weather Service.

The Edwardsville high extended southwestward to Granite City and this is a region that is frequently downwind of one or both of the urban-industrial complexes at St. Louis and Wood River. The major low in the seasonal rainfall pattern was located W and SW of St. Louis in a region that is usually upwind of storms moving across the urban-industrial area. There was . a relatively strong high located in the bottomlands of the confluence of the Missouri and Mississippi Rivers in figure B-l, and this is likely related to topographic influences. The bottomlands are a heat-moisture source, and thus an area that is favorable for the development and/or intensification of convective activity.

Another relatively strong high was located in the SE quadrant of the network. This area is downwind of St. Louis with storms moving across the urban area from the NW, is subject to possible bluffs effects, and is downwind of the Ozark foothills with westerly flow or storm movements from W to E. Thus, the SE high is believed to be related to both urban and topographic influences. A secondary region of relatively heavy rainfall was located in the Ozark foothills in the SW quadrant of the network.

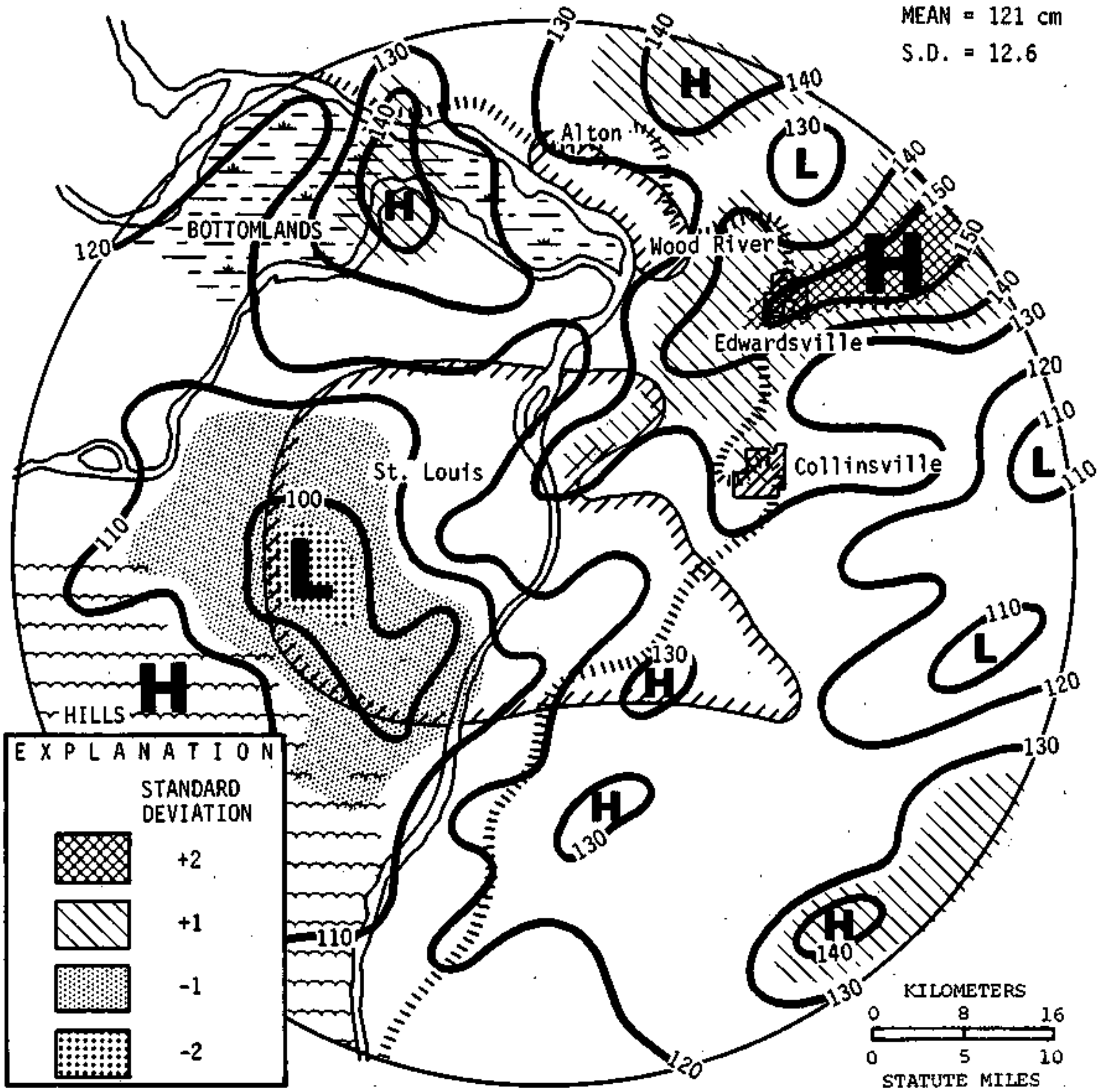


Figure B-1. Total summer rainfall (cm), 1971-1975

Individual seasonal maps are shown in figures B-2 through B-6. Network means ranged from 63% of normal (1971) to 103% (1973). Two years were near normal (101, 103%), and three years were moderately to much below normal (81, 69, 63%), based upon interpolation of the NWS long-term normals for stations in the network region. The Edwardsville high was pronounced in three years (1971, 1972, 1975), was displaced southwestward to the Granite City area in 1973, and was smaller and less intense than usual in 1974. The major low (WSW of St. Louis) was readily apparent in all years except 1971. The bottomlands high was also present in four years. The high area in the SE quadrant could be identified in all years, although its position varied somewhat. In general, the major features of the 5-year seasonal pattern were consistent from 1971 through 1975. Consistency in the seasonal pattern was greater than in the individual months discussed later in this section.

a. JUNE-AUGUST 1971

b. JUNE 1971

c. JULY 1971

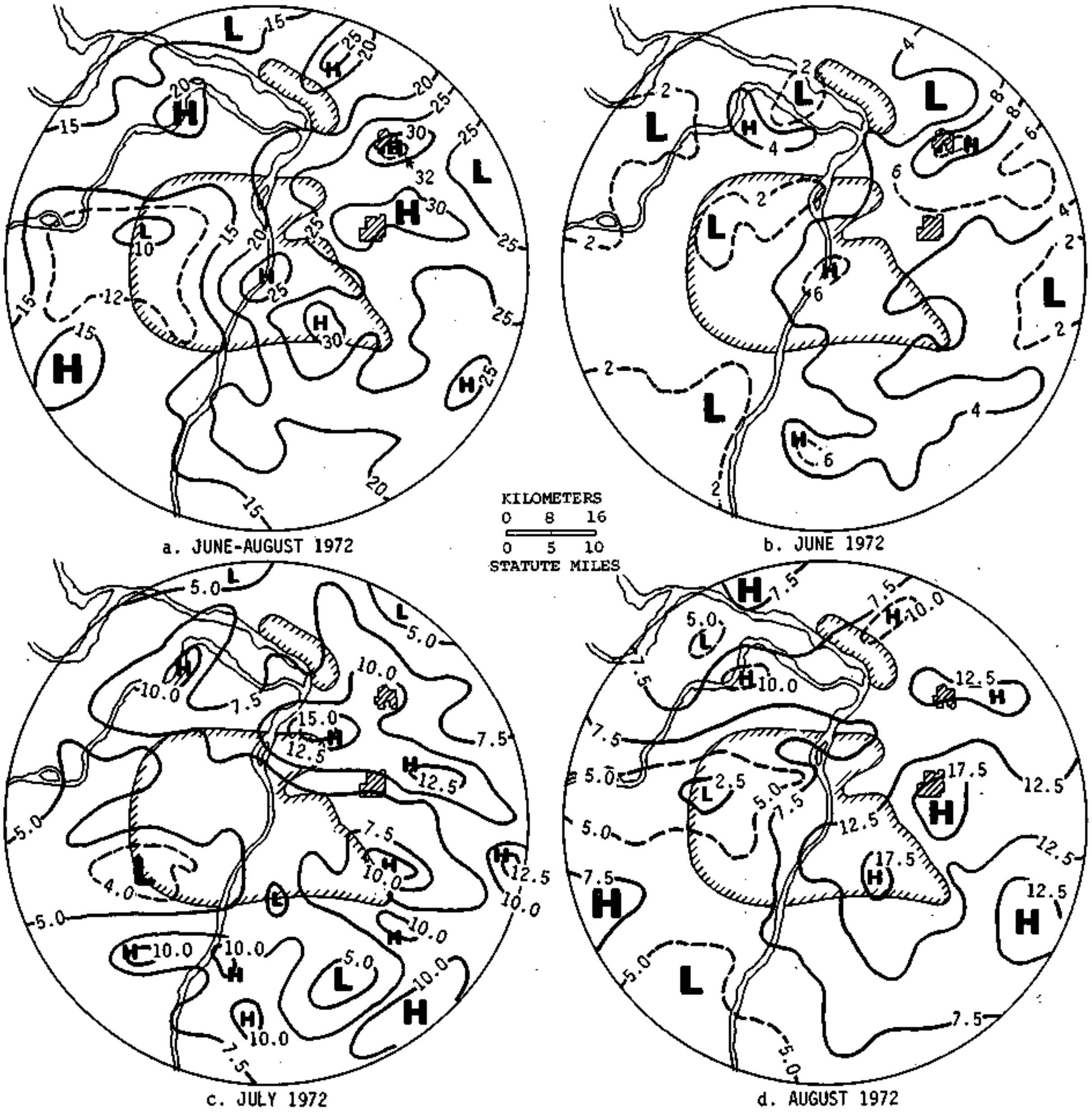
d. AUGUST 1971

Figure B-2. Monthly and seasonal rainfall (cm) in 1971

Monthly Rainfall

The 5-year pattern of total rainfall for June is shown in figure B-7a, and the individual monthly patterns for each year are presented in figures B-2b through B-6b. The 5-year total rainfall for June was only 67% of normal, and individual months ranged from 32% of normal in 1972 to 125% in 1973. Only 1973 had above normal rainfall. Thus, the June 5-year pattern should most nearly represent the rainfall distribution in relatively dry periods.

The most pronounced feature of the June 5-year map was the high rainfall center in the Edwardsville area. The maximum 5-year total of 66.88 cm (26.33 inches) in the center of



a. JUNE-AUGUST 1972
b. JUNE 1972
c. JULY 1972
d. AUGUST 1972

Figure B-3. Monthly and seasonal rainfall (cm) in 1972

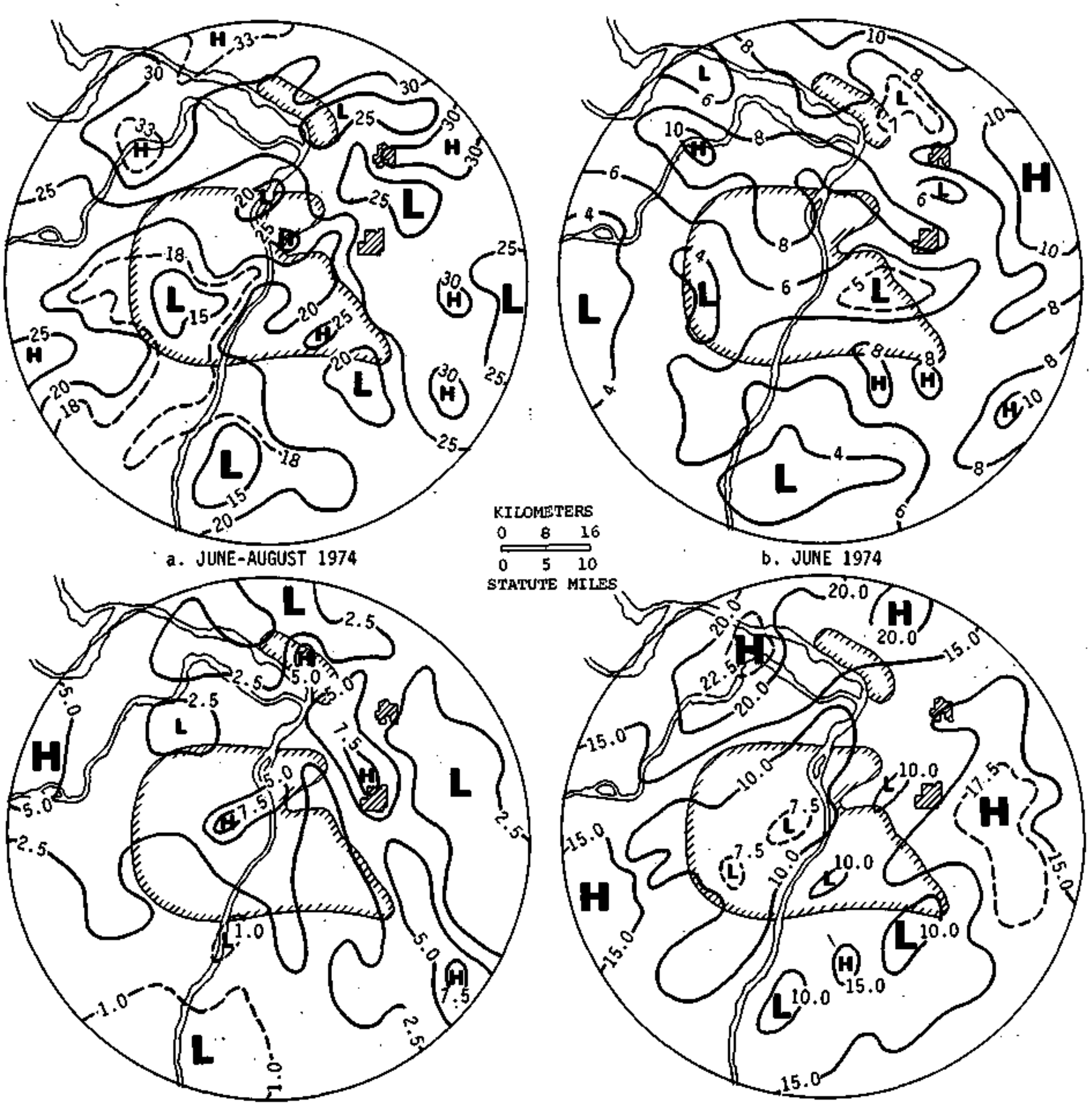
this high was over 20% above normal and was over 80% greater than the network average. As pointed out several times in this report, the Edwardsville area frequently lies downwind of storms crossing both the St. Louis and Alton-Wood River areas, and the region of exceptionally heavy rainfall extending from St. Louis to NE of Edwardsville in figure B-1 is believed to be strongly related to urban influences. Minor highs occurred in the river bottomlands west of Alton-Wood River, in the Ozark foothills in the SW part of the network, and in the SE quadrant which is subject to potential hills-bluffs and urban effects when storms move across St. Louis from NW-SE. Thus, the major high in June appears to be strongly related to potential urban effects and the secondary highs to topographic influences.

a. JUNE-AUGUST 1973 b. JUNE 1973

c. JULY 1973 d. AUGUST 1973

Figure B-4. Monthly and seasonal rainfall (cm) in 1973

Examination of the individual June maps for 1971-1975 in figures B-2b through 6b shows that the major high rainfall area in the Edwardsville region was pronounced in three years, 1971, 1972, and 1975, when amounts in its center were over twice the network mean. All of these months had below-normal rainfall. In the other two years, the Edwardsville high was present, but not as pronounced, and in one year (1974), it was displaced from its usual position. In all years, there was a low W and/or SW of St. Louis. Thus, these major features of the total rainfall pattern for 1971-1975 (figure B-7a) were generally consistent throughout the sampling period. Other highs and lows which are believed to be topographically related were not as con-



a. JUNE-AUGUST 1974

b. JUNE 1974

c. JULY 1974

d. AUGUST 1974

Figure B-5. Monthly and seasonal rainfall (cm) in 1974

sistent during the five Junes. Thus, it appears that the largely urban-related high in the Edwardsville area is a more consistent feature than those related to topographic factors.

Rainfall for each July is shown in figures B-2c through B-6c. Network means ranged from a high of 10.52 cm (4-14 inches) in 1971 to a low of 2.87 cm (1.13 inches) in 1974. This is a variation from 115 to 32% of normal. The total rainfall pattern for July during 1971-1975 (figure B-7b) shows a pronounced area of relatively heavy rainfall extending nearly W-E from the bottomlands near Alton to just E of Wood River. A region of relatively low rainfall extended across the central part of the network through St. Louis, and another high area, oriented W-E,

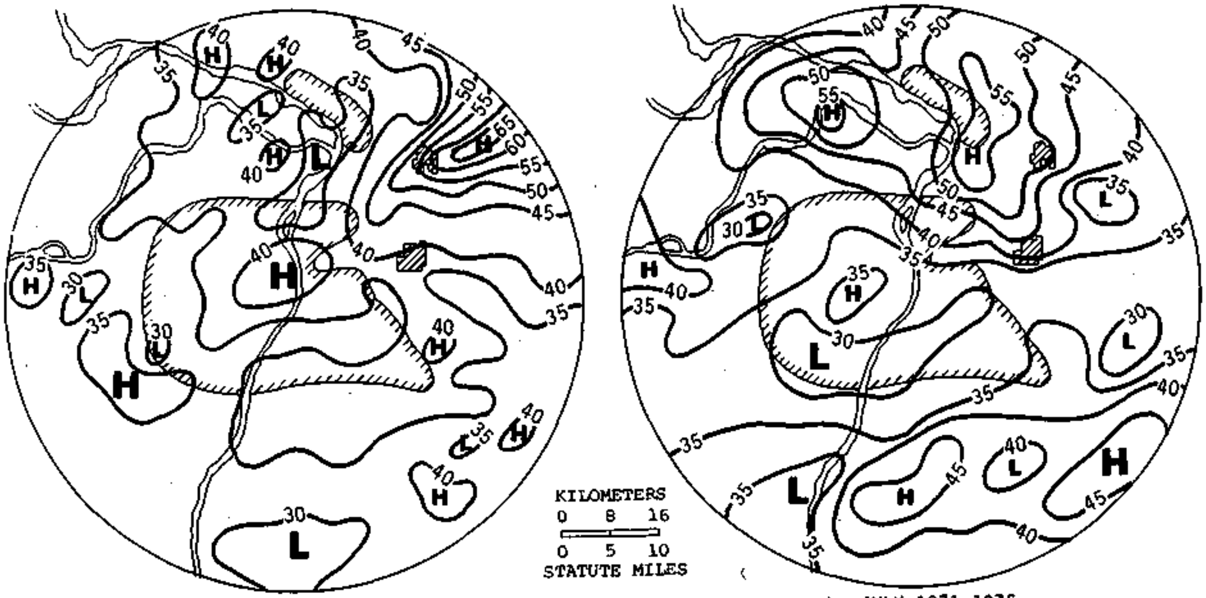
a. JUNE-AUGUST 1975 b. JUNE 1975

c. JULY 1975 d. AUGUST 1975

Figure B-6. Monthly and seasonal rainfall (cm) in 1975

extended across the southern part of the network. For the five years, the network July rainfall was approximately 88% of normal.

Examination of the July rainfall patterns for individual months in figures B-2c through B-6c shows a region of relatively heavy rainfall extending W-E in the northern part of the network in four of the five years. This high was usually in the vicinity of the bottomlands in the confluence of the Mississippi and Missouri Rivers and extended across the Alton-Wood River region. The northern high was suppressed southward in 1972 and was absent in 1974. The persistence of this high is then reflected in the 5-year rainfall pattern for July in figure B-7b which shows two distinct highs, one in the bottomlands and the other in the Wood River area.



a. JUNE 1971-1975

b. JULY 1971-1975

c. AUGUST 1971-1975

Figure B-7. Total monthly rainfalls (cm), 1971-1975

During the 5-year period, a low area was consistently present in July through the central part of the network, including the St. Louis urban area. This produced the W-E low across the St. Louis area in the 5-year pattern in figure B-7b. The other persistent feature of July rainfall during 1971-1975 was the presence of a region of relatively heavy rainfall across the southern part of the network. This southern high was present in all individual Julys except 1974, and produced the three southern high centers shown by the 5-year pattern.

Evidence of urban enhancement of July rainfall is not indicated downwind (E) of St. Louis in the 5-year pattern of figure B-7b. Actually, the pattern is similar to the dry season pattern identified by Huff and Changnon (1972) in their earlier study of the urban climatology of the St. Louis area. However, the St. Louis low occurred in both above-normal and below-normal months, so it does not appear to be related strongly to general rainfall conditions.

The 5-year July pattern does show a relatively strong high in the Wood River area which may be related to effects from the oil refineries, steel mills, and other heavy industry located upwind (SW) of the Wood River high. Other highs in the 5-year pattern appear to be related to possible bottomlands effects in the confluence of the rivers, and to the Ozark foothills in the southern part of the network.

The 5-year pattern of total rainfall for August is shown in figure B-7c, and the individual monthly patterns are illustrated in figures B-2d through B-6d. The most pronounced features of the 5-year pattern were an area of relatively heavy rainfall in and immediately east of the St. Louis industrial area (east of the Mississippi) and a large low area west of St. Louis. This low also extended northeastward to the Wood River region. In general, the rainfall was heavier in the region east of the Mississippi which is frequently downwind of the urban-industrial complexes. The major low is in a region (W of St. Louis) that is usually upwind of the St. Louis urban-industrial area. The network mean for August in the five years was 99% of normal and this resulted from three above-normal and two below-normal years ranging from 21 to 156% of normal. Thus, the August rainfall for the 5-year period should reflect close to average conditions for the network region, and sampling from a wide range of weather conditions.

The individual monthly maps for August in figures B-2d through B-6d show that the high rainfall region east of St. Louis was present as a primary or secondary high in the same general region during all five years, and, therefore, was persistent under various types of rainfall conditions. Other features of the 5-year map (figure B-7c) were not nearly as persistent during the sampling period. For the five years, the total rainfall at the center of the high in the eastern urban-industrial area of St. Louis was approximately 40% above the network mean. This large departure from the network mean is best explained by urban enhancement of rainfall in storms crossing the urban-industrial complex of St. Louis.

Departures from Network Mean

Another aid in evaluating the urban and topographic anomalies is to determine the departure of the rainfall at each raingage from the network mean rainfall. A convenient way to evaluate the findings is to express the raingage rainfall as percent of network mean precipitation. This has been done in figures B-8a through B-8d for seasonal and monthly rainfall during the summers of 1971-1975, based on the climatic sample.

The seasonal map (figure B-8a) shows positive departures of 20 to 30% in the Edwardsville high and 10 to 20% in the bottomlands high. Similarly, the primary low west of St. Louis recorded amounts that were 80 to 85% of the network mean. The departures at the center of the Edwardsville high were two to three standard deviations greater than the network mean, and the low center had amounts that were approximately two standard deviations below the network average.

The June map (figure B-8b) shows values 60 to 80% greater than the network mean, and this was the greatest areal departure for any month. Other departures did not exceed 20% in June. The Edwardsville maximum was over three standard deviations greater than the mean. Six raingages recorded values over three standard deviations from the mean, and this is considered strong evidence of the urban anomaly, when such differences are maintained over a period of five years.

a. JUNE-AUGUST 1971-1975

b. JUNE 1971-1975

c. JULY 1971-1975

d. AUGUST 1971-1975

Figure B-8. Ratios of gage to network mean rainfall by month and season, 1971-1975

Maximum July departures (figure B-8c) were recorded in the bottomlands and Wood River areas where they ranged from 30 to 50%. August departures (figure B-8d) were greatest in the region immediately east of St. Louis where they reached values of 30 to 40% at several stations.

References to figure B-8 show that the large departures are grouped rather than scattered in a random manner. It is this grouping that is considered most indicative of precipitation anomalies in the METROMEX Network, particularly in the Edwardsville region of relatively heavy rainfall and in the area west of St. Louis having relatively light precipitation.

Statistically, one would expect about 11 gages (5% of 225 gages) to equal or exceed two standard deviations and two gages to exceed three standard deviations. On the seasonal map, 12 stations had ratio values that were equal to or greater than two standard deviations. This is very close to what would be expected statistically. However, five of these gages (nearly one-half) were clustered in the Edwardsville area. There were the expected two gages that exceeded three standard deviations, and these were in the Edwardsville area also.

In June, which contributed the most to the Edwardsville seasonal high, there were nine gages that exceeded two standard deviations in the Edwardsville region. Also, there were six gages that exceeded three standard deviations. In July, 10 stations exceeded two standard deviations and these were mostly in the Wood River region. In August, 11 stations equaled or exceeded two standard deviations.

Thus, analyses of the monthly and seasonal departures indicate a clustering of the large departures, and this clustering is very outstanding in the Edwardsville region in the June and total seasonal rainfall patterns. Although not conclusive proof, this analysis provides another piece of evidence supporting the urban anomaly and its maximization in the Edwardsville area.

Distribution of the Edwardsville Deviations

The cause of the Edwardsville anomaly was further investigated through determination of the departure from network mean rainfall in the Edwardsville area in each of 330 storms which produced measurable rainfall in the network. The Edwardsville area was defined by a rectangle enclosing 9 raingage stations (see figure B-25). The deviations were grouped into positive and negative values and ranked. The network mean rainfall, synoptic storm type, and storm motion were determined for each deviation, so that their relationship with these storm parameters could be determined.

From the rankings of the deviations, it became apparent that a major portion of the Edwardsville anomaly produced by the positive deviations occurred in a relatively small portion of the storms. Also, negative deviations far outnumbered the positive deviations. Among the 330 storms, only 76 (23%) had positive deviations. There were 146 cases of negative deviations and 108 storms in which no deviation occurred. However, 85 of the negative deviations occurred with storms producing no rain in the Edwardsville area. Those storms with no deviation were mostly very light rainfalls having network means less than 1 mm (0.04 inch). Thus, 23% of the network storms were responsible for the Edwardsville anomaly.

Further investigation showed that 23 of the storms with positive deviations in the Edwardsville area contributed 83% of the total rainfall accumulated in the 76 positive deviations. Thus, most of the Edwardsville anomaly was compiled in only 7% (23/330) of the network storms. Analyses of network mean rainfalls in these 23 storms showed them ranging from 2.75 mm (0.11 inch) to 53.00 mm (2.09 inches). However, over 50% of the storms produced network means exceeding 12.5 mm (0.50 inch) and 73% produced network means exceeding 6 mm (0.24 inch). Thus, the large positive deviations tended to be associated with relatively heavy storms in the surrounding region. Over 50% of these storms produced mean rainfalls exceeding 25 mm (1.0 inch) in the 9-station Edwardsville area.

Figure B-9 shows the network rainfall pattern associated with the 23 storms largely responsible for the Edwardsville anomaly. The mean in the Edwardsville area was 68.6 cm (27 inches) compared with a network mean of only 28.0 cm (11 inches). The Edwardsville mean was 2.45 times the network mean and the 9-station mean was over 3 standard deviations above the network mean. No other region in the network experienced rainfall close to that in the Edwardsville area.

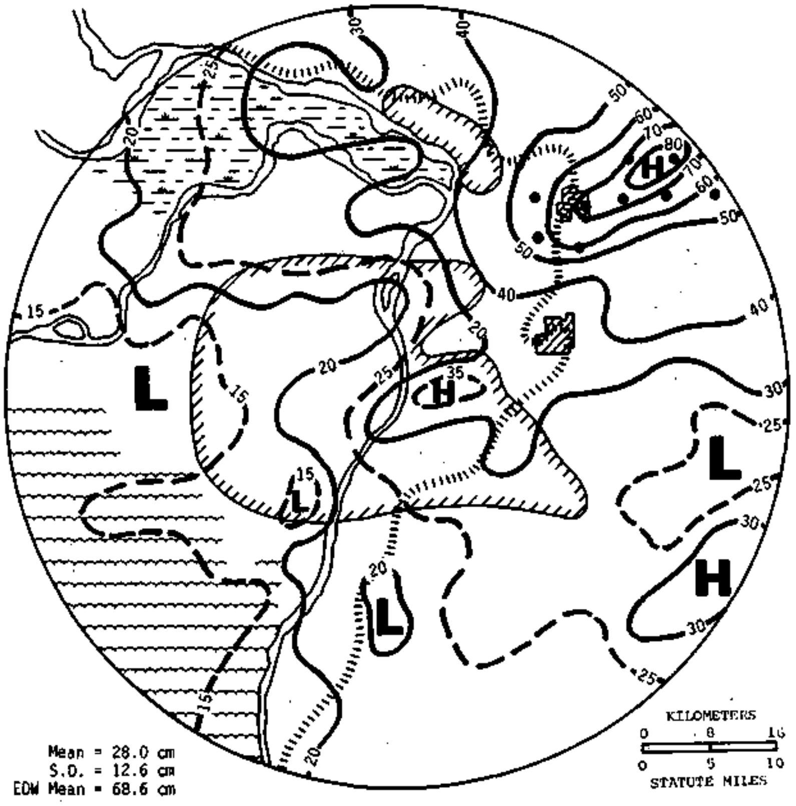


Figure B-9. Rainfall distribution in 23 storms largely responsible for the Edwardsville anomaly

The 23 storms were grouped according to storm movement and synoptic storm type. Squall lines were the most frequent cause of these storms. They accounted for 12 of the occurrences, followed by cold fronts with 5 occurrences and squall areas with 4 occurrences. None was associated with unorganized air mass storms. Thus, these three types were associated with 91% (21) of the storms, which is much above the average frequency of these storm types which were associated with 53% of the network storms during 1971-1975. Squall lines were associated with 12 (52%) of the 23 storms, whereas their average frequency for the 5-summer period was 25%. Squall lines are the heaviest rain producers among the various synoptic types, based on average rainfall per storm (see section on synoptic weather relations).

Analyses of storm movements showed that 12 (52%) of the 23 storms had raincells moving from the WSW, and 6 storms (26%) had cell movements from the SW. Combining all 1971-1975 storms, 32% moved from the WSW, and 20% from the SW. Thus, WSW movements were much more frequent than average in the 23 storms strongly associated with the Edwardsville anomaly. Surface winds were from the SE or SW quadrants in 21 of the 23 storms, and these winds usually occur in advance of summer convective storms.

The foregoing analyses have shown that the Edwardsville anomaly is produced largely by a relatively few storms which occur in organized storm systems producing relatively heavy rainfall in the surrounding area. These anomaly producers are most frequently squall lines in which the convective elements are moving from the WSW or SW, which would result in traverses across the urban-industrial regions (East St. Louis-Granite City-Wood River) in the direction of Edwardsville. The storms occur most frequently in June (10/23) and during near normal to relatively wet months, although 6 (26%) did occur in the 6 driest months of the 15-month sampling period. Time did not permit more detailed analyses of the 23 individual storms, but this would be most desirable and could contribute to explanation of the urban-induced anomaly.

Rainfall Patterns Grouped by Storm Intensity

As a part of the general rainfall analyses, the seasonal rainfall patterns were determined for storms of various intensity, based upon the objective storm sample for the five summers. Total rainfall at each gage was determined for those storms in which the rainfall was less than 2.5 mm (0.10 inch), 2.5 to 6.0 mm (0.10-0.24 inch), 6.1 to 12.5 mm (0.25-0.49 inch), 12.6 to 25.4 mm (0.50-1.00 inch), and > 25.4 mm. The frequency of rainstorms in each of the above groups was also determined for each network raingage. The primary purpose of this study was to ascertain whether the urban anomaly is present in storms of all intensities, or whether it is primarily associated with heavier storms, as suggested by METROMEX studies of those storms producing 25 mm or more of rainfall (Huff and Schlessman, 1974), and by earlier climatic studies (Huff and Changnon, 1973).

Figure B-10 shows the pattern of total rainfall in the various storm groups. The rainfall distribution in the lightest storms (< 2.5 mm) shows a rather random pattern. The Edwardsville high in the seasonal total rainfall pattern (figure B-1) is replaced by an area of light rainfall, and the low W and SW of St. Louis is replaced by an area of heavy rainfall relative to the network mean of 50 mm (1.95 inch). Also missing is the bottomlands high. In many respects, the pattern is the opposite of the total rainfall pattern.

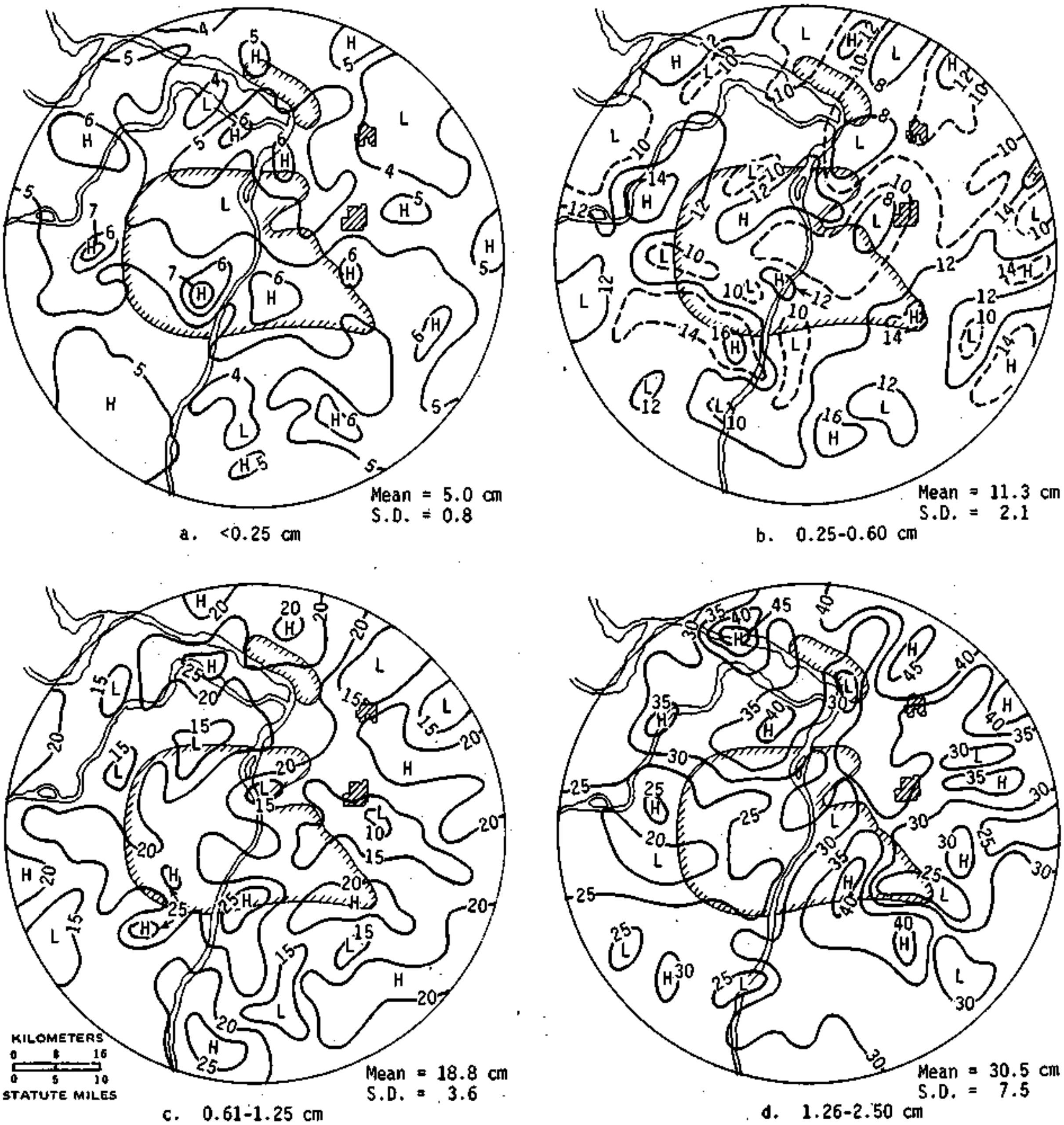
Figure B-10b illustrates the pattern for storms producing 2.5-6.0 mm of rainfall. A rather random distribution of small areas of relatively light and heavy precipitation is indicated, but one of the high areas is located in the Edwardsville region.

The pattern for storm rainfalls of 6.1 to 12.5 mm in figure B-10c does show a strong high in the bottomlands, but a low is situated in the Edwardsville area. However, the seasonal high in the SE quadrant of the network also appears on this map, and relatively light rainfall is indicated in the metropolitan area and some areas west of the city. This pattern resembles the seasonal pattern more closely than the previous maps.

Figure B-lOd shows the distribution of network rainfall in storms producing 12.6 to 25.4 mm. The bottomlands high and the upwind low of the seasonal pattern of total rainfall are present. Generally heavy rainfall is indicated in the Edwardsville region, although the peak amounts are displaced somewhat from the seasonal maximum. Overall, the pattern is quite closely correlated to the total rainfall pattern.

However, the really close relationship is between the patterns for rainfall exceeding 25 mm and the total seasonal rainfall, as shown by comparing figures B-l and B-79. This is not surprising, since 42% of the network rainfall occurred in storms of 25 mm or more, compared with 27, 17, 10, and 4%, respectively, for storms in the groups that include storms of 12.6 to 25.4 mm, 6.1 to 12.5 mm, 2.5 to 6.0 mm, and less than 2.5 mm. The two heaviest groups combined accounted for over two-thirds of the summer rainfall, so that these storms dictated the seasonal pattern to a large extent. As pointed out elsewhere in the discussion of heavy storms, the major high in the Edwardsville area resulted primarily from storms producing 25 mm or more.

Figure B-11 shows the frequency of storms in the various groups. These maps provide further verification of the role of heavy storms in producing the Edwardsville high.- Within the central part of the Edwardsville high (gages 37, 38, 50, 51, 52), the total frequency of storms was approximately 8% below the network average. However, the frequency of 25-mm storms was



Mean = 5.0 cm
S.D. = 0.8
a. <0.25 cm

Mean = 11.3 cm
S.D. = 2.1
b. 0.25-0.60 cm

Mean = 18.8 cm
S.D. = 3.6
c. 0.61-1.25 cm

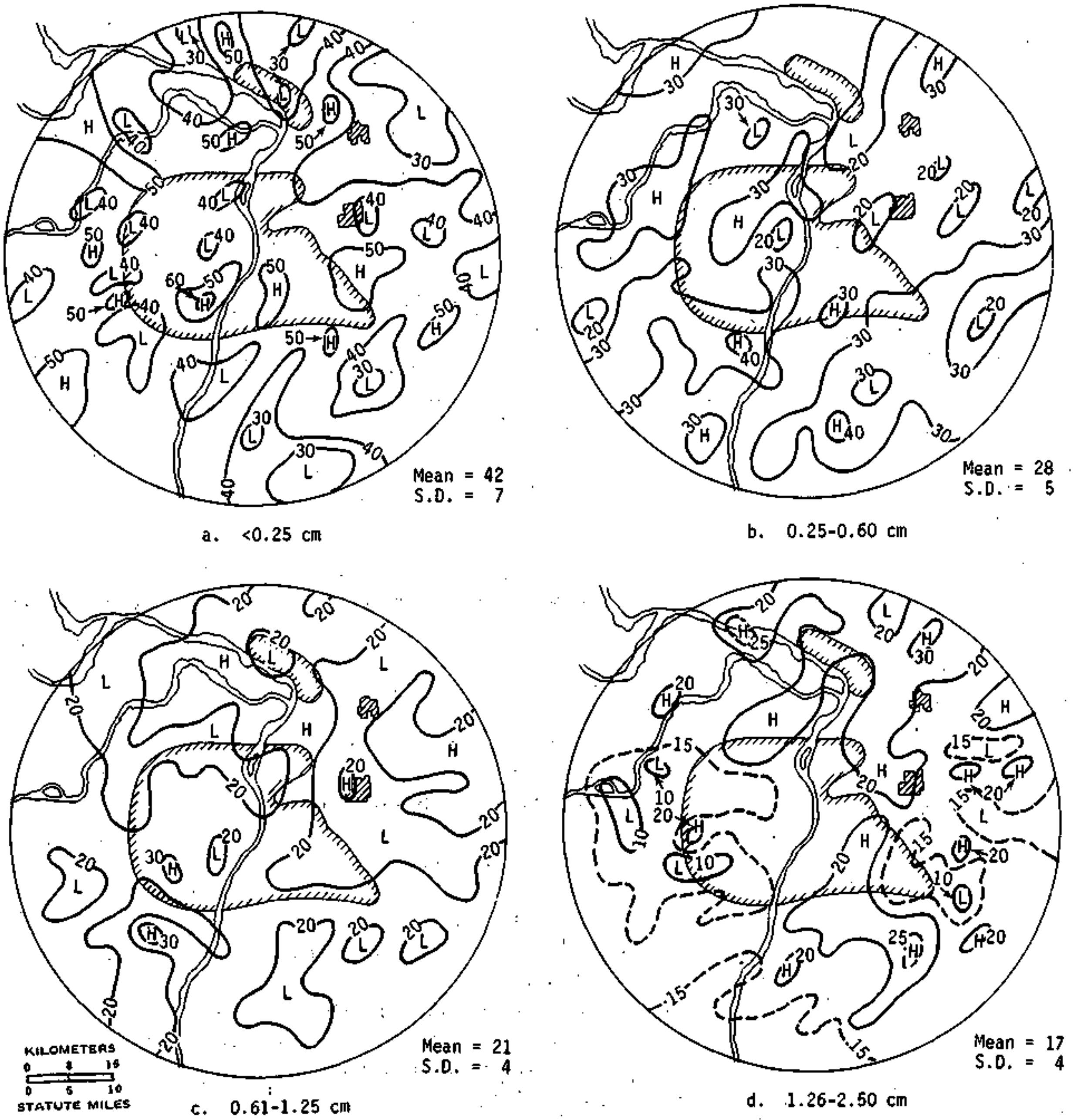
Mean = 30.5 cm
S.D. = 7.5
d. 1.26-2.50 cm

Figure B-10. Pattern of total rainfall by storm intensity group, 1971-1975

nearly twice (175%) the network average frequency of these storms. Similarly, the Edwardsville high had the network average of 17 storms in the group having rainfall of 12.6 to 25.4 mm, but had 9, 17, and 28%, respectively, fewer storms in the categories of 6.1 to 12.5 mm, 2.5 to 6.0 mm, and < 2.5 mm.

Comparison of Patterns in Wet and Dry Periods

Analyses were made to determine whether the rainfall distribution varied between wet, dry, and moderate rainfall periods. For this purpose, the 15 months in the 5-summer sample



a. <0.25 cm

b. 0.25-0.60 cm

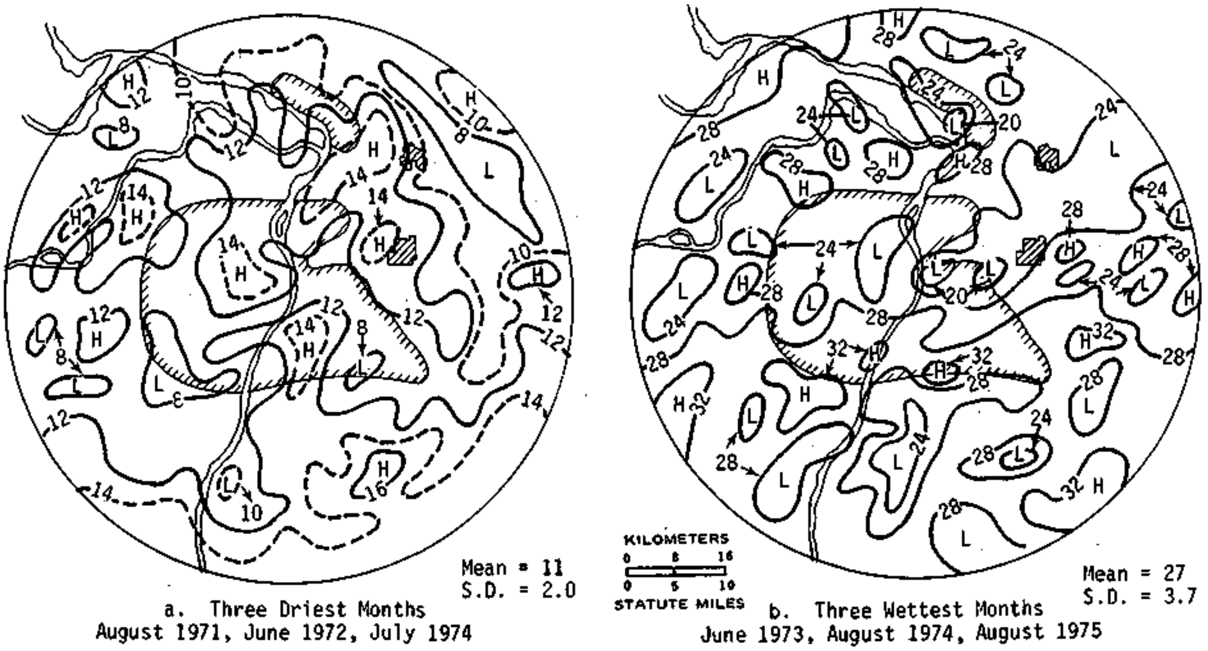
c. 0.61-1.25 cm

d. 1.26-2.50 cm

Figure B-11. Frequency of rains by stprm intensity group, 1971-1975

were divided into five groups of three months each. These were designated dry, moderately dry, near normal, moderately wet, and wet periods. Maps were then prepared showing the distribution of total rainfall and frequency of measurable rain days in each group.

Figure B-12a shows the frequency distribution of rainy days for the dry period which consisted of August 1971, June 1972, and July 1974.. Total rainfall varied from 21 to 32% of normal in these three months. The frequency map shows a trend for rainfall to occur most often in exceptionally dry periods along the river valleys, in the vicinity of the urban area, and in the hill regions in the SW and SE parts of the METROMEX Network. The high in these parts of the



a. Three Driest Months
August 1971, June 1972, July 1974

b. Three Wettest Months
June 1973, August 1974, August 1975

Figure B-12. Frequency of rains for dry periods and wet periods

network is likely related to both hill and river valley effects (moisture source), since the Kaskaskia basin is located just off the SE part of the network.

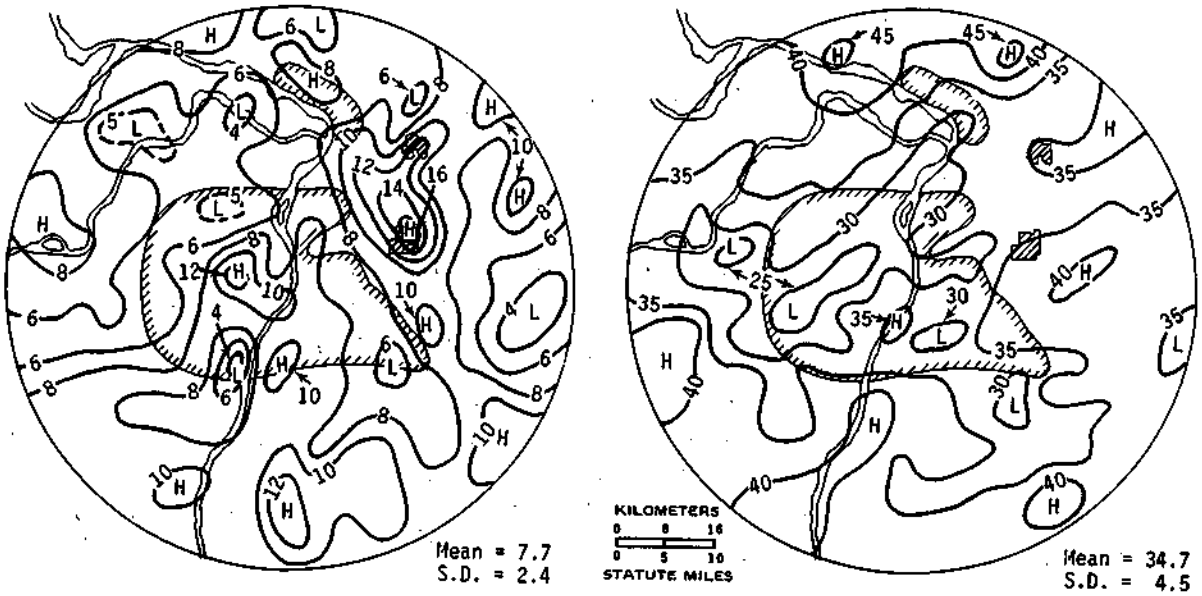
Thus, inadvertent modification by the city and topographic factors are apparently present in relatively dry months. In turn, this provides evidence that the weather modification potential is present in dry periods, and that some success in alleviating water shortages might be achieved during drought conditions.

Figure B-12b shows the frequency distribution of rainy days in the three months of heaviest rainfall. These included June 1973, August 1974, and August 1975. Monthly totals varied from 125 to 156% of normal in these three months with an average of 140%. The urban high is not indicated in the heavy rain months and the high and low areas have a more random distribution than in the dry months discussed above.

Examination of frequency maps for the other periods (not shown) indicated a pattern in the moderately dry months similar to that for the exceptionally dry months. The maps for near normal and above normal periods showed nearly random distribution of highs and lows, quite similar to the heavy rain pattern of figure B-12b.

Figure B-13a shows total rainfall for the three dry months. The heaviest rainfall occurred along the Mississippi River Valley in and downwind (east) of the St. Louis urban area and in the SE quadrant of the network. Similar to the frequency distribution, there appears to be a tendency for urban and topographic effects to beoperating in exceptionally dry periods, and this is favorable from the standpoint of the potential of weather modification in drought conditions.

Figure B-13b shows the total rainfall pattern for the wet months which averaged 140% of normal. The Edwardsville-Granite City high, the most pronounced feature of the 5-summer. period, is evident. In fact, the heavy rainfall map is similar in most areas to the total 5-surnmer map of figure B-1. Therefore, the urban and topographic factors appear to be operating in the establishment of the total rainfall pattern, although their presence was not readily apparent in the frequency map of figure B-12b. The Edwardsville-Granite City high definitely was not



a. Three Driest Months,
August 1971, June 1972, July 1974

b. Three Wettest Months
June 1973, August 1974, August 1975

Figure B-13. Total rainfall (cm) for dry months and wet months

present on the frequency map. This implies that this major high of figure B-1 is partially produced in relatively rainy months, but the increase is due to enhancement of ongoing storm systems rather than more frequent rains.

Total rainfall maps for the other periods (not shown) all indicated many features of the total 5-year map of figure B-l, including the Edwardsville-Granite City high. Although all features of the 5-summer map were not present on all period maps, most were and these were most pronounced on the maps for moderately wet and wet periods.

Computations were made of the rainfall excess in the Edwardsville high by comparing the average rainfall in that region with the network average. This was done for each of the wet, dry, and moderate groups. Gages 38, 50, 51, and 52 were used to represent the core of the 5-summer Edwardsville high. Results showed that the rainfall in the dry periods was 40% greater in the Edwardsville high than the network average; Similarly, the 4-station mean was 88% greater in the moderately dry months, only 1% greater in the near normal period, 32% more in the moderately wet months, and 10% greater in the wet months. Combining the six dry-type and the six wet-type months, it was found that the Edwardsville high exceeded the network average by 74% in the relatively dry months, compared with 20% in the relatively wet months. These computations indicated that the urban effect, which is primarily responsible for the Edwardsville excess rainfall is relatively stronger in dry periods. The total amount of excess rainfall (departure from network mean) in the Edwardsville high averaged 9.55 cm for the six dry months and 6.50 cm for the six wet months.

In general, the analyses of relatively wet, moderate, and dry rain months indicated that the urban and topographic factors are operating under all types of precipitation climate. During dry months, a trend for rainfall to occur more frequently along river valleys, in hilly regions, and in heavily urbanized regions was noted. These findings are favorable from the standpoint of weather modification potential, particularly in drought conditions when water shortages are likely to become critical. The results suggest that certain topographic and land use features (river valleys, hills, urban areas) are favorable regions to initiate weather modification activities during dry periods.

FALL, WINTER, AND SPRING PRECIPITATION ON NETWORK

F. A. Huff

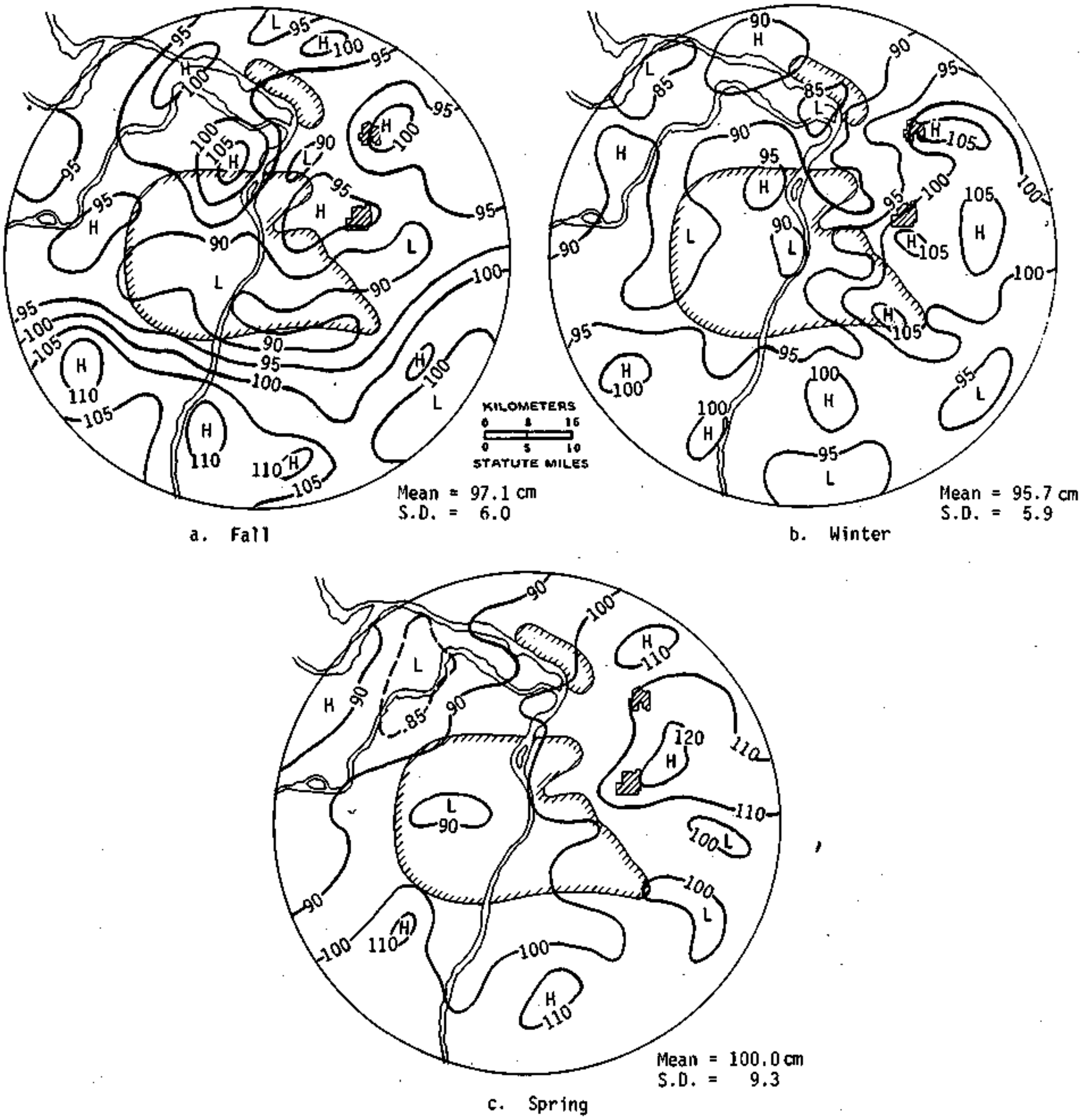
Limited analyses of the spatial distribution of precipitation were performed for fall (September-November), winter (December-February), and spring (March-May) on the METROMEX network. During these three seasons, the network was on a reduced operational schedule with raingages spaced approximately 10 km apart instead of the 5-km spacing used in summer. However, except for early fall and late spring the spatial variability is much less than during summer, so the off-season network should provide reliable distribution patterns. Data were complete for four falls (1971-1974), four winters (1971-1972 through 1974-1975), and three springs (1972-1974). Analyses have been restricted mostly to monthly and seasonal precipitation. However, for the first three winters the data were stratified by the 500-mb winds and synoptic weather types associated with each storm. Isohyetal analyses of individual storms have been performed also for the first two winters to search for evidence of urban effect.

Fall Precipitation

Total precipitation for four falls (1971-1974) is shown in figure B-14a. The network mean of 97.08 cm (38.22 inches) was 9% above the long-term normal for the network region, based upon records of the National Weather Service (NWS). The heaviest precipitation did not occur in the Edwardsville-Granite City region as in summer. However, there was a secondary high indicated in this region and there were other similarities to the summer pattern. Thus, there were also secondary highs over the bottomlands and in the SE quadrant of the network. There was also a low W of St. Louis which is similar to the summer pattern, but in fall this low extends eastward across the network.

As pointed out in the discussion of the summer diurnal patterns, this W-E low across the network is present in summer also, except for late afternoon when convective activity maximizes over and E of St. Louis. This convective period then masks out the low area in the total summer rainfall pattern of figure B-1. With convective activity much less frequent in fall than in summer, the W-E low is maintained in the network pattern of total seasonal rainfall. The heaviest fall precipitation occurred in the hilly regions in the extreme SW and S parts of the network, and this area is located near secondary highs in the summer pattern.

The relative variability was considerably less in fall than in summer. Thus, the coefficient of variation was 6% for the four falls compared with 10% for the five summers. On the basis of the monthly and seasonal analyses of fall precipitation, it is not possible to determine whether the secondary highs in the Edwardsville area, where the deviation from the network mean is 10% or less, reflect an urban-induced enhancement of precipitation. Also, the high in the Edwardsville region was present in only two of the four falls for which METROMEX data were available. If an urban effect is present in fall, our analyses indicate that it is relatively weak in comparison with the summer anomaly.



a. Fall

b. Winter

c. Spring

Figure B-14. Total fall, winter, and spring precipitation

Winter Precipitation

Figure B-14b shows the total precipitation pattern for the four winters. The network average was 95.66 cm (37.66 inches) which was 42% above normal, based on long-term precipitation records of the NWS in the experimental area. Similar to the 5-summer pattern of figure B-l, the precipitation was considerably greater east of the Mississippi River which is usually downwind of the urban-industrial areas, based upon storm movements and low-level wind directions. The

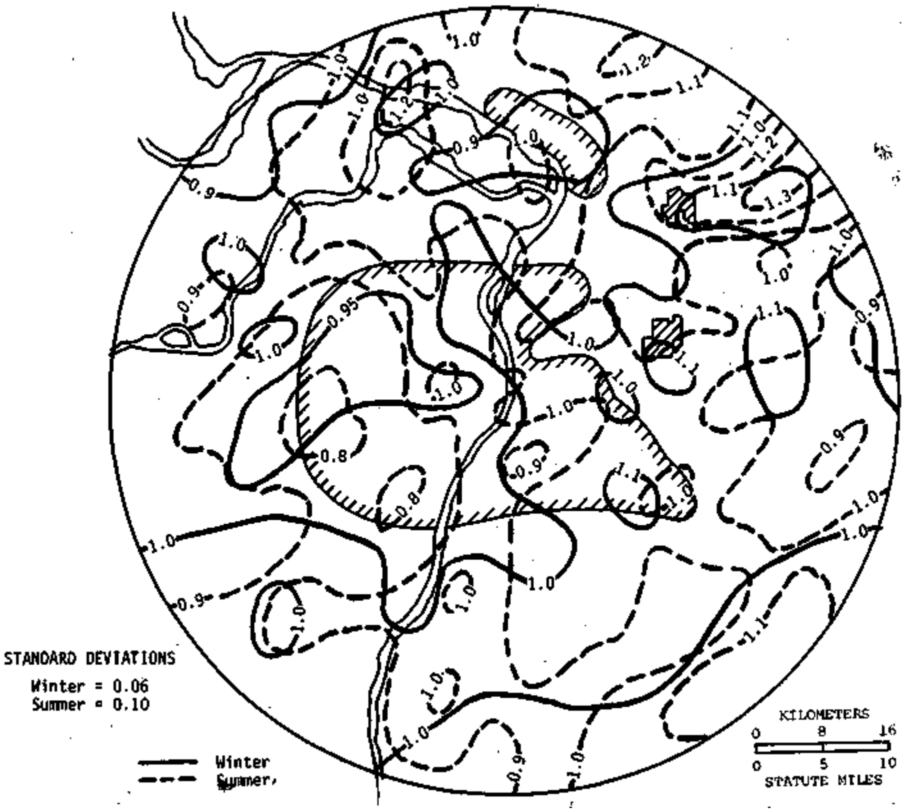


Figure B-15. Ratios for summer and winter rainfall

maximum precipitation of 112 cm (44.10 inches) was recorded E of Edwardsville where the summer maximum was located also. The maximum was 17% above the network mean. Differences were much larger in the summer when the peak amounts in the Edwardsville area were 30 to 35% above the network mean. Another feature of the winter map that is similar to the summer pattern is the location of a major low area over and west of St. Louis.

Figure B-14b shows secondary highs located in the SW to SE parts of the network where the precipitation may be enhanced by the Ozark foothills in those regions. In general, spatial variability within the network was small compared with summer. The coefficient of variation of the winter precipitation was 6%, whereas it was 10% in summer.

Figure B-15 shows the spatial patterns of winter and summer precipitation obtained by dividing the precipitation at each raingage by the network mean. This provides further definition of similarities and differences between the two seasons. The only ratios exceeding 1.0 in winter were located E and NE of St. Louis in the region of Edwardsville-Collinsville-Belleville. Over the rest of the network, ratios generally varied from 0.9 to 1.0. Note also that the bottomlands high, which is pronounced on the summer map, was eliminated except for one small area having a maximum ratio of 1.04. This heat-moisture source would not be expected to influence the winter precipitation, so that any enhancement would have to be from the bluffs or associated with infrequent plume movement off the urban-industrial region.

The urban anomaly (if present) is difficult to evaluate for two reasons. First, it is apparently small compared with summer. Secondly, precipitation normals for the Midwest published by the National Weather Service indicate a gradual decrease in winter precipitation from the SE to NW, and this may be a factor contributing to the 4-winter pattern. However, the region NE-E-SE of St. Louis is a region of relatively heavy rainfall in all seasons, regardless of climatic patterns and departures from normality during the sampling period. As pointed out earlier, the 4-winter precipitation was 42% above normal in the experimental area. The 5-summer rainfall was only 83% of normal. However, both seasons had quite similar patterns east of St. Louis.

Inspection of maps for the individual winter months (not shown) indicated an Edwardsville high in each of the three months. The December map was very similar to the seasonal map. Precipitation was much heavier in December than in January or February during the sampling period, and this explains the close correspondence between the December and winter patterns. For example, at gage 52 in the center of the Edwardsville high for winter, the total December precipitation for the four winters was nearly equal to the January-February total. However, both the January and February patterns had a high in the Edwardsville area, and both indicated a low west of St. Louis. Elsewhere in the network the features varied somewhat between the three months.

For the first three winters, isohyetal patterns were developed for the precipitation patterns associated with storms of various synoptic type. Storms were divided into the following synoptic types: cold fronts, warm fronts, occluded fronts, stationary fronts, combinations of lows and fronts, low centers, waves on fronts, post-frontal, and non-frontal.

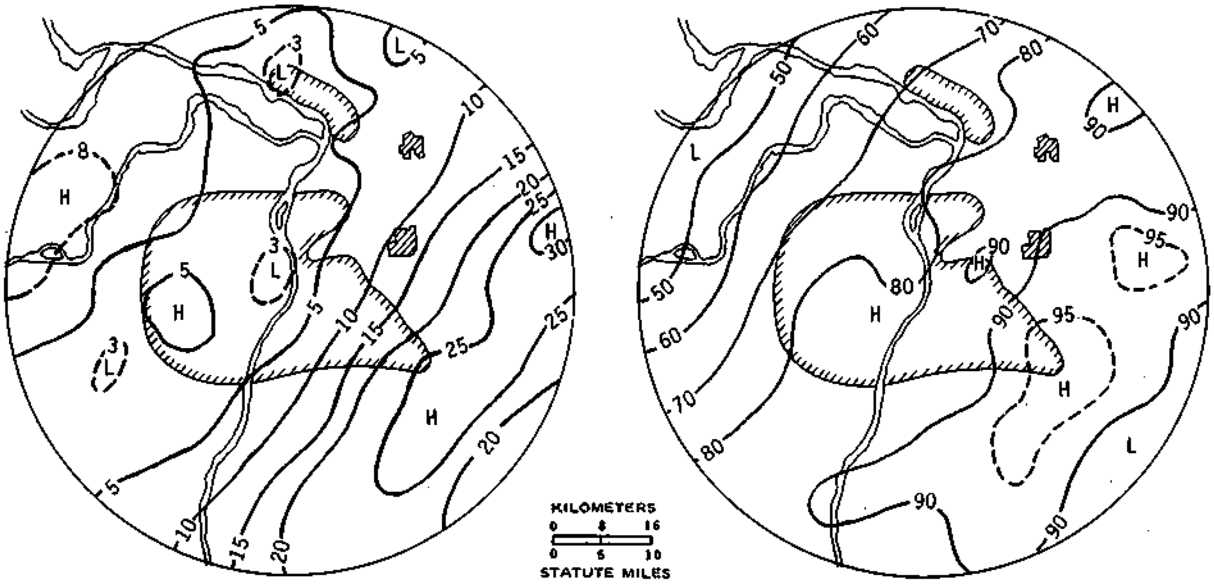
The most common synoptic type was the passage of lows with their associated warm and cold fronts (combination of lows and fronts). These accounted for approximately two-thirds of the winter precipitation. Consequently, the isohyetal pattern for this type was very similar to the pattern for total winter precipitation. Nothing outstanding was noted among the other types, and none contributed more than 6 to 8% of the winter total precipitation. In view of the control of the winter pattern by the large-scale systems (lows plus frontal passages), this analysis was not carried further.

Analyses were made of individual storm periods for the winters of 1971-1972 and 1972-1973. Findings were similar to those obtained with summer precipitation. That is, the seasonal patterns were dominated by a few relatively heavy storms, and these storms maximized most frequently east of the Mississippi. For example, there were six storms in which amounts in excess of 25 mm (1 inch) were recorded on the network during the first two winters. All had their major or secondary maximum in the NE or SE quadrants which are usually in the path of storms moving across the urban-industrial area. Isohyetal patterns for these storms are shown in figures B-16 and B-17.

Spring Precipitation

Figure B-14c shows the total rainfall pattern for spring (March-May) during the three years for which data were sufficiently complete to provide a reliable seasonal pattern. The pattern is similar to summer in several respects. The heaviest rainfall occurred east of the Mississippi, and a low was located just west of St. Louis. The major high area was located in the NE quadrant with secondary highs in the SE quadrant and in the Ozark foothills in the SW corner of the network. However, the bottomlands high of summer was replaced by a low in spring.

The network mean for spring was 100.00 cm (39.37 inches), and this is approximately 15% above the long-term mean for the area indicated by records of the National Weather Service. Rainfall amounts in the center of the heavy rainfall centers in the NE quadrant were approximately two standard deviations and 15 to 20% above the network mean. All of the 10 heaviest

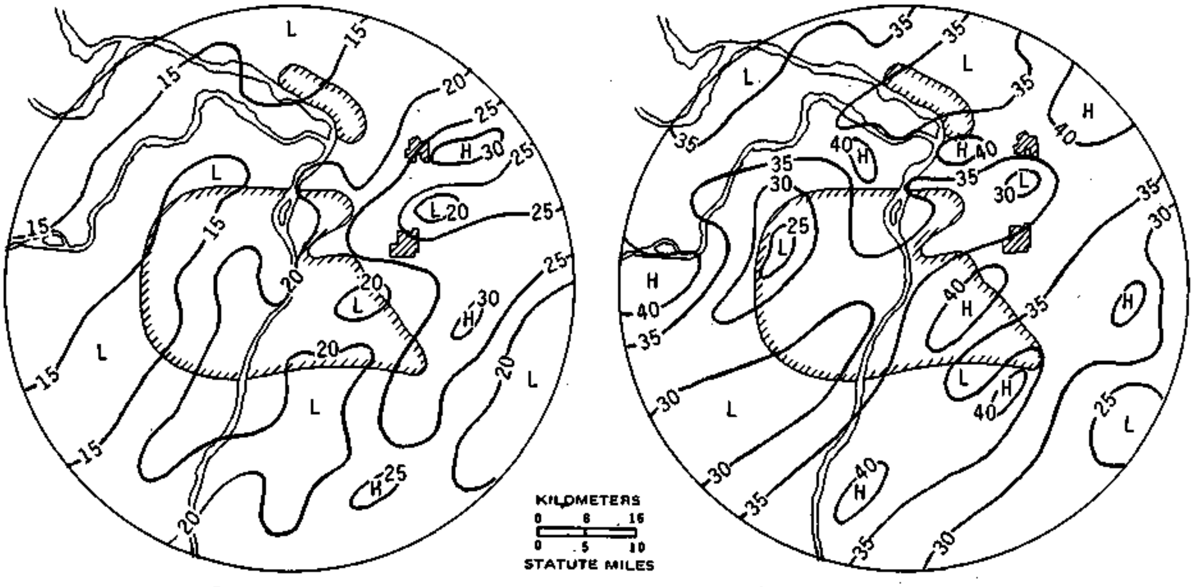


a. 6-7 December 1971　　b. 9-10 December 1971

c. 13-15 December 1971

Figure B-16. Isohyetal patterns (mm) of major storms in winter of 1971-1972

amounts in the network were clustered in the Edwardsville-Collinsville region of the NE quadrant. Although the limited analyses performed on the spring data cannot conclusively establish an urban effect, the clustering of heavy rainfalls in the same general region as in summer is considered strong evidence of an urban anomaly during this season. Furthermore, long-term normals, based on 1931-1960 data, show a pronounced high at Edwardsville compared with values at 12 other stations in the METROMEX circle or located within 32 km (20 mi) of the experimental network.



a. 5-6 December 1972 b. 11-13 December 1972

c. 28-30 December 1972

Figure B-17. Isohyetal patterns (mm) of major storms in winter of 1972-1973

Summary

Limited analyses were made of the precipitation distribution in the METROMEX network during fall, winter, and spring. In all three seasons, precipitation was relatively heavy east of the Mississippi, similar to the summer distribution. In winter and spring, the major high was in the NE quadrant of the network (St. Louis-Edwardsville-Collinsville region), similar to summer, and in fall a secondary high occurred in the Edwardsville area. A low just west of St. Louis was present in all three seasons, and this is also similar to summer. The NE quadrant is most frequently downwind of the urban-industrial area, on the basis of storm and low-level wind motions, and the region west of St. Louis is infrequently downwind for the same reason. Thus, the fall, winter, and spring patterns do provide evidence of an urban effect similar to that found for summer.

However, the excess precipitation in the highs of the NE quadrant, as measured by deviations from the network mean precipitation, were less in fall, spring, and winter. Thus, an urban effect, if present, is apparently more pronounced in summer, as indicated by findings in an earlier climatic study of eight major cities by Huff and Changnon (1973). The spring rainfall excess in the NE quadrant was closest to summer and the spring precipitation climate most resembles that of summer among the three seasons.

Analyses of individual storms in winter showed that the cold season pattern is dictated by major storm systems and a relatively few heavy storms, and this is also similar to the summer situation.

WEEKDAY-WEEKEND OCCURRENCES OF RAINFALL

F. A. Huff

The frequency of rainfall occurrences and the percent of the total summer rainfall during 1971-1975 were determined for weekdays and weekends. There is some reduction in industrial activity on Saturday and Sunday. Therefore, a decrease in the frequency and intensity of rainfall might be discernible on weekends if aerosols from industrial activity have a strong influence on the urban anomaly. This decrease would be expected to occur over and downwind of the industrial areas, which are located primarily on the east side of St. Louis and in the Wood River area. Over the 5-year period, the downwind effect should be most pronounced E and NE of the industrial areas in view of the prevailing movement of storms in the region. The weekday-weekend change could be reflected in both the frequency of measurable rainfall and in the total amount of rainfall. Huff and Changnon (1973) found evidence of weekday-weekend differences in an earlier climatic study of precipitation enhancement by major urban areas.

Analysis of Rainfall Frequency

The total frequency of measurable rainfall in the METROMEX Network was determined for each day of the week during the summers from 1971 through 1975. Frequency maps were then prepared for each day, for 2-day periods, for Monday through Friday (weekdays), and for Saturday plus Sunday (weekend). Inspection of the various frequency patterns showed no strong evidence of differences between weekdays and weekends. The patterns showed a rather random distribution of high and low frequencies throughout the network. This was similar to earlier findings for the first three years of the project (Huff and Schlessman, 1974).

In view of the above findings, it was decided to make an additional analysis of weekday-weekend relations in which the frequency of storm rainfall was computed for the five selected areas shown in figure B-18. These included 1) the portion of St. Louis west of the Mississippi River, which is a combination of commercial, industrial, and residential areas, 2) the industrial area lying east of the river, 3) Alton-Wood River which has considerable heavy industry, including oil refineries and a steel plant, 4) a downwind area located a few miles ENE of central St. Louis, near Collinsville (gages 82-84 and 100-102), and 5) a control area located WSW of St. Louis, where exposure to the urban effects would rarely occur because of the predominating storm movements from W to E (gages 107-109 and 124-126). Six gages were located in each area.

The three urban areas were selected because of the possibility that the urban effect could be producing more frequent light rains in certain weather conditions, and these could frequently dissipate before leaving the immediate urban area. If so, they could be masked out in the sampling variation (background noise) associated with the 5-summer period. The downwind area was selected as a potential major effect area close to the major industrial zone east of the river. The upwind control serves as a comparison area to aid in interpretation of the urban and downwind analytical results.

Results of this analysis are summarized in table B-1, where the average number of occurrences are shown for each day of the week, the weekday period from Monday through

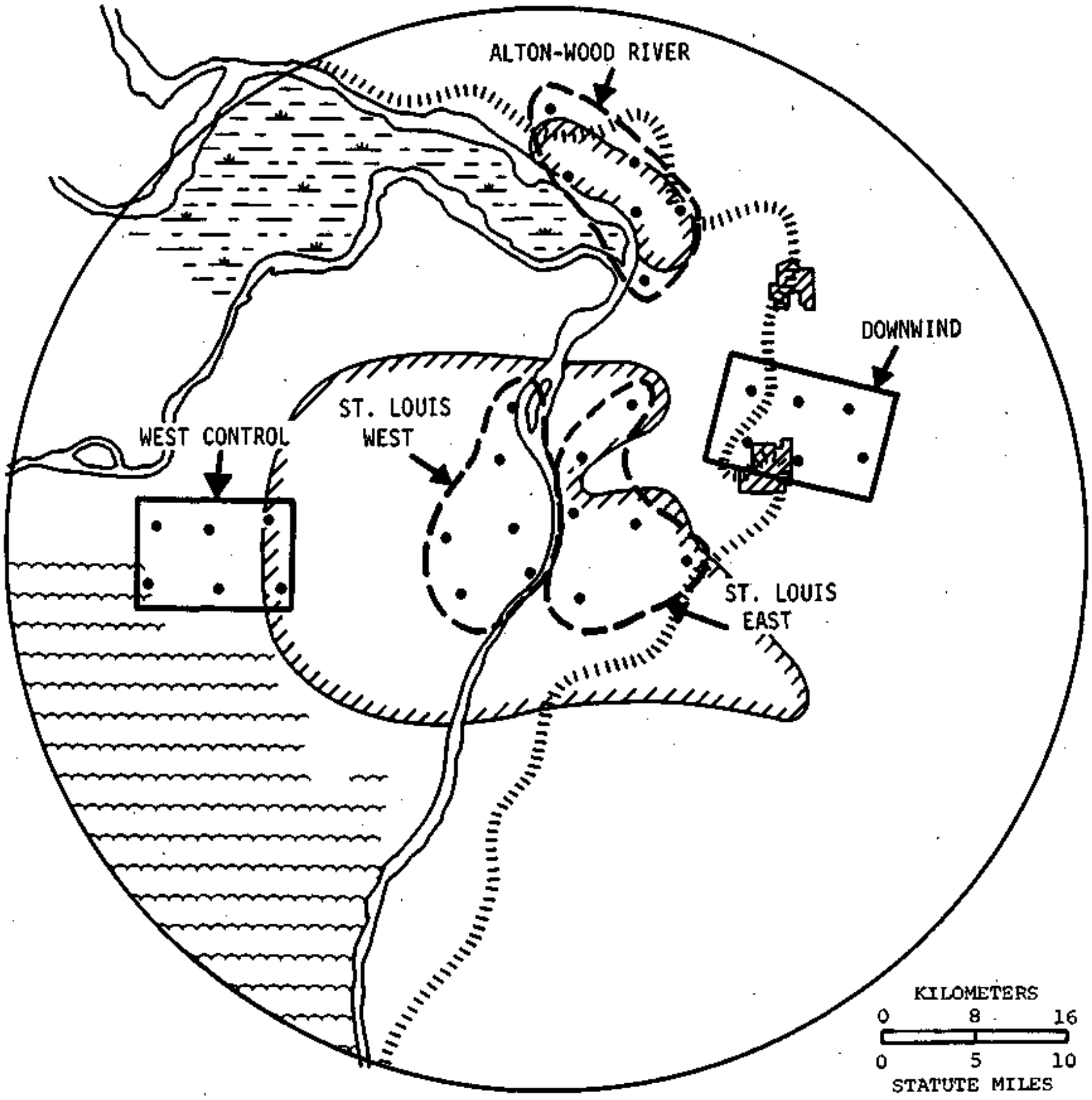


Figure B-18. Weekday-weekend comparison areas

Friday, the weekend (Saturday and Sunday), and a mid-week period (Tuesday-Thursday) that would not be affected by close-down procedures on Friday or start-ups on Monday. Also, the percent of total occurrences is shown for each category.

The expected percentage frequency of measurable rainfall is 14.3% for any given day, 28.6% on Saturday plus Sunday, 42.9% for the mid-week period, and 71.4% for Monday through Friday. This assumes no preference for rain occurrence on particular days of the week. Table B-l shows that the highest 1-day percentage occurred on a weekday (Friday) in St. Louis East and Alton-Wood River, and on a weekend day (Saturday) in the other urban area (St. Louis West). The downwind area maximized on a weekday (Wednesday), but the non-effect area (West Control) also maximized on the same weekday. Saturday and Sunday were not among the three days with lowest frequency in any of the areas.

The weekend combination was above the normal or expected percentage (28.6%) in all five areas. The weekday combination (Monday-Friday) was less than normal (71.4%) in all areas.

Table B-1. Comparison of Weekday and Weekend Frequency of Measurable Rainfall during Summer on METROMEX Network, 1971-1975

	St. Louis West		*St. Louis East*		*Alton-Wood River*		*Downwind*		*West control*	
Day	*Number*	*Percent*	*Number*	*Percent*	*Number*	*Percent*	*Number*	*Percent*	*Number*	*Percent*
Monday	17.1	12.6	15.5	11.6	18.0	12.9	17.7	12.9	15.3	11.6
Tuesday	14.3	10.6	14.8	11.3	15.3	11.0	15.8	11.5	14.2	10.9
Wednesday	21.2	15.7	20.3	15.4	23.7	17.0	25.8	18.7	23.3	17.7
Thursday	14.7	10.9	14.3	10.9	14.3	10.4	15.5	11.3	15.5	11.8
Friday	23.5	17.3	23.2	17.6	25.2	18.1	21.8	15.8	19.8	15.0
Saturday	23.3	17.2	22.5	17.1	22.8	16.4	19.2	14.0	22.7	17.2
Sunday	21.2	15.7	21.3	16.1	19.8	14.2	21.7	15.8	20.8	15.8
Monday through Friday	90.8	67.1	88.1	66.8	96.5	69.4	96.6	70.2	88.1	66.9
Tuesday through Thursday	50.2	37.1	49.4	37.5	53.3	38.4	57.1	41.5	53.0	40.4
Saturday through Sunday	44.5	32.9	43.8	33.2	42.6	30.6	40.9	29.8	43.5	33.1

The mid-week combination was less than expected (42.9%) in all five areas, and this is the period when urban enhancement would be expected to maximize provided that industrial activity is reduced substantially on weekends.

The above statistics do not suggest urban enhancement of summer rainfall by industrial stack effluents; in fact, the data would suggest a suppression, if anything. However, the upwind control area also shows below-normal weekday and above-normal weekend frequencies. The differences could be the result of sampling variations in the 5-summer sample. Furthermore, it is quite possible that the reduction in industrial activity on weekends is insufficient to alter substantially its effect on the local rainfall distribution. Most large industries now operate on a 7-day week, and weekend close-downs are largely associated with smaller plants which may have minimal effect, if any, on the precipitation distribution.

Analysis of Rainfall Amounts

Analysis of total rainfall on weekdays and weekends was made following the same procedures described earlier for rainfall frequency. Both total rainfall and percent of total rainfall were computed. Inspection of network maps of total rainfall and percent total rainfall did not indicate any distinct trend for more rainfall over or downwind of the urban-industrial areas on weekdays than on weekends. Therefore, the selective area analysis used for the rainfall frequency analysis was performed for total rainfall also.

A brief summary of the selective area analysis is provided in table B-2. In this table, percent of total rainfall has been shown for each of the five areas for the weekdays (Monday-Friday), mid-week (Tuesday-Thursday) and weekends (Saturday-Sunday). For weekdays, both of the St. Louis areas were near the normal percentage of 71.4% that would be expected if there was no urban effect. Alton-Wood River was well below normal with 67.6%, and the downwind area was a little below normal at 70.7%. The control area was well above normal with 76.2%. All areas except the West Control were below the mid-week normal of 42.9%. On weekends, only Alton-Wood River and West Control showed substantial differences from the normal of 28.6%. Alton-Wood River with 32.4% of its rainfall on weekends had more than expected, assuming a random distribution of daily rainfall with no urban effect. Similarly, West Control was well below normal with 23.8% on Saturday and Sunday.

Strictly from the percentages in table B-2, one would conclude that there is an extraneous effect causing more rainfall to occur on weekdays than on weekends in the West Control. However,

Table B-2. Comparison of Total Rainfall between Weekdays and Weekends, Summer, 1971-1975

Area	Percent of total rainfall Monday through Friday	Tuesday through Thursday	Saturday through Sunday
St. Louis West	72.5	41.0	27.5
St. Louis East	71.1	41.8	28.9
Alton-Wood River	67.6	39.2	32.4
Downwind	70.7	42.7	29.3
West Control	76.2	48.0	23.8

there is no evidence of any urban effect in this region. Any topographic influence on the rainfall should not be affected by day of the week. Thus, it would appear that this is likely a sampling vagary in the 5-summer sample.

Referring to the four potential urban-effect areas in table B-2, only Alton-Wood River had much departure from the normally expected percentages in a random distribution. Here, there was an above-normal amount of rain on weekends and below-normal amounts for the weekday periods. This is opposite of what would be expected with an urban enhancement effect associated with aerosol output from an urban-industrial area. Therefore, this 5-summer distribution must be a sampling vagary or an industrial suppression whose causes we do not understand at this time.

Heavy Rainstorm Analyses

Since various analyses had shown that the urban precipitation anomaly is strongly related to heavy rainstorms, the weekday-weekend analyses were repeated, using only those storms which produced 25 mm or more of rainfall at one or more gages during the 5-summer period. Results are summarized in tables B-3 and B-4, where comparisons for the five areas are shown for the weekday, mid-week, and weekend periods.

The greatest frequency of 25-mm storms on weekdays was in the West Control. This also was the case in the mid-week period of Tuesday-Thursday. Although the frequency of heavy storms was above average in the period from Monday-Friday, this effect was most pronounced in the West Control where the urban effect would be least. Thus, there was no evidence of urban-induced increases in the frequency of heavy rainstorms on weekdays.

Similar to the findings with all rainfall combined, an urban suppression effect would be indicated, if anything, by this data sample. This, of course is in disagreement with various other analyses, and it is concluded that the frequency of these storms is unaffected by the urban industrial output of atmospheric pollutants, or the effect is too small to be identified in the natural variability of the 5-summer sample.

Similar conclusions were reached from the total rainfall distribution in 25-mm storms which is summarized in table B-4. Examination of data from several other raingage clusters in the network also supported the findings obtained with the five areas presented in tables B-l through B-4.

Table B-3. Comparison of Weekday and Weekend Frequency of 25-mm Storms during Summer on METROMEX Network, 1971-1975

Area	Percent of total occurrences Monday through Friday	Tuesday through Thursday	Saturday through Sunday
St. Louis West	87.0	40.0	13.0
St. Louis East	80.8	41.7	19.2
Alton-Wood River	72.4	35.4	27.6
Downwind	75.9	41.4	24.1
West Control	92.4	46.7	7.6

Table B-4. Comparison of Total Rainfall between Weekdays and Weekends in 25-mm Storms, Summer, 1971-1975

Area	Percent of total rainfall Monday through Friday	Tuesday through Thursday	Saturday through Sunday
St. Louis West	83.4	35.0	16.6
St. Louis East	73.5	37.9	26.5
Alton-Wood River	70.5	35.9	29.5
Downwind	73.8	44.2	26.2
West Control	94.5	46.1	5.5

Summary

Analyses of the frequency and amount of rainfall on weekdays and weekends were made for the five summers of 1971-1975. No evidence was found for more frequent or more intense rainfall to occur in potential urban-effect regions on weekdays than on weekends, as might be expected with urban enhancement of precipitation within and downwind of the urban-industrial area.

Comparison of the potential urban-effect statistics with those for an upwind control (no-effect) area indicated similar weekday-weekend distributions of rainfall frequency. All areas showed below-normal frequencies on weekdays and above-normal occurrences on weekends. This suggests the weekday-weekend differences in the five summers may be related to sampling variations, and that any differential urban effect between weekdays and weekends is too small to be identified in the background of natural variability.

Analyses of total rainfall also showed no evidence of greater rain production by storms on weekdays than on weekends in and downwind of the major urban-industrial areas. These statistics suggest a weekday suppression of rainfall, if anything. The control area showed a strong trend for more rainfall on weekdays than weekends, whereas the potential urban-effect areas, in general, indicated above-normal amounts on weekends and below-normal totals on weekdays. However, this could also be a sampling vagary.

Thus, it is concluded that differences in the urban enhancement of rainfall between weekdays and weekends is non-existent or too small to be identified in the noise of natural relative variability in the 5-summer sampling period. Major industries, including those which are likely sources of viable raindrop nuclei (steel plants, oil refineries, etc.) operate on a 7-day production week in the modern industrial world, and only relatively small industries are likely to close down or substantially reduce production activities on weekends.

Furthermore, there is no evidence of an urban enhancement related to automobile exhaust products which conceivably could affect the rainfall regime. With heavy concentrations of traffic during the early forenoon and late afternoon on weekdays in the urban area, any exhaust-related enhancement would result in a trend for heavier and/or more frequent rainfall on weekdays. Of course, a suppression effect by exhaust products could produce relatively heavy weekend rainfall as shown in tables B-1 through B-4, but, enhancement rather than suppression is indicated by all other types of analyses performed on the METROMEX data.

DIURNAL DISTRIBUTION OF SUMMER RAINFALL

F. A. Huff

The diurnal distribution of summer rainfall was studied to determine whether the urban precipitation anomaly varies substantially during the day, and, if so, to ascertain the magnitude of such time variations and whether there are spatial variations in the diurnal distribution. Such information is useful in helping to determine the magnitude, location, and causes of the urban anomaly. From the standpoint of practical application, definition of the diurnal distribution characteristics of the urban anomaly in time and space provides a useful analytical tool for predicting the intensity of the urban precipitation effect under synoptic weather conditions favorable for energizing the anomaly.

The diurnal distribution was examined by calculating the amount of rainfall and the percentage of the total summer rainfall for each hour of the day for the 5-summer period. Inspection of the plots indicated that many of the spurious aberrations in the distribution could be eliminated by computing moving averages of the distribution. Consequently, all results presented here are based upon 3-hour averages. Diurnal distributions were also examined for each summer month separately, but differences appeared to be well within the limits of sampling error, so the three months were combined. All diurnal analyses are based upon the objective storm sample for which hourly amounts had been computed.

Time Distribution Characteristics

Figure B-19 shows the average diurnal distribution of rainfall and average frequency for the network, the Edwardsville High, and the Upwind Control. In this graph (and those that follow) the distribution is represented by 3-hour moving averages of the percent of total summer rainfall for 1971-1975. The percentage graphs permit direct comparisons between various areas of the network where considerable variability occurs in the normal summer rainfall. Diurnal distributions for other selected areas are presented in figures B-20 through B-22. These are areas exposed to various external effects (see locations on figure B-25).

Figure B-19b shows the greatest percentage of the seasonal rainfall on the network occurring in the 3-hour period, 1500-1800 CDT. This period immediately follows the diurnal peak in solar heating. Other factors being equal, low-level instability maximizes in the afternoon hours, and this, of course, is favorable for the development of convective clouds, and for energizing the urban anomaly mechanisms by accelerating the movement of surface air to cloud-base level.

An average of 20% of the network summer rainfall occurred from 1500 to 1800 during the five summers. With no diurnal effect, 12.5% of the rainfall would be expected to occur in any 3-hour period. Thus, the late afternoon maximum was 60% greater than the expected no-effect percentage. A secondary maximum during the evening (2000-2300) closely coincides with development of the nocturnal heat island maximum. However, this secondary maximum was also present at stations not subject to the heat island effect. It is apparently associated with the large-scale nocturnal thunderstorm anomaly that is prevalent in the Midwest, and may be intensified by urban mechanisms. Figure B-19 shows the diurnal minimum occurring in late

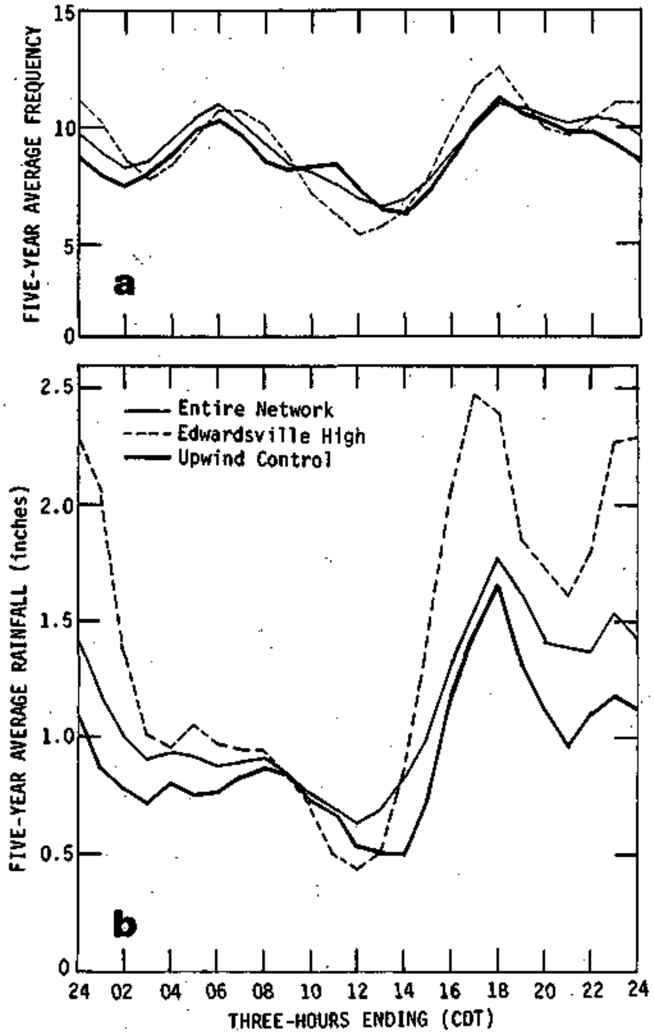


Figure B-19. Three-hour moving five-year averages of frequency (e) and rainfall (b) June-August 1971-1975

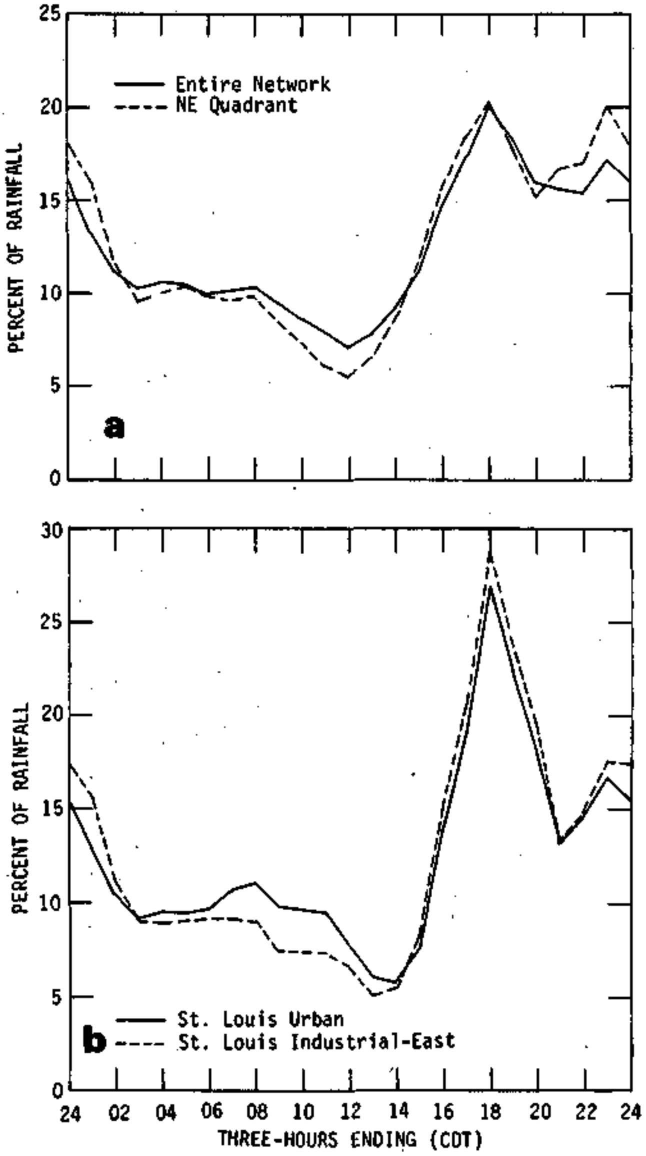


Figure B-20. Percent of total rainfall in three-hour period ending at given time, June-August 1971-1975

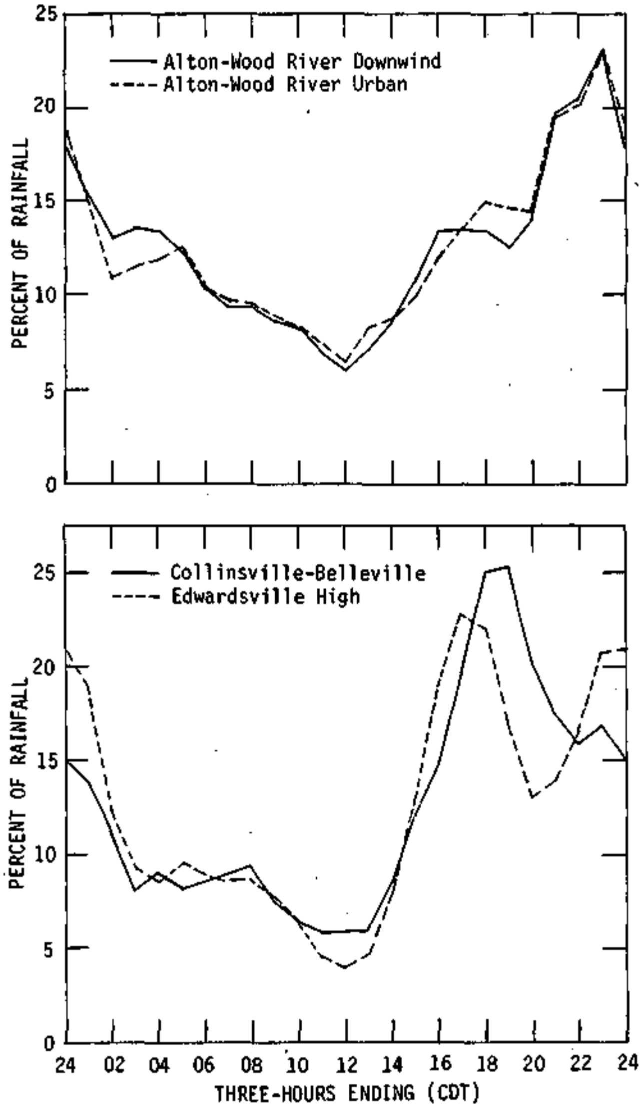


Figure B-21. Percent of total rainfall in three-hour period ending at given time, June-August 1971-1975

forenoon (0900-1200) in the network average, and this time of minimum was prevalent throughout most of the network. The network minimum of 7% is only about one-third of the afternoon maximum. Figure B-19 clearly illustrates the large diurnal differences in summer rainfall, particularly from early forenoon to late afternoon.

Figure B-20a shows the average diurnal distribution in the NE quadrant of the METROMEX Network where the urban anomaly appears to be most pronounced. In this region, the late evening maximum is equivalent to the primary afternoon maximum exhibited in the network average. The late evening maximum and large afternoon maximum were also approximately equal in the NW quadrant, but the afternoon maximum was much more pronounced in the SW and SE quadrants. It is believed that urban enhancement is superimposed upon both the afternoon and evening maxima in regions frequently 1) downwind of the low-level winds in the metropolitan area, and 2) in the path of storms crossing the urban region.

Figure B-20b shows diurnal curves for the St. Louis Urban and St. Louis Industrial-East areas. These are the two areas where the late afternoon maximum was most pronounced with 28 to 29% of the total 5-summer rainfall recorded from 1500 to 1800 CST.

Figure B-21a shows graphs for the Alton-Wood River Urban and Downwind areas. Both show a pronounced maximum in late evening (2000-2300), rather than the late afternoon maximum of the St. Louis region. This suggests that the destabilizing action of solar heating is of much greater significance in the large urban area of St. Louis compared with the relatively small Alton-Wood River urban area. Conversely, a nocturnal mechanism appears to be more important in the northern half of the network than in the southern and central parts. Since the same type of curve was obtained for the bottomlands which are usually upwind of Alton-Wood River, the late evening maximum may be associated with both urban and topographic factors operating in conjunction with the large-scale nocturnal thunderstorm anomaly.

Figure 21b shows curves for the Collinsville-Belleville and Edwardsville areas. The Collinsville-Belleville curve is similar to those for the immediate St. Louis area just to the west. That is, the late afternoon maximum is very pronounced, and the late evening maximum is relatively weak in comparison. However, the Edwardsville curve shows a late evening maximum that is nearly equal to the afternoon rainfall peak, and thus indicates that both the solar (daytime) and nocturnal mechanisms are active in this area. This helps to explain why the 5-summer maximum of total rainfall occurs in the Edwardsville area.

Figure B-22 shows curves for the hilly regions of the network. Both the SW Hills and the SE Hills-Bluffs show a primary maximum in late afternoon and a secondary peak in late evening, similar to the average network curve of figure B-19. The time variation in the hill curves is less than for the potential urban-effect curves discussed above. For example, the peak-valley range for SW Hills is 9% compared with 23% for St; Louis Industrial-East and 17% for Alton-Wood River Urban. Thus, it appears that the urban environment exerts a stronger influence on the diurnal distribution than the hills.

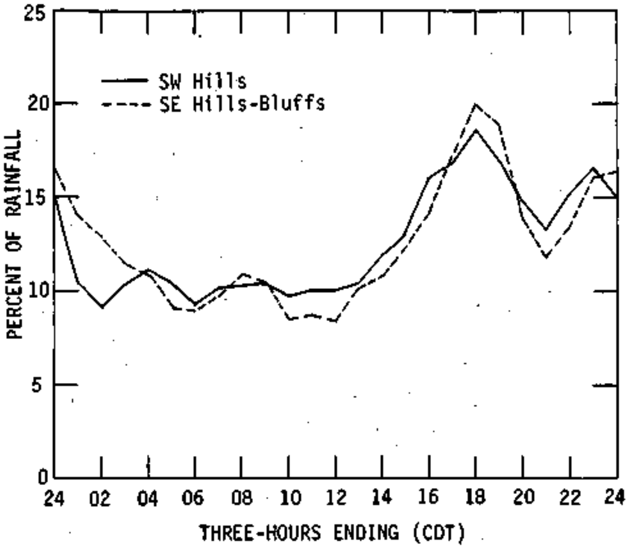


Figure B-22. Percent of total rainfall in three-hour period ending at given time, June-August 1971-1975

Table B-5 summarizes a comparison of the magnitude and time of occurrence of highs and lows in the diurnal distribution of selected areas within the METROMEX Network. As discussed previously, these areas represent various degrees of urban and topographic effects, combinations of these effects, and a control (no-effect) area (see following section and figure B-25). The six areas listed after the network values in table B-5 are considered to be the most pronounced areas of urban effect. In all cases, the highest percentage of the total summer rainfall occurred in

Table B-5. Diurnal Extremes in Selected METROMEX Areas, Expressed in Percent of Total Summer Rainfall

	Highest		*Second highest*		*Lowest*	
Area	*Time**	*Percent*	*Time**	*Percent*	*Time**	*Percent*
Network	18	20	23	17	12	7
St. Louis Suburban West	18	24	23	17	12	6
St. Louis Urban	18	27	23	17	14	6
St. Louis Industrial-East	18	29	23	17	13	5
CLV-BLL	18	25	23	17	12	6
EDW	17	23	24	21	12	4
GRC-EDW	18	24	23	21	12	5
ALN-WDR Urban	23	23	18	15	12	6
ALN-WDR Downwind	23	23	17	14	12	6
Refinery Area	23	23	18	18	12	7
ALN-WDR Bottomlands	21	21	5	14	12	7
SW Hills	18	19	23	15	2	9
SE Hills-Bluffs	18	20	24	16	12	8
BLL Bluffs	18	22	8	10	13	6
SE High	19	18	15	14	11	9
Upwind Control	18	23	23	16	13	7

***3 hours ending at indicated hour (CDT)**

late afternoon, but late evening percentages were nearly equal in the region NE of St. Louis, extending from Granite City to Edwardsville. Late forenoon was the time of minimum rainfall in the urban-effect regions. The afternoon maximum was 4 to 6 times the forenoon minimum in these areas.

The primary and secondary maxima are reversed in the Alton-Wood River area where potential urban-industrial and topographic effects are both present. The maximum-minimum ratio in these areas is smaller than in the St. Louis urban-effect regions. This indicates a more pronounced diurnal effect related to the St. Louis urban anomaly.

The hills and bluffs areas show a late afternoon maximum, similar to the St. Louis urban-effect areas. However, the diurnal variation is considerably less. The maximum-minimum average ratio is 4.9 for the St. Louis urban-effect areas, compared with 3.5 for the Alton-Wood River region, 2.6 in the hills-bluffs areas, and 2.6 in the Upwind Control (no-effect) area. Thus, these tabulations provide additional indication of the relative strength of the urban enhancement of summer rainfall in the experimental area.

A strong indication of whether the urban effect is operating during the peak diurnal rainfall periods and the magnitude of the effect can be obtained by comparing the deviation of rainfall in major effect areas with the network mean for these periods (refer to figure B-25 for location of selected areas). This has been done in table B-6 for both rainfall amounts and frequency of measurable rainfall. Differences are shown as percentage deviations from the network mean for both the late afternoon and late evening maxima. Peaks in each distribution are used although they are sometimes 1 hour apart.

During the afternoon, peak rainfall in the Edwardsville High (1400-1700) exceeded the network mean (1500-1800) by 40%, and this increased to 50% in the evening maxima. These are large variations and indicate the presence of external forces, which in this case are believed to be primarily the urban enhancement mechanisms. Furthermore, these deviations are considerably greater than the total seasonal departure which averaged 23% among the 9 stations in this area. This indicates the urban effect is more pronounced in these heavier rainfall periods, and this is a trend observed in all of the surface rainfall analyses.

The frequency of measurable rainfall was 12 and 10%, respectively, greater than the network mean in the afternoon and evening peak periods. This does show a trend for more frequent rainfall during the diurnal peaks in the major urban-effect area, but it is of much smaller magnitude than the rainfall amount differences. However, for total seasonal rainfall (all hours combined) the frequency in the Edwardsville High was 8% less than the network

Table B-6. Average Percentage Departures of Rainfall Frequencies and Amounts from Network Averages in Selected Areas during 3-Hour Periods of Maximum Rainfall

	Deviations (%) from network average					
	Rainfall amounts			*Rainfall frequencies*		
Area	*Daytime*	*Night*	*All hours*	*Daytime*	*Night*	*All hours*
EDW High	+40	+50	+23	+12	+10	-8
GRC-EDW	+38	+42	+18	+12	+14	-3
St. Louis Urban	+25	-12	-10	+13	+2	+2
St. Louis Industrial-East	+48	+5	+1	+5	+9	-1
CLV-BLL	+36	+5	+6	+8	+6	+1
Upwind Control	-4	-23	-18	0	-11	+1

Note: Daytime, 1400-1700 or 1500-1800 CDT; Night, 2000-2300 or 2100-2400 CDT; All hours, season totals with no diurnal stratification average, so there does appear to be a substantial increase in the number of rainfalls in the Edwardsville High during the peak diurnal periods.

The Granite City-Edwardsville area of table B-6 had large positive departures of rainfall amount in both periods, and the frequency deviations are similar to the Edwardsville High which is part of the Granite City-Edwardsville area. The deviations are much greater than the all-hours (seasonal) deviation of+18%.

It is obvious that the afternoon is the primary period of rainfall enhancement over the central part of St. Louis (St. Louis Urban), and that there is no indication of urban stimulation during the late evening when the heat island maximizes over the city. This is largely the case over the industrial region east of the Mississippi also, where table B-6 shows a 48% deviation from the network mean during the afternoon peak, and only a small increase at night that had the same order of magnitude as the all-hours deviation. This trend also continues farther eastward as indicated by the deviations for the Collinsville-Belleville area.

Computations for the Upwind Control, where the urban effect is insignificant, show that the large average deviation of total rainfall from the network mean for all hours (-18%) was substantially reduced in the afternoon peak period. This relative increase in rainfall may be due largely to convective activity moving off the Ozark foothills located S and SW. The evening deviation shows no evidence of enhancement in this area; in fact, the deviation is slightly below its 5-summer average for all hours.

Rainfall frequencies showed smaller deviations than rainfall amounts in all five urban-effect areas during the afternoon rainfall maximum. However, the afternoon deviations are greater in a positive direction than the all-hours frequency deviations in these urban-effect areas, so that an increased frequency of measurable rainfall is indicated during the heavy rainfall period. Except for St. Louis Urban, the night deviation in frequencies is also greater in a positive direction than the all-hours deviation in the urban-effect areas.

In the Upwind Control, the frequency deviations are close to average in the afternoon, but are well below average in the evening when the Ozark topographic effect is less active.

Figure 19b shows diurnal curves of the frequency of measurable rainfall and total rainfall for the network, Edwardsville High, and the Upwind Control. These are seasonal averages for the 5-year sampling period. The frequency curves show only small differences throughout the day, and these are greatest during the diurnal peak rainfall periods. However, differences between the major high area in the network (Edwardsville High) and both the network mean and the major no-effect area (Upwind Control) are certainly significant. Examination of the curves shows that the Edwardsville High exceeds the network mean in total rainfall throughout the day, except from about 0900 to 1300 CDT. The greatest differences occur in the late afternoon and late evening maxima. Differences are small between 0300 and 1300, so that much of the excess rainfall (departure from mean) in the Edwardsville High occurs from early afternoon to late evening. Approximately 89% of the total excess was recorded in two 3-hour periods, 1400-1700 and 2100-2400 CDT. Positive and negative departures nearly balanced each other from midnight to noon.

Use of the Upwind Control as a base of comparison with the Edwardsville High reveals the same general trends as with the network mean distribution. The Upwind Control curve is nearly parallel to the network mean curve but at a slightly lower level.

The foregoing results indicate that the urban anomaly is much stronger than average during the two major peaks of total rainfall in the diurnal distribution. This concurs with other findings, such as those revealed by the heavy rainstorm analyses; that is, the urban-effect mechanisms are most productive when atmospheric conditions are most favorable for the natural precipitation processes.

Spatial Distribution Characteristics

Maps of the network were drawn to show the spatial distribution of average summer rainfall by 3-hour periods. These maps were derived from the objective storm sample, since 5-minute amounts were used in deriving hourly rainfall totals. As pointed out elsewhere, the objective storm sample total for the five seasons is somewhat less than the climatic sample used in deriving figure B-1, because much of the early June data was not suitable for deriving 5-minute amounts, although storm totals were measured during the entire month.

The 3-hour maps showed that rainfall tends to develop earliest in the hilly regions. The network average was least during the 0900-1200 period, but pronounced highs occurred over the Ozark foothills SW of St. Louis and in the hills-bluffs area in the SE quadrant of the network. At that time, rainfall in the extreme SW part of the network was 50 to 100% above the network average.

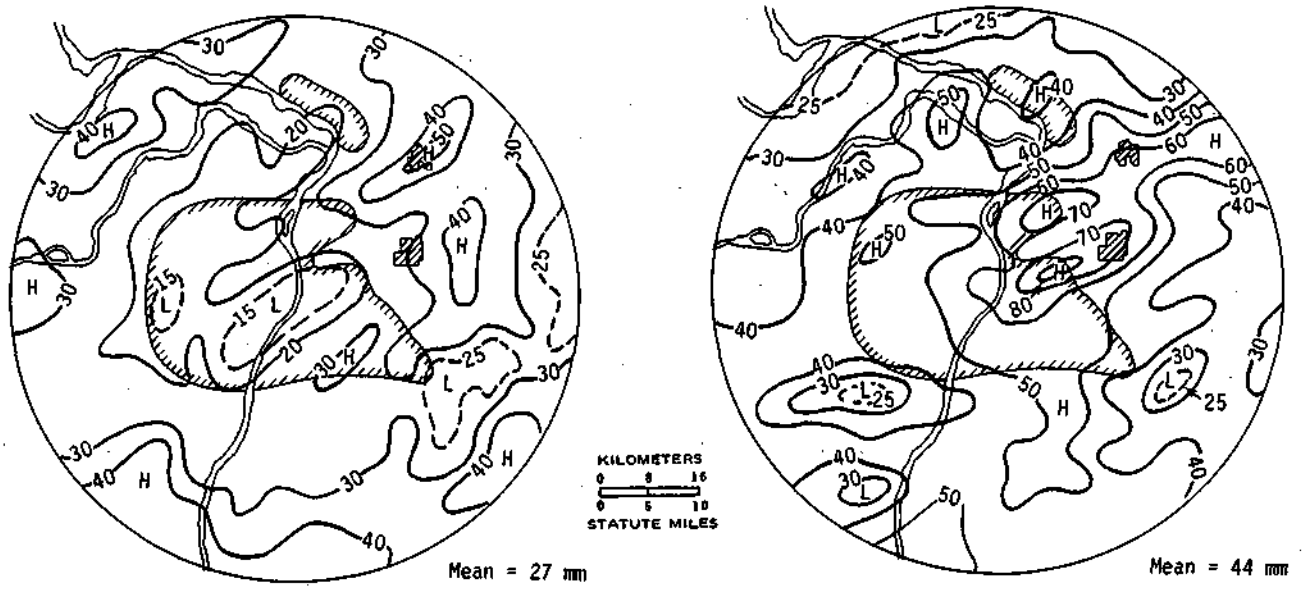
The first major indication of the urban effect appeared in the map for 1200-1500 (figure B-23a) when solar heating maximizes. At that time, highs are located in the Edwardsville-Collinsville area, and the Edwardsville high appears to be the downwind extension of a weak high shown over the Wood River industrial area on the map for 0900-1200.

The map for 1500-1800 (figure B-23b) illustrates conditions during one of the peak periods of urban-induced convective activity. A strong high extends NE from the industrial region of St. Louis to the Edwardsville area, and this high encompasses the region in which the urban effect would be expected to maximize from consideration of most frequent storm movements and low-level wind flow. Maximum amounts exceeding 75 mm (3 inches) were recorded in the center of the St. Louis-Edwardsville high rainfall region. The network mean was 44 mm (1.74 inches); thus, the maxima in the St. Louis-Edwardsville region were approximately 70% greater than the network mean and nearly three standard deviations above the mean. All 10 stations in the network with amounts exceeding two standard deviations were clustered in this region. Therefore, the rainfall pattern of late afternoon provides strong evidence of an urban enhancement of the regional rainfall.

Rainfall in the bottomlands, where a relatively strong rainfall high appears in the seasonal pattern (figure B-l), becomes relatively heavy in late afternoon also. In fact, a generally high rainfall region extends along the Missouri River Valley into the bottomlands in figure B-23b for 1500-1800. Thus, the bottomlands high develops considerably later than another topographic-related high in the Ozark foothills, but it also persists strongly into the evening hours.

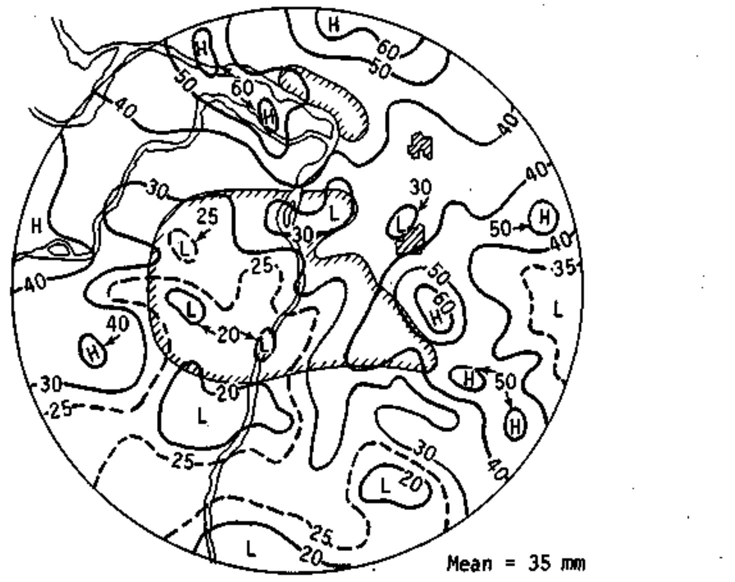
Figure B-23c shows the spatial pattern for 1800-2100 CDT. The large high area over the immediate St. Louis area has been displaced eastward. This is a logical sequence in view of the common west to east movement of convective systems. Other relatively strong highs are indicated in the bottomlands (NWquadrant) and NE (usually downwind) of Alton-Wood River. This suggests a later development of convective activity in these areas, and appears to be a reasonable sequence, since the large metropolitan area of St. Louis would tend to stimulate convective activity at an earlier time than the relatively small Alton-Wood River area. Also, convective development in the river bottomlands, a moisture source, is likely to lag developments in the hills of the SW part of the network where relatively strong convective activity appeared to generate first during the day.

The map for 2100-2400 (not shown) had the strong rainfall maximum in the Edwardsville area discussed earlier in conjunction with the time distributions. This late evening peak in the distribution extended from Granite City to Edwardsville, and resulted in a diurnal peak equivalent to the afternoon maximum in this region. However, this high did not extend E of St. Louis as did the afternoon peak. In fact, a region of generally light rainfall extended W-E



a. 1200-1500 CDT

b. 1500-1800 CDT



c. 1800-2100 CDT

Figure B-23. Spatial distribution of average summer rainfall for selected three-hour periods

across St. Louis. As indicated earlier, the late evening peak in the Granite City-Edwardsville area is likely associated with urban enhancement of the natural nocturnal thunderstorm anomaly through interactions of the urban heat island (which maximizes in late evening) and atmospheric processes.

A pronounced decrease in rainfall occurred in the network from late evening (2100-2400) to early morning (0000-0300). The network mean decreased from 36 mm to 23 mm (36% change). The most outstanding feature for 0000-0300 (not shown) was the high in the extreme northern part of the network where it could be affected by flow off the bottomlands and the Alton-Wood River area.

Another interesting feature of the 3-hour patterns was the persistence of an area of relatively light rainfall oriented approximately W-E through the St. Louis urban area. This low was most pronounced in the 0000-0900 period, but was replaced by an area of relatively heavy rainfall only in the late afternoon (1500-1800). The replacement of the persistent low by a high when diurnal conditions are most favorable for movement of surface air to cloud level is another indication of the presence of an urban enhancement that has a pronounced diurnal variation.

Diurnal heating is an important factor in stimulating the urban enhancement mechanisms whether they be dynamical, microphysical, or a combination of both. Thus, solar heating tends to destabilize the atmosphere near the surface which, in turn, accelerates the movement of surface generated contaminants to cloud base level. Changnon and Huff (1957) in a study of cloud distributions in Illinois found that summer cumulus occur most frequently in southwestern Illinois (Springfield) from 1200 to 1500 CST, but that cumulonimbus develop most often in the late afternoon. Thus, the unusually high proportion of summer rainfall in late afternoon in the immediate urban area of St. Louis (figure 23b) suggests an urban enhancement effect superimposed upon the natural diurnal heating effect.

The urban enhancement factor is indicated quite clearly in figure B-24, which shows the percentage of total summer rainfall throughout the network that occurred in 3-hour periods from 1200 to 2100 CDT. Figure B-24a shows the percentage pattern for 1200-1500. Weak highs are located E and NE of the St. Louis urban-industrial region and over the southern and southwestern part of the network where hill and bluff effects are present. This is the period when cumulus are most frequently observed to develop in the summer.

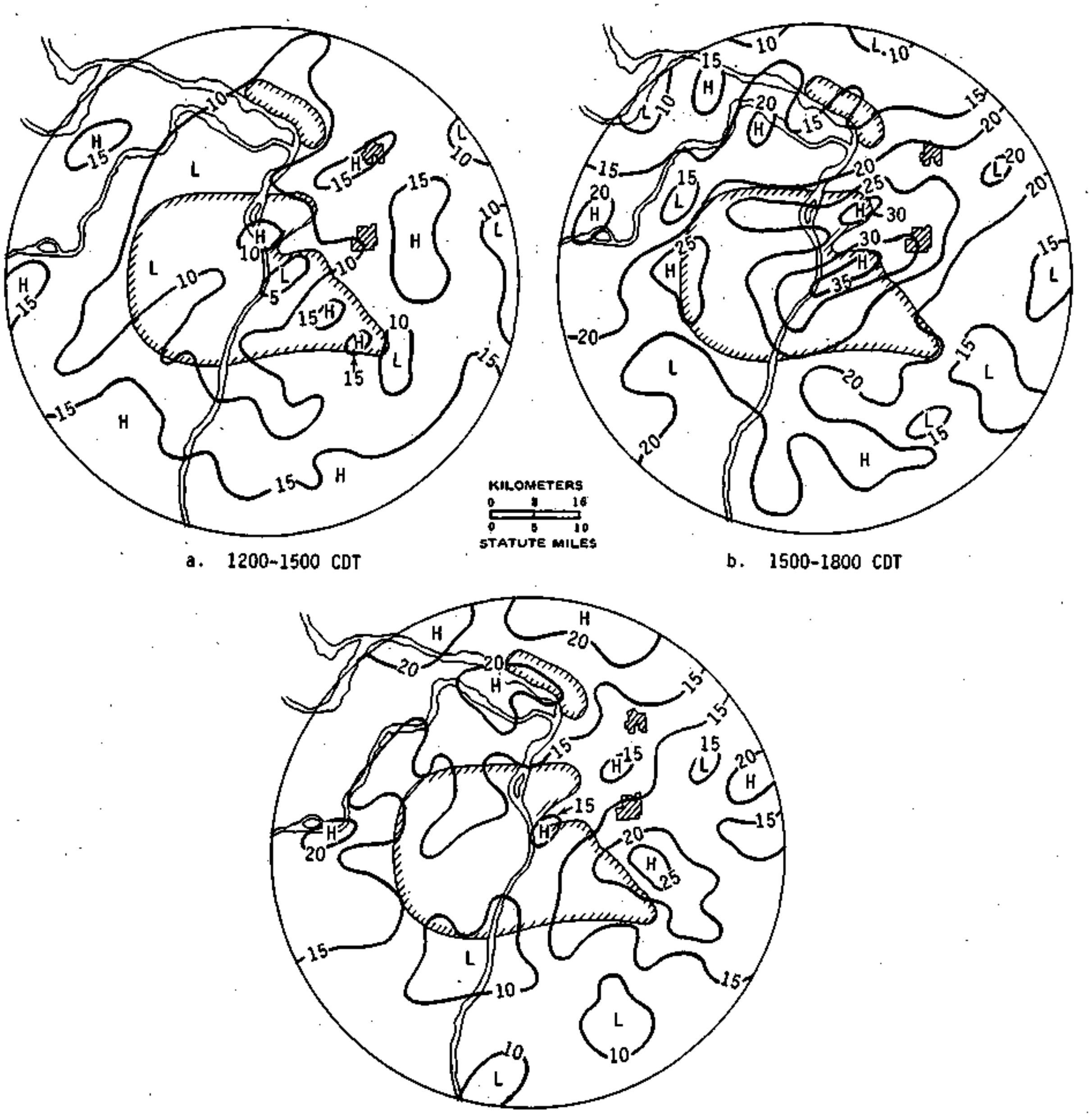
The most interesting map is for 1500-1800 (figure B-24b) when cumulonimbus tend to develop most frequently. Over the eastern industrial region of St. Louis extending from Granite City southward, 30 to 35% of its total summer rainfall was recorded. The network mean was 20% and the standard deviation 5%. Note that all percentages of 30% or greater are clustered in the urban-industrial region. As pointed out earlier, most of the rainfall excess (departure from network mean) in the East St. Louis-Collinsville-Belleville area resulted from afternoon and early evening rainfalls.

Figure B-24c shows the percentage pattern for 1800-2100. The high over the immediate industrial area at 1500-1800 was displaced eastward, as storms which developed or intensified over the urban area drifted in this direction.

Summary

Analyses of the time and space distributions of summer rainfall were made on a diurnal basis for the five summers of 1971-1975. Results indicated that the Edwardsville anomaly, where the urban effect apparently maximizes, is produced by excessively heavy rainfalls from early to late afternoon (1400-1700) and during the late evening (2100-2400). The urban enhancement in the afternoon is stimulated by destabilizing of the lower atmosphere by solar heating. Thus, the anomaly is likely related to a combination of natural diurnal heating and urban thermal-aerosol outputs. Conditions favorable for the development of convective activity in upwind feeder regions are also likely involved in positioning of the afternoon maximum. These feeder regions include the relatively hot, humid Missouri River Valley and Missouri-Mississippi bottomlands W and NW of the city, and the Ozark foothills SW of the urban area.

The evening maximum in the Edwardsville area is believed to be associated with interactions between the urban heat island, which maximizes at that time, and atmospheric processes. The



a. 1200-1500 CDT

b. 1500-1800 CDT

c. 1800-2100 CDT

Figure B-24. Percentage of total rainfall occurring in selected three-hour periods

urban mechanisms appear to be enhancing the natural nocturnal thunderstorm anomaly that extends into the METROMEX Network. Overall, the afternoon and evening maxima account for approximately 89% of the rainfall excess in the Edwardsville anomaly.

Other heavy rainfall areas located E of St. Louis are produced mostly by the afternoon maximum when up to 35% of the total summer rainfall was recorded over the eastern industrial area of St. Louis.

Diurnal rainfall curves were constructed for selected areas where 1) the urban effect is believed to be most pronounced, 2) topographic effects are a major factor, and 3) no significant urban or topographic effect is present. These indicated that the urban effect is responsible for larger variations in the diurnal distribution than topographic influences. Thus, for the SW Hills, the percent of total rainfall had a range of 9% from the forenoon minimum to the afternoon maximum. Similar ranges were 15% for the Upwind Control, 23% for the St. Louis Industrial-East, and 19% for the Edwardsville High. These and similar findings for other selected areas lead to the conclusion that the urban environment exerts a stronger influence on the diurnal distribution than the small-scale topographic factors in the network.

Analyses of the frequency of measurable rainfall indicated a trend for more frequent rainfall in the major urban-effect areas, but the increase is of much smaller magnitude than the rainfall amount differences. Thus, in the Edwardsville High the frequency of measurable rainfall was 12 and 10%, respectively, greater than the network mean in the peak rainfall periods of afternoon and evening. However, rainfall amounts were 40 and 50%, respectively, greater than the network mean during these maximum rainfall periods.

Spatial analyses showed that rainfall tends to develop earliest in the Ozark foothills. The urban effect develops most frequently in the early afternoon (1200-1500), and becomes pronounced in the late afternoon (1500-1800). A drift eastward and lessening of the urban enhancement is indicated in the early evening (1800-2100). This is followed by a second maximum in the Edwardsville area from 2100-2400, and this evening maximum is also quite pronounced in other areas in the NE and NW quadrants of the network. Except for mid to late afternoon, a W-E oriented low extends through St. Louis. Replacement of the persistent low by a high when diurnal conditions are most favorable for movement of surface air to cloud level is another indication of an urban enhancement mechanism that has a pronounced diurnal trend.

COMPARISON OF URBAN AND TOPOGRAPHIC EFFECTS IN SELECTED NETWORK AREAS

F. A. Huff and J. L. Vogel

Selection of Comparisons

As part of the analyses of METROMEX data, 17 areas were selected for rainfall comparisons within the raingage network. These areas were selected to represent various degrees of urban, topographic, and combined urban-topographic effects on the rainfall spatial distribution. Locations are shown in figure B-25. Comparisons between areas were made for each summer month and the summer season (June-August) from data for 1971-1975.

Two types of volume comparisons were made. These included analyses of 1) average rainfall volume in all storms combined for each area during the 5-year sampling period, and 2) average volume in those storms which produced 25 mm (1 inch) or more of rainfall. As pointed out frequently in this report, the precipitation anomalies in the St. Louis region, particularly the urban anomaly, result primarily from above-average rainfall in storms which produce moderate to heavy rainfall amounts naturally.

The frequency of storm events in the selected areas was also investigated. For all storms combined, the average frequency per gage of storms with measurable rainfall was determined for each selected area. For those storms with 25 mm or more of rainfall, the number of times that each gage recorded amounts of this magnitude was calculated and the average frequency per gage in each area was determined. The volume and frequency statistics then provide a means to help evaluate the network rainfall anomalies produced by urban or topographic effects superimposed on the natural rainfall pattern.

The terms "upwind" and "downwind" in this study are used in a climatological sense only. That is, downwind refers to those areas that are predominately in the flow of air or the path of storms moving across the potential effect area (urban or topographic barrier), whereas upwind refers to areas that are infrequently in the path of flow or storm movement across an urban or topographic area. Thus, the region southwest of St. Louis is classified as a no-effect area with respect to urban enhancement of rainfall; only a very small portion of the regional precipitation in summer occurs with northeasterly flow or storms moving from the northeast across the urban area. Since all no-effect areas are occasionally a potential effect area, and all effect areas are not always subject to rainfall modification, the climatological type of estimates obtained in this study should be conservative with respect to defining the enhancement quantitatively. Other analyses in which the effect and no-effect areas are defined in each particular storm, based on flow and storm movement, are discussed elsewhere in this report.

The 17 areas used in this study are shown in figure B-25 and described in table B-7. The areal sizes range from 93 km^2 (36 mi^2) to 536 km^2 (207 mi^2). Areas were selected both within and downwind of both urban-industrial centers (St. Louis and Alton-Wood River), in the most rugged hill area (Southwest Hills), in the bluffs regions, the bottomlands, and in a mostly rural region of apparent small (if any) urban or topographic enhancement effect (upwind control).

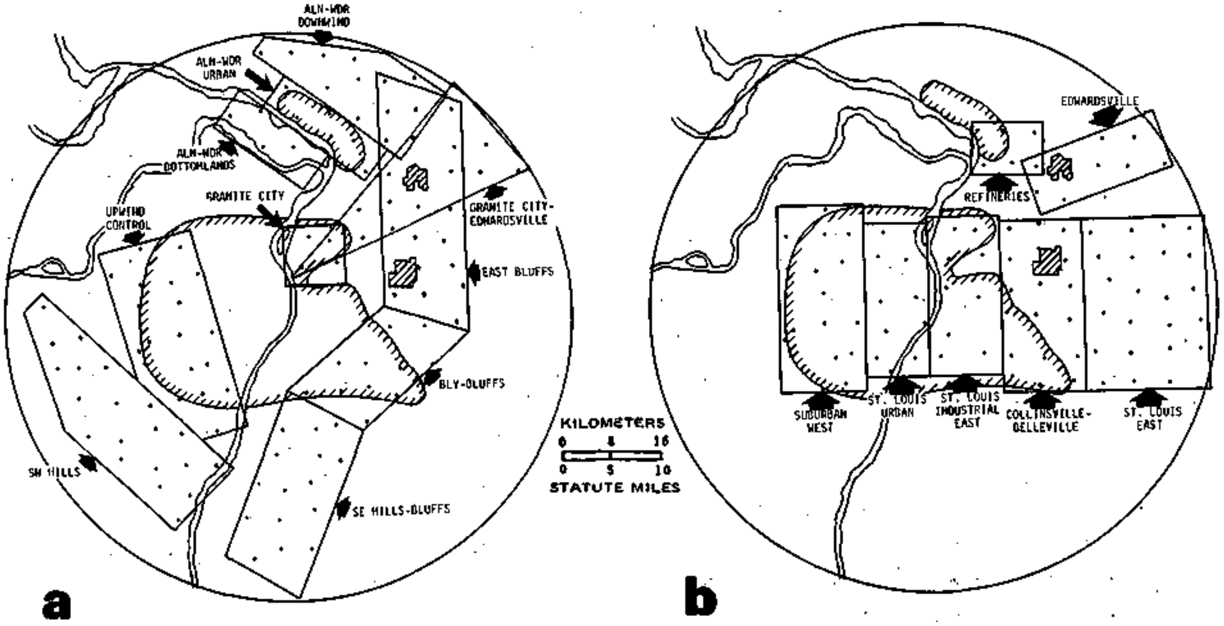


Figure B-25. Selected comparison areas of effect and no-effect

Results of Analyses Combining All Storms

As indicated earlier, analyses were made of the volume and frequency of total rainfall and rainfall from storms which produced amounts of 25 mm (1 inch) or more. The volume data were normalized by dividing the total rainfall volume in each area by the size of the area to provide rainfall volume per km^2, and thus permit direct comparison of data from areas of various size.

Table B-8 shows areal comparisons of normalized rainfall volume for the 5-summer period. The Upwind Control was selected for comparison with all other areas. Comparisons were made by computing the ratio of rainfall volume in each area to that in the comparison area. The Upwind Control was subject to only minor, if any, modification by topographic or urban forces. The comparison ratios for the Upwind Control then provide the best available measure of the effect of the various urban, topographic, and combinations of urban and topographic effects.

For the 5-summer period, the highest seasonal ratio was obtained between the Edwardsville high rainfall center and the Upwind Control. The average ratio of 1.49 is considered indicative of a strong urban effect, since this region is frequently downwind of two potential enhancement sources (St. Louis and Alton-Wood River). Although the East Bluffs also pass through this region, they are relatively low (less than 550 ft MSL) and their effect, if any, should maximize farther east. Furthermore, among the three bluff areas, rainfall enhancement should be greatest in the Southeast Hills-Bluffs which are the highest and also are frequently downwind of another potential topographic enhancement source, the Southwest Hills. However, table B-8 shows a ratio of 1.24 in these relatively high bluffs, and this is the smallest ratio among the three bluffs. Thus, it is concluded that the Edwardsville ratio of 1.49 (49% greater than the control) is largely related to urban enhancement effects, but there may be some bluffs contribution since the Edwardsville rainfall maximum area closely coincides with the low bluffs through that region.

The second highest ratio for summer rainfall with the Upwind Control (1.44) occurred in the Granite City-Edwardsville area which incorporates parts of the Granite City, Edwardsville,

Table B-7. Description of Comparison Areas

Nomenclature	Area km²	Area mi²	Area type	Description
Suburban West	443	171	Suburban	Largely residential
St. Louis Urban	256	99	Urban	Central city – commercial and industrial
St. Louis Industrial-East	210	81	Industrial	Major industrial area of St. Louis – much heavy industry
Granite City	93	36	Industrial	Steel plant, potentially strong nuclei source
ALN-WDR Urban	140	54	Urban-industrial	Primarily industrial center, moderate commercial-residential
Wood River Refineries	140	54	Industrial	Oil refineries, potentially strong nuclei and moisture source
Edwardsville	210	81	Downwind (urban)	Heavy rainfall center frequently downwind of St. Louis and ALN-WDR
Granite City-Edwardsville	373	144	Downwind (urban plus bluffs)	Includes parts of Granite City, Edwardsville, and East Bluffs potentially strong urban and weak bluff enhancement
Collinsville-Belleville	420	162	Downwind (urban plus bluffs)	Downwind of St. Louis with partial overlapping by bluffs – potential urban-topographic combined effect
ALN-WDR Downwind	303	117	Downwind	Downwind of ALN-WDR and bottomlands
St. Louis East Downwind	536	207	Downwind	Near limit of expected urban-effect and downwind of bluffs
Southwest Hills	466	180	Topographic (hills)	Most rugged hills in network, rarely urban-affected
Southeast Hills-Bluffs	373	144	Topographic-urban (hills plus bluffs)	Primarily subject to downwind effect from SW hills and bluff modification, but occasionally downwind of St. Louis
Belleville Bluffs	256	99	Urban-topographic	Downwind of St. Louis and subject to bluff effect
East Bluffs	536	207	Urban-topographic	Low bluffs in area but downwind of both St. Louis and ALN-WDR
ALN-WDR Bottomlands	93	36	Topographic	Heat-moisture source for convective developments upwind of ALN-WDR
Upwind Control	490	189	No-effect	Mostly rural with potential for small hill or urban effect, if any

and East Bluffs areas. In view of the freezing nuclei source (Granite City steel plant) and the frequent downwind position of this area with respect to St. Louis and Alton-Wood River, a potentially strong enhancement would be expected.

The Granite City area (figure B-25a) should be subject to an urban effect only, since there are no apparent topographic sources of enhancement in its vicinity. Therefore, the relatively high summer ratio of 1.31 with Upwind Control appears to be related to an urban-industrial effect. The St. Louis Industrial-East also belongs in this category. Its ratio of 1.22 is somewhat less than the Granite City ratio but still indicative of a relatively strong enhancement. The average ratio for the network was 1.20. All ratios higher than the average occurred in areas which appear to be subject to urban or a combination of urban-topographic effects.

The ratio for the only area which appears to be entirely (or nearly so) restricted to hill effects is the Southwest Hills where the summer ratio was 1.09, indicative of an approximate 9% enhancement from hill effects in this region where the hills are the highest and most rugged in the network. It is interesting to note that the area designated Upwind Control lies just N-NE of the Southwest Hills, but no evidence of rainfall enhancement was found.

Table B-8. Comparison of Average Monthly
and Seasonal Rainfall Volumes in Selected Areas during 1971-1975

Area	*Ratio to upwind control area* *Summer*	*June*	*July*	*August*
Suburban West	0.99	0.99	1.02	0.98
St. Louis Urban	1.10	1.11	1.04	1.14
St. Louis Industrial-East	1.22	1.15	1.12	1.36
Granite City	1.31	1.21	1.29	1.40
Alton-Wood River Urban	1.34	1.34	1.55	1.15
Wood River Refineries	1.38	1.44	1.72	1.04
Edwardsville	1.49	1.98	1.41	1.22
Granite City-Edwardsville	1.44	1.75	1.43	1.24
Collinsville-Belleville	1.28	1.22	1.15	1.44
Alton-Wood River Downwind	1.38	1.38	1.61	1.19
St. Louis East Downwind	1.19	1.22	1.05	1.29
Southwest Hills	1.09	1.03	1.10	1.13
Southeast Hills-Bluffs	1.24	1.13	1.29	1.27
Belleville Bluffs	1.26	1.17	1.07	1.48
East Bluffs	1.37	1.51	1.37	1.26
Alton-Wood River Bottomlands	1.34	1.32	1.54	1.18
Upwind Control	1.00	1.00	1.00	1.00

The Southeast Hills-Bluffs area is subject to two potential topographic effects which are the bluffs and the Southwest Hills located in a direction (W) frequently upwind. The urban effect would probably be minor, since it would mostly occur with NNW-NNE storm movements, and these are associated with less than 10% of the storms. Thus, the ratio in this area is believed to be largely related to topography and probably represents the maximum topographic effect in the network. The summer ratio of 1.24 is equivalent to the ratio in the urban effect area of St. Louis Industrial-East, but lower than the Granite City urban-effect ratio of 1.31, and much less than the combined urban-topographic effect areas of Granite City-Edwardsville and Edwardsville, which are believed to be primarily urban affected.

If we take a very conservative viewpoint with respect to the urban effect, we can assume that the SE Hills-Bluffs ratio of 1.24 is entirely related to a topographic effect and this should be a network maximum. However, we will now assume the same degree of bluffs effect in the Edwardsville area and the Granite City-Edwardsville areas. Then, dividing the above two ratios, 1.49 and 1.44 by the SE Hills-Bluffs ratio of 1.24, we should obtain a conservative measure of the urban effect. This yields ratios of 1.20 and 1.16, respectively, and indicates urban-induced enhancements of approximately 20 and 16% in summer rainfall in these areas. These are close to the apparent urban-effect ratio of 1.22 (22% enhancement) in St. Louis Industrial-East.

A more realistic assumption would be that the maximum topographic effect is equivalent to that obtained for the relatively rugged Southwest Hills or somewhere between the apparent Southwest Hills and Southeast Hills-Bluffs effects. Assuming the Southwest Hills ratio also portrays the hill effect in the Southeast Hills-Bluffs area, the bluff effect can be estimated by dividing the ratios for these two areas (1.24/1.09). This indicates an approximate 14% increase from bluffs enhancement. Now dividing the Edwardsville ratio of 1.49 by 1.14, a ratio of 1.31 is obtained, which indicates an approximate 31% increase in summer rainfall in the Edwardsville area due to urban effects. Similarly, an urban-induced increase averaging 26% is indicated for the Granite City-Edwardsville area. These are in excellent agreement with the strictly urban-effect ratios of 1.31 at Granite City and 1.22 in St. Louis Industrial-East which are not exposed to the potential bluffs effect.

The above modified ratios for Edwardsville and Granite City-Edwardsville are still somewhat conservative with respect to the urban effect, since the lower bluffs in these regions would be expected to induce a lesser enhancement of storm rainfall than the higher bluffs in the SE part of the METROMEX Network. In any case, the foregoing analyses indicate a substantial urban enhancement that appears to reach a summer maximum of 30% or more in the Edwardsville and Granite City areas and 20 to 30% in other areas frequently subjected to the urban-industrial effects of St. Louis.

Comparing the three St. Louis urban ratios in table B-8 provides further insight into the urban effect. The Suburban West ratio indicates no urban effect. The St. Louis Urban ratio of 1.10 indicates a modest enhancement over the central city, which is followed by an increase to 1.22 in the major urban-industrial region east of the central city. This is a logical progression, since it indicates little or no effect upon initial contact with the largely residential suburbs (assuming a prevailing westerly component of storm movement). With some stimulation of convective systems in the form of heat, nuclei, turbulence, or convergence on the west side of the city, the enhancement should increase with time and with a potentially stronger input over the central city. The effect should increase still further with the longer travel time and input in the eastern industrial part of the metropolitan area. This progression of apparent urban enhancement is another indicator of an urban effect and its relative magnitude.

The bottomlands are a heat-moisture source and, therefore, conducive to convective development. For this reason, a portion of the bottomlands SW of Alton-Wood River was selected for comparison tests. It had been hypothesized previously (Huff, 1975) that the bottomlands are likely to enhance the development of convective entities which may then move across Alton-Wood River from the S-SW-W. These would then maximize over the urban area and continue downwind with possible further rainfall increases in the downwind region. One evaluation of this combined topographic-urban effect can be made from the three Alton-Wood River ratios (Bottomlands, Urban, and Downwind) in table B-8. Reference to the summer ratios shows a. mean of 1.34 in the Bottomlands, which indicates a relatively strong enhancement in this area which is subject to topographic influences plus potential urban effects when low-level winds are from the SSW-S-SSE. However, no significant increase in ratio is indicated over the Alton-Wood River Urban and Downwind areas. Strictly from this analysis, the conclusion would have to be that the overall effect of the Alton-Wood River Urban region, except possibly for the refinery area, is insignificant. The refinery area is a likely contributor to the Edwardsville high.

Examination of the monthly ratios in table B-8 shows that the Edwardsville maximum was strongest in June, but relatively strong in all three months. The Edwardsville ratio ranked first in June, sixth in July, and ninth in August among the 16 stations compared with the Upwind Control. In general, the heaviest rainfall and therefore the highest ratios occurred in the Edwardsville area in June, in the Alton-Wood River region in July, and in the Collinsville-Belleville area in August. Rainfall was heaviest in the Southwest Hills during July and August. The heaviest rainfall in the bluffs areas varied between months. The SE Hills-Bluffs precipitation was relatively heavy in July, whereas June rainfall was dominant in the East Bluffs and August rainfall in the Belleville Bluffs.

The frequency of storms with measurable rainfall was analyzed in the comparison areas to help determine whether the anomalies were related to greater storm frequencies, and, if so, whether the volume or frequency effect was more important. Measurable rainfall was defined as 0.25 mm (0.01 inch) or more at a gage. For each area, the number of measurable rainfalls at each raingage was determined and an average for the area calculated. The statistic for comparison was the average number of occurrences of measurable rainfall per gage.

Table B-9. Comparison of Average Summer Rainfall Volumes in 25-mm Storms within 17 Selected Areas during 1971-1975

Area	*Ratio, given area to upwind control*	*Percent of total rainfall from heavy storms*
Suburban West	1.02	35
St. Louis Urban	1.16	37
St. Louis Industrial-East	1.49	42
Granite City	1.77	46
Alton-Wood River Urban	1.62	41
Wood River Refineries	1.82	45
Edwardsville	2.37	55
Granite City-Edwardsville	2.13	51
Collinsville-Belleville	1.75	47
Alton-Wood River Downwind	1.74	43
St. Louis East Downwind	1.49	43
Southwest Hills	1.24	39
Southeast Hills-Bluffs	1.45	40
Belleville Bluffs	1.60	44
East Bluffs	1.89	48
Alton-Wood River Bottomlands	1.61	41
Upwind Control	1.00	34

For the five summers, the total frequency ranged between 111 and 126 occurrences with a median of 118 among the 17 comparison areas. The highest frequency (126) occurred in the Belleville Bluffs, followed by Alton-Wood River Bottomlands (123), and St. Louis Urban (121). The lowest frequency (111) occurred in the Edwardsville area. It is immediately obvious that the Edwardsville rainfall maximum was produced by greater volumes of storm rainfall with respect to the rest of the network, rather than by more frequent occurrences of storms. Furthermore, no strong inverse correlation was indicated since the Upwind Control and Suburban West, areas of relatively light rainfall (see figure B-1), had 120 and 118 occurrences, respectively, close to the network median.

Thus, there was little correlation between rainfall volume and rainfall frequency for the 5-summer period. Therefore, it is concluded the rainfall enhancement by urban and topographic effects resulted primarily from stimulation of ongoing storms rather than the development of new storm systems.

Heavy Rainstorm Relations

Further investigation of the urban and topographic anomalies was made through analyses of the distribution of heavy rainstorms in the 17 selected areas. Heavy storms were defined as those producing 25 mm (1 inch) or more of rainfall at a raingage. Average rainfall volume per km^2 was calculated for the portion of the summer rainfall produced by such storms in each of the selected areas during the 5-summer sampling period. Ratios of each normalized volume to that of the Upwind Control were then determined. Results are summarized in column 1 of table B-9.

Comparison of the ratios in this table with those for total summer rainfall in table B-8 show much higher ratios in the heavy storms in those areas which are potentially subject to urban, topographic, or combinations of urban and topographic effects. Thus, the rainfall volume in heavy storms in the Edwardsville area averaged over twice that in the Upwind Control; This analysis, plus other analyses discussed elsewhere in this report, has led to the conclusion that the anomalies result largely from stimulation of ongoing storms by environmental factors. In any case, the anomalies appear to be more closely related to storm intensity than to storm frequency.

Following the same analysis procedures used in the previous discussion of total summer rainfall, the hill effect in the heavy storms produced an average increase of 24% over that recorded in the Upwind Control. The bluffs effect calculated from the data for Southwest Hills and Southeast Hills-Bluffs was found to be approximately 17%. Adjusting the Edwardsville data for the bluffs effect resulted in an urban-related increase of approximately 100% in the heavy storms. A similar computation indicated an urban-induced increase of approximately 80% in the Granite City-Edwardsville area. These values compare favorably with the 77% increase calculated for Granite City. Within the urban area of St. Louis, no appreciable effect was indicated in the residential region designated Suburban West. The urban effect increased to 16% over the central city (St. Louis Urban) and to 49% in the industrial area east of the Mississippi River. Trends were similar to those found for total rainfall, but the anomalies appear to be much more pronounced in the heavy storms.

In the Alton-Wood River region, there was indication of a slight increase of about 7% downwind of the urban area, but no difference between the bottomlands and the urban area. Again, this indicates independence of the urban and bottomlands effect (which is unlikely with the bottomlands lying S and SW of Alton-Wood River) or only a small urban effect. The oil refinery ratio of 1.82 in table B-9 is about 13% greater than either Alton-Wood River Urban or Bottomlands, so this may reflect the effect of the most concentrated industrial zone in the Alton-Wood River area, and one which is a potential source of raindrop nuclei, moisture, and additional heat.

Column 2 in table B-9 shows the percent of the total summer rainfall produced by the heavy storms. This reaches a peak (55%) in the Edwardsville area where the urban anomaly appears to maximize, and is least in the Upwind Control (34%). In general, the percentages are largest where the urban effect is most pronounced, and least upwind of the urban-industrial areas (west of the Mississippi).

The frequency of 25-mm storms was investigated also. Results indicated the expected maximum in the Edwardsville area where an average of 19 were recorded, compared with a low of 8 in the Upwind Control. Other high frequencies were recorded in Granite City-Edwardsville (17), East Bluffs (15), Refineries (14), and Collinsville-Belleville (14). Low occurrences were 9 in Southwest Hills, 8 in Suburban West, and 9 in St. Louis Urban.

Summary

Analyses were made of the rainfall distributions in 17 selected areas within the METROMEX Network. Computations of average rainfall volume per km^2 were made for all summer storms combined for 1971-1975 and for heavy storms producing 25 mm or more of rainfall. Frequency of measurable rainfall in the five summers was made for 1) all storms combined and 2) for the frequency of 25-mm storms. Areas were selected to represent regions exposed to urban environmental effects, topographic effects, combinations of the two potential effects, plus a relatively large no-effect area for comparison purposes.

For all summer storms combined, results indicated a maximum urban effect northeast of St. Louis and southwest of Alton-Wood River. The urban effect appears to reach a maximum of

30 to 35% in the region from Granite City to Edwardsville. The bluffs effect was calculated to be approximately 14%, and the hill effect (Ozark foothills) amounts to an increase of about 9%. The urban effect was not measurable in the western suburbs, increased to about 10% across the central city (commercial area) and to 22% in the heavily industrialized area just east of the Mississippi River.

The urban effect is difficult to evaluate in the Alton-Wood River area, because of interactions with 1) the bottomlands (topographic effect) which are frequently upwind of the urban area, and 2) the St. Louis metropolitan region which is upwind with southerly flow in the low levels. Similar summer ratios were obtained between the Upwind Control and the Bottomlands, Alton-Wood River Urban, and Alton-Wood River Downwind areas. However, these ratios indicate no significant trend for summer rainfall to be enhanced by the Alton-Wood River urban area.

Analyses of monthly ratios between the Upwind Control and the potential effect areas indicated the maximum urban effect in the network (Granite City-Edwardsville region) is greatest in June and least in August. However, the urban effect appears to maximize in August immediately east of St. Louis (Granite City-Collinsville-Belleville). Urban and topographic effects apparently maximize in the bottomlands and Alton-Wood River in July.

Analyses of the frequency of measurable rainfall indicated the anomalies are not correlated well with rain frequency. For example, the Edwardsville area, where rainfall volume maximized during the five summers, had the lowest frequency of measurable rainfall, whereas the Upwind Control where the 5-summer rainfall volume was least, had an average frequency with respect to the network.

Analyses of the rainfall volume in heavy storms (25 mm or more) showed the same trends as all storms combined, but the indicated percentage increases in rainfall in the anomaly areas were much greater in most cases. As expected, the frequency of 25-mm storms maximized where the rainfall volume from these storms was greatest.

RELATION BETWEEN SURFACE WINDS, STORM MOVEMENT, AND RAINFALL

J. L. Vogel and F. A. Huff

Basis for Analyses

If the urban environment enhances rainfall downwind of urban-industrial regions, this should be reflected in the rainfall patterns when the data are stratified by low-level wind directions and movement of the convective entities within the advancing storm system. The low-level winds are a measure of the direction of movement of the urban plume (aerosols, moisture, heat) which provides the environmental input to the rain-bearing clouds in the storm system.

In this study, the average surface wind during the 1 to 3 hours prior to rainfall was used to estimate the movement of the urban plume. When winds were relatively strong, the plume direction (surface wind movement) could be adequately defined in the hour prior to rainfall, but in light winds it was sometimes necessary to average over a longer period to obtain a reliable estimate. Surface winds were grouped on a quadrant basis (SE, SW, NW, or NE).

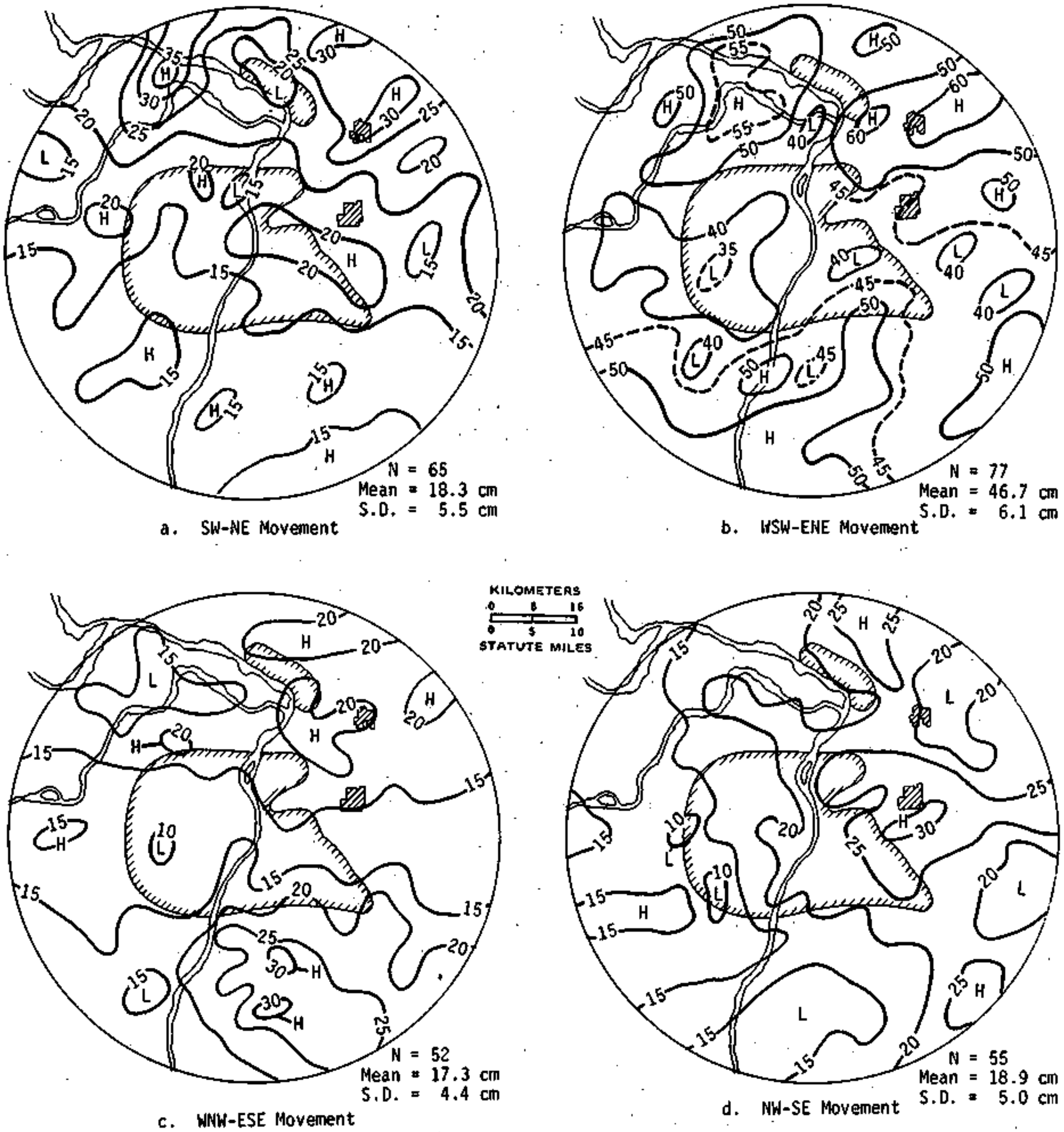
Surface raincell and radar data were used to determine the motion of convective entities (raincells) within a storm system. These were grouped into twelve 30-degree segments. Additionally, raincell movement could be classified indeterminate when motion could not be defined reliably through the use of radar and raingage data.

In analysis of rainfall patterns, isohyetal maps were first constructed for each of the storm movements. The data were then further subdivided and rainfall patterns constructed for each storm movement in each surface wind quadrant. The frequency distribution of storm movements in the 5-summer period is shown in table B-10. For the 1971-1975 period, storms moved most frequently from the WSW and SW. Movements from the NE and SE quadrants were very infrequent. Among moving raincells, only 1% moved from the NE quadrant (NNE, NE, ENE) and 3% from the SE quadrant (ESE, SE, SSE). The frequent WSW and SW storm movements would carry cloud systems across substantial portions of the urban-industrial regions where they would be exposed to environmental inputs and then into the NE quadrant of the raingage network where the major rainfall anomaly was identified in the 1971-1975 period.

Rainfall Patterns with Various Storm Movements

Figure B-26 shows the rainfall patterns associated with the four storm movements producing the most rainfall in the summers of 1971-1975. Storms moving from the SW produced the heaviest rainfall in the bottomlands, downstorm (NE) of Alton-Wood River, and in the Edwardsville area which would be downstorm of Granite City and the northern part of St. Louis with SW storm movements.

More interesting is the rainfall pattern associated with storms moving from the WSW (figure B-26b) which is the most frequent direction of movement and the one associated with approximately 42% of the total objective storm rainfall on the network during 1971-1975. This pattern shows the major high over the Edwardsville area, followed closely by a bottomlands high. The network pattern is strikingly similar to the total 5-season rainfall pattern in figure B-1. The primary and secondary highs and the major low are in close proximity in the two spatial distributions.



a. SW-NE Movement

b. WSW-ENE Movement

c. WNW-ESE Movement

d. NW-SE Movement

Figure B-26. Rainfall patterns with various storm movements

Table B-10. Frequency of Storm Movements, 1971-1975

	Number of storms					*1971-1975*	
	1971	*1972*	*1973*	*1974*	*1975*	*Total number*	*Percent of total*
SSW	1	2	5	12	4	24	7
SW	10	16	11	11	16	64	20
WSW	13	13	17	17	17	77	23
WNW	9	11	9	13	11	53	16
NW	6	15	11	16	7	55	17
NNW	4	3	2	6	4	19	6
NNE	1	0	1	1	1	4	1
NE	0	0	0	0	0	0	0
ENE	0	0	0	0	0	0	0
ESE	0	0	0	0	1	1	0+
SE	0	0	0	2	1	3	1
SSE	1	2	0	0	1	4	1
Stationary	0	0	0	2	1	3	1
Indeterminate	2	7	9	0	5	23	7
Total	47	69	65	80	69	330	100

Figure B-26c shows the network rainfall pattern associated with storms moving from the WNW. The major high is located in the SE quadrant in a region which would be downstorm of the Ozark foothills in the SW quadrant with WNW-ESE storm movements. Minor highs are indicated in the Edwardsville and Wood River areas where they would be downstorm of some industrial activity, but a strong case for urban involvement cannot be made with this pattern.

Figure B-26d shows the spatial distribution of rainfall in storms moving from the NW. Here, there are again indications of urban involvement since the heaviest rainfall occurred E of St. Louis and downstorm of the Granite City industrial area.

Overall, the rainfall patterns in figure B-26 suggest the likelihood of urban involvement in the location of regions of heaviest rainfall. However, it would appear that movement of the urban plume taken in conjunction with storm movements should provide a better indication of the urban involvements. This is discussed in the following paragraphs.

Rainfall Patterns with Surface Wind and Storm Movements

Analyses indicated that 45% of the rainfall occurred with SE surface winds preceding the onset of rainfall. Similarly, 40% occurred with SW surface winds, 7% with NW winds, and 8% with NE winds. Thus, 85% of the rainfall was associated with surface winds from the SE or SW quadrants, so that these are by far the most important to investigate. Table B-11 shows the percent of total rainfall associated with the various storm movements and surface wind directions.

With SE surface winds, storms moving from the WSW produced 29% of the 5-summer total rainfall, and along with storms moving from the SW and NW accounted for 69% of the total rainfall. Figure B-27a-b shows the rainfall patterns associated with SE surface winds and storms moving from the WSW and NW.

Storms moving from the WSW produced a region of relatively heavy rainfall in the northern part of the network, extending from the bottomlands through the Wood River area into the Edwardsville region. With low-level winds from the SE quadrant, the urban plume would be carried into the NW quadrant of the network. With plume ingestion into cloud bases in the NW

Table B-11. Percentage Distribution of Rainfall Stratified by Storm Motion and Surface Wind Direction, Summers of 1971-1975

	Percent of total rainfall			
Storm movement from	*SE surface winds*	*SW surface winds*	*NW surface winds*	*NE surface winds*
SSW	13	1	0	0
SW	20	13	2	1
WSW	29	52	58	67
WNW	15	13	25	29
NW	20	9	9	2
NNW	2	1	6	<0.5
NNE	0	1	<0.5	0
NE	0	0	0	0
ENE	0	0	0	0
ESE	<0.5	0	0	0
SE	1	0	0	1
SSE	0	<0.5	0	0
Indeterminate	<0.5	<0.5	<0.5	<0.5
Total rainfall, *cm*	48.9	43.9	7.2	8.3
Percent of all network rainfall	45	40	7	8

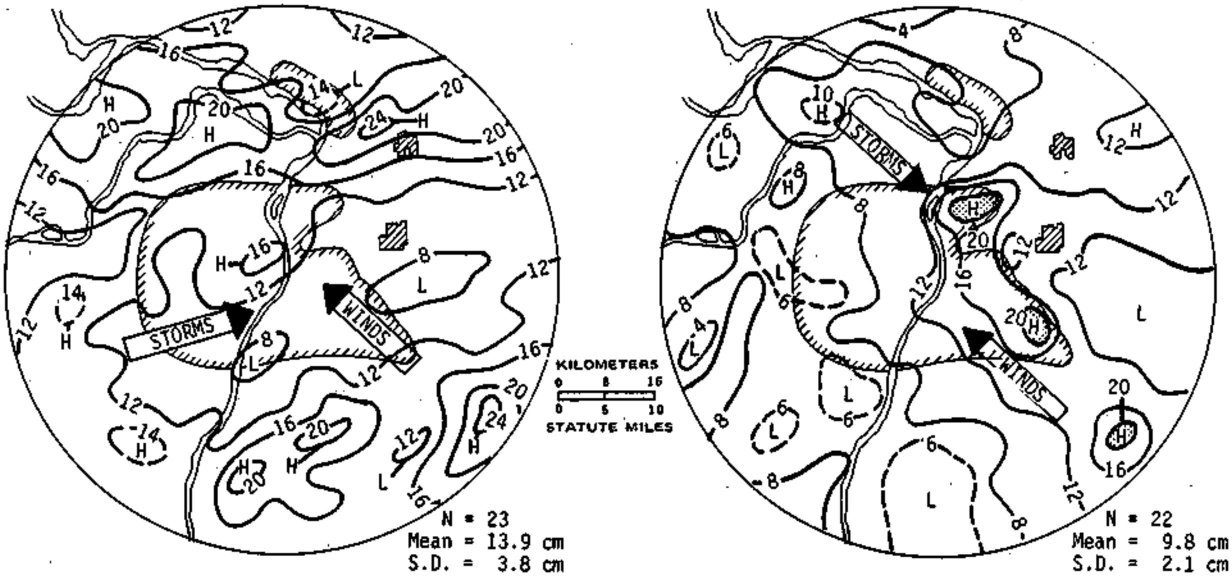
quadrant, the urban enhancement could be expected to occur somewhat later in the NE quadrant. One of the major highs was located in this quadrant, but others also occurred in the NW quadrant. The NW centers could be associated with a combination of urban and bottomlands effects with low-level flow from the SE.

Another relatively heavy rainfall area was established in the southern part of the network in figure B-27a, and this region lies in the path of storms moving from WSW across the Ozark foothills. Therefore, this anomaly is likely a topographic effect.

Figure B-27b shows the rainfall pattern associated with SE surface winds and storms moving from the NW. This pattern is very indicative of an urban effect. The region of heaviest rainfall occurred E and SE of St. Louis in a region located in the path of storms moving across the eastern industrial area of St. Louis after possible ingestion of the urban plume NW of the city.

Figure B-28a-b shows the rainfall patterns associated with SW surface winds and storms moving from the WSW and NW. These movements were associated with 71% of the total rainfall in storms having SW surface winds. The WSW pattern in figure B-28a shows the major highs located along a NE-SW line from Edwardsville to Granite City. With low-level winds blowing the urban plume northeastward and storms moving from the WSW, these highs could very likely be associated with urban effects. Rainfall amounts in the Edwardsville-Granite City highs were over two standard deviations above the network mean rainfall, and rainfall in the center of the Edwardsville high was three standard deviations above the network mean.

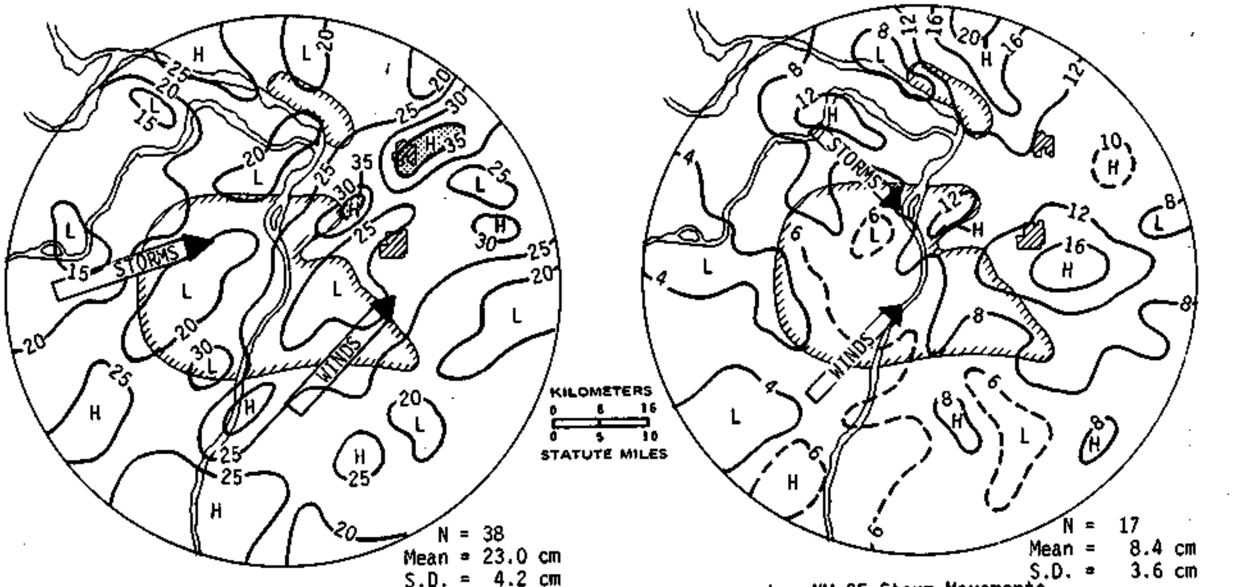
Figure B-28b shows the rainfall pattern associated with SW surface winds and storms moving from the NW. Relatively light rainfall occurred on the network in these storms compared with those moving from the WSW. The rainfall pattern appears quite random, but there is some suggestion of an urban involvement E of St. Louis. There would be little opportunity for ingestion of the low-level plume into cloud bases as storms approached and reached the city. Plume exposure would take place over and NE of St. Louis, so a strong urban effect relatively close to the urban area would not likely be found in the network rainfall distribution.



a. WSW-ENE Storm Movements

b. NW-SE Storm Movement

Figure B-27. Rainfall patterns with SE surface winds and storms from the WSW and NW



a. WSW-ENE Storm Movements

b. NW-SE Storm Movements

Figure B-28. Rainfall patterns with SW surface winds and storms from WSW and NW

Reference to surface wind-storm movement patterns of rainfall with NW and NE surface winds did not reveal any particular evidence of an urban enhancement of rainfall. In general, rainfall was very light and the patterns quite random in their spatial distributions of highs and lows in the network.

Conclusions

The investigation of spatial rainfall patterns associated with various combinations of surface winds and storm movements provided additional evidence of urban effects on rainfall by the urban-industrial complex. However, the evidence was not consistent enough between the various wind-motion combinations to provide conclusive proof of an urban involvement. However, when added to the results of numerous rainfall analyses performed as part of the METROMEX research, the wind-storm motion findings are useful in establishing the veracity and magnitude of the urban anomaly.

In agreement with other METROMEX analyses, the strongest evidence of the urban effect was found with those combinations of storm motion and surface winds that were the major rain producers on the network during 1971-1975. Thus, it was found that storms moving from the WSW, which were associated with 42% of the 5-summer rainfall, produced a strong urban high in the rainfall pattern in the Edwardsville area where the urban anomaly apparently maximizes. Among the various surface wind-storm motion combinations, storms moving from the WSW with SE surface winds were the major rain producer, and the rainfall pattern showed the heaviest network rainfall along a line from Edwardsville to Granite City in the region of maximum urban effect.

EXTENDED AREA RAINFALL FINDINGS

Paul T. Schickedanz and Stanley A. Changnon, Jr.

During the first year of METROMEX, 1971, all summer rainfall measurements were from a dense recording raingage network located within the 424cm (26-mi) radius research circle shown on figure B-29. Results suggested extension of urban-induced rainfall changes beyond this network, so additional recording gages were installed before the summer of 1972 in an area east (labeled "extended area" on figure B-29) of the circle (Changnon, 1973). For this extension of the network, gages were installed at a coarser density (210 km^2 or 81 mi^2 per gage) than the density of the gages within the research circle (24 km^2 or 9 mi^2 per gage). A coarser network was chosen to provide greater areal coverage with the limited number of available gages.

Although the density of 210 km^2 per gage was retained during the summers of 1973, 1974, and 1975, the recording gages in the extended network area were replaced by non-recording gages starting in 1974. The extended network data were used primarily to ensure adequate areal measurement of any urban effects on summer rainfall which extended eastward beyond the confines of the METROMEX research circle. The denser inner network was chosen to study rainfall from individual convective entities (raincells) and study of these could not be pursued with the limited gages and areal spread desired in the extended area.

Data and Analysis

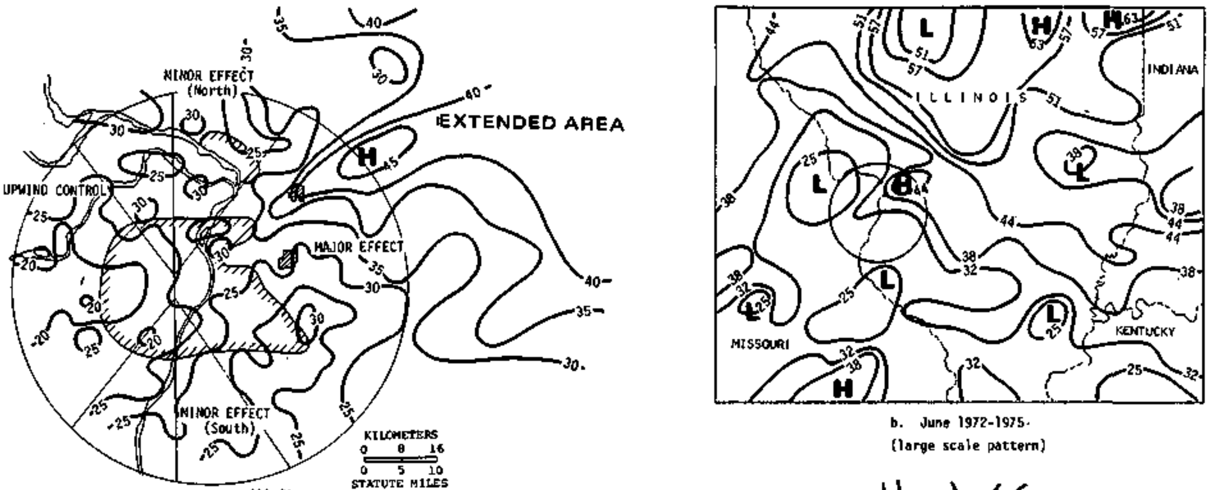
. Since storm rainfall totals were studied extensively in the METROMEX analysis of rainfall in the research circle, and have proven to be a useful tool for assessing urban effects, they were also used in the investigation of rainfall in the extended area. Total rainfall at each gage in the extended area for each storm period was easily derived for the 1972 and 1973 summers from the recording gages in this area. However, division of gage rainfall into storm periods was not as easy for the summers of 1974 and 1975 because of the lack of recording gages. Therefore, storm totals in the Extended Network (EN) were determined in the following manner.

First, an initial approximation to the storm periods in the EN was made from an inspection and comparison of.the 24-hour totals from the EN with the P-storm (Processing storm) periods for the Research Circle Network (RCN). The approximate storm periods were used to obtain approximate P-storm totals at each EN gage and were plotted on base maps similar to figure B-29. Estimations of any missing rainfall amounts were made from the plotted storm totals.

The P-storm periods including their totals on the EN were then compared to the O-storm (Objective storm) periods and their totals on the RCN to obtain O-storm totals throughout the EN.

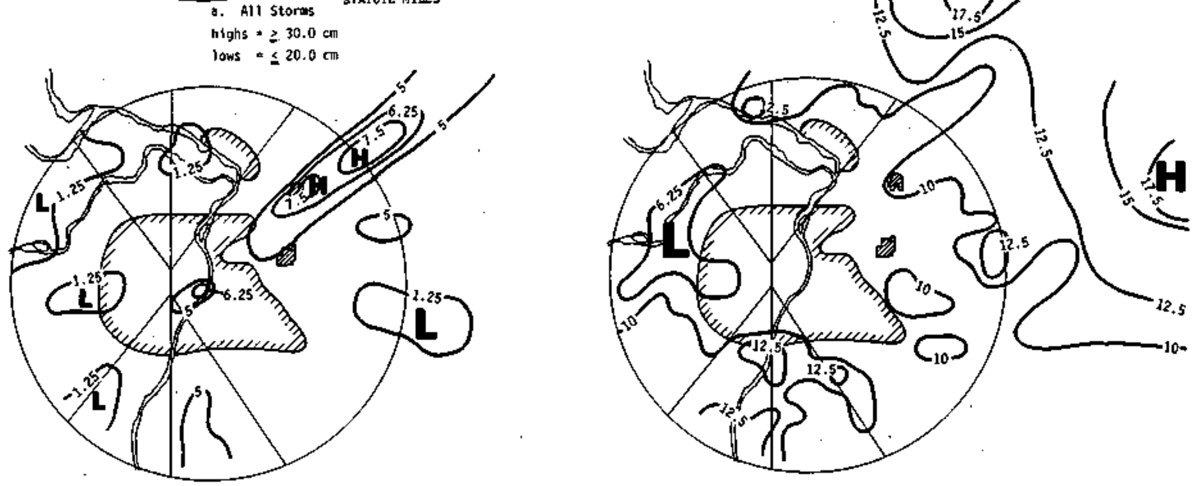
[Note. P-storm is a preliminary grouping of rainfall totals which is essential in quality control procedures in the reduction of rainfall data from raingage charts. O-storm is a final grouping of storms based on objective definition and delineation. See Schickedanz and Busch (1975) for further details.]

If the P-storm periods for the EN matched or were an extension of the O-storm periods of the RCN, then the O-storm periods were assumed to be the same as those of the P-storms on the EN (which was frequently the case). If the P-storm period overlapped several O-storm periods, a determination as to which storm(s) to assign the rain total was made by visual comparison of the O-storm patterns on the RCN with the EN P-storm patterns. Usually, the O-storm most likely to have rain on the EN could be easily identified. Sometimes, all rain was assigned to one O-storm. Other times, when more than one O-storm was present on the RCN, rain totals were divided between O-storms.



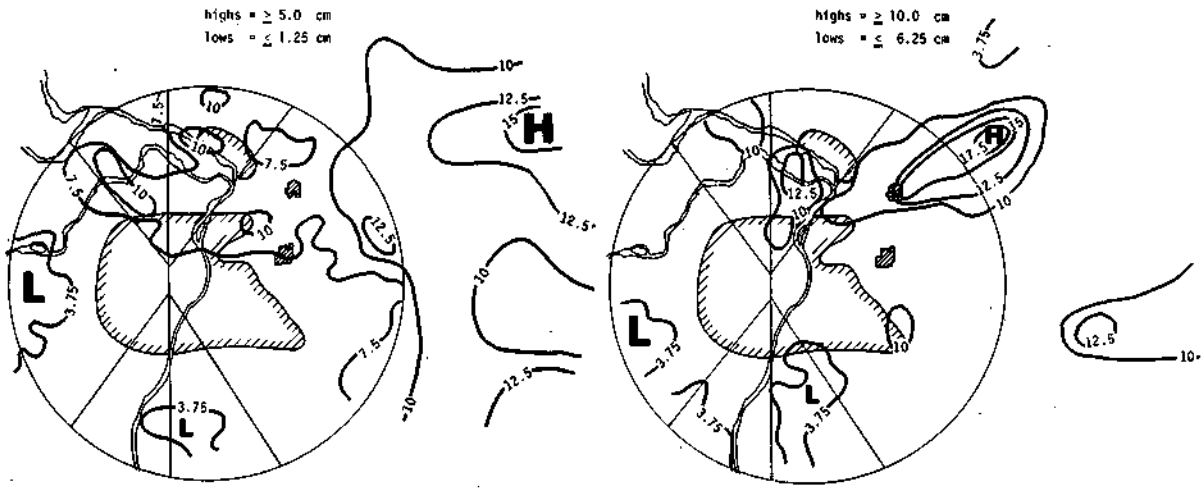
a. All Storms
highs = ≥ 30.0 cm
lows = ≤ 20.0 cm

b. June 1972-1975
(large scale pattern)



c. June 1972
highs = ≥ 5.0 cm
lows = ≤ 1.25 cm

d. June 1973
highs = ≥ 10.0 cm
lows = ≤ 6.25 cm



e. June 1974
highs = ≥ 7.5 cm
lows = ≤ 3.75 cm

f. June 1975
highs = ≥ 10.0 cm
lows = ≤ 3.75 cm

Figure B-29. Total storm rainfall patterns for June 1972-1975

EN rain was used only when it could be considered to be part of the O-storm period (i.e., the P-storm periods had to be within one hour of the rain, which is the separation time of objective storms on the RCN). This resulted in discarding light rains on the EN during the evenings of June 19-20, 1974, and June 21, 1975. In addition, light rain on the EN on August 30, 1975, was discarded because the two O-storms in this day were both confined to the extreme western part of the network and it was judged that the EN rain could not be part of these O-storms. It should be noted that many of the O-storms on the RCN did not have recorded rain on the EN. Thus, many of the O-storms of the RCN never reached the EN.

This means of ascertaining O-storm rainfalls on the EN during the summers of 1974 and 1975 was complex and semi-subjective, and is a limitation in the analysis and results. Another limitation is that even though the density of the EN was much greater than that of the cooperative climatological network of the National Weather Service, it was still less than that of RCN. It should be recognized that the differing network densities of the RCN and EN create difficulties in a rigorous comparison of areal means in the extended area with those of the RCN or subdivisions thereof. It was concluded that an assessment of the extended area rainfall on a storm basis would be meaningful and indeed was necessary, in spite of the limitations mentioned above. Such an assessment is important because of the interest in "extra-area" effects, in the context of both intentional and unintentional precipitation modification.

Monthly Results

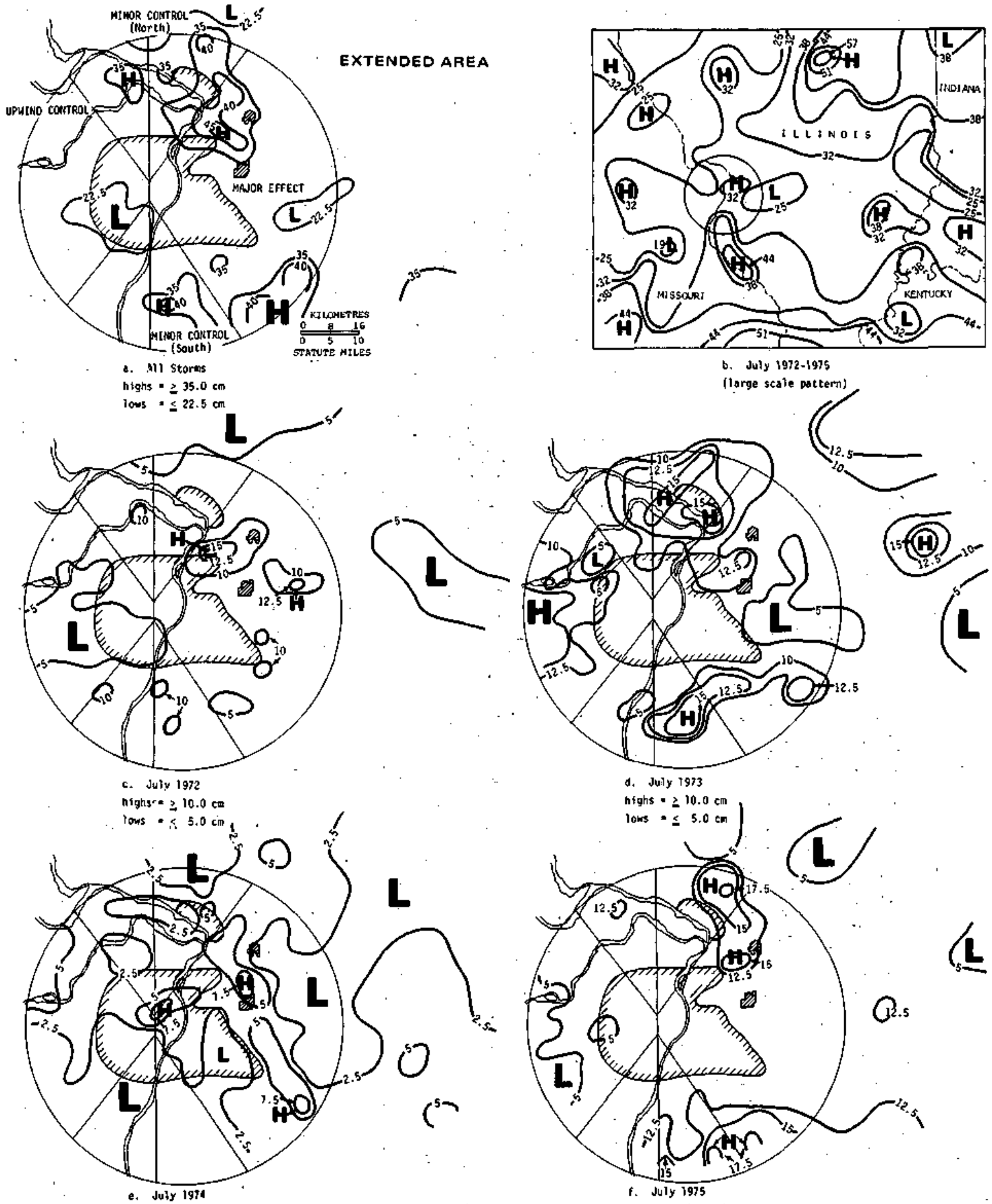
The stratification of the rainfall data by months was found to be important for both storm and cell rainfall on the RCN. Studies involving this monthly stratification indicate that the locations of the rainfall anomalies shift when their locations are compared to differing cell movements and wind directions during each of the three summer months during 1971-1975. Thus, a montly stratification was also applied in these studies of the extended area rainfall.

The total rainfall pattern for June 1972-1975 is shown on figure B-29a. Clearly, the Edwardsville high to the NE stretches over a large portion of the extended area. Just as clearly, the urban-industrial related high in July (figure B-30a) is located in the Wood River-Edwardsville-Granite City area, but it is generally confined to the research circle. During August, the 1972-1975 major rainfall high is located in the St. Louis area and is again confined to the research circle (figure B-31a).

Studies of the O-storms and raincells on the RCN and EN in June indicate that the major rain-producing storms in the Edwardsville area during June had their primary movement toward the ENE and a secondary motion toward the ESE. This suggests that St. Louis is a major potential source region and that Wood River is a secondary source region. [Here, the term "source region" is defined as those urban and/or industrial areas which are likely to be releasing heat, nuclei, and possibly moisture (treatment agents) to the atmosphere.]

Since the Edwardsville high extends over a large portion of the extended network, and may reach even further, the monthly rainfall patterns over the large area comprising a portion of Missouri, Illinois, and Indiana were constructed (figures 29b, 30b, and 31b). The data for these patterns were obtained from the National Weather Service cooperative raingage network. A few stations used in earlier climatological studies by Huff and Changnon (1970) were terminated in 1970 and were unavailable for this study. Therefore, data from the METROMEX gages nearest to those stations were also used in constructing the large area pattern.

The network pattern of June rainfall for 1972-1975 (figure B-29a) should be compared to , a larger (2-state) pattern seen in figure B-29b. Here the available raingages of the climatic network



a. All Storms
highs = ≥ 35.0 cm
lows = ≤ 22.5 cm

b. July 1972-1975
(large scale pattern)

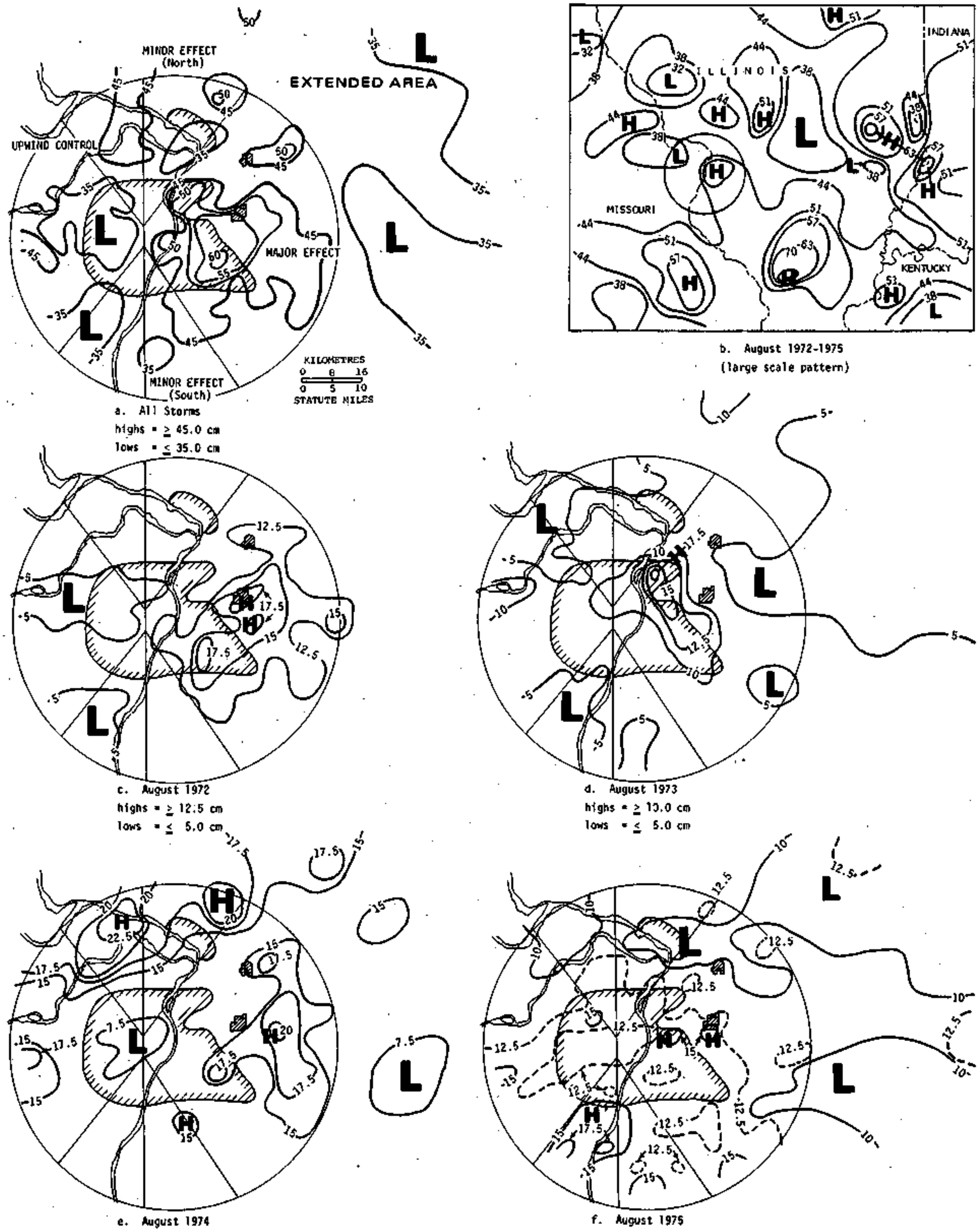
c. July 1972
highs = ≥ 10.0 cm
lows = ≤ 5.0 cm

d. July 1973
highs = ≥ 10.0 cm
lows = ≤ 5.0 cm

e. July 1974
highs = ≥ 7.5 cm
lows = ≤ 2.5 cm

f. July 1975
highs = ≥ 12.5 cm
lows = ≤ 5.0 cm

Figure B-30. Total storm rainfall patterns for July 1972-1975



a. All Storms
highs = ≥ 45.0 cm
lows = ≤ 35.0 cm

b. August 1972-1975
(large scale pattern)

c. August 1972
highs = ≥ 12.5 cm
lows = ≤ 5.0 cm

d. August 1973
highs = ≥ 10.0 cm
lows = ≤ 5.0 cm

e. August 1974
highs = ≥ 15.0 cm
lows = ≤ 7.5 cm

f. August 1975
highs = ≥ 15.0 cm
lows = ≤ 10.0 cm

Figure B-31. Total storm rainfall patterns for August 1972-1975 have been used. This broad scale pattern reveals 1) there was a general west-to-east increase in June rainfall for the 4-year period that crossed the RCN, and 2) the high to the NE of St. Louis was isolated and localized. In fact, the westward protuberance of the heavier June rainfall located about 80 to 160 km (50 to 100 mi) NE of St. Louis (figure B-29b) apparently was a localized phenomenon.

Figures B-29c-f portray the four individual June patterns for 1972, 1973, 1974, and 1975 in the METROMEX Network. Two kinds of patterns are shown. June 1972 and June 1975 show the distinct localized high to the NE of St. Louis, whereas the Junes of 1973 and 1974 had heavy rain in the extended area and a localized high 30 km (19 mi) to the ENE of St. Louis. In general, the most consistent feature was the presence of a localized high to the NE-ENE of St. Louis (and E-ESE of Wood River) in every June.

Major rain-producing storms in the Wood River-Edwardsville area (figure B-30a) during July had primary cell movements toward the SE with a secondary peak toward the NE. This suggests that the major source region was Wood River and a secondary source region was St. Louis.

A broader area pattern of the July total rainfall for 1972-1975 that appears in figure B-30b is based on climatological stations in Illinois and Missouri. This reveals a typical July rain pattern with randomly distributed highs and lows. In general, the values suggest a general low in the St. Louis area except for the localized highs just east of the city and to the south (>30 km) of St. Louis. Clearly, the localized, urban-related high of figure B-30a is restricted and not a part of some large scale rainfall feature elsewhere in the 2-state region.

The rain patterns of the four Julys (1972-1975) of figure B-30c-f reveal that the localized high in the St. Louis-Alton area existed in each year. This reveals persistence and is supportive of the urban effects. A high to the south, shown in the 4-year total pattern (figures B-30a and b) is found only in two years (1973 and 1975) and is largely the result of the heavy rains in that area in 1975. Thus, it is not a persistent, year-after-year feature like the St. Louis high.

Major rain-producing storms in the St. Louis effect area during August had their primary cell movement toward the SE. This fact coupled with the total rain pattern (figure 31a) suggests that the St. Louis area was the major source region for these August storms.

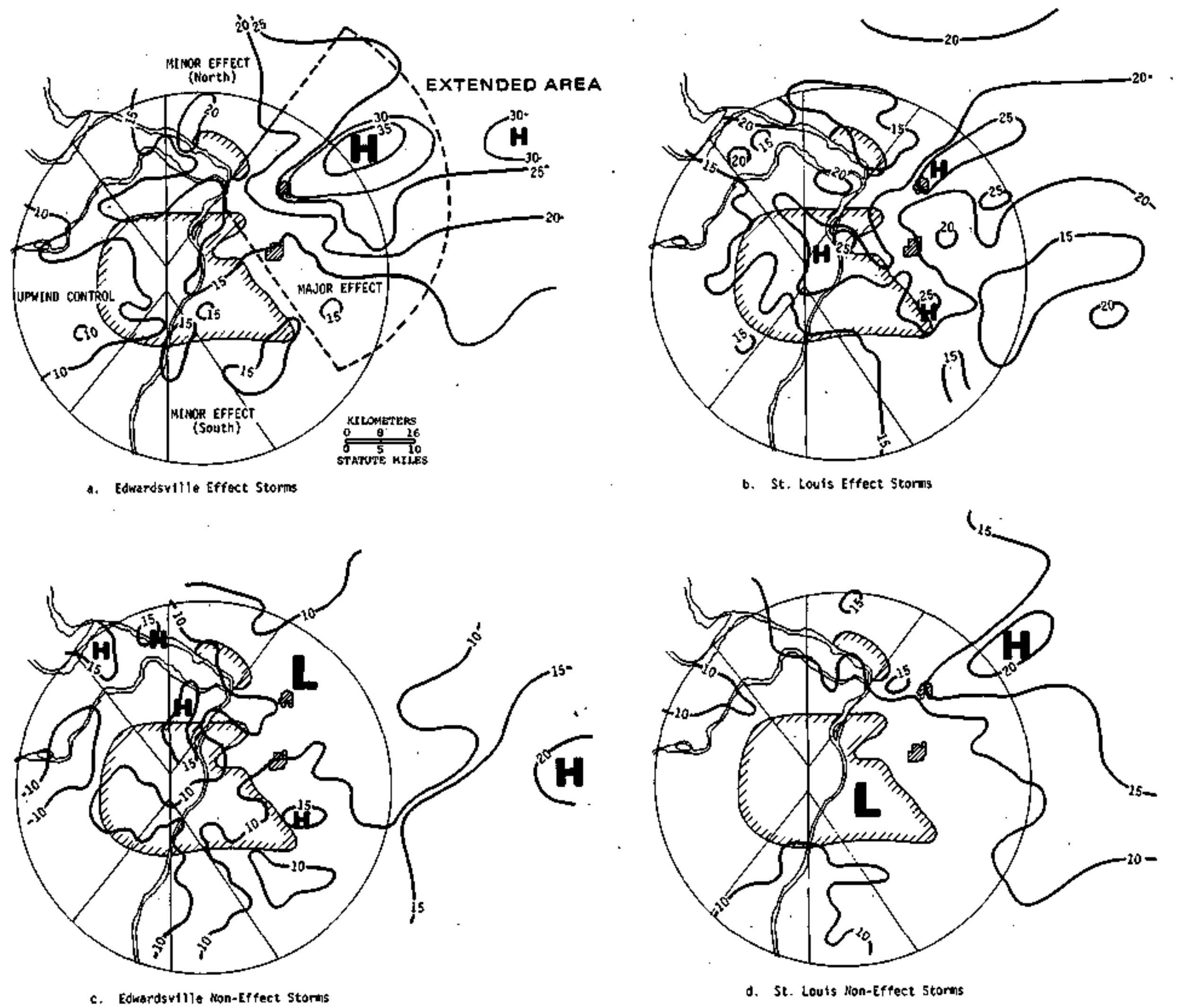
The total August (1972-1975) rainfall pattern for the broader 2-state area appears in figure B-31b. This shows 1) a large rainfall low west of St. Louis, 2) a mixture of highs and lows north of St. Louis, and 3) highs south (60 to 100 km or 37 to 62 mi) of St. Louis. The localized urban high is detected by these climatic network stations, and is a distinctly isolated feature in the patterns similar to others. It is not a part of the major high.

Inspection of the major high and low rain areas in each of the four Augusts sampled (figures B-31c-f) reveals the presence of the apparent urban-related high to the east of St. Louis in every year. Highs and lows appear in other parts of the RCN in each year, but none is consistent in all years. Highs appear far west of St. Louis in two years (1974 and 1975), and lows occur to the southwest and west of the city in two years (1972 and 1973).

Comparison of Effect and Non-Effect Storm Patterns

In order to more clearly determine the areal extent of the St. Louis and Edwardsville anomalies, and thereby the spread of the urban-industrial effect, the storms which contributed to these anomalies were investigated further.

In studies regarding the O-storms on the RCN, a determination of effect and non-effect storms was made by the multivariate technique of factor analysis. This technique was used to select those storms which maximized in the St. Louis area and those that maximized in the Edwards-



a. Edwardsville Effect Storms

b. St. Louis Effect Storms

c. Edwardsville Non-Effect Storms

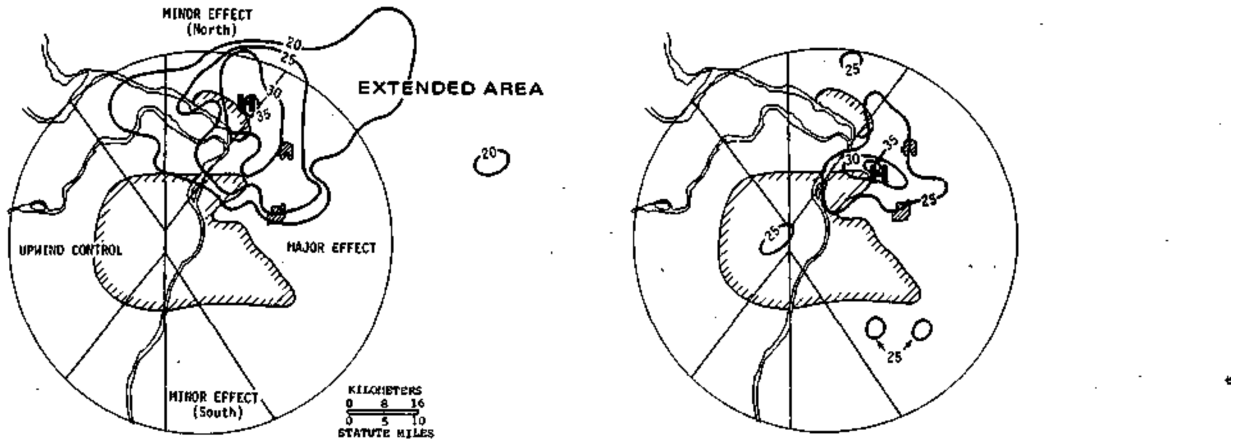
d. St. Louis Non-Effect Storms

Figure B-32. Effect and non-effect storm patterns during June 1972-T975 for Edwardsville and St. Louis (Isohyets in cm)

ville area. Since the rainfall highs were produced by these storms, they were considered to be the storms most likely to be affected, or the "effect storms," of the St. Louis area and of the Alton-Wood River area. Storms which did not maximize in the Edwardsville area were considered to be Edwardsville non-effect storms. Similarly storms which did not maximize in the St. Louis area were considered to be St. Louis non-effect storms.

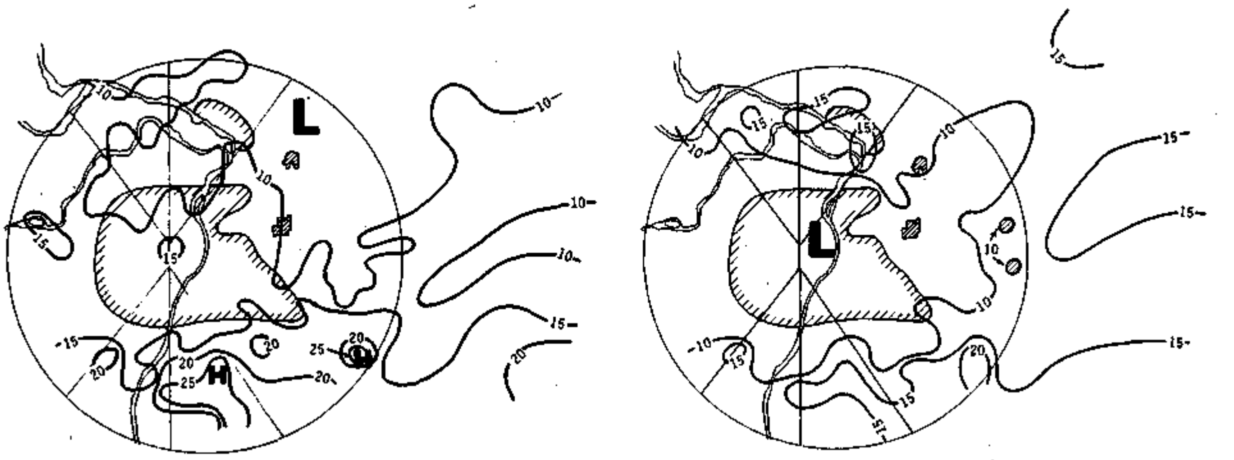
The rainfall patterns based on the Edwardsville effect storms in June are shown on figure B-32a. Clearly, the rainfall anomaly extends beyond the RCN and into the EN. This would indicate that the Edwardsville anomaly extends beyond the major and minor effect areas and into the extended area.

In this regard, it is noted that partitioning of the RCN and EN into 1) upwind control, 2) major effect, 3) minor effect, and 4) extended area, originally called the downwind control area, was based on radar climatological data for cell movements and durations, and were hypothe-



a. Edwardsville Effect Storms

b. St. Louis Effect Storms



c. Edwardsville Non-Effect Storms

d. St. Louis Non-Effect Storms

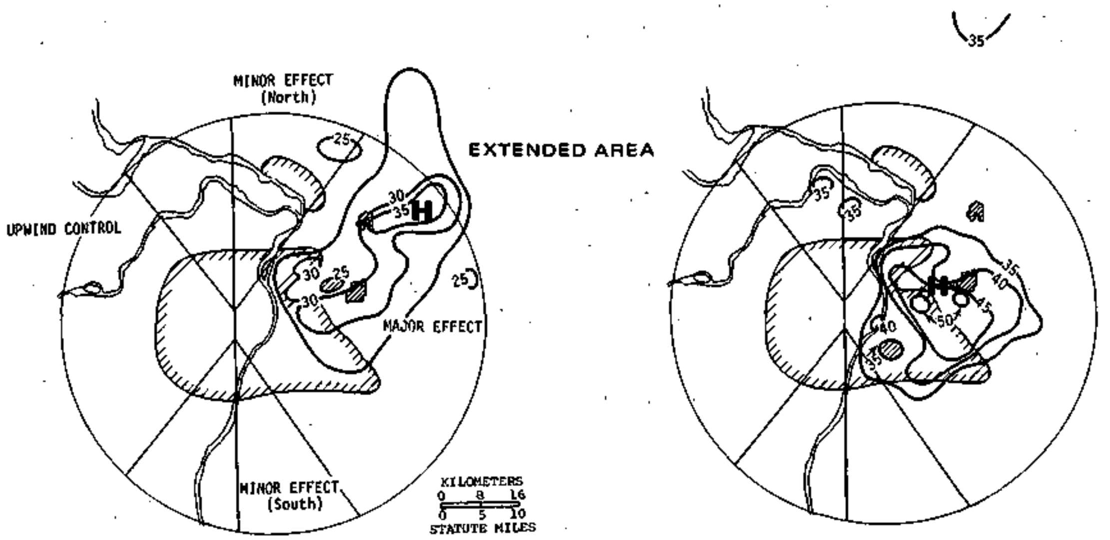
Figure B-33. Effect and non-effect storm patterns during July 1972-1975 for Edwardsville and St. Louis (Isohyets in cm)

sized by Huff and Changnon (1970) prior to the collection and evaluation of METROMEX data. Because they are based on *a priori* hypothesis, comparisons of these areas are quite useful.

However, the 1970 partitioning was made before the discovery during METROMEX that the Wood River industrial area is also a source of effects that alter the atmosphere. Thus, in addition to the previously postulated areas, a Wood River major effect area of the same orientation, size, and shape has been superimposed on figure B-32a (dashed outline). This illustrates that the Edwardsville high was likely produced by the combined effects of St. Louis and Wood River.

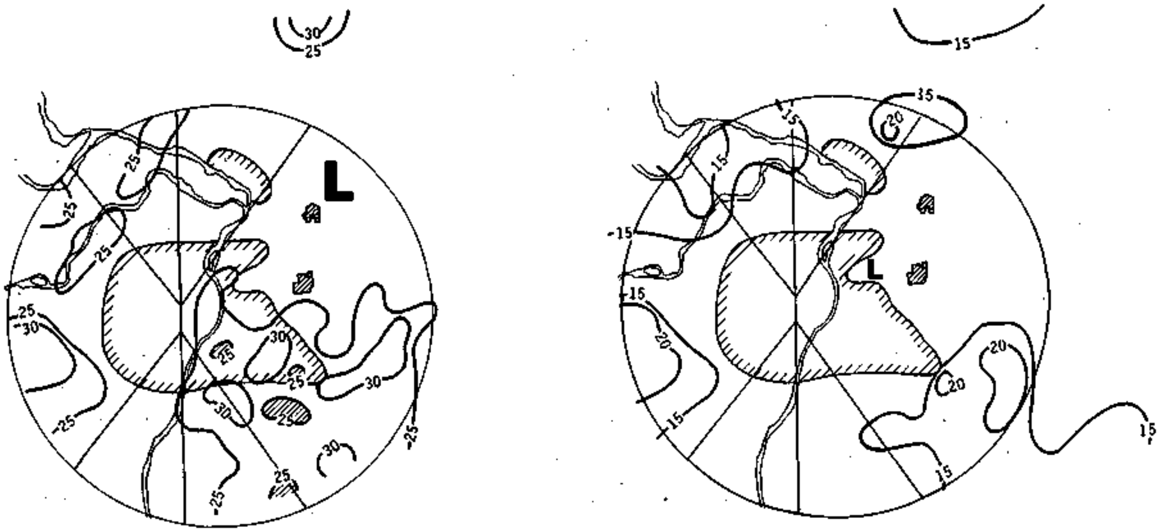
The isohyetal pattern based on the St. Louis effect storms for June are shown on figure B-32b. The St. Louis effect appears weak in June, but it is associated with the Edwardsville effect, implying some influence close to the city and downstorm. This is also reflected by the total June pattern on figure B-29a. These storms produced a rainfall anomaly in the Edwardsville area with an extension to the NE.

The non-effect storms for Edwardsville (figure B-32c) show a high in the eastern portion of



a. Edwardsville Effect Storms

b. St. Louis Effect Storms



c. Edwardsville Non-Effect Storms

d. St. Louis Non-Effect Storms

Figure B-34. Effect and non-effect storm patterns during August 1972-1975 for Edwardsville and St. Louis (Isohyets in cm)

the EN. The St. Louis non-effect storms (figure B-32d) show an anomaly in the Edwardsville area with an extension into the EN. It should be realized that a storm classed as St. Louis non-effect could also be classed as an Edwardsville effect storm, and added into each class if it had a high in the Edwardsville area and a low east of St. Louis.

The Edwardsville effect storms for July (figure B-33a) show the major anomaly to be in the Wood River-Edwardsville area and to be generally contained within the research circle. The St. Louis effect storms (figure B-33b) show the rainfall anomaly to be in the Wood River-Granite City area. Previous studies of O-storms in the RCN indicate that the major rain-producing storms in the St. Louis area during July had modal cell directions toward the NNE. This indicates that the St. Louis area could occasionally be a source region for the rainfall anomaly on figure B-33b.

The non-effect Edwardsville storms for July (figure B-33c) have their rainfall high in the southern part of the RCN with a general north-to-south gradient. The non-effect St. Louis storms (figure B-33d) have high rainfall in the northern and southern portions of the RCN and in the EN.

The Edwardsville effect storms for August (figure B-34a) show the anomaly to be based in the

Table B-12. Areal Means of Point Rainfall from Varying Rainfall Patterns
during summers, 1972-1975

	Mean rainfall (cm)				
	Upwind control	*Major effect*	*Minor effect (north)*	*Minor effect (south)*	*Extended area*
All storms					
June	**20.3**	**27.3**	**27.5**	**23.5**	**34.5**
July	**25.8**	**29.9**	**33.7**	**30.3**	**27.9**
August	**36.6**	**45.3**	**41.0**	**40.8**	**36.7**
Summer	**82.6**	**102.5**	**102.2**	**94.6**	**99.1**
Edwardsville effect storms					
June	**9.7**	**17.2**	**17.2**	**13.5**	**20.4**
July	**13.5**	**18.8**	**25.8**	**11.7**	**16.9**
August	**13.3**	**22.9**	**20.0**	**15.0**	**19.1**
Summer	**36.5**	**58.9**	**63.0**	**40.2**	**56.4**
St. Louis effect storms					
June	**14.1**	**18.8**	**16.3**	**14.4**	**19.5**
July	**19.2**	**20.8**	**21.1**	**19.8**	**13.9**
August	**24.1**	**34.2**	**29.0**	**29.7**	**24.9**
Summer	**57.4**	**73.8**	**66.4**	**63.9**	**58.3**
Edwardsville non-effect storms					
June	**10.6**	**10.1**	**10.3**	**10.0**	**14.1**
July	**12.3**	**11.1**	**7.9**	**18.6**	**11.0**
August	**23.2**	**22.4**	**21.0**	**25.8**	**17.6**
Summer	**46.1**	**43.6**	**39.2**	**54.4**	**42.7**
St. Louis non-effect storms					
June	**6.2**	**8.5**	**11.2**	**9.1**	**15.0**
July	**6.6**	**9.1**	**12.6**	**10.5**	**14.0**
August	**12.4**	**11.1**	**12.1**	**11.2**	**11.9**
Summer	**25.2**	**28.7**	**35.9**	**30.8**	**40.9**

Edwardsville-Collinsville-East St. Louis area and to be generally confined to the RCN. Thus, many of the Edwardsville effect storms during August were also classed as St. Louis effect storms. The St. Louis effect storms for August (figure B-34b) show the major anomaly to be in the St. Louis area, and to be contained within the major effect area of the RCN. These storms clearly dominate the August total rain pattern of figure B-3 la.

The point rainfall values of the total storms and the effect and non-effect rainfall patterns for 1972-1975 shown on figures B-29 through B-34 were averaged according to the upwind control, major effect, minor effect, and extended areas. These averages are listed in table B-12.

A comparison of the different areas for all storms indicates that the rainfall is greater in the effect areas than in the upwind control area during July and August. The largest areal mean for July occurs in the minor effect (north) and the largest areal mean for August occurs in the major effect area. The extended area values are similar to the upwind control values, and this indicates that the urban-industrial effect is limited to the research circle during these two months.

This conclusion is further strenghtened by the Edwardsville effect storms which also have their largest means in the effect areas during July and August. The largest mean occurs in the minor effect (north) area in July and in the major effect area during August. This is further indication of a more westerly location of the anomaly during July (figure. B-30a) than in June (figure B-29a).

It also indicates that the Wood River area should be considered as a source region, even though it was not considered in the *a priori* definition of the effect and control areas.

The St. Louis effect storms also have their largest means in the effect areas during July and August. However, the largest St. Louis effect clearly occurs in August when the major effect area has the largest areal mean.

A further comparison of the different areas for all storms in June indicates that the largest mean occurred in the extended area instead of in the effect areas. This is also true for the Edwardsville effect storms. However, if the Wood River and St. Louis areas are considered as source regions (figure B-32a), then it is clear that the largest mean would occur in this *a posteriori* hypothesized "major effect" area (dashed outline). Thus, although the June anomaly extends beyond the research circle (beyond 40 km or 25 mi) its extent is also an equivalent distance from the Wood River source region as the August anomaly is from the St. Louis source region (figures B-29a, B-31a, B-32a, B-34b).

The Edwardsville effect storms on figure B-32a indicate a smaller anomaly in the eastern portion of the extended area. However, it is much smaller than the major anomaly to the west of it.

The Edwardsville non-effect storms have their largest means in either the minor effect (south) or in the extended area. The St. Louis non-effect storms generally have their largest means in the extended area. Thus, the values in the effect areas are generally lower than values in the extended area.

The definition of effect and non-effect was based on the presence or absence of the rainfall anomaly. Therefore, there is the possibility that the absence of the anomaly in the non-effect storms may represent a reduction of the effect area rainfall. However, this possibility appears unlikely for St. Louis non-effect storms since summer values for effect areas are greater than summer values for upwind control areas. In the Edwardsville non-effect storms, summer values for major effect and minor effect (north) areas are less than those of the upwind control, but the summer value for the minor effect (south) is still larger than the upwind control. Also, the "all storms" comparison for summer indicates that effect areas have larger values than the upwind control areas. Thus, it is unlikely that the total rainfall has been decreased in the storms for which the anomaly is absent.

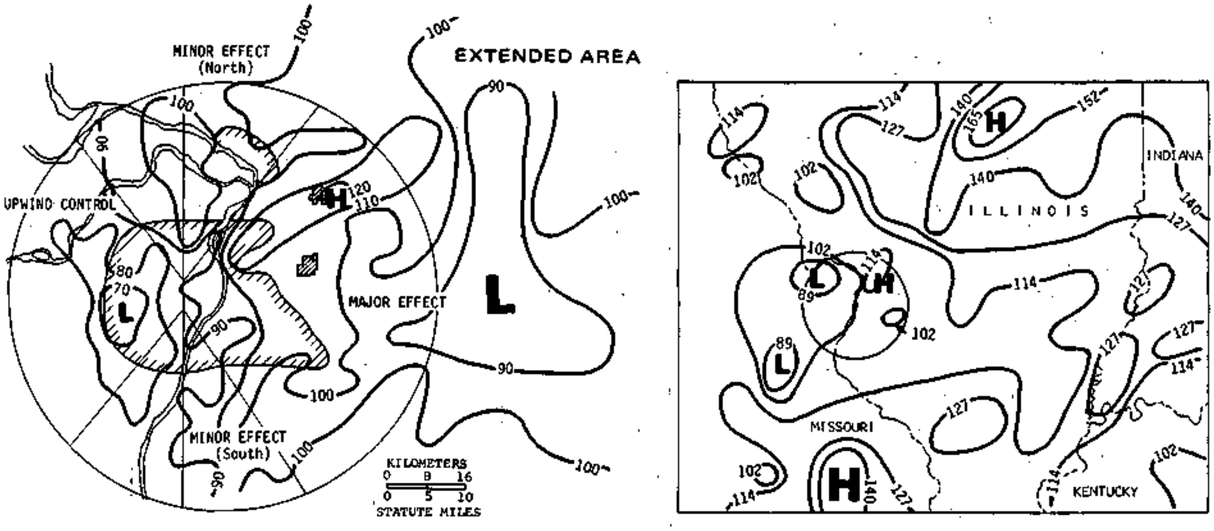
Summer Rainfall Results

The 4-summer total rainfall map (figure B-35a) combines the major features of the three monthly totals. Basically, the 4-summer pattern suggests a west-to-east increase throughout the St. Louis area with values of 80 to 90 cm (32 to 36 inches) in the west and 90 to 100 cm (36 to 40 inches) in the far east. The apparent urban-related high of 100 to 120 cm or 40 to 47 inches is superimposed on this general west-east gradient. Table B-13 shows the yearly areal averages for the five areas.

The 2-state, broader area portrayal of the summer rainfall in the 1972-1975 period is offered in figure B-35b, and it is based on stations in the NWS climatic network. This larger scale

Table B-13. Average Summer Rainfall (cm) in Areas of Possible Urban Effects and No Effects

	Recent (1972–1975)	*Early (1941–1968)*	*Difference early — recent*
Upwind control	20.6	27.4	6.8
Minor effect (north)	25.4	27.6	2.2
Minor effect (south)	23.9	28.2	4.3
Major effect	25.9	30.4	4.5
Extended area (control)	24.7	27.4	2.7



a. Summer 1972-1975
highs = ≥ 100.0 cm
lows = ≤ 90.0 cm

b. Summer 1972-1975
(large area pattern)

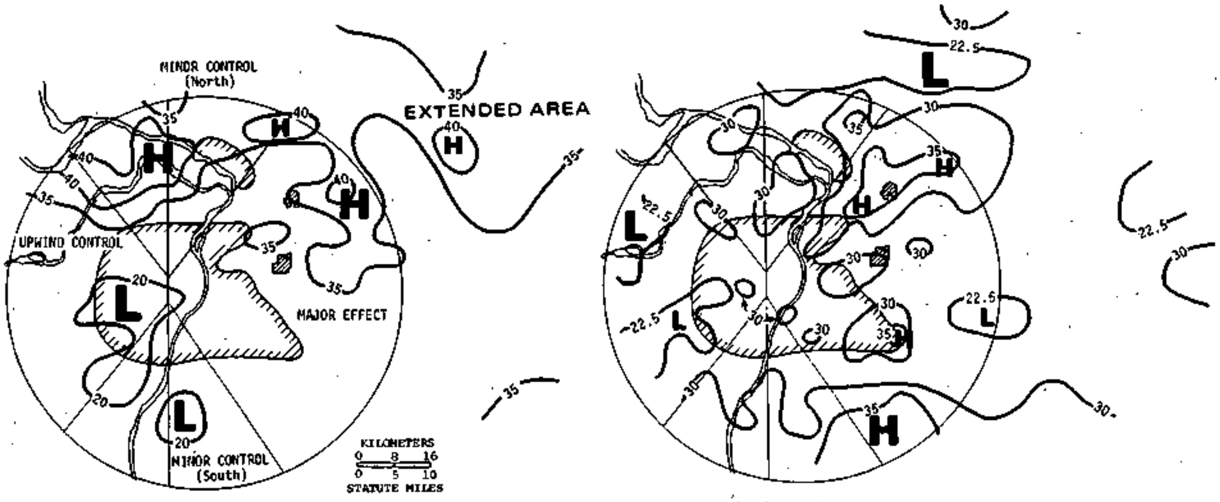
c. Summer 1972
highs = ≥ 25.0 cm
lows = ≤ 15.0 cm

d. Summer 1973
highs = ≥ 30.0 cm
lows = ≤ 20.0 cm

Figure B-35. Total storm rainfall patterns for summer

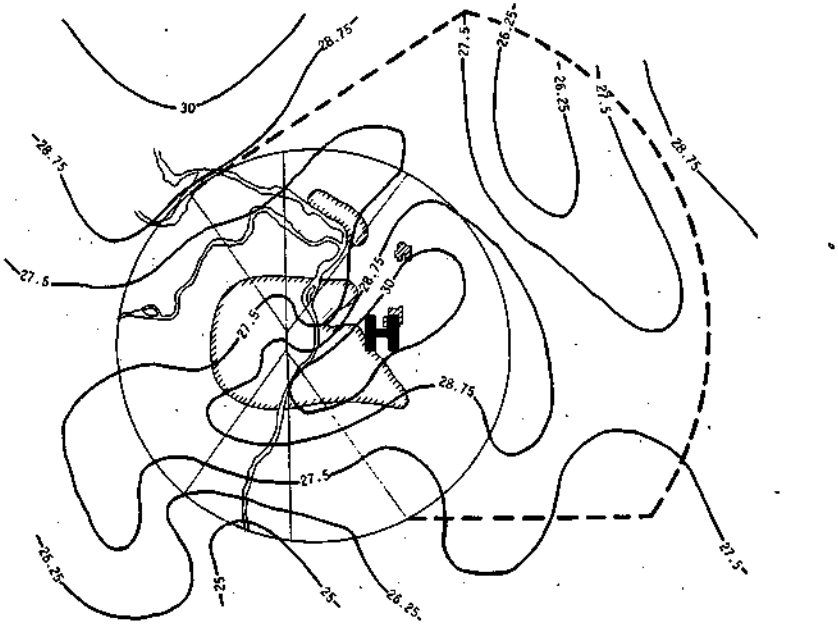
pattern indicates four major features relevant to the smaller scale METROMEX Network area. First, a major trough (low) of rainfall (<114 cm or 45 inches) with a WNW-ESE orientation extended from central Missouri through the St. Louis area and on to the ESE across southern Illinois and into Kentucky. Secondly, a major, more severe rainfall low (⩽102 cm or 40 inches) existed in the area in and west of St. Louis. Third, a major high of heavy rainfall (⩾140 cm or 55 inches) existed in eastern central Illinois.

All of these three features appear to be the result of mesoscale natural variations in the summer rainfall pattern without any known local or mesoscale land use effects. The fourth important feature shown on figure B-35b is the small isolated high (⩾114 cm or 45 inches) just northeast of St. Louis. Thus, the apparent urban effect was to produce a localized high of ⩾114 cm in an area where about 102 cm (40 inches) was indicated. Of further importance is the fact that the high near St. Louis was in a major low, was *not* a feature of any broad scale high, and was distinctly smaller than any other high on the isohyetal map.



e. Summer 1974
highs = ≥ 35.0 cm
lows = ≤ 20.0 cm

f. Summer 1975
highs = ≥ 30.0 cm
lows = ≤ 22.5 cm

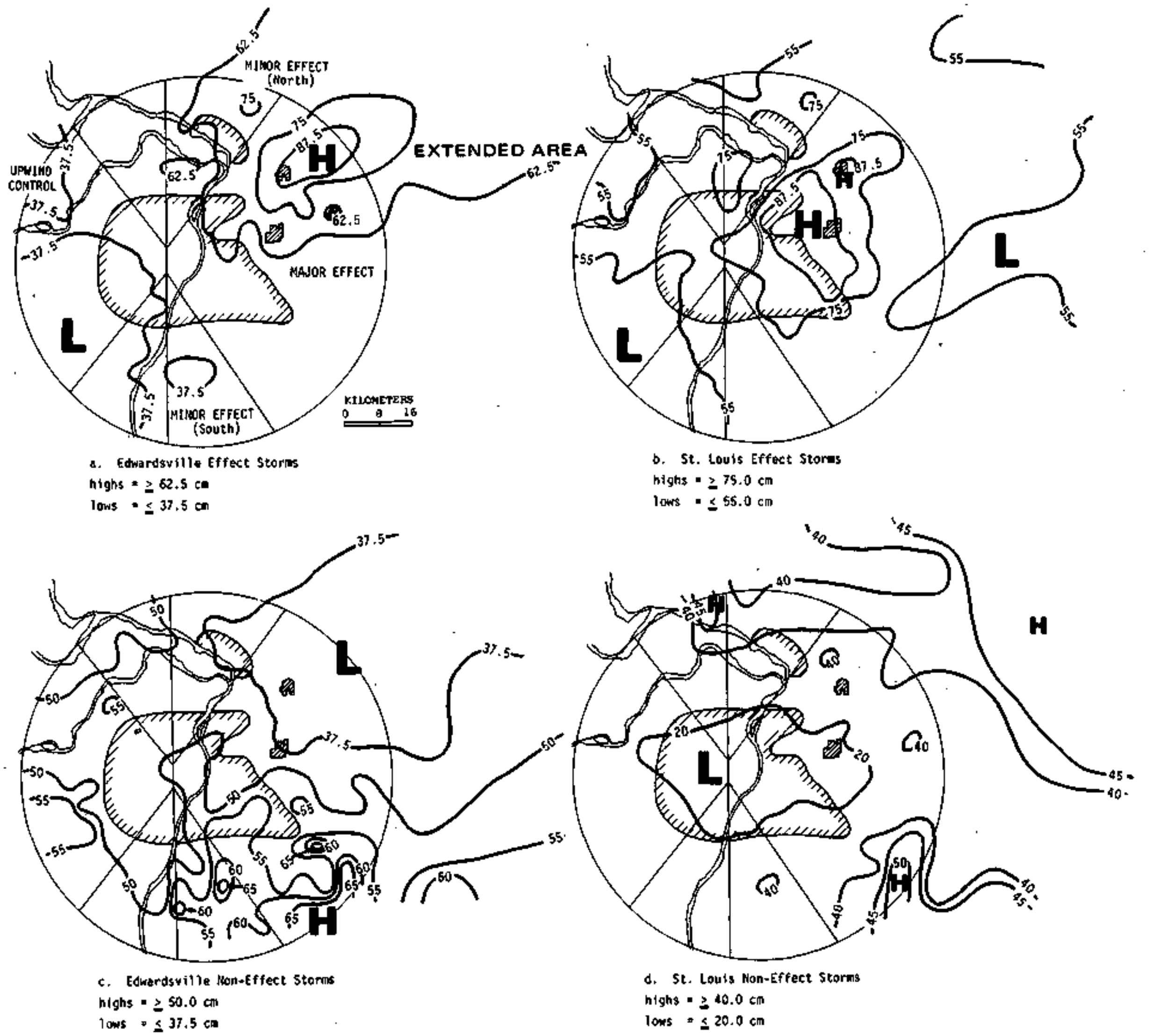


g. Average Summer Rainfall Pattern for 1941-1969

Figure B-35. *(concluded)*

An estimate of the climatological reality of the 4-year sample (figure B-35b) can be gained by comparing the pattern to that of the 29-year prior period, 1941-1969 (Huff and Changnon, 1973) shown in figure B-35g. This much longer period pattern shows 1) the urban high in and east of St. Louis extending to the NE (like figures B-35a and b), 2) lower rainfall areas to the west and SW of St. Louis (also like figures B-35a and b), and 3) rainfall values to the east (extended area) comparable to those to the west of the city. Thus, the 4-year sample largely differs by indicating a high in the bottomlands NW of the city, and relatively heavier rainfall in the Alton-Wood River area and in the eastern extended area.

These different features in the 1972-1975 period could be interpreted as due to small sampling size (natural variability) and/or increased urban effects on rainfall to the north and to the far east beyond that appearing in earlier years when the metropolitan area was smaller. These differences are confirmed in table B-13 which shows the early period vs recent period differences. The minor effect (north) area and extended area have averages that are much less different than the other three areas.



a. Edwardsville Effect Storms
highs = ≥ 62.5 cm
lows = ≤ 37.5 cm

b. St. Louis Effect Storms
highs = ≥ 75.0 cm
lows = ≤ 55.0 cm

c. Edwardsville Non-Effect Storms
highs = ≥ 50.0 cm
lows = ≤ 37.5 cm

d. St. Louis Non-Effect Storms
highs = ≥ 40.0 cm
lows = ≤ 20.0 cm

Figure 8-36. Effect and non-effect storm patterns during summer 1972-1975 for Edwardsville and St. Louis

The relative dryness of the area west of St. Louis in 1972-1975 is revealed by the large differences (6.8 cm or 2.7 inches) and by comparing figure B-35g with B-35b.

The persistence of the 4-summer total pattern (figure B-35a) was examined by comparing the summer patterns for each year in the 1972-1975 period (figures B-35c-f). The 1972 pattern contains the principal 4-year features: a major high east of the city, a low to the west, and heavier rain in the extended area east than that to the west of St. Louis. The 1973 summer pattern (figure B-35d) is quite different with many scattered highs (>30 cm or 12 inches) to the west, over the city, to the far east, the north, and to the south of St. Louis, although lows exist to the west. The pattern for 1974 (figure B-35e) has a high to the NE, but like 1973, it also has a high in the river bottoms NW of St. Louis. Again, the lowest rainfall is to the west of the large area network. In 1975 (figure B-35f), the major high to the NE of St. Louis appears again with the lowest rain to the west. A high appears in the extreme south and to the NW in the bottoms.

In summary, the four summer patterns reveal a general persistence of four major features: 1) a high of rainfall in or just east-northeast of St. Louis, 2) a high to the northwest of St. Louis

(3 of 4 years), 3) lowest rainfall to the west or southwest of St. Louis, and 4) heavier rain in the extended network area (40 to 60 km or 25 to 37 mi) east of St. Louis than to the west. The 1973 pattern was the most unlike those of the other three summers.

Figures B-36a through B-36d present the 4-summer patterns based on the effect storms (St. Louis and Edwardsville) and the no-effect storms for these two areas hypothesized as reflecting urban effects. The total rain for the 52 storms in 1972-1975 defined as Edwardsville effect (potential urban-industrial effects from St. Louis and Alton-Wood River) is portrayed in figure B-36a. The high is centered in the RCN but extends well beyond the circle by some 15 km (9 mi). The lowest rain is to the SW (<37.5 cm or 15 inches) and the broad area of heavier rain (>62.5 cm or 25 inches) extends beyond the large-area network. The pattern based on the 68 St. Louis effect storms in 1972-1975 appears in figure B-36b. The high just east of St. Louis is very distinct and localized with lows to the west and east. Those to the east are of the same magnitude as those in the west.

The opposite of the Edwardsville effect storms were the 23 storms defined on a statistical basis as "no effect" storms in the Edwardsville area during 1972-1975. Their cumulative pattern (figure B-36c) shows a low to the northeast, as expected by definition, and the highest rainfall to the southeast of St. Louis. The 215 St. Louis no-effect storms were combined to produce the 4-year total pattern (figure B-36d) showing highs to the N and NE and to the SE.

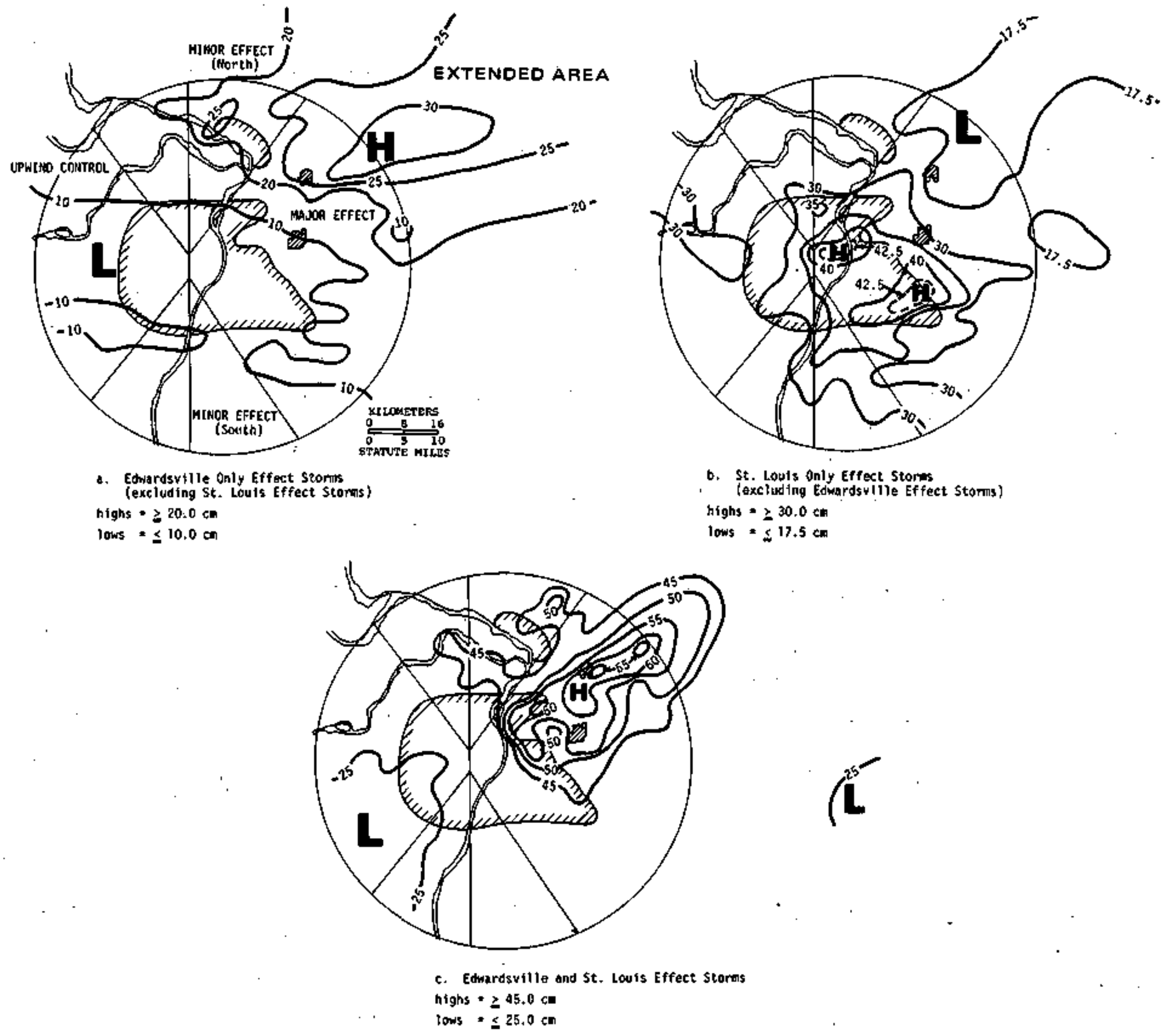
Since figures B-36a and b were so revealing as to the areal extent of effects in the summer rain patterns classed as "effect storms," they were studied further. The definition of Edwardsville effect, essentially a high in the NE area, could and did incorporate several storms that were also highs in the St. Louis effect area, the area just east of the city. The 23 Edwardsville effect storms that did *not* have associated highs also classed as St. Louis effects were used to construct figure B-37a. The high center is contained within the extended area network but the high is broad and appears to extend east beyond the network (>80 km or 50 mi from downtown St. Louis).

In a similar fashion, figure B-37b presents the pattern based on the 39 St. Louis effect storms which were *not* also effect (high) in the Edwardsville area. Such a selection produces a very localized high with the center ESE of St. Louis. There were 29 storms in 1972-1975 that were classed as having both St. Louis effect and Edwardsville effect. The resulting total rainfall map (figure B-37c) shows a high that is well delineated within the RCN and EN.

Thus, over the 4-year period, only the *Edwardsville only* effect storms indicated a general high that ran beyond the extended network area. These appeared to be different from the *St. Louis only* pattern (figure B-37b) and the *St. Louis plus Edwardsville* effect patterns (figure B-37c) which had highs confined largely to within 40 km (25 mi) of St. Louis.

Discussion and Summary

There is a clear indication that the areal extent of the urban-related rainfall anomaly is limited to within 30 km (18.6 mi) of the city during the months of July and August. This conclusion is based on the rainfall patterns and the comparison of areal means based on an *a priori* definition of the upwind control, major effect, minor effect, and extended areas. However, the definition was made prior to the discovery in METROMEX that the Wood River industrial area is also a source of agents that affect the atmosphere. This discovery suggests that the placement of the Edwardsville anomaly seen largely in June, extends farther downwind than originally expected since the Wood River industrial region is also farther east than the St. Louis source region, which was used in the *a priori* definition of effect and control areas.



a. Edwardsville Only Effect Storms (excluding St. Louis Effect Storms)
highs = ≥ 20.0 cm
lows = ≤ 10.0 cm

b. St. Louis Only Effect Storms (excluding Edwardsville Effect Storms)
highs = ≥ 30.0 cm
lows = ≤ 17.5 cm

c. Edwardsville and St. Louis Effect Storms
highs = ≥ 45.0 cm
lows = ≤ 25.0 cm

Figure B-37. Edwardsville effect only, St. Louis effect only, and joint Edwardsville-St. Louis effect only storms

Since the Edwardsville anomaly is at its greatest in June, it could be argued, in *a posteriori* fashion, that the areal means for this month might be the greatest in the original "downwind control" (extended) area. The persistence of the apparent urban-related highs in June, July, and August of all four years supports the reality of the urban effects. In all three summer months, these small urban-related highs are indeed localized anomalies, not a part of larger-scale heavier rain areas. However, the St. Louis related highs are no greater than highs found in rural areas elsewhere in Illinois and Missouri. Because of the areal and time persistence of the monthly anomalies adjacent to St. Louis, one can conclude they are the result of local influences, but the effect of added rainfall is no greater than nature produced elsewhere in a broader 2-state region.

The analysis of effect storms (those with either the Edwardsville or St. Louis *high rain* anomalies present in the RCN) further supports these conclusions. In addition the analysis of non-effect storms (those with the Edwardsville and St. Louis *high rain* anomalies absent from the research circle) does not suggest a reduction of rainfall in the research circle. Furthermore, since the rainfall anomaly is not present in the research circle during the non-effect storms, this implies that the atmospheric conditions were not conducive to urban-related effects on rainfall, either to increase or decrease it. It also appears unlikely that the atmospheric conditions would be conducive to the delayed effect leading to higher rainfall in the extended area. Thus, it would appear that the higher rainfall in the extended area during some of the non-effect storms was a part of the variation in the natural rainfall distribution during 1972-1975.

This analysis of the extended area rainfall collected during METROMEX suggests that the major portion of the urban effect occurs within 0 to 40 km (25 mi) of the city with a smaller effect in the 40 to 80 km (25 to 50 mi) range.

A previous study by Schickedanz (1973a, 1974a) of monthly and seasonal rainfall downwind of St. Louis and other cities in the Midwest indicated a similar conclusion. In that earlier study, data over a multi-state area were used so that the influence of the urban areas out to large distances could be explored. The results of this earlier climatological study suggested that most, if not all, of the urban effect on precipitation occurs within 80 km (50 mi) of the urban center. The current study suggests, in addition, that most, if not all, of the urban-industrial effect on precipitation during July and August occurs well within 40 km (25 mi) whereas during June there is some extension of the effect into the 40 to 80 km (25 to 50 mi) range.

Study of the summer rainfall over the large network area generally supported the conclusions derived from the monthly analyses. During 1972-1975 the hypothesized major effect and the minor effect (north) areas averaged 1.27 to 2.54 cm (0.5 to 1.0 inch) more rain than the gradient based on the upwind control and extended area averages would predict. The St. Louis area during the summers of 1972-1975 was in a broad rainfall trough. Yet, a localized urban-induced high was distinguishable within this trough.

The 4-year period was about 2.54 to 5.08 cm (1 to 2 inches) drier than long-term normal values, but the 4-year pattern exhibited all the major features of the long-term (1941-1969) pattern. However, comparison of the 1972-1975 average rainfall values for the five hypothesized effect and no-effect areas with those of 1941-1969 suggests two interesting shifts. Relatively higher rainfall occurred in 1972-1975 in both the minor effect north (Alton-Wood River) area and in the extended area NE. Increases in these two areas could be due to natural variation (sampling size vagaries), or due to the influence of the urban-industrial effects of the Alton-Wood River area where industry has expanded rapidly since 1960. The results for the *Edwardsville only* effect storms support the conclusion that relatively higher rain during 1972-1975 fell to the north and NW of St. Louis as a result of inadvertent weather modification.

Careful examination of the summer effect-storm classifications revealed that when the predominant storm motion was from the SW (as in June), the St. Louis and Wood River effects led to a rain maximum that began about 10 to 15 km (6 to 9 mi) beyond the effect areas and extended out 45 km (28 mi) beyond the centers of these areas. When the preferred storm motion was slower and more westerly (as in July and August) the urban-related rain maximum began at the effect regions and extended out about 30 km (18.6 mi). The maxima were all about the same length (30 km) in both cases, but they were placed differently because of storm motion.

Comparison of the individual summer rain patterns in the 1972-1975 period revealed persistence in the occurrence of the urban-revealed rainfall highs. Their center varied from year-to-year but was always there. Other rain highs appeared within the network, including the extended area, in any given year, but these were not persistent and evident in any given place in more than 2 of the 4 years.

The summer isohyetal patterns, taken in totality, reveal three major results. First, they do not suggest an urban-related decrease in rainfall beyond the urban-induced localized highs. Second, they suggest that urban rain increases are at a maximum anywhere from 0 to 45 km (28 mi) east of the city center. Third, there is a suggestion of a slight urban-related increase of rain out to 80 km (50 mi) NE of St. Louis. This extended effect occurs only under certain storm conditions typical of June when storm motions are relatively fast and from the SW. This extension of higher rainfall beyond 40 km (25 mi) NE of St. Louis is apparently partially a result of the effects of the Alton-Wood River area.

SYNOPTIC WEATHER RELATIONS

John L. Vogel

INTRODUCTION

A major objective of METROMEX was to determine the atmospheric conditions in which the urban-industrial region of St. Louis affects the precipitation processes. Especially important are the atmospheric processes which are existent during the passage of rain periods through the METROMEX research area. To achieve this objective, the synoptic-scale and mesoscale weather features that existed during the occurrence of a rain period were studied through an intensive analysis of atmospheric conditions over and beyond the research area.

The data used for this analysis included 1) the 3-hourly surface maps, 2) the hourly radar depiction charts, 3) the upper air maps, 4) soundings from surrounding National Weather Service (NWS) stations and those available from the METROMEX operations, 5) the hourly weather observations of stations within the METROMEX circle (STL, BLV, SUS, ALN, and CAH), 6) METROMEX radar observations, and 7) the various surface weather networks operated by the Water Survey. In addition, hourly teletype data were obtained and certain synoptic and mesoscale features were analyzed on an hourly basis for some rain periods.

Previous synoptic weather typing of rain periods (often called storms) in Illinois was done by Hiser (1956), Huff and Shipp (1968), and Huff and Vogel (1976). However, in all three instances, the data set used for typing was the Daily Weather Map series of the NWS. Only one or two surface weather maps and one upper air chart were available for each day. The weather typing under these circumstances could not be as detailed as that desired for the METROMEX analyses. These earlier studies showed that the distribution of rainfall over Illinois during the summer is highly dependent on the more intense weather events.

Within the METROMEX synoptic weather study, eight major rain-producing storm types were identified including

1) Squall lines (SL)
2) Squall zones (SZ)
3) Cold fronts (CF)
4) Warm fronts (WF)
5) Static fronts (SF)
6) Pre-and post-front (P&PoF)
7) Air mass (AM)
8) Low pressure centers (L)

The definition of each of these synoptic weather types follows.

Squall Line Storms

A nonfrontal group of thunderstorms accompanied by a trigger mechanism, usually a short wave trough. The convective activity associated with the storm systems was intense, well-orgainized, and often times was arrayed in a narrow band or line of active thunderstorms.

Squall Zone Storms

A mesoscale system of thunderstorms organized into an area or cluster and independent of a frontal zone. These storms, like squall lines, tended to move across large regions of the Midwest, and an upper-air impulse was usually discernible.

Frontal Storms

Precipitation formed within 120 km (75 mi) of a surface front (cold, static, or warm). There was no synoptic evidence that this precipitation was associated with a squall line or squall zone which, on occasion, moved 40 km (25 mi) or more ahead of the fronts.

Pre-Frontal and Post-Frontal Storms

Precipitation associated with a frontal structure but at a distance of 120 to 240 km (75 to 150 mi) ahead or behind a front (cold, static, or warm).

Air Mass Storms

A shower or thunderstorm generated within an unstable air mass. No large scale or mesoscale synoptic causes were evident. The resulting convective activity was usually widely scattered to scattered and weak.

Low Pressure Storms .

A cyclonic storm situated so close to the research circle that it was not possible to associate the precipitation with a frontal or mesoscale weather structure. These systems are rare during the summer months.

FREQUENCIES OF SYNOPTIC WEATHER CONDITIONS

During the five summer periods from 1971 through 1975 a total of 330 objective rainstorms and 228 days with rain occurred in the research circle. Each rainstorm was classified according to the weather conditions that were dominant during the formation of the storm within, or its passage through, the METROMEX research circle. Table B-14 gives the frequency of the eight major weather classes and the number of rain days for each summer season and for the five seasons combined.

The most frequent rain-producing synoptic weather class was air mass (showers and thunderstorms) which accounted for 90 rain events, or over 27% of all rainstorms. The second most frequent synoptic classification was the squall zone which comprised 83 separate storm events or 25% of all the storms. Together these two synoptic weather events were responsible for over 50% of all the rainstorms. Both of these synoptic classifications usually occurred within warm, moist air masses which dominated the general weather conditions in the METROMEX area during summer. However, a squall zone was usually accompanied by a discernible shortwave trough in the upper air pattern, and the rain elements were organized into a cluster or group of showers and/or thunderstorms with motion continuity in time and space. Conversely, air mass storms were characterized by widely scattered showers and thunderstorms which developed in an apparent random manner with no organized movement and little, it any, continuity in time and space.

Squall lines (48 storms) and cold fronts (46 storms) were the next most frequent weather types associated with rain events over the METROMEX Network. They together represented about 28% of the total events. Squall line and cold front storms represent the most organized weather systems observed to cause precipitation within the research area. The squall lines were characterized by intense, well organized lines of convection and were normally accompanied by strong, upper air impulses. Often these storms (31 of them) were embedded within the warm, moist air mass characteristic of the Midwest during the summer. At other times (17 storms) they were observed to occur 40 to 160 km (25 to 100 mi) in advance of an approaching cold front. The shower and thunderstorm activity which accompanied cold fronts was often well organized,

Table B-14. Frequency of METROMEX Synoptic Weather Types,
June-August 1971-1975

	Number of rainstorms									
	SL	*SZ*	*CF*	*SF*	*WF*	*P&PoF*	*AM*	*LOW*	*Total*	*Rain days*
1971	5	17	7	5	1	4	6	2	47	40
1972	11	11	6	4	3	9	24	1	69	44
1973	12	16	6	2	3	4	21	1	65	46
1974	7	19	15	6	3	8	21	1	80	50
1975	13	20	12	2	4		18		69	48
1971-1975	48	83	46	19	14	25	90	5	330	228
Average	9.6	16.6	9.2	3.8	2.8	5.0	18.0	1.0	66	46

but occasionally cold fronts moved across the research circle with only widely scattered convective elements producing only light rainfall amounts.

The other four rain-producing weather types (pre- and post-frontal storms, static fronts, warm fronts, and low pressure areas) were responsible for the remaining 19% of the 330 total weather events. Pre- and post-frontal precipitation occurred on 25 occasions, but these rain systems were typically weak with poorly organized convective elements. Static fronts produced 19 rainstorms and the rain elements with this weather type were the most organized of these four infrequent weather systems. Usually the fronts were located south of the research circle and the heavier precipitation within these systems was associated with waves which moved along the static front from the west. Warm fronts during the summer tended to be weak with poorly organized frontal structures. Only five low pressure areas were observed to control the precipitation processes within the network, and they had weak pressure gradients.

The greatest number of objective storms in any one year was 80 in 1974. This year also had the greatest number of rain days. The year with the least number of objective storms and rain days was 1971 with 47 storms and 40 rain days. Two possible reasons exist for the low totals in 1971. This was the first summer of raingage operation and during the first 10 days of June not enough raingages were open to allow utilization of the objective storm definition. In addition, a climatic analysis of the 1971 rain data showed it was the driest summer during the 5-year period, with the network receiving only 63% of normal rainfall (see section on seasonal rainfall, page 13).

Other major differences between years included the small number of air mass storms during the summer of 1971, the increase in frequency of cold front storms in 1974 and 1975, the low number of squall line storms in 1971 and 1974, the absence of low pressure and pre- and post-frontal storms in 1975, and the low number of squall zones in 1972.

RAINFALL AMOUNTS AND SYNOPTIC WEATHER CONDITIONS

The network rainfall which occurred with each synoptic weather type in the five individual summers and for the 5-year period is presented in table B-15. The network average rainfall for the five summers was 112.85 cm (44.4 inches). Of this total 50.5% or over 57 cm (22.4 inches) came from squall lines, even though squall lines were the cause of less than 15% of all rainstorms. Squall zones, which were associated with 25% of all storm events, produced 28.22 cm (11.1 inches) or 25% of the total rain. Cold fronts were the third most prolific rain producer with 14 cm (5.5

Table B-15. Total and Percent of Total Rainfall by Weather Types, Summers 1971-1975

	Total rainfall (cm)						*Percent of total rainfall*					
	1971	*1972*	*1973*	*1974*	*1975*	*1971-1975*	*1971*	*1972*	*1973*	*1974*	*1975*	*1971-1975*
SL	6.22	10.77	16.41	5.03	18.59	57.02	38.0	55.4	66.7	21.4	64.4	50.5
SZ	7.82	2.82	3.96	5.97	7.65	28.22	47.8	14.5	16.1	25.4	26.5	25.0
CF	0.46	3.33	1.91	6.50	1.80	14.00	2.8	17.1	7.7	27.6	6.2	12.4
WF	0.41	0.33	0.60	0.76	0.08	2.18	2.5	1.7	2.5	3.2	0.3	1.9
SF	0.66	1.12	0.59	4.62	0.43	7.42	4.0	5.8	2.4	19.6	1.5	6.6
P&PoF	0.18	0.18	0.93	0.36	0	1.65	1.1	0.9	3.8	1.5	0	1.5
AM	0.15	0.86	0.18	0.21	0.33	1.73	0.9	4.5	0.7	0.9	1.1	1.5
LOW	0.48	0.02	0.03	0.10	0	0.63	2.9	0.1	0.1	0.4	0	0.6
Total	16.38	19.43	24.61	23.55	28.88	112.85						

inches) or 12% of all summer rains. These three weather types produced 88% of the total summer rainfall, even though they were associated with only 54% of all the precipitation events.

Most of the rain which fell over the METROMEX Network was caused by organized mesoscale or synoptic scale convective systems. Thus, if the urban-industrial area is acting to modify significantly the precipitation over and beyond (east) of the city, the major interaction between the urban-industrial complex and passing rainstorms must partially occur with these weather types. Since these weather types generally produce the most intense rainfall within summer weather systems, a modification process could be expected to be apparent in the higher rainfalls.

A total of 7.42 cm (3 inches) of rain fell from static front storms accounting for approximately 7% of the total summer rainfall. Only 6.19 cm (2.5 inches) or less than 6% of the total rain was associated with the remaining four weather types (warm fronts, pre- and post-frontal, low pressure areas, and air mass).

Air mass storms occurred most frequently, over 25% of the time, but they produced only 1.73 cm (0.7 inch), or less than 2% of the total METROMEX summer rainfall. This was due to the isolated nature of their formation and the lack of any definitive mesoscale or synoptic scale perturbation which might increase the number or intensity of rain-producing elements. If urban-industrial effects are influencing conditions with this storm type, it would not make significant changes in the total rainfall and would be difficult to detect, as shown by Huff (1971) for planned weather modification experiments.

Of the five summer seasons 1974 had the most unusual distribution of rainfall by weather types. This was the only summer when cold fronts (with 28% of the total) exceeded squall lines or squall zones as the most prolific rainfall producer. In addition, static front storms accounted for nearly 20% of the 1974 summer rainfall, much higher than the average amount of rainfall caused by this weather type in other years. Over 90% of the static front rainfall during 1974 was due to an unusually long and intense summer static front during late August when the average network rainfall was 4.20 cm (1.7 inches). This single storm period produced nearly 60% of the total rainfall associated with the 19 static fronts for all five summers.

Squall line or squall zone storms were the greatest producers of summer rainfall, except for the summer of 1974. Most of these storms occurred within the warm, moist tropical air mass which so often blankets the St. Louis area during the summer. Thus, over 75% of the total summer rainfall occurred within zones of warm air with organized convective activity, even though these two weather events produced less than 40% of the rain events (table B-14).

Table B-16. Storm Average Point Rainfall for All Gages and for Gages with Rain, 1971-1975

	1971	1972	1973	1974	1975	All storms 1971-1975
			Point Average rainfall (cm)			
SL	1.24	0.98	1.37	0.72	1.43	1.19
SZ	0.46	0.26	0.25	0.31	0.38	0.34
CF	0.07	0.56	0.32	0.43	0.15	0.30
WF	0.41	0.11	0.20	0.25	0.02	0.16
SF	0.13	0.28	0.30	0.77	0.22	0.39
P&PoF	0.05	0.02	0.23	0.05		0.07
AM	0.03	0.04	0.01	0.01	0.02	0.02
LOW	0.24	0.02	0.03	0.10		0.13
			Point average per storm (cm) for gages with rain			
SL	1.30	1.34	1.75	1.02	2.01	1.57
SZ	0.76	0.56	0.56	0.66	0.64	0.64
CF	0.23	1.50	1.04	1.14	0.56	0.94
WF	0.58	0.25	0.79	0.41	0.15	0.41
SF	0.36	0.74	0.71	2.67	0.56	1.09
P&PoF	0.38	0.15	0.53	0.23		0.33
AM	0.43	0.33	0.18	0.15	0.30	0.28
LOW	0.64	0.23	0.15	0.61		0.51

During the five summer periods low pressure areas were observed to occur on an average of once a summer, and they caused less than 1% of the total rainfall. This is in agreement with the general climatic patterns established by Morgan et al. (1975), who showed a relative minimum in the occurrence of low pressure areas over the lower and mid-Mississippi Valley during the months of June, July, and August.

Generally less than 2% of the rainfall in each summer was due to air mass storms. The only year which was an exception was 1972 when nearly 5% of all the rain was due to air mass storms. This was also the summer when the frequency of air mass storms maximized.

The rainfall amounts from cold front storms varied considerably between years, ranging from 2.8% of the summer precipitation in 1971 to nearly 28% of the summer rains in 1974. In the summer of 1974 it was the most productive synoptic rain class.

Warm fronts and pre- and post-frontal rainstorms varied little from summer to summer, and neither synoptic type was associated with more than 4% of the summer total rainfall in any given year.

Table B-16 gives the average point rainfall values (within the research circle) for each synoptic weather type, and for each summer and for the five summers. For all the storms in the five summers, the average point value for squall lines (1.19 cm or 0.5 inch) was three times more than that of any other synoptic type. The second most productive synoptic rainfall type was the static front with an average storm gage rainfall of 0.39 cm (0.16 inch). Squall zones with 0.34 cm (0.13 inch) and cold fronts with 0.30 cm (0.12 inch) followed closely. The remaining synoptic weather types averaged less than 0.2 cm (0.08 inch) of precipitation at each raingage.

Squall lines produced the heaviest point averages in all years except 1974 when static fronts yielded slightly higher amounts. However, this 1974 value was unusually high for static fronts and resulted largely because of an unusually long time period (over 40 hours) defined by the objective storm criteria. In general, rainfall in static fronts was not nearly as intense in other years, averaging only 0.22 cm (0.08 inch) per gage. Point averages with squall zones were quite consistent from year to year. Individual summer values for cold fronts showed considerable scatter about the 5-year mean of 0.30 cm (0.12 inch), varying from 0.07 to 0.56 cm (0.03 to 0.22 inch). This was apparently influenced by a number of cold fronts which passed across the research circle with only small amounts of rainfall associated with their passage.

The rainfall produced by the synoptic weather types was further studied to examine for intensity-areal coverage values and differences. The average point rainfalls based only on the data from gages with rain (no zero gage amounts) for each storm type and for each summer and the total summers are also presented in table B-16. For the five summers, squall lines had the highest average (at those gages with rain) with 1.57 cm (0.62 inch). Static fronts followed with 1.09 cm (0.43 inch), but once again this was largely due to the long intense storm in 1974. If this one storm was deleted, the average point value for static front events would drop from 1.09 to 0.56 cm (0.22 inch). The third highest rainfall occurred with cold fronts, averaging 0.94 cm (0.37 inch) of rain at a point for each storm.

The most dramatic difference in average point rainfall amounts based on all gage data (including gages with zeroes) and that for only gages with rain occurred with air mass conditions. The average rainfall based on all gages was 0.02 cm (0.008 inch), but for just those gages with rain the average amount was 0.28 cm (0.11 inch). This large difference is due to the widely scattered nature of air mass storms which can be locally intense. This is shown very clearly in table B-17 which defines areal coverage of rainfall. The storm average areal coverage for air mass conditions, based on the five summers, was only 6.9% of the network area. Thus, the rain from air mass storms usually covered only 360 km^2 of the 5200 km^2 network (139 mi^2 of 2000 mi^2 network).

Squall line storms had the highest rainfall rate at each gage in three of the five summers (table B-16), and for all five summers the average rainfall catch at each gage was over 1 cm (0.40 inch) in each event. Cold fronts in three of the five years also recorded an average catch in excess of 1 cm at each gage. During the other two summers (1971 and 1975) the average rainfall at each gage with cold front storms was considerably lower. Of the two synoptic events which were the most organized and usually most recognizable, squall lines consistently produced gage rainfall amounts in excess of 1 cm. Cold fronts did not exhibit the same consistency. The average rainfall per gage within cold front storms varied from 0.23 to 1.50 cm (0.1 to 0.6 inch) at each gage, whereas the rainfall in squall line storms varied from 1.02 cm to 2.01 cm (0.41 to 0.80 inch).

As previously mentioned, the percent of areal coverage of rainfall within the network for each of the storm types is presented in table B-17. Squall line storms and squall zone storms usually produced rain that covered a greater percentage of the network than any other weather type. On the average, squall line occurrences for the 5-year period produced measurable rainfall

Table B-17. Percent of Area with Storm Rainfall by Synoptic Types, 1971-1975

	1971	*1972*	*1973*	*1974*	*1975*	*1971-1975*
SL	95.0	72.9	78.3	70.4	71.4	75.7
SA	60.5	46.5	43.7	47.3	60.8	52.4
CF	29.2	37.2	30.9	37.6	26.9	32.6
WF	69.7	47.1	26.4	62.5	14.0	38.1
SF	39.0	38.0	40.0	28.7	39.4	35.7
P&PoF	11.7	12.6	44.1	20.1		19.9
AM	5.7	11.0	4.3	5.7	6.0	6.9
LOW	37.6	16.3	17.2	17.2		25.2

over 75% of the network. Rain from cold fronts, warm fronts, and static fronts normally covered 30 to 40% of the research circle. Low pressure areas, based on a limited sample of five storms, averaged rain over 25% of the network, whereas pre- and post-frontal storms encompassed 20% of the circle.

The data from this study indicate that modification of summer air mass storms appears unlikely to produce meaningful quantities of added rainfall. Even though the average point rainfall of a storm is 0.28 cm (0.11 inch) where rain occurs, the areal coverage of these storms is small. Planned weather modification to augment rain during these storms to achieve a substantial increase in the areal volume of rainfall would need to enlarge or increase the number of rain elements, not make those existing more efficient. However, if weather modification can significantly increase point rainfall amounts and the areal extent of rain within organized rain systems, such systems could be treated (seeded) more efficiently and economically than the air mass storms because of their continuity in time and space. They tend to propagate and move in a coherent manner, whereas air mass storms tend to form in a random pattern.

RAINFALL PATTERNS AND SYNOPTIC WEATHER CONDITIONS

The possibility that the St. Louis and the Alton-Wood River urban-industrial complexes modify or initiate precipitation systems as they move across them was investigated on the basis of rain patterns associated with the different synoptic weather types. Other results in this report indicate a summer increase in rain downstorm (east) of St. Louis and Alton-Wood River. With this concept, the 5-year summer rainfall patterns of each synoptic weather class were examined. Relevant to such an investigation is information on the motion of the rain elements.

For each of the 330 storms, the dominant motion of the principal rain entities was determined from the motion of raincells and radar echoes. These "storm" motions were grouped into 30° sectors. Storms which moved from 181° to 210° were classed as moving from the SSW, storms which moved from 211° to 240° were classed as SW, and so on. In three storms no apparent convective entity motion could be detected, and these storms were classed as stationary (static). In some cases the data were not sufficient to affix motion to the rain elements which made up a rainstorm and these storms were classed as "indeterminate." Table B-18 presents the frequency of rainstorm motions classed by synoptic types. These motions will be used to help examine the possible effect the St. Louis urban-industrial region might have on the downstorm precipitation pattern. In the text which follows, the dominant convective entity motion of the storms will be referred to as storm motion.

Squall Line Storms

Almost all squall line storms were observed to travel from westerly directions. The most frequent direction was from the WSW and nearly two-thirds (29 of 48) of all squall line storms were observed to move from the SW quadrant (SSW, SW, and WSW). Thus, if St. Louis and Alton-Wood River do modify squall line systems, the greatest precipitation maximum should be found to the NE of these two metropolitan areas.

Figure B-38a shows the 5-summer rainfall pattern from *squall line* storms. The average network rainfall from these storms was 57.02 cm (22.5 inches) representing over 50% of the total 5-summer rainfall, as was shown in table B-15. A broad maximum (>60 cm or 24 inches) is noted

Table B-18. Frequency of Rainstorm Motions
by Synoptic Type, 1971-1975

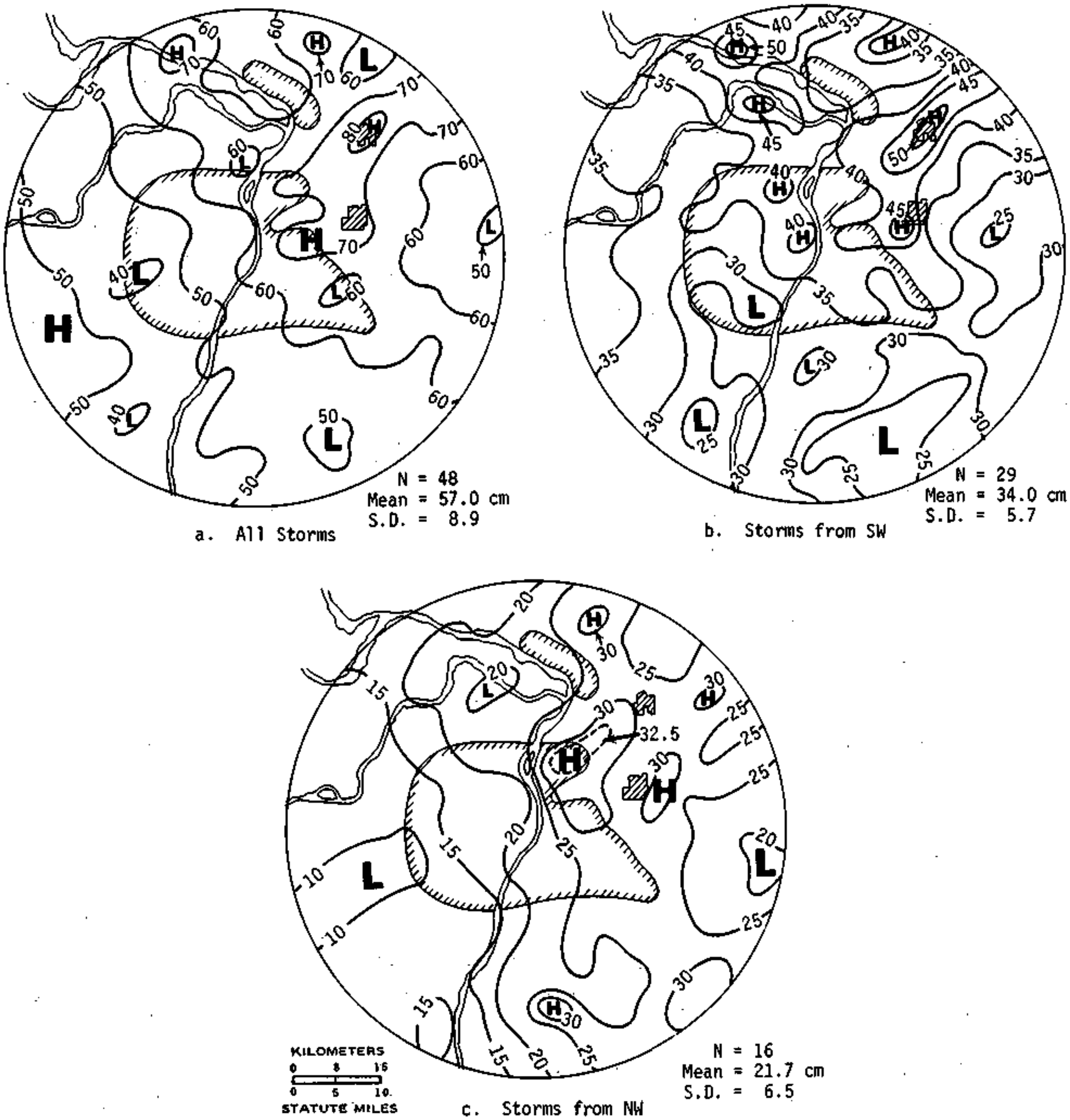
	Number of storms								
	SL	*SZ*	*CF*	*WF*	*SF*	*P&PoF*	*AM*	*LOW*	*Total*
SSW	5	3	1	4		2	9		24
SW	9	23	3	3	3	1	21	1	64
WSW	15	24	11	1	6	8	11	1	77
WNW	7	14	12	1	5	4	9	1	53
NW	9	8	8	2	3	5	18	2	55
NNW	0	3	7	0	0	3	6	0	19
NNE		2	1				1		4
NE									
ENE									
ESE							1		1
SE		1			1		1		3
SSE		2				1	1		4
Stet	1	1					1		3
Indeterminate	2	2	3	3	1	1	11		23
Total	48	83	46	14	19	25	90	5	330

over the NE sector of the research circle, with localized highs of ⩾70 cm (28 inches) NE of Alton-Wood River, in the NW bottomlands, and extending northeast from St. Louis. Thus, a definite downstorm rainfall maximum is evident where storm motions would predict, indicating squall line storms are modified by the urban-industrial environment. A major low was situated to the west of St. Louis. As would be expected, the squall line pattern resembles the overall 5-summer rain pattern shown in figure B-1.

This apparent urban effect leading to downstorm enhancement of squall line precipitation systems was further examined with the rainfall patterns from those squall line storms with movement either from the SW or NW quadrants. The resulting rainfall patterns are shown in figures B-38b and c.

The total rainfall pattern for squall line storms moving from the SW (figure B-38b) increased from SW to NE with a broad precipitation maximum over the NE quadrant, or downstorm from the urban-industrial complex. Highs were noted northeast of St. Louis and Alton-Wood River, and in the NW bottomlands. Over 50% of the time (15 of 29 storms), the low-level winds associated with these storms were from the SE so that the urban affected air was often advected NW of the city prior to the initiation of the rain. It is possible that under these circumstances the squall lines'ingest both urban source air and additional moisture and heat from the NW, bottomlands. When the low-level winds are from the SW, storms which move from the SW would ingest the urban affected air over and NE of the city within the urban plume. The St. Louis urban plume has been observed in many different directions and many kilometers downwind from St. Louis (Haagenson and Morris, 1974; Shea, 1976). Thus, urban effects on the squall line storms would begin over the city and also could extend beyond the city within the downwind urban plume.

Squall lines with predominately NW moving rain elements showed a general maximum over the east half of the precipitation network (figure B-38c). The network average rainfall for these 16 storms was 21.65 cm (8.52 inches). If the ⩾30 cm (12 inches) highs are urban related, these storms appear to react to the urban effect over smaller downwind areas than the storms which moved from the SW. They could be slower moving or not as long lasting, or the urban plume could be weaker, or the stability of the air mass could be less. However, the low-level winds in 9 of the 16 storms



a. All Storms

b. Storms from SW

c. Storms from NW

Figure B-38. Rainfall patterns for squall line storms, 1971-1975

were from the SE, and in such cases, the squall line systems would begin sampling the urban air NW of the urban-industrial area. Thus, increased rainfall should appear over and to the NW of St. Louis. The shape of 20-cm (8-inch) isohyet (figure B-38c) suggests such an effect. Furthermore, the eastward extent of the effect should not be as great as with SW motion cases.

The pattern from those storms which move from the SW (figure B-38b) indicates it takes approximately 40 minutes for the system to fully react with heavy surface rain. This was determined by assuming the urban effect begins to influence the storm system over the central part of St. Louis. The heaviest rain was approximately 30 km (18.7 mi) downstorm from the city center. Since the average squall line storm in Illinois is moving at 50 km/hr (~31 mph) (Changnon and Huff, 1961), the reaction time for the storms would be 0.6 X 60 minutes or 36 minutes. Thus, it appears that within squall line storms with a dominant NW convective element movement the urban effect may first be ingested into the storm in the vicinity of the NW bottomlands.

The squall line rainfall patterns based on motions for each of the 30° sectors from SSW through NW showed that the primary rainfall maximums were always downstorm from the urban region. For example, when the storms moved from the SSW (191 to 210°), the greatest precipitation maximums were noted N and NE of St. Louis. As the storm movement shifted to the W the rainfall maximums rotated to the E, and with NW motions the maximum was SE of the city. No storms were observed to move from the NNW. The number of squall line storms with distinct maximums downstorm or over St. Louis are shown below. This listing indicates that 32 storms maximized downstorm from St. Louis. All storm motions showed that more storms maximized downstorm from St. Louis.

	Number of storms		
Storm motion	*Yes*	*No*	*Total*
SSW	3	2	5
SW	7	2	9
WSW	10	5	15
WNW	4	3	7
NW	8	1	9
Total	32	13	45

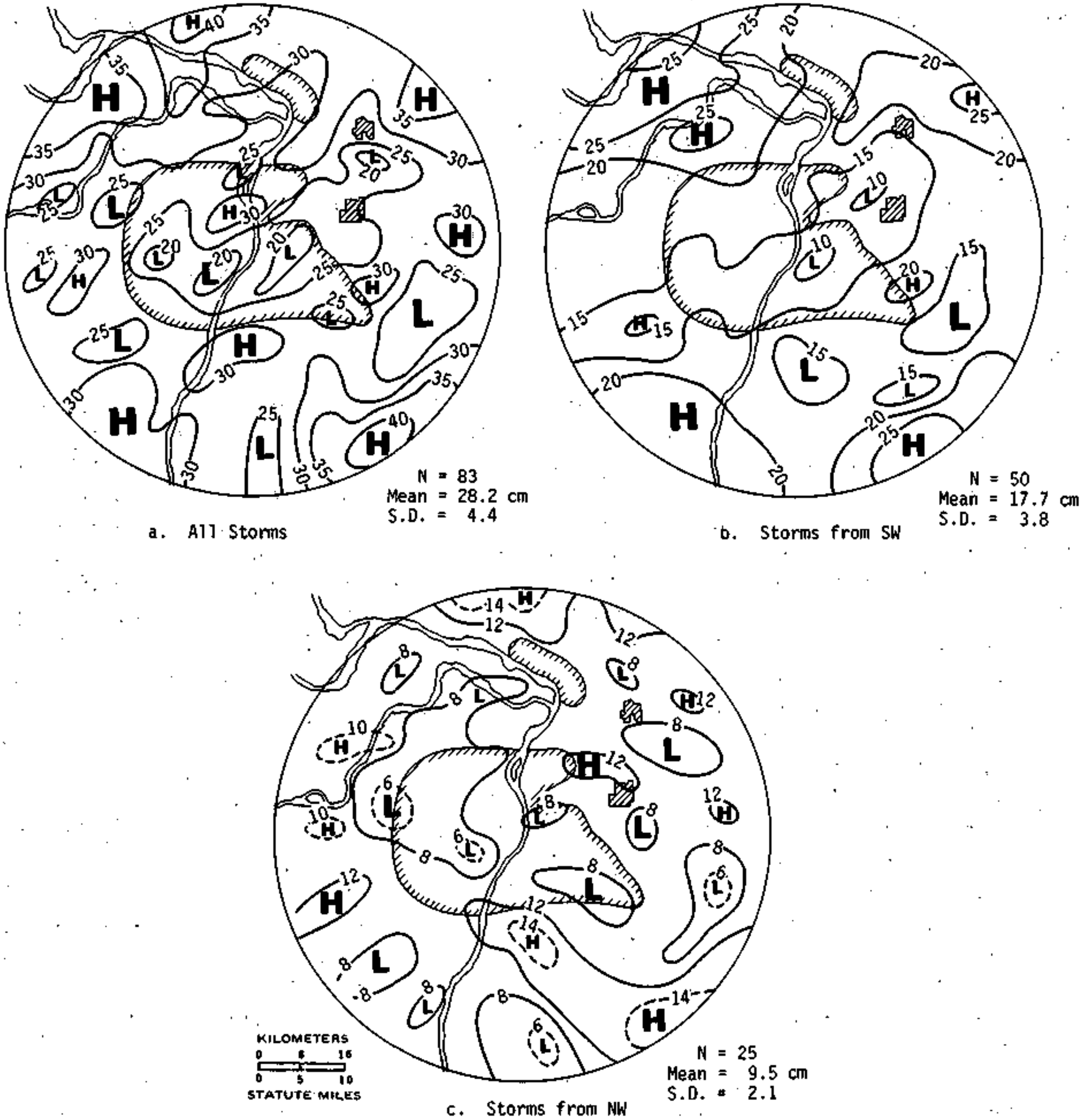
These results further suggest that the urban region modifies squall line conditions. These storms covered the greatest area and were the most productive rainstorms observed. The rainfall maximums in 71% of these storms were situated over or downstorm from the urban region.

Squall Zone Storms

Squall zone storms averaged 28.22 cm (11 inches) or nearly 25% of the total 5-summer rainfall. Over 90% of all these storms moved from westerly directions, with nearly 60% of the storms coming from the SW quadrant. Nearly 50% of the low-level winds were from the SE and 42% from the SW. Therefore, if these storms are affected by the urban region, a precipitation maximum can be anticipated in the arc from the NE through SE beyond St. Louis, and NE and S of Alton-Wood River.

Figure B-39a shows the total rainfall from *squall zone* storms. The rainfall from these storms maximized to the NW, NE, and SE of St. Louis, all at distances >25 km (15.6 mi). A broad minimum curves across the southern part of the city of St. Louis. Portions of this minimum are in the very region where one would predict a maximum, particularly if the urban-industrial regions significantly enhance the storms moving from the NW quadrant. Also, the maximum to the NW cannot be attributed to the city, but it is possible that the river bottomlands, a strong moisture and heat source, might have enhanced these storms as they moved across the region. The urban-industrial area appears to have only a minor effect upon total rainfall with squall zone storms.

The rainfall patterns for squall zone storms moving from the SW and NW were also determined (figures B-39b and c). Southeast low-level winds were observed prior to 24 of the squall zone storms moving from the SW, and SW low-level winds were observed prior to 21 storms. The



a. All Storms

b. Storms from SW

c. Storms from NW

Figure B-39. Rainfall patterns for squall zone storms, 1971-1975

rainfall pattern for these storms indicated a broad minimum from the southwest across St. Louis, with precipitation highs over the bottomlands and NE of Edwardsville (figure B-39b), The precipitation minimum over the metropolitan region is puzzling, especially since the gages in the region south of St. Louis had more occurrences of squall zone rainfalls than any other region. This rainfall minimum may indicate that at times the smaller, less organized squall zone storms may be negatively affected as they move across St. Louis. The large number of storms (24) with

SE low-level winds may have advected the St. Louis plume into the vicinity of the bottomlands contributing to the rainfall maximum observed there.

In the 25 squall zone storms moving from the NW, low-level SE winds were observed in 13 storms and SW winds in 10 storms prior to the initiation of rainfall over the network. The rainfall pattern from squall zone storms which moved from the NW showed three minor highs (>12 cm or 4.72 inches) E and SE of St. Louis (figure B-39c). All other maximums are situated on the north edge of the circle and in the SW. A minimum was situated west of the city and there were several scattered minimums on the east side of the Mississippi River. No clear indications of urban-industrial effects on rainfall exist, unless they are displaced further downstorm.

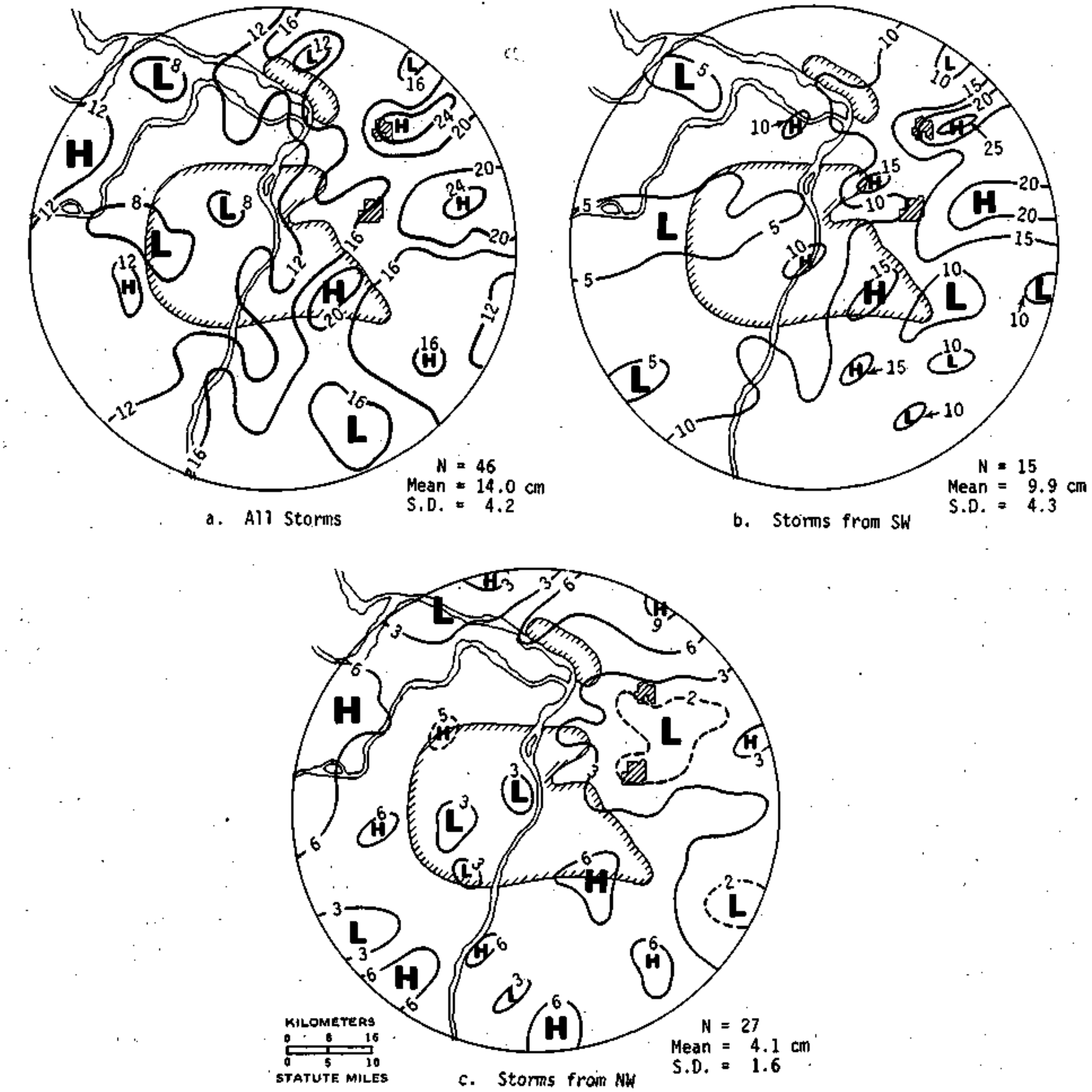
Cold Front Storms

The dominant convective entity motion in 70% of the cold front storms was the 90 degree sector from 241 to 330°, or from the WSW through the NW with SW low-level winds over 50% of the time and NW low-level winds in 25% of the storms. Thus, the precipitation pattern, if it is being altered by the urban complex, should exhibit a rainfall maximum NE through SE of St. Louis and Alton-Wood River. The network rainfall pattern from cold front storms which produced 14 cm (5.5 inches) or about 12% of the network total rainfall in 1971-1975 is shown in figure B-40a. Highs in the rainfall pattern appear to the NE, E, and SE of St. Louis and Alton-Wood River. In fact, the area east of the Mississippi River is characterized by a broad, arc-shaped rainfall high, while the region west of the Mississippi River is a broad precipitation minimum with the center situated west of St. Louis. The pattern suggests that cold front storms are affected by the urban region, leading to increases in the downstorm rainfall.

Only 15 cold front storms moved from the SW quadrant, but they produced nearly 71% of all the cold front rainfall. The average point rainfall per storm was 0.66 cm (0.26 inch) for the network and 1.34 cm (0.53 inch) when based on those gages with rain in each storm. Thus, these storms were usually intense and comparable to squall line storms. Southwest low-level winds prevailed over 70% of the time for 1 to 3 hours prior to the initiation of cold frontal storms moving from the SW over the network, so the urban effect should be dominant over and NE of the city. Thus, if the urban region is inadvertently enhancing cold fronts moving from the SW, a precipitation maximum can be expected NE of the urban-industrial complex. The rainfall pattern from these storms (figure B-40b) has major highs NE and E of St. Louis. Thus, it would appear that the city does actively enhance the cold frontal precipitation in these more intense cold front situations.

The rainfall from cold front storms which moved from the NW quadrant was not nearly as intense as that from the cold front storms which moved from the SW. The network average rainfall from the 27 storms was 4.1 cm (1.62 inch). The average gage rainfall for each storm was only 0.15 cm (0.06 inch) and the average rainfall for those gages with rain was 0.54 cm (0.22 inch). The prevailing low-level winds in the cold front storms which moved from the NW exhibited considerable variation. In 37% of the storms the low-level winds were from the SW; in 33%, from the NW; in 15%, from the NE; and in 15%, from the SE. If St. Louis was enhancing these storms, a general maximum should be found SE through SW of the urban region.

The cold frontal rainfall pattern for storms with a NW motion (figure B-40c) shows a number of minor rainfall maximums on the west and south sides of the circle and another maximum situated on the north edge of the research circle. Minimums were situated over the bottomlands, St. Louis, Edwardsville-Collinsville, and on the SE edge of the network. The rainfall maximums south of the urban area hint at a possible enhancement of some of the rainstorms. However,



a. All Storms

b. Storms from SW

c. Storms from NW

Figure B-40. Rainfall patterns for cold front storms, 1971-1975

the general rainfall pattern from these storms does not indicate that the urban-industrial region has an apparent effect upon cold frontal storms from the NW.

The cold frontal storms which moved from the SW were considerably stronger than the cold front storms which moved from the NW. The rainfall pattern would indicate that the storms which moved from the SW had a positive effect upon the rainfall downstorm from the urban region, while the storms which moved from the NW showed little or no active enhancement of the precipitation downstorm from the metropolitan area.

Interestingly, the average rainfall per storm in the cold front storms moving from the NW was similar to the rainfall intensity measured within squall zone storms. The squall zone storms also exhibited little or no active enhancement within the rainfall pattern. However, the squall line storms and the cold front storms moving from the SW, both with high and similar rainfall intensities, appear to exhibit considerable enhancement of the precipitation. These results suggest that the urban region actively enhances the stronger, more organized weather systems and riot the weaker convective systems.

Static Front Storms

During the five summer periods only 19 static front storms produced rainfall. The average network rainfall for all static fronts was 7.42 cm (2.93 inches) or almost 7% of the network total. Approximately 50% of the convective entities within static front storms moved from the SW quadrant and 40% moved from the NW quadrant. Thus, if the urban-industrial complex is inadvertently modifying these entities as they move across St. Louis, there should be a rainfall maximum in the area from NE to SE of St. Louis.

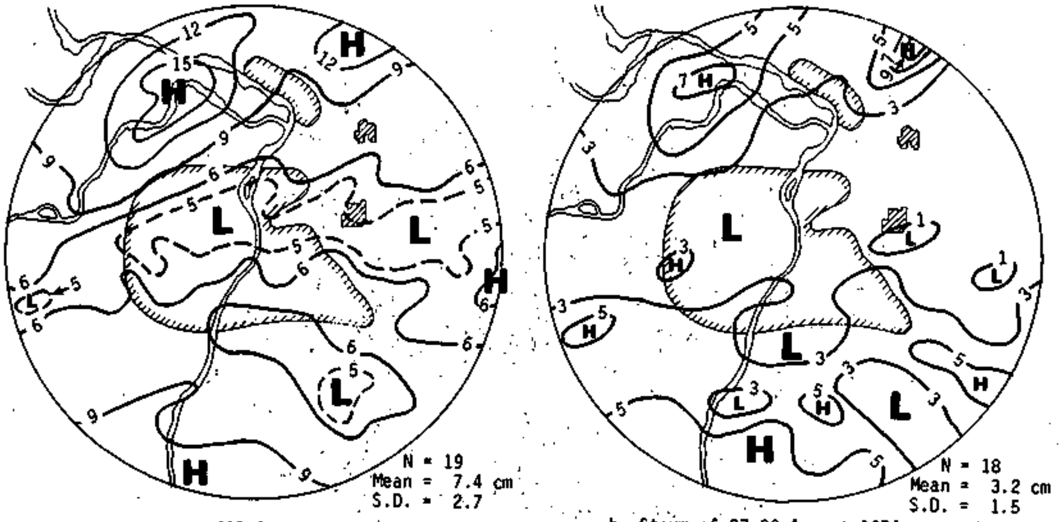
The rainfall distribution of static fronts (figure B-41a) indicates a broad maximum across the northern sector with major highs situated over the bottomlands and NE of Alton-Wood River. A secondary maximum was observed on the extreme southern edge of the network. A broad minimum with an east-west orientation exists in the center of the network across St. Louis. The rainfall pattern for all static fronts except the unusually long and intense storm of 27-29 August 1974 was similar (figure B-41b) to that for all static front storms. The major difference in the two patterns is magnitude of the rainfall.

The rainfall patterns from static front storms which had dominant convective entity motions from the SW quadrant maximized over the bottomlands and NE of Alton-Wood River. The storms which moved from the NW indicated rainfall highs over the S and SW portions of the network. Thus, little if any indication of urban rain enhancement is indicated and there is, in figures B-41a and b, a good suggestion of urban decrease in rain. However, the sample size is small. During most static front situations, the static front was situated south of St. Louis, and most of the rain is caused by "overrunning" or a wave moving along the front. Thus, it is possible that the low-level winds below the cloud base during the lifetime of the storm may be more important in determining possible urban effects than the movement of the convective element within rainstorms.

There were five static front storms with low-level winds from the SE. In three of these storms the convective motion was from the WSW, one moved from the SW, and the motion of the fifth storm was from the WNW. A rainfall maximum might be expected to the NE to N of St. Louis and Alton-Wood River if the urban plume was being ingested into the overrunning air mass. Figure B-41c shows the rainfall pattern from these storms with maximums over the bottomlands and NE of Alton-Wood River, and a minimum extending on an E-W line across St. Louis.

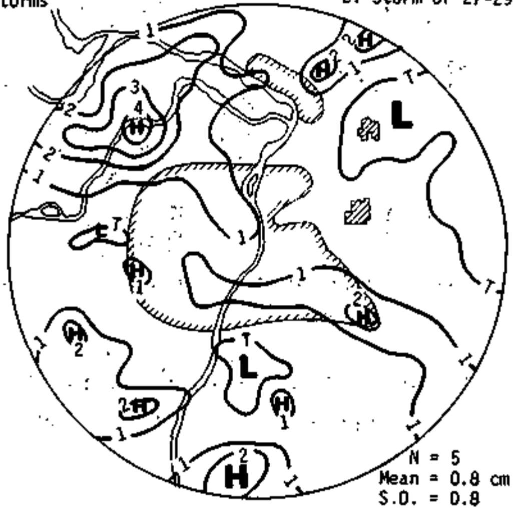
With low-level winds from the SW quadrant there were three storms with motions from the SW, one from the WNW, and one from the NW. Maximums N and NE of St. Louis and Alton-Wood River could be expected. Figure B-41d shows such a pattern with rainfall over the bottomlands and NE of Alton-Wood River.

Six static front storms had low-level winds from the NE. The dominant convective entity motion in three of these storms was from the WSW, one was from the NW, one from the SE, and the motion in one of these storms was indeterminate. This collection of six storms included the storm of 27-29 August 1974. Rainfall maximums could be expected SW to W of St. Louis and Alton-Wood River if they were actively enhancing the rainfall downwind. Figure B-41e indicates

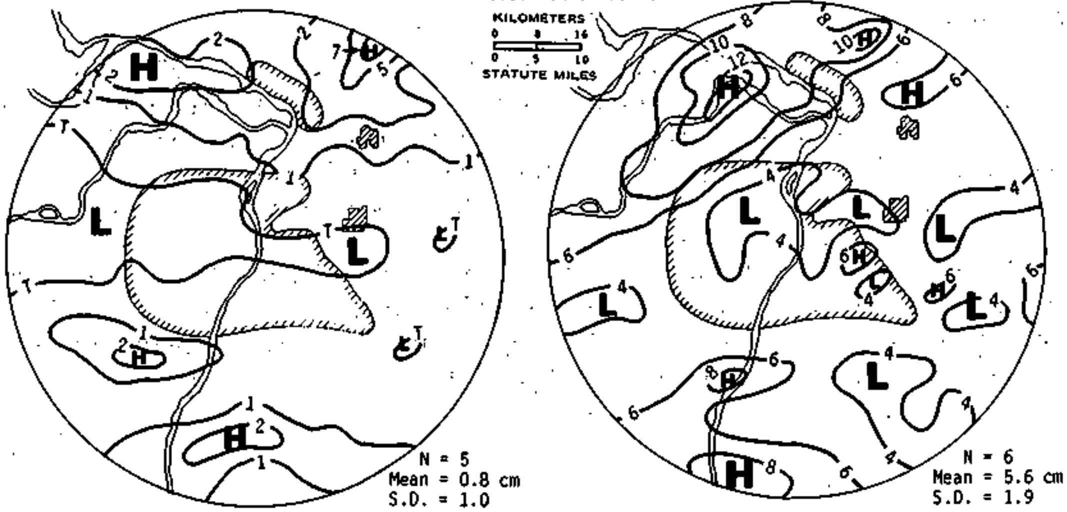


a. All Storms

b. Storm of 27-29 August 1974 removed



c. Low-level Winds from SE



d. Low-level Winds from SW

e. Low-level Winds from NE

Figure B-41. Rainfall patterns for static front storms, 1971-1975

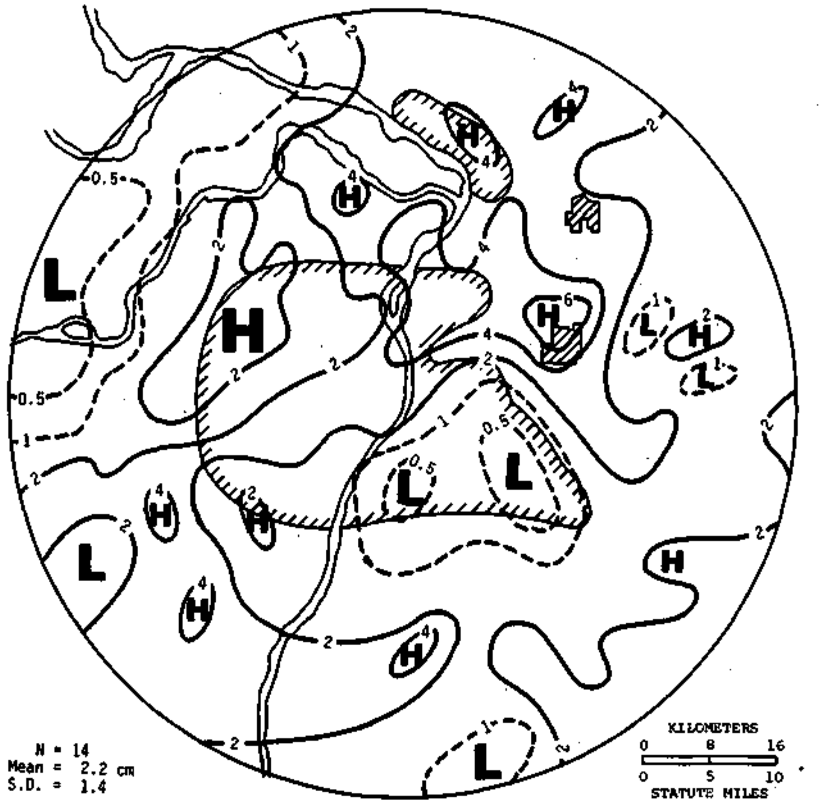


Figure B-42. Rainfall pattern for warm front storms, 1971-1975

that rainfall maximums were observed over the bottomlands and Alton-Wood River. The rainfall pattern without the storm of 27-29 August 1974 is similar. Little or no urban effect was evident within these storms.

Warm Front Storms

A network average of 2.18 cm (0.86 inch), or about *2%* of all rain, fell with warm front storms. The dominant rain element motion in nearly 60% of these 14 storms was from the SW quadrant, with most of the storms moving from the SSW and the SW. Southeast low-level winds prevailed prior to nine of these storms. Significant rainfall maximums might be expected NNE and NE of St. Louis and Alton-Wood River if these two urban regions are exerting an urban influence upon warm frontal rain systems.

The warm frontal rainfall pattern based on the 14 storms (figure B-42) shows rainfall maximums just NE of St. Louis and Alton-Wood River. Minimums were found over the southern and western parts of the research circle. The sample is small, but results suggest that the urban-industrial complex does enhance warm frontal precipitation. No attempt was made to stratify these storms by the prevailing convective entity motion.

Pre- and Post-Frontal Storms

There were 25 pre- and post-frontal storms sampled during the summers of 1971-1975, and the dominant storm motion was almost equally divided between the SW and NW quadrants. The low-level winds were from the NW in 11 storms, from the SW prior to 9 storms, and from the NE in the remaining 5 storms. If the city is enhancing these storm systems, a general maximum might be expected NE through SE of St. Louis. The network average rainfall from these storms was 1.65 cm (0.65 inch).

The rainfall pattern in these storms (figure B-43) shows a general high over the SE part of the circle with a secondary high to the WNW. A general minimum was noted over the north and east part of the network. It is possible that storms which moved from the NW quadrant were enhanced by the urban environment and those from the SW were decreased. However, the rainfall amounts and the sample size are small, and the average network area covered by precipitation in any given storm was generally less than 20%. Conclusions must be viewed as very tentative.

Air Mass Storms

During the five METROMEX summers, air mass storms were the most frequent rain-producing weather type. Nearly half of these storms moved from the SW quadrant and over 35% moved from the NW quadrant. However, the average areal coverage of each storm was less than *7%* of the network and the average point rainfall within that small area was only 0.3 cm. Thus, if St. Louis is initiating, enhancing, or decreasing rainfall within these systems, the pattern-sought

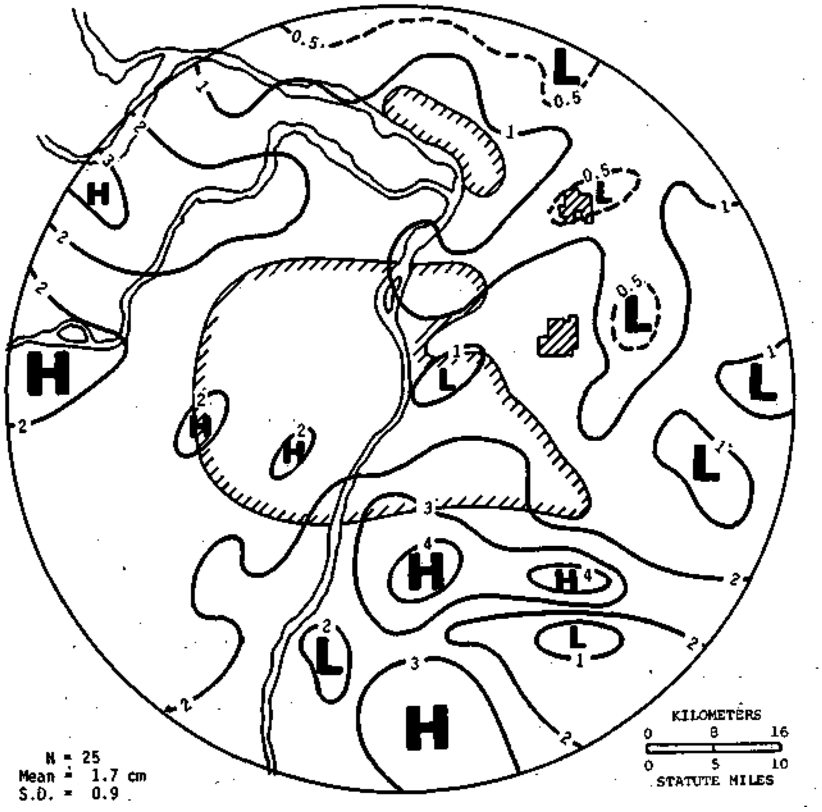
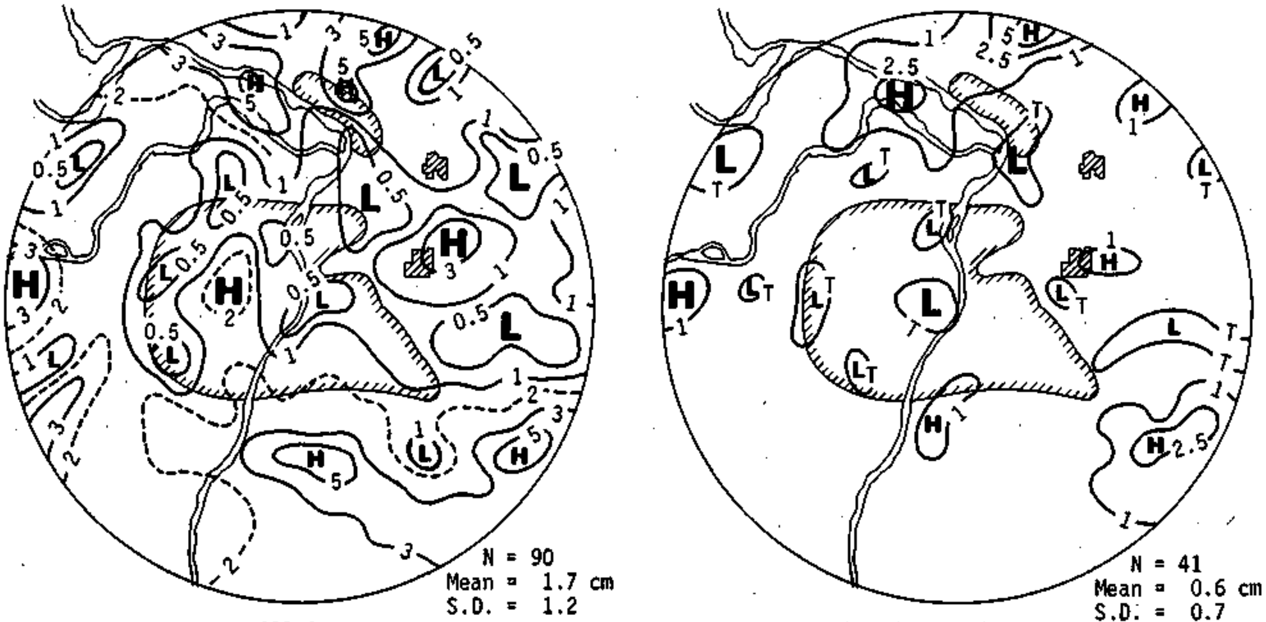
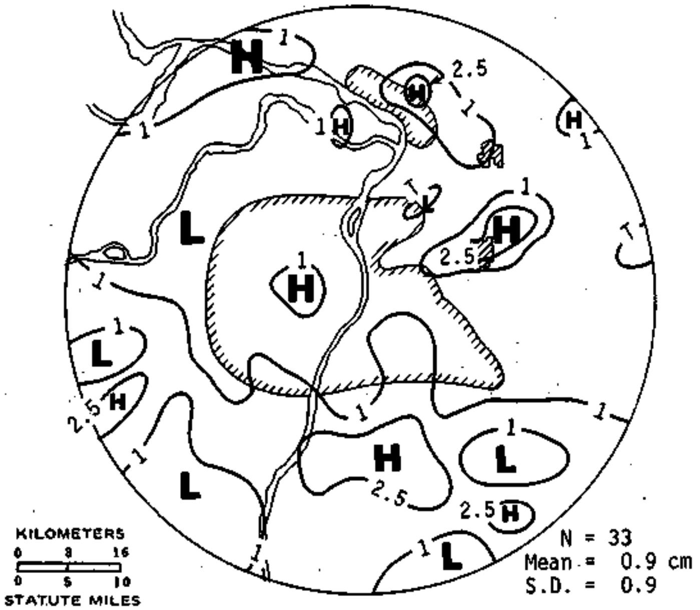


Figure B-43. Rainfall pattern for pre- and post-frontal storms, 1971-1975



a. All Storms b. Storms from SW



c. Storm from NW

Figure B-44. Rainfall patterns for air mass storms, 1971-1975

indication will not be too meaningful. Conceptually, it should show a general rainfall maximum over and to the NE, E, and SE of St. Louis.

The rainfall pattern from air mass storms (figure B-44a) shows a series of rainfall maximums and minimums seemingly scattered chaotically across the network. However, air mass storms can be expected to maximize over hill regions (Changnon, et al., 1975) and maximums were observed over the foothills of the Ozarks (W and SW edge of the circle) and south of East

St. Louis. A maximum was also situated over the NW bottomlands which serves as a heat and moisture source, and small locally induced storms might be expected to develop and/or maximize within these regions. Other small rainfall highs were noted NE of Alton-Wood River and east of St. Louis approximately 1 to 10 km (0.62 to 6.2 mi). Since the average lifetime of an air mass summer thunderstorm is one hour or less (Byers and Brahiam, 1949), it is possible that the rainfall within these maximums was enhanced by the urban environment. The primary rainfall minimum (<1.0 cm or 0.39 inch) began in west St. Louis and extended eastward, suggesting that the city either did not increase total air mass rainfall, or in fact may have decreased it.

A large number of air mass storms were sampled during the five METROMEX summers. Nearly half of these storms had motions from the SW quadrant and almost 40% of the sample moved from the NW quadrant. The network mean rainfall from SW air mass storms was 0.55 cm (0.22 inch) in 41 storms, and the average point rainfall based on those gages with rain was 0.25 cm (0.1 inch). The air mass storms from the NW averaged 0.93 cm (0.37 inch) over the network in 33 storms, and the average point rainfall in the gages with rain was 0.28 cm (0.11 inch). The mean gage rainfall in those gages with rain was comparable, but the areal extent of rain in the storms from the NW was greater than that for SW air mass storms.

The SW air mass rainfall pattern (figure B-44b) shows rainfall maximums over the bottomlands, NE of Alton-Wood River, and at the SE edge of the circle. There is some indication that the bottomlands affect rainfall. The air mass storms which moved from the NW (figure B-44c) showed maximums over and SE of Alton-Wood River and over and SE of St. Louis. These rainfall maximums might be urban related, but the 33 sample size is small.

Although air mass storms were the most frequent type during the five summers, they also were the smallest storms sampled and less than 2% of the total network rain came in these storms. Huff (1971) has pointed out the need for many years of rain data from air mass storms before any firm conclusions can be reached about the possible modification of this storm type by planned weather modification. Thus, even though the rainfall pattern suggests that the urban-industrial regions might be enhancing such storms under certain conditions, any firm conclusions cannot be established from this type of study of these storms.

Low Pressure Storms

Only five low pressure storms occurred in 1971-1975, and less than 1% of all the summer rain fell from this weather type. The dominant convective entity motion was from the NW quadrant for three of the storms and from the SW quadrant in the other two storms. Rainfall could be expected to maximize NE to SE of St. Louis and Alton-Wood River if either region were actively enhancing the rainfall. The rainfall pattern for low pressure area storms (figure B-45) shows rainfall maximums NE and SE of St. Louis, and over the NW bottomlands. A broad general minimum was noted west of the Mississippi River. There is some indication that the urban area might have influenced the precipitation pattern downstorm from St. Louis and Alton-Wood River. Once again, the sample is small and such a conclusion must be considered tentative.

Figure B-45. Rainfall pattern for low pressure storms, 1971-1975

MIXING HEIGHT

Mixing height has proven to be a useful tool in air pollution forecasting in recent years (Holzworth, 1967; Wuerch, 1972). This parameter gives the height within which the lower atmosphere can be expected to be thoroughly mixed. It is a measure of the amount of convection that is contained in the lower atmosphere, and is controlled by the surface heating and at times the prevailing synoptic conditions.

For example, when the St. Louis region is dominated by a strong anticyclonic circulation through a deep layer, a temperature inversion is often present in the lower 3000 m (~ 10,000 feet) of the atmosphere, even on a hot summer day. This would effectively provide a barrier through which air from the lower atmosphere cannot be expected to penetrate. Thus, free mixing in the lower atmosphere would be confined to the layer from the surface to the base of inversion. On other days, the surface heating is such that the mixing height extends well above 700 mb, and can be considered unlimited. A study of rainfall, synoptic types, and mixing heights was made to discern whether urban influences were apparent when mixing heights went to cloud base or higher (allowing urban effluents to affect clouds), or were not apparent when the mixing height was confined below cloud base.

Mixing height for this study was defined as the lowest altitude (MSL) at which the sounding showed either a temperature inversion or an isothermal layer in the region from the surface to 700 mb. If the mixing height was above 700 mb it was assumed to be unlimited. The data for this study were derived from St. Louis radiosonde data taken by the National Weather Service

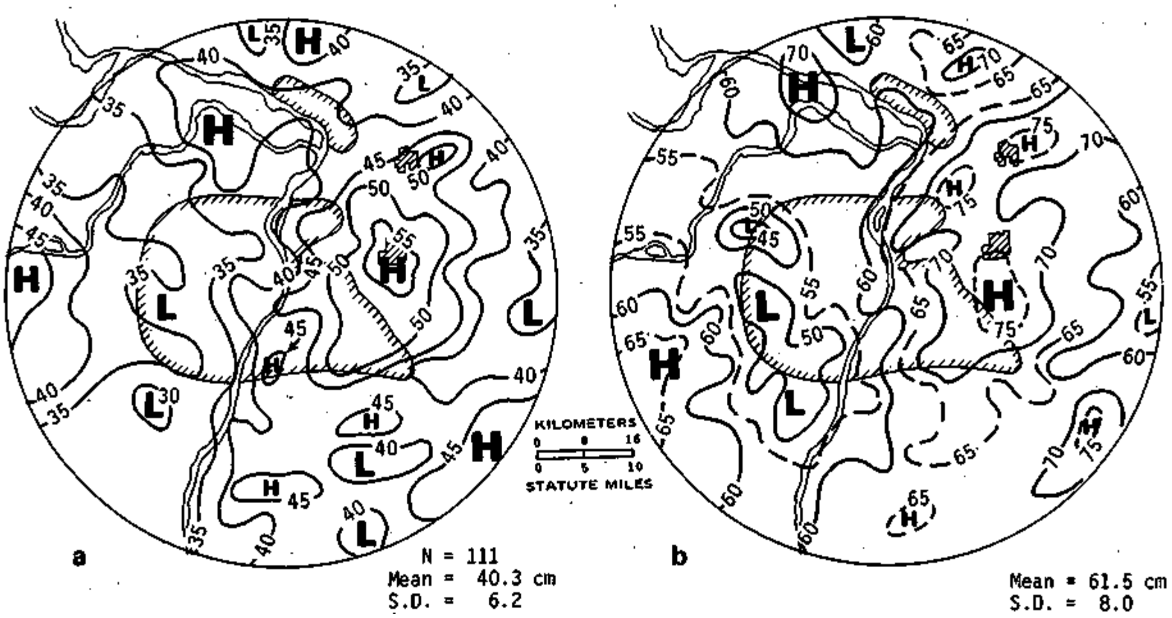


Figure B-46. Rainfall pattern for storms used in mixing height study (a) and total network pattern from 0900-2100 CDT (b)

(NWS) in 1971 and 1972, and from the upper air radiosondes operated by the Water Survey in 1973, 1974, and 1975. All soundings were made within the METROMEX Network. The soundings from the NWS were made at 0700 CDT and 1200 CDT on week days. The Water Survey radiosondes were operative only during parts of each summer, and generally the soundings were released from late morning to early evening. Thus, the rainstorm sample analyzed and presented is based primarily on rainfall events which occurred during the daytime.

Rainfall Patterns and Mixing Heights

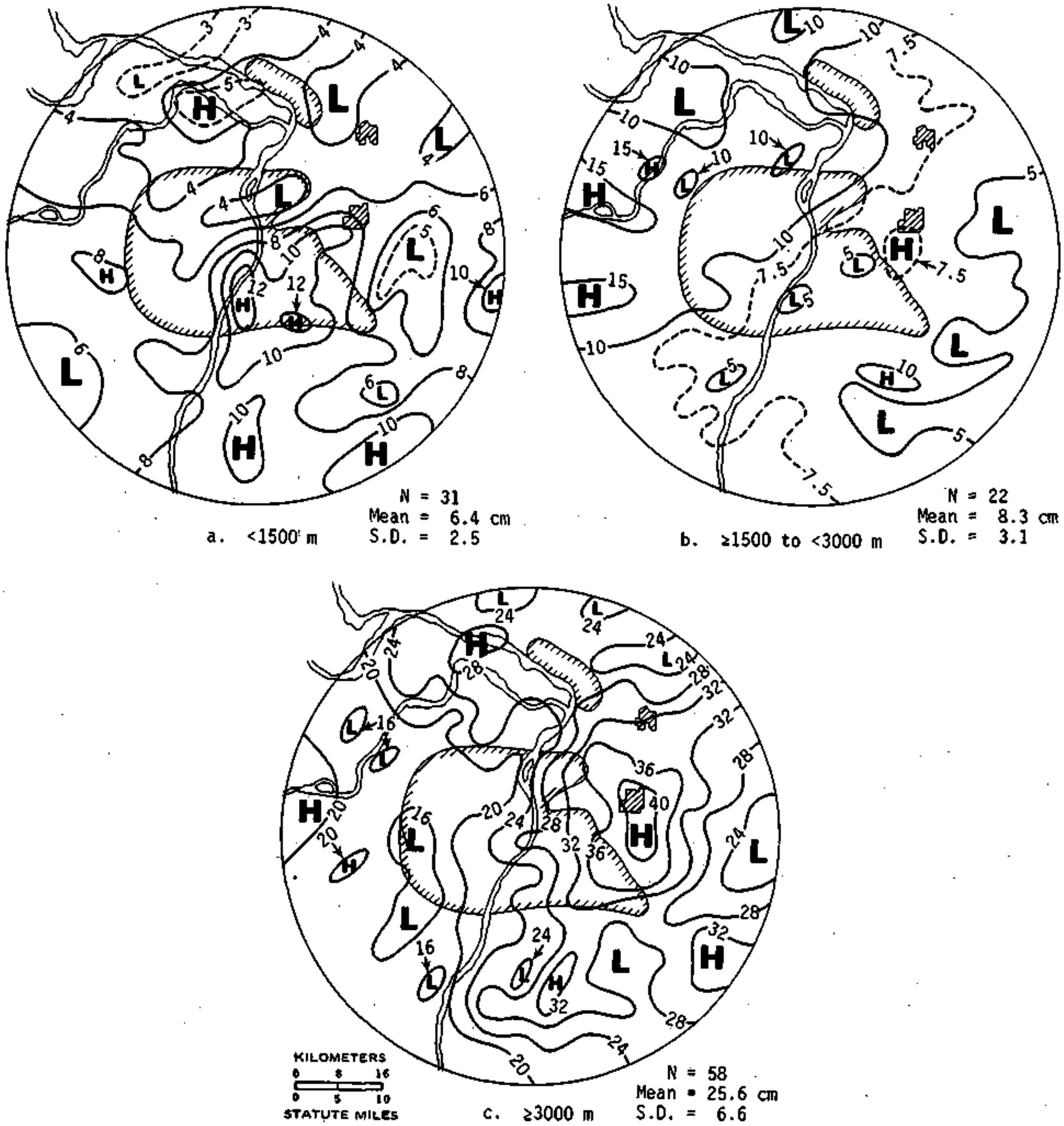
From the five summers 111 objective rainstorms with adequate mixing height data were analyzed. The total rainfall pattern from these storms shows a general rainfall maximum east of St. Louis (figure B-46a). Minor highs were situated over the west edge and south part of the network, and the rainfall minimum was located west of St. Louis. The pattern resembles the overall 5-summer pattern for the daytime period of 0900 to 2100 CDT (figure B-46b).

Nearly 50% of the 111 storms moved from the SW quadrant and almost 40% moved from the NW quadrant. Rainfall maximums can be expected NE through SE of St. Louis and Alton-Wood River if these urban regions are enhancing the rain systems as they move across the network. Such a pattern exists and it would appear that many of these rainstorms were affected by the urban region.

Rainfall patterns were determined for all storms that had mixing heights falling into three categories:

1) **Surface to 1499 m (~5000 ft)**
2) **1500 to 2999 m (~5000 to 10,000 ft)**
3) **3000 m (~10,000ft) and greater**

The rainfall pattern from the first category is shown in figure B-47a. Over 50% of the storms moved from the SW quadrant and 40% of the storms moved from the NW quadrant in



a. <1500 m N = 31 Mean = 6.4 cm S.D. = 2.5

b. ≥1500 to <3000 m N = 22 Mean = 8.3 cm S.D. = 3.1

c. ≥3000 m N = 58 Mean = 25.6 cm S.D. = 6.6

Figure B-47. Rainfall pattern for storms at various mixing height categories

this 31-storm sample. The mean network rainfall was 6.38 cm (2.5 inches). There was a rainfall maximum over the south part of the metropolitan area and a general precipitation minimum over the northern half of St. Louis and downstorm of Alton-Wood River. There is no clear evidence of any substantial rainfall increase due to urban effects.

The rainfall pattern for the storms which had mixing heights between 1500 to 2999 m is shown in figure B-47b. Over half of these storms moved from the SW quadrant and nearly 35% of the storms moved from the NW quadrant. Nearly 40% of these storms had low-level winds from the SE prior to the storm initiation. Thus, a rainfall maximum might be expected N to E of St. Louis if urban conditions were enhancing the clouds under these conditions. The rainfall pattern from these storms shows a general precipitation maximum W and NW of St. Louis. The region east of the Mississippi River is a minimum. It would appear that the urban region had little if any effect on this 22-storm sample. In fact, there is a suggestion of an urban related decrease.

A 58-storm sample was obtained for those storms embedded in air masses with a mixing height of 3000 m or greater. The mean network rainfall in this sample was 25.6 cm (10.08 inches). Approximately 80% of the storms had dominant convective entity movement from the west, and these movements were nearly equally divided from the NW and SW quadrants. Rainfall maximums NE through SE of St. Louis could be expected if the urban region was actively enhancing these rain systems. The rainfall pattern from these storms (figure B-47c) shows a general maximum NE, E, and SE of the urban region. The rainfall over the rest of the network, except for a general minimum west of St. Louis was very near the network mean. It would appear from this rainfall pattern that the urban-industrial region does enhance rainstorm systems when there is mixing of the urban environment through a deep layer of the troposphere. The rainfall patterns for those storm systems which were embedded in air masses with mixing heights of. less than 3000 m show little or no evidence of any urban effect.

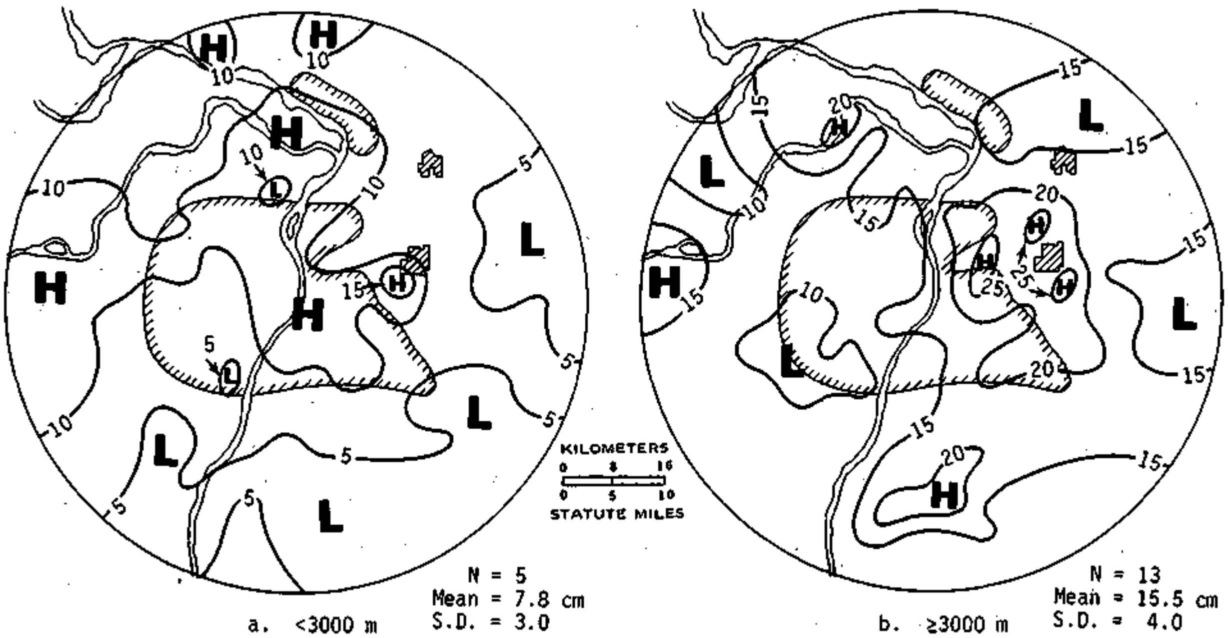
Thus, the effects of the urban environment appear to be most pronounced when there is mixing through a deep layer of the atmosphere and when there is intense and natural convection as found in squall zones. No rainfall maximums were observed downstorm from Alton-Wood River in this sample. However, it was shown earlier that most of the rain in that region fell at night, and this sample was primarily of daylight conditions.

Storm Types and Mixing Heights

The 111 rain-producing events with mixing height information were studied according to the synoptic weather types. The frequency of the types sorted by increments of 500 m mixing heights are given in table B-19. Approximately 34% of all storms were sampled, and the distribution of these storms by synoptic type is comparable to the overall distribution of all weather types (table B-14). Rainfall patterns were developed for those types with a frequency of 10 or more storms. Air mass storms were most frequent within this sample, however, the rainfall pattern for air mass storms was spotty and not indicative of urban effects on rainfall.

Table B-19. Frequency of Weather Types by Mixing Height (meters)

	Surface to 499	*500 to 999*	*1000 to 1499*	*1500 to 1999*	*2000 to 2499*	*2500 to 2999*	*3000 or greater*	*Total*
SL		1	1		2	1	13	18
SZ	3		1	3	3	3	10	23
CF	1		1		2		10	14
SF	3	1	2				1	7
WF	1	1					1	3
P&PoF	2	2		2		1	2	9
AM	3	2	5			5	20	35
LOW	1						1	2
Total								111



a. <3000 m

b. ≥3000 m

Figure B-48. Rainfall from squall line storms with mixing heights less than and greater than 3000 meters

Squall Line Storms. Almost 58% of the total rainfall sampled in the 111 storms was produced by squall lines. Squall line storms were the most intense weather type during the 5-summer period, and since they are always typified by deep convection in the atmosphere, it is possible that these storms could be modified even if the mixing height of the air mass is shallow, or less than 3000 m.

Five of the 18 squall line storms sampled had mixing depths less than 3000 m. The motion of the convective entities in these storms was from the SW quadrant. In four cases the low-level winds were from the SE quadrant, and in the fifth case the low-level winds were from the SW. Therefore, if St. Louis was acting to increase the rainfall from these storms, a precipitation maximum could be expected N to NE of St. Louis. A rainfall maximum was observed over, N, and W of the St. Louis urban area (figure B-48a). Low rainfall amounts were observed on the east and south portions of the circle. It would appear that the urban region might act to enhance the rainfall in some of these cases, although the results are not conclusive and the sample is small.

The rainfall pattern from squall line storms embedded in air masses with mixing heights of 3000 m or greater is presented in figure B-48b. The motion of these storms was almost equally divided between the SW and NW quadrants. Six of the storms had low-level winds from the SE and six were from the SW. A rainfall maximum could then be expected in the areas NE, E, and SE of the St. Louis urban region, if urban effects existed and a precipitation maximum did occur directly east of St. Louis. It would appear that the urban environment was actively enhancing the precipitation downstorm from St. Louis within these storms.

Thus, these results suggest that in many squall line storms, regardless of the mixing height, effects of the urban-industrial region on their precipitation processes are evident. The atmosphere instability associated with squall line storms appears to be more than ample to overcome the more stable air mass through which they were propagating.

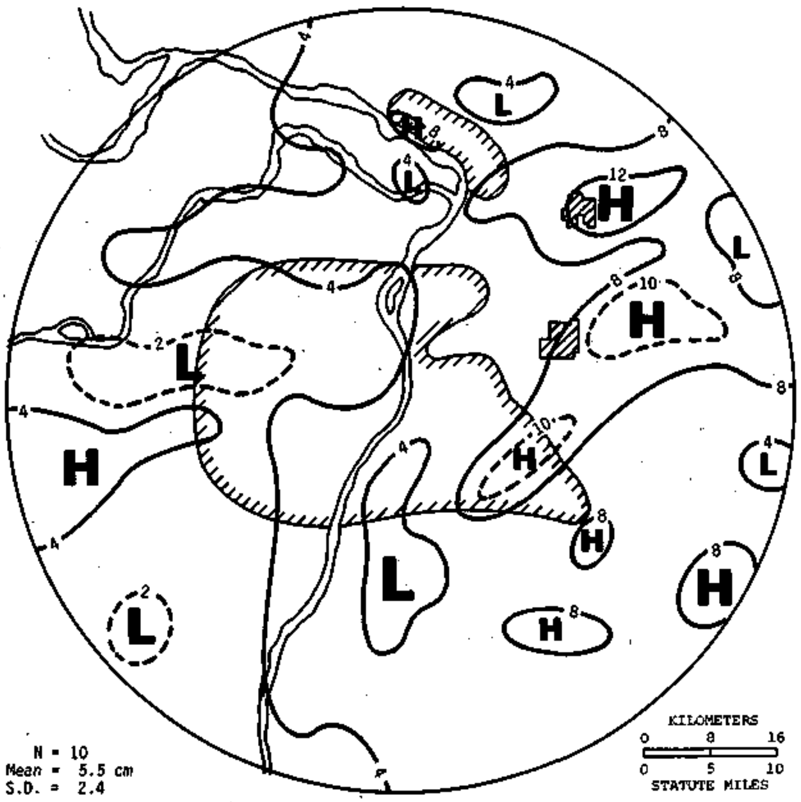


Figure B-49. Rainfall from cold front storms with mixing heights greater than 3000 meters

Cold Front Storms. Fourteen cold front storms occurred when the mixing height could be determined. Four of these storms had mixing heights less than 3000 m. The rainfall pattern from these four storms was spotty and the network rainfall was only 0.18 cm (0.07 inch).

In the 10 storms sampled with mixing heights greater than 3000 m, seven had convective elements which traveled primarily from the NW quadrant and three from the SW quadrant. In 6 of the 10 storms, the low-level winds prior to storm initiation were from the SW. With such a distribution, an urban effect leading to a downstorm rainfall maximum could be expected NE through SE of the St. Louis urban region. Such a downstorm maximum is shown in figure B-49. The rainfall maximum near Edwardsville may be the result of intensification from both St. Louis and Alton-Wood River, since both SW and NW storms were in this sample.

Squall Zone Storms. Nearly 20% of the rainfall sampled within the 111 storms with mixing height data fell in squall zone storms. Little urban effect was evident in the pattern of these storms. Of the 23 storm samples, 13 storms occurred within air masses which had mixing depths less than 3000 m. In eight of the storms the convective element motion from the SW dominated the individual storms. If urban effects exist, the rainfall pattern should be altered NE and E of the St. Louis urban-industrial complex. A rainfall minimum was observed due east of St. Louis with isolated rainfall maximums over the south part of the network (figure B-50a). This rainfall pattern was similar to the squall zone rainfall pattern with SW storm movement (figure B-39b). With mixing depths less than 3000 m the urban region appears to be decreasing the rainfall from squall zone systems which moved across the network.

In the 10 squall zone storms which were embedded in air masses with mixing depths of more than 3000 m, four moved from the NW quadrant and three from the SW quadrant. An

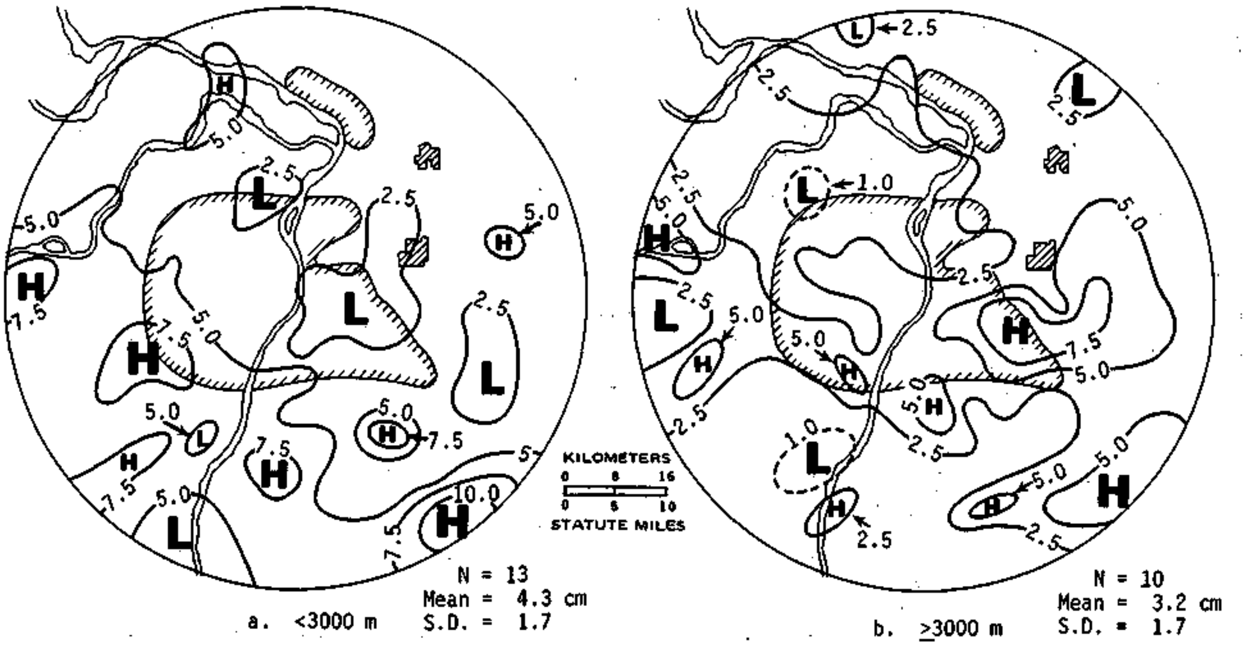


Figure B-50. Rainfall from squall zone storms with mixing heights less than and greater than 3000 meters

effect should appear east of the city, and figure B-50b shows a rainfall maximum was observed east of St. Louis. It would appear that squall zone storms which occur in a deep mixed layer are enhanced by the urban region. However, the sample is small and must be treated with caution.

SUMMARY AND CONCLUSIONS

This evaluation of synoptic weather conditions, and their relationship to possible urban effects on rainfall, was based largely on conceptualization of where rain changes could be expected (by study of the storm motions and low-level flow or trajectory of the urban plume) and then examination of various 5-summer rainfall patterns for various weather types.

The most frequent weather type that occurred during the five summers was the air mass type storm. However, the total rainfall from these storms was less than 2% of the total and they had little impact upon the rainfall distribution within the research circle. The rainfall patterns from these storms do not indicate much of an urban effect although a decrease is suggested. If there is an urban impact upon these storms it would take many years of similar rainfall data to discern the effect because they typically have very little rain. However, detailed case studies of these storms have suggested an urban effect linked to their growth (Vogel, 1975; Cataneo and Jones, 1975).

Table B-20 provides a general summary of the rainfall patterns stratified by synoptic type and mixing height as presented in this section. It indicates that the urban-industrial regions within the metropolitan St. Louis region may have exerted negative or no rainfall effects upon static front storms, squall zone storms, air mass storms, and cold front storms from the NW. However, there were indications of possible urban-industrial enhancement of squall zone storms with deeply convective air masses (mixing depth greater than 3000 m).

Table B-20. General Summary of Rainfall by Synoptic Weather Types

Storm stratification	*Results*
Squall line – all	Maximum NE quadrant – enhancement
Squall line – SW	Maximum NE quadrant and bottomlands – enhancement
Squall line – NW	Maximum Edwardsville-East St. Louis – enhancement
Squall zone – all	Minimum close to St. Louis, maximums distant NE and SE – decrease or no effect
Squall zone – SW	Low St. Louis to Collinsville, maximum NE of Edwardsville – decrease in rain
Squall zone – NW	Maximum distant SE – no effect
Cold front – all	High NE quadrant – effect
Cold front – SW	High Edwardsville and E of Collinsville – effect
Cold front – NW	Mixture of highs and lows – no effect
Static front – all	Highs bottomlands and S, low over, E, and W of St. Louis – decrease
Static front – SW	Highs over bottomlands and NE of Alton-Wood River – questionable
Static front – NW	Maximum over SW part of network – no effect or decrease
Warm front – all	High Granite City and Collinsville – possible enhancement (small sample)
Pre- & post-frontal – all	Mixed – possible increase and decrease (small sample)
Air mass – all	Mixed – decrease or no effect
Air mass – SW	High Alton-Wood River – slight increase, but questionable; minimum over St. Louis – decrease
Air mass – NW	Mixed – no effect
Low – all	High Edwardsville, bottomlands, and SE – possible increase but questionable (small sample)
Mixing heights	
0-1500 m	High S of St. Louis, low NE – possible increase SE and decrease NE
1500-3000 m	Low E of Mississippi – no effect or decrease
> 3000 m	Maximum E – increase
Squall line < 3000 m	Maximum Collinsville – slight increase
> 3000 m	Maximum East St. Louis and Collinsville – increase
Cold front < 3000 m	Maximum Edwardsville-Collinsville-Belleville – increase
Squall zone < 3000 m	Maximum SW and S, low East St. Louis to Collinsville – decrease
> 3000 m	Maximum East St. Louis and Belleville – increase

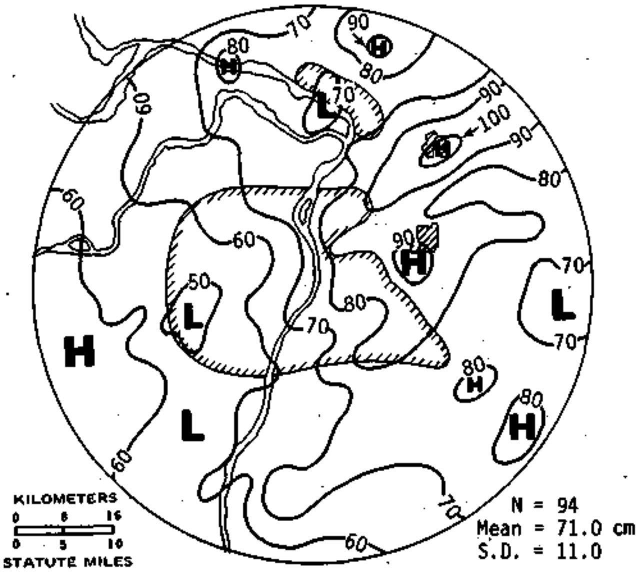


Figure B-51. Rainfall pattern for combined squall line and cold front storms, 1971-1975

Over 88% of the network rainfall occurred from squall line, squall zone, and cold front storms. Thus, 50% of the storm events caused nearly 90% of the storm rainfall. If the St. Louis and Alton-Wood River urban-industrial regions are measurably enhancing total summer precipitation, it seems reasonable to expect the effect to be occurring within these more organized storm events.

The rainfall pattern from squall zone storms exhibited no evidence that the urban region had an effect during these conditions. The total rainfall pattern from the squall line storms and that for cold front storms which moved from the SW showed definite increases in the rainfall pattern beyond the city. Figure B-51 shows the combined rainfall pattern based on all squall line and cold front storms. There is a general rainfall maximum in the NE quadrant with over a 30-cm increase in rainfall from central St. Louis to Edwardsville. Thus, the major urban-industrial impact upon the precipitation pattern occurs in the more organized weather situations which tend to have the most intense rainstorms. This agrees with the earlier work of Huff and Changnon (1972). Patterns of other synoptic types showed some possible urban enhancement, but the sample size is too small to make any firm conclusions.

Mixing height, which is a measure of convection and potential for the percent of urban effluents to clouds, showed the greatest urban enhancement of rain occurred when the atmosphere was well mixed through a deep layer (>3000 m). The most intense convective storms (cold fronts and squall lines) were found to be most actively affected by the urban-industrial region. Squall zone storms, whose pattern exhibited little or no urban effect when stratified by storm direction, show a possible urban effect for 1) rain increase when the air mass in which the storms were embedded was deeply convective and 2) a rain decrease when the mixing height was shallow.

The St. Louis urban region appears to inadvertently enhance rainfall during more intense, deep convective system. Other weather systems showed little, and in some cases, negative urban-industrial effects.

2. SEVERE LOCAL STORMS

THUNDER ANALYSIS FOR METROMEX

Stanley A. Changnon, Jr.

INTRODUCTION

An investigation of thunderstorms through study of the occurrence of audible thunder activity was pursued as a primary goal of METROMEX. As part of the investigation of potential urban effects on severe local storms, the thunder research effort sought to define and explain any anomalies in summer (June-August) thunder activity that were potentially related to urban-industrial effects on the atmosphere in the St. Louis region. Climatic studies of available, albeit limited, historical thunder data (Huff and Changnon, 1972) showed a local increase of 20% in thunder days.

The initial study of 1971-1973 METROMEX data indicated a 25% increase in thunder activity in the area just east of St. Louis (Huff and Changnon, 1973; Changnon, 1974). In these publications, the detailed analyses of the 1971-1973 METROMEX data are described along with detailed listings of the data for the thunder activity in the St. Louis region in those first three years of METROMEX. This report presents the detailed data for the 1974-1975 period to make these data also available in published form. However, the major purpose of this report is to summarize the 5 -year findings in thunderstorm activity in the St. Louis area.

The possible urban effects on summer thunderstorm frequencies in 1971-1975 were investigated by use of point thunder data for 13 points within the METROMEX study region of 4000 mi^2 or 10,400 km^2 (figure B-52). The nature and magnitude of the effect on thunderstorm activity were investigated by studying

- The frequency of thunder days
- The nature of discrete thunder periods
- The time of thunder occurrence
- Thunder frequency or rate
- Thunderstorm relationship to precipitation-causing weather conditions

The thunder days and thunder periods were analyzed on both spatial and temporal scales to define any potential anomalies and their causes.

The basic inferences about where urban area storm anomalies could occur were based on raincell and radar echo data on storm behavior in the region. As shown by Changnon et al. (1976), storm motion in the area is from westerly directions. Hence, storms that could be affected by the city could begin to exhibit effects over the metropolitan area and over the area lying to the northeast, east, and southeast of the metropolitan area. Data from points, or stations, to the west of the metropolitan area were considered to exhibit no urban effects, whereas data from sites in the metropolitan area were considered to reflect possible urban effects. Data from stations immediately east of the city were also considered to be potentially affected by urban influences. Raincell lengths, indicative of storms, typically do not exceed 20 miles (32 km). Two thunder-recording points located 35 to 45 miles (56 to 72 km) east of the city were installed to examine for any "downwind effects." They were considered sufficiently far east of the metropolitan area and thunderstorm path lengths to be beyond the lifetime of thunderstorms that developed or passed over the city. They might be potentially urban affected but it was considered unlikely unless urban generated storms led to more storm development.

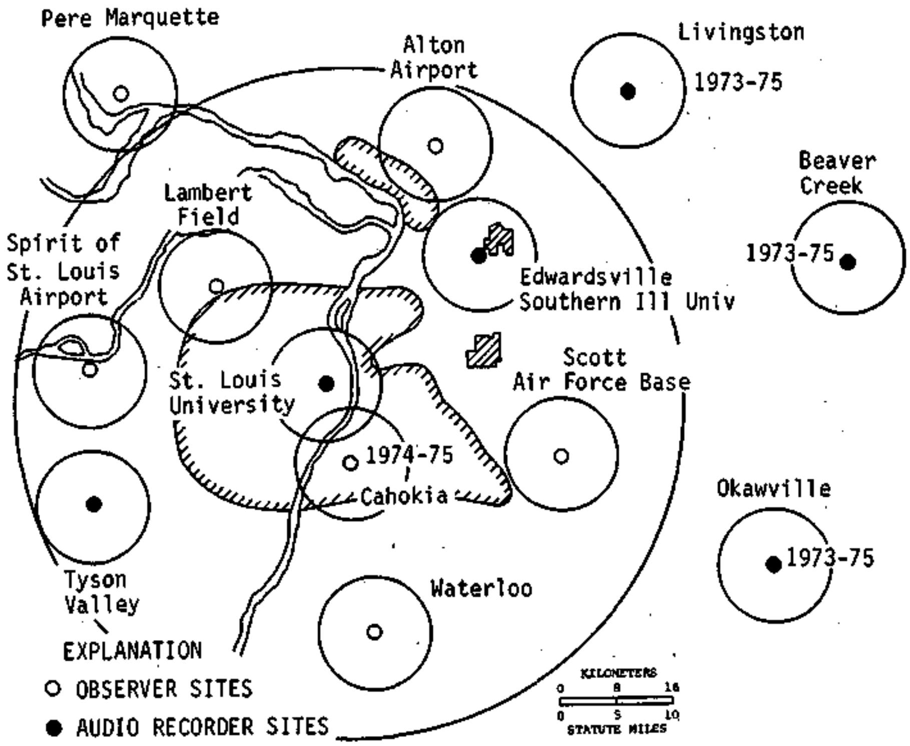


Figure B-52. Thunder observation sites

DATA

There were two basically different sources of thunder data, although each source had certain variations in how the data were collected (see table B-21).

A primary source of thunder data is that found in the standard weather observations which include observations of thunder by the observers. Three of these (Lambert Field of the National Weather Service, Scott Air Force Base, and the Pere Marquette (PMQ) Weather Station maintained by the Water Survey) were manned continuously by trained weather observers, with a lightning detector apparatus assisting at PMQ. These stations provide excellent thunder data. There were four other weather observation stations in the region from which thunder data were derived, but these have certain observational limitations. The Alton Airport, Cahokia Airport, and the Spirit of St. Louis Airport (see figure B-52) were manned by observers of the Federal Aviation Agency during most hours of the day. As noted in table B-21, observations often were not made between 2200 and 0600 CDT and conceivably thunder occurrences were missed during these early morning hours. The seventh observational station from which thunder data were secured was that of the cooperative weather observer of the Environmental Data Service located at Waterloo, Illinois (see figure B-52). This observer has a potential for recording thunder anytime during the day, but presumably can "miss" certain thunder occurrences. Hence, the records must be considered somewhat suspect.

Figure B-52 reveals that the seven observer sites with potential thunder data did not provide good areal coverage of the METROMEX Network. Hence, a major activity of the thunder study of METROMEX was to develop remote, and hence automatic, audio thunder recording units. These were designed and built as part of the METROMEX project (Gardner, 1976). The

Table B-21. Sources of Summer Thunder Data during 1971-1975

Name of station	*Type of station*	*Periods of operation* *Hours of day*	*Months and years*
Tyson Valley	Recorder, 4 microphones	24	July-August 1971 June-August 1972-1975
St. Louis University	Recorder, 4 microphones	24	July-August 1971 June-August 1972-1975
Edwardsville (SIE)	Recorder, 4 microphones	24	July-August 1971 June-August 1972-1975
Livingston	Recorder, 1 microphone	24	June-August 1973-1975
Beaver Creek	Recorder, 1 microphone	24	June-August 1973-1975
Okawville	Recorder, 1 microphone	24	June-August 1973-1975
Pere Marquette	Weather observer and lightning detector	24	June-August 1971-1975
Lambert Field	NWS observer	24	June-August 1971-1975
Scott Air Force Base	U.S. Air Weather Service observer	24	June-August 1971-1975
Alton Airport	FAA observer	16 to 18*	June-August 1971-1975
Cahokia (Airport)	FAA observer	16 to 18*	June-August 1974-1975
Spirit of St. Louis Airport	FAA observer	16 to 18*	June-August 1971-1975
Waterloo	EDS cooperative observer	24**	June-August 1971-1975

*Stations generally closed between 2200 and 0600 CDT and missed some of the thunder observations

**Observer has potential for 24-hour observations but probably misses nocturnal activity

six sites of these recorders are listed in table B-21 and are shown on figure B-52. The automatic thunder recording stations at the Tyson Valley, St. Louis University, and Edwardsville (Southern Illinois University) sites were a different model and type from those installed in Livingston, Beaver Creek, and Okawville. As will be noted in table B-21, the Tyson Valley, St. Louis University, and Edwardsville sites were operated in the summers of the 1971-1975 period, except for June 1971 when installation and testing were in progress. The other three recorder stations of a different and simpler design were built in 1972 and then operated during the summers of 1973-1975.

The first three stations installed for the full 5 years each had 4 microphones and a multichannel recording system which would allow analysis of the direction of the thunder occurrence. Their components are described by Gardner (1976). The other three recorder sites installed in 1973, which were in the extended area east of the main network circle, each had only one microphone and a simpler recording system. These were built and installed in 1973 in response to results indicating a need to define the eastward extent of the high thunder incidence area revealed by the values at Scott Air Force Base and Edwardsville sites for 1971-1972 (Changnon and Huff, 1973).

It should be noted that there is a considerable difference in the type of thunder data available from the observational sites, compared with the recorder sites. The principal useful information that can be obtained from the seven observational sites is whether thunder occurred or did not occur on a given date. At stations including Lambert Field, Pere Marquette, and Scott Air Force Base the beginning and ending times of the thunder are sometimes recorded, along with an indication of whether the thunder was moderate or intense, at least at discrete often hourly observational times.

The six automatic thunder recording stations provided much more extensive information on thunder including the exact beginning and ending times of the thunder and the occurrence of all thunder peals. This allowed a counting of the thunder frequency or rate per unit time. Much of the detailed analysis of the thunder information was focused on the data from the thunder recorders rather than the less time-accurate and informative data from the observational stations.

Table B-22. Terminology and Definitions of Different Classifications of Thunder Data

Thunder days:	Based on point data for a midnight to midnight period with thunderstorm occurrences, as defined by audible reports of thunder either by the recorder or by observation station sites.
Thunder periods:	A thunder period is a period having had two or more thunder peals in a given 15 minute period and is separated from other thunder periods by one or more hours with no thunder peals. Note that several thunder periods can occur in one day. These were based on point records of audible thunder as determined at only the thunder recorder sites.
Thunder rate segments:	There were periods when the thunder rate of occurrences remained constant, within four levels. A thunder period could have one or more such segments. There were four classes of thunder rates based on the frequency per hour, although they did not have to persist for an hour. The *very light* rate was based on a frequency of 5 peals or less per hour; the *light* (or occasional) frequency was based on 6 to 11 peals per hour (or hourly rate); the *moderate* frequency was based on the occurrence of 12 to 60 peals per hour; and the *intense* was based on an hour of more than 60 peals.
Network thunder periods:	These are periods in the METROMEX network when one or more points had "thunder periods" that exhibited a time and space coherence associated with a precipitation system existing in the raingage network. In a given day, including a thunder day, there could be more than one network thunder period.

The analysis of thunder data from various data sources required certain classifications of the data. These classifications, or definitions, are presented in table B-22.

In the previous METROMEX reports concerning results for the 1971-1973 period, detailed listings of the dates with thunder were presented for the individual stations. Tables B-23 and B-24 itemize the dates during 1974 and 1975 when thunder occurred. Tables B-25 and B-26 present the itemized listing of the 1974 and 1975 network thunder periods. These show the thunder period date and for each date, the stations with thunder. Listings such as these were used in the plotting of thunder distributions with each storm period.

Table B-23. 1974 Thunder Dates

	June	*July*	*August*
Beaver Creek	5, 14, 15, 19, 20, 21, 22, 30	8, 9, 10, 20, 28	2, 3, 11, 17, 18, 31
Livingston	8, 9, 11, 14, 15, 19, 20, 21, 22, 30	8, 9, 10, 12, 15, 20, 22, 28	1, 10, 11, 13, 18, 26, 27, 28, 31
Okawville	6, 14, 15, 20, 22	4, 11, 20, 22, 28, 30	2, 3, 13, 31
Southern Illinois University-Edwardsville	5, 6, 11, 14, 15, 19, 20, 22, 30	8, 9, 10, 12, 20, 22, 28, 30	2, 9, 10, 13, 18, 26, 27, 28, 31
St. Louis University	7, 11, 13, 14, 15, 22, 30	7, 8, 9, 10, 11, 12, 13, 14, 15, 20, 22, 28	2, 12, 13, 17, 24, 28, 31
Tyson Valley	9, 13, 14, 15, 19	8, 9, 13, 14, 15, 20, 28	2, 10, 11, 13, 17, 28, 31
Waterloo	6, 13, 22	12, 14, 28	9, 10, 13, 17, 22, 31
Lambert Field	5, 6, 7, 9, 14, 22, 30	7, 9, 13, 15, 20, 22, 28	2, 10, 28, 31
Scott Air Force Base	6, 7, 9, 11, 14, 19, 22, 30	8, 9, 10, 12, 20, 22, 28	2, 9, 13, 15, 18, 27, 28, 31
Alton Airport	6, 14, 19, 22, 30	8, 9, 10, 12, 20, 22, 28	1, 2, 9, 10, 12, 26, 27, 28, 31
Spirit of St. Louis Airport	6, 9, 19, 30	14, 20, 28	10, 11, 13, 14, 17, 28, 31
Cahokia	7, 11, 14, 19, 30	8, 10, 12, 14, 20, 28	1, 2, 12, 13, 27, 28, 31
Pere Marquette	14, 19, 22, 30	13, 20, 28	1, 2, 10, 11, 13, 28, 31

Table B-24. 1975 Thunder Dates

	June	*July*	*August*
Southern Illinois University-Edwardsville	15, 16, 20, 22, 23, 25, 27	6, 11, 13, 17, 19, 30	1, 13, 14, 25, 26, 28, 29
Beaver Creek	14, 16, 17, 20	5, 6, 17, 18, 23, 30	1, 2, 5, 15, 25, 26, 29
Okawville	1, 15, 16, 17, 20, 23, 24, 26	5, 6, 19, 20, 23, 31	2, 14, 15, 17, 25
Livingston	1, 2, 14, 15, 16, 17, 20, 22, 25, 26	4, 5, 6, 13, 17, 19, 23, 24, 30, 31	2, 3, 5, 14, 25, 26, 28, 29
St. Louis University	1, 13, 14, 15, 16, 17, 20, 22, 23, 24, 25, 26	5, 6, 11, 12, 13, 14, 17, 18, 19, 20, 23, 30	2, 3, 5, 13, 14, 15, 17, 25, 26, 28, 29
Tyson Valley	13, 14, 15, 16, 17	10, 11, 12, 17, 24, 30, 31	1, 3, 5, 6, 8, 14, 17, 25, 29, 30
Lambert Field	1, 5, 14, 15, 16, 17, 20, 22, 23, 24, 25	5, 6, 11, 12, 13, 17, 18, 19, 20, 23, 30, 31	3, 5, 14, 17, 25, 26, 29
Alton Airport	1, 14, 16, 20, 22, 23, 24, 25	5, 6, 11, 13, 17, 19, 20, 23, 30, 31	14, 25, 29
Spirit of St. Louis Airport	1, 16, 22, 23, 25	6, 11, 13, 17, 18, 19, 23, 30 31	3, 5, 13, 14, 17, 25, 28, 29
Scott Air Force Base	1, 5, 13, 14, 15, 16, 17, 20, 21, 22, 23, 25 26	4, 5, 6, 11, 12, 13, 14, 17, 18, 19, 23, 30, 31	5, 13, 14, 15, 17, 26, 28
Cahokia	13, 14, 20, 22, 23, 25, 26	4, 6, 11, 13, 17, 19, 23, 30	3, 14, 15, 17, 25, 26, 28
Waterloo	5, 14, 15	6, 12, 17, 18, 19, 20, 23	5, 14, 17, 25
Pere Marquette	1, 14, 15, 16, 20, 25	5, 11, 13, 19, 23	25, 29

Table B-25. 1974 Network Thunder Periods

Thunder period date	*Stations with thunder*
June 5	STL, SIE, BVK
June 6	ALN, SIE
June 6	WLO, BLV, OKV
June 6	STL
June 6–7	STL, BLV
June 7	SLU
June 8	LVT
June 9	BLV, TYV, LVT, STL
June 11	BLV, SIE
June 11	BLV, LVT, SLU
June 13–14	WLO, TYV, SLU, LVT
June 14	CAH, STL, ALN, PMQ, SLU, SIE, OKV, LVT, BVK
June 14–15	BLV, STL, ALN, PMQ, TYV, SLU, SIE, OKV, LVT, BVK
June 19	BVK, LVT, SIE, BLV, CAH, STL, ALN, PMQ, TYV
June 20–21	BVK, LVT, OKV, SIE
June 22	OKV, LVT, BVK, SIE, BLV, STL, ALN, PMQ, WLO
June 22	LVT
June 30	SUS, PMQ, BLV, CAH, STL, ALN, LVT, BVK, SIE
July 4	OKV
July 7	STL, SLU
July 8	SLU, TYV, SIE, CAH, BLV, LVT, BVK, ALN
July 9	SLU, LVT
July 9	SIE, SLU, TYV, BVK, LVT, BLV, STL, ALN
July 10	LVT, BVK, SIE, SLU, BLV, CAH, ALN
July 11	OKV, SLU
July 12	WLO, BLV, CAH, ALN, LVT, SIE, SLU
July 13	SLU, PMQ, STL, TYV
July 14	SLU, TYV, WLO, CAH, SUS
July 14	SLU, TYV
July 15	STL, LVT, TYV, SLU
July 20	TYV, SLU, SIE, LVT, BVK, BLV, STL, SUS, OKV, ALN
July 22	STL, SLU, BLV, OKV, SIE, ALN, LVT
July 28	SLU, TYV, SIE, LVT, BVK, OKV, CAH, BLV, STL, ALN, SUS, PMQ
July 30	SIE, OKV
August 1	PMQ, CAH, ALN
August 2	BVK, OKV, SIE, SLU, PMQ, WLO, STL
August 2	BVK, OKV, SIE
August 2–3	BVK, OKV, SIE, SLU, TYV, PMQ, WLO, BLV, CAH, STL, ALN, LVT
August 9–10	WLO, BLV, ALN, SIE
August 10	TYV, SIE, LVT, STL, PMQ
August 11	TYV, LVT, PMQ, BVK, ALN
August 12	ALN, SLU, CAH
August 13	TYV, SLU, SIE, CAH, OKV, LVT, SUS, PMQ, WLO, BLV
August 14	SUS
August 15	BLV
August 17	SLU, TYV, SUS
August 17	WLO
August 18	BLV, SIE, LVT, BVK
August 22	WLO
August 24	SLU
August 26	LVT, ALN, SIE, BLV, CAH
August 27	LVT, ALN, SIE, BLV, CAH
August 28	PMQ, ALN, LVT, SIE, STL, SUS, TYV, SLU, CAH, BLV
August 31	PMQ, ALN, WLO, OKV, BVK, LVT, SIE, STL, SUS, TYV, SLU, CAH, BLV

Table B-26. 1975 Network Thunder Periods

Thunder period date	*Stations with thunder*
June 1–2	SUS, PMQ, STL, SLU, ALN, SIE, BLV, LVT, OKV
June 5	STL, WLO, BLV
June 13	SLU, TYV, CAH, BLV
June 14–15	PMQ, STL, TYV, WLO, SLU, CAH, ALN, SIE, BLV, LVT, BVK, OKV
June 16–17	PMQ, SUS, TYV, STL, SLU, ALN, SIE, BLV, LVT, BVK, OKV
June 20	STL, SUS, SLU, CAH, SIE, ALN, BLV, LVT
June 23	ALN, STL, SLU, CAH, ALN, SIE, BLV, OKV
June 24	STL, ALN, SLU, OKV
June 25	SUS, PMQ, STL, SLU, CAH, BLV, SIE, ALN, LVT
June 26	CAH, SLU, BLV, LVT, OKV
June 27	SIE
July 4	CAH, BLV, LVT
July 5–6	SUS, PMQ, STL, SLU, CAH, WLO, BLV, SIE, ALN, LVT, BVK, OKV
July 6	SLU, CAH, BLV
July 10	TYV
July 11	PMQ, SUS, TYV, STL, SLU, CAH, BLV, SIE, ALN
July 12	TYV, STL, SLU, WLO, BLV
July 13–14	PMQ, STL, SUS, SLU, CAH, BLV, SIE, ALN, LVT
July 17	SUS, TYV, STL, SLU, CAH, WLO, BLV, SIE, LVT, BVK, ALN
July 18	BVK
July 18	SUS, STL, SLU, BLV, WLO
July 19	STL, SLU, CAH, SIE, ALN, LVT, OKV
July 19	SUS, STL, SLU, WLO, CAH, BLV, SIE, ALN, LVT, OKV
July 19	BLV, WLO, LVT, PMQ
July 19–20	STL, SLU, WLO, OKV, ALN
July 20	WLO
July 20	WLO
July 23	PMQ, SUS, WLO, SLU, STL, CAH, BLV, ALN, BVK, OKV
July 23–24	STL, PMQ, LVT, BLV
July 24	TYV
July 30	TYV, SUS, STL, SLU, CAH, BLV, SIE, ALN, LVT, BVK
July 31	SUS, STL, TYV, SLU, BLV, ALN, LVT, OKV
August 1	SIE, BVK, TYV
August 2	SLU, BVK, LVT, OKV
August 3	SUS, STL, TYV, SLU, CAH, LVT
August 5	LVT, BVK, BLV, WLO, SLU, STL, ALN, TYV
August 13	TYV, SUS, SLU, BLV, SIE
August 14	SLU, CAH, BLV, WLO, OKV
August 14	SLU, CAH, WLO, BLV, SIE, ALN, LVT
August 15	CAH, BVK, OKV
August 15	SLU, CAH, BLV, BVK
August 17	SUS, STL, SLU, CAH, BLV, OKV
August 17	WLO, BLV, CAH, SLU, TYV, SUS, STL
August 25	TYV, PMQ, SLU, CAH, SIE, ALN, LVT
August 25–26	PMQ, STL, SUS, TYV, SLU, WLO, CAH, BLV, SIE, ALN, LVT, BVK, OKV
August 28	SUS, SLU, CAH, BLV, SIE, LVT
August 29	LVT
August 29	ALN, LVT, BVK
August 29	PMQ, TYV, SUS, STL, SLU, SIE, ALN, LVT, BVK
August 30	TYV

Frequencies of Thunder Days

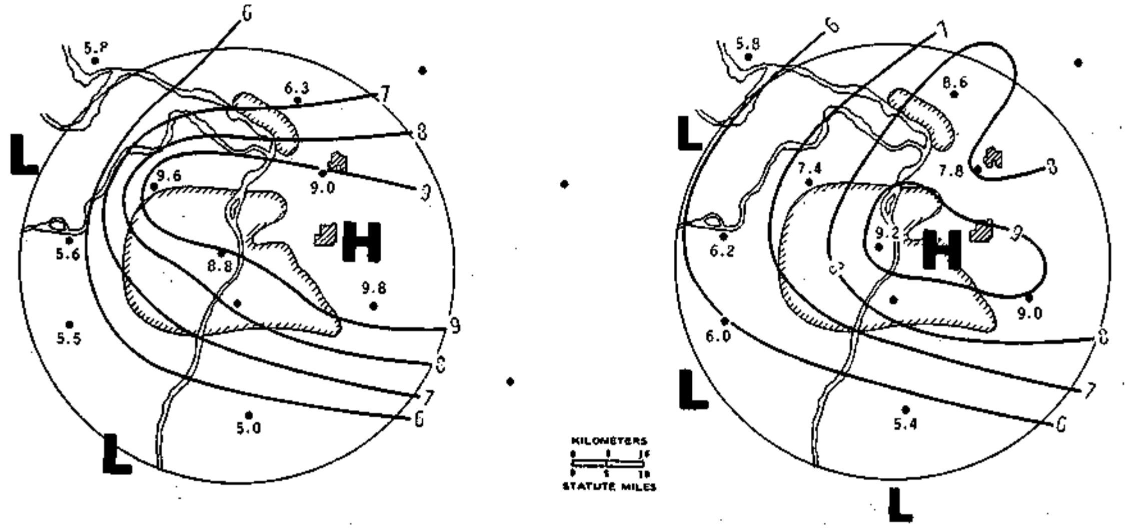
The frequencies of thunder days for each month and year at each station are summarized in table B-27. Shown for each of the months are both 5-year totals (1971-1975) and 3-year totals (1973-1975). The 3-year totals were included to permit comparisons of the frequencies of thunder days during the period when the "far east" (Okawville, Beaver Creek, and Livingston) stations were in operation. Considerable year-to-year variability is evident in the counts for most months. For example, the July frequencies of thunder days at the Pere Marquette station (PMQ) range from a low of 3 days in July 1974 to a high of 10 thunder days in July 1973, a 3-fold difference. Inspection of this temporal variability of thunder days indicates at least a 2-fold difference at most stations in all months.

The patterns of average numbers of thunderstorm days for the three summer months and: for the 1971-1975 period are shown in figure B-53. The June pattern (figure B-53a) shows low values at the stations west of the St. Louis area with a decided maximum beginning over the metropolitan area and extending eastward through Edwardsville and Scott Air Force Base. The July pattern also shows low values to the west and south of the metropolitan area with a decided maximum over the metropolitan area and to the north over the Alton-Wood River industrial area. This high over the metropolitan area again appears to extend eastward and potentially northeastward across the study region. The August pattern (figure B-53c) differs from those of

Table B-27. Number of Thunder Days at Each Station

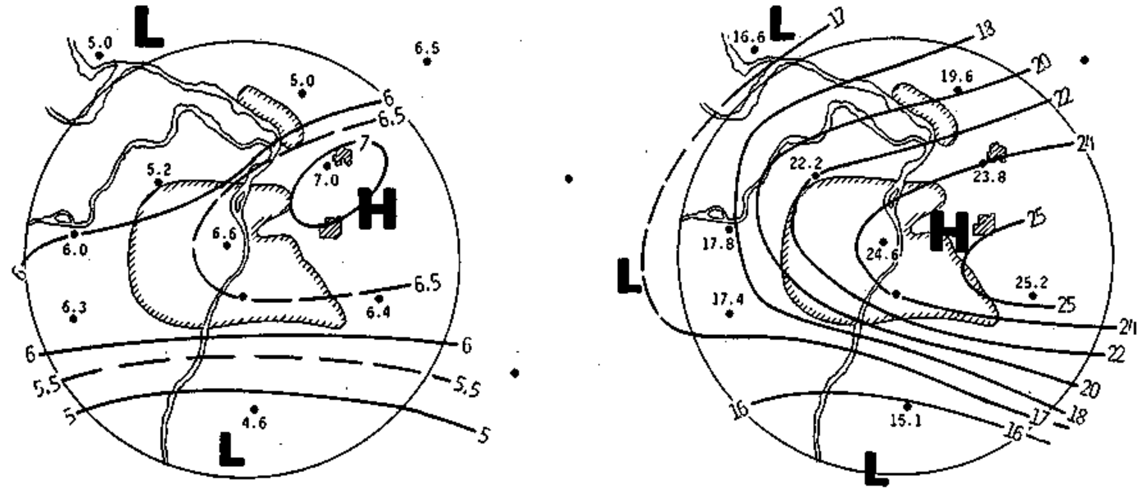
	TYV	*SLU*	*SIE*	*LVT*	*BVK*	*OKV*	*PMQ*	*SUS*	*STL*	*CAH*	*ALN*	*BLV*	*WLO*
June													
1971							8	7	11		8	12	7
1972	5	6	8				5	5	6		4	4	3
1973	7	10	11	7	6	9	6	7	12		6	12	9
1974	5	7	9	10	8	5	4	4	8	5	5	8	3
1975	5	12	8	10	4	8	6	5	11	7	8	13	3
5-year total	22*	35*	36*				29	28	48		30	49	25
3-year total	17	29	28	27	18	22	16	16	31		19	33	15
July													
1971	5	5	7				7	6	7		9	8	4
1972	4	5	5				4	6	4		8	6	7
1973	7	11	13	9	6	10	10	7	7		9	11	6
1974	7	12	8	8	5	6	3	3	7	6	7	7	3
1975	7	13	6	10	6	6	5	9	12	8	10	13	7
5-year total	30	46	39				29	31	37		43	45	27
3-year total	21	36	27	27	17	22	18	19	26		26	31	16
August													
1971	4	6	5				4	1	4		2	4	3
1972	5	5	9				7	8	6		7	8	5
1973	6	4	5	4	7	5	5	6	5		4	4	5
1974	7	7	9	9	6	4	7	7	4	7	9	8	6
1975	10	11	7	8	7	5	2	8	7	6	3	8	4
5-year total	32	33	35				25	30	26		25	32	23
3-year total	23	22	21	21	20	14	14	21	16		16	20	15

*4-year, 1972–1975 totals



a. JUNE AVERAGE THUNDER DAYS 1971-1975

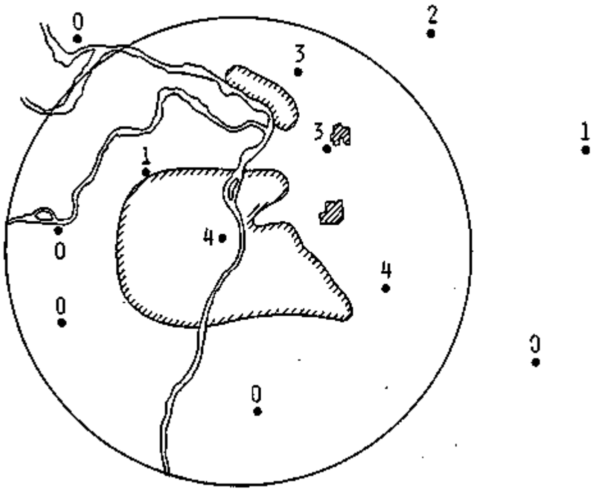
b. JULY AVERAGE THUNDER DAYS 1971-1975



c. AUGUST AVERAGE THUNDER DAYS 1971-1975

d. SUMMER AVERAGE THUNDER DAYS 1971-1975

Figure B-53. Average number of thunderdays for 5-year period



Note: If tied with another station, each counted, and with 15 possible months there were 3 ties, so the total frequency was 18.

Figure B-54. Number of times monthly summer total ranked highest in the network, 1971-1975

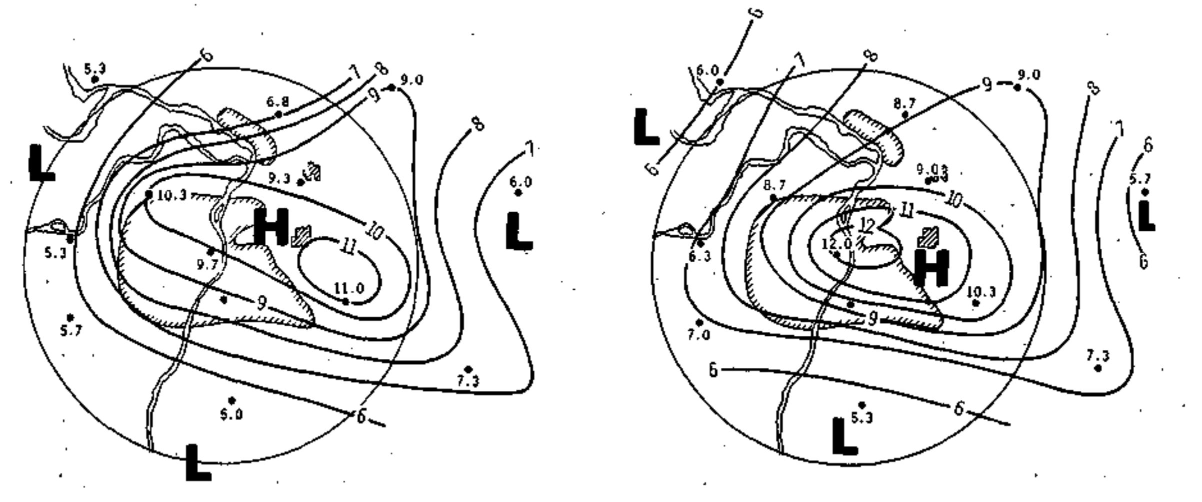
June and July. Basically, low values exist to the north and south of the metropolitan area with a ridge of high values extending along a west-east axis. However, the highest values (the 6.5 and higher averages) are located over the city and extend northeastward to Edwardsville.

The summer average pattern, figure B-5 3d, shows low values in the non-urban effect regions to the southwest and northwest of the St. Louis metropolitan area. Sizeable increases in thunder day frequencies from these rural values of 15 to 18 days occur dramatically, reaching nearly 25 days per summer in central St. Louis. High values extend to the east and northeast from the metropolitan area. To help illustrate that this pattern is not dominated by an excessive number of thunderstorm days in one or two years, figure B-54 is presented. It is based on the number of times monthly thunder day totals at each station ranked highest among all station values in that given month. Here we see that out of 15 possible months (June-August, 1971-1975) the monthly values of the St. Louis University and Scott Air Force Base each ranked first in four months. The Edwardsville and Alton Airport monthly values each ranked highest in three months. It is clear that the peak of monthly thunderstorm activity during 1971-1975 was concentrated in and east of the metropolitan area. The monthly and summer frequencies of thunder days for the 5-year period strongly suggest local effects on thunderstorm frequencies, both over the city and eastward from it.

Thunder in the 1973-1975 period, when there were data from the three far east recorders, was also studied to check the pattern beyond the basic METROMEX circle and to compare it with that in the circle. The monthly and summer average patterns for the 1973-1975 period are exhibited in figure B-55. The June pattern (figure B-55a) closely resembles that for the 5-year period (figure B-53a), but has slightly higher values in the metropolitan area. The far east data indicate a decrease in the urban-related frequencies to the east and southeast (Beaver Creek and Okawville). However, the higher value at Livingston (to the northeast), which matches the high value at Edwardsville, suggests an extension of the urban-related high to the northeast. This extension of high frequency could be related to atmospheric influences of the Alton-Wood River industrial area.

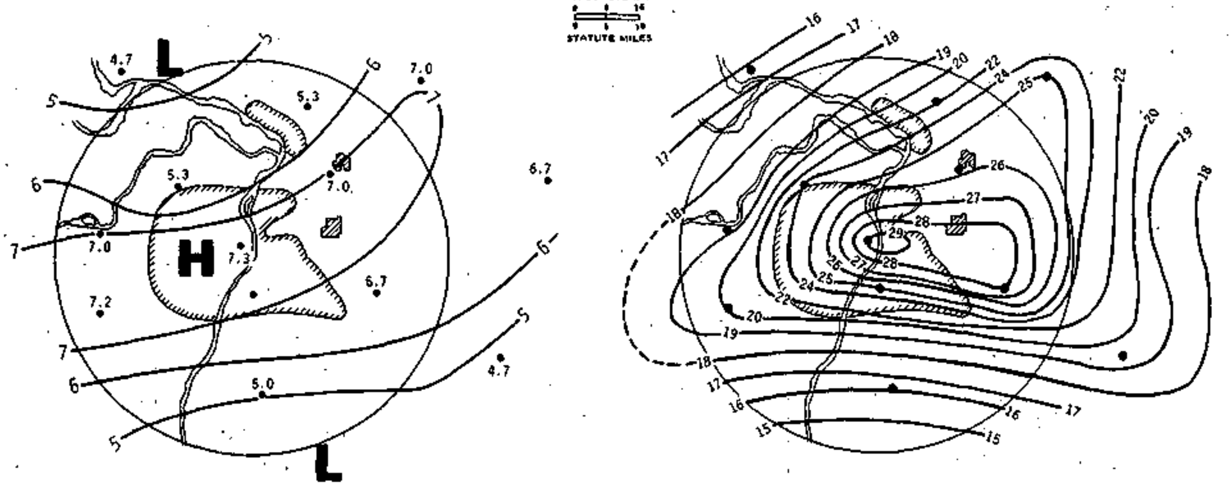
This possibility is further supported by the July pattern (figure B-55b) for 1973-1975. It resembles the 5-year pattern (figure B-53b), but has values in the high frequency area over and east of the city that are somewhat higher than the 5-year totals. The far east values at Beaver Creek and Okawville suggest a considerable diminishment of activity beyond the high that develops over the city and extends about 20 mi (32 km) to the east. The August average pattern for 1973-1975 (figure B-55c) closely resembles the 5-year pattern, having a general west-east ridge with low values north and south of the metropolitan area.

The resulting summer average pattern for the 1973-1975 period (figure B-55d) matches, in general, that shown for the 5-year period (figure B-53d). However, the values in the presumed urban-effect area, the metropolitan area and that immediately east of it, range from 2 to 5 days higher. The 3-year pattern of figure B-55d exhibits major features including 1) the generally low values to the southwest and northwest of the city, 2) high values beginning over the central city and fanning out eastward for 20 mi (32 km) with an extension to the northeast (potentially related to the Alton-Wood River area), and 3) a diminishment of the high urban frequencies 30 to 35 mi (48 to 56 km) to the east. In fact, the averages of the two easternmost stations are of the same general magnitude of those found to the west at Tyson Valley, Spirit of St. Louis Airport, and Pere Marquette, all considered to be unaffected by urban influences. The differences in these frequencies of these 5 stations are due to natural areal variations in thunderstorm activity. Hence, it would appear that the increase in thunderstorm activity of up to 29 days per summer at the St. Louis University station, nearly a 50% increase, is urban-related.



a. JUNE AVERAGE THUNDER DAYS BASED ON 1973-1975

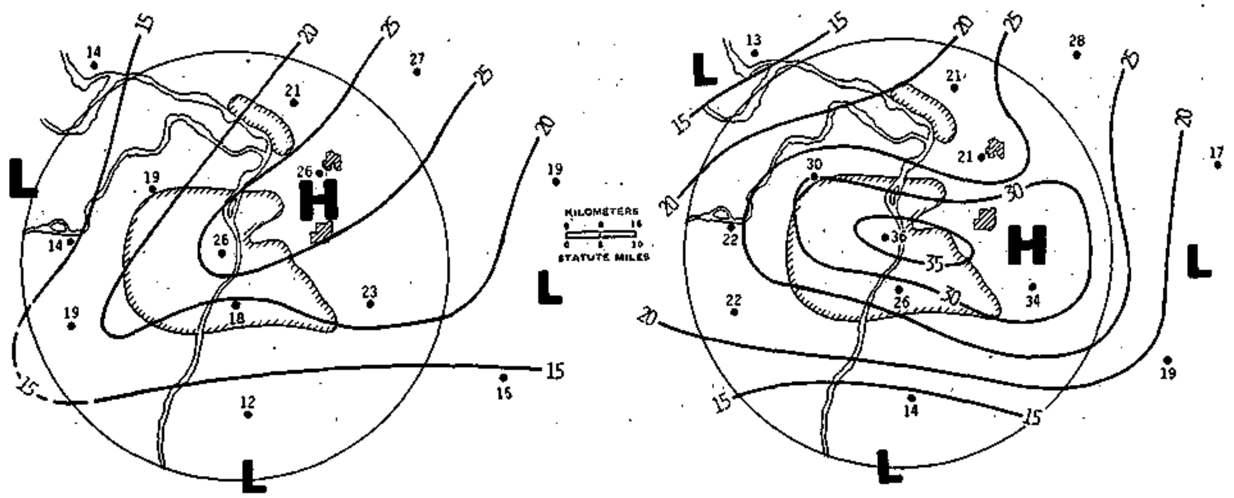
b. JULY AVERAGE THUNDER DAYS BASED ON 1973-1975



c. AUGUST AVERAGE THUNDER DAYS BASED ON 1973-1975

d. AVERAGE NUMBER OF SUMMER THUNDER PERIODS IN 1973-1975

Figure B-55. Average number of thunder days for 3-year period



a. 1974 THUNDER DAYS

b. 1975 THUNDER DAYS

Figure B-56. Summer thunder day patterns for 1974-1975

Table B-28. Comparison of Rural and Urban Summer Average Thunder-Day Frequencies

1971-1975 period

Rural (west)		*Urban (city and east)*	
PMQ	= 16.6	SLU	= 24.6
SUS	= 17.8	SIE	= 23.8
Tyson Valley	= 17.4	BLV	= 25.2
Mean	= 17.3	Mean	= 24.5

Difference [(U-R)/R] = 42%

1973-1975 period

Rural		*Urban (city and east)*	
PMQ	= 16.0	SLU	= 29.0
SUS	= 18.6	SIE	= 25.3
Tyson Valley	= 20.4	BLV	= 28.0
Beaver Creek	= 18.4	Livingston	= 25.0
Okawville	= 19.3	Mean	= 27.1
Mean	= 18.5		

Difference [(U-R)/R] = 46%

The rural summer average values were compared with those considered to be indicative of the greatest potential urban effects. As shown in table B-28, the 1971-1975 values of the three rural stations located to the west of St. Louis were compared with those of the three potentially affected stations in and to the east of St. Louis. The difference in the mean of their averages, 7.2 thunder days per summer, is an urban increase of 42% over the rural thunder days for the 5-year period. Also shown is a comparison for the 1973-1975 period, but using the far east stations in the comparison. Both the rural and urban averages are higher in the 3-year period than in the 5-year period, but the difference between the urban and rural values of 8.6 days per summer represents a 46% urban increase over the surrounding rural values. Thus, it would appear that the urban influence in its major effect area is producing more than a 40% increase in the average number of thunderstorm days.

The summer thunder day patterns for 1974 and 1975 are presented in figure B-56. These patterns are similar to those found for the individual summers of 1971, 1972, and 1973 (Changnon, 1974). In each of the five summers the area of highest thunderstorm frequency *always* included the St. Louis University and Edwardsville stations. In each of the five summers, the lowest thunderstorm values and patterns occurred in the south, west, and northwest portions of the network. Hence, the average patterns for the 3-year (figure B-55d) and 5-year (figure B-53d) periods appear to be "climatologically reliable" and based on a consistent presence of 1) a high frequency in and to the northeast and east of the city, and 2) a low frequency in the rural area to the west of the city.

The frequency of network thunder days in each summer month of the five years is shown in table B-29. This analysis was based on data from the circular METROMEX Network area. These values reveal that the greatest number of thunder days occurred in June, followed by July and then August. Year-to-year variability was not as great in June as it was in July and August when near 2-fold differences existed. Note that August 1973 had experienced only 7 thunder days in the circular area, compared with 18 thunder days during August 1974.

Frequencies of Point Thunder Periods

The automatic audio thunder recording devices allowed definition of discrete periods of thunder, based on at least 2 peals in a 15 minute period and at least 1 hour with no thunder between periods (see table B-22). The thunder periods were defined for 1971-1975 on the basis of the three recorder sites in the circular network (figure B-52), and for 1973-1975 with the same sites plus the three recorder sites located in the far east area. It should be noted that these data do not allow as accurate or detailed pattern analyses as those based on thunder day data.

Table B.-29. Number of Thunder Days in Circular Network Study Area

	June	*July*	*August*	*Summer total*
1971	**17**	**9**	**11**	**37**
1972	**12**	**10**	**12**	**34**
1973	**14**	**14**	**7**	**35**
1974	**12**	**13**	**18**	**43**
1975	**14**	**16**	**12**	**42**
Totals	**69**	**62**	**60**	**191**

Table B-30. Number of Summer Thunder Periods for Each Year

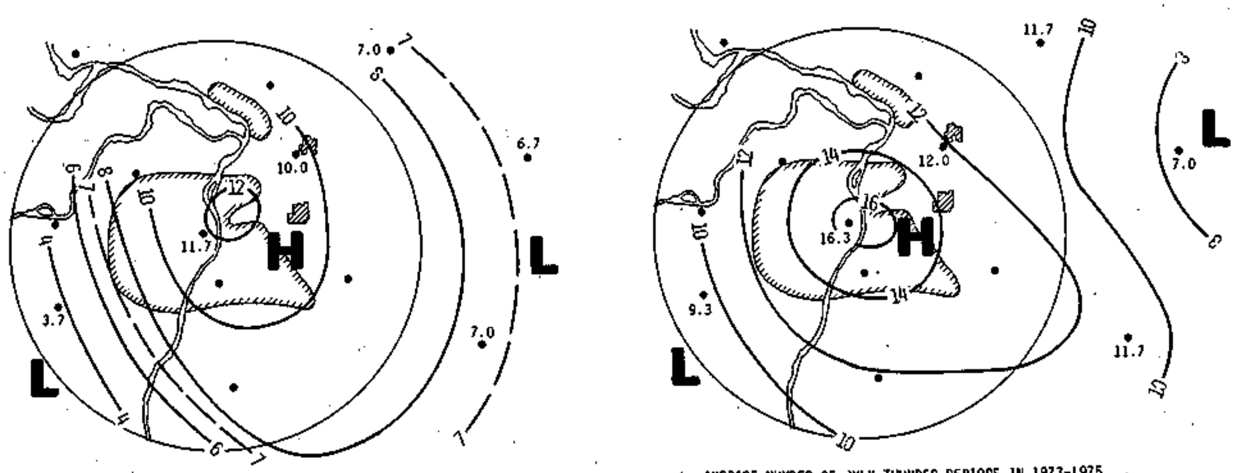
	Tyson Valley (west)	*St. Louis University (city)*	*Edwardsville (east)*	*Livingston (far NE)*	*Beaver Creek (far east)*	*Okawville (far SE)*
1971	**12***	**11***	**17***			
1972	**21**	**22**	**28**			
1973	**20**	**34**	**37**	**25**	**24**	**34**
1974	**21**	**38**	**36**	**34**	**25**	**19**
1975	**26**	**47**	**24**	**28**	**17**	**21**
Totals						
1971–1975	**100**	**152**	**142**			
1973–1975	**67**	**119**	**97**	**87**	**66**	**74**

***No data for June 1–30 and July 1–12**

The number of summer thunder periods for each year at these six recorder sites are listed in table B-30. The 1971 values are not comparable with those of the other years because of the missing data during June and early July 1971. However, comparison of the annual totals from the 1972-1975 period suggests a fair amount of variation between years, particularly at the St. Louis University site. Comparisons of the totals shown in table B-30 reveal considerable regional difference. Tyson Valley, which is a rural west location unaffected by the city, has a value for 1973-1975 of 67 periods, and this compares favorably with the thunder period totals at the far east stations which had values of *66*, 74, and 87. Clearly, the totals at St. Louis University and Edwardsville, in and near the city, are much greater than the rural station totals.

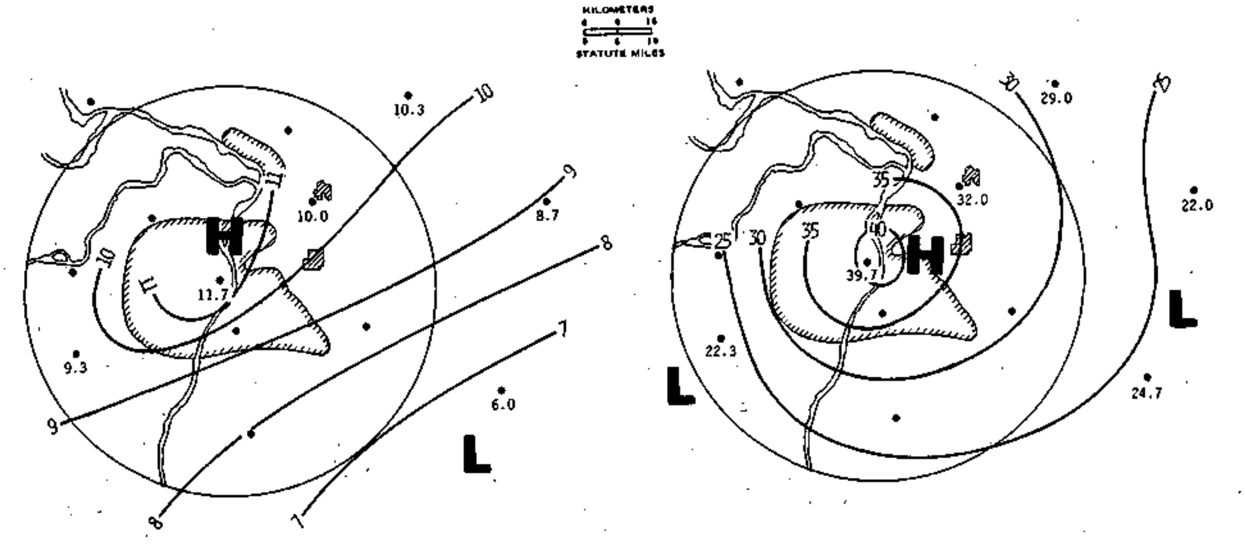
These regional differences are further revealed in table B-31: Here the monthly and summer average number of point thunder periods for the 5-year period at the three recorder sites is shown. These are arranged in the table to illustrate west-to-east variations, and inspection of the June, July, and August totals shows a west-to-east increase. In June, the city and east site averages are equal; in July, the St. Louis University total is greatest; in August, the Edwardsville total is greatest. The resulting summer average totals in table B-31 show a sizeable urban increase. If one assumes that the city and the east values are representative of urban effects, they have an average of 31.5 thunder periods per summer. The difference between that and the rural west site is 10.5 thunder periods. This difference, expressed as a percent of the rural value of 21 thunder periods, indicates a 50% increase in thunder periods. This compares favorably with the 42 and 46% increases shown in table B-28 for the average summer thunder day frequencies.

The average monthly and summer thunder period values for 1973-1975 are plotted in figure B-57. The June pattern (figure B-57a) shows a marked high over the metropolitan area with values greater than 10 thunder periods, as compared to the lower values to the west and east. A similar pattern is evident in July (figure B-57b) with a marked maximum centered over the city and low values again in the rural west and east. These patterns are very similar to those



a. AVERAGE NUMBER OF JUNE THUNDER PERIODS IN 1973-1975

b. AVERAGE NUMBER OF JULY THUNDER PERIODS IN 1973-1975



c. AVERAGE NUMBER OF AUGUST THUNDER PERIODS IN 1973-1975

d. SUMMER AVERAGE THUNDER DAYS 1973-1975

Figure B-57. Average monthly and summer thunder periods, 1973-1975

found for thunder days in June and July (figures B-55a and b). The average thunder period pattern for August (figure B-57c) also shows a high over the city but with more of a west-east elongated pattern with the low values to the south. This pattern also agrees with the average thunder day pattern for 1973-1975 shown in figure B-55c. Clearly, there is a good relationship between the point frequency of thunder days and thunder periods.

The average summer pattern of thunder periods for 1973-1975 (figure B-57d) shows the marked urban increase in values with up to 40 periods over the city. Rural values to the west and east of St. Louis have less than 25 thunder periods.

Table B-32 expresses these monthly and summer thunder period values according to averages calculated for the urban and rural regions. The values of the three sites (St. Louis University, Edwardsville, and Livingston) were averaged to form an apparent urban effect region, and those of the three other sites (Tyson Valley, Beaver Creek, and Okawville) were grouped to form a rural frequency. The average regional values in June show an urban-rural difference of 3.8 thunder periods which indicates a 66% increase for the urban values. The July and August values show 43

Table B-31. Average Number of Point Thunder Periods for 1971-1975 at Three Recorder Sites

	Tyson Valley (west)	*St. Louis University (city)*	*Edwardsville (east)*
June	5	10	10
July	8	13	11
August	8	9	10
Summer	21	32	31

Table B-32. Comparison of Urban and Rural Average Thunder Period Values, 1973-1975

	*Urban**	*Rural***	*U-R*	*(U-R)/R*
June	9.6	5.8	3.8	66%
July	13.3	9.3	4.0	43%
August	10.7	8.0	2.7	34%
Summer	33.6	23.1	10.5	45%

*Includes St. Louis University, Edwardsville, and Livingston

**Includes Tyson Valley, Beaver Creek, and Okawville

and 34% increases, respectively. The summer difference in thunder periods for the 3-year period, 10.5 thunder periods, is a 45% increase over the rural frequency of 23.1 thunder periods. This 45% increase compares well with the 3-year average summer thunder-day increase of 46% shown in table B-28.

Patterns of Thunder Occurrences during Network Thunder Periods

There were 211 network thunder periods during 1971-1975, and these were classified according to four patterns to investigate the general distributional characteristics of thunderstorms in these network thunder (and rainfall) periods.

One class was labeled *widespread* and was based on those thunder periods when all nine stations in the circle recorded thunder. The Cahokia station data for 1974-1975 were not included. The *west-only* classification included an occurrence of thunder at any one or any combination of the following four stations: Pere Marquette, Spirit of St. Louis Airport, Tyson Valley, and Lambert Field without thunder at any other station in the circle and east of these four. The third class was labeled *east-only* and was assigned to those thunder periods when thunder occurred at any one or any combination of the following four stations: Alton Airport, Edwardsville, St. Louis University, and Scott Air Force Base. All other thunder periods which did not fulfill these previous three classifications were labeled as *widely scattered patterns.* A fifth classification was added in the analysis of the 1973-1975 data. It was labeled *far east only* and was based on those thunder periods when any or all of the stations in the far east (Livingston, Beaver Creek, and/or Okawville) were the only stations reporting thunder.

Table B-3 3 summarizes for each year the number of thunder periods within the first four distributional patterns. Inspection of the 5-year totals shows that the widely scattered pattern with 109 thunder periods leads. The east-only patterns occurred in 39 periods, or 18% of the 211 total periods in the 5-year sample. The west-only, representing nonurban conditions, totaled 22 periods, or 10% of the total. Thus, the east-only total minus west-only total, a difference of 17 periods, represented a 77% increase over the west-only value of 22. Comparison of the west-only values and east-only values for each year shows that the east-only totals in every summer exceeded those in the west, indicating a consistent increase and that the sizeable difference was not due to one summer.

The monthly frequencies of the network pattern classifications are presented in table B-34. The monthly totals reveal that July leads with 77 periods, closely followed by June with 72. Inspection of the widespread frequencies shows the greatest number of these events in June, whereas widely scattered thunder situations are most frequent in July. The west-only monthly frequencies are very similar. However, the east-only values are greatest in June and decrease during the summer.

Table B-33. Number of Network Thunder Periods in Summers of 1971-1975 Sorted by Areal Distribution of Thunder Patterns*

	Number per distributional patterns				
	*Widespread at all sites***	*Widely scattered*	*West only*	*East only*	*Total*
1971	11	13	7	11	42
1972	6	18	4	8	36
1973	6	22	3	7	38
1974	8	27	5	9	49
1975	10	29	3	4	46
Totals	41	109	22	39	211
Percent of total	20	52	10	18	100

*Excludes dates of thunder in only far east area

**For all 9 sites (less Cahokia) in circular study area

Table B-34. Number of Network Thunder Periods in 1971-1975 Sorted by Areal Distribution of Thunder Patterns

	Widespread at all sites	*Widely scattered*	*West only*	*East only*	*Far east only**	*Total***
June	18	31	7	16	5	72
July	12	46	7	12	5	77
August	11	32	8	11	8	62
Totals	41	109	22	39	18	211

*For 1973-1975 only

**Total excludes far east values

They remain greater than the west-only values in all three months. The east-only frequencies in all three months closely match the widespread case frequencies. Also shown on table B-34 are the monthly frequencies of the thunder periods defined solely by the far east stations. These show a total of 18 such cases in three years (9 in 1973, 5 in 1974, and 4 in 1975). The greatest frequency occurred in August which had 8 such thunder periods.

If the east-only minus west-only differences reflect urban-related increases, the difference in June of 9 days (see table B-34) represents a 129% increase. The 5-period difference in July represents a 71% increase over the west-only value, and the difference of periods in August represents a 38% increase over the west-only value. These monthly differences exhibit the same general decrease with ,time shown in table B-32 for the point thunder period averages. Both showed the greatest urban-rural difference in June, becoming less in July and even less in August.

TEMPORAL ANALYSES

Duration of Thunder Activity

The analysis of duration of thunder occurrences was based solely on the data from the six audio recorder sites. Data from the observation stations were considered inadequate for these analyses. The duration analyses were based on two definitions of the duration of thunder. First, the point thunder period, a discrete period of thunder activity of any rate of thunder occurrence, was studied. A second, more exhaustive duration analysis was based upon "thunder segments." These are discrete periods, often one or more within a thunder period, each having a rather uniform rate of thunder peals. The "very light" rate was defined as 5 or less peals per hour; the "light" rate as 6 to 11 peals per hour; the "moderate" rate as 12 to 60 peals per hour; and "intense" rate as more than 60 peals per hour. There will be more thunder segments than thunder periods since point thunder periods can and were occasionally composed of two or more segments. For instance, a typical thunderstorm event recorded at a point might start with a very light segment, change to light frequency after 20 minutes, and then change to intense for a period of time. In the 1971-1975 period, the St. Louis University site had 152 thunder periods, but the analysis of thunder rates showed it had 293 thunder (rate) segments.

The various spatial results indicated there were apparently more days and more thunder periods per day in urban areas than in the rural areas. These spatial results were investigated further by a temporal analysis of the point durations to answer the question, "Were the urban increases evident in the duration of thunder?"

Table B-35 presents the total minutes of thunder at the six recorder stations for the 3-year and 5-year periods. The 5-year totals show that the greatest duration of thunder during the five summers occurred at the St. Louis University site which had 21,955 minutes (366 hours) with thunder. This means that thunder was occurring at that site during 3.4% of the total summer time. Values at Edwardsville are slightly less, 18,568 minutes, and the Tyson Valley rural station west of St. Louis had markedly fewer minutes of thunder. Table B-35 also presents the average durations of the thunder periods. For the 5-year period, the longest duration was 144 minutes at St. Louis University, followed by those at Edwardsville and Tyson Valley. The differences in these durations are not great. The St. Louis-Tyson difference (18 minutes) represents a 14% increase in the city value over the rural value.

Also shown in table B-35 are the total durations of thunder for 1973-1975 at the six recorder stations. Quite sizeable differences are apparent with the three largest values being at the three stations (St. Louis University, Edwardsville, and Livingston) which the thunder day and thunder period analyses had indicated were potentially urban affected. These three stations had 3-year totals of thunder minutes that were about two or more times greater than the values of the rural stations (Tyson Valley, Beaver Creek, and Okawville). Comparison of the average durations for the 3-year period of the three urban-effect stations with those of the three rural stations reveals that the urban stations have an average value of 145 minutes as compared to 93 minutes at the rural stations. The resulting difference, 52 minutes, represents a 56% increase over the rural mean of 93 minutes.

The duration study also included analysis of the thunder rate segments, periods of time during thunder periods when a given rate of thunder peals was occurring. The point number of thunder rate segments, sorted by the four classes of thunder rate frequencies, are presented in table B-36. The number of these segments in the moderate and intense classes were summed to enable comparison of the relatively higher rates. The average number of segments in the "moderate plus intense" class for the three urban stations (SLU, EDW, LVT) is 111, compared with an average of 65 for the three rural stations (TYV, BVK, OKV). The resulting difference, 46 segments for the 3-year period, represents an increase of 71% over the rural average. Similarly, the difference between total number of segments of the three urban stations and that of the three rural stations reveals an increase of 50% for the urban stations. An urban area increase in segments is not unexpected since the thunder periods exhibited increases also.

The total duration of thunder in each of the four intensity classes was divided by the number of segments (table B-36) to derive average durations for each of the various thunder rates. These averages are presented in table B-37. Comparison of the values in each rate class, except the very

Table B-35. Duration of Thunder Periods

	1971-1975			1973-1975		
	Total duration, min	*Total thunder periods*	*Average duration, min*	*Total duration, min*	*Total thunder periods*	*Average duration, min*
Tyson Valley	12,637	100	126	6,249	67	93
St. Louis University	21,955	152	144	16,703	119	140
Edwardsville	18,568	142	131	10,335	97	107
Livingston				16,428	87	189
Beaver Creek				5,630	66	85
Okawville				7,431	74	100

Table B-36. Number of Point Thunder Rate Segments, Defined by Thunder Rate Frequencies, During Point Thunder Periods, 1971-1973

	Number of segments per rate class					
	Very light	*Light*	*Moderate*	*Intense*	*Moderate plus intense*	*Total*
Tyson Valley	13	31	26	57	83	127
St. Louis University	52	75	53	76	129	256
Edwardsville	25	43	37	59	96	164
Livingston	39	83	44	65	109	231
Beaver Creek	48	34	17	31	48	130
Okawville	58	57	29	35	64	179

Table B-37. Average Durations of Various Thunder Rate Segments, 1973-1975

	Durations, minutes, for rate classes				
	Very light	*Light*	*Moderate*	*Intense*	*All segments*
Tyson Valley	38	52	61	45	49
St. Louis University	56	68	48	82	65
Edwardsville	44	54	64	81	63
Livingston	48	71	57	95	74
Beaver Creek	49	40	43	48	43
Okawville	46	53	36	49	47
Urban mean*	49	64	56	86	67
Rural mean**	44	48	46	47	46
U-R difference	5	16	10	39	21
(U-R)/R, *percent*	11	33	22	83	46

***Urban mean based on averages of St. Louis University, Edwardsville, and Livingston**
****Rural mean based on averages of Tyson Valley, Beaver Creek, and Okawville**

light class, reveals that the urban stations (St. Louis University, Edwardsville, and Livingston) generally have averages exceeding those of the three rural stations. This is further demonstrated in table B-37 by the differences between the 3-station urban mean values and the 3-station rural mean values. In every class interval, the urban mean exceeds the rural mean. The differences represent an 11% urban increase in the very light rate, 33% in the light rate category, 22% in the moderate rate, and an 83% increase in the intense thunder rate. The mean intense period duration of the urban stations is 86 minutes compared with 47 minutes for the rural stations. The comparison of all segments shows the typical urban-station thunder segment is 67 minutes long compared with 46 minutes in the rural areas, the difference representing an increase of 46% in the urban area.

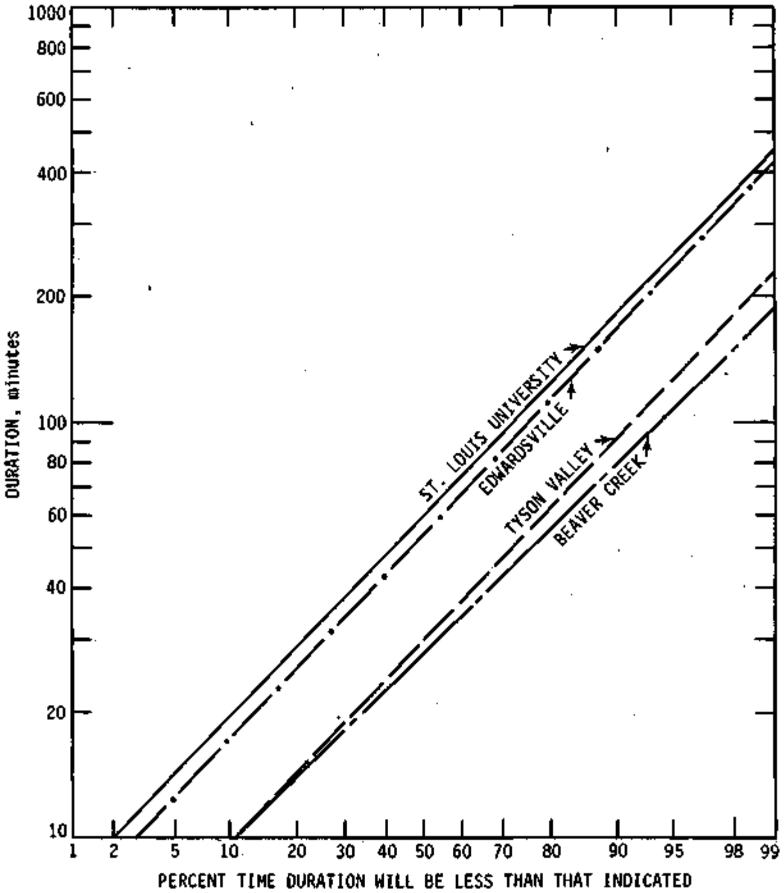


Figure B-58. Distribution of duration in intense thunder segments, 1973-1975

Thus, the duration analysis for thunder activity in the St. Louis area shows that the stations in, east, and northea'st of the city not only had more thunder days and more periods of thunder but also had more thunder segments, and when thunder occurred it had a longer duration, particularly when intense thunderstorm activity was prevalent.

The considerable difference in the duration of the intense thunder segments led to an analysis of the frequency distribution of the durations at four stations, two urban and two rural. The resulting frequency curves appear in figure B-58. This allows for evaluation of the differences throughout the duration spectrum.

As is shown in figure B-58, the durations of the intense segments at St. Louis University and Edwardsville are markedly different from those of the two rural stations, Tyson Valley and Beaver Creek. For instance, 20% of the time intense durations at the rural stations are 13 minutes or less compared with 28 minutes or less at the two urban stations. Similar major differences exist at the longer durations, indicating that the duration and the characteristics of thunder segments are markedly different at locales where the thunder has been potentially affected by the urban-industrial areas.

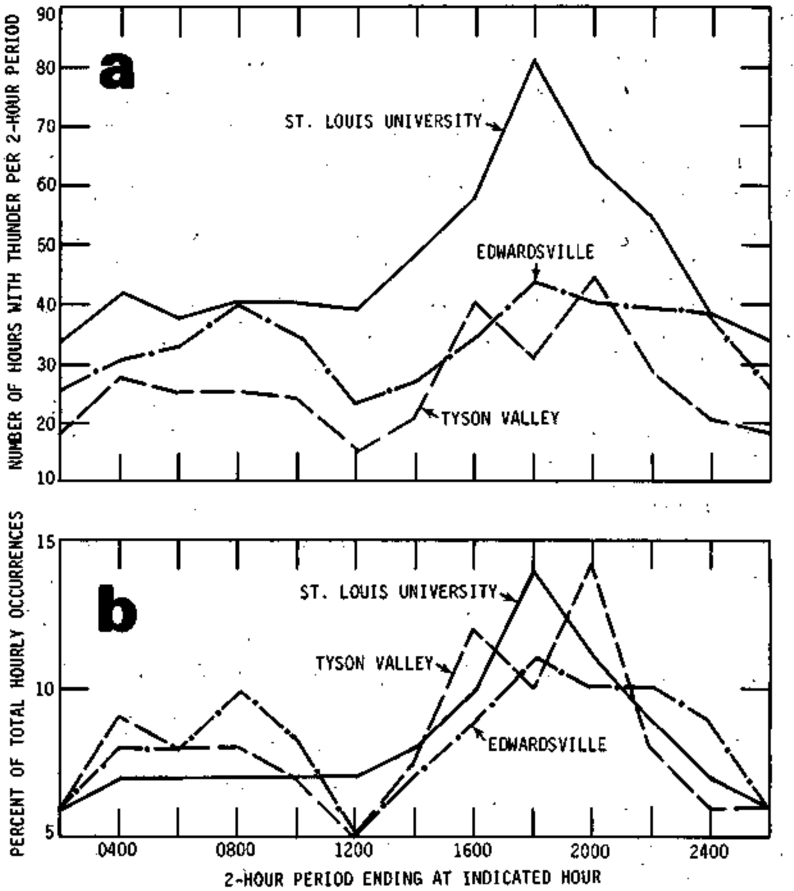


Figure B-59. Diurnal distributions of thunder occurrences, 1971-1975

Diurnal Distributions

The distribution of the thunder occurrences throughout the day, at individual stations and for urban and rural groupings of stations, was studied primarily to examine for the time when urban effects were occurring. One analysis was based on the three recorder stations with data for 1971-1975. The number of thunder occurrences (at any rate) in each clock hour were counted and used to construct figure B-59a. These are 2-hour totals for the three recorder stations in the primary research circle, St. Louis University, Tyson Valley (rural west), and Edwardsville (affected area east). Comparison of the curves in figure B-59a reveals that St. Louis University, which has a higher total number of thunder periods than any other station (table B-30), leads the rural station in Tyson Valley in all hours of the day by sizeable margins. Edwardsville which also has a considerably larger number of thunder periods in the 1971-1975 period than Tyson Valley, also exceeded Tyson Valley in most 2-hour periods. The two stations have comparable values during the peak period of thunderstorm activity, 1400 to 2000 CDT, but in the other 18 hours of the day, including the nocturnal period, Edwardsville values exceed the Tyson Valley values. Notably, both urban-affected stations show a peak during the 1600-1800 CDT period when Tyson Valley showed a recession.

Figure B-59b displays the same values as in B-59a, but expressed as a percent of their individual totals. Comparisons of these "relative values" indicates that the urban effect at the St. Louis station is relatively important in relation to Tyson Valley during the period from 1000 to 1400 CDT. This is a low frequency period at both Tyson Valley and Edwardsville, and this relative increase at St. Louis suggests that thunderstorm activity due to the city initiates earlier in the day. Also, the earlier daily maximum at St. Louis University and Edwardsville is made apparent in figure B-59b. The Edwardsville curve indicates this area east of the city achieves a relatively greater frequency of thunderstorm activity during the evening hours, 2000 to 2400 CDT and then again from 0600 to 1000 CDT, suggesting inducement of nocturnal thunderstorms.

To gain further information on the areal differences in the diurnal distribution of thunder activity, the 1973-1975 period was investigated with data from the six recording stations. The values for each 3-hour period were expressed as a percent of the station totals and appear in table B-38. Inspection of the 3-hour maximum values reveals that the urban stations peak earlier, in the 1500-1800 CDT period, whereas two of the three rural stations peaked in the 1800-2100 CDT period. Also, Edwardsville and Livingston (urban effect) had their minimum values from 0900-1200 CDT, whereas all three of the rural stations (Tyson, Beaver Creek, and Okawville) had their minimum in the 0000-0300 CDT period.

There were sufficient differences between these two groups of stations to develop means of their average percentages. These 3-station urban mean percentages and the 3-station rural percentages appear on figure B-60. Comparison of these relative curves displays the differences in the timing of the maximum values with an earlier peaking at the urban stations. These relative curves also reveal that the urban values, beginning at 2100 CDT, remain relatively higher until 0600. This indicates, as in figure B-59b for Edwardsville, an apparent nocturnal effect related to the urban-industrial effects. Conversely, the rural values are relatively higher from 0600 to 1200 CDT suggesting that the urban-induced conditions may decrease thunder activity. Also, the urban value for 1200-1500 CDT is relatively greater, indicating a more rapid initiation of afternoon thunderstorm activity over the city.

A third investigation of diurnal variations of thunder occurrences was based on the intense thunderstorm rates (peals occurring at a rate of more than 60 per hour). Table B-39 presents the diurnal distribution of the intense thunder activity at the recording stations. Totals of each 3-hour period are expressed as a percent of the stations totals. Comparison of the station values suggests a difference from results revealed in table B-38 and figure B-60. At the three rural stations the maximum 3-hour period of intense activity occurs from 1500-1800, but at two of the three potentially urban-affected stations (Edwardsville and Livingston) the maximum of intense thunderstorm activity occurs three hours later, 1800-2100 CDT. Also there is a difference in the time of the minimums with the rural stations achieving a minimum from 0000 to 0300, whereas two of the urban stations (St. Louis University and Edwardsville) achieved minimum values later in the morning.

Table B-38. Percent of Total Hourly Thunder Occurrences in 3-Hour Periods, 1973-1975, for Each Recorder Site

3-hr period, CDT	St. Louis University	Edwardsville	Livingston	Tyson Valley	Beaver Creek	Okawville
00-03	9	9	11	8	8	6
03-06	10	12	11	10	11	11
06-09	10	11	10	12	14	14
09-12	10	7	9	9	12	10
12-15	13	12	12	12	9	9
15-18	22	18	18	19	22	16
18-21	17	17	18	22	13	21
21-24	9	14	11	8	11	13

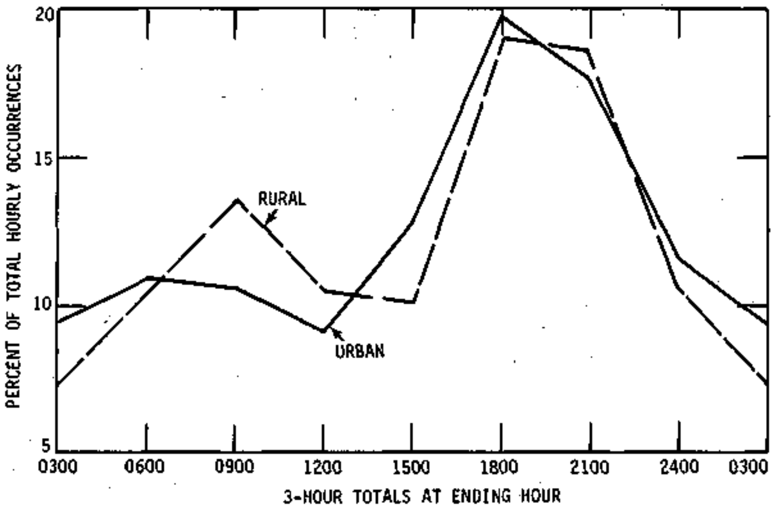


Figure B-60. Diurnal distribution of thunder occurrences at urban (SLU, EDW, LVT) and at rural (TYV, BVK, OKV) stations

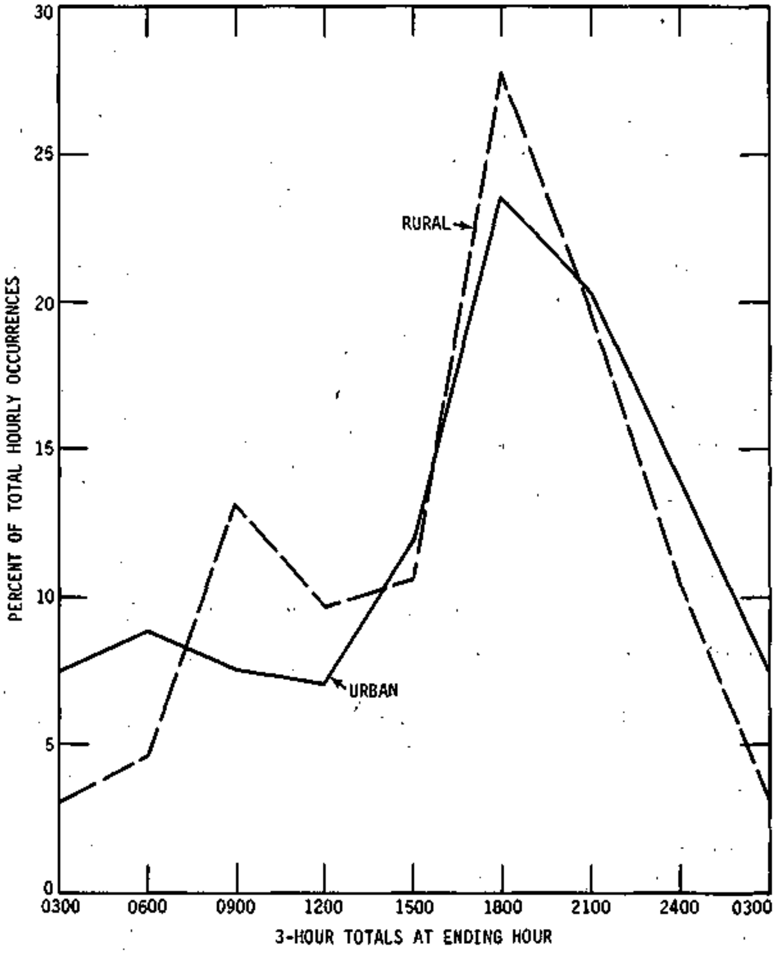


Figure B-61. Diurnal distribution of intense thunder occurrences at urban (SLU, EDW, LVT) and at rural (TYV, BVK, OKV) stations

Table B-39. Diurnal Distribution of Hourly Occurrences of Intense Thunder Periods, by 3-Hour Totals, 1973-1975

3-hr period, CDT	*St. Louis University*	*Edwardsville*	*Livingston*	*Tyson Valley*	*Beaver Creek*	*Okawville*
00-03	7.5	6.9	7.9	2.1	3.8	3.2
03-06	6.3	10.4	9.9	5.2	5.7	3.2
06-09	8.1	5.2	8.9	18.7	7.5	12.9
09-12	9.8	2.3	8.9	11.5	3.9	14.5
12-15	15.0	9.6	11.4	17.7	9.3	4.8
15-18	28.9	21.7	19.3	23.9	34.0	25.8
18-21	15.6	24.3	20.3	12.5	24.5	22.6
21-24	8.7	18.3	13.7	8.3	11.3	12.9

The 3-hour percentages shown in table B-39 for the three potential urban stations were averaged, as were the percentages of the three rural stations, to develop 3-hour urban and rural mean percentages. These mean percentages appear in figure B-61 to facilitate comparison of urban-rural differences in intense thunder activity. Comparison of the two curves revealed that the urban area leads in intense thunderstorm activity from 2100 until 0600 indicating a nocturnal enhancement of intense activity. Conversely, the urban values are less than the rural from 0600 to 1200 suggesting an urban-induced reduction in the morning hours.

SYNOPTIC WEATHER CONDITIONS WITH THUNDER CONDITIONS

Synoptic weather conditions during network thunderstorm periods were investigated to discern those conditions most favorable to the local enhancement of thunderstorm activity. Two analyses were made. The first used the four distributional classes, or patterns of thunderstorm activity across the network, established by spatial analysis. These included network thunder periods when thunder was 1) widespread (at all 9 stations in the circle), 2) in the east only (representing potential urban effect conditions), 3) in the west only (representing occurrences west of St. Louis and without urban effects), and 4) widely scattered conditions when thunderstorm activity did not cover the entire circle and was irregularly distributed so as not to fulfill any of the three previous distributional classes.

Comparison of the 211 network thunder periods with their synoptic weather types, as defined in the synoptic weather section (page 85), revealed that there were seven types associated with the summer thunderstorm activity in the METROMEX Network. Table B-40 displays the number of network thunder periods sorted according to the seven synoptic weather types and to the thunder distributional patterns. For example, there were four thunder periods in the network when thunder was widespread and was produced during cold frontal conditions. Cold fronts accounted for 38 of the 211 thunder periods.

The values appearing in table B-40 were also expressed as a percent of their pattern totals (table B-41) and as percentages of the weather type total (table B-42). Inspection of the percentages for the 41 thunder periods with widespread thunder activity shows these were largely caused by squall line (46%) and squall area (37%) conditions, as would be expected. Widely scattered thunderstorm conditions were produced by all of the seven weather types, but they also were largely produced by squall line and squall area conditions. The 22 west-only cases, a relatively small sample, are shown to be largely related to the squall area conditions with 46% of the total.

Table B-40. Synoptic Weather Types with Network Thunder Periods Classed According to Patterns of Thunder Distribution, 1971-1975

Synoptic weather type	Number per thunder distribution classification					
	Widespread at all sites	*Widely scattered*	*West only*	*East only*	*Far east**	*5-year total**
Cold front	4	18	5	11	2	38
Warm front	0	6	0	2	1	8
Post cold front	0	4	0	1	1	5
Air mass	2	13	5	14	10	34
Squall line	19	29	0	0	0	48
Squall area	15	33	10	7	4	65
Stationary front	1	6	2	4	0	13
Totals	41	109	22	39	18	211

*For 1973–1975 only, and totals exclude these values

Table B-41. Distribution of Network Thunder Patterns with Number by Synoptic Weather Classification Expressed as Percent of Pattern Total

Synoptic weather type	*Widespread at all sites*	*Widely scattered*	*West only*	*East only*	*Total periods*
Cold front	10	17	23	28	18
Warm front	0	5	0	5	4
Post cold front	0	4	0	3	2
Air mass	5	12	23	36	16
Squall line	46	27	0	0	23
Squall area	37	30	46	18	31
Stationary front	2	5	8	10	6
Totals	100	100	100	100	100

Table B-42. Distribution of Synoptic Weather Classes with Number of Network Thunder Pattern Expressed as Percent of Weather Type Total

Synoptic weather type	*Widespread at all sites*	*Widely scattered*	*West only*	*East only*	*Total*
Cold front	11	47	13	29	100
Warm front	0	75	0	25	100
Post cold front	0	80	0	20	100
Air mass	6	38	15	41	100
Squall line	40	60	0	0	100
Squall area	23	51	15	11	100
Stationary front	8	46	15	31	100
Network average	20	52	10	18	

The east-only thunder periods, with a total of 39 cases, show a percentage distribution (table B-41) indicating relatively high values for cold front and air mass conditions.

The percentages presented in table B-42 allow a relative comparison of the distribution within the synoptic weather types. Inspection of the cold front values reveals that cold fronts were relatively frequent in the scattered and the east-only patterns. Twenty-nine percent of the cold frontal cases were in the east-only category, compared with 13% in the west-only. The warm front and post cold front types, both relatively small samples of 8 and 5 cases, respectively, had all their occurrences in the widely scattered and the east-only categories. The air mass percentages in table B-42 reveal that these conditions were not frequent when widespread thunder existed. However, the air mass conditions were relatively important in the west-only and were very frequent with the east-only with 41% of all air mass conditions occurring with the east-only distribution.

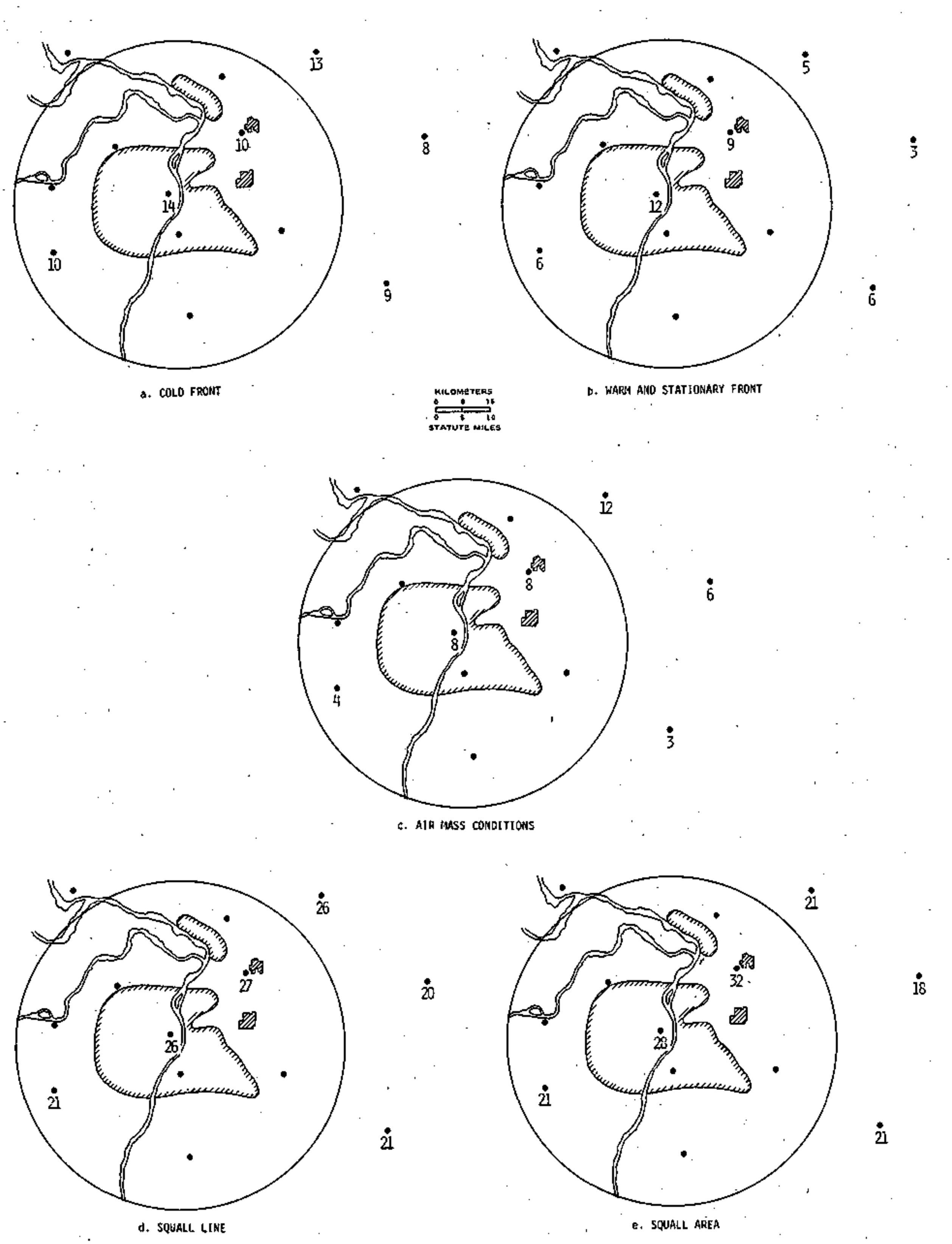
As was seen in table B-41, the squall line and squall area cases in table B-42 are largely concentrated in the widespread and scattered conditions. Stationary front conditions, although a small sample of 13, are relatively important in the scattered and east-only patterns.

Comparisons of the frequencies in the synoptic classes for the west-only and the east-only stations help point to the synoptic conditions when potential urban effects exist. Inspection of their percentages in table B-41 reveals an apparent urban inducement of thunderstorm conditions during 1) cold front conditions (28% to 23%), and 2) air mass conditions (36% to 23%). The east-only also shows slightly larger percentages for warm front, post cold front, and stationary fronts, but these differences are minor. The fewer east-only cases in the squall area conditions suggest urban diminishment of thunder activity in these conditions.

Thunder periods during 1973-1975 at the six thunder recording stations were classified according to the synoptic weather conditions they were associated with. The frequencies at each of these six stations and for five weather types are shown in figure B-62. The cold front pattern has some suggestion of urban effects with the highest value, 14 thunder periods, occurring at St. Louis University site, and with a second highest value at Livingston, also considered a potentially urban affected site. The warm front and stationary front values were combined in this analysis because of the similarity in their general atmospheric conditions during summer precipitation periods and because their samples were small. The resulting frequencies (figure B-62b) show a very distinct localized maximum over and just beyond the city. The air mass frequencies (figure B-62c) also indicate a very distinct urban-industrial maximum with the highest level at Livingston which may reflect influences on storm activity by the Alton-Wood River industrial area. The squall line frequencies (figure B-62c) reveal that the three potential urban sites (St. Louis University, Edwardsville, and Livingston) all have higher totals than the three unaffected rural sites. Importantly, the fifth, and last, major synoptic case analyzed, squall areas (figure B-62e) also exhibit an apparent urban effect, although it is more localized and centered on St. Louis and Edwardsville.

The findings in figure B-62 thus suggest existence of urban effects in the thunder periods in all synoptic classes. The effect patterns tend to be more localized to St. Louis with the warm-stationary front and squall area cases. This could suggest shorter lived affected storm activity which does not extend to Livingston, or that the Alton-Wood River effects are small or nonexistent during these atmospheric conditions. Conversely, the frequencies for air mass conditions and squall line conditions suggest an extension of the inadvertent effect to Livingston, as well as an effect over the city, indicating potential effects from Alton-Wood River, combined with a northeasterly extension of affected storm activity.

Comparison of the three urban-effect stations (St. Louis University, Edwardsville, and Livingston) and their mean value with those of the three rural stations allows a calculation of their difference for each synoptic class. These differences, expressed as a percent of the rural value, suggest the following urban-related increases: cold front = +35%, warm-stationary front = +74%, air mass conditions = +116%, squall line conditions = +29%, and squall area = +35%. Thus, during all synoptic weather conditions, the point thunder and period results suggest some form of localized enhancement of thunderstorm activity.



a. COLD FRONT

b. WARM AND STATIONARY FRONT

c. AIR MASS CONDITIONS

d. SQUALL LINE

e. SQUALL AREA

Figure B-62. Thunder period frequencies by synoptic weather types, 1973-1975

SUMMARY

Results of the various comparisons of potential urban-related thunderstorm characteristics and rural thunderstorm characteristics are summarized in table B-43. The various urban-rural comparisons between summer thunder days, summer thunder periods, east-only versus west-only thunder patterns, the durations of thunder periods, and areal variations with all primary synoptic weather types indicate *urban-related increases in all cases*. These increases range from a low of 11% for the very light thunder rates up to 116% for the urban versus rural differences in air mass thunder periods. The total lack of decreases in any of the urban-related thunderstorm criteria strongly suggests that there were major urban effects to increase thunderstorm activity.

Thunderstorm characteristics appear to be affected by the St. Louis urban-industrial areas in every conceivable way. In the urban area and to the east and northeast of it, there were more thunder days, more periods of thunder, longer periods of thunder when storms occurred, and more frequent and longer periods of intense thunderstorm activity.

These increases in thunderstorm activity occurred in all three summer months, but were greatest in June and least in August (table B-43).

The diurnal distributions of the urban thunderstorm conditions suggested that the urban effects existed in all hours, but were relatively greatest in the 1000 to 1400 CDT period, indicating urban influences help get thunderstorm activity started sooner than that in rural areas. Over the city and in areas beyond the city, the urban effects also lead to greater thunderstorm activity at night.

Table B-43. Urban-Related Increases in Thunderstorm Characteristics

	Increase, (U-R)/R, percent		
Summer Thunder Days			
Urban region vs rural region, 1971-1975	42		
Urban region vs rural region, 1973-1975	46		
Summer Thunder Periods			
Urban region vs rural region, 1971-1975	50		
Urban region vs rural region, 1973-1975	45		
Pattern Frequency			
East-only vs west-only, 1971-1975	77		
Durations of Thunder, Summer			
Periods at urban (3) stations vs rural (3) stations, 1973-1975	56		
Urban vs rural for very light thunder rates, 1973-1975	11		
Urban vs rural for light thunder rates, 1973-1975	33		
Urban vs rural for moderate thunder rates, 1973-1975	22		
Urban vs rural for intense thunder rates, 1973-1975	83		
Synoptic Weather Conditions and Summer Thunder			
Urban vs rural thunder periods for cold fronts	35		
Urban vs rural thunder periods for warm-stationary fronts	74		
Urban vs rural thunder periods for air mass	116		
Urban vs rural thunder periods for squall lines	29		
Urban vs rural thunder periods for squall areas	35		
	June	*July*	*August*
Monthly Differences			
Average point periods, urban vs rural	66	43	34
East-only vs west-only network thunder periods	129	71	38

The intense thunderstorm frequencies reveal a depression in the urban storms during the 0600 to 1200 CDT period suggesting urban effects produced decreases at that time.

The synoptic weather analyses indicated that the conditions most favorable for urban-related thunderstorm increases included cold front, warm front, and air mass types. However, the point thunder period results suggested the presence of the urban effects during squall line and squall area conditions (table B-43). The more localized nature of the thunder increases in squall area, cold front, and stationary front conditions suggests a minimal effect from the Alton-Wood River industrial area. The more widespread enhancement evident in the air mass and squall line conditions suggests enhancement by Alton-Wood River industrial area, as well as by the St. Louis area.

STUDIES OF URBAN EFFECTS ON HAIL CHARACTERISTICS IN METROMEX

Stanley A. Changnon, Jr.

INTRODUCTION

One aspect of the METROMEX studies by the Water Survey was an investigation of hail characteristics in and around St. Louis to determine whether the frequency and characteristics of hail were altered by urban-industrial factors. Climatic studies of local historical data had indicated a localized increase of 150% in the number of days with hail during the 1949-1968 period (Huff and Changnon, 1973). METROMEX data for the 1971-1972 period indicated an 80% increase in hailfall frequencies in a fan-shaped area extending from 5 to 20 mi (8 to 32 km) east of St. Louis (Huff, 1973). Historical crop-hail insurance records substantiated these findings, with a pattern of loss in the area showing a maximum located 10 to 20 mi (16 to 32 km) east-northeast of St. Louis (Changnon, 1976).

The goals of the hail-focused research were 1) to delineate any anomalies in surface hail including its frequency, duration, and intensity, and 2) to ascertain those conditions when such hail anomalies occurred. Another difficult goal sought was to define the causes for any hail anomalies. This goal could only be resolved through a comprehensive analysis of all urban factors and all weather and precipitation data, not just the hail data alone.

The primary area of study in the 5-year field program was the circular network area of 2200 mi^2 (5700 km^2). Each of the 225 recording raingage sites in the network also had a hail sensor, labeled a hailpad, to sense hailstones. A careful areal and temporal delineation of hail over such a wide area necessitates a large number of hail sensors since hail is such a small-scale phenomenon (Changnon, 1970). In the last three years of METROMEX (1973-1975), hailpads were installed at several raingages in the extended network area to the northeast of the circle.

This section of the report initially describes the sources of hail data and the types of analyses performed. The next portion represents network statistics for the years 1974-1975. Detailed presentations of data for these two summers complete the publication of detailed hail data already available for 1971 and 1972 (Huff, 1973), and for 1973 (Huff, 1974). The next three portions focus on the hail results for 1971-1975, treating the hail information for the entire network, information derived from the point hail data, and the hailstreak information for the 5-year period.

DATA AND ANALYSIS

Most of the hail data investigated were obtained from 219 hailpads with one located at each of the recording raingage sites in the circular study area. Each hailpad consisted of a 1-foot square (30 X 30 cm) polystyrene pad (1 inch or 2.5 cm thick) wrapped in aluminum foil and held horizontally in a metal frame (Towery and Changnon, 1976). The number and sizes of hailstorms were determined for each hailfall, and the impact energy of hail was calculated from the size-frequency information. The time of the hail and its duration at each site was obtained from the adjacent recording raingage. Each gage had been modified so that hail could fall into the bucket causing a "spike" on the recording chart for each stone (Changnon, 1966). Added hail information was obtained from field observers and hail insurance recprd.s. In general, hailpads were changed by field personnel one or two days after each hailstorm to minimize uncertainties arising from repeated hailstorms at a point.

The classification of various hail characteristics for this study was based on earlier stated definitions (Changnon, 1970). Starting with hail at a point, a period of semi-continuous hail falling from a single storm passing over that point was defined as a "hailfall." It generally lasts only a few minutes, but occasionally for 10 to 20 minutes. In a hailfall, hail generally falls continuously although there may be up to 1 minute between hailstones. In the analysis of each hailfall, we determined the time of occurrence, duration, number of hailstones, impact energy, largest hailstone size, and amount of rain in the storm that produced the hail.

The network-focused analysis of hail-producing conditions was performed on the basis of the objective rainstorm periods. These were periods of precipitation on the network associated with given synoptic weather conditions such as cold fronts or squall lines. All hailfalls associated with a given objective rainstorm period (there could be more than one such period in a day) were defined as "hail periods." These were identified by plotting all the hailfalls and their times on the individual rainstorm maps. The hail periods were investigated according to the synoptic weather conditions producing the hail along with the identification of the largest hailstone measured during the period and the number of points with hail classified according to their occurrence in the western half of the network or in the eastern half.

Further, more complicated analyses of hail periods focused on individual hailstorms. Hailfalls plotted on each hail period rainstorm map were studied to detect coherent temporal relationships between hailpad sites. This involved knowledge of raincells and radar echo data for each period to determine the likely motion of hail cells within storm cells. Inspection of the temporal data, in concert with the associated storm cell motion, allowed delineation of "hailstreaks."

A hailstreak is defined as an area of continuous hail production having space and time continuity. It could be defined by data at only a point (if no surrounding sites had hailfalls) or by many hailpad sites. Hailstreaks thus represent, at the surface, an entity of hail (hail cell) produced in a thunderstorm. For each hailstreak, its maximum width, area, duration, average energy, average number of stones per square foot, maximum hailstone diameter at any one site, and mean rainfall were determined on the basis of data for all hailpad sites in the streak. If the hailstreak was defined on the basis of only one hailpad, no attempt was made to estimate the hailstreak duration, length, width, or area. These values for hailstreaks delineated by two or more sites are generally suspected to be underestimates of the true streak values.

An important aspect of the hailstreak analysis related to the determination of whether a hailstreak occurred with a storm, or raincell, that was potentially affected by the urban area or with a storm that was clearly not affected by the urban area. An affected storm was defined as one that passed over or initiated over the urban area. This manner of delineation of potential effect and no-effect hailstreaks contains assumptions and tends to be biased. Clearly, certain storms that did not pass or initiate over the urban-industrial areas of St. Louis or Alton-Wood River could be affected by urban-industrial influences in a plume from the city, and no-effect classified hailstreaks could reflect potential urban effects. Furthermore, this definition assumed that all raincells passing over or initiating over the urban-industrial areas have some potential urban effect. It is believed that the assumptions involved in this urban effect classification tend to underestimate, if anything, potential urban effects.

A major feature of the ensuing hailstreak analysis, as well as that for point hailfall data and hail period data, was a focus on their diurnal distribution and their association with synoptic weather conditions. Such analyses were performed to reveal the types of conditions when urban effects on hail were most prevalent.

NETWORK HAIL STATISTICS FOR 1974 AND 1975

The 1974 and 1975 hail data are summarized in tables B-44 and B-45. The information is presented on a hail period basis. For example, on table B-44, we see that a hail period occurred on 6 June 1974 with the first hail at 0620 CDT and the last hail at 0635 CDT. It was produced by squall area conditions and the largest hailstone anywhere in the network was 0.91 inch (2.31 cm) in diameter. Three points (hailpads), all located in the eastern half of the network, had hailfalls and these data defined three hailstreaks in that period. All streaks were classified as being urban affected. The average impact energy of the three hailstreaks was 0.93 ft lbs/ft^2 (1.26 J/0.1 m^2).

Inspection of table B-44 shows that there were 20 hail periods in 1974 with 7 in June, 6 in July, and 7 in August. In 4 of the 20 periods, hailstones exceeded 1 inch (2.54 cm) in diameter and in most hail periods stones exceeded 0.5 inch (1.27 cm) in diameter.

Comparison of the east versus west distributions of hailfalis is informative. For each hail period, the number of points with hail west of a north-south line through the center of the network (St. Louis) and the number east of this line were determined. This simple approach to regionally separating potential urban-effect hailfalis from potential no-effect hailfalis shows for 1974: 1) greater frequency in the west in five periods, 2) two periods when the values were equal, and 3) the total in the eastern half was larger in 13 periods. The totals for the 1974 summer show the preponderance of hailfalis in the eastern half of the network with an average of 15 per hail period in the east versus 8 per period in the west. The east versus west ratio for 1974 was 1.8 (298/161). East versus west ratios in prior years had been 1.7 in 1971 (31 versus 18), 2.3 in 1972 (75 to 32), and 1.7 in 1973 (127 to 74).

Another way to evaluate for urban effects during hail periods is to compare frequencies of effect and no-effect hailstreaks. Comparison of these values in table B-44 reveals that in 11 hail periods the number of effect streaks exceeded the no-effect frequency and in 9 hail periods the no-effect exceeded the effect frequency of hailstreaks. On 5 hail periods only effect hailstreaks occurred, and all hailstreaks were no-effect in only 2 periods. The 1974 totals (table B-44) indicate an average of 6 effect streaks per hail period compared with 5 hailstreaks for the no-effect cases, indicating a slight increase in the number of effect cells. This difference is relatively greater when one considers the fact that on any given day, the area swept out by raincells (storms) classed as urban-affected is almost always a much smaller area than the no-effect area of the circle. In general, the total area of potential effect was 20 to 30% of the entire circular area. Thus, there is a much greater chance in any given period for no-effect cells to be sampled. The difference in the number of periods when all streaks were effect (June 6 and July 8, 9, 12, and 15) and the number when only no-effect hailstreaks occurred (July 14 and August 14) indicates 2.5 times more hail periods potentially due to urban conditions.

Another way used to compare effect hailstreaks with no-effect hailstreaks on the 20 hail periods in 1974 was by study of their average energy values shown in table B-44. Comparisons were based on conditions when both effect and no-effect hailstreaks occurred (13 periods of the 20). The average energy of the effect hailstreak exceeded that of the no-effect streaks on 9 periods,

Table B-44. Summary of 1974 Network Hail Data

Hail period	Network period of hail time, CDT Begin	End	Synoptic weather type	Largest hailstone diameter in.	Number of points with hailfalls West*	East*	Hailstreaks classed by urban effect Effect	No effect	Average point energy (ft lbs/ft²) in hailstreaks (network) Effect	No effect
6/6	0620	0635	Squall area	0.91	0	3	3	0	0.93	none
6/9	0310	0345	Squall line	0.79	3	11	7	4	0.30	0.28
6/13	1935	2140	Squall area	0.87	11	1	1	9	0.85	0.46
6/14	1350	1450	Squall area	0.40	6	4	1	6	0.20	0.10
6/14-15	1650	0030	Squall line	1.50	29	100	17	14	1.53	0.55
6/19	0500	0718	Squall line	0.47	10	10	5	9	0.04	0.03
6/22	0155	0915	Squall area	1.60	46	60	21	13	2.17	2.34
7/8	1715	1730	Squall area	0.74	0	3	3	0	0.82	none
7/9	1950	2048	Squall area	0.66	0	6	5	0	0.22	none
7/12	1505	1621	Warm front	0.71	0	6	5	0	0.30	none
7/14	1800	1812	Squall area	0.97	3	0	0	1	none	3.36
7/15	0207	0215	Cold front	0.35	2	0	2	0	0.02	none
7/28	0500	0820	Squall area	0.67	7	7	1	6	0.09	0.34
8/2 (am)	0200	0620	Stationary front	0.56	4	6	1	4	0.01	0.12
8/2 (pm)	1345	2008	Cold front	1.19	19	44	17	18	0.85	0.30
8/9	1330	1524	Squall area	0.70	1	5	4	1	0.38	0.24
8/13	1025	1321	Squall line	0.77	15	14	7	6	0.32	0.58
8/14	1740	1920	Stationary front	0.62	0	3	0	2	none	0.46
8/17	1345	1835	Stationary front	1.12	4	5	2	3	4.10	1.91
8/31	1910	2025	Cold front	0.77	1	10	9	2	1.93	0.53
Totals					161	298	111	98	15.06	11.60
Means					8	15	6	5	0.84	0.77

*Refers to west and east halves of network circle

Table B-45. Summary of 1975 Network Hail Data

Hail period	Network period of hail time, CDT Begin	End	Synoptic weather type	Largest hailstone diameter in.	Number of points with hailfalls West*	East*	Hailstreaks classed by urban effect Effect	No effect	Average point energy (ft lbs/ft²) in hailstreaks (network) Effect	No effect
6/5	0912	0920	Squall area	0.52	0	1	0	1	none	0.31
6/14-15	2325	0035	Squall line	0.74	6	10	7	6	0.48	0.42
6/16-17	2035	0255	Squall area	1.71	17	13	9	17	2.16	0.27
6/20	1545	2046	Squall line	0.92	12	13	11	7	3.19	1.12
6/23	1510	1520	Squall line	0.40	1	3	1	2	0.11	0.01
6/24	1945	1955	Air mass	0.46	3	0	0	1	none	0.11
6/25	1210	1618	Squall area	0.62	3	0	1	2	0.44	0.14
6/26	1230	1701	Squall area	0.81	3	5	2	6	1.14	0.36
7/5-6	1515	0739	Squall line	1.14	31	29	23	29	0.37	0.54
7/12	1250	2010	Cold front	0.84	6	5	2	5	4.34	0.73
7/13-14	1405	2147	Squall area	0.61	4	15	12	4	0.43	0.35
7/17	1300	1521	Squall line	0.91	3	3	2	2	5.16	2.95
7/18	1205	1415	Squall area	1.80	4	1	1	4	0.35	1.50
7/19	1347	1515	Squall area	0.67	8	1	2	5	0.60	2.02
7/23	1040	1455	Squall area	0.93	9	6	0	14	none	0.76
7/30	1310	1920	Air mass	0.56	2	3	3	2	0.09	0.22
8/17	1530	1705	Stationary front	1.06	7	3	2	5	2.92	2.83
8/29	1430	1604	Squall line	0.71	1	4	4	1	0.26	0.01
Totals					120	115	82	113	22.64	14.65
Means					7	6	5	6	1.51	0.81

*Refers to west and east halves of network circle compared with 4 periods where the no-effect energy values exceeded the effect values. Hence, there is a strong indication of greater energy, or hail intensity, produced in the urban-affected hailstreaks. This is also reflected in the 1974 means calculated for the effect and no-effect hail streaks of 1974. The effect mean value is 0.84 ft lbs/ft^2 (1.14 J/0.1 m^2) compared with 0.77 (1.04) in the no-effect hailstreaks.

Similar summarized hail period data for 1975 are presented in table B-45. There were 18 hail periods in 1975 with 8 in June, 8 in July, and only 2 in August. Hailstones exceeding 1 inch (2.54 cm) in diameter occurred in 4 periods, and as in 1974, maximum hailstone sizes exceeded 0.5 inch (1.27 cm) in most of the 1975 hail periods. Comparison of the frequencies of hailfalls on the eastern half of the network with those on the western half shows nearly equal numbers, 115 to 120; 1975 was the only year in the five studied when the west-half frequency exceeded the east-half frequency. Comparison of the east versus west frequencies for the 18 periods show that in 9 periods (50%), the total in the west exceeded that in the east, whereas on 8 days the east total was greatest. The ratio of east to west in 1975 was 0.96. East-to-west ratios in prior years were 1.7 in 1971, 2.3 in 1972, 1.7 in 1973, and 1.8 in 1974.

Further comparison of the hail periods in 1975 was based on the frequencies, of effect and no-effect hailstreaks. Totals shown in table B-45 reveal 113 no-effect streaks occurred compared with 82 effect streaks. This made 1975 the only year of the five-year METROMEX sample when the number of effect streaks did not exceed the no-effect total. There were no days when only effect streaks occurred, but there were 3 periods when only no-effect streaks prevailed. Comparison of the 18 hail periods in 1975 on the basis of which class was predominant showed that on 5 periods the effect frequency exceeded the no-effect, whereas on 12 periods the no-effect frequencies exceeded the effect frequencies.

A final comparison of the 1975 hail periods was performed on the basis of the average streak energy values shown in table B-45. Totals indicate a sizeable difference with a mean of 1.51 ft lbs/ft^2 (2.05 J/0.1 m^2) for effect hailstreaks compared with 0.81 (1.1) for the no-effect hailstreaks. This indicates an 86% difference (increase) in the energy of the effect hailstreaks.

Patterns based on the point hail frequencies of 1974 and 1975 appear in figures B-63 and B-64. Comparison of these reveals that there was much more hail in 1974 than in 1975. Four similar pattern features appear on both maps. Relatively high frequency areas are located 1) just east of a line between St. Louis and Alton-Wood River, 2) 10 to 15 miles east of St. Louis in a general north-south oriented line, and 3) northwest of St. Louis in the river bottomlands. , The fourth common feature is the major low frequency area west and southwest of the St. Louis area. These same four features were evident in at least two of three years of the 1971-1973 period.

Both years had sizeable areas with no hailfalls (the St. Louis city summer average is 0.4 hail days, or about 1 per 2 years). The highest point value of hailfalls was 5 in 1974, at points located northwest and east of St. Louis. Maximum point values in 1975 were 4 hailfalls, also found at points northwest of St. Louis and east of St. Louis.

The hail patterns for 1974 and 1975 both suggest local enhancement of hail by St. Louis and by the surface effects produced by the warm and moist river bottomlands.

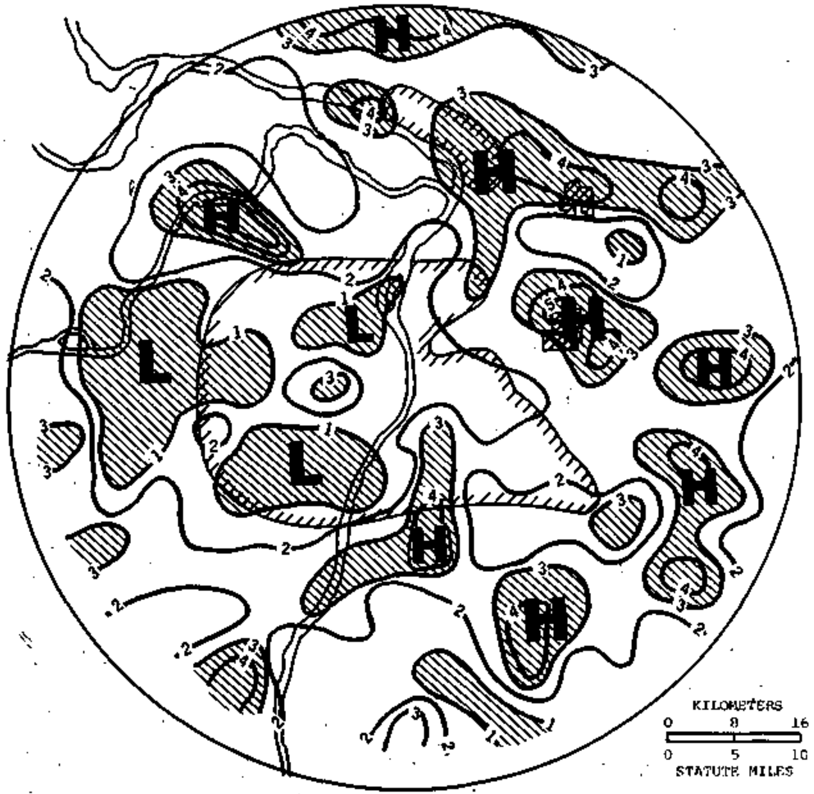


Figure B-63. Hailfall pattern in 1974

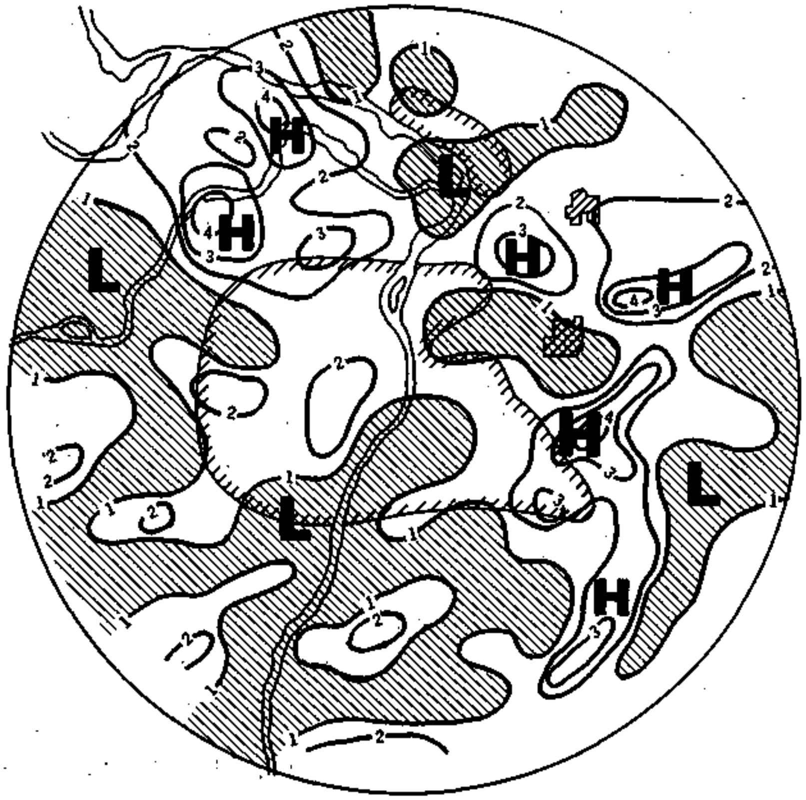


Figure B-64. Hailfall pattern in 1975

HAIL NETWORK FINDINGS

The 1971-1975 statistics on network hail periods were examined in various ways. Table B-46 presents the frequency of hail periods by month and year for the 5-year period. Considerable year-to-year variation exists, ranging from a low of 10 network hail periods in 1971 to a high of 20 in 1974 with a 5-year total of 83. The monthly totals reveal that hail was most prevalent in June, decreasing with time during July and August. This is typical of the historical distribution of hail in the area which peaks in the spring months and declines through summer (Changnon, 1977).

An important analysis of the network hail periods related to the synoptic weather conditions associated with the occurrence of hail. Table B-47 presents the frequency of synoptic weather conditions in each of the five summers for all the network rain periods and all the network hail periods. Table B-48 is a 5-year summary of the values presented in table B-47. The values in both tables clearly reveal that the most unstable weather conditions, squall lines and squall areas, were the prime producers of network hail periods, 57 of the total 83.

Table B-46. Number of Network Hail Periods

	June	*July*	*August*	*Total*
1971	**4**	**4**	**2**	**10**
1972	**5**	**2**	**9**	**16**
1973	**8**	**7**	**4**	**19**
1974	**7**	**6**	**7**	**20**
1975	**8**	**8**	**2**	**18**
Totals	**32**	**27**	**24**	**83**

The percentages in table B-48 reveal that these two weather conditions accounted for nearly 70% of all the hail periods. The percentages show that 58%, 29 of the 50 squall line cases in the METROMEX network, produced hail. Other high percentages shown in table B-48 included those from squall areas, warm fronts, stationary fronts, and cold fronts. The high value of 40% for low conditions is interesting, but the small sample may negate any significance in this value. It is noteworthy that the air mass conditions which lead the network with 90 rain producing conditions produced only 3 of the 83 hail periods in the network. Although evidence was seen in the thunderstorm studies of considerable urban effect on thunder activity during air mass conditions, instabilities were often not sufficient in air mass cases to produce hail.

Tables B-44 and B-45 presented a number of effect and no-effect hailstreaks for 1974 and 1975, respectively. Similar counts of effect and no-effect hailstreaks in the prior three years are presented in table B-49 along with values for 1974-1975. These values show that in all years except 1975, the effect frequency exceeded the no-effect frequency. The 5-year totals indicate a slightly greater number of effect hailstreaks. The difference in the 5-year totals is 14 more effect hailstreaks, which is 4% more than the no-effect total. This is only a slight difference, and it should be remembered that in most storm periods the spatial distribution of effect and no-effect areas was such to favor (make larger) the no-effect category.

Figure B-65 is based on the diurnal distribution of network hail periods during the 5-year period. That is, an hour of occurrence of hail was counted for the clock-hour encompassed by the network hail periods, as shown for 1974 and 1975 in tables B-44 and B-45, respectively. The distribution of hail in the network with a peak in hours from 1500 to 1800 suggests a good sample of the hail climate since historical data (Changnon, 1970) reveal this to be the peak time of hail in southern Illinois. The minimum is in the 3-hour period from 0900 to 1200.

The yearly means of hailstreak energy values, sorted according to effect hailstreaks and no-effect hailstreaks, are presented in Table B-50. These represent the means from each year, and repeat those for 1974 and 1975 shown in tables B-44 and B-45. In four out of five years, the mean energy of the urban effect hailstreaks exceeded that of the no-effect hailstreaks. The

Table B-47. Frequency of Synoptic Weather Conditions Producing Network Rain and Hail Periods

	1971		*1972*		*1973*		*1974*		*1975*	
Synoptic weather type	*Total number*	*Number with hail*	*Total number*	*Number with hail*	*Total number*	*Number with hail*	*Total number*	*Number with hail*	*Total number*	*Number with hail*
Squall lines	5	3	11	6	14	10	7	4	13	6
Squall areas	17	5	11	2	16	4	19	9	20	8
Pre-cold front	0	0	2	0	0	0	4	0	0	0
Cold front	7	1	7	4	6	2	15	3	12	1
Post-cold front	2	0	6	0	3	0	1	0	0	0
Pre-warm front	0	0	0	0	1	0	0	0	0	0
Warm front	1	0	3	2	3	2	3	1	4	0
Stationary front	5	0	4	0	2	1	6	3	2	1
Post stationary front	2	0	1	0	0	0	3	0	0	0
Air mass	6	0	24	1	21	0	21	0	18	2
Low	2	1	1	1	1	0	1	0	0	0
Totals	47	10	70	16	67	19	80	20	69	18

Table B-48. The 1971-1975 Totals of Synoptic Types with Network Rain Periods and Hail Periods

	5-year total	*Totals with hail*	
		Number	*Percent*
Squall line	50	29	58
Squall areas	83	28	34
Pre-cold front	6	0	0
Cold front	47	11	23
Post-cold front	12	0	0
Pre-warm front	1	0	0
Warm front	14	5	36
Stationary front	19	5	26
Post-stationary front	6	0	0
Air mass	90	3	3
Low	5	2	40

5-year averages show the urban effect hailstreaks had a value that is 96% greater than the no-effect average, with a difference of 0.53 ft lbs/ft^2 (0.72 J/0.1 m^2).

A further comparison of the urban effect and no-urban effect hailstreaks on the basis of their energy values is presented in table B-51. Here, for each hail period in the network, the mean energy values of the urban effect and no-urban effect hailstreaks were compared and classed according to whether urban effect exceeded no-effect, whether no-effect exceeded effect values, or whether they were equal. These were based on hail periods when there were both effect and no-effect hailstreaks. For example, in 1971 (see table B-46) when there were 10 hail periods, only 3 of those hail periods had both effect and no-effect streaks, and the urban effect values exceeded the no-effect in all 3 periods. Comparison of these annual values in table B-51 reveals that the cases of effect greater than no-effect exceeded the other categories in every year. In 38 of these 53 hail periods, the effect area mean energy value exceeded the no-effect energy value, in 2 periods they were equal, and in 13 periods the no-effect exceeded the effect values. This frequency is revealed in table B-52 with frequencies sorted by the synoptic weather types producing the hail and rain periods. Considering the sampling size, there does not appear to be any preference for effect area energy to be greatest in any one Weather type. The effect area mean energy values were compared with the no-effect area means from this 53 period sample and their differences were statistically tested. The t-value determined by the t-test was +2.57

Table B-49. Frequency of Hailstreaks by Effect and No Effect Classes

	Urban effect	*No effect*
1971	26	14
1972	47	38
1973	101	90
1974	111	98
1975	82	113
Totals	367	353

Table B-50. Mean Hailstreak Energy, ft lbs/ft^2

	Urban effect	*No effect*
1971	0.33	0.02
1972	0.46	0.56
1973	0.58	0.09
1974	0.84	0.77
1975	1.51	0.81
Average	1.08	0.55

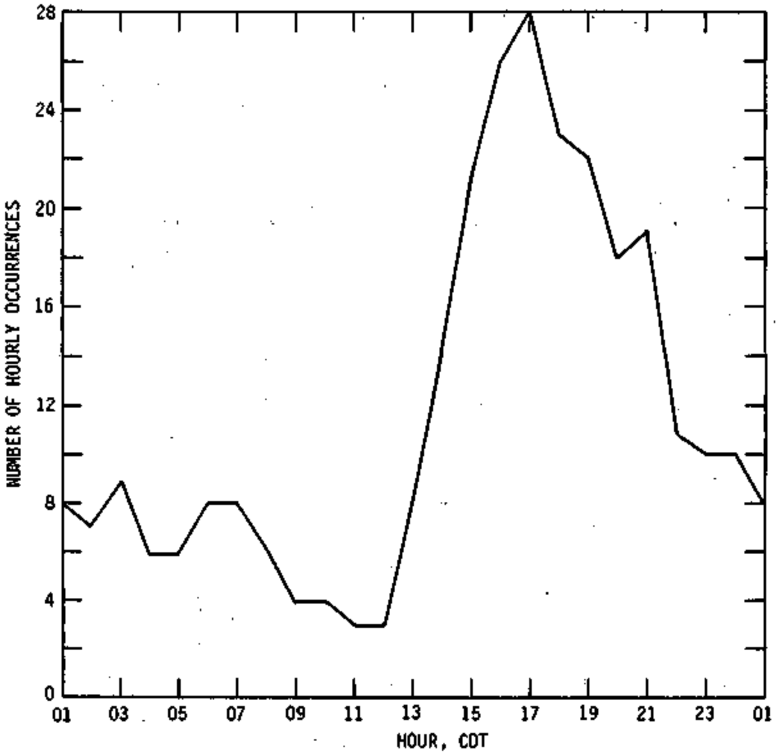


Figure B-65. Diurnal distribution of hail based on network hail periods

Table B-51. Annual Frequencies of Hail Periods Based on Differences in Mean Energy Values of Effect and No-Effect Hailstreaks

	Energy of effect hailstreaks exceeds energy of no-effect hailstreaks (E>NE)	*Energy of no-effect streaks exceeds energy of effect streaks (NE>E)*	*Energy equal E = NE*
1971	3	0	0
1972	8	0	1
1973	9	4	0
1974	8	4	1
1975	10	5	0
Total	38	13	2

Table B-52. Frequency of Hail Periods Sorted by Effect and No-Effect Mean Energy Values and Synoptic Weather Conditions

Weather type	*Number of times E > NE*	*Number of times NE > E*	*Number of times E = NE*	*Frequency as percent of total*
Cold front	5	1	0	83
Stationary front	3	1	0	75
Squall line	17	6	2	68
Squall area	12	4	0	75
Air mass	1	1	0	50
Total	38	13	2	72

which has a **1-tail** probability of 0.005. Thus, the differences between the effect values and the no-effect values were significant at a probability of >0.99. There is less than one chance in a hundred that the generally greater effect values are due to chance.

The remaining 30 hail periods in the network were cases when there were either effect hailstreaks or no-effect hailstreaks during the periods. Comparison of the energy values of these is not as valid, but comparison of the frequency of such hail periods is valuable. The yearly totals of these cases are shown in table B-53. In three of the five years there were more urban-effect only periods than there were periods with only no-effect hailstreaks. In one year (1973) there was a tie, and in 1975 there were more periods with no-effect hailstreaks than there were urban-effect only periods. The 5-year totals show a greater frequency of urban-effect only periods, which is relatively great when one realizes that the urban-effect area on any given day is typically a smaller precipitation area than the no-effect area. The difference between the 5-year totals of four periods, expressed as a percent of the no-effect only periods (13), gives a 31% increase in effect-only periods.

Table B-53. Hail Periods with Either Only Urban Effect Hailstreaks or with Only No-Effect Hailstreaks

	Urban effect only periods	*No effect only periods*
1971	5	2
1972	4	3
1973	3	3
1974	5	2
1975	0	3
Totals	17	13

POINT AND AREA HAILFALL RESULTS

Data Sample and Study Areas

The 5-year data sample for the 219 points (hailpad sites) in the circular network was the basis for an investigation of various point hailfall characteristics. These point (hail over a one-square-foot sensor) measurements included the number of times hail occurred at each point, the sizes of all hailstones, the numbers of hailstones, the duration of the hailfalls, and the impact energy values at each point (hailpad). Basically, these analyses began with the plotting of the averages, median values, and extreme (maximum) values from the 5-year period on network base maps. Such spatial arrays allow for examination of areal variations in the hailfall values. Patterns were developed on each map and comparisons were made of the patterns including the areas of highest and lowest values.

To assist in the pattern and urban evaluation, two arbitrarily chosen divisions of the network were developed. First, the network was divided into an eastern hemisphere and a western hemisphere, as shown in figure B-66. Values for the western half and the eastern half were compared as a crude estimate of urban effects (east) and no-urban effects (west). A more definitive delineation of the urban effect area and the no-effect area was developed from the frequencies of raincell motions and radar echo motions (Changnon et al., 1976).

The storm motion results showed that about 90% of all summer convective cells moved from the southwest, west-southwest, west, west-northwest, or northwest. Superposing such motions on the St. Louis and Alton-Wood River potential urban effect areas (figure B-66) resulted in the delineation of a network effect area which incorporates the central St. Louis and Alton-Wood River metropolitan districts and the areas extending to the northeast, east, and southeast from them. Hailfalls within this fan-shaped area were considered to represent potential

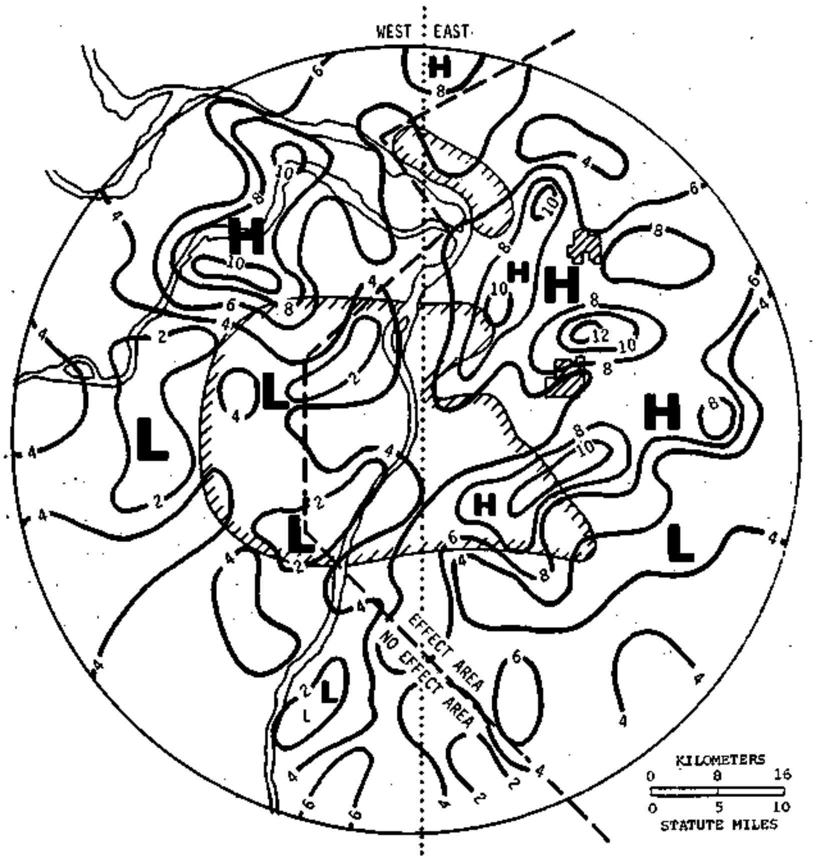


Figure B-66. Pattern based on hailfalls for 1971-1975

urban influences since most hail-producing storms therein had developed or passed over the urban-industrial areas. Hailfalls in the area to the west of this demarcation line represented hail from storms likely unaffected by any urban conditions. Obviously, a certain proportion of the hailfalls in the "effect" area were not urban affected, but differences between the effect area values and the no-effect area values were considered representative of the magnitude of any urban effects on point hailfall values. There were 110 hailpad sites in the effect area and 109 in the no-effect area, and the two areas were essentially of equal size.

Hailfall Frequencies

The number of point hailfalls (hailstorms) in the network at each site were plotted and the resulting pattern (figure B-66) reveals certain major features. First is an area of relatively low frequencies in the southwestern portions of the network. This is an area where the summer total rainfall was also lowest. The values shown in figure B-66 should be related to the network mean of 4.9 hailfall occurrences for the 5-year period. This compares favorably with the long-term mean summer value from St. Louis which would equate to 4 hail occurrences during a 5-year period. Thus, most of the area west and south of St. Louis was low and below the network mean.

The most notable high hail incidence area is that enveloped by 6 or more occurrences located to the northeast, east, and southeast of St. Louis in roughly a crescent shape. Within this area of $\geqslant$ 6 occurrences are five separate areas of $\geqslant$ 8 occurrences (more than 60% above the network mean) to the east of St. Louis. In four of these areas there are two or more points where the number of hailfalls were ⩾ 10, representing twice the network mean. The highest point value was 13 at a site just northeast of Collinsville. Basically, the high hailfallareas shown in figure B-66 agree favorably with the placement of the higher summer rainfall values.

A second area of high hail incidence is located to the northwest of the city, in and just east of the floodplain area of the Mississippi and Missouri Rivers. Within this localized high area, values of up to 11 hailfalls occurred at two sites, one near St. Charles and one in the floodplain west of Alton. This high hail incidence area is also in agreement: with a localized rainfall high that is apparently related to the floodplain effects on storm incidence and intensity;

The average point hailfall value based on the 110 hailpads in the effect area was 5.5, compared with a point average of 4.3 hailfalls in the no-effect area delineated in figure B-66. The difference of 1.2 represents a 28% increase in the effect area over the average in the no-effect area. The point average hailfall occurrences in the eastern half of the circular network were 5.4, compared with an average of 4.2 in the west, a difference that represents, a 29% increase over the western value.

In summary, the 5-year hail pattern shown in figure B-66 is very similar to the 5-year summer rainfall pattern. Areal mean increases appear to be on the scale of 30% with certain localized areas of high incidence suggesting 200% or greater increases in the number of hailfalls potentially related to urban effects. The area of urban increased hail is relatively small, as defined by the ⩾ 6 frequencies, and the increased hail area is located from 5 to 20 mi (8 to 32 km) beyond the city.

Hailstone Sizes

For each hailfall at each hailpad site, all hailstone sizes were calculated. From each of these hailfall distributions, the average hailstone size and the maximum hailstone size were identified. Then for each hailpad site, the median value of all the hailfall average hailstone sizes during 1971-1975 was determined and plotted. A second pattern analysis was based on the diameter of the largest hailstone measured during the 1971-1975 period.

Figure B-67 is a pattern based on the diameters, in inches, of the medians of the average hailstone sizes. In many respects this pattern is similar to the hailfall occurrences pattern of figure B-66. In general, small diameter stones were common in the area west and southwest of St. Louis. Larger hailstones were typical in the floodplain area northwest of St. Louis, and in two fan-shaped areas east of St. Louis and Alton-Wood.River. Areas where two and more hailpads had median hailstone diameters that exceeded 0.6 inch (1.52 cm) are found in the Alton-Wood River area, along a north-south sector *26* mi (32 km) east of St. Louis, and in one area in the extreme southern portion in the network. The average point hailstone diameter for the 5-year period, based on the median data at all 219 points, was 0.44 inch (1.12 cm). The median values in the effect area had an mean of 0.5 inch (1.27 cm) diameter, compared with 0.38 inch (0.97 cm) for the 109 sites in the western half of the network. The difference of 0.12 inch (0.30 cm) suggests a 32% increase in hailstone diameters due to urban effects. The hailstone diameter difference between the eastern and western half of the network was less, 0.08 inch (0.20 cm), or a 16% larger diameter in the eastern half of the circle.

Figure B-68 presents the pattern based on the diameters of the largest (maximum) hailstones that occurred at each of the 219 sites during the 5-year period. This pattern is somewhat dominated by certain localized very severe storms. For example, the major hailstorm on 12 August 1973 in the Granite City area (Changnpn and Semonin, 1975) produced very large hailstones that

Figure B-67. Median hailstone diameters, inches, during 1971-1975

Figure B-68. Maximum hailstone diameters, inches, 1971-1975 resulted in the area of ⩾ 2-inch (5.1 cm) diameter values (figure B-68), the largest stones in the network during the 1971-1975 period. It is interesting to note the locations of the eight discrete areas where maximum stone diameters were ⩾ 1.5 inches (3.8 cm). Six of these areas exist within St. Louis or immediately east of it. A seventh lies in the floodplain area northwest of St. Louis and one south of St. Louis. A major area of large stones is that enveloped by the ⩾ 1-inch (2.54 cm) sizes that extends from Wood River south through Granite City, eastward through Collinsville, and southward to Belleville and thence westward. This crescent-shaped area is amazingly coincident with the major high in hail frequency shown in figure B-66. This suggests that this was an area 1) of more hail incidences, and 2) of greater hailstone sizes. As in other hail patterns in figures B-66 and 67, the smallest maximum hailstone diameters (figure B-68) occurred in the area west and southwest of St. Louis.

The network average diameter of the maximum hailstones was 0.74 inch (1.88 cm). The average of the maximum values in the effect area was 0.82 inch (2.08 cm) compared with 0.67 inch (1.70 cm) for the maximum hailstone sizes in the no-effect area. The difference of 0.15 inch (0.38 cm) in these maximum hailstone diameters represents a 22% increase in the effect area. The value of the east half was 0.81 inch (2.06 cm), compared with 0.68 (1.73 cm) in the west half, an east-west difference of 0.13 inch (0.33 cm) representing a 19% greater mean stone diameter in the eastern half of the circle.

Frequency of Hailstones

The total numbers of hailstones of any size that occurred during the 1971-1975 period were counted for each of the 219 hailpad sites. The average point (1 ft^2 or 0.1 m^2) total for the 5-year period was 315 hailstones. The pattern based on these point frequencies is shown on figure B-69, and two large areas with ⩾ 400 hailstones per point are shown. One extends from southeast of St. Louis to the north just east of Collinsville and Edwardsville, and it closely resembles the major hail occurrence maximum and the hailstone size maximum. In general, areas with more hailfalls should be areas with relatively more hailstones so the agreement of the patterns of figures B-66 and B-69 is not surprising.

The other large area with values of ⩾ 400 stones extends from St. Louis to the northeast up through Alton-Wood River and then spreads westward through the Missouri-Mississippi River floodplain. Extremely high point totals, defined as those with ⩾1000 hailstones in the 5-year period, are labeled in figure B-69. One is in the floodplain northwest of St. Louis, one is immediately west of St. Louis, one in St. Louis, and three immediately east of St. Louis. Clearly, the major area of greatest hailstone frequencies is the one where values exceed 600, extending from the Belleville area to the north-northeast.

The average point value in the effect area east of St. Louis was 372 hailstones at a point, compared with 259 at a point in the no-effect area west of St. Louis. This difference of 113 hailstones at a point represents a 44% increase, presumably due to urban effects on storm activity and intensity.

Another analysis of the frequency of hailstones was based on the greatest number occurring at a point during any one hailfall. The resulting pattern of these maximum values for a single hailfall appears on figure B-70. Low values exist to the west and southwest of St. Louis. High values, those exceeding 400, exist at six locations; one northwest of St. Louis (in the floodplain), one over the city, and four east of the city.

The network average value for the maximum single hailfall was 195 hailstones which is more than half of the network average total hailstones of 315 for the 5-year period. The average of the

'Figure B-69. Total hailstones, 1971-1975

Figure B-70. Maximum number of stones at a point from one hailfall during 1971-1975 maximum values in the effect area was 217 compared with 172 in the no-effect area, a 26% increase. The greatest number of hailstones in a single storm in any one point was 952 stones at the hailpad site in south St. Louis. Three other hailpads had more than 800 hailstones in a single hailfall including one to the northwest and two to the east of St. Louis. As with the other point hailfall characteristics previously examined (total occurrences, sizes of hailstones, and numbers of hailstones), the maximum number of stones per storm event shows similar features with highs over and east of the city, a high to the northwest of the city, and lows to the west and southwest of St. Louis.

Point Duration of Hailfalls

The duration of each hailfall at each hailpad site was determined from the modified raingages and used to calculate the average point duration of hail at each site for 1971-1975. The pattern based on these point averages is shown in figure B-71. The network average duration at a point was 1.7 minutes. Thus, values greater than 3 minutes are of some significance. Two major areas with these longer durations appear. As in the previous hailfall patterns, a major high extends from the Belleville area to the northeast toward Edwardsville. The second major high in the duration values begins over St. Louis and also extends to the northeast to the Granite City and Alton-Wood River area. The longest averages are in the Granite City area where point values greater than 4 minutes are average.

Of interest is the fact that there is no major area of longer hail durations in the floodplain area northwest of St. Louis where previous hail patterns (figures B-66 and B-70) revealed a distinct tendency for more hailfall occurrences, larger hailstones, and greater number of hailstones. Apparently, localized effects of hail activity there did not lead to making durations longer (bigger hail volume aloft and/or slower moving storms). The mean value of the averages within the effect area was 1.9 minutes, compared with 1.6 minutes as a mean for the no-effect area. The resulting difference (0.3 minute) represents a 19% increase in durations in the effect area.

The longest point hailfall duration values from any one storm in 1971-1975 were plotted and a pattern derived (figure B-72). As in many other patterns, higher values occurred to the east of St. Louis in a crescent-shaped area extending from Belleville northeast and just east of Collinsville and Edwardsville. The highest values ($\geq$ 20 minutes) exist in the Granite City area and were a result of the spectacular storm of 12 August 1973 that produced greater than 2-inch diameter hailstones in the same area (figure B-68). However, inspection of the pattern based on the maximum number of hailstones (figure B-70) reveals that this was not an area of exceptionally large number of hailstones from a single hail period. As noted in the past, when exceptionally large hailstones occur in Illinois, there often are not extremely large numbers of hailstones, but. the hailfall duration tends to be quite long, often resulting from a rather stationary storm (Changnon, 1977).

Impact Energy

From a crop and property damage standpoint, the single most important hailfall value is the impact energy imparted by the hailstones. Energy is an integration of amount of ice, hailstone size, and wind speed with the hailfall.

The individual hailpad energy values calculated for each hailfall were used to determine a median energy value at each point. The pattern based on these median energy values (ft lbs/ft^2)

Figure B-71. Average point hailfall duration, minutes, 1971-1975

Figure B-72. Longest hailfall duration, minutes, from any one storm during 1971-1975

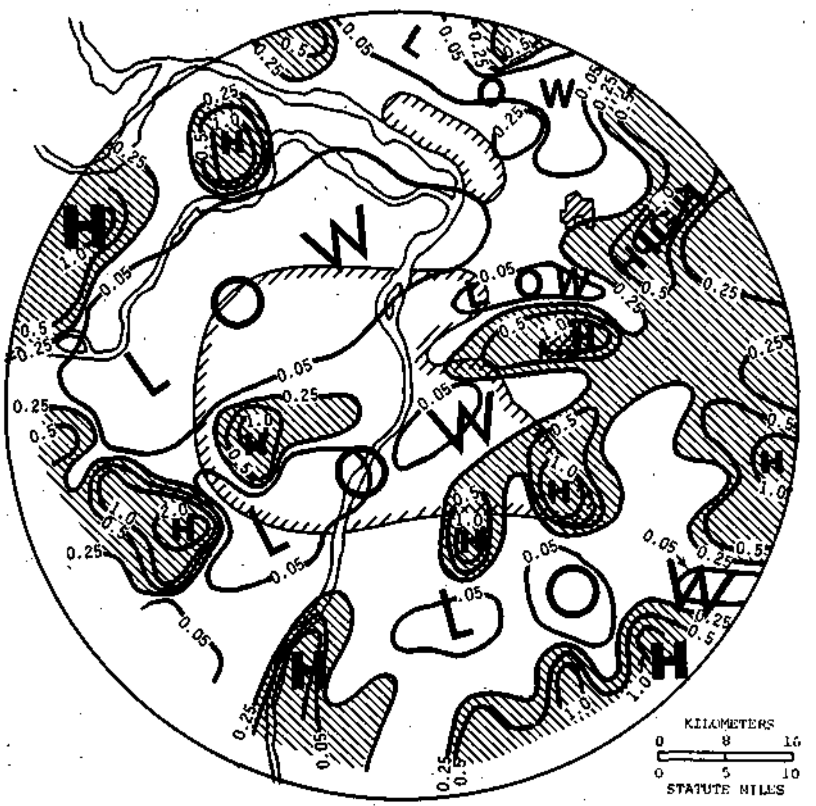


Figure B-73. Median energy values (ft lbs/ft^2) for hailfalls in 1971-1975

is shown in figure B-73. The network average value is 0.26 ft lbs/ft^2 (0.35 J/0.1 m^2). Thus, the areas enclosed by the iso-energy lines of $\geqslant$ 0.25 (0.34) represent above average values. The largest of these areas is that found east of the city extending approximately from the Belleville-East St. Louis area northeastward, and located east of Collinsville and Edwardsville. Again, this is in the area shown in the previous figures to be where hailfalls were most frequent, stone sizes tended to be largest, number of hailstones were greater, and hailstone durations longest. Hence, the high in the energy pattern in this area is not unexpected. Isolated highs based on point values of greater than 1.0 ft lbs/ft^2 (1.356 J/0.1 m^2) are shown distributed throughout this eastern region. Other isolated high value areas are found along the extreme southern part of the network, to the southwest of St. Louis (where many other hail values were relatively low), and to the northwest in the floodplain region. Three large areas having very low median energy values are found including the one to the west and northwest of St. Louis, one to the southwest of the city, and one across the southern portion of the network.

It is interesting to compare the 5-year median energy pattern with the pattern based on township average loss cost values of the crop-hail insurance companies (figure B-74). Loss costs are computed as total township losses divided by township liability (both values in dollars) multiplied by 100. Hence, the larger values shown in figure B-74 reflect higher average crop loss experiences over the 20-year period, 1951-1970. Comparison of the features of this crop-hail loss pattern with those shown in figure B-73 (based on the median energy values) is very revealing. First, the quite high loss area ($\geqslant$ \$1.5) in the Edwardsville, Collinsville, and Belleville areas is found in the

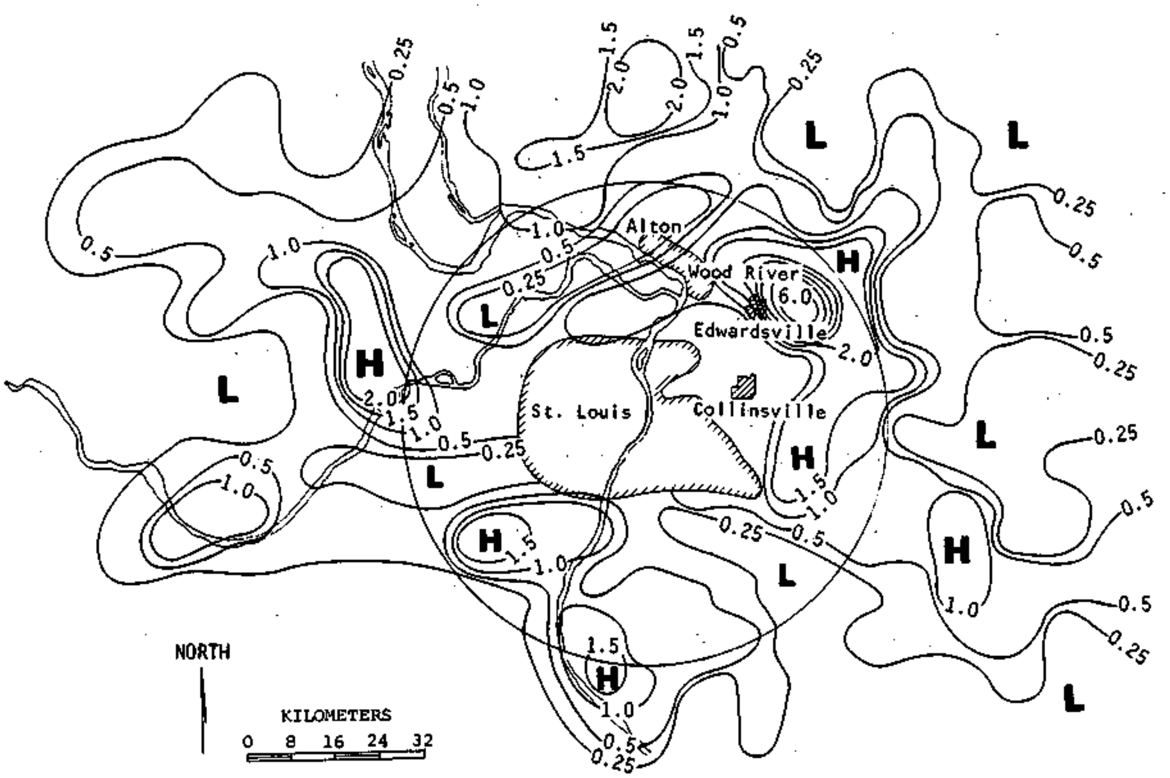


Figure B-74. Township average loss cost values of crop-hail insurance

energy pattern in figure B-73. Furthermore, the low loss cost values (≤ $0.5) to the northwest of St. Louis are also shown in the energy pattern to be a low area. The high loss area southwest of St. Louis (≥ $1.5) was also found to be a high energy area. Thus, the 5-year energy pattern on figure B-73 has many features that resemble the longer term crop-hail loss pattern of the region, indicating an adequate sample of hailfalls during the 1971-1975 sampling period. The patterns of energy and loss suggest urban effects on hail in the region beyond St. Louis.

The energy values in the effect area were used to determine the median value which was 0.09 ft lbs/ft^2 (0.12 J/0.1 m^2), as compared to the median value of 0.06 (0.08) in the no-effect area. The resulting difference (0.03) represents a 50% increase in energy in the effect area over the no-effect area.

The findings on the median energy values were further verified by the pattern based on the maximum energy values found in any one hailfall (figure B-75). This pattern shows point high values in and east of St. Louis (network average was 3.7 ft lbs/ft^2 or 5 J/0.1 m^2). Much of that area has values greater than the network average, and several areas exceed 10 ft lbs/ft^2 (13.56 J/0.1 m^2). Other high single storm energy values were found in the floodplain area northwest of St. Louis. In general, lower maximum energy values are found in the region west and southwest and south of St. Louis. The average effect area value based on the maximum values was 3.90 (5.29), 12% higher than the average in the no-effect area (3.48 ft lbs or 4.72 J).

Figure 8-75. Maximum energy (ft lbs/ft^2) in any given hailfall in 1971-1975

Diurnal Distribution of Hailfalls

The number of hailfalls in each 6-hour period (0001-0600, 0601-1200, 1201-1800, and 1801-2400 CDT) were determined, and plotted on a map. The resulting patterns for the four periods are shown in figure B-76.

The early morning period (figure B-76a) shows that about half of the network points never experienced hailfalls during the period ending at 0600 CDT. The network average point value is 0.6 hailfall. Many of the higher values, those ⩾ 2, occurred in the northern half of the network. No suggestion of urban effects appears in this pattern. Means of the effect and no-effect areas for this 6-hour period were equal.

The pattern based on the late morning period, 0601-1200 CDT (figure B-76b), reveals this to be the period of least hail activity during 1971-1975. The network point average is 0.3 hailfall. The occurrence of little hail during this 6-hour period is in agreement with long-term climatological findings for the area (Changnon, 1968). There is no suggestion of urban effects on the pattern for this 6-hour period, and the means for the effect area and no-effect area are equal, both 0.3.

The afternoon pattern (figure B-76c) shows much greater hail activity although there are still sizeable areas which did not have hailfalls during this 6-hour period in 1971-1975. The network average point value was 1.05 hailfalls, and areas with ⩾ 2 hailfalls are relatively high frequency zones. The largest area of ⩾ 2 hailfalls in the afternoon begins in St. Louis and extends eastward through Granite City and Collinsville. Within that area there were several smaller areas that had 3 or more hailfalls, and 4 hailpad sites had 4 or more hailfalls in the afternoon. The

a. 0001-0600 CDT

b. 0601-1200 CDT

c. 1201-1800 CDT

d. 1801-2400 CDT

Figure B-76. Number of hailfalls in 6-hour periods, 1971-1975 average point occurrence in the effect area is 1.2, compared with 1.0 in the no-effect area. The difference of 0.2 hailfalls represents a 20% increase due to urban effects in the afternoon.

The pattern based on hailfalls during the 1801-2400 CDT period (figure B-76d) reveals this to be the period of greatest hail activity during the summers of 1971-1975. The point average frequency was 1.36 hailfalls. Comparison of the effect area values with the no-effect area values in this 6-hour period reveals this to be the period of greatest urban effects. This is in agreement with the thunderstorm findings which show a nocturnal maximum in urban-related activity before 2400 CDT. The effect area point average number of hailfalls in this 6-hour period is 1.7 compared with 1.0 in the no-effect area, a 70% increase. Interestingly, the no-effect area average in this 6-hour period of 1.0 is comparable to that in the afternoon period. Thus, the evening maximization of hailfall activity in the effect area is the result of urban effects. The pattern (figure B-76d) shows sizeable highs (values ⩾ 2 at a point) throughout the area east of St. Louis, and in and just east of the floodplain area northwest of St. Louis. There are sizeable areas west and south of St. Louis with no hailfalls during this 6-hour period.

Summary of Urban Effects on Hail

The mean and median values of the effect and no-effect areas and of the east and west halves of the network area are summarized in table B-54. The differences between the area means (or medians) expressed as a percent of either the west (or of the no-effect area) are also included. In every case, the *urban effect area values exceed the no-effect values* with increases ranging from 12 to 50%. Differences between the east and west also generally show greater values in the east. Every aspect of the point hailfall characteristics supports a conclusion that there are urban effects on hail activity east of the city. It is clear that there also is a localized effect on hail related to the floodplain area northwest of St. Louis.

The urban effects appear to result in a more sustained production of hail and more frequent production of hail east of the city. The number of hail occurrences are greater (due largely to effects from noon to midnight), and the effects lead to more hailstones, larger hailstones, longer hailfall durations at a point, and as a result, greater point impact energies. The net result is the production of more crop-hail loss in the area just east of St. Louis.

HAILSTREAK RESULTS

Two analyses of the hailstreak data collected during the 1971-1975 period were performed. One analysis concerned storm periods when hailstreaks occurred both in potentially urban affected storms and in the no-effect storms. There were 53 such storm periods in the 5-year period producing 625 hailstreaks. This represents 67% of all the hailstreaks in the 5-year period and 64% of all the hail periods. On the other 30 hail periods in the 5 years, either no-effect only or effect only hailstreaks occurred. For the 53 storm periods with both effect and no-effect hailstreaks, various comparisons were made including 1) average point energy values in the streaks, 2) area within streaks (defined by two or more points), 3) average point duration, 4) duration of streaks (defined by 2 or more points), 5) average point rainfall in the streaks, 6) average of the maximum hailstone size in the streaks, and 7) total number of hailstreaks.

The second analysis was based on all 720 hailstreaks that occurred in the 83 hail periods during the summers of 1971-1975. Statistics were derived for all effect streaks, for all no-effect

Table B-54. Summary of Regional Differences in Point Hailfall Values for 1971-1975

	East	*West*	*(E-W)/W percent*	*Effect*	*No effect*	*(E-NE)/NE percent*
Number of points	109	111		110	109	
Average point hail occurrences	5.4	4.2	29	5.5	4.3	28
Median of median hailstone diameters	0.50	0.42	16	0.50	0.38	32
Average maximum hailstone diameters	0.81	0.68	19	0.82	0.67	23
Average of total hailstones (ft^2)	355	271	31	372	259	44
Average of maximum number stones (ft^2) in single storm	208	181	15	217	172	26
Average of longest duration in single storm	3.3	2.2	50	3.3	2.4	37
Mean of average point durations	1.8	1.6	12	1.9	1.6	19
Medians of median energy values	0.08	0.07	14	0.09	0.06	50
Average of maximum energy values in single storm	3.59	3.82	-6	3.90	3.48	12
Average number of occurrences at a point						
a. 0001-0600	0.7	0.5	40	0.6	0.6	0
b. 0601-1200	0.3	0.3	0	0.3	0.3	0
c. 1201-1800	1.1	1.0	10	1.2	1.0	20
d. 1801-2400	1.7	1.0	70	1.7	1.0	70

hailstreaks, and for all 720 hailstreaks. Statistics derived included: 1) point hailfall durations, 2) diurnal distribution, 3) hailstreak durations, 4) hailstreak maximum lengths, 5) hailstreak maximum widths, 6) areas of hailstreak, 7) hailstreak energy values, 8) number of hailstones, and 9) maximum hailstones in a streak.

Effect and No-Effect Hailstreaks in Same Period

During 1971-1975, there were 53 storm periods when both effect and no-effect hailstreaks occurred. Comparisons for those 53 days allow a potentially more definitive assessment of effect and no-effect characteristics of hailstreaks. Hailstreaks classed as affected were those from storm cells (radar and/or raingage classified) which developed over or crossed the St. Louis and/or Alton-Wood River areas. The no-effect hailstreaks came from cells which did not develop or cross these two urban-industrial areas. Basically, most effect hailstreaks occurred within the fan-shaped area shown on figure B-66 which consisted of exactly half of the circular network. However, for any given hail period, with storm (cell) motions from one predominating direction, the affected hailstreaks generally occurred in less than one-fourth of the total network area. Thus, the statistics on the frequency of hailstreaks per hail period are biased in favor of the larger area in the no-effect region.

Examination of the summer hailstreak values in each year (table B-55) reveals that the effect frequency exceeded the no-effect frequency in 1971, 1972, and 1973. However, in 1974 and 1975, the no-effect frequency exceeded the effect frequency of hailstreaks. There were 625 hailstreaks in these 53 storm periods with 19 more effect hailstreaks in the total, representing 6% more than the number of no-effect hailstreaks (303). As shown in table B-55, there were 27 periods when the number of effect hailstreaks exceeded the no-effect number, 2 periods when the effect and no-effect hailstreaks were equal, and 24 periods when the no-effect frequency exceeded the effect frequency. The difference of 3 periods (27 versus 24) suggests a 13% increase in the number of periods when effect streaks exceeded the number of no-effect hailstreaks.

Table B-55. Number of Effect and No-Effect Hailstreaks in Storm Periods When Both Occurred, 1971-1975*

		Number of hailstreaks		
	Number of storm periods	*Effect*	*No effect*	*Difference, E - NE*
1971	3	19	12	7
1972	9	40	27	13
1973	13	88	72	16
1974	13	93	95	-2
1975	15	82	97	-15
Totals	53	322	303	19

*Number of storm periods when E number > NE number = 27; number of storm periods when NE number > E number = 24; number of storm periods when E number = NE number = 2

Table B-56. Comparison of Hailstreak Characteristics from Storm Periods When Both Effect and No-Effect Hailstreaks Occurred

					Number of storm periods			
Hailstreak characteristic	*Effect*	*No effect*	*Average difference E - NE*	*Difference as percent of NE*	*E = NE*	*E > NE*	*NE > E*	*Difference E - NE*
Hailstreak area, mi^2	14.4	14.0	0.4	3	1	10	12	-2
Average point hailfall duration, *min**	2.9	2.1	0.8	40	5	35	11	24
Duration of hailstreak, *min***	16.2	13.8	2.4	17	1	10	7	3
Average of maximum hailstone in streak, *in.*	0.55	0.45	0.10	22	1	33	16	17
Average point energy, *ft lbs/ft*^{2}	1.0	0.5	0.5	100	1	37	15	22
Average point rain, *in.*, in hailstreak**	0.69	0.68	0.01	2	2	24	26	-2

*Total periods slightly less than 53 total periods because of missing data

**Based on hailstreaks defined by 2 or more points. This eliminated some storm periods when either the effect or no-effect streak(s) was not defined by 2 or more points.

Six basic characteristics of the hailstreaks are listed in table B-56. The averages reveal little difference between effect and no-effect streaks in their 1) areal size, or 2) the average point rainfall values. In fact, for both of these hailstreak categories, the number of periods when the no-effect values exceeded the effect value was slightly higher than the converse (E > NE).

However, for the four other characteristics shown in table B-56, the effect values were decidedly greater than the no-effect values. The average of the maximum hailstone sizes showed effect values were 22% greater than no-effect values with a difference of 17% in the hailstreak duration. Major larger effect values existed for the average point duration (+40%) and with average energy (+100%). Note also that the number of periods when E > NE was quite a bit higher than those when NE > E for hailstone size, point duration, and energy. Thus, this comparison of effect and no-effect hailstreaks occurring during the same storm periods show that the affected streaks were slightly larger, slightly longer lasting, often produced bigger hailstones, and lasted much longer at a point. All of these resulted in a sizeable larger average energy value in the effect hailstreaks.

Another comparison of the hailstreak values was based on results of a study of the synoptic' weather conditions associated with each storm period and the hailstreaks. The number of hailstreaks associated with each of the six hail-producing conditions (when effect and no-effect hailstreaks occurred together) appears in table B-57. The major differences between effect and no-effect hailstreaks, both in magnitude and percentage (and when the total frequencies of hailstreaks are considered), are those with squall lines (+36 hailstreak difference and +24%), and in stationary fronts (—14 in streaks and —64%). The sizeable negative percentage difference in air mass and warm front cases are of little consequence in view of the small frequency in each class, 12 and 3 hailstreaks, respectively. The slight differences in squall areas (—3) and in cold fronts (+5) suggest no measurable effects on frequencies during these weather conditions. In summary, the results suggest 1) an urban enhancement of hailstreak activity during squall lines, and 2) an urban diminishment of hailstreaks during stationary frontal conditions.

Average hailstreak characteristics for the five principal weather categories associated with hailstorms are shown in table B-58. Of interest are the differences in the magnitudes of the effect averages for any category. For instance, in the hailstreak area category, the squall line values are small (11.4/mi^2 or 29.53/km^2) whereas the stationary front values are largest (37.5/mi^2 or 97.12/km^2). Examination of the effect values for stationary front cases show them to be relatively larger in all characteristics except average point duration and average rainfall inside the streaks. Thus, although the number of effect hailstreaks in stationary fronts is smaller (averages of 2 effect versus 5 no-effect streaks in the hail period), the much greater areal extent of effect hailstreaks (37.5 vs 8.0 mi^2 or 97 vs 21 km^2) results in more total area of hail in the effect area (2 × 37.5 = 65 mi^2 or 168 km^2) than in the no-effect area (5 hailstreaks × 8 = 40 mi^2 or 103.6 km^2) for an average storm period. Large differences between synoptic classes for the average effect values are found for hailstreak duration (9 to 28.5), frequency of hailstreaks (2 to 8), average point duration (1.7 to 3.3), average energy (0.7 to 1.8), and average point rainfall (0.38 to 0.82). Squall line conditions have the most urban effect streaks (8 versus 6 no-effect), but the average area of effect hailstreaks is small (11.4 mi^2).

Table B-59 presents the effect versus no-effect differences of table B-47 expressed as a percent of the no-effect value. In all five synoptic weather categories, the effect values exceed the no-effect for average maximum hailstone size, average point duration, and for average energy. Thus, urban enhancement of hail is suggested in most weather classes. All cold front hailstreak values shown in table B-59 range from no differences up to 333% increases in effect hailstreaks. However, the air mass results are those most suggestive of no-urban enhancement with effect values smaller in 4 of the 7 characteristics.

Characteristics of All Hailstreaks

There were 720 hailstreaks in the 1971-1975 period and these were studied. Various characteristics were developed for all hailstreaks including 1) time of initiation of the hailstreak, 2) average point duration, 3) average energy, 4) average point number of hailstones, 5) maximum hailstone size, and 6) average rainfall in the hailstreak. For those 191 hailstreaks which hit 2 or more hailpad sites, additional characteristics were calculated including 1) maximum hailstreak length, 2) maximum streak width, 3) area, and 4) duration of the hailstreaks.

The number of hailstreaks available for each of these 10 streak characteristics varied because of missing data in certain cases. For example, energy values were available for 662 hailstreaks but no energy values were available for 58 hailstreaks because the hailpads were either damaged or unavailable.

Table B-57. Hailstreak Data Associated and Synoptic Weather Classes for Periods with Effect and No-Effect Hailstreaks, 1971-1975

Weather class	*Number of effect*	*Number of no effect*	*Total*	*Difference E − NE*	*Difference as percent of NE*
Warm front	0	3	3	−3	−100
Cold front	38	33	71	+5	+15
Stationary front	8	22	30	−14	−64
Squall lines	189	153	342	+36	+24
Squall area	82	85	167	−3	−4
Air mass	5	7	12	−2	−28
Totals	322	303	625	+19	+6

Table B-58. Comparisons of Average Hailstreak Characteristics for Different Synoptic Weather Conditions and for Storm Periods When Both Effect and No-Effect Hailstreaks Occurred, 1971-1975

	Difference, effect average − no effect average													
Synoptic weather condition	*Average streaks per storm event*		*Average area, mi^2*		*Average streak duration, min*		*Average of maximum hailstone diameter, in.*		*Average point duration, min*		*Average energy, ft lbs/ft^2*		*Average point rainfall, in.*	
	E	*E − NE*	*E*	*E − NE*	*E*	*E − NE*	*E*	*E − NE*	*E*	*E − NE*	*E*	*E − NE*	*E*	*E − NE*
Cold front	6	+1	8.3	+1.2	16.1	±0	0.5	±0	3.3	+1.6	1.3	+1.0	0.82	0.17
Stationary front	2	−3	37.5	+29.5	28.5	+14.3	0.6	+0.1	1.7	+0.8	1.8	+0.6	0.38	−0.19
Squall line	8	+2	11.4	−4.1	15.6	+3.1	0.5	+0.1	2.7	+0.5	0.9	+0.5	0.80	+0.02
Squall area	5	±0	15.5	+2.7	15.1	+1.9	0.6	+0.2	2.9	+0.8	0.9	+0.3	0.58	±0
Air mass	3	−1	13.8	−31.6	9.0	−30.0	0.7	+0.1	2.7	+0.1	0.7	+0.5	0.56	−0.04

Table B-59. Hailstreak Differences (Effect-No Effect) for Various Synoptic Classes Expressed as a Percent of the No-Effect Average Value, 1971-1975

	Hailstreaks per storm event	*Average area*	*Average hailstreak duration*	*Average maximum hailstone size*	*Average point duration*	*Average energy*	*Average rainfall in streak*
Cold front	+15	+17	±0	±0	+94	+333	+26
Stationary front	−64	+369	+100	+20	+90	+50	−100
Squall line	+24	−26	+25	+25	+23	+125	+3
Squall area	−4	+21	+14	+50	+38	+50	±0
Air mass	−28	−70	−77	+16	+4	+250	−6

Table B-60. All Hailstreak Characteristics for 1971-1975

	Effect			*No effect*			*All hailstreaks*		
	Mean	*Median*	*Number*	*Mean*	*Median*	*Number*	*Mean*	*Median*	*Number*
Average point duration, *min*	2.7	2.0	301	1.9	1.0	263	2.3	1.0	564
Begin time of streaks, *CDT*		1724	320		1525	287		1630	607
Duration of streak, *min*	14.9	12.0	106	14.2	12.0	78	14.6	12.0	184
Maximum length, *mi*	7.2	6.1	106	6.9	5.8	85	7.0	6.0	191
Maximum width, *mi*	2.0	1.3	106	1.7	1.2	85	1.9	1.3	191
Area, mi^2	15.6	6.1	106	15.3	6.0	85	15.5	6.0	191
Average point number of stones, ft^2	74.0	27.0	335	54.3	17.0	322	64.5	21.0	657
Maximum hailstone diameter in streak, *in.*	0.55	0.50	335	0.44	0.42	322	0.50	0.46	657
Average point energy, *ft lbs/ft^2*	1.08	0.11	339	0.55	0.04	323	0.82	0.08	662
Average rain in streak, *in.*	0.80	0.68	336	0.66	0.50	305	0.73	0.60	641

Table B-60 presents results for all summer hailstreaks during the 1971-1975 period. The mean, median, and total number (with data) values are listed for all streaks plus those for all the effect and no-effect hailstreaks. Comparison of the effect and the no-effect values with the values of all hailstreaks allows one to compare the differences found in the effect and no-effect categories. All the effect hailstreak characteristics have means that are larger than the no-effect values. The median of the initiation times of hailstreaks is later for the effect than the no-effect category by 2 hours (1724 CDT versus 1525 CDT).

A comparison of the E — NE values for both the means and medians of table B-60 is facilitated in table B-61 where the differences are shown along with the differences expressed as percent of the no-effect values. First, the E — NE differences for the number of streaks reveal that the effect frequencies are larger for every hailstreak characteristic. Differences range from 4% on point numbers of stones and for maximum hailstone size up to 35% in duration of hailstreaks.

Examination of the percentage differences shown for the mean values in table B-61 reveals that all the effect values are greater, ranging from 2% on hailstreak area up to 96% for average point energy. In a similar vein, the effect median values are all greater except for duration of hailstreaks which shows no difference.

In general, the differences shown for durations of hailstreaks, maximum lengths, maximum widths, and areas of hailstreaks are quite small regardless of whether it is the mean or median value. Differences for the other five hailstreak characteristics are much greater. A ranking of the percentage differences for the means and for the median shows the greatest difference is in energy, with point duration percentages ranking second, point hailstone frequencies ranking third, maximum hailstone sizes ranking fourth, and averages rainfall ranking fifth.

In summary, the effect hailstreaks are generally not larger in their areal scale, duration, length, and width. However, the effect hailstreaks generally produce more intense hailfalls which is directly related to the longer point duration and hence more hailstones and bigger stones. The longer duration, more stones, and bigger hailstones combine to produce the greatest differences shown, which is in energy at the surface. This suggests that within urban-affected hailstorms, the volume of hail produced aloft is not larger, but the volume tends to have more hailstones produced within it. It is noteworthy that the median percentage differences shown in table B-61 are all greater than the percentage differences of the means, for any given characteristic.

The differences between the characteristics of the effect and no-effect hailstreaks for the 5-year period are presented in added detail in tables B-62 through B-70. The frequencies of hailstreaks in these tables are sorted by intervals or various classifications chosen to reveal distributions. Examination of table B-62 shows that there were more no-effect hailstreaks having 1 to 2 minute durations, but for all longer duration (3 minutes and longer) the frequencies of effect hailstreaks equaled or exceeded the no-effect frequencies (and by large differences).

Table B-63 shows the distribution of hailstreaks sorted by their durations. Differences between effect and no-effect frequencies are not great in the first four 5-minute classes, but for durations of 21 minutes or longer, there were 22 hailstreaks in the effect category compared with 11 in the no-effect category. Thus, there is a tendency for a few effect streaks to have much longer durations although their mean and median differences are not great (table B-61).

The number of hailstreaks of varying lengths appears in table B-64. There is not much difference in the E and NE frequency for lengths of 3 up to 9 mi (4.83 to 14.5 km), but for the longer hailstreaks (> 9 mi or 14.5 km) there are more in the effect class, 25 versus 15 in the no-effect.

Table B-65 presents the frequencies of hailstreaks sorted by their maximum widths. A striking preference to greater width in the effect streaks is shown. All width categories of > 0.6 mi (0.97 km) show a greater number of effect streaks.

Table B-61. Differences between Effect and No-Effect Hailstreaks during 1971-1975

Hailstreak characteristic	Means		Medians		Number of streaks	
	E - NE difference	*Difference as percent of NE*	*Difference*	*Difference as percent of NE*	*E - NE difference*	*Difference as percent of NE*
Average point duration, *min*	+0.8	+42	+1.0	+100	+38	+14
Duration of streak, *min*	+0.7	+5	±0	±0	+28	+35
Maximum length, *mi*	+0.3	+4	+0.3	+6	+21	+25
Maximum width, *mi*	+0.3	+18	+0.1	+8	+21	+25
Area, mi^2	+0.3	+2	+0.1	+2	+21	+25
Average point frequency of stones, ft^2	+19.3	+36	+10	+60	+13	+4
Maximum hailstone diameter, *in.*	+0.11	+25	+0.08	+20	+13	+4
Average point energy, $ft\ lbs/ft^2$	+0.53	+96	+0.07	+172	+16	+5
Average point rainfall in streak, *in.*	+0.14	+21	+0.18	+36	+31	+10

Table B-62. Number of Hailstreaks Sorted by Average Point Hailfall Durations, 1971-1975

	Number per given duration periods, minutes					
	1 to 2	*3 to 4*	*5 to 6*	*7 to 8*	*9 and longer*	*Total*
Effect	194	66	27	6	8	301
No effect	203	40	12	6	2	263
Total	397	106	39	12	10	564

Table B-63. Number of Hailstreaks Sorted by Hailstreak Durations, 1971-1975

	Number per given duration periods, minutes							
	1 to 5	*6 to 10*	*11 to 15*	*16 to 20*	*21 to 25*	*26 to 30*	*≥ 31*	*Total*
Effect	4	32	30	18	9	7	6	106
No effect	5	20	26	16	6	1	4	78
Total	9	52	56	34	15	8	10	184

Table B-64. Number of Hailstreaks Sorted by Maximum Length, 1971-1975

	Number per given length category, miles						
	3 to 5	*5 to 7*	*7 to 9*	*9 to 11*	*11 to 13*	*≥ 13*	*Total*
Effect	28	40	13	11	6	8	106
No effect	28	29	13	6	4	5	85
Total	56	69	26	17	10	13	191

Table B-65. Number of Hailstreaks Sorted by Maximum Width, 1971-1975

	Number per given width category, miles							
	0.1 to 0.5	*0.6 to 1.0*	*1.1 to 1.5*	*1.6 to 2.0*	*2.1 to 2.5*	*2.5 to 3.0*	*≥ 3.1*	*Total*
Effect	5	30	32	16	2	5	16	106
No effect	7	29	22	13	1	1	12	85
Total	12	59	54	29	3	6	28	191

Table B-66 shows the frequencies of hailstreaks sorted by the areal extent of the streaks. Effect frequencies are greater for the areas of 3-5, 5-10, 10-15, and $\geqslant$ 31 mi^2 (7.77-13, 13-26, 26-39, and $\geqslant$ 80 km^2), whereas no-effect values are greatest for the classes 1-3, 15-20, and 20-30 mi^2 (2.59-7.77, 39-52, and 52-77.7 km^2). No preference appears for either classification in the area size analysis, and this is supported in tables B-60 and B-61.

Table B-67 presents the frequency distribution of hailstreaks sorted by the average point number of hailstones inside the streaks. The no-effect hailstreaks have the greatest frequency in most of the lower frequency classes (1-10, 11-20, and 31-50 hailstones per square foot). The effect hailstreaks have the greatest frequencies in the other classes including all those for 51 or more hailstones per square foot.

The frequency of hailstreaks sorted by the maximum hailstone size inside the streak appears in table B-68. Again, the no-effect hailstreaks exceed the effect frequencies in the smaller sizes, 0.05 to 0.6 inch (1.27 to 1.52 cm), whereas the effect hailstreaks exceed in the larger sizes.

The distribution of hailstreaks classified by their average impact energy values appears in table B-69. The no-effect frequency is greatest in the lower energy classification, 0.01 to 0.05 ft lbs/ft^2 (0.013 to 0.07 J/0.1 m^2), and in the 0.21 to 0.4 class (0.28 to 0.54 J), but the effect hailstreaks are more frequent in all other seven energy classifications. In particular, the effect hailstreak frequencies are much greater than for the no-effect streaks in the higher > 1.1 ft lbs/ft^2 (1.49 J/0.1 m^2) classes.

Another frequency comparison of effect and no-effect hailstreaks is that based on the various rainfall values, as shown in table B-70. The no-effect hailstreaks lead in the three lowest rainfall categories, whereas the effect hailstreaks were most frequent in the heavier rainfall categories. This is as expected from the greater effect values for mean rainfall shown in table B-61.

The times of hailstreak initiation were classified according to each (clock) hour. The resulting hourly distributions for the 320 effect hailstreaks and the 287 no-effect hailstreaks appear in figure B-77. The effect values are basically much greater than the no-effect frequencies in the mid-afternoon (1500 to 1700 CDT), and again from 2000 CDT through 0400. Differences in their frequencies are not great during the 0200 to 1200, both being quite low. Of interest is the considerably fewer effect hailstreaks than no-effect hailstreaks during the hours ending between 1300 and 1500 CDT. This may suggest urban diminishment of hail activity during the early afternoon, followed by enhancement in most hours from 1500 until 0400 CDT.

CONCLUSIONS

Many of the results from the 5-year summer hail data sample suggest that it was a near-normal hail period in the St. Louis region. For example, the point average throughout the network of 4.9 hail days during 5 summers is only slightly larger than the long-term (St. Louis station) value of 4.0 hail days. The 1971-1975 data also indicated the maximum amount of hail activity during June with a decrease in frequency through July and August. This often is the trend found in long-term experience. The monthly values showed 32 hail periods in June, 27 in July, and 24 in August. Furthermore, the pattern of impacted energy from the hailfalls over the network closely resembled the 1951-1970 crop-hail loss pattern. Thus, the METROMEX sample for hail seems to have been reasonably representative of longer recent period experiences, at least since potential urban effects developed in the last 30 years (Huff and Changnon, 1972).

Table B-66. Number of Hailstreaks Sorted by Area, 1971-1975

	Number per given areas, square miles							
	1 to 3	*3 to 5*	*5 to 10*	*10 to 15*	*15 to 20*	*20 to 30*	*≥ 31*	*Total*
Effect	17	24	35	10	4	1	15	106
No effect	19	18	25	3	9	4	7	85
Total	36	42	60	13	13	5	22	191

Table B-67. Number of Hailstreaks Sorted by Average Point Number of Hailstones, 1971-1975

	Frequency based on number of stones per square foot								
	1-10	*11-20*	*21-30*	*31-50*	*51-70*	*71-100*	*101-200*	*-201*	*Total*
Effect	79	63	34	35	22	22	32	38	335
No effect	110	65	28	36	19	16	30	18	322
Total	189	128	62	71	41	38	62	56	657

Table B-68. Number of Hailstreaks Sorted by Maximum Hailstone on Streak, 1971-1975

	Number per diameter class, inches							
	.05-.20	*.21-.4*	*.41-.6*	*.61-.8*	*.81-1.0*	*1.01-1.5*	*-1.51*	*Total*
Effect	35	101	73	78	23	20	6	335
No effect	49	108	91	49	16	8	1	322
Total	84	209	164	127	39	28	7	657

Table B-69. Number of Hailstreaks Sorted by Average Impact Energy, 1971-1975

	Number per energy class, ft lbs/ft²									
	.01-.05	*.06-.1*	*.11-.2*	*.21-.4*	*.41-.6*	*.61-1.0*	*1.1-2.0*	*2.1-3.0*	*≥ 3.1*	*Total*
Effect	132	37	38	25	19	20	21	19	28	339
No effect	174	21	26	31	12	19	16	9	15	323
Total	306	58	64	56	31	39	37	28	43	662

Table B-70. Hailstreaks Classified by Average Point Rainfall in Hailstreak, 1971-1975

	Number per rainfall class, inches								
	.01-.2	*.21-.4*	*.41-.6*	*.61-.8*	*.81-1.0*	*1.01-1.5*	*1.51-2.0*	*2.01*	*Total*
Effect	58	59	39	47	38	45	30	20	336
No effect	68	62	44	46	18	38	19	10	305
Total	126	121	83	93	56	83	49	30	641

During the METROMEX study period, there were 83 hail periods, or rain periods with hail. Of these, 53 simultaneously produced hail that was classed as originating in storm cells with no urban effect and also in cells that developed or crossed over this city, labeled as "effect" hail. In the 30 other hail periods hail either fell only from urban effect storms or from storms not urban-affected. In the 83 hail periods there were 720 hailstreaks, individual entities of hail defined at the surface.

Those classed as effect hailstreaks totaled 367, and 350 were classed as no-effect hailstreaks. The difference in their frequencies is very slight, only 4%. However, it should be noted that in most hail periods, the area of the network where effect hailstreaks could occur generally represented about 25% of the circular network area. Thus, on an areal basis, 50% more no-effect hailstreaks should be detected if the areal distribution were equal.

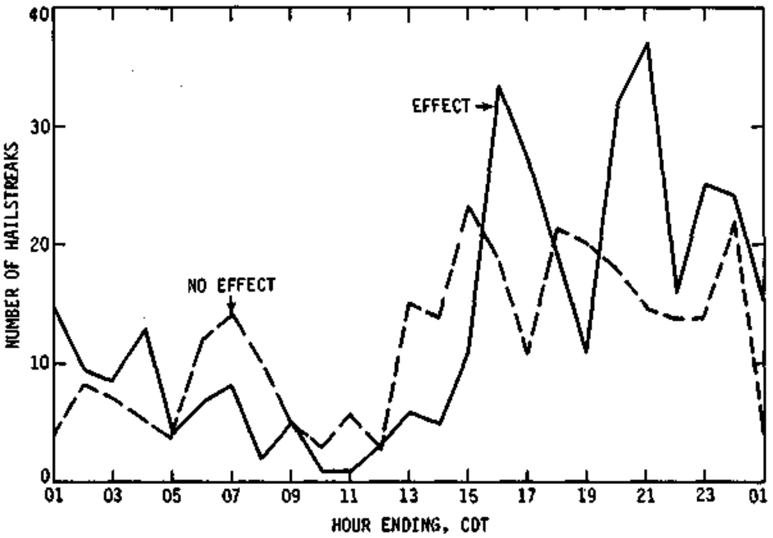


Figure B-77. Frequency of effect and no-effect hailstreaks by hour

The 5-year data on the point hailfalls produced a pattern which resembles the 1971-1975 rainfall pattern in the network. The major features of the hailfall pattern were 1) a low incidence area to the west and southwest of St. Louis; 2) a high frequency area (ranging from 6 up to 13 hailfalls at a point) in a crescent shaped area to the northeast, east, and southeast of St. Louis and located at a radius of 5 to 20 miles from the city; and 3) a secondary hail high to the northwest of the city in the flood plains. These same major features were found in the other patterns based on hailstone sizes, the frequencies of hailstones at a point, and the mean energy values. The crescent shaped high was found to the east of St. Louis in all of the hail features. This agrees with the 1951-1970 pattern of crop-hail losses for the area which has a major high to the northeast of St. Louis near Edwardsville.

Various comparisons of hailfall and hailstreak characteristics for the 5-year period were made on the basis of values in the potential urban effect areas and the potential no-effect area. Results of several of the key comparisons are listed in table B-71.

The frequency of hail periods when only urban effect hail occurred was 31% greater than the frequency of hail periods when only no-effect hail occurred. Comparison of the 53 hail periods which had both effect and no-effect hail occurrences reveals that the number of times when the effect mean energy value exceeded the no-effect mean energy value was 282% greater than the no-effect frequency. In 80% (four of five years) the effect area mean energy values exceeded the no-effect area mean energy. For the 5-year sampling period, the mean energy value in the effect area was *96%* greater than that in the no-effect area.

Various hailfall values shown next in table B-71 including the average frequency of hailfalls, median hailstone diameter, and average number of hailstones per unit area all show moderate, 28 to 44% , increases in the effect area storms. Comparison of time hail frequencies in the effect versus no-effect areas during the day reveals a moderate increase from 1200 to 1800 CDT with the major increase occurring between 1800 and 2400 CDT. No increases are shown in the morning hours.

Another set of comparisons shown in table B-71 is based on hailstreak characteristics when both effect and no-effect hailstreaks occurred during the 53 hail periods. Very small differences are shown for areas of hailstreaks and their duration, but sizeable increases are shown for

Table B-71. Comparison of Effect and No-Effect Hail Values for 1971-1975

Frequency of hail periods with urban effect *only* hail vs no-effect *only* hail periods*		+31%
Frequency of hail periods (with effect and no-effect hail) when effect area mean energy > no-effect mean energy*		+282%
Percent of years in 1971–1975 period when effect area mean energy > no-effect mean energy		80%
Mean energy in effect area vs that in no-effect area*		+96%
Average frequency of point hailfalls, effect area vs no-effect area*		+28%
Median hailstone diameter in effect area vs that in no-effect area*		+32%
Average hailstones per square foot, effect hail area vs no-effect hail area*		+44%
Effect area hailfall frequency vs no-effect area frequency, differences for 6-hour periods*	00–06 CDT	0
	06–12 CDT	0
	12–18 CDT	+20%
	18–24 CDT	+70%
Comparison of hailstreak characteristics (E vs NE) for 53 hail periods when both effect and no-effect hailstreaks occurred*	Hailstreak durations	+7%
	Areas of hailstreak	+3%
	Average point (1 ft^2) duration	+40%
	Maximum hailstone diameter	+22%
	Point (1 ft^2) number of hailstones	+36%
	Energy	+100%
	Mean rainfall in hailstreaks	+21%

Comparison of effect and no-effect hailstreak characteristics with various synoptic weather conditions*

	Frequency of streaks	*Energy*
Cold fronts	+15%	+333%
Squall lines	+24%	+125%
Squall areas	−4%	+50%
Stationary fronts	−64%	+50%
Air mass	−28%	+250%

*Difference, E − NE, expressed as a percent of no-effect value

the other hailstreak characteristics including point duration (+40%), the maximum hailstone diameter (+22%), and the point number of hailstones (+36%). These last three values effectively combine to produce a much greater difference in energy as shown, +100%. Even the mean rainfall in the effect hailstreaks was 20% greater than that in the no-effect hailstreaks.

The final set of comparisons shown in table B-71 is based on the characteristics of all effect and no-effect hailstreaks sorted according to various major synoptic weather conditions associated with hail. In cold front and squall line conditions there is apparent urban enhancement in the number of hailstreaks as well as in the energy values. However, the frequency of hailstreaks appears to be diminished, particularly with stationary fronts, but in all weather conditions there appears to be an urban enhancement in the energy of the hailfalls.

Some information indicating how and when the urban area is affecting hail production can be summarized from these results. Urban effects on hail activity begin to appear at the time of maximum heating and continue on into the night. Urban effects on hail occur with all synoptic weather conditions which produce hail in the area. However, urban effects on hail appear to be most effective in the squall line and cold front conditions, those with generally the more organized and faster moving convective systems. Urban effects are least on hail during the isolated air mass storm conditions when hail is normally quite infrequent.

The findings showing that urban effects do not lead to longer lasting hailstreaks or larger hailstreaks are of considerable interest. The urban effects produce more hail entities in a storm volume and more hailstones in a given entity. One could conclude that the St. Louis urban effects lead to more and to stronger updrafts, which will support more hail growth; but these urban effects do not lead to longer, more sustained updrafts which would result in not only more hail per unit area but longer hailstreaks. Thus, the hail results suggest that the urban effect leads to the intensification of updraft velocities if one accepts that concept of hail growth. The greater frequency of points with hail in the effect areas also supports the concept of urban effects on storm dynamics. This would lead to more and stronger updrafts which in turn would create more hail volumes aloft in a given storm system. The placement of the increased hail activity, 5 to 20 miles beyond the city, when coupled with normal storm motions suggest effects on storm dynamics beginning directly over the urban area.

DISTRIBUTION OF HEAVY RAINSTORMS

F. A. Huff

As part of the METROMEX research on inadvertent weather modification, analyses have been made of the potential urban and topographic effects upon heavy rainfall events. If urban areas intensify or moderate naturally occurring heavy rainstorms, the frequency and magnitude of flood-producing storms within and downwind of these areas will differ from those experienced in rural areas. This would affect the design and engineering requirements for urban and suburban sewer systems. Also, surface water quality (sedimentation and chemical contamination) could be affected. There is increasing nationwide concern with sewer surcharging and such allied problems as basement inundations from storm water, particularly in view of current federal and state environmental regulations. As a result, information on rainfall frequencies expected to occur several times per season, on the average, has become of much greater importance to the hydrologist. If the urban environment increases the frequency of heavy rainfalls, this also becomes a concern in the utilization of planned weather modification to alleviate agricultural and municipal water supply shortages.

A heavy rainstorm is defined as one in which 25 mm (1 inch) or more of rainfall is recorded at a raingage (sampling point). Both the METROMEX study and earlier urban climatic studies (Huff and Changnon, 1973) have indicated that the urban anomaly is closely related to storms which are producing moderate to heavy rainfall naturally. The heavy rainstorm analyses herein are based upon the objective method of storm classification.

Monthly and Seasonal Patterns of 25-mm Storms

Figure B-78 shows the frequency distribution of 25-mm storms during the summers of 1971-1975. A pronounced high was located in the Edwardsville area, where the recorded maximum of 23 at gage 38 was twice the network mean of 11.5 occurrences and over three times the network standard deviation of 2.9. Least frequent occurrence of heavy storms was west of St. Louis. In general, the network pattern is similar to that for total rainfall (figure B-1) and indicative of a major urban effect and a secondary topographic effect on the distribution of heavy rainfall.

The distribution of total rainfall in 25-mm storms is shown in figure B-79, and is also similar to the total storm rainfall pattern of figure B-l. A maximum of 91.90 cm (36.18 inches) was recorded NE of Edwardsville and this is nearly twice the network mean of 47.17 cm (18.57 inches) and nearly 8 times the standard deviation of 11.56 cm (4.55 inches). Again, the primary low was located W-SW of St. Louis which is usually upwind of the urban-industrial area. At the center of the Edwardsville high, over 60% of the total summer rainfall occurred in the 25-mm storms. Only 30 to 35% of the summer rainfall occurred in 25-mm storms immediately W and SW of St. Louis.

Examination of the distribution of 25-mm storm rainfall by months for the 5-year period showed patterns strikingly similar to those for total rainfall. Thus, the 25-mm pattern for June (not shown) indicated a pronounced high in the Edwardsville area and secondary highs in the bottomlands, Ozark foothills, and the SE quadrant of the network. This pattern was nearly a mirror image of the total rainfall pattern of figure B-7.

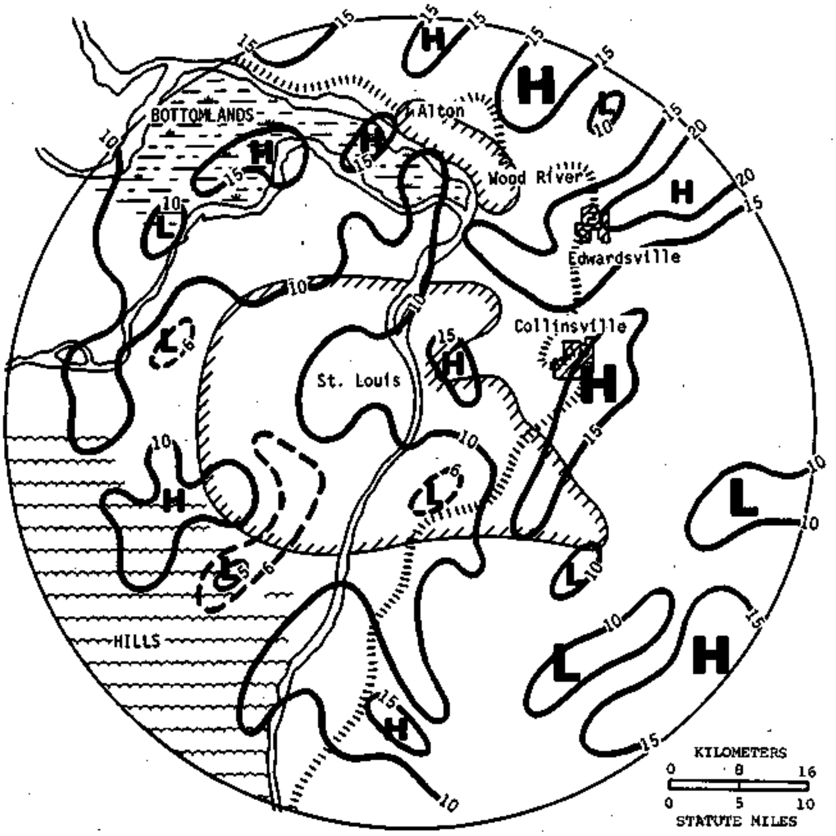


Figure B-78. Frequency of storm rainfall of 25 mm or more during summers of 1971-1975

Similarly, features of the July pattern for 25-mm storms were nearly identical with those for total rainfall. Highs in the 25-mm pattern occurred NE of Wood River, in the bottomlands, the Ozark foothills, and the SE quadrant. For August, both the 25-mm and total storm patterns showed major highs over and just east of the St. Louis urban-industrial area with secondary highs in the Edwardsville area and the SE quadrant. Both August patterns indicated relatively heavy rainfall east of the Mississippi and relatively light amounts west of the river.

Relation between Storm Intensity and the Major Network High

A comparison was made of the difference in rainfall for 1971-1975 between stations in the Edwardsville high and the network mean rainfall for total summer rainfall and for the rainfall associated with storms of various intensity. For this comparison, total summer rainfall was based on the objective storm totals, since the storm analyses were made with the objective storm data. The purpose of the comparisons was to determine how much of the rainfall excess (departure from network mean) in the Edwardsville area could be explained by the more frequent occurrence of heavy rainstorms. '

Five stations that encompassed the core of the Edwardsville high (stations 37, 38, 50, 51, 52) were selected for the comparative analysis. Comparisons were made for storm rainfall in five classifications of intensity.

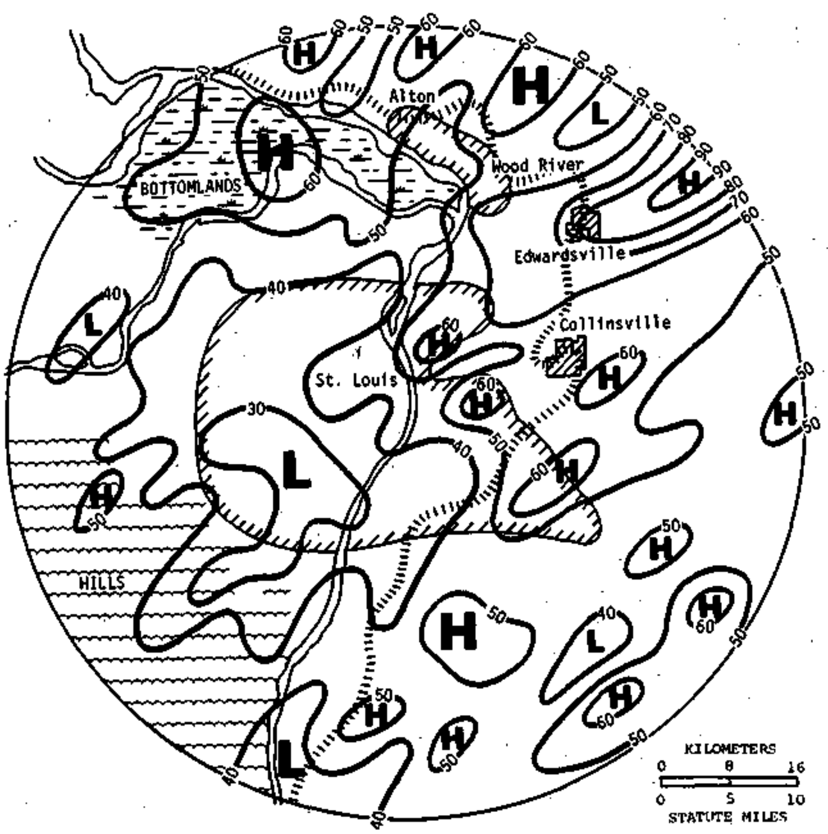


Figure B-79. Total rainfall in 25-mm storms, 1971-1975

Table B-72. Contribution of Storms of Various Intensity to the Summer High in the EDW Area, 1971-1975

	Difference (cm), EDW-network for given range of storm rainfall (mm) for summer, 1971-1975					
Gage	*<2.5*	*2.5-5.9*	*6.0-12.4*	*12.5-24.9*	*≥25.0*	*Total*
37	-1.17	-0.30	-12.12	+10.34	+28.98	+25.73
38	-1.83	-1.45	-0.33	-7.26	+44.75	+33.88
50	-1.04	-0.86	-3.43	+1.42	+40.28	+36.37
51	-1.65	-2.13	+2.18	-6.40	+36.53	+28.53
52	-1.07	+0.33	-5.74	+2.46	+35.36	+31.24
Average	-1.35	-0.88	-3.89	+0.11	+37.18	+31.17

Results are summarized in table B-72 where differences between the total rainfall at the five stations and the network mean are shown for the five storm classifications. Also shown are the total differences between each gage and the network mean, plus average differences in each classification for the various intensities. From table B-72 it is obvious that the rainfall excess in the core of the Edwardsville high is produced almost entirely by the rainfall excess in the heavy storms (≥ 25 mm or 1 inch). Only gage 37 had a substantial portion of its excess produced in storms of light or moderate intensity. Reference to the 5-station averages shows all except 0.11 cm (0.04 inch) was contributed by the heavy storms. Conversely, part of the rainfall excess in the 25-mm storms was offset by larger rainfall amounts in the relatively light storms producing amounts up to 12.4 mm (0.49 inch).

Time Distribution

Analyses were made of the time distribution of rainfall in the 25-mm storms to 1) investigate possible differences in the urban-effect, topographic-effect, and no-effect areas of the network, and 2) determine whether there is any distinct trend for the most intense rainfall to occur in the early, middle, or late parts of these heavy storms. There was particular interest in determining whether the heaviest rainfall tends to occur early in the urban-effect storms, shortly after initial exposure to the urban environment.

The 25-mm storms were divided into three groups including those having durations of 3 hours or less, 3.1 to 6 hours, and 6.1 to 12 hours. None of these storms lasted more than 12 hours, on the basis of the objective storm definition. For comparison purposes, six raingages were selected in each of several areas, as shown in figure B-80. One area was selected in the vicinity of Edwardsville where the 5-summer rainfall maximum occurred, and where it appears that the urban effect is most pronounced. Other areas were selected in the bottomlands (primarily topographic effect), downwind of Alton-Wood River (urban effect), immediate St. Louis urban area, downwind (east) of St. Louis, upwind of St. Louis (no-effect or control area), the SW hills (Ozark foothills), and SE of St. Louis where both urban and topographic effects are likely, depending upon storm movement and the low-level winds.

All storms at the six stations were combined in compiling the statistics for each selected area, and all areas were combined to obtain the network distributions. In each of the three duration groups, the storms were subdivided into those in which the heaviest rainfall occurred in the

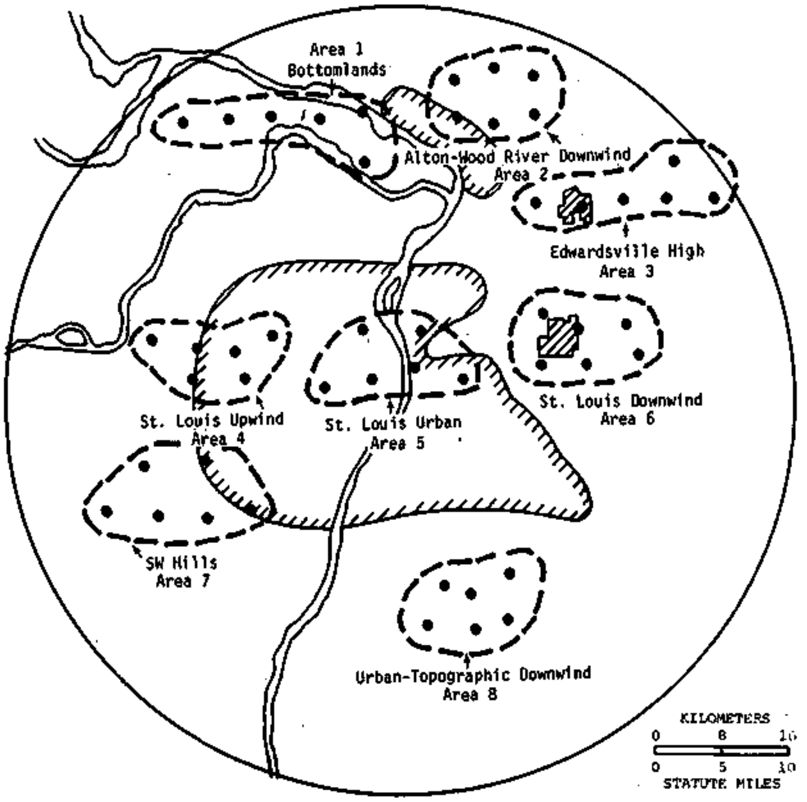


Figure B-80. Subareas used in time distribution analyses of heavy rainstorms

Table B-73. Quartile Relations in Heavy Storms with Durations of 3 Hours or Less

	Frequency of rainfall maximization in each quartile					
	All areas combined		*Areas 3, 5, 6*		*Areas 1, 4, 7*	
Quartile	*Number*	*Percent*	*Number*	*Percent*	*Number*	*Percent*
1	72	29	22	18	28	45
2	101	41	55	47	20	32
3	59	24	29	25	12	20
4	16	6	12	10	2	3
Totals	248	100	118	100	62	100

first, second, third, and fourth quarters of the storm. This classification has been used in previous studies of the time distribution in midwestern storms (Huff, 1967a).

In the short duration storms of 3 hours or less, the heaviest rainfall occurred most frequently in the second quartile when all gages in the eight comparison areas were combined. As shown in table B-73, 41% of the rainfalls sampled had their maximum amounts in the second quarter of the storm, compared with 29 and 24%, respectively, in the first and third quartiles. Only 6% maximized in the latter stages of the storms. Table B-73 also shows statistics for the combination of the three major urban-effect areas (areas 3,5,6 of figure B-80), and for the three areas west of the Mississippi where topographic effects would be the main impetus superimposed on the general synoptic weather conditions.

The second quartile was also the period in which the heaviest rainfall occurred most frequently in the urban-effect areas of St. Louis. In fact, the second-quartile storms dominated in all comparison areas east of the Mississippi. Thus, in the short-duration heavy rainfalls, the most intense rainfall in the urban-effect areas tends to occur after the storm is well under way. A typical storm in this group would last 2 hours, so the heaviest intensities would then most likely occur from 30 minutes to 60 minutes after initiation of surface rainfall.

Table B-73 shows that the first-quartile storms were most frequent in the areas generally upwind of the St. Louis urban-industrial area (W of the Mississippi). Thus, in a typical 2-hour storm, the heaviest rainfall would tend to occur most often in the first 30 minutes following initiation of surface rainfall. As discussed in other sections of this report, the urban effect appears to be much stronger than any of the potential topographic effects in the METROMEX experimental area. Heavy storms (25-mm or more) occur more frequently in the urban-effect areas and tend to produce a greater volume of rainfall than similar storms in the topographic-effect areas. The later maximization of rainfall intensity in the urban-effect storms may be related to time required for new developments in the urban area to reach their peak output, and for downwind mergers of convective entities to occur. Longer duration storms are discussed in the following paragraphs.

First-quartile storms dominated in all areas in those storms lasting 3.1 to 6 hours. Table B-74 shows the quartile distributions for all areas combined, the three St. Louis urban-effect areas, and the three areas west of St. Louis. After evaluating the data for each of the eight areas and various combinations of these areas, it was concluded that the time distribution in the urban-effect storms is not significantly different from that in the topographic-effect or no-effect areas.

The major difference in the two sets of storms ($\leqslant$ 3 hours and 3.1-6.0 hours) was the shift in maximum intensity from the second quartile in the shorter storms to the first quartile in the longer duration storms. However, this is not really a disagreement. In a first-quartile storm of 4-hour duration, the maximum intensity would occur within the first hour, and in 1.25 hours

Table B-74. Quartile Relations in Heavy Storms with Durations of 3.1 to 6 Hours

	Frequency of rainfall maximization in each quartile					
	All areas combined		*Areas 3, 5, 6*		*Areas 1, 4, 7*	
Quartile	*Number*	*Percent*	*Number*	*Percent*	*Number*	*Percent*
1	71	65	28	58	18	69
2	20	18	11	23	5	19
3	11	10	5	11	2	8
4	8	7	4	8	1	4
Totals	110	100	48	100	26	100

in a 5-hour storm. It was pointed out previously that in a typical short-duration storm of 2 hours, the maximum intensity would tend to occur from 30 to 60 minutes after rain initiation.

The sample of storms was much smaller in the group having durations of 6.1 to 12.0 hours. Thus, among the 48 network stations included in the 8 sampling areas, there were only 53 occurrences of storms in this duration group, compared with 110 cases in the group from 3.1 to 6 hours and 248 storms having durations of 3 hours or less. Thus, 60% of the 25-mm storms had durations of 3 hours or less, 27% lasted 3.1 to 6.0 hours, and only 13% precipitated for more than 6 hours. In the long-duration storms of 6.1 to 12 hours, the heaviest intensity again occurred most frequently in the first quartile. A total of 34 (64%) of the 53 cases were first quartile storms.

Distribution of Heavy Hourly Rainfall

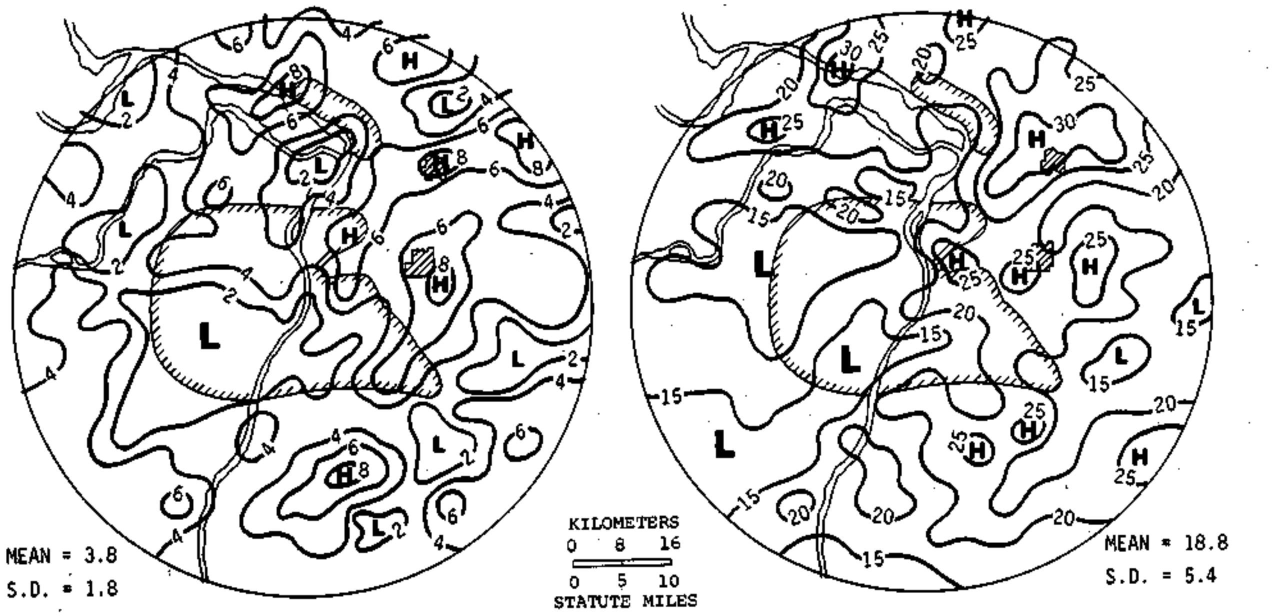
As part of the investigation of the relationship of heavy rainstorms to the network anomalies, analyses were made of the distribution of hourly amounts equaling or exceeding 12.5 mm (0.5 inch) and 25 mm (1 inch). These intensities are usually associated with the heavy rain producers and, therefore, occur infrequently as indicated by the network mean frequencies of 18.8 and 3.7 occurrences, respectively, for the 12.5-mm and 25-mm intensities during the five summers. The frequency distributions of the 12.5-mm and 25.0-mm hourly amounts are shown in figure B-81.

The spatial distributions are very similar for the two intensities, and are strikingly similar to the total summer rainfall pattern of figure B-1 and the patterns for both the frequency distribution and total rainfall associated with the heavy rainstorms in figures B-78 and B-79. The Edwardsville high, the bottomlands high, the upwind low, and the SE quadrant highs are all outstanding features of the hourly maps.

The results of the hourly rainfall analysis provide further verification of the extreme importance of heavy rainstorms and heavy intensities within storms in establishing the total rainfall pattern of figure B-1. Various analyses discussed in this report indicate that the urban and topographic anomalies are closely related to external mechanisms operating during naturally favorable conditions for the development and sustainment of convective precipitation. Consequently, it is most important to establish how and to what extent the external mechanisms operate under various synoptic conditions.

Summary and Conclusions

Analyses of heavy rainstorms, defined as those producing gage amounts of 25 mm (1 inch) or more, were made to investigate their relationship to the urban anomaly. Results showed a pro-



a. Frequency of hourly rainfall ≥ 25mm

b. Frequency of hourly rainfall ≥ 12.5mm

Figure B-81. Distribution of heavy hourly rainfalls, 1971-1975

nounced maximum in both the frequency of heavy storms and in the rainfall produced from these storms in the Edwardsville area where the urban anomaly apparently is strongest. At the center of the Edwardsville high, over 60% of the total summer rainfall occurred in these storms, whereas in the network low situated WSW of St. Louis only 30 to 35% of the summer rainfall was associated with the heavy storms. The heavy storm effect was most pronounced in June, and dominated the total rainfall pattern for that month.

Analyses of rainfall for five stations in the center of the Edwardsville high indicated that the total rainfall excess in that area was produced almost entirely by heavy storms yielding 25 mm (1 inch) or more.

Analyses of the time distribution of storm rainfall indicated no significant difference in the distribution characteristics of rainfall in urban-effect, topographic-effect, and no-effect areas. In general, the heaviest rainfall in short-duration storms (less than 3 hours) occurred most often in the second quarter of the storm period, whereas it occurred in the first quarter in storms lasting more than 3 hours.

Analyses of heavy hourly rainfalls producing amounts equaling or exceeding 12.5 mm and 25 mm (0.5 and 1 inch) showed a spatial distribution that is strikingly similar to the total summer rainfall pattern for the five summers. Thus, the Edwardsville high, the bottomlands high, the upwind low, and the SE quadrant high of the total rainfall pattern were all outstanding features of the hourly maps.

All of the analyses reported in this section provide evidence of the extreme importance of heavy rainstorms and heavy intensities within storms in establishing the total rainfall pattern in the METROMEX Network and the urban anomaly within the experimental area.

DISTRIBUTION OF HEAVY RAINCELLS

F. A. Huff

Since the METROMEX Network has been the largest urban meteorological network in existence, it provides an excellent opportunity to improve our knowledge of urban and localized topographic effects upon all types of precipitation. In this section, the properties of intense raincells, which are closed isohyetal entities within the enveloping isohyet of the parent storm system, are summarized and potential urban and topographic influences on them are discussed.

Raincells, which are determined from 5-minute rainfall amounts at the 225 raingages, are the basic storm entity from which heavy, short-duration rates develop in thunderstorm-dominated climates such as the Midwest. During the summers of 1971 through 1975, 8119 of these cells were completely contained within the circular METROMEX Network. Primary emphasis in the raincell analyses has been placed on urban effects of* concern to hydrologists.

With 225 gages distributed over a 5200-km^2 (2000-mi^2) area, a relatively large sample of raincells has been collected. By investigating the properties of the more intense cells among this 8119-cell sample, much can be learned about the general characteristics of these small-scale events and their importance in urban hydrology, especially those rainfall properties applicable to the various problems of urban sewer design and engineering. Network raincell data collected over several years, can be particularly useful in defining short-period rain rates expected to occur several times per year or season. For example, the METROMEX data have already provided considerable help in a study performed for the Illinois Environmental Protection Agency which needed information on the frequency of seasonal precipitation amounts expected to occur one to five times per season for time intervals of 5 to 60 minutes.

Raincell Data and Analytical Procedure

In the METROMEX studies, a raincell was defined as a closed isohyetal entity within the overall enveloping isohyet of a rainstorm system; that is, it defines an isolated area of significantly greater intensity than the system enveloping isohyet, and must last for more than 5 minutes to qualify as a cell. When raincells develop apart from a multicellular rain system, no system enveloping isohyet is present, and the cell is uniquely defined by the separation between rain and no rain(Schickedanz, 1973b). Complete cells are defined as those which spent their entire lifetime on the network; that is, they developed, matured, and dissipated within the confines of the METROMEX Network, so that all phases can be studied. A raincell may be one of several convective entities within a mature thunderstorm.

From the 1971-1975 sample of 8119 complete raincells, those having mean rainfall equaling or exceeding 6 mm (0.25 inch) were selected for detailed hydrometeorological analyses. This provided a sample of 659 cells which is approximately 8% of the total number analyzed. However, the 659 heavy cells accounted for 51% of the total water yield (rainfall volume) from the 8119 cells. This illustrates their great importance in evaluating the urban anomaly.

In evaluating the general characteristics of the 659 intense raincells, numerous definitive parameters were determined. These included such parameters as the raincell volume (water yield), mean rainfall, area encompassed, cell duration, movement, path length, rainfall gradient, and diurnal distribution. The time of initiation of each cell was determined to ascertain whether preferential periods of occurrence prevailed. The synoptic weather storm type in which each cell occurred was also recorded to determine if the intense cells were biased toward development in particular types of weather conditions.

The stratification of the heavy raincell data had to be limited because of the inclusion of only 8% of the total sample in the hydrometeorological analyses. First, the sample was divided into three basic types for evaluation. There were urban-effect (U), topographic-effect (T), and no-effect raincells (C). A cell was placed in the urban-effect group if it developed over one of the two urban-industrial areas (St. Louis and Wood River) or passed over one of these areas during its lifetime.

Similarly, topographic-effect cells were those which developed over or crossed a distinct topographic feature. The two significant features in the METROMEX Network (figure B-1) are the Ozark foothills in the southwestern part of the network and the bottomlands in the northwestern quadrant. Initially, these were placed in separate groups, but were later combined because of the small sample size.

No-effect cells were then defined as those which had no contact with the urban environment or topographic features during their lifetime; these were essentially rural cells moving across the relatively flat farmlands within the network.

Of the 659 heavy raincells, 331 were classified as no-effect (control) cells, 224 were urban-effect cells, and 72 were topographic cells. The remaining 32 cells in the 659-cell sample were combinations involving cells exposed to two of the effect regions. Analyses were limited to the three major groups. These were then further subdivided into moving and quasi-stationary cells, in which those having a path length less than 5 km (3 mi) were classified quasi-stationary. This division was made because the characteristics of these two types showed considerable variance.

The relatively small sample of topographic-effect cells results from the network layout. With the circular network of 5200 km^2 (2000 mi^2) centered on St. Louis (figure B-1), urban-effect cells will be sampled much more frequently than topographic-effect cells moving across the Ozark foothills in the southwestern corner of the network and the river bottomlands in the northwestern quadrant.

The sampling frequency of the topographic features is limited because these areas are located near the network boundary, and because the topographic-effect cells sometimes become involved with the urban environment also as they move across the network. The sampling of the no-effect (control) cells is relatively frequent, because on any given day much of the area west and some of that east of St. Louis can have cell generation and movement without contamination by the urban environment or conflict with the major topographic features.

Typical Raincell Properties

Medians of several important raincell parameters of moving and quasi-stationary cells are shown in tables B-75 and B-76. These illustrate their general magnitude in typical or average conditions and how the parameters vary between moving and quasi-stationary cells and between urban-effect, topographic-effect, and control cells.

Table B-75. Raincell Medians in Moving Cells with Mean Rainfall of 6 mm or More, Summers, 1971-1975

Raincell parameter	Medians for given parameter		
	Urban effect	Topographic effect	Control
Mean rainfall, *mm*	9	9	9
Area, *km*^{2}	132	111	98
Mean intensity, *mm/hr*	13	14	16
Volume, *m*^{3}	12.45×10^5	10.60×10^5	9.25×10^5
Duration, *min*	42	38	33
Path length, *km*	12	11	8

Table B-76. Raincell Medians in Quasi-Stationary Cells with Mean Rainfall of 6 mm or More, Summers, 1971-1975

Raincell parameter	Medians for given parameter		
	Urban effect	Topographic effect	Control
Mean rainfall, *mm*	10	10	9
Area, *km*^{2}	54	44	44
Mean intensity, *mm/hr*	30	27	36
Volume, *m*^{3}	4.99×10^5	4.25×10^5	3.39×10^5
Duration, *min*	20	22	15
Path length, *km*	1	0+	0+

Referring to tables B-75 and B-76, volumes, areas, and durations are substantially larger in the moving cells than in the quasi-stationary cells, but differences in cell mean rainfall are insignificant. Naturally, the path length of the moving cells by definition has to be much greater. However, the quasi-stationary cells tend to have more intense rainfall during their lifetime than do the moving cells, as indicated by the mean intensity medians. Thus, the quasi-stationary cells tend to be much smaller in areal extent, duration, and water output (volume) than the moving cells, but while they last they tend to rain harder than the moving cells.

With regard to water output at the surface, the moving cells are approximately 2.5 times more productive than the quasi-stationary cells. Since the moving cells tend to rain longer at a slower rate, they are less likely to produce soil erosion, and surface runoff could be less of a problem. These observations are in general agreement with studies of heavy, flood-producing storms in Illinois in which flash floods are produced most frequently by quasi-stationary convective activity within mesoscale areas ranging from a few hundred to several thousand square miles (Huff, 1967b; Huff and Changnon, 1964; Huff et al., 1958).

Table B-77 shows the effect of combining moving and quasi-stationary cells to obtain a measure of the net effect from all cells exposed to urban or topographic influences. Naturally, the parameter values fall between the moving and quasi-stationary cells. For many applications, the net effect of all cells would be most useful. However, the separation into moving and quasi-stationary types can be useful in evaluating causes of the urban and topographic effects, since they provide a more detailed breakdown of the events.

Table B-78 shows ratios between the U, T, and C cells. This shows that the water yield from the heavy raincells (volume) tends to be much greater in the effect cells, and substantially greater in the urban-effect than in the topographic-effect cells. The water yield differential is largely due to greater areal extent, since volume is the product of area and rainfall depth. As

Table B-77. Raincell Medians in All Cells
with Mean Rainfall of 6 mm or More, Summers, 1971-1975

Raincell parameter	*Urban effect (U)*	*Topographic effect (T)*	*Control (C)*
	Medians for given parameter		
Mean rainfall, *mm*	10	9	9
Area, km^2	99	91	60
Mean intensity, *mm/hr*	17	16	23
Volume, m^3	9.31×10^5	7.25×10^5	5.49×10^5
Duration, *min*	35	34	24
Path length, *km*	8.0	6.5	3.6

Table B-78. Raincell Median Ratios in All Cells
with Mean Rainfall of 6 mm or More, Summers, 1971-1975

Raincell parameter	*U/C*	*T/C*	*U/T*
	Medians for given parameter		
Mean rainfall, *mm*	1.11	1.00	1.11
Area, km^2	1.65	1.52	1.09
Mean intensity, *mm/hr*	0.74	0.70	1.17
Volume, m^3	1.70	1.33	1.28
Duration, *min*	1.46	1.42	1.03
Path length, *km*	2.22	1.81	1.23
Rainfall gradient, *mm/km*	1.08	1.00	1.08

evident in tables B-75 and B-76, only small differences in mean rainfall (rainfall depth) exist among the three types. The relatively large ratios for both duration and path length indicate that the larger areas encompassed by effect cells are strongly related to the longer lives of these cells which cause them to sweep out larger areas and travel farther than the control (rural) cells.

In summary, comparison of the urban, topographic, and control medians in tables B-75 through B-78 show that volume, area, and duration tend to be larger in the urban than in the topographic cells, and both exceed the control values. There is little difference among the three types in mean rainfall, but mean rainfall rates are greater in the control cells. Thus, the analyses indicate that the urban environment enhances the total water output more than do the topographic features, but both indicate a substantial effect when compared with the control values.

As indicated above, the greater water output in the effect cells results from larger cells (areally) that last longer than the no-effect cells, but, the no-effect cells tend to rain harder, on the average, within their boundaries. A possible explanation is that the urban and topographic inputs to the precipitation processes (inadvertent weather modification) tend to make convective entities grow larger horizontally and last longer, but also reduce rain rates. This suggests that weather modification operations may produce additional water output within a given area at less intense rates than would occur naturally.

Comparative Analyses of Water Yield from Effect and No-Effect Raincells

The preceding discussion has been concerned with typical raincell properties as portrayed by the medians of the distributions of urban-effect, topographic-effect, and no-effect cells. More detailed comparison of differences in heavy (rainfall ⩾6 mm) raincell characteristics among these three types has been presented in tables B-79, B-80, and B-81. These tables were derived from frequency distribution curves constructed for each parameter from the available data sample.

Table B-79. Comparison of Water Yield between Urban-Effect (U), Topographic-Effect (T), and No-Effect (C) Raincells among Moving Cells with Mean Rainfall of 6 mm (0.25 in) or More during Summers of 1971-1975

Cumulative percent of raincells	Cell volumes (10^{-6} m^3) equaled or exceeded			Volume ratios		
	U	T	C	U/C	T/C	U/T
5	47.47	27.13	30.33	1.57	0.89	1.75
10	33.66	20.96	22.69	1.48	0.92	1.61
20	23.06	16.03	16.40	1.41	0.98	1.44
30	17.76	13.44	13.19	1.35	1.02	1.32
40	14.80	11.84	10.97	1.35	1.08	1.25
50	12.45	10.60	9.25	1.35	1.15	1.17
60	10.73	9.62	8.01	1.34	1.20	1.12
70	9.25	8.76	7.03	1.32	1.25	1.06
80	7.89	7.89	6.17	1.28	1.28	1.00
90	6.47	7.03	5.12	1.26	1.37	0.92
95	5.55	6.41	4.56	1.22	1.41	0.87
N	142	41	137			

Table B-80. Comparison of Water Yield between Urban-Effect (U), Topographic-Effect (T), and No-Effect (C) Raincells among Quasi-Stationary Cells with Mean Rainfall of 6 mm (0.25 in) or More during Summers of 1971-1975

Cumulative percent of raincells	Cell volumes (10^{-6} m^3) equaled or exceeded			Volume ratios		
	U	T	C	U/C	T/C	U/T
5	19.97	14.67	10.60	1.88	1.38	1.36
10	14.67	11.22	8.26	1.78	1.36	1.31
20	10.11	8.01	6.04	1.67	1.33	1.26
30	7.77	6.29	4.81	1.62	1.31	1.24
40	6.23	5.12	4.01	1.55	1.28	1.22
50	4.99	4.25	3.39	1.47	1.25	1.17
60	4.07	3.51	2.84	1.43	1.24	1.16
70	3.27	2.90	2.40	1.36	1.21	1.13
80	2.59	2.34	2.03	1.27	1.15	1.11
90	1.97	1.85	1.66	1.19	1.11	1.06
95	1.73	1.66	1.54	1.12	1.08	1.04
N	82	31	194			

They show the magnitude of the parameter values along the curve and the ratio of the effect to no-effect values at selected points along the frequency curves.

A major source of information on the urban and topographic effects on rainstorms has come from these comparative analyses of heavy raincells (Huff, 1975). Of major importance is the difference in water output exhibited by the effect and no-effect cells, as measured by raincell volumes. Raincell volume integrates the effects of rainfall intensity, rain duration, speed of movement, and horizontal extent of raincells. Water yield is a most important consideration from both hydrological and agricultural considerations.

Tables B-79 and B-80 show comparison of the frequency distributions of water yield from the three types of cell stratification for moving and quasi-stationary raincells. Table B-79 for moving cells shows that both percentage and absolute magnitude differences increase with increasing cell volumes; that is, the urban effect tends to be greater among large than among small cells. For example, the highest 30% of the rainfall volumes in the urban cells were 35% or more

Table B-81. Comparison of Water Yield between Urban-Effect (U), Topographic-Effect (T), and No-Effect (C) Raincells among All Cells with Mean Rainfall of 6 mm (0.25 in) or More during Summers of 1971-1975

Cumulative percent of raincells	*Cell volumes (10^{-5} m^3) equaled or exceeded*			*Volume ratios*		
	U	*T*	*C*	*U/C*	*T/C*	*U/T*
5	36.99	26.76	21.45	1.72	1.25	1.38
10	27.37	19.97	15.91	1.72	1.26	1.37
20	18.86	14.06	10.97	1.72	1.28	1.34
30	14.55	10.97	8.51	1.71	1.29	1.33
40	11.47	8.88	6.78	1.69	1.31	1.29
50	9.31	7.28	5.49	1.70	1.33	1.28
60	7.52	5.92	4.50	1.67	1.32	1.27
70	6.04	4.75	3.58	1.69	1.33	1.27
80	4.62	3.70	2.77	1.67	1.33	1.25
90	3.21	2.59	1.91	1.68	1.35	1.24
95	2.34	1.97	1.42	1.65	1.39	1.19
N	224	72	331			

greater than those of the no-effect (rural) cells, and this corresponds to a curve difference (U - C) equal to or greater than 4.57×10^5 m^3 (370 acre-feet). Thus, this table provides evidence of.an increasing urban effect with increasing raincell yield from natural causes, and this is in agreement with other analyses which show the urban effect to be generally greatest in moderate to heavy storms.

The T/C ratios do not show an increase with increasing water yield (larger cells); in fact, an opposite trend is indicated. That is, the difference between the T cells and the C cells becomes proportionally greater among cells with relatively small water yields. In view of the relatively small sample of topographic cells (41), the crossover in ratios at the upper end of the frequency curve may be a sampling vagary, rather than a real trend. In any case, both urban-effect and topographic-effect cells have larger median values of water output than do the control cells, and this is supporting evidence for frequent enhancement of natural rainfall processes by topographic factors and the urban environment. On the basis of the frequency distributions, the urban effect is substantially larger than the hill-bottomlands effect in the METROMEX Network.

Table B-80 summarizes the frequency distribution of cell water yields for the quasi-stationary cells. With this cell type, both the U and T cells show maximum differences from the C cells among the larger cells; that is, the volume ratios decrease from the upper end to the lower end of the frequency distributions. Again, the U — C differences are substantially larger than the T — C differences, and the U volumes exceed the T volumes throughout the distribution. Thus, with both moving and quasi-stationary cells, the urban effect is more pronounced than the topographic effect.

For hydrologic applications and most other uses, the major interest is in the net effect of the urban and/or topographic effects on the rainfall distribution characteristics in the affected area. Therefore, table B-81 shows the combined or net effect of urban and topographic influences on the distribution of water yield in heavy raincells. The urban effect is pronounced. Thus, the median water yield is 70% greater than in the control cells and ranges from 65 to 72% along the frequency distribution curves. The topographic enhancement is less, having a median of 33%, and a range from 25 to 39% along the frequency curves. As indicated by the U/T ratios in the last column of table B-81, the urban effect is approximately 20 to 40% greater than the topographic effect with a median of 28% in the 1971-1975 sample. It is again emphasized that the topographic sample is small compared with the other two cell types, and should be considered only a first approximation of the average enhancement associated with the hills and bottomlands in the St. Louis region.

Table B-82. Sample Sizes for Storm Types and Comparison Areas

Storm type	Urban		Topographic		Control		All types	
	Number	Percent	Number	Percent	Number	Percent	Number	Percent
Squall line	124	55	26	35	172	52	322	51
Squall area	51	23	22	31	72	22	145	23
Cold front	30	13	12	17	51	15	93	15
Warm plus static front	12	5	10	14	21	6	43	7
Air mass	6	3	2	3	9	3	17	3
Others	1	1	0	0	6	2	7	1
Totals	224	100	72	100	331	100	627	100

Distribution of Heavy Raincells by Synoptic Storm Type

Analyses were made to determine how the heavy raincell distribution was related to basic types of synoptic storm systems. The synoptic types and their sample sizes are shown in table B-82. This table shows that the heavy cells are most frequently associated with squall systems (squall lines plus squall areas) which account for 74% of the cells, and squall lines alone occurred with 51% of the heavy rain producers. Squall systems are most often associated with cold fronts; squall systems plus cold fronts occurred in 89% of the cases. The non-frontal air mass storms which are the most frequent type of storm in summer accounted for only 3% of the heavy cell occurrences. Thus, intense corivective activity is largely restricted to organized storm systems, particularly squall systems which frequently precede cold front passages.

It is interesting to compare the frequency distribution of heavy raincell types (table B-82) with the frequency of rainstorms grouped by synoptic type (table B-83) discussed in the section on synoptic rainfall relations. The frequency distributions of cold fronts, squall areas, and warm plus stationary fronts do not vary greatly between the heavy raincells and rainstorms. The major differences are in the frequency of squall lines and air mass storms. Only 14% of the rainstorms were classified squall lines compared with 51% of the heavy cell occurrences. Only 3% of the heavy cells were classified air mass compared with 27% of the 1971-1975 rainstorms. Thus, although squall lines were the most frequent producer of heavy raincells, such storms rank only third in frequency of occurrence. However, other analyses showed they do account for 50% of the total summer rainfall. Similarly, although air mass storms are the most frequent (27%), they produced only 2% of the total summer rainfall. Thus, the probability of heavy water yields is most likely to occur in the presence of squall line activity.

Table B-84 shows median water yields for the various synoptic storm types in urban-effect, topographic-effect, and no-effect cells. The greatest median outputs occurred with squall lines and cold front passages, and the smallest median was with the air mass storms. Among the three major rain producers (squall lines, squall areas, and cold fronts), the largest differences between urban-effect and no-effect cells occurred with the cold fronts and squall lines which are strongly related to each other. The median outputs were also greatest with squall lines or cold fronts in the topographic-effect and no-effect cells. Thus, these two types are the most likely to produce intense rainfall in summer convective storms in the St. Louis area. Considering the frequency of occurrence (table B-82) and median rain

Table B-83 Frequency of Rainstorms Grouped by Synoptic Type

Storm type	Number of storms	Percent of storms
Squall line	48	14
Squall area	83	25
Cold front	46	14
Warm plus static front	33	10
Air mass	90	27
Low center	5	2
Others	25	8

Table B-84. Medians of Raincell Volumes Grouped by Synoptic Weather Types

Synoptic type	Volume, m^3			Ratios		
	Urban (U)	Topographic (T)	Control (C)	U/C	T/C	U/T
Squall line	1.05×10^6	1.00×10^6	5.36×10^5	1.96	1.87	1.05
Squall area	7.90×10^5	7.48×10^5	5.08×10^5	1.56	1.47	1.06
Cold front	1.14×10^6	6.77×10^5	5.52×10^5	2.07	1.23	1.68
Warm plus static front	8.10×10^5	7.14×10^5	4.07×10^5	1.99	1.75	1.13
Air mass	6.77×10^5		3.00×10^5	2.26		

volumes (table B-84), a major portion of the urban anomaly would be expected to occur with cold fronts and squall systems. This is borne out by the 5-summer patterns of monthly and seasonal rainfall grouped by synoptic type, and discussed in the section on synoptic rainfall relations.

Other analyses showed that the large differences in water yield between the urban and control cells are related most strongly to differences in cell areas and duration rather than to differences in cell mean rainfall. Thus, for squall lines the U/C ratio was 2.02 for cell area and 1.75 for duration compared with 1.15 for mean rainfall. Similar medians for cold fronts were 2.18 (area), 1.43 (duration), and 0.90 (mean rainfall). The combination of larger areas and duration leads to relatively large differences in path length. Median U/C ratios of path length were 1.97 (squall lines), 2.00 (squall areas), and 2.60 (cold fronts).

Computation of median rain intensities (table B-85) showed that the topographic-effect and control cells tend to have substantially greater intensities than the urban-effect cells. Overall, the differences were most pronounced between urban and control cells. The combined results of the computations of water yield, cell area, duration, mean rainfall, and rain intensity indicate that inadvertent weather modification by the urban area leads to a tendency for urban-effect cells to increase their natural water yield, but at the same time to decrease in mean rainfall intensity. That is, the urban-induced increase in cell water yield apparently results from increases in cell area and duration with an associated decrease in rain rate.

Movement of Heavy Raincells

The movement of heavy raincells which produced 51% of all the cellular rainfall sampled within the METROMEX Network during 1971-1975 was investigated. Quasi-stationary cells were omitted from this analysis. Movement of the cells determines to a considerable extent where the urban-induced rainfall will occur with respect to the metropolitan area. Movement distributions were determined for urban-effect, topographic-effect, and no-effect cells. Direction of movement was specified by 30-degree sectors of azimuth with azimuth referring to the *direction from which the cell was moving.*

Table B-85. Median Intensity of Heavy Raincells Grouped by Synoptic Type

Synoptic type	Rain intensity mm/hr		
	Urban	Topographic	Control
Squall line	17.0	16.5	27.0
Squall area	15.6	22.4	17.8
Cold front	15.6	24.5	25.3
Warm plus static front	14.4	15.1	25.2
Air mass	9.1		11.8

The frequency distribution of cell directions is summarized in table B-86. Urban-effect cells moved most frequently from 210 to 299° (SW to WNW). They are also the directions which are most likely to subject moving cells to exposure over large portions of the urban-industrial area. Both the topographic-effect and control cells moved most frequently from 240 to 299°. Only a

Table B-86. Frequency of Heavy Raincells Grouped by Movement

Azimuth (degrees)	Number and percent of total for given area					
	Urban		Topographic		Control	
	Number	Percent	Number	Percent	Number	Percent
181-209	5	3.5	11	8.0	2	4.9
210-239	31	21.8	16	11.7	4	9.8
240-269	31	21.8	27	19.7	12	29.3
271-299	28	19.7	25	18.2	10	24.4
300-329	20	14.1	17	12.4	6	14.6
330-359	10	7.0	13	9.5	1	2.4
1-29	5	3.5	6	4.4	2	4.9
30-59	3	2.1	1	0.7	1	2.4
60-89	0	0	6	4.4	0	0
91-119	4	2.8	4	2.9	0	0
120-149	0	0	4	2.9	1	2.4
150-179	5	3.5	7	5.1	2	4.9
Totals	142		137		41	

Table B-87. Frequency of Heavy Raincells Grouped by Time of Day

Time (CDT)	Number and percent of total for given area					
	Urban		Topographic		Control	
	Number	Percent	Number	Percent	Number	Percent
00-03	11	4.9	3	4.2	22	6.7
03-06	9	4.0	5	6.9	17	5.2
06-09	6	2.7	5	6.9	40	12.1
09-12	9	4.0	5	6.9	18	5.4
12-15	37	16.5	9	12.5	59	17.9
15-18	93	41.6	22	30.6	72	21.8
18-21	31	13.8	14	19.5	60	18.2
21-24	28	12.5	9	12.5	42	12.7
Totals	224		72		330	

small percentage of the raincells moved from an easterly direction (01 to 179°), so the urban-effect from the heavy raincells would be expected to occur mostly east of the urban-industrial region, as shown by the seasonal rainfall pattern discussed elsewhere.

Diurnal Distribution of Heavy Raincells

Table B-87 shows the frequency distribution of heavy raincells grouped by time of day when they initiated. The most frequent occurrence of all three cell types was in the late afternoon (1500-1800), but the frequency of urban-effect cells was significantly greater during this period than were the other two types. During the afternoon, the urban heat output (heat island) is superimposed on the diurnal peak in solar heating, and this tends to accelerate destabilization of the low-level atmosphere. In turn, this increases the convective potential for cloud formation or enhancement, through strengthening of vertical motions and, possibly, through accelerating the transport of condensation and/or ice nuclei from stack outputs to cloud-base level.

The frequency of urban-effect cells at 1500 to 1800 was 2.67 times greater than the number occurring in the 12 hours from midnight to noon. Over 84% of the heavy urban-effect cells occurred from noon to midnight. This includes the afternoon hours when diurnal heating plus urban heat output provide a more favorable atmosphere for convective development, and the evening hours when mesoscale storm systems that develop in the afternoon are likely to persist.

Examination of the topographic and control frequencies in table B-87 shows that 25% of the topographic-effect cells and 29% of the control cells occurred in the hours from midnight to noon, compared with only 16% of the urban-effect cells. Thus, the urban-effect cells (as expected) show a stronger association with surface heating, and their concentration in afternoon indicates a relatively strong dependency upon this mechanism for development and/or enhancement of convective precipitation.

Summary and Conclusions

Analyses were made of the apparent urban and topographic effects upon the distribution of heavy raincells, which are the basic storm entity associated with heavy, short-duration rates in thunderstorm-dominated climates, such as the Midwest. This information is especially useful to urban hydrologists, since significant enhancement of heavy rain intensities by the urban environment will affect the design requirements for urban stbrm-sanitary sewer systems in metropolitan regions.

For this study, analyses were made of those raincells which had a mean rainfall of 6 mm (0.25 inch) or more in the METROMEX Network during 1971-1975. This included 659 cells, or approximately 8% of those sampled during the 5-summer period. Only cells which spent their entire lifetime on the network were used. Cells were defined as closed isohyetal entities (intensity centers) within the enveloping isohyet of the parent storm system, and had to last for more than 5 minutes to qualify. Cells were grouped into three general classes which included those exposed to the urban-industrial complex at some time during their life, those coming under the possible influence of the two significant topographic features in the network (Ozark foothills and river bottomlands), and those which were not contaminated by either of these exposures. No effort was made to segregate bluff exposed cells since the bluffs occur on such a small portion of the network area. The uncontaminated cells were largely restricted to the surrounding flat farmlands and were used as a control in evaluating the urban and topographic effects.

The heavy raincells were subdivided into moving and quasi-stationary cells for study of their properties. Analyses indicated that volumes (total water yield), areas, and durations are substantially larger in moving cells, but mean rainfall variation's are insignificant. However, quasi-stationary cells tend to rain harder (more intense) while they last. The moving cells exposed to urban or topographic effects had median water outputs that were 2.5 times greater than the quasi-stationary cells. Since moving cells tend to rain longer at a slower rate, they are less likely to produce soil erosion and runoff will not peak as rapidly.

Comparison of urban, topographic, and control cells showed that volume (water yield), area, and duration tend to be substantially greater in the urban than in topographic cells, and both exceed control (no-effect) cells. Mean rainfall rates, however, were greater in the no-effect cells. Thus, indications are that the urban environment enhances the total water output more than do the topographic features, but both have a substantial effect compared with no-effect cells. The greater output in the effect cells is produced by larger cells (areally) that last longer than the no-effect cells, and overbalances a tendency for the no-effect cells to rain harder during their shorter life. This suggests that the inadvertent weather effects tend to make convective entities grow horizontally and last longer, but to suppress rain rates also. This implies that weather modification may produce additional water output within a given area, but, at the same time, reduce potential disbenefits from excessive rain rates.

Comparative analyses of the water yield from effect and no-effect raincells showed substantially greater output in the urban-effect and topographic-effect cells. Thus, the median water yield from the urban-effect cells was found to be 70% greater than in the no-effect cells, whereas the topographic-effect was somewhat less with a median 33% greater than the no-effect cells. Thus, the urban effect was found to be a stronger influence than the topographic-effect. In fact, the urban median water yield was 28% greater than that of the topographic cells.

Analyses of the distribution of heavy raincells by synoptic weather type showed that these cells usually occurred in conjunction with organized weather systems. Approximately 51% of the cells occurred with squall systems (squall lines and squall areas), whereas only 3% resulted from non-frontal, air mass showers.

Other analyses showed that the heavy cells moved most frequently from the SW, WSW, and WNW, which accounted for 63% of the urban-effect cell movements, 50% of the topographic-effect cells, and 64% of the no-effect cells. The heavy cells initiate most frequently in the late afternoon, and this is particularly true with the urban-effect cells which are subjected to the combined destabilizing effects of peak solar heating and the man-made urban heat island in the afternoon. Approximately 42% of the urban cells initiated from 1500 to 1800 CDT, and this is nearly 30% more than originated in the 12-hour period from midnight to noon.

From the heavy cell analyses, we find that a typical urban-effect cell will produce 70% more rainfall than a no-effect cell, occur within a squall line in the late afternoon, move from the WSW, grow in areal extent as it becomes exposed to the urban environment, and maximize ENE to NE of the urban-industrial area.

OTHER SEVERE LOCAL STORM PHENOMENA

Stanley A. Changnon, Jr.

Some investigations of METROMEX concerned severe storm conditions other than heavy rains, thunderstorms (lightning), and hail. Attention was given to high surface wind speeds and to tornado activity during METROMEX.

High Surface Winds

Detailed gust data were collected at 8 sites distributed around the circumference of a circle with a radius of about 20 mi (32 km) from the center of St. Louis. These were cup and vane anemometers on 15-ft (4.6-m) masts. Analyses focused on maximum gusts recorded during each hour.

An indication of possible urban effects on severe storms is in the spatial frequency of strong gusts during the summers of 1971-1975. One analysis was based on a count of the strongest gust in each hour. Data were grouped on the basis of three wind stations located to the SW, W, and NW of St. Louis (classed as having no potential urban effect), and three stations located to the SE, E, and NE of St. Louis. These were classed as potentially urban affected sites since they were either in or near to the areas of greater thunder (figure B-53) and hail frequencies (figure B-66). All stations chosen were 15 to 20 mi (24 to 32 km) from the center of the city.

The average point frequencies of maximum hourly gust ≥ 30 and ≥ 40 mph (48 to 64 km/hr) appear in table B-88. The effect area frequency of hours with ≥ 30 mph gusts is double (100% increase) the no-effect area frequency. The difference in gusts ≥ 40 mph reveals a 91% increase in the urban effect area. These are sizeable but not unlike several of the urban-rural (effect-no effect) percentage differences obtained for certain characteristics of thunderstorms, hailfalls (energy), and heaviest raincells. All the gusts at the effect and no-effect sites during 1971-197.5 were associated with thunderstorms. Synoptically, the gusts occurred with squall lines and areas and with cold fronts. None occurred with either stationary front or air mass conditions.

Information on the wind direction during higher winds was sought. Data from four wind sites to the west of St. Louis (classed as no urban effect) and four to the east (classed as potential urban effect) were grouped. The data available consisted of the average wind speeds and directions for 10-minute periods for each hour (beginning 10 minutes before the hour) for the 1972-1975 period. The resulting combined frequencies are shown in table B-89. These are based on the

Table B-88. Comparison of Summer Maximum Hourly Gust Frequencies in the Effect Area and No-Effect Areas, 1971-1975

	Number of gusts at a point			
	≥ 30 mph		*≥ 40 mph*	
	Average	*Range*	*Average*	*Range*
Effect area	34	27-45	6.3	5-8
No-effect area	17	10-25	3.3	2-5
Difference	17		3.0	
E - NE/NE, *percent*	100		91	

Table B-89. Percent of Timte the Average 10-Minute Winds Taken at Each Hour Were ≥ 22 mph, 1972-1975

	WNW	NW	NNW	N	NNE	NE	ENE	E	S	SSW	All otber directions
West*	0	8	8	23	15	15	15	8	8	0	0
East**	7	26	13	7	20	7	0	0	13	7	0

*West is a combination of Pere Marquette, Lambert Field, Weiss, and Spirit of St. Louis (13 values)

**East is a combination of values from Alton, Nazles, Lemonton, and Scott Field (15 values)

direction totals of the number of occurrences (hours) when the speed was ≥ 22 mph (35 km/hr). There were 13 such occurrences in the four western (no-effect sites) in the 1972-1975 period, and there were 15 such occurrences in the four eastern sites (effect area). As shown in table B-89, both distributions, expressed as a percent of the total occurrences, show a predominance of northerly directions. The no-effect had 69% of their totals from northerly directions (NW through N to NE) and 73% of the effect occurrences were northerly. Basically, there were no major regional differences although the east sites had more from the NW with 46% compared to 13% from the WNW, NW, and NNW. Although there were more higher gusts to the east of St. Louis (table B-88), the directions of higher speeds (table B-89) did not show any marked regional differences.

Tornadoes

The data on tornadoes and funnels aloft from *Storm Data* (EDS) for the summers of 1971 through 1975 were studied. The goal was to inspect for any evidence of urban effects in their patterns. During the 15-month sample, there were 10 tornadoes and 7 funnels aloft recorded within a 60-mi (97-km) radius of St. Louis. It should be noted that the summer season is not a primary tornado season in this region and a low frequency of events in 5 years makes derivation of conclusions about urban effects on tornadoes very difficult.

The distribution of the tornadoes and funnels by month and year are of interest (table B-90). There were no tornadoes or funnels in 1972 and only 1 in 1975.

The pattern of tornadoes and funnels aloft during the five summers of METROMEX is shown in figure B-82. No obvious urbah effect is apparent in the tornado pattern. Three tornadoes occurred in the area of the rainfall and hail anomaly with an equal number in a similar sized area west of St. Louis. Two were far to the west and two far to the east of St. Louis.

The pattern of funnels aloft does show a concentration in the St. Louis and Alton "effect areas." Six of the seven funnels sighted were in this potential effect area. However, a key aspect in interpreting these statistics is the density of population. This is particularly relevant to the sightings of funnels aloft, as opposed to tornadoes which leave damage. The higher density population in and around the St. Louis metropolitan area improves the chances of a funnel aloft being sighted, as opposed to sightings in the rural areas. Although the pattern of funnels aloft suggests a concentration in and just beyond the metropolitan area, this could be totally a result of population viewer density, and not due to urban effects on the atmosphere. It is concluded that there is no obvious effect of the city on tornadoes during the 5-summer sample of METROMEX.

Table B-90. Yearly Distribution of Tornadoes

	Number of tornadoes	Number of funnels
1971	1	1
1972	0	0
1973	7	0
1974	2	5
1975	0	1

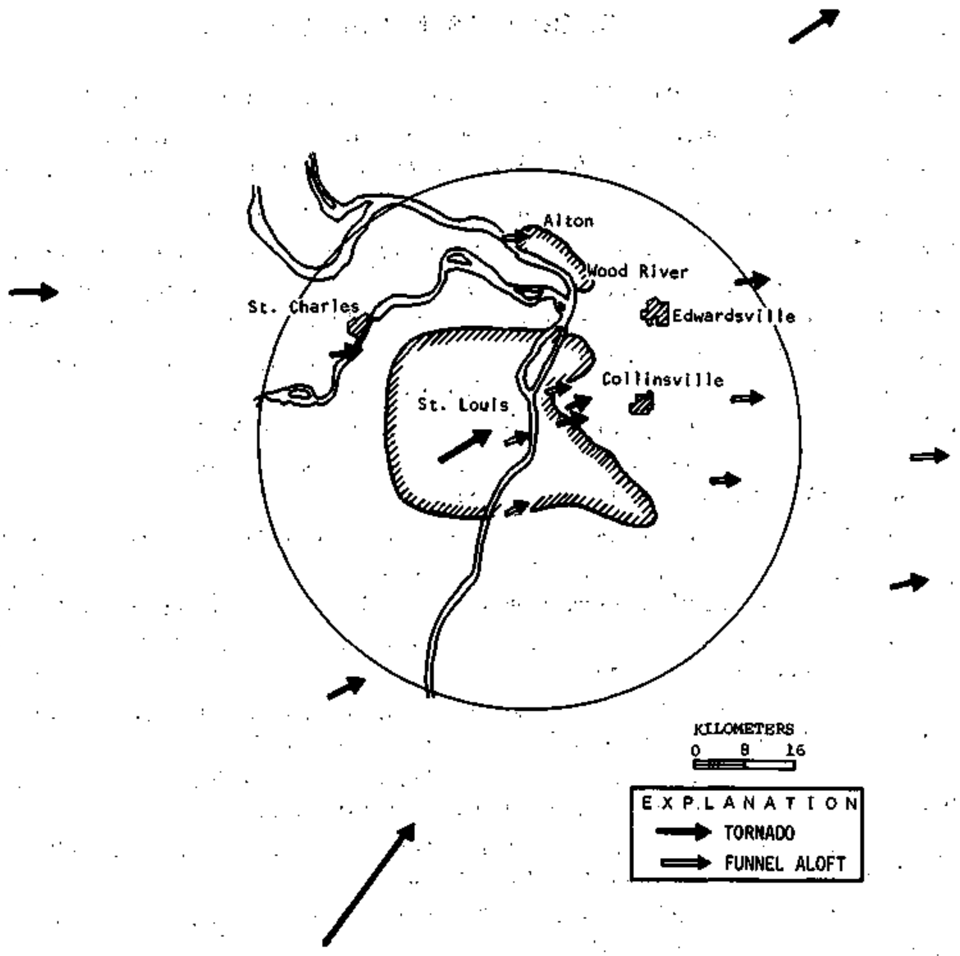


Figure B-82. Summer tornadoes and funnels aloft, 1971-1975

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Part C. Impacts of Urban Modified Precipitation in the St. Louis Area

*Stanley A. Changnon, Jr.**

INTRODUCTION

The Water Survey's involvement in the study of urban effects on precipitation, both at Chicago (Changnon, 1968, 1970) and at St. Louis (Huff and Changnon, 1972; Changnon et al., 1976) was prompted by state concerns over possible inadvertent changes in precipitation quantity and quality. The Water Survey's basic mission is the scientific study of the water resources of Illinois, and precipitation is the major input into the water resources of the state. Areas in and east (downstorm) of Chicago (Lake Michigan) and of St. Louis (Illinois) are major urban and industrial water supply areas for the state.

Climatic studies by Survey scientists of possible urban precipitation anomalies were pursued during the 1960s (Changnon, 1962, 1968, 1969a). These pointed to the possibility of sizeable (10 to 40%) urban-induced increases in the amount of warm season rainfall and related storminess. These studies could not totally resolve critical questions about the apparent increases, including their physical dimensions, their magnitude, their causes, and their ensuing impacts on water resources (Changnon et al., 1971). These questions could only be resolved by an intensive field investigation of an urban anomaly. Hence, Survey scientists, in conjunction with scientists of other institutions, launched in 1971 a 6-year program focusing on the St. Louis area and called METROMEX. METROMEX had four components:

1) Identification of anomalies in summer rain and storms
2) Study of the causes of any of these anomalies
3) Means to predict and translate findings to other cities
4) The impacts of anomalies on the biosphere and on man and his activities

For at least 700 years persons who have dwelt in large cities have been at least vaguely aware that their climate was different from that of their rural cousins. Awareness of the higher intercity temperatures, lower winds, and smokier conditions occurred because of great urban-rural differences. These weather differences began to be quantified at several European cities at least 100 years ago such that the "urban heat island" has been widely known for many years (Landsberg, 1970).

The wide adoption and use of better atmospheric measurement devices, beginning late in the 19th Century in the United States, resulted in the initiation of records that by the 1950s had sufficient lengths so that a few interested climatologists were able to quantify urban-rural climatic differences with certainty. These pioneer researchers eventually found that all features of the climate including the humidity, radiation, clouds, rainfall, and storms were different inside large cities. Differences found in many cities in the northern hemisphere have been averaged to provide the urban-rural differences shown in table C-1 (Changnon, 1973a).

One interesting result of the relatively few urban climatic studies done in the 1950s and 1960s was the suggestion that the urban effect on climate was extending well beyond the city to conditions aloft, clouds, and rainfall (Landsberg, 1962; Changnon, 1969). All other urban effects on climatic conditions were contained within the city where the "forcing functions" (heating, buildings, and pollutant sources) were located.

**All sections of Part C contributed by S. A. Changnon except "Design of Hydrologic Structures," page 215.*

Table C-1. Weather Changes Noted on the Northern Hemisphere Resulting from Major Urbanization

	Average changes as a percent of rural conditions		
Weather conditions	*Annual*	*Cold season*	*Warm season*
Solar radiation, *langleys*	-22	-34	-20
Temperature, °*C*	+2	+3	+1
Humidity, *relative*	-6	-2	-8
Visibility, *frequency*	-26	-34	-17
Fog, *frequency*	+60	+100	+30
Wind speed, *mph*	-25	-20	-30
Cloudiness, *frequency*	+8	+5	+10
Rainfall, *amount*	+14	+13	+15
Snowfall, *amount*	+10	±10	
Thunderstorms, *frequency*	+16	+5	+29

This possible areal extension of an urban effect on weather well beyond the city raised the spectre of 1) a group in one place accidentally doing something potentially harmful to others elsewhere, and 2) man beginning to demonstrate that his land use; changes has the capability to; modify his climate over large areas. This was perceived by the scientific community as a threatening situation, particularly where cities are sufficiently close to form a megalopolis and to have possible interactive effects on weather and climate.

These and a host of other intriguing scientific and environmental questions posed by the suggested urban-produced cloud and rain anomalies led to climatic studies of nine cities (Huff and Changnon, 1973; Sanderson et al., 1973; Eichenlaub and Bacon, 1974). Warm season increases in rain, thunderstorms, and hail were indicated in or near the seven largest cities including Houston, New Orleans, Washington, D.C., Detroit, St. Louis, Chicago, and Cleveland. All are cities with populations over 1 million. The two smaller cities (under 1 million population) that were studied, Tulsa and Indianapolis, did not have apparent urban rain anomalies in or beyond them. The amount of thunderstorm increase appears to be related to city population (Changnon, 1972).

This chapter deals with the fourth objective of METROMEX, the study of selected atmospheric and environmental impacts identified as relating to the St. Louis altered precipitation. Amazingly little has been done to measure the effect of urban weather changes on man and his activity at other cities (CEM, 1977). Primary topics of impact research by the Water Survey in METROMEX have concerned the potential effects of the urban-altered precipitation anomalies on water resources and agriculture.

The effects of the St. Louis urban-industrial complex on atmospheric processes that produce weather impacts are those most clearly defined. Since these weather impacts are the direct (immediate) results of urban effects on atmospheric processes, they are presented first. The alterations in both the frequencies and magnitude of various weather conditions result in a locally different climate that exists in and directly above the city and extends in a plume-like fashion beyond the city. Urban effects on clouds have been noted out to 100 km (62 miles) and effects on air quality well beyond 200 km (124 miles) (Principal METROMEX Investigators, 1976).

The ensuing impacts from the weather changes that have been identified as existing or likely (usually second and then third order impacts) have been grouped according to seven major topics. These include impacts on water resources, agriculture, business and industry, ecology, human health and activities, atmospheric sciences, and institutions. In some instances the listed impacts are actually responses to the impacts. These classification areas include some separation of impacts and some overlap. For example, the impacts of added hail damage are treated in the agricultural economic context and in the context of business (insurance industry). The consequences of more occurrences of heavy rain rates (a direct impact) which produce increased soil erosion (a secondary impact) are treated as an agricultural impact, a water resource impact, and an institutional response (all tertiary impacts and/or responses).

IMPACTS OF ALTERED ATMOSPHERIC PROCESSES ON WEATHER AND CLIMATE

The urban area alters atmospheric processes in a variety of ways and these alterations produce changes in the weather on many days which result in a change in climate. These weather and climate changes are direct impacts. The temperature, moisture, winds, and visibility (due to urban aerosols) are all altered by 5 to 15% at the surface in and adjacent to the St. Louis urban area. These perturbations are often found to extend vertically from 500 to 2000 m (1600 to 6500 ft) on summer afternoons (Semonin and Changnon, 1974).

The city, in general, through alterations of the local temperature, moisture, and wind fields plus the additional nuclei from aerosols, acts to trigger or enhance cloud and rain activity. This often occurs in urban-produced convergence zones (developed in the low-level wind flow), and the place of cloud activity and ensuing rainfall depends on the surface conditions, direction of the flow on any given day, and the degree of atmospheric instability (Changnon et al., 1976).

It is well to realize that the urban-rural differences in various climatic conditions change constantly, fluctuating with time and space such that the downtown St. Louis temperature may be 10°C warmer than the rural area at night and only 1°C different at noon. Or on a given day, it may be 5°C different in the midday. The urban-related rain increases found from 1 to 40 km (25 mi) east of St. Louis will occur on some days but will not exist on other days. Thus, the urban and downwind climate varies considerably according to the actual weather conditions. In a discussion of impacts of inadvertent weather modification it is appropriate to first discuss those direct effects noted in atmospheric phenomena.

Effect on Convective Clouds

Convective clouds are found to be increased by 5 to 20% over and beyond St. Louis and the Alton area (Grosh, 1977). The cloudier conditions occur from midday to evening and generally extend eastward from the city out to 50 km (31 mi). This increased cloudiness likely produces slightly lower (<1°C) afternoon temperatures on some days by reducing the incoming solar radiation.

Precipitation forming inside the urban clouds typically starts at lower levels than in rural clouds, indicating large urban-generated aerosols could assist in the coalescence process. However, clouds over the city have their bases generally 300 to 600 m (~ 1000 to 2000 ft) higher than rural clouds, reflecting the thermodynamic influence of the city, lifting the condensation level.

Major convective storm clouds have been found to merge more often just east of St. Louis than anywhere else in the St. Louis region (Changnon, 1976a), and this is a result of the more frequent urban-generated clouds and storm cells (Changnon et al., 1976). The morphology of the urban-induced rainfall then typically involves urban initiation (due to thermodynamic effects coupled with microphysical effects) of clouds and precipitation during and often before other storms develop naturally. These locally triggered storms occasionally initiate other local storms, and the more frequent storms within the urban area in turn tend to merge to produce heavier rain, stronger winds, and hail as they move to the east of the city. Internal characteristics of convective clouds, both those over and downwind of St. Louis, differ from those elsewhere (Braham, 1974). The rainfall is also urban enhanced in some existing precipitation systems that move through the area (Changnon and Semonin, 1975).

Effect on Summer Rainfall

As a result of these conditions, summer rainfall is found to be 5 to 30% greater east of St. Louis, in a fan-shaped area extending out 40 km (25 mi), than elsewhere in the area. The placement and magnitude of this increased rainfall on any given day or in any given summer vary according to the weather conditions and their frequencies, as shown elsewhere in this report. There is no appreciable change in the rainfall beyond this area of increase. Local rain increases occur in all types of summer seasons including wet, dry, and normal conditions (Huff and Changnon, 1972).

The effects of the city on convective clouds and precipitation are also realized in severe local weather phenomena. The frequency of short-duration heavy rainfall rates and heavy rainstorms is increased in a fan-shaped (4000 km^2 or 1500 mi^2) area east of St. Louis. Dettwiller and Changnon (1976) have shown a 37% increase in the annual maximum daily rainfall values at St. Louis, and Huff (1976a) used METROMEX data to show that in the Edwardsville area east of St. Louis the number of heavy ($\geqslant$25 mm or 1 inch) rainstorms is 93% greater than elsewhere in the area. Huff and Changnon (1972) studied regional historical data on point frequencies of storms $\geqslant$ 25 mm and found a 41% increase in the Madison-St. Clair County area east of St. Louis. Huff (1975a) showed that the maximum 5-minute rainfall rates in urban-affected storms were 43% higher than the rates in non-urban storms.

The pattern based on the number of point occurrences of 5-minute rain amounts of 2-year or greater recurrence interval value (11.43 mm or 0.45 inch) for 1971-1975 is shown in figure C-1. The greater number of high values ($\geqslant$ 3 occurrences) are in the effect area delineated downwind of the St. Louis and Alton-Wood River areas (containing 111 raingages). The no-effect (west) area has extensive regions of 0, or no occurrences of 5-minute amounts of this magnitude. The difference between the point averages in the effect and no-effect areas indicates an 83% increase. A similar analysis of the 1-hour values of 2-year or greater recurrence interval values (38.1 mm or 1.5 inches) indicated a 37% increase in the effect area.

It is clear that the urban effects on summer precipitation produce 1) an increase in the point (and hence the effect area) frequency of heavy short-duration rainstorms, and 2) an increase in the heavier rainfall rates. The increase varies from 37% up to 93% depending on the area and type of rain event under comparison. The six readily available percentage values listed above <37, 93, 41, 43, 83, and 37%) all represent sizeable increases.

Effect on Severe Storms

The frequencies of thunderstorms in this area east of St. Louis are also increased, being 45% greater than elsewhere. The duration of thunder periods is 56% greater, and periods of very frequent lightning are 83% greater than those elsewhere. Strong surface wind gusts (> 48 km/hr or 30 mph) in the downwind area are 100% more frequent. Hail was found to be dramatically

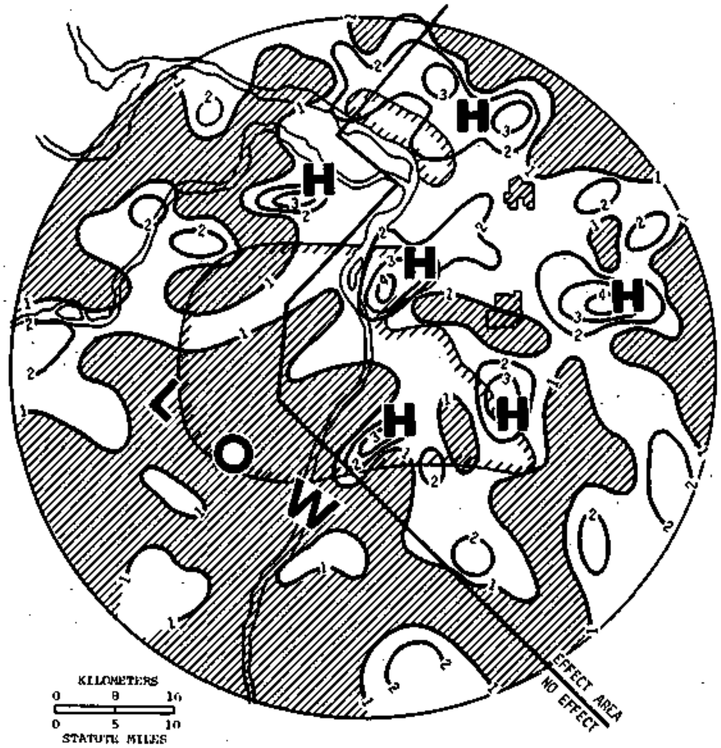

Figure C-1. Pattern based on point frequencies of 5-minute rainfall values of 2-year or greater recurrence interval value, 1971-1975

altered east of St. Louis with more hail days, more hailstorms, and greater hail intensity (number and sizes of hailstones). However, there is no evidence collected during METROMEX that the urban conditions affect tornado activity.

Gatz (1974) and Semonin (1976) have shown how the quality of the summer rainfall is altered in and beyond St. Louis. A portion of these general increases in pollutants in rainwater is a result of the added rain anomalies, probably proportional to the total increase in rainfall quantity, 5 to 30%.

The urban effects on some weather and climate conditions are classed as "direct impacts" (see figure C-2). This involves the effects on the atmospheric processes and the ensuing changes in rain, hail, lightning, and other weather conditions at the surface.

WATER RESOURCES IMPACTS

The increases in total average rainfall, in the number and intensity of heavy rainfall events, and in pollutants in the rainfall all impact on most local water characteristics and activities related to water resources. These impact areas include water supply, sewage treatment, water quality, flooding, and the design of hydrologic structures.

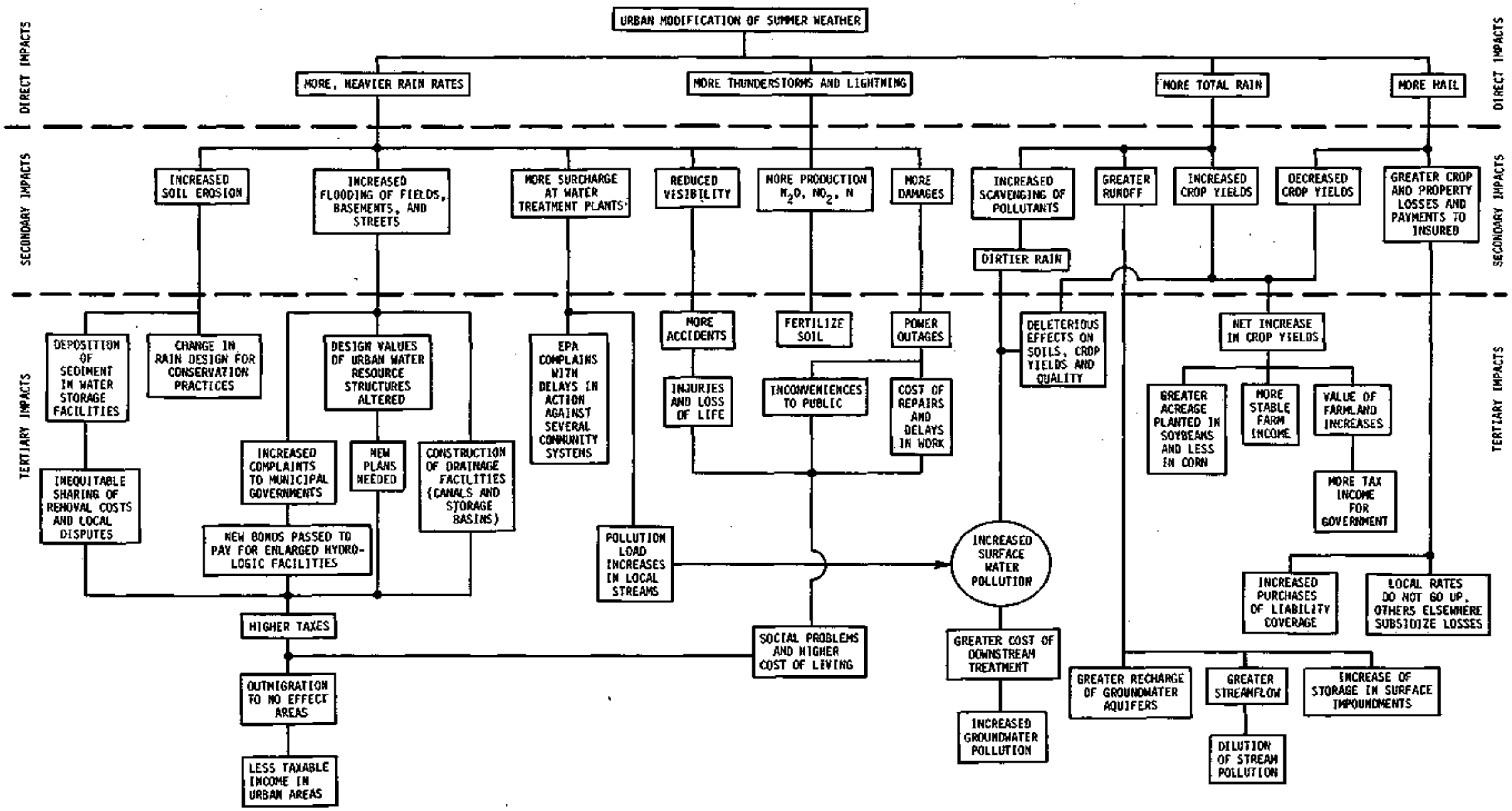

Figure C-2. Interrelated impacts of certain precipitation anomalies

Water Supply

The likelihood of increased rainfall in northwestern Indiana, related to effects of the Chicago area, was studied, and partially resolved, by analysis of the streamflow of the Kankakee River (Hidore, 1971). The streamflow increase from added rainfall was assessed to be 32%.

An analysis of streamflow data for two small basins downwind of St. Louis (see figure C-3) was performed to examine for possible changes due to the increased summer rainfall. This was accomplished by comparing the warm-season values of runoff for one small basin (Canteen Creek), centered in the area of recent rainfall increase, with those of another small basin (Indian Creek) located on the edge of the high rainfall area. Neither basin underwent any major land use changes in the 1941-1975 period; thus, an increase in warm-season streamflow beginning in the 1950s should appear in the Canteen Creek values if the rainfall increase over the basin actually occurred and was of sufficient size to affect the flow. The curves, based on 5-year moving averages of warm season (May-September) flow (figure C-3), reveal a near-continuous positive departure in the Canteen Creek (major rain increase area) values beginning after 1954. During the 1941-1955 period the average May-September runoff of Canteen Creek was 136 mm (5.34 inches) and that of Indian Creek was 108 mm (4.27 inches). Their difference (27 mm or 1.07 inches) was 20% of the Canteen Creek flow. Since 1955 the Canteen value was 111 mm (4.37 inches), the Indian value was 76 mm (3.00 inches), and their difference of 35 mm (1.37 inches) was 31% of the Canteen flow. The warm season runoff increase on Canteen Creek that is related to the urban-induced rainfall increase is 11%. Thus, one secondary impact of more total rain is greater runoff (figure C-2).

Effect of the summer season rain and subsequent runoff increases on groundwater supplies is difficult to ascertain since long-term groundwater data are generally not available and because warm season rainfall may not affect appreciably the groundwater resources (i.e., it may evaporate, run off, or be used by plants and transpired).

Immediately downwind (east) of St. Louis is the 454-km^2 (175-mi^2) floodplain of the Mississippi River. This area is effectively a closed aquifer, composed of unconsolidated sands and gravels 37 m (120 ft) thick which are underlain by impermeable rock. Groundwater recharge comes largely from rainfall and infiltration from local streams (Schicht and Jones, 1962). This essentially closed hydrologic system is very dependent on direct rainfall recharge and is very responsive to it. Unlike many areas, groundwater in this area is responsive to heavy (> 12 mm or 0.47 inch) summer rainfall (Changnon, 1973b) and thus should reflect some of the urban-increased summer rainfall. Huff (1975a) has shown that about 50% of the increased rainfall comes from increased heavy rains ($\geqslant$ 25 mm or 1 inch). However, the heavy and complex pumpage pattern negates any specific determination of the rainfall impact on groundwater levels. This is the second most heavily populated and industrialized area in Illinois, and it depends almost entirely on the local groundwater for its supply with an average pumpage of 100 mgd. Knowledge of the hydrologic cycle, coupled with the runoff and heavy rainfall results, suggests the urban-produced rainfall increase yields about a 5% increase in shallow groundwater recharge in the summer. This is a tertiary impact, as shown in figure C-2.

These groundwater estimates and runoff differences indicate that the added summer rainfall results in an increase in the volume of surface water and groundwater. The increased runoff enhances supplies in local farm ponds, in local reservoirs, and in the Mississippi River. In general, these increases are slight, being 15% or less of the total seasonal input into these storage facilities from the added rain in the affected area (~ 3100 km^2 or 1200 mi^2).

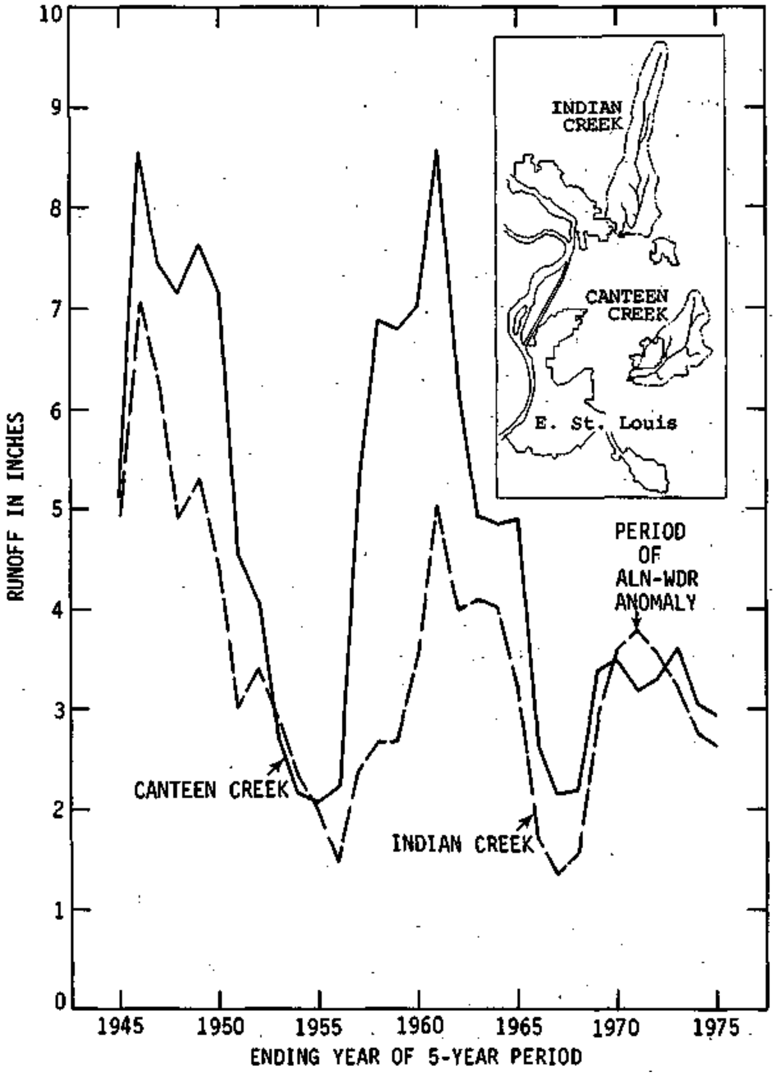

Figure C-3. Five-year moving averages of warm season (May-September) runoff on two basins

Sewage Treatment

In general, summer season increases in runoff have a beneficial impact on sewage treatment. Increased streamflow means more dilution and lower concentrations of pollutants in the stream water (Huff, 1975).

The 30 to 50% increases in heavy rain events and rain rates east of St. Louis (a direct impact, figure C-2) have led to secondary impacts including an increased frequency of surcharges, or bypasses of wastewater treatment plants in the area.. The Illinois EPA has reported a considerable problem with communities in the Mississippi River floodplain east of St. Louis. Detailed records of bypasses of the sewage treatment plant at Belleville (located in the anomaly area) kept since 1952 show totals of 58 for 1953-1957, 60 for 1958-1962, 60 for 1963-1967, 84 for 1968-1972, and 84 for 1973-1977. Hence, a 40% increase has developed in recent years as the anomaly developed and intensified. These bypasses lead to added stream and river pollution downstream of local treatment plants, a tertiary impact of the heavier rain anomaly (figure C-2).

USEPA regulations call for different levels of wastewater treatment (increased) when streamflow (for wastewater release) is 2.5 times or more above "dry weather flow." The Illinois EPA reports (Helfand, 1975) that defining dry weather flow in itself is a problem in the anomaly area because the urban-related shift in summer rainfall has created new and higher levels of low flows. Each Illinois community measures and reports its daily effluent (water) quality to the EPA who checks this against the regulations established for each community. These community records for the 1973-1975 period indicate that the regulation levels are exceeded about twice as often (97% increase) in the anomaly area as in communities located to the east of the anomaly. Disputes between adjacent communities over wastewater treatment and flooding problems and between individual communities and the regional water management entity have erupted frequently.

The sewage and water quality problem in the floodplain communities is further compounded by the sandy soils and near surface levels of the shallow groundwater. The seasonal and shorter term fluctuations in the level of this high groundwater occur at the depth of the sewer lines, cause them to shift, resulting in breaks that cause underground spillage into the groundwater. The heavy rain anomaly has helped cause many communities east of St. Louis to have difficulty in meeting state and federal standards for waste treatment. However, the EPA has generally delayed action against several communities because of the complexity of the issue.

Surface Water Pollution

Surface water pollution relating to the rain anomalies was extensively investigated as part of a 2-year project within METROMEX (Huff, 1975b). One phase of this study focused on the effects of atmospheric effluents of St. Louis and Alton-Wood River on the water quality in the streamwaters of two small basins, one located in the center of the region that is frequently downwind of these urban-industrial areas, and the other less frequently downwind. Sampling of streamwater and atmospheric deposition in the basins was done on a weekly basis for a 15-month period beginning in June 1973. Sampling was also carried out in selected storms on the two basins, Canteen Creek (58 km^2 or 22.5 mi^2) and Indian Creek (96 km^2 or 37 mi^2). Urban-generated surface pollutants are not a major source of stream contamination in these essentially rural basins. Chemical constituents in the streamwater and rainwater studied included calcium, magnesium, sodium, potassium, zinc, total dissolved minerals, nitrates, chlorides, and sulfates.

Analyses showed that antecedent rainfall is a very important factor in establishing streamwater concentrations (Huff, 1976b). However, no specific antecedent period (1 to 7 days) was found to relate most strongly to weekly measurements of concentration. Study of temporal variations of chemical concentrations in streamwater during warm season rains indicated that only minor changes usually occur during and immediately following convective rainstorms on these small basins. Time distributions generally exhibited a flat pattern (little change with time).

Separation of the dry and wet components of the weekly deposition samples indicated that over an extended period of time the wet (rainwater) and dry deposition were about equal. However, the rate of deposition is much greater in rainfall which occurs in only a small percentage (6 to 10%) of the total hours per season or year. Analyses indicated that the dry deposition rate is usually less than 10% of the wet rate, and with some elements the dry rate is only 1 to 2% of the storm rainfall rate.

Table C-2 provides values of the atmospheric contribution in summer to surface (basin) pollution from particulates discharged into the atmosphere from commercial, industrial, and residential sources.

Table C-2. Atmospheric Deposition on Canteen Creek and Indian Creek Basins and Streamwater Concentration of Chemical Constituents during Summer, 1973 and 1974

Basin	*Ca*	*Mg*	*Na*	*K*	*Zn*	*NO_3*	*Cl*	*SO_4*	*Rainfall (in.)*
Median deposition, *lbs/week*									
Canteen Creek	5108	563	315	495	23	2385	1260	9,473	
Indian Creek	6068	629	666	665	481	7807	1961	27,121	
Median weekly deposition, *lbs/mi²*									
Canteen Creek	227	25	14	22	1	106	56	421	
Indian Creek	164	17	18	18	13	211	53	733	
Average concentration in streamwater, *mg/l*, Summer 1973									
Canteen Creek	106	40	27	5	0.3	9	28	302	10.66
Indian Creek	57	25	15	5	<0.1	10	15	82	11.18
Average concentration in streamwater, *mg/l*, Summer 1974									
Canteen Creek	134	47	31	4	1	4	29	403	8.19
Indian Creek	68	31	18	4	<0.1	9	16	95	11.67

Table C-2 also shows the average concentration of various chemical constituents getting into the streamwater for two summers of sampling on the two basins. These values allow a comparison of the concentrations between various pollutants on each basin as well as differences between the two streams. On both basins the highest values occur with sulfates and calcium. The lowest concentrations occur with zinc, potassium, and nitrates.

The highest chemical concentrations occurred in the fall of 1973 when runoff was the lowest among the five seasons. In most cases, concentrations were higher in the Canteen Creek (more in the anomaly area) streamwater than in Indian Creek streamwater, especially with respect to those constitutents with relatively high concentrations (SO_4, Ca). An inverse relationship between chemical concentrations and rainfall is indicated by comparing the 1973 and 1974 values and the rain differences (table C-2). As Huff (1976b) found, the sulfate concentrations appear to be more acutely affected by the rainfall on the two basins than most of the 'other chemical constituents analyzed.

Computations were made of total basin deposition of wet and dry fallout (atmospheric deposition) and the total stream load of selected chemical constituents in the 12-month period, June 1973 through May 1974. Table C-3 presents the atmospheric deposition of each constituent expressed as a percent of the total stream load of that constituent. Results show that the atmospheric deposition was small compared with the annual stream load on both basins, except for sulfates and nitrates on both basins and zinc on Indian Creek. Atmospheric deposition of nitrates on Canteen Creek was equivalent to 51% of the stream load, and the zinc deposition on Indian Creek was more than twice the annual stream load. Otherwise, the atmospheric deposition ranged from about 1% of the total stream load for sodium on both basins to approximately 10% for potassium on Canteen Creek. It is believed that the abnormally high zinc deposition results from one or more industrial sources, and it is likely that the high nitrate and sulfate depositions are also related to some upwind concentrated source(s).

These results are not meant to imply that atmospheric sources are not important in stream pollution. It does indicate that for most chemical constituents studied, the surface sources of streamwater pollution are much greater than the atmospheric contribution, at least on these two basins east and N.NE of St. Louis. Since rainfall produces about half of the deposition, or half the deposition values shown in table C-2, the urban increased summer rainfall of about 5% (Indian Creek) and 20% (Canteen Creek) can only be assumed to be responsible for a small fraction (2.5%

in Indian and 10% in Canteen) of the atmospheric deposition percentage shown on table C-2. These small percentage but still large bulk contributions appear infinitesimal when compared to the total atmospheric contributions (table C-3) shown as being generally small in relation to those from surface sources.

Table C-3. Atmospheric Deposition Expressed as a Percent of Stream Load for Selected Chemical Constituents during 12-Month Period

Chemical constituent	*Percent for given basin and constituent*	
	Canteen Creek	*Indian Creek*
Sulfates	14.5	17.4
Nitrates	51.6	43.2
Chlorides	2.2	5.2
Calcium	4.6	6.4
Magnesium	1.5	1.7
Sodium	1.5	0.6
Potassium	10.2	8.3
Zinc	15.7	223.0
Total dissolved minerals	6.0	10.0

Groundwater Quality

Another extensive phase of the water quality study of METROMEX involved a 2-year effort to study 1) the general effect of precipitation scavenging of urban-industrial pollutants on groundwater quality, and 2) to investigate the possibility that groundwater quality had deteriorated more rapidly in a region where urban induced precipitation enhanced total rainfall (Schicht, 1977). Groundwater was studied in the American Bottoms, the floodplain of the Mississippi River that extends over 454 km^2 (175 mi^2) east of St. Louis. The floodplain lies largely where the urban-induced rainfall increase occurred. This area, composed of sand and gravel aquifers, has been a prolific source of water for more than 70 years which has helped lead to the great industrial and urban development found in the area. Most groundwater sampling was done at wells in three areas within the floodplain: the Alton-Wood River area, the East St. Louis-Granite City industrial area, and a semi-rural area east of East St. Louis.

Data collection consisted of weekly groundwater samples at 6 sites plus a high frequency of samples from a large number of wells during June and September of 1973 and 1974. The groundwater samples were analyzed for a number of chemical constituents including calcium, magnesium, sodium, potassium, zinc, total dissolved minerals, nitrates, chlorides, sulfates, alkalinity, and hardness.

The chemical quality of the groundwater in the study area was first investigated by Bowman and Reeds (1907). Bruin and Smith (1953) noted relatively high sulfate contents in areas of high groundwater withdrawals which also coincide with highly urbanized and industrialized areas. They also reported that the chemical quality of the groundwater was highly variable from place to place and at various depths. There have been reports of an increase in the mineral content of the groundwater. For example, because of the gradual increase in the mineral content of groundwater, two municipalities in the area east of St. Louis relocated their well fields that had been in a urban-industrial complex.

Changnon (1973b) first suggested from a study of historical groundwater chemistry data that rainfall may be instrumental in increasing the mineral content of the groundwater. The chloride and sulfate contents from one well considered largely unaffected by localized surface pollution sources were analyzed for trends during the 1944-1965 period. The 5-year moving averages of sulfates and chlorides are depicted in figure C-4. The 1957-1963 period shows a sizeable increase.

The 5-year moving annual rainfall averages at a raingage near the test well (figure C-4) also are presented to show their fluctuations. The average rainfall in 1943-1954 period was 78.2 cm (30.80 inches), but it increased by 5.8 cm (2.3 inches) to an average of 102 cm (40.11 inches) in the 1955-1966 period. The rapid increase in groundwater pollution since 1954 appears to be potentially related to the greater atmospheric pollution in the area. Changnon could not discern

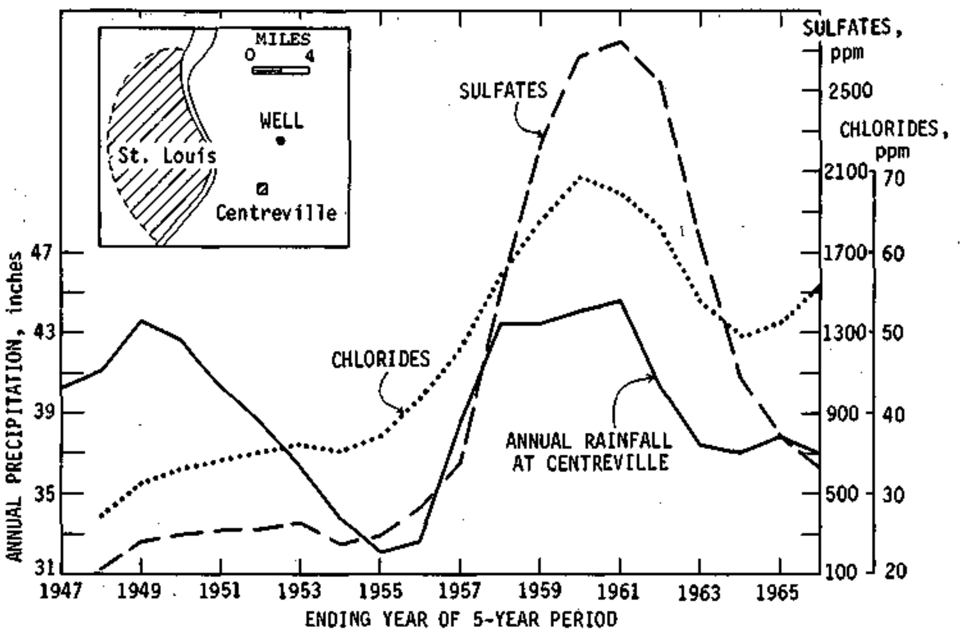

Figure C-4. Five-year moving averages of sulfates and chlorides in groundwater at a well east of St. Louis and of annual rainfall at Centerville

how much of this increased groundwater pollution was due to dry fallout captured by surface water and subsequent infiltration; how much was due to direct rainfall scavenging in the atmosphere followed by infiltration; or the quantity from surface pollutant sources. However, Changnon concluded that the correspondence of the 1955-1966 rain and pollution curves in figure C-4 indicated that the rainfall, including the 5.8 cm (2.3-inch) increase apparently related to urban effects, was partially instrumental in the increases in groundwater pollution.

Selected results of the intensive 1973-1974 METROMEX study (Schicht, 1977) are presented in table C-4. Shown are median values of the chemical constituents of groundwater samples collected during September of 1973 and 1974. Most of the analyses were made from samples collected in two areas, the Alton-Wood River area and in and near East St. Louis. Infiltration of water from the Mississippi River could be one reason for the differences shown in table C-4 between the two sampling areas. Conditions for infiltration in the Alton area have been more favorable in recent years than those in the East St. Louis area. Many samples collected in the Alton area were from wells that could be affected by induced infiltration, whereas only a few of those in the East St. Louis area were from wells that could be affected by river water.

Chemicals in Mississippi River water collected near St. Louis are also summarized in table C-4. If induced infiltration has an effect on groundwater quality in the Alton area, the chemical concentrations in the river would be lower than those in the groundwater. As Schicht (1977) claims, inspection of table C-4 shows this to be evident for most constituents. However, groundwater-river differences in zinc and potassium are small, and the nitrate concentrations in the river were significantly higher than those in the groundwater.

Changes in groundwater quality from atmospheric pollutants are partially dependent on the percent of total precipitation that reaches the water table (groundwater recharge), on the percent of precipitation that evaporates and transpires, and to some extent on the hydrogeolbgy of the aquifer. Most of the precipitation that falls on the surface and seeps into the ground is returned to the atmosphere by evaporation and transpiration and is lost as far as groundwater recharge is

Table C-4. Chemical Constituents in Groundwater from Wells
East of St. Louis, in Mississippi River, and in Atmospheric Deposition

(Median values in milligrams per liter)

	*Groundwater samples**				*Atmospheric deposition as a percent of*	
	Alton-Wood River	*East St. Louis*	*Mississippi River at St. Louis***	*Atmospheric deposition east of St. Louis†*	*River water*	*Ground-water‡*
Ca	99	160	56	5	9	4
Mg	26	44	20	0.7	4	2
Na	16	48	14	0.4	3	1
K	4	6	3	1.1	37	22
Zn	.01	.03	0	0.19	>100	950
NO_3	2	3	15	3	20	120
Cl	22	71	19	0.8	4	2
SO_4	98	247	56	7	13	4
TDM	492	847	306	20	7	3

*Median of 45 samples (days) based on measurements in September 1973 and 1974.
**Monthly values, November 1972 – September 1974.
†Rainout and dry fallout combined from weekly samples at 3 sites, 1973–1974.
‡Groundwater value used was an average of two areas.

concerned. According to Schicht (1965), groundwater recharge in the effect area east of St. Louis from precipitation averages about 19.8 cm (7.8 inches) per year, and the annual evapotranspiration is about 74 cm (29 inches). Hence, only about 20% of the annual average precipitation goes into groundwater storage.

Schicht made comparisons of concentrations of chemical constituents in rainfall with their concentrations in groundwater. As shown by the percentages in table C-4, median concentrations of atmospheric deposition for most constituents were less than 10% of the concentrations found in groundwater or river water. The zinc concentrations in rainfall (approximately 50%) and dry fallout (approximately 50%), together representing the total deposition, are significant compared to the concentrations in the groundwater and river; hence soil pollution by zinc is indicated. Zinc is readily attenuated by soil materials, particularly by small amounts of clay. The potassium content in atmospheric deposition is also significant compared to its content in groundwater and river water. However, potassium is also moderately attenuated by soil materials. The nitrate content in rainout and dry fallout is also significant compared to its content in groundwater, 120%, and river water, 20%. However, plant uptake of nitrates in soil is significant.

In summary, at the concentration levels measured during this study by Schicht, it appears highly unlikely that the scavenging of urban-industrial pollutants by the additional summer rain contributes significantly to the degradation of the groundwater quality. However, the issue is compounded by the infiltration effects of the Mississippi River and by the direct well pollution by local industrial sources.

Further research on the effects of the added rainfall on groundwater quality by Schicht (1977) concerned long-term trends in groundwater quality. Occasional analyses for chlorides and sulfates have been available since 1906 from a well field in a rural area near Edwardsville. Groundwater withdrawals (figure C-5) and sulfate concentrations have increased gradually since 1906. Chloride concentrations do not show a gradual increase, but indicate a significant increase after 1960. It is difficult to attribute the changes in sulfates and chlorides to precipitation scavenging of pollutants. However, the rain anomaly developed in the 1950s shortly before the time the chlorides increased. Changes in water quality in the East St. Louis area have been attributed

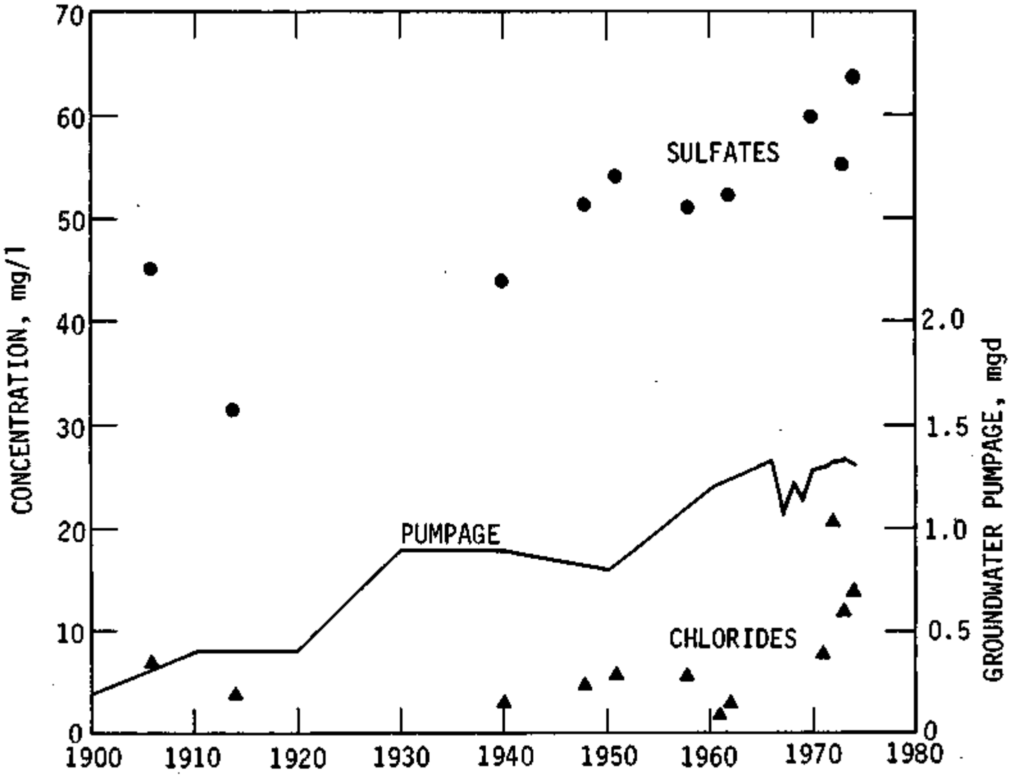

Figure C-5. Sulfate and chloride contents and groundwater withdrawals in the American Bottoms, 1900-1974

to upward movement of highly mineralized water from the bedrock formations that are immediately beneath the sand and gravel aquifer (Bruin and Smith, 1953). The type of increase in sulfates shown in figure C-5 indicates it could be attributed to the upper movement of water from the bedrock (Schicht, 1977).

In addition to the chemical data from this 2-year study, a large number of chemical analyses were made from samples in the floodplain taken during 1972 and in the 1946-1948 period. Chloride and sulfate maps for the period 1946 through 1958 were compared with maps for the period 1972-1974, and the amount of change in each appears in figures C-6 and C-7. As shown in figure C-6, three areas have an increase in chloride greater than 30 mg/1. The area of increase that parallels the Madison-St. Clair County line corresponds to a major highway, and the increase in chlorides could be contributed to the recent heavy use of road salt. The other areas of increase in chlorides correspond to urban-industrial complexes where industrial activity plus road salt are probably the major contributors to the increases.

Four areas (figure C-7) show an increase in sulfate content and all are associated with urban-industrial complexes. Areas that show decreases in chlorides and sulfate contents are influenced by infiltration of water from the Mississippi River. Areas that show increases in chlorides and sulfates also correspond to major centers of groundwater withdrawal (Schicht, 1965), and vertical upward movement of highly mineralized water from the bedrock could be considered as a contributor to the increase in chloride and sulfate content.

Most of the groundwater quality results obtained during METROMEX were based on data from 1973-1974 taken near two urban-industrial complexes. Sampling was compounded by industrial pollution and by the lack of samples in the more rural portions of the area where the precipitation anomaly is greatest. Groundwater was more highly mineralized in the vicinity of East

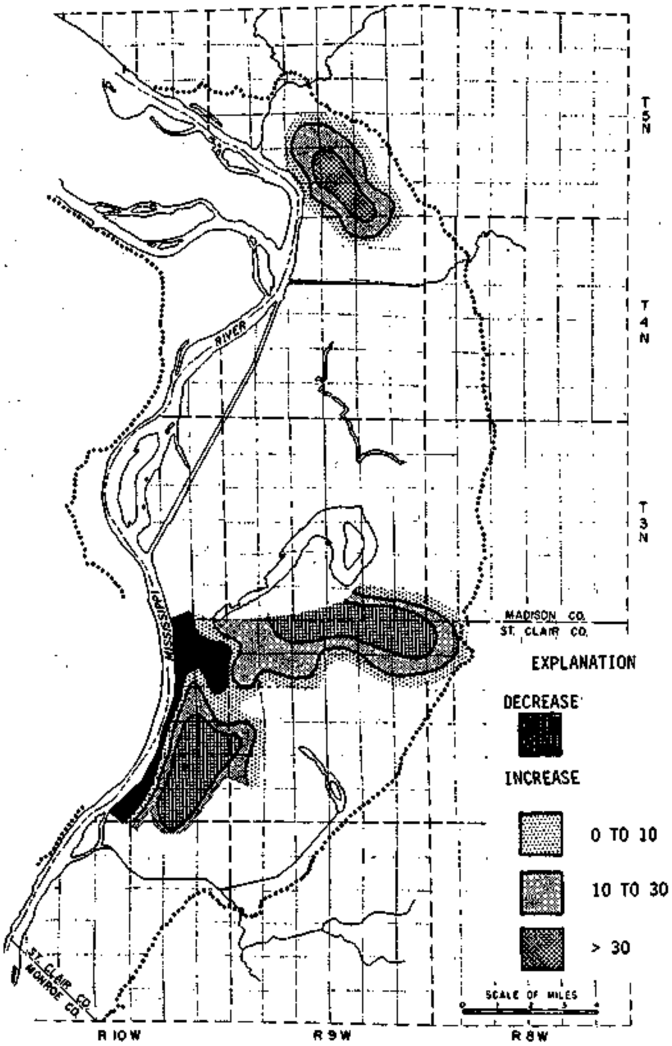

Figure C-6. Change in chloride content (mg/l) between the 1946-1958 and 1972-1974 periods

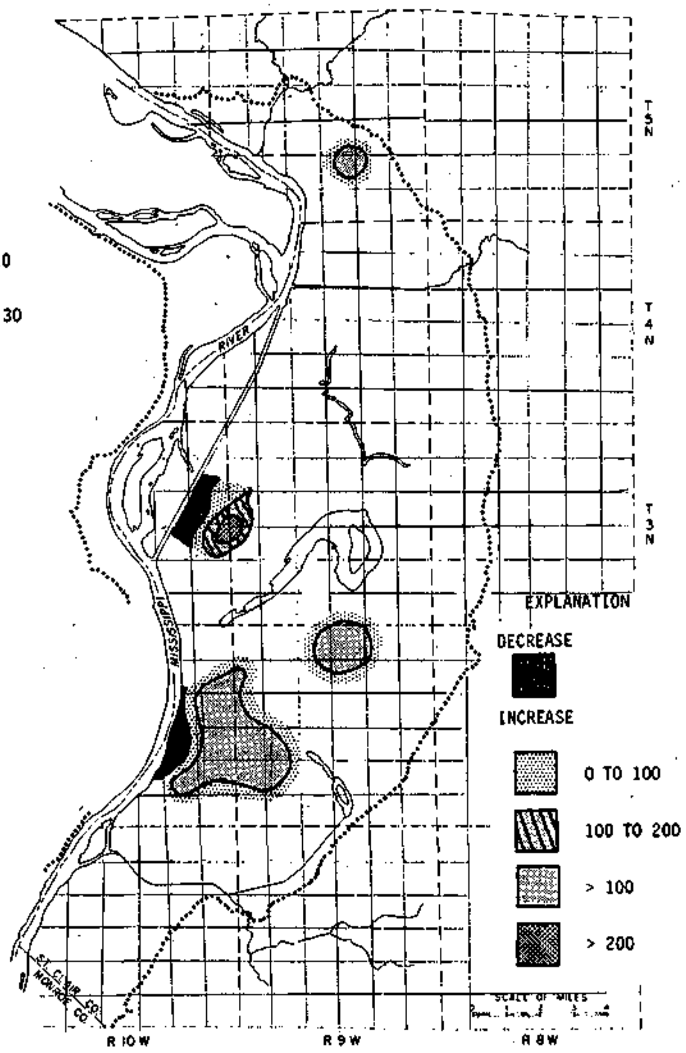

Figure C-7. Change in sulfate content (mg/l) between the 1946-1958 and 1972-1974 periods

St. Louis than in Alton, partly because of greater infiltration of less polluted river water in the Alton area. Comparisons of concentrations of chemical constituents in atmospheric deposition and in groundwater were made. Precipitation scavenging of urban-industrial pollutants contributes to the degradation of the groundwater quality, although degradation is difficult to quantify.

Long-term changes in groundwater quality were also investigated. A rural well field indicated a gradual increase in sulfates since the early 1900s but it appears to correspond to a gradual increase in pumpage and the resulting upward movement of high sulfate water from the bedrock. Chloride concentrations did not show a gradual increase but increased significantly in the 1960s about when the precipitation anomaly began to appear. There was no readily apparent reason for the increase in the chlorides other than the atmospheric pollutants. Shifts in the chloride and sulfate contents in the industrial parts of the American Bottoms appeared to be dominated by pollutants infiltrating from direct industrial sources. Thus, the complex of factors affecting the groundwater quality, as well as quantity, in and near the Mississippi River and the heavy industrial areas, makes its difficult, if not impossible, to measure the exact impact of the precipitation-borne pollutants on groundwater quality. However, at the more rural sites, it appears that certain pollutants in groundwater such as chlorides, zinc, and potassium have increased as a result of atmospheric deposition. The amount contributed by the urban-increased rainfall (anomaly) is very slight, probably only 5 to 10% of the total groundwater concentration of any pollutant (see also the sections on soils, pages 215 and 229).

Flooding

The occurrence of more heavy, short-duration rainfall rates and storm events (direct impacts) lead to high runoff rates producing flooding and soil erosion, both identified as secondary impacts (figure C-2). As noted in the previous section, a portion of the urban-related summer rainfall anomaly occurs in the American Bottoms, the 454-km^2 (175-mi^2) floodplain east of St. Louis. This floodplain is extremely flat and poorly drained. Helfand (1975) has reported on the increased incidences of local flooding and ponding in floodplain communities such as Wood River and Granite City. He estimated that situations leading to flooded streets and basements are twice as frequent now in the floodplain area as they were 20 years ago. Clearly, the 40 to 80% increases in heavy storm events related to urban effects are a significant factor in the 100% increase in local flooding. This flooding delays traffic and damages property (SIMRPC, 1975). Complaints by citizens to their city governments have occurred (Wilmarth, 1977), leading to the passage of a bond issue in one community for an improved storm and sewer drainage system.

The urban-related increases in runoff from the more frequent heavy rainfall events also affect the operation and management of hydraulic structures in the floodplain (Wilmarth, 1977). Major canals, storage basins, and flood gates exist to drain and/or control the flow of water within the floodplain and between the floodplain and the Mississippi River. The management of high water is made more difficult by the fact that the anomaly related runoff from the higher ground to the east of the floodplain descends over sharp bluffs into the floodplain and is thereby accelerated.

The floodwater management problem in the floodplain is not resolved, and major canals and floodwater storage basins are being planned for construction in the floodplain by the U.S. Corps of Engineers and the Southwestern Illinois Metropolitan and Regional Planning Commission. This planning and construction are tertiary impacts (figure C-2) but very costly ones. Total cost of proposed projects is $73.6 million. This includes channel improvements and new hydraulic structures adding up to $27.5 million for the Blue Waters Ditch Project (U.S. Army Corps of

Engineers, 1974); $25 million for Harding Ditch; $18.5 million for the Cahokia Canal; and $2.5 million for a detention basin for Little Canteen Creek (SIMRPC, 1975). The sizeable increase in heavy rain events, coupled with urban growth has made many hydrologic facilities that were adequate in 1950 now inadequate. Hence, one of the key economic impacts of the urban-delated weather anomalies rests with the urban-produced increase in heavy rain events which in turn has led to a need for expensive additions and improvements to local floodwater management facilities.

The urban-related increases in rainfall rates, particularly the heavy rates (Huff, 1975a), have also affected soil erosion, especially in the rolling farmlands east of the floodplain and in the bluffs (15 to 46 m or 50 to 150 ft high with steep slopes) separating the plain from the higher country. First, 55% of all the erosion in this area occurs in summer (ARS, 1972), the time of the rain anomaly. The rainfall factor most affecting erosion is the magnitude of short-duration (5 to 30 minutes) high rainfall rates.

A soil erosion estimation equation developed by the U.S. Department of Agriculture was used to calculate erosion in the St. Louis region. This equation includes rainfall variables, slope variables, soil types, and type of tillage. Use of a rainfall value in the equation that was based on non-anomaly area values yielded an average summer estimate of 8.3 tons per acre of soil eroded. Adjustment of the equation's rainfall value for the heavy rainfall regime in the St. Louis-produced anomaly area yielded an estimate of 11.1 tons per acre per summer. Thus, the added erosion (2.8 tons) represents a 34% increase in erosion, much of which is transported in local streams thus degrading local water quality.

The added soil load in the streams, particularly that from the higher elevation rural area within the anomaly, has considerable impact on streamwater quality and on the floodplain (Wilmarth, 1977). The streamwater carrying loads of eroded soil particles during high runoff periods descends into the floodplain where, due to the extreme flatness of the terrain, the streamflow is greatly slowed. Furthermore, this excess flow is often stored in special basins because the major drainage canals cannot handle it. The change in the flow, either slowed (in the canals) or stopped (in the basins), causes much of the sediment to be dropped. Silting in the storage basins and the costs of its removal have become a major problem for the Eastside Levee District which manages and maintains many of these hydrologic facilities. Estimated sediment deposited in the rivers and canals located within the southern 80% of the American Bottoms is 645,871 tons per year (SIMRPC, 1975). The lack of local, on-farm erosion control has led to planning for either 369 sediment catchment basins (at a cost of *$6.6* million), or a sediment removal program for the minor drainage channels (at an annual cost of $1.8 million).

Design of Hydrologic Structures*

Huff (1975a, 1976a) and Huff and Vogel (1977) have presented extensive results showing the magnitude of the heavy rainfall anomalies and the resulting possible shifts in design values for local hydrologic structures and operations. This section presents the hydrometeorological results and implications for design resulting from the METROMEX rain data.

METROMEX studies of heavy rainstorms and the distribution of heavy raincells within storms have provided strong evidence that the frequency distribution of these events, which are of major importance in the design and operation of urban water resources systems, is significantly altered by the urban environment. In the major effect areas of large urban-industrial areas, urban storm sewer systems, which are usually designed on the basis of rainfall records collected at airports or other nearby climatic stations, are very likely to be under-designed for the loads they will be required to carry. The increase in the frequency-intensity regime of heavy rainfalls at

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**This section contributed by F. A. Huff*

St. Louis is most pronounced in short-duration events which produce excessive rainfalls for storm periods of 3 hours or less. Unfortunately, these short-duration, extreme rainfall events are the major cause of urban flooding and the associated property damage and health hazards created by these events.

The importance of adjusting hydrologic design criteria and real-time system operations to account for the urban enhancement of heavy rainfall is clearly illustrated by referring to the distribution of 25-mm (1-inch) rain events discussed in an earlier section of this report. These heavy storm events, the major portion of which have durations of 3 hours or less in the warm season, occurred twice as often in the region of major urban enhancement of rainfall as over the rest of the METROMEX Network. In other regions where the urban effect is less pronounced, increases of 10 to 50% in the frequency of heavy rainstorms occurred in the 1971-1975 sampling period.

Heavy raincells are defined as those producing cell mean rainfalls of 6 mm (0.25 inch) or more at the ground. These are the basic elements of heavy storm systems and are the convective entities which in combination produce the heavy, short-duration storms in thunderstorm-dominated climates such as the Midwest. These convective storms are primarily responsible for the flash floods which are major damage producers, particularly in urban areas. METROMEX analyses show that heavy cells that were exposed to the urban environment produced 70% more water yield (rainfall) volume than did the heavy cells exposed only to the surrounding rural environment. These cells have an average duration of approximately 40 minutes and a path length of 8 km (5 mi) in the urban major effect region. Because of this urban enhancement, the normal frequency of 5-minute to 30-minute rain rates, which are an important consideration in the design of sewer system branches (laterals), occur much more often and produce heavier rainfalls than in the surrounding region.

In conclusion, the major point is that the urban effect does intensify naturally occurring storms of moderate to heavy intensity, and this causes an increasein the frequency and magnitude of flood-producing storms in the downwind areas of large urban-industrial complexes compared with the surrounding areas. In turn, this will affect the design requirements for the flow and storage of water in urban and suburban storm sewer systems. Adjusting for the urban effect is becoming increasingly important with the present emphasis on improved sewer design and engineering. There is increasing national concern with sewer supercharging and such allied problems as basement inundations from storm water, particularly with current requirements to meet federal, state, and local environmental regulations. Failure to consider urban effects could cause problems in meeting the established requirements for urban water resources systems.

AGRICULTURAL IMPACTS

The study of agricultural impacts related to the urban weather anomalies has focused 1) on possible shifts in the yields of the primary crops, corn and soybeans, and 2) on changes in agricultural practices in the effect area. Measures of the local alterations of crop yields was achieved through a double "target-control" analysis wherein the yields in the effect (target) area were compared with those in a surrounding (control) area for the pre-anomaly period and post-anomaly period.

The urban-increased temperatures and cloudiness appear to have no notable effect on agricultural practices or local yields. The length of the growing season in the rural areas has not been altered, and the primary urban-produced weather change relating to agriculture is that due to precipitation. The effects of more rainfall, dirtier rain, and more hail and wind damage were investigated and found to be identifiable.

Effects of Urban Precipitation on Corn and Soybean Yields

The urban-related increases in summer rainfall immediately downwind of St. Louis should be reflected in the yields of crops that are highly dependent on rainfall in summer. Of course, effects will be complex because of added hail and wind, shifting agricultural technologies, and the unknown influences of air and water pollution. Corn and soybeans are the principal crops of the region and are very responsive to rainfall in July and August (Changnon and Neill, 1967).

Prior studies of the effect of additional water in the July-August periods during the 1931-1965 period on corn yields in the Madison-St. Clair County area, which is immediately downwind (east) of St. Louis, revealed that during an average 20-year period there would be 3 years when any added water would decrease yields becauscnatural rainfall had been excessive; 3 other years when added water would have very little effect since the natural rainfall was near optimum; and 14 years when increased water would increase yields somewhere between 8 and 28% (Changnon, 1969b). Within this latter 14-year (too dry) category, it was found that a 12.7-mm (0.5-inch) rain increase in the July-August period would generally produce 1.5 to 2.0 bu/acre more corn. Determination of county mean rainfall values from the 1949-1968 average July-August rainfall pattern based on limited data indicated that the St. Clair-Madison County "effect area" averaged 10.16 mm (0.4 inch) more than the average of the five surrounding Illinois counties and thus should have realized 1 to 2 bu/acre higher corn yields. Climatic and METROMEX studies both indicated that this added rainfall appears to be related to the urban-industrial effects of the St. Louis metropolitan area.

To examine for the urban-related effect on crop yields, a double target-control analysis was performed using both 1) effect and control areas, and 2) effect and control periods. First, corn and soybean data of the two counties where the historical data indicated a rain increase had developed about 1950 were compared with the yields of five surrounding Illinois counties (Jersey, Bond, Washington, Clinton, and Monroe) where no rainfall effect was apparent (figure C-8). The regional differences in the yields were then compared on a temporal basis since 1) the rain increase occurred only in more recent years, and 2) the soils of the seven counties are not homogeneous.

Comparisons were defined for the crop yield differences obtained for *wet* seasons (greater than 125% of average); *near normal* seasons (all the area having rain between 75 and 125% of normal); and *dry* July-August seasons (less than 75% of average). For a given season to be assigned to the wet or dry classes, at least 75% of the 7-county area had to experience rainfall that fell within the class. Such a 3-class comparison allowed assessment of the increases for widely differing July-August seasons. It should be noted that a few years did not qualify for any of these three classes because of the unusual rainfall variations in the area.

Temporal comparisons of the summer rainfall in the area immediately downwind (east) of St. Louis with that in the urban area revealed that a slight increase was apparent beginning in the mid-40s, but that the rain increase became most notable during the 1950s (Huff and Changnon, 1972). Hence, the wet, near-normal, and dry seasons during a 16-year period (1930-1945) well before 1950 were chosen as the "control period" for comparison with similar seasons from the post-1950 period (1961-1976), considered the "anomaly period" or later period in the 2-county area. The years 1931 and 1941 in the control period and the years 1968, 1971, and 1976 in the recent period did not qualify because of the unusual rainfall variations.

Within the period of the rainfall anomaly (1961-1976), there were four years (table C-5) with dry July-August periods (less than 75% average rainfall over more than 75% of the area).

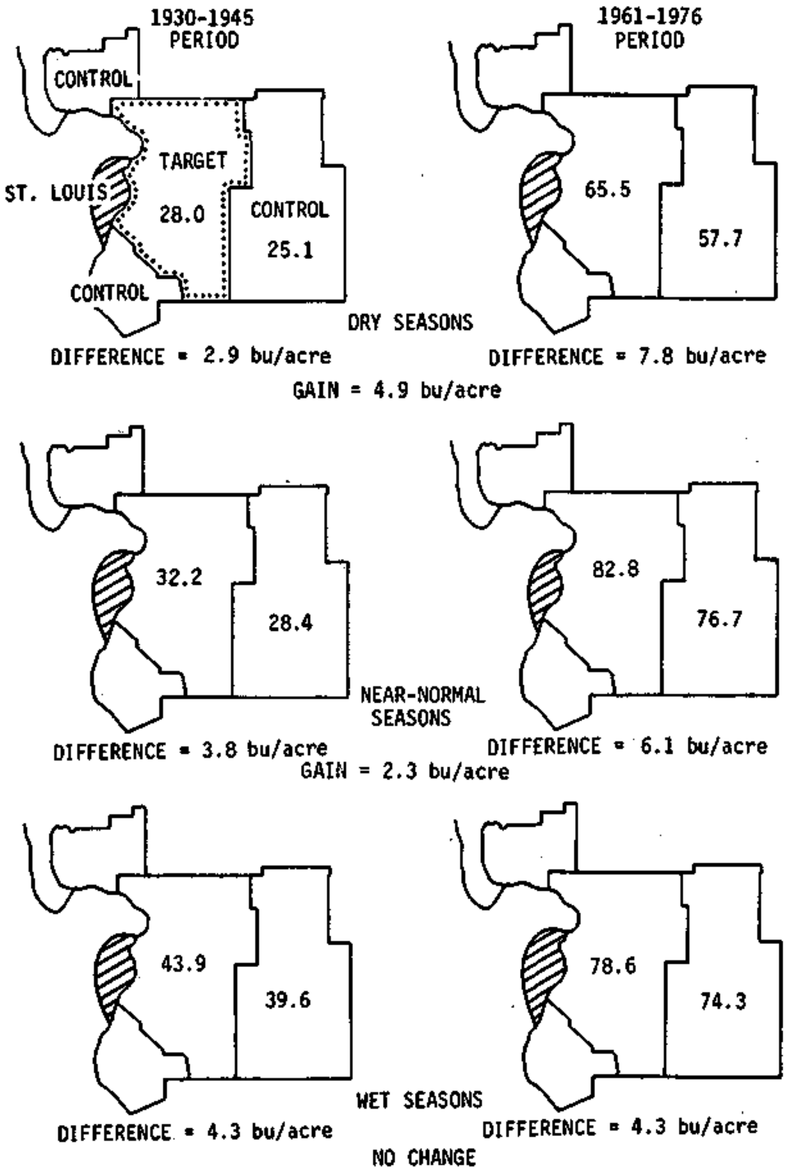


Figure C-8. Average corn yields in the target and control counties in wet, near-normal, and dry summers for 1930-1945 and 1961-1976 periods

The yields in these four dry years in the two "effect" counties (St. Clair and Madison) were averaged, and these averages were compared with the averages of the five control (surrounding) counties. The results for the corn data are shown in table C-5, and the difference was 7.8 bu/acre. A similar dry-year regional comparison was performed with the data from the "no-effect" or pre-anomaly period (1930-1945). There were six years in this period and the average corn yield in the effect area was 28.0 bu/acre, as compared to 25.1 bu/acre in the control area, a difference of 2.9 bu/acre (table C-5).

The regional values of the two periods are shown in figure C-8. Results of subtracting the differences in the dry, normal, and wet seasons furnish a measure of the early-to-late "change,"

Table C-5. Comparisons of Temporal Changes in Corn Yields of the Effect (Anomaly) Area Downwind of St. Louis and Those of Surrounding Control Areas

	*Dry summers**			*Near-normal summers**			*Wet summers**		*All summers*	
	Yields (bu/acre)			*Yields (bu/acre)*			*Yields (bu/acre)*		*Yields (bu/acre)*	
Year	*Effect area***	*Control area***	*Year*	*Effect area*	*Control area*	*Year*	*Effect area*	*Control area*	*Effect area*	*Control area*
Early years (1930-1945)										
1930	21.5	18.8	1934	9.0	11.6	1932	41.5	38.0		
1933	20.0	18.2	1935	34.0	30.4	1939	45.3	40.9		
1936	15.0	15.0	1938	38.0	33.4	1942	45.0	39.8		
1937	39.5	35.4	1940	40.5	33.8					
1943	38.5	32.8	1944	39.6	32.9					
1945	33.5	30.3								
Average	28.0	25.1		32.2	28.4		43.9	39.6	32.9	29.4
Difference (E − C)	2.9			3.8			4.3		3.5	
Later years (1961-1976)										
1964	59.0	49.6	1963	70.0	69.0	1961	71.5	67.8		
1966	62.0	54.5	1965	84.0	71.8	1962	71.0	65.4		
1970	59.5	53.0	1967	98.0	90.0	1969	78.1	73.0		
1973	81.5	74.0	1972	85.0	83.0	1975	93.8	91.0		
			1974	77.0	70.0					
Average	65.5	57.7		82.8	76.7		78.6	74.3	76.2	70.1
Difference (E − C)	7.8			6.1			4.3		6.1	
Shift, later difference − early difference	+4.9			+2.3			±0		+2.6	

*Dry summer defined as one in which the July-August rainfall across 75% of the 7-county area was < 75% of normal; near-normal defined as one in which the July-August rainfall across the entire area was > 75% and < 125% of normal; wet summer defined as one in which the July-August rainfall across 75% of the 7-county area was > 125% of normal.

**Effect area is the average yield of Madison and St. Clair counties; control area is the average yields of 5 surrounding counties (Monroe, Clinton, Bond, Jersey, and Washington).

if any existed. The change in the corn yields of the dry seasons represented a 4.9 bu/acre gain or increase in the effect area.

Near-normal July-August rainfall seasons are also shown in table C-5. The time change in corn yields shown in the yields from these near-normal rainfall seasons indicated a gain of 2.3 bu/acre (figure C-8). The regional difference in wet seasons in the no-effect (early) period was 4.3 bu/acre (table C-5), and the difference was the same in the effect period. Thus, the urban-related rainfall increase in "wet" July-August seasons produced no apparent change in yields. The average yields of the near-normal summers (of the 1961-1976 period) are higher than those of the wet summers indicating that some of the wet summers were sufficiently wet to harm corn production.

Corn yield data from all the 14 years classified in the no-effect (early) period were summed, averaged, and compared with those from the 13 years in the anomaly (late) period to obtain an overall expression of the average corn yield increase for the 1961-1976 period (see table C-5). This revealed that the change in the recent period amounted to 2.6 bu/acre per year. The 16-year (late) average yield of the two-county area was 76 bu/acre; thus, the urban-produced rain increase represented 3.4% of the total yield. In dry summers, the increase was 7.5% of the total yield, and in near normal summers the average increase was 2.8% of the total effect area yield. The corn yields in the early period (effect and control) were compared with those in the late period, and a 2-way analysis of variance showed the recent differences were significant at the 5% level.

Table C-6. Comparison of Ratios of Corn Yields in Effect and No-Effect Periods

Area	*Yield ratio, late (effect) to early (no-effect) time periods* *Dry summers*	*Near-normal summers*	*Wet summers*	*All summers*
Effect	2.34	2.58	1.79	2.33
Control	2.29	2.70	1.87	2.38
Difference, (E – C), *percent*	+5	-12	-8	-5

Table C-7. Comparisons of Temporal Changes in Soybean Yields of the Effect (Anomaly) Area with Those of Control Areas

	*Dry summers**	*Near-normal summers**	*Wet summers**	*All summers*
Effect – control differences, bu/acre				
Early period**	+2.3	+2.0	+2.0	+2.1
Late period**	+4.0	+3.2	+3.0	+3.4
Difference (early – late)	+1.7	+1.2	+1.0	+1.3
Difference, *percent,* of late period yield in effect area	+6	+4	+3	+4
Ratios, late period/early period				
Effect area	1.92	1.88	1.73	1.88
Control area	1.87	1.91	1.75	1.88
Difference, *percent*	+5	-3	-2	±0

*Dry summers are defined as those with rainfall < 75% of normal over ≥ 75% of the 7-county area; near-normal summers are defined as those with rainfall > 75% and < 125% of normal in the 7-county area; wet summers are defined as those with rainfall > 125% of normal in the 7-county area.

**Early period is a summer within the 1930-1945 period; late period is a summer within the 1961-1976 period.

It could be argued that the temporal changes in yields here attributed to increased rainfall were partially due to an uneven regional adoption of technological practices, particularly the increased use of nitrogen fertilizers in the 1961-1976 period. Basically, it was assumed that adoption of technological advances was generally similar in both time and degree in all 7 counties, although technological responses may have differed because of differences in basic soil types.

The issue of possible uneven temporal technological adoption in the effect and control areas was investigated by the use of ratios of average corn yields between the early and late periods for the effect area and for the control (no-effect) area. Ratios were computed for the dry, near-normal, and wet summers, as shown in table C-6.

The ratio for the late period to the early period in the control area was 2.29, or an increase of 129% from the first to the second time period. Similarly, in the effect area this ratio was 2.34, indicating a yield increase of 134% from the early to late period. The increase in yield was then 5% greater (1.34 — 1.29) in the effect area. Similar comparisons for the normal and wet summers show 12 and 8% decreases from the early to the late period, respectively. However, the absolute increases in bu/acre in the late period were greater for the normal summers, as shown in table C-5. Based strictly on the percentage statistics of table C-6, it could then be argued that the yield increases in normal and wet summers from the first to the second time period were at least partially due to technology, and the reactions to technological practices were somewhat greater in the area with lower initial yields (control area).

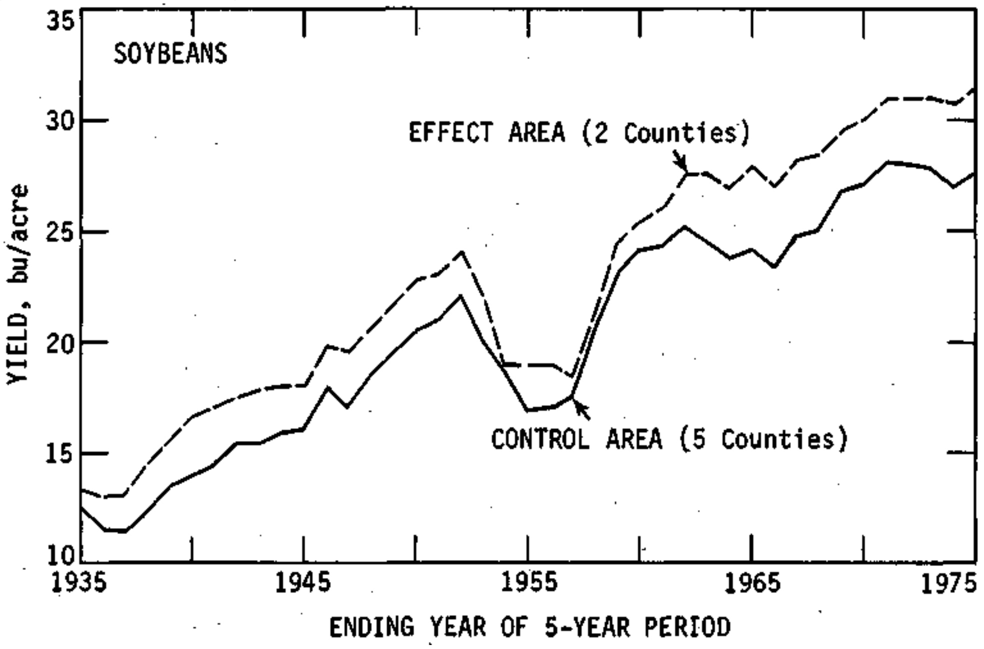


Figure C-9. Comparison of soybean yields between effect and control areas east of St. Louis based on 5-year moving averages

A similar analysis to that just described for corn yields was performed for soybean yields. Table C-7 shows the effect vs control area differences in the early period (1930-1945) and later (anomaly) period (1961-1976) are shown in table C-7. These reveal, as with corn, the greatest gain in the dry summers (1.7 bu/acre) with an average of 1.3 bu/acre for all summers. Figure C-9 shows the trends on the effect and control area soybean yields, based on 5-year moving averages, from 1930 through 1975. Notable is the ever widening difference in yields that began in the late 1950s (plotted as the values for 1960 and later).

Also shown in table C-7 are the ratios of the late vs early periods for the effect area and the control area. Their differences reveal a relative gain in the effect area of 5% in dry summers and relative decreases in the normal and wet summers. Consideration of the total gains in soybean yields, and the plus and minus relative percentages shown in table C-7, indicates that 1) the rain had a yield-increasing effect in the anomaly (effect) area, particularly in dry years, and 2) there also likely was a greater improvement in yields in the control area through technological practices.

The net, all summer, increase in soybean yields in the effect area of 1.3 bu/acre is 4% of the effect area average yield (32 bu/acre) for 1961-1976. The percentage increases shown in table C-7 for dry summers is +6%, for near-normal summers +4%, and for wet summers +3%.

Effects of Added Hail, Heavy Rains, and Pollutants on Crop Yields

The yield shifts described in the previous sections for the anomaly area were predicated on the hypothesis that they largely reflected the net effects of altered rainfall quantity. Actually, they are an integration of *all* weather influences on crop production including more rain, more hail, higher wind gusts, and dirtier rain.

To obtain an evaluation of the crop losses due to added hail and wind, crop insurance records for the townships in the St. Louis area were obtained from the Crop-Hail Insurance Actuarial Association. These covered the 1948-1975 period, the only data available in Illinois and Missouri insurance records. Hence no pre-anomaly analysis was possible.

The township loss cost values (amount of loss ÷ liability × 100) were plotted and mapped (see figure B-74 in hail section). Loss cost is an adjustment for varying liability and allows for valid regional and temporal comparisons of losses. These values established the presence of a locally high loss area in portions of the two effect counties (Madison and St. Clair Counties) where loss costs were 100% greater than elsewhere in southern Illinois. The METROMEX measurements of hailfalls showed a sizeable increase in hail frequency and in intensity (a measure of wind and hail volume) in the same area.

Integration of the amount of liability and the losses in the townships of the two effect counties and those in the townships of the five Illinois control counties (see figure C-8) allowed calculation of the average crop hail (and related wind) losses in the two areas. Their differences indicated that the average *additional* loss in the effect area was 0.6 bu/acre in corn yields (1% of the total yield), and 0.2 bu/acre in soybean yields (1% of the total yield) for the 1948-1975 period. This added loss in the 2-county effect area amounts to 88,700 bushels of corn annually and 36,400 bushels of soybeans.

The agricultural effects of additional pollution scavenged and deposited by the added summer rainfall in the effect area could not be ascertained. Semonin (1976) has shown that, on the average, the rain in portions of the effect area is relatively acid (pH < 4.5), but the pH of the rainfall is quite variable within the area. As will be shown in the next section, the corn and soybean yields in the effect area do not seem to reflect any measurable benefit or harm from the pollution. The added zinc deposited in the area should have a beneficial effect on the local horseradish production since zinc aids its growth (Semonin, 1977).

A third possible effect on agricultural production related to the urban-induced rain anomaly is due to added soil erosion. In the section on water resources, it was shown that the urban-increased rain rates were increasing soil losses by 34% in the effect area. Again, the calculations of net yield effects, when compared to what crop yield-weather (rain) relationships predict (Changnon and Neill, 1967), do not reveal any measurable effect of this loss in soil. Apparently the urban-produced heavy rain anomaly (and resulting soil loss) has not been active for a sufficiently long period to result in soil losses large enough to be detectable as affecting yield values.

Net Effects of Summer Rain Anomalies on Agricultural Production

The results of the foregoing yield analyses are summarized in table C-8. These show that yield increases in corn and soybeans, without the associated hail-wind losses, would be 3.2 bu/acre for corn and 1.5 bu/acre for soybeans. Study of crop-yield and weather relationships using 1931-1965 data (Changnon and Neill, 1967) indicated that the observed rainfall increases in July and August would produce increases of this magnitude. In general, the yield shifts (table C-8) without the hail-wind losses are as great as predicted by the urban rain increase input into weather-yield regression relationships. Hence, no sizeable effect due to altered (poorer) rain quality or due to loss of soil is apparent.

The gains from the summer rainfall increases have essentially overwhelmed the losses due to added hail and wind and any presumed decreases due to added atmospheric pollution and soil erosion. The net yield increases, as shown in table C-8, are 2.6 bu/acre for corn and 1.3 bu/acre for soybeans.

The average farm acreage in the effect area has, since 1961, been 56 acres in corn and 69 acres in soybeans. Coupling the net yield increases (table C-8) with these acreages indicates that the average impact (benefit) of the altered weather on the typical farm has been 146 more bushels of corn per year and 90 more bushels of soybeans. Extending these values to the 2-county effect area (2642 farms) reveals a regional annual increase of 385,732 bushels of corn and 237,000 bushels of soybeans. The 10% average July-August rain increase over the 2-county area produces a 3% (corn) to 4% (soybeans) increase in the major crop yields.

Table C-8. Effects of Summer Precipitation Anomalies on Crop Yields in Effect Area

	Yield, bushels/acre	
	Corn	*Soybeans*
Net yield shifts, all summers	+2.6	+1.3
Hail-wind losses	-0.6	-0.2
Yield shifts without hail-wind losses	3.2	1.5
Predicted shifts based on average rain changes input into rain-crop yield equations (Changnon and Neill, 1966; Changnon, 1968)	+2 to +3	+1 to +2

Translation of these values to monetary gains depends on price assumptions. In recent years prices have typically been $2.0 per bushel for corn and $6.0 per bushel for soybeans. Use of these values and the average yield gains per farm (for 1961-1976) indicates a net monetary gain per farm pf $832 ($292 for corn and $540 for soybeans).

The gains for the effect area are sizeable. The added corn production (at $2.0 per bushel) is $771,464, and that for soybeans (at $6.0 per bushel) is $1,422,000. Thus, the average area gain at these prices has been about $2.2 million per year.

The yield gains are greatest in dry summers (7.5% for corn and 6.0% for soybeans) when the increases are of appreciable value to the farmers. In the wet summers no corn yield effect is realized and that to soybeans (1 bu/acre, or 3%) is slight. This greater increase in dry and near-normal summers with little or no increase in wet summers has resulted in a more stable farm income, noted as a tertiary impact (figure C-2). Thus, there has been both greater income and more income stability from this locally modified weather. This is a prediction found elsewhere (Changnon et al., 1977) as an outcome of successful planned weather modification.

Effects on Agricultural Practices

The previously described effects on crop production of the urban rain anomaly should have further, third-order impacts on agricultural practices and related activities. If some or many of the local farmers perceive their local weather-related yield benefits (and losses to severe storms), they could adjust to them in many ways.

One way for a farmer to adjust to the weather is in crop planting strategies. Temporal shifts of acres planted in soybeans or in corn in the effect area, as opposed to average shifts in the 5-county control area, were studied. The net benefit yield analysis showed that the owner (and tenant) of an average farm gained $832 annually due to the urban weather anomaly, and most of this increase ($540 or 65%) was due to increases in soybean yields. Corn yield benefits, although bigger in total bushels, were not nearly as important largely because of the higher prices for beans.

The soybean acreage shifts are presented in table C-9. This analysis shows a relative gain of 6% in the number of acres planted in the effect area, as compared to those in the control area. A similar analysis of the corn acreage showed a relative decrease with the growth in acreage planted to corn in the effect area being 16% less than the growth in the control area. This relative shift to more soybean acreage and to less corn acreage in the effect area is economically consistent in that the rain anomaly produced more total dollar benefits from soybean yield increases than from corn yield increases. These relative shifts in corn and soybean acreage in the effect area suggest that at least some local farmers were aware that the 2-county area of the anomaly had, for some reason, a greater potential for soybean yield gains. Whether due to awareness of the rain anomaly or not, some recognized the yield implications and adopted strategies to increase their benefits.

Table C-9. Shifts in Acreage Planted in Soybeans in Effect Area and Control Area

Period	*Percent of total acres in soybeans*	
	Effect	*Control*
Early (1931-1945)	**1.7**	**1.5**
Late (1960-1974)	**21.5**	**17.9**
Late to early ratios	**12.65**	**11.93**

Difference, effect ratio–control ratio = 0.72

Difference (0.72) ÷ control ratio (11.93) = 6.0%

Another possible reflection of the impact of the urban weather anomaly on yields is in the value of agricultural lands. Increased benefits, higher incomes, and more stable incomes should produce in recent years (if locally recognized) a relative increase in the value of the agricultural lands in the effect area. The early and late values for the effect and control areas are shown in table C-10. The temporal shift in the ratios of effect to control values, the difference between 1.40 and 1.45 (0.05), represents a 3.6% (0.05 ÷ 1.40) relatively greater increase in agricultural land values in the effect area. The regional difference in the early vs late ratios (6.2 — 6.0 = 0.2) in table C-10 also reflects a 3.3% greater gain in value in the effect area.

These comparisons both suggest a slight but relatively greater increase in the value of agricultural lands in the effect area than in the control area during a period when the urban rain anomaly was present. That is, the effect area agricultural land value since 1960 has been 3 to 4% more than regional control values predicted. This finding further supports the concept 1) that some local farmers were aware of the greater agricultural benefits resulting from the anomaly, and 2) that as a result, they were willing to pay more for this land. This is a tertiary impact (figure C-2) but one that further relates to increased taxable income to the government (see institutional impacts, page 236).

The added hail (direct impact) which produces losses to crops and property (secondary impacts) could lead to 1) increased purchases of insurance coverage (liability), and 2) altered insurance rates in the effect area. Liability data of the Crop-Hail Insurance Actuarial Association were obtained, and the totals for the 2-county effect area and a 3-county control area (Bond, Clinton, and Washington) are shown in table C-11. This 3-county control area was chosen because METROMEX hail results showed this to be unaffected by urban-influenced hailfalls and neither the METROMEX nor National Weather Service data sources offered hail information in the extreme north (Jersey) and south (Monroe) control areas.

After adjusting the dollar liability values for differences in areal extent (table C-11), the resulting difference shows the effect area value to be higher by $63 per square mile. This increase, expressed as a percent of the control value, shows the liability purchased in the effect area was 12% higher than that in the control area. This further indicates that some of the local farmers in the effect area have perceived the greater hail loss and have increased their coverage. The relatively greater income from the higher yields also allows for more expenditures including more insurance coverage, which in turn effectively decreases farm income.

The added crop-hail loss has not been reflected in increased insurance rates in the effect area. As shown in a study of hail suppression (Changnon et al., 1977), a sizeable and prolonged shift in hail loss is needed before rates are changed. Furthermore, crop-hail insurance companies typically do not set different rates for relatively small areas in the Midwest. Illinois is divided by most companies into four rate regions, each covering 20 or more counties. A tertiary impact of this situation, as shown in figure C-2, is the fact that rates in the effect area have not gone up commensurate with the higher loss. Hence, those insured elsewhere (depending on the company) are subsidizing the greater loss in this area.

Another agricultural response, at least institutionally, to the increased erosion from higher rain rates has occurred in the Soil Conservation Service. Beginning in 1973, local SCS county advisors altered (increased) the rain factors within the design criteria they use to advise local farmers for conservation methods (weirs, grass-waterways, terracing, etc.). The degree of implementation

Table C-10. Values of Agriculture Lands in Effect and Control Areas

	Value of agricultural land per acre *Effect area*	 *Control area*	 *Ratio, effect to control*
Early period (1930-1939)	$75	$53	1.40
Late period (1961-1970)	$464	$321	1.45
Ratio, early to late	6.2	6.0	

Table C-11. Analysis of Crop-Hail Insurance Liability in Premiums, 1948-1974

	Effect area	*Control area*
1948-1974 total liability	$20,585,000	$22,806,000
Annual liability/mi^2	$575	$512
Difference, E-C	$63/mi^2	

of these adjustments by local farmers is unknown; However, the soil conservation practices, in general, have not been well adopted nationally with only 25 to 35% of the farms employing recommended practices (Ackermann, 1976).

Other Effects on Agriculture

A likely minor but interesting potential agricultural impact relates to the 40- to 80-% increases in thunder and lightning activity in the 2-county area. Griffing (1977) has shown that thunderstorms are likely to be an important interim source of oxides of nitrogen for areas in and near them. Some of these (NO, NO_2, N_2O) are likely deposited locally in the heavy rain with the thunderstorms, and should be effective in helping furnish nitrogen to the soil, a critically important fertilizer for corn and soybeans. However, not even a qualitative estimate of this nitrogen addition by thunderstorms can be made and the impact remains vague.

BUSINESS AND INDUSTRY IMPACTS

Agribusiness

The impacts of the rain-increased yields and resulting tertiary impacts (more farm income, higher farmland values, changes in soybean and corn acreage, etc.) have not been traced to local agribusiness. However, some idea of effects can be derived from a study of the potential impacts of successful planned weather modification (Changnon et al., 1977) in which probable impacts on agribusiness in the adopting (or affected) area were identified. Relatively minor (slight) impacts that should exist in the effect area east of St. Louis, as compared to the no effect areas, include 1) increased profitability to farm equipment firms; 2) increased sales of fertilizers, herbicides, and pesticides; 3) increases in the number and favorability of loans; and 4) additional crop storage space and transportation usage to handle the added production.

The greater number and intensity of hailstorms, and the resulting higher crop and property losses, impact slightly on the insurance industry. To date, the private insurance companies have not increased their rates in the effect area. However, losses there are greater and their profitability in the 2-county area is lower. As more farmers seek more insurance coverage, a trend already noted in the liability (table C-11), the relative amount of loss expressed by the companies will increase due to the locally concentrated nature of hailstorm damage. This likely will not result in any major problem, because of the statewide or larger base of selling by most companies, but it may lead to rate adjustments in the effect area.

Planned Weather Modification Industry

The results of METROMEX, including the operational experience (Cataneo, 1974), have several impacts on the weather modification industry (Semonin and Changnon, 1975). Since there has been only one experiment in the Midwest and it occurred 15 years ago, the METROMEX information has practical applications for both research experiments and for operational (commercially supported) weather modification efforts in the Midwest.

The field operations and the evaluation procedures of METROMEX have provided valuable lessons applicable to the design of a planned weather modification experiment in Illinois. Experience in conducting the tracer releases into clouds has indicated that cloud-base seeding can be successful (Semonin, 1972). These tracer operations have also shown that the real-time display of quantitative radar data is necessary if cloud-base aircraft seeding is to be used. The complexity of the convective systems common in the Midwest and their occurrence in all hours require excellent radar data and communications to aircraft to provide guidance and a margin of safety for the flight crews involved in cloud seeding.

The METROMEX synoptic-rain results are encouraging for planned weather modification. The fact that squall lines exhibit the potential for rainfall enhancement is particularly important since they are the major rain producers of the summer. A capability to provide sizeable increases in air mass rainfall would have little net benefit since they produce so little of the total summer rainfall. On the other hand, the synoptic results do suggest that increases in rainfall from squall lines will be accompanied by increases in hail. Interestingly, the net economic effect of more rain and more hail, as found at St. Louis, is a benefit.

The METROMEX results also suggest that large urban-generated condensation nuclei help initiate the coalescence process and thus make more clouds produce rain (Semonin and Changnon, 1974). This suggests the hygroscopic modification process should be considered for the Midwest.

Urban effects also led to local showers and convective storms during regional dry periods. These kept the immediate urban and rural area from being as droughty as other nearby areas. This suggests there is some hope to partially alleviate some drought conditions, and it illustrates those weather conditions when rain presumably could be purposely induced during dry summer periods (Huff and Semonin, 1974).

Changnon et al. (1976) have shown that the enhancement of the rainfall in the St. Louis area often occurs as a result of more mergers of the greater number of convective cells generated over the city area. This suggests that dynamic (heavy) seeding to change the ice phase so as to increase cloud growth and to secure merging is a feasible way to enhance rainfall in the Midwest.

METROMEX flight operations have shown the complexity of cloud conditions and poor visibility at low levels, both a hinderance to cloud-base seeding. Upper-level seeding, at or above the freezing level would be relatively easier for visual operations.

Results suggest that both ice-phase seeding (to induce cloud growth and mergers) and hygroscopic seeding would be effective in the Midwest, at different times of the day and in different synoptic weather conditions. Major rain-producing systems, like squall lines, have the potential for being seeded to increase rain (and possibly hail). METROMEX results also indicate that the cloud-base seeding approach will work, but it will be difficult and will require many aircraft.

Upper-level seeding may be a more effective approach for cloud seeding. Ground-based tracer releases in the urban area indicated some materials were getting to cloud-base level, but this was due largely to urban-induced convective motions and atmospheric mixing.

Impacts on Utilities

Water supply systems in the effect area will be impacted by the anomaly, as discussed in the water resources impacts section. There will be benefits from the added water to the surface storage sources and groundwater sources. The atmospheric-related increased rain pollution is slight and of little consequence to local water utilities.

One of the impacts to the power industry and their consumers in the effect area is an increase in power outages due to lightning strikes. Data on all outages in the 1972-1975 period were obtained from the Illinois Power Company. The pattern of outages, based on township frequencies, is shown in figure C-10. Also shown is the thunder-day pattern established from the 1973-1975 METROMEX data. The outage pattern confirms the validity of the METROMEX thunderstorm and lightning anomaly. It shows a concentration of outages in the suburban area east of St. Louis. Outages are 5 to 10 times greater there than those in the eastern counties (Bond and Washington). These outages are both costly and inconvenient to the power company, the public, business; and industry in the effect area.

Table C-12 presents the average number of outages per township for the 5 counties with data. The general effect area (Madison and St. Clair Counties) values are 6 to 7 times greater than those in the no-effect area. Also given in table C-12 are the average number of outages per 10 miles of power lines. This figure allows for regional comparison without bias of areal differences in the target (lines). These values also support the fact that the effect area has more lightning outages, but the difference between the two effect counties (Madison and St. Clair) and the control values is not as great as the unadjusted township values.

Other Impacts

In general, business and industrial structures in the area suffer from the urban-generated weather anomalies. The increased storminess (hail, wind, and lightning) produce losses. One such case (Changnon, 1977a) involved the collapse of an industrial roof during an urban-affected severe storm in 1973. The accumulation of heavy rain on a flat roof because the downspouts were clogged with hail resulted in too heavy a load. Such damages are likely covered by insurance and thus result in either higher premiums for buyers or losses to the insurance companies. Clearly, storm-related losses produce work delays and other secondary but unmeasured losses.

Another structural loss is produced by rain-borne pollutants. Acid rain has been noted to damage paint and stone type structures (Tobin, 1976). However, no direct measures of such impacts on buildings have been made in the St. Louis area. Semonin (1976) presents rain quality data which shows that the industrial area of East St. Louis-Granite City experiences, on the average, quite acid rainfall.

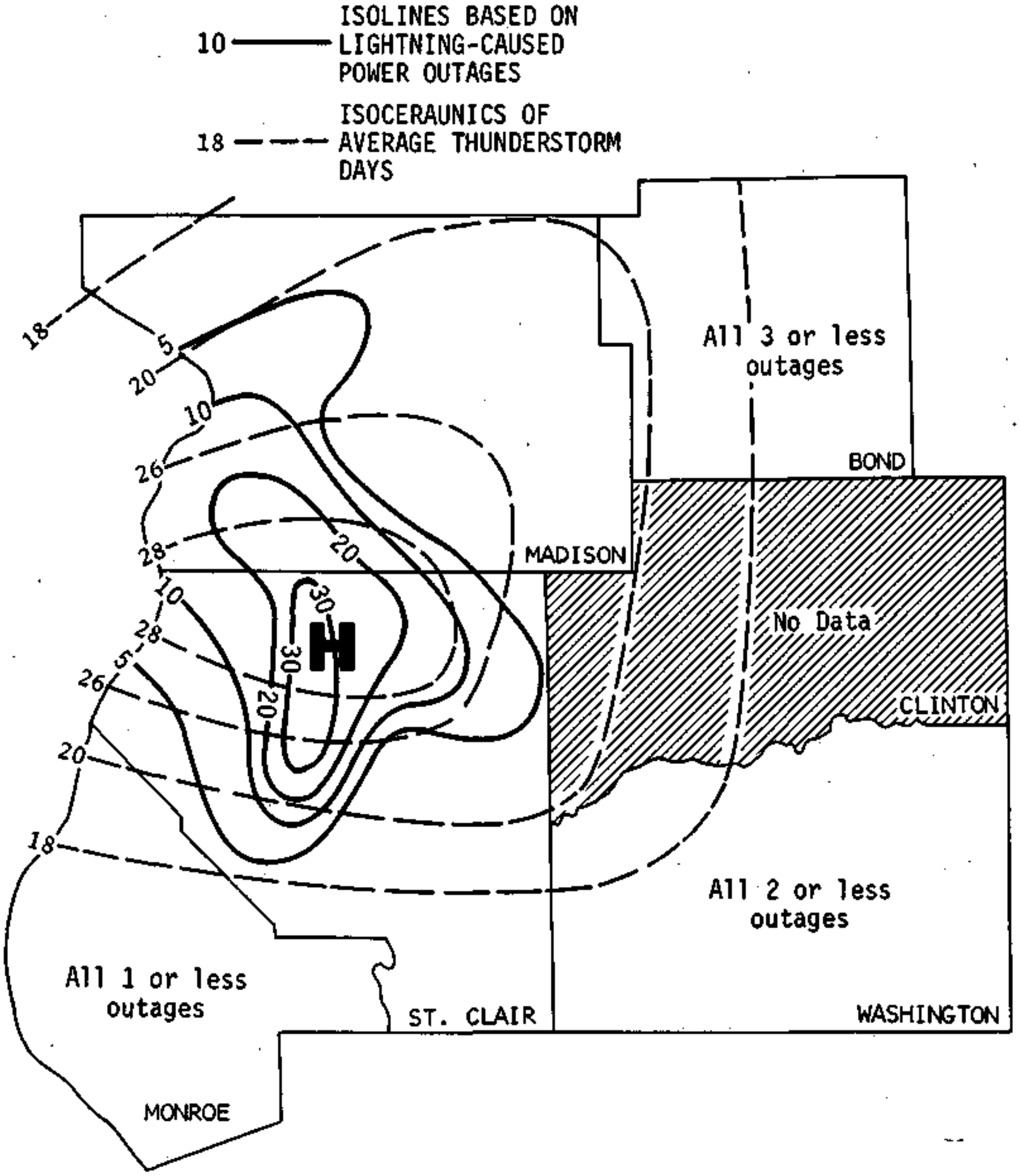


Figure C-10. Pattern of lightning-caused summer power outages in 1972-1975 based on township frequencies (source Illinois Power Company), and pattern of average summer thunderstorm days 1973-1975

Table C-12. Power Line Outages during 1972-1975 Period, Reported by Illinois Power Company

County	*Area (mi²)*	*Number of outages*	*Average outages per township*	*Miles of wire*	*Number of outages per 10 miles of wire*
Madison	737	119	7.0	314	3.8
St. Clair	663	135	7.3	252	5.3
Bond	380	27	2.4	104	2.6
Washington	561	16	1.0	159	1.0
Monroe	190*	6	1.2	42*	1.4

*Northern half of county only (full county size = 389 mi²) since IPC covers only that area.

ECOLOGICAL EFFECTS

Plants and Trees

The possibility exists that the localized urban-industrial alterations in rain and related conditions will affect some flora. Interest in this possibility has resulted in several studies of rain effects on the growth of trees.

Harmon and Elton (1971) and then Ashby and Fritts (1972) initiated ecologically oriented studies based on analyses of tree rings in and around the La Porte (Indiana) area downwind of Chicago where Changnon (1968, 1970) found an urban-related rain increase. Harmon and Elton showed a weather-related anomaly in tree rings in the area that they ascribed to a "more favorable rainfall" climate resulting from a combination of urban effects on rainfall and of lake effects on weather. Ashby and Fritts concluded that trees in the area showed increasing effects of man-made pollution on growth. Their analysis of rainfall could only partially support a precipitation change because a 30% increase in warm season rainfall was too insignificant to be detectable statistically. Their results showed that the total precipitation variable could explain only about 25% of the total variability in tree ring size. Similar studies have not been pursued in the St. Louis area because the La Porte results indicate the rain effect is probably too minor to be detected (Changnon, 1976b).

Air pollution injury to trees and other plants is a problem in the St. Louis area (Lanphear, 1970). How much of this is attributable to increased pollution deposition by the added rainfall is not clear. Half the deposition of pollutants occurs in rain (Huff, 1975b) and if the urban rain anomaly of +20% is linearly related to the amount of deposition, linear calculations would suggest that 10% of the total summer pollution deposition is due to the rain anomaly.

In the early part of the 20th Century, air pollution in the St. Louis area was so severe that evergreens and certain other plants often did not survive. This damage was associated with SO_2 from smoke in the burning of soft coal by many local industries. Local regulations enacted in 1939-1940 reduced the level of SO_2 by more than 75% by 1950. Lanphear's studies showed SO_2 damage to sugar maples and ginkgo trees, primarily in June and July, and it was not associated with high temperatures nor drought conditions. Although damage was noted in the city and St. Louis County, it was usually greatest within 3.2 to 4.8 km (2 or 3 mi) of sources.

Hume (1968) noted pollution damage to trees (Chinese elms, locusts, sycamores), shrubs (lilacs, mock orange), and vines in the East St. Louis area. Plant vigor was notably reduced and leaves were visibly damaged. Hume claims the general lack of flora in this industrial area is a result of pollution damage. The extent of this type of damage beyond the St. Louis-East St. Louis area has not been documented, and it is hard to assess what impact the urban rain anomaly has on plants. Clearly, more rain should encourage growth, as found in the crop yields. It appears that much of the area relatively close (1.6 to 4.8 km or 1 to 3 mi) to industrial-vehicular sources, and hence to dry deposition, receives much of the observed plant damage.

Soils

The previously mentioned erosion of top soils is likely one of the most important impacts of the urban rain anomaly. Calculations indicate a 34% increase in soil loss (2.8 tons per acre per year) related to the local increase in high rain rates.

The effect of added rain-borne pollutants on soil quality has not been measured directly east of St. Louis. It appears quite likely that soil pollution has been increased and part of this is due to the rain anomaly. The rain, surface water, and groundwater quality analyses (Huff, 1975b; Schicht, 1977) indicate that expected amounts of zinc, nitrates, and potassium in groundwater do not appear there because of their attenuation (capture) on soil particles. The calculated zinc "cycle" in the northern floodplain area is interesting. The atmospheric deposition east of St. Louis is 0.19 mg/1 (table C-4) with 0.08 mg/1 in the local streamflow (Canteen Creek) and 0.01 mg/1 in the groundwater. Thus, 0.10 mg/1 or 53% is left in the soil. Since the anomaly in the area accounts for about 10% of the total deposition (20% of the 50% of the total deposition from rainfall), the rain anomaly adds 0.019 mg/1. Thus, the anomaly induced added zinc is double the amount found in the groundwater. If the anomaly induced zinc deposition is equally distributed, then it accounts for 10% of the zinc found in the soil (0.01 mg/1) and in the streamwater, (0.008 mg/1), and 10% of that in the groundwater (0.001 mg/1).

The effect of the added soil pollution on the growth and production of plants and crops is unknown, although the crop yield analyses suggested no apparent effects. Certain pollutants (nitrates) in soil and a more acid soil can be helpful to certain crops. Semonin (1977) reports that acid soils are beneficial to the growth of horseradish, a plant widely grown in the floodplain. If soil pollution due to the anomaly is helping or hurting plants and crops, it is likely a very minor effect.

Animals

No direct measurements of possible effects of the urban rain anomaly on wild or domestic animals have been made. Havera (1973) studied the effects of various weather variables on the population of rabbits in the area. He concluded that rainfall in summer months had no detectable relation to the number of rabbits in the Illinois areas east of St. Louis. The occasional incidence of very large hailstones, potentially related to urban influences, could produce death and damage to domestic animals (chickens, hogs, etc.) and to small game animals. Basically, no impact on animals is believed to exist.

IMPACTS ON HUMAN HEALTH AND ACTIVITIES

Health and Safety

It has long been recognized that excessively high temperatures affect health and occasionally result in death to the elderly and to those with certain illnesses (heart and respiratory diseases). St. Louis produces a heat island that increases the high daytime summer temperatures (Jones and Schickedanz, 1974), and health problems obviously result. However, the urban additions of rainfall and severe weather in and beyond St. Louis are not known to produce any direct effects on health. Added cloudiness east of St. Louis may be slightly beneficial on some days for reducing maximum temperatures by 1 or 2°C.

The rain anomaly can have a sizeable effect on transportation, causing either delays or accidents, which can produce injuries and loss of life. For example, downdrafts from thunderstorms can and do produce accidents to aircraft, particularly to large jets on landing. A recent assessment of impacts of inadvertent weather modification (CEM, 1977) pointed to this problem. Since results at St. Louis show a 40% increase in thunderstorms and their durations over and around St., Louis, the anomaly increases the thunderstorm danger to commercial aircraft operating in the St. Louis area. The crash of a commercial airliner on its landing approach at St. Louis in 1973 appeared to occur in the gust front generated by downdrafts of an urban-affected thunderstorm (Schickedanz and Gatz, 1975).

The urban-related 30 to 90% increase in heavy rain events in a densely populated urban and suburban region reduces visibility on highways and arteries and decreases traction. These factors obviously help in causing vehicular accidents, injuries, and occasional deaths. How many of the accidents and resulting losses are attributable to the urban added severe weather is unknown. However, it is likely of major significance, both economically and to human health and life. An on-going investigation will better define this impact (Farhar, 1977).

Shifts in Human Activities and Related Impacts on Income, Cost of Living, and Taxes

Tobin (1976) made an extensive study of how climate changes affect urban areas. He showed that heavier rain and poorer visibility (like the anomaly at St. Louis) resulted in increased crime. This, in turn, results in more police activity and added costs in law enforcement. Sassone (1976) points to a positive linear relationship in urban areas between rain amount and 1) costs for education, and 2) costs for sanitation and sewage treatment. Hence, taxes for law enforcement, education, and water resource systems should be increased in the effect area as a result of the rain anomaly. The magnitude of the effect is unmeasured at St. Louis.

Polluted heavier rain, and acid rain in particular, will increase damage to paint and stone on houses. This will lead to higher repair costs, and in general, air pollution reduces median property values (Tobin, 1976). As a result, income from property taxes decreases. This is likely confined largely to the metropolitan area.

The sum of these likely (but unquantified) impacts (higher personal taxes, lower property values, and decreased tax income to cities) from the "bad weather anomaly" may have helped encourage outmigration of the more wealthy white population to suburbs beyond the effect area. This, in turn, resulted in relatively more low income residents in the urban center and then less taxable income for the affected urban governments. (See also the section on institutional impacts, page 236.) In a sense, the urban-produced rain anomaly helps produce a series of events that lead to urban decay.

Hoch (1976) revealed that not all social impacts of increased rainfall are adverse. His findings show that a 20% rain increase, such as that found in Madison and St. Clair Counties (and not in St. Louis), will lead to a 1.8% increase in average wages for an area in the central United States. Crocker (1976) showed that altered climate, including more rain, would alter the local demand for market purchased goods (e.g., more rain gear). This could affect the stocks and income of commercial firms in the effect area.

In essence, these interpretative impacts (without direct measurements in the St. Louis area) suggest that living in the effect area will be more costly (higher taxes for several reasons) and will simultaneously increase income. The higher costs coupled to the rain pollution damages form a sequence of events that act to help cause or reinforce existing 1) outmigration from the city and weather effect areas, and 2) the development of slums, both resulting from a host of other socio-economic reasons. A major question is whether the amount of social impact of the weather anomaly on this sequence could ever be measured. Tobin (1976) indicates that few urban or nearby affected rural dwellers realize that by choosing to live in or near the city they have chosen a climate different from the rural one. Thus, the social and real costs resulting from the urban anomaly, which help lead some people to relocate (urban to rural), may be largely unknown or unrecognized by most local dwellers whose responses are third order impacts to recognized second order impacts (see figure C-2).

IMPACTS ON ATMOSPHERIC SCIENCES

Forecasting of Weather

METROMEX results offer the capability to better understand and thus to better forecast precipitation conditions in and around St. Louis and other urban areas (Changnon, 1977b). Any improvements in rainfall forecasts in areas where 70% of the nation's population reside have clear advantages in planning personal and industrial activities.

Analyses of the synoptic weather conditions when urban effects on rain develop have pointed to the fact that under certain conditions, such as squall line and cold frontal passages, urban effects will act to enhance the rainfall (Vogel, 1974). Of particular relevance to man and his activities will be the improved capability to forecast those conditions when urban effects combine with nature to produce 25 mm (1-inch) or greater rainfalls in and/or beyond the city (Huff, 1976a). Better forecasts of these conditions would be of considerable value to local transportation systems and the operations of water resource systems. METROMEX results on wind and other atmospheric conditions describing the atmospheric stability indicate 1) the area and time where urban-induced clouds will form (usually before natural clouds), and 2) those conditions (times and days) when urban effects will initiate local showers and storms (Vogel, 1975; Changnon and Semonin, 1975).

Planned Weather Modification and Cloud Physics

METROMEX has generated a host of results relating to both experimental and operational aspects of weather modification (Changnon, 1977b). These include information as to seeding technologies, seeding methodologies, modification potential in various weather and climatic conditions, and operational aspects. Several of these have been enumerated in the prior section on business and industry impacts (see page 225).

The rainfall in the area "downwind" of the St. Louis-related rain effect area (beyond 40 km or 25 mi east of St. Louis) approximated that measured west of St. Louis. This suggests that increases in rainfall produced through intentional cloud seeding over localized areas in the Midwest may not produce an increase or decrease in rainfall beyond the major effect (seeded) area (Changnon, 1976b).

Braham (1974) has described several urban-related changes in cloud droplet sizes, illustrating how certain cumuliform clouds could be made more stable and less apt to rain. Changnon (1976a) studied radar echo behavior as part of METROMEX, and found that echoes that resulted from merged echoes grew faster (50%), became taller (52%), and lasted longer (122%) than non-merged echoes. The simultaneous increase in rainfall rates, hailfalls, and surface gusts found east of St. Louis suggests that modification to change one of these conditions (rain) may change them all (Changnon, 1977b).

These and many other results (Auer and Dirks, 1974) illustrate the large variety of useful results and information generated by METROMEX that help increase basic knowledge in the field of cloud physics. Changnon et al. (1976), and Boatman and Auer (1974) have developed extensive hypotheses of how urban conditions affect both the microphysics and dynamics of clouds. Braham and Squires (1974), in an inventory of cloud physics, described the value of METROMEX studies to the field of cloud physics. The results are exhaustive and significant, and the interested reader is encouraged to read the many papers and reports of all METROMEX groups.

Network Design and Operations

Changnon (1975) used METROMEX results to review all of the various factors that go into the design and operations of a successful mesoscale network, including its data processing.

The major network measurements defined by the METROMEX goals as being essential included the following *anomaly related network components:*

1) Raingage network
2) Hail sensor network
3) A thunderstorm network
4) Weather radars

Other network instrumentation was designed to address the goal of defining possible causes of the anomaly, recognizing that the above anomaly instrumentation would help provide answers to the cause issue. Basically, the network measurements to define causes had to measure the winds, temperature, moisture, aerosols, and clouds above the surface and largely in the lower 2000 m (6562 ft) of the atmosphere (surface to cloud base). The networks established *to measure surface conditions* included:

1) Rainwater and dry fallout sampling network using total and sequential samplers
2) Temperature and humidity recording network
3) Pressure network
4) Recording wind speed and direction system
5) Aerosol and CN samplers and other chemistry devices
6) Measurements of atmospheric electricity parameters

Further within the context of establishing the causes of the anomalies, certain other network instrumentation relating to the *measurements of the low-level atmosphere* were deemed essential, and these included:

1) Time-lapse cloud cameras
2) A lidar and acoustic sounders
3) Satellites
4) Pilot balloon networks
5) Radiosonde network

Mesoscale networks like the several used in METROMEX often involve complicated operations and hence they require quality staff and instrumentation. Certainly, data quality is the central aim of mesoscale operations. Representative data of high quality are obtained through careful attention to comparable siting of instrumentation, good servicing and frequent calibrations, and finally to careful editing and thorough checking of the data. Successful operations of extensive mesoscale networks require a well-executed management effort. All too frequently this is not obtained because of inadequate funding of any one of several key areas including quality and adequacy of the instrumentation, personnel, and data processing effort.

A final comment about METROMEX implications for mesoscale networks concerns the fact that experience has shown that mesoscale network data often are later used for a variety of purposes beyond those originally intended (Huff and Changnon, 1966). In other words, the network and its data frequently return the investment in many ways beyond that originally planned, and this is an important factor in assessing the cost effectiveness of meso-networks. An important aspect of this consideration is the retention, if at all possible, of all the data procured during network operations. The METROMEX network data have been retained in various tape and film files for use by the atmospheric sciences community.

Cataneo (1974) described the field operations of METROMEX and thus helped illustrate how to conduct complicated meteorological field programs involving several different meteorological research groups. Since a large number of field personnel and types of equipment were involved in METROMEX, certain critical phases of operation existed. One that was present throughout the operational period was maintenance of the many instruments utilized by the project. This necessitated constant monitoring by all personnel involved and required the services of a full-time individual in the field who was responsible for overseeing the operations including forecasting. Adequate communication and cooperation were imperative in all aspects of METROMEX, but especially during the joint-group aircraft operations which were dependent upon weather conditions that often changed rapidly requiring operations to respond accordingly.

Information for Numerical Modeling

Computer modeling using 1-dimensional and 2-dimensional cloud models (Ochs, 1974; Ochs and Semonin, 1976) and mesoscale models (Auer and Dirks, 1974) has been extensively employed in METROMEX. These models have been primarily used to help understand the physical relationships between the urban surface and effluents and the atmospheric behavior. They have pointed to the importance of surface temperature anomalies in affecting wind fields and initiating clouds, and the possible role of urban condensation nuclei in rain formation.

One resulting impact of METROMEX has been to help refine and develop numerical models suitable for interpreting midwestern convection and for predicting the occurrence and magnitude of urban rain anomalies at other cities. The extensive field data generated by the METROMEX Network and meteorological aircraft have also had an impact on modeling research being performed by other scientists (Silverman and Nelson, 1975; Chen, 1976).

Setting Research Priorities

Some extremely valuable aspects of METROMEX have been 1) to dimensionalize, for the first time, a major case of inadvertent weather modification, 2) to help delineate further research needed in inadvertent weather modification, and 3) to generate interest among the scientific community in inadvertent weather modification. Changnon (1973a) defined the few knowns and many scientific unknowns of inadvertent weather modification. This led to an assessment of research needs (Changnon, 1974). A critical finding was the extreme importance of identifying those self-amplifying mechanisms, such as a megalopolis, that could lead from local weather changes to regional climatic changes and on to hemispheric and global changes. A key research recommendation made by Changnon (1974) which was based on results of METROMEX and other urban climatic studies, is as follows:

> Urban-related weather changes, other than rainfall, are relatively localized, and are being studied more comprehensively than any other form of inadvertent modification. However, the key problem in this area is the *scale of the atmospheric effects likely to occur from super cities and the growing arrays of cities.* Understanding of the effects of single super cities needs to be developed before launching research into a megalopolis.

The impact of METROMEX on research efforts and their priorities has been reflected in several places. An ERDA-sponsored energy workshop in 1975 (ERDA, 1975) focused on many METROMEX results to develop research recommendations for ERDA. Two workshops sponsored by the NSF have concerned inadvertent weather modification and both have focused heavily on METROMEX results to define future research priorities (Blanchard, 1975; CEM, 1977).

Prediction of Urban Anomalies Elsewhere

A major goal of METROMEX was to develop sufficient understanding of the causes of urban precipitation modification, in conjunction with cloud and mesoscale modeling, to allow prediction of anomalies at other cities with a minimum of measurements. A conceptual model involving use of synoptic weather conditions and radar echo characteristics has been proposed for testing at Chicago, as part of the Chicago Area Program (Changnon and Semonin, 1978). As yet, understanding of the St. Louis anomaly and model development are not adequate for quality predictions.

However, it has been important to learn from METROMEX (Changnon et al., 1976) that the 1971-1975 rain findings agreed well with the earlier climatic studies of the St. Louis (then potential) anomaly (Huff and Changnon, 1972). This helps verify the reality of the earlier climatic findings about several other urban centers in humid climates (Huff and Changnon, 1973). The fact that the magnitude of the urban thunder anomalies found by climatic analyses at several cities was linearly related to population (see figure C-11), when coupled with the knowledge that the St. Louis thunder anomaly was conclusively established in METROMEX, gives greater credence to the climatic findings and the predictive equation shown in figure C-11.

Understanding Climate Change

A major concern of the scientific community in recent years has been to understand climatic changes and the possible role man has or could have in changing climate (MIT, 1970; Landsberg, 1970).

METROMEX has improved knowledge of this issue. METROMEX findings indicate that the spatial extent of an urban area's alterations of climate is limited. Many of the changes are truly local and exist largely within the urban complex and a few hundred feet above it. A few other

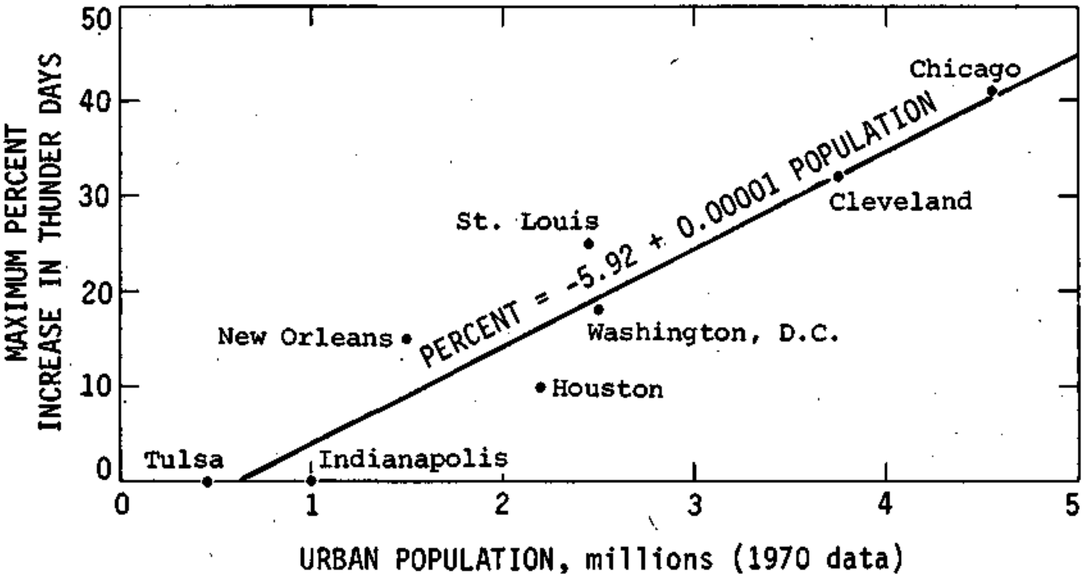


Figure C-11. Relationship between urban area population and maximum percentage increase in thunderdays in or near urban area changes, particularly those of visibility, clouds, and rainfall, extend 16 to 48 km (10 to 30 mi) downwind and thus produce mesoscale climatic differences.

However, the ability of METROMEX results to specify how the complexities of an urban-industrial area affect the weather *to induce a climatic change* has been critically important both in establishing proof of man-made climate change well beyond the city itself, and in understanding how the change occurs (Changnon et al., 1976).

A key issue within the field of man-made climatic change concerns the areal scale of the changes. Hence, a significant question relating to urban effects on climate concerns the potential combined effects from megalopolises. Could they be additive and trigger climatic changes on the macroscale? The chief problem evolving in this area, and one that is still poorly understood, is the degree and areal scale of the climatic changes that may occur from growing arrays of cities. We are at a stage when knowledge of weather effects from megalopolises can be put to advantage in designing city arrays so as to minimize undesirable effects. Of greater consequence is the portent for reaching critical levels that could help lead to global, or at least macroscale, weather and climate changes from our growing megalopolises. Attention to the local and mesoscale atmospheric alterations, their causes, and their possible amelioration is needed since we are at a stage when the urban arrays may still be partially controlled within our economic-political system.

INSTITUTIONAL IMPACTS

The institutional impacts have been presented last since they are all tertiary impacts (and responses) occurring as a result of the direct (weather) impacts and the secondary impacts (figure C-2). The origins and explanations for many of these institutional impacts are found in the prior sections of this text.

Local and Regional Institutions

The shifts in cloudiness, rainfall, and severe storms and the host of secondary impacts that occur within the 2-county area east of St. Louis collectively, directly or indirectly affect most local governmental institutions. It is doubtful that many of these institutions are aware of the scale of the weather changes and the impacts that affect them. Release of information about METROMEX has been extensive (RTI, 1976), but the extent and severity of the impacts have not reached many who would make decisions. For example, it is not easy to discern the added heavy rain from that which nature provides.

There is also a lack of use of the METROMEX results by those who have been well-informed about the impacts. For example, considerable efforts, beginning in i973, have been made by Survey scientists to inform water resource engineers in the St. Louis area about the sizeable changes in heavy rainfall, sufficient to require a major shift in the design of hydrologic structures. Yet to date very little application of the new values has been made as most individual government institutions, their engineers, or consulting firms still design around the old and inadequate (and less costly) rainfall-runoff values. Use of the newer and correct design values will take time.

The areal scale of the water problems in the floodplain, particularly the floodwater issue including basin sedimentation, has defied well-organized local solutions. Nearly 200 governmental agencies (city, township, county, regional, state, and federal) have varying jurisdictions in the 2-county effect area. The inability of these agencies to function coherently either 1) in developing regional water resource (quantity and quality) plans, or 2) in developing adequate management, operations, and maintenance of regional water resource systems is readily apparent. Wilmarth (1977), who is aware of the design implications of the urban-produced heavier rainfall regime, indicates that the general lack of adoption of these correct design values by engineers reflects the lack of a centralized authority for controlling and implementing water resource design values. However, the new suburb of Fairview Heights, in the floodplain area, has used the METROMEX produced heavier rain design criteria in their design and construction of city storm drains and sewer system.

Major findings of METROMEX are the heavy rain increases and their implications for the water resource systems in the anomaly area. These findings, however, are largely not being responded to because there are no regulatory agencies with anomaly scale authority, and because of the multitude of uncoordinated, only partially responsible local governmental entities. This outcome may not be surprising for several reasons. Sassone (1976), after a study of 196 cities, concluded that local climate effects are not significant in explaining total municipal costs.

Tobin (1976) adds further insight to this problem of general lack of governmental action and responses to weather-related problems. He noted two factors in his study of the urban-related rain anomaly at La Porte, Indiana, a situation similar to St. Louis and its rain anomaly. First was the areal separation (32 km or 20 mi) between the La Porte rainfall anomaly and the causative factor, Chicago. The second was the plethora of governmental units in the area, producing a fragmentation and absence of political responsibility. These two factors essentially make the "producer" of the effect (the city) free from responsibility and regulation. As Tobin states, "Those responsible are not those bearing the cost."

This same situation is apparent in the anomaly produced increase in local flooding east of St. Louis. Those who should help pay for the added costs for management, operation, and maintenance of flood control systems, plus new expensive hydrologic facilities, are not paying. Under the existing taxing structure, those in the problem area (the floodplain) pay the costs for the additional water and related problems like sediment removal. Those in the upland rural country where much of the anomaly and heavy rain occurs, and hence where the large volume of runoff and sediment is generated, do not pay the costs of the water management problems of the floodplain. The added costs could also be argued to rest with the metropolitan area which is producing the added heavy rainfall.

Tobin (1976) indicates that non-decisions and no action describe the attitude of local government to date toward inadvertent weather modification. This results largely because few urban area residents realize that they live in a different and potentially worse climate. Tobin predicts that when the undesirable urban-induced weather changes intensify and when more citizens in the urban-effect area become aware of them, these factors will lead to demands for public action. This could change the past pattern wherein public officials have not, at least consciously, allocated funds to handle the consequences of the urban modified climate.

One type of institution that with proper authority could help implement use of critical information from METROMEX are the local planning agencies. The Southwestern Illinois Metropolitan and Regional Planning Commission (SIMRPC) has planning authority for a 7-county area that includes the anomaly (effect) area. SIMRPC is guided by a 108-person commisssion representing all forms of government, and the agency is aware of the regional water resources problems and the anomaly findings relevant to water resources. However, they are essentially unable to convince many communities of the need to adopt proper anomaly related design criteria. SIMRPC also does not have the authority to force adoption, and generally is in a secondary position to the Corps of Engineers for obtaining planning funds for regional water resource developments. SIMRPC is currently involved with the East-West Gateway Coordinating Council (of St. Louis) in a Section 208 water quality planning project sponsored by the federal EPA. This plan will incorporate relevant findings from METROMEX.

It was shown in the section on impacts on human activities how the locally altered precipitation would affect taxes. First, Hoch (1976) calculated that a 20% increase in rainfall in an area would increase wages 1.8%. In the rural upland effect area agricultural benefits will increase income and this agrees with Hoch's calculations. Value of agricultural lands has also increased as a result of the anomaly and the net effect of this has been to increase tax income for local, state, and federal governments. Sassone (1976) concluded that rain modification will affect long-term social costs, with added rain producing higher costs for local education, storm systems, and sewage treatment. These public sector costs will necessitate higher taxes and in essence may negate the added tax income resulting from the anomaly.

In the urban and rural effect areas in the floodplain, added taxable income will occur for the reasons stated above, but the total will be less because of the relatively smaller amount of agricultural lands and resulting income benefits. The relatively greater water resources costs (due to urban flooding, complex water system operations, increased sewage plant costs, sedimentation and sediment removal in drainage canals and storage basins, etc.) in the floodplain will bring much greater costs and higher taxes to those living in the floodplain. These higher costs and taxes, borne heavily by the east side urban areas, help cause outmigration of the wealthier citizens. This in turn leads to a lower income and a lower taxable urban base, followed by poorer urban services and less fiscal capability to deal with water resource problems. If available, more federal funds must be used to subsidize local urban needs. Thus, the nation is helping to partially pay for the urban water resources problems created by the anomaly.

A qualitative assessment of the urban anomaly's impact on institutions in the effect area suggests 1) net benefits to institutions in the rural areas and suburban communities in the uplands, and 2) net disbenefits to governmental institutions in the floodplain area. As the regional water problems and their costs, particularly those caused by the anomaly, become known to the local public, action relating 1) to more equitable tax support of costs, and 2) to proper design, conservation, and operational practices for water systems will likely develop. Then public officials and institutions would react. One possible outcome includes giving the local regional planning commission more authority to regulate or develop a regional (anomaly scale) water resources institution (district) with the authority to perform these tasks and to raise taxes needed on a more equitable basis.

Federal Agencies

One set of relevant impacts of the METROMEX results includes those to federal agencies that must encourage energy development (ERDA) and set controls (EPA), based on knowledge of environmental impacts related to energy production and other human alterations of the land surface. The St. Louis studies have shown that urban-produced alterations of clouds and rain are largely the result of the entire urban agglomeration, not just one easily controllable human or industrial activity (Changnon et al., 1976).

METROMEX results have shown that the fossil-fuel power plants around St. Louis are among the major contributors to the local SO_2 concentrations in the air. Furthermore, METROMEX results have shown that the conversion of SO_2 to sulfates is aided by the cloud processes; thus conversion to sulfate and the acid rain problem are partially aided by the increase in urban clouds.

Although METROMEX has not been aimed at the control-optimization issue of air pollution, the project has defined several pollution aspects that relate to fossil-fuel power plants. These include 1) how plants should be spatially distributed, and 2) how they should be allowed to release effluents so as to minimize effects of clouds and rainfall quality. The increases in convective clouds and rainfall initiation related to a large refinery complex near St. Louis suggest that large industrial complexes and future power parks with concentrated releases of waste heat, moisture, and aerosols to the atmosphere of a humid continental climate will produce frequent convective clouds and increased rainfall. In general, the METROMEX information also relates to another basic thrust of certain governmental research control programs, that being the effect of altered land use on weather and climate. .

As noted in the previous section on local taxes, the anomaly in agricultural areas generates higher personal incomes and thus more income tax to the IRS for the federal government to use. However, it appears that the anomaly related water resource problems in the floodplain area contribute to costly 1) planning, operational, and development programs for the federal government (Corps of Engineers); 2) urban flooding damages and resulting renovation (HUD and FHA); and 3) water quality monitoring and treatment development (EPA). The net economic effect is likely one of disbenefits, more costs than income from the anomaly, to the federal government.

Other impacts on federal agencies include the local adjustment by the Soil Conservation Service of the USDA to the new heavy rain values in their local design criteria for terraces and other control structures. METROMEX results on conditions for rain initiation and intensification have been presented to the St. Louis area weather forecasters of the NWS. These should eventually be incorporated in the local forecast criteria. Increased storm losses (hail, rain, and wind) to crops will also impact on the local loss payments of the FCIC.

Other impacts include the METROMEX generated findings relating to research needs and priorities for inadvertent weather modification. These have affected the research programs of NSF and ERDA.

Knowledge of the locally increased thunderstorm occurrences with their attendent increases in hailfalls and downdrafts (gust fronts) which affect private and especially commercial jet aircraft, will be valuable to the FAA. Increased thunderstorm incidences of 40 to 50% affect air terminal operations in a variety of ways.

A host of impacts, both benefits and disbenefits, occur to a large number of federal agencies as a result of the urban-generated precipitation anomaly at St. Louis.

SUMMARY OF IMPACTS

The many impacts noted as a result of the METROMEX studies of urban-altered summer clouds, rainfall, and storminess are listed in tables C-13 through C-16. The impacts have been rated in three ways. First, the effect has been classed as having a general benefit, disbenefit, or neutral impact to the major impacted group. Second, the percent change, if known, is listed. Third, the significance of the impact, chosen subjectively by considering socio-economic factors, is identified as being major, minor, or unknown. Finally, the means by which each impact was identified is shown. These included direct measurement (M); partial direct measurement plus calculations using indirect evidence (M_I); those not based on local direct measurements but on *calculations* of related data (NM_C); and those not based on local measurements but *inferred* from results from other locals (NM_I).

The frequency of the impacts in the St. Louis area, sorted according to the various weather producing conditions, is presented in table C-17. Here, distributions are shown for the level of significance and the effect. The two ill-defined minor effects, albeit beneficial, of the added afternoon cloudiness are not listed specifically but are included in the "all impacts" totals. The classes related to added storminess (more thunder, hail, winds, and heavy rains) result, as expected, in a large number of disbenefits. There were 30 impacts related to the stormier conditions in the effect area east of St. Louis, and 25 of these were classed as disbenefits. All of the 15 stormy related impacts classed as significant were identified as disbenefits. The summarization of impacts from more total rainfall and pollutants (table C-17) shows a variety of impacts but a tendency for beneficial ones, 14 of 26 total impacts. Seven of the nine major impacts were listed as beneficial.

Table C-17 also presents the distribution of all 58 impacts. The minor impacts show an even distribution (11 vs 11) in the benefit and disbenefit categories. However, 17 of the 24 major

Table C-13. Impacts Related to Added Clouds and Thunderstorms

Impacts	*Effect**	*Change***	*Significance†*	*Means of identification‡*
More Clouds (over and east of St. Louis)				
Lower afternoon temperatures on some days				
Agricultural production	B	Unk	Mi	NM_I
Health	B	Unk	Mi	NM_I
More Thunder, Lightning, and Related Winds				
More nitrogen in rain	B	Unk	Unk	NM_I
More power outages	D	+50%	Ma	M
More lightning damages	D	Unk	Unk	NM_I
More wind damages	D	Unk	Mi	NM_I
Wind damages to aircraft operations	D	Unk	Ma	M_I
Knowledge of greater damages as input to federal agencies	B	Unk	Mi	M_I

*Effect classed as a benefit (B), disbenefit (D), and neutral (N).

**Percent change, + or -, or unknown (Unk), based on the most common area-wide value if several were available.

†Significance classed as major (Ma), minor (Mi), or unknown (Unk).

‡Means of identification classed as measured (M), measured partially and partly calculated (M_I), not measured but calculated (NM_C), and not measured but inferred from results from other locales (NM_I).

Table C-14. Impacts Related to More Hail and Related Winds

Impact	*Effect**	*Change***	*Significance†*	*Means of identification‡*
Increased crop-hail losses	D	+100%	Ma	M_I
Increased property damages	D	Unk	Mi	NM_I
Actual loss to total corn yields	D	+1%	Mi	M_I
Actual loss to total bean yield	D	+1%	Mi	M_I
Added purchases of insurance	N	+12%	Mi	M
Decreased farm income	D	Unk	Mi	NM_I
Increased income to insurance companies	B	Unk	Mi	NM_I
No insurance rate increase	B (locally)	Unk	Mi	M

*Effect classed as a benefit (B), disbenefit (D), and neutral (N).

**Percent change, + or −, or unknown (Unk), based on the most common area-wide value if several were available.

†Significance classed as major (Ma), minor (Mi), or unknown (Unk).

‡Means of identification classed as measured (M), measured partially and partly calculated (M_I), not measured but calculated (NM_C), and not measured but inferred from results from other locales (NM_I).

Table C-15. Impacts of Higher Rain Rates and More Heavy Rainstorms

Impacts	*Effect**	*Change***	*Significance†*	*Means of identification‡*
More bypasses of sewage treatment	D	+40%	Ma	M
More fluctuations in groundwater levels	D	Unk	Ma	NM_I
More frequent urban flooding–traffic and damages	D	+100%	Ma	M_I
Increased soil erosion in uplands	D	+34%	Ma	NM_C
Increased sedimentation of streams	D	Unk	Ma	NM_I
Sedimentation in floodplain facilities	D	Unk	Ma	NM_I
Added operations and management of floodplain water facilities	D	Unk	Mi	NM_I
Added drainage systems	D	Unk	Ma	NM_I
Altered design for hydrologic structures	D	Unk	Ma	M
Added soil losses on crop production	D	Unk	Mi	NM_I
Decreased visibility to transportation	D	Unk	Ma	NM_I
Decreased visibility and increased crime	D	Unk	Unk	NM_I
Cost of using new rain design data	D	Unk	Mi	M_I
Inequitable taxing for water problems	D	Unk	Ma	NM_I
Lack of action by local governments	D	Unk	Ma	NM_I
Higher water resource costs for federal agencies (planning, renovation, treatment)	D	Unk	Ma	M_I

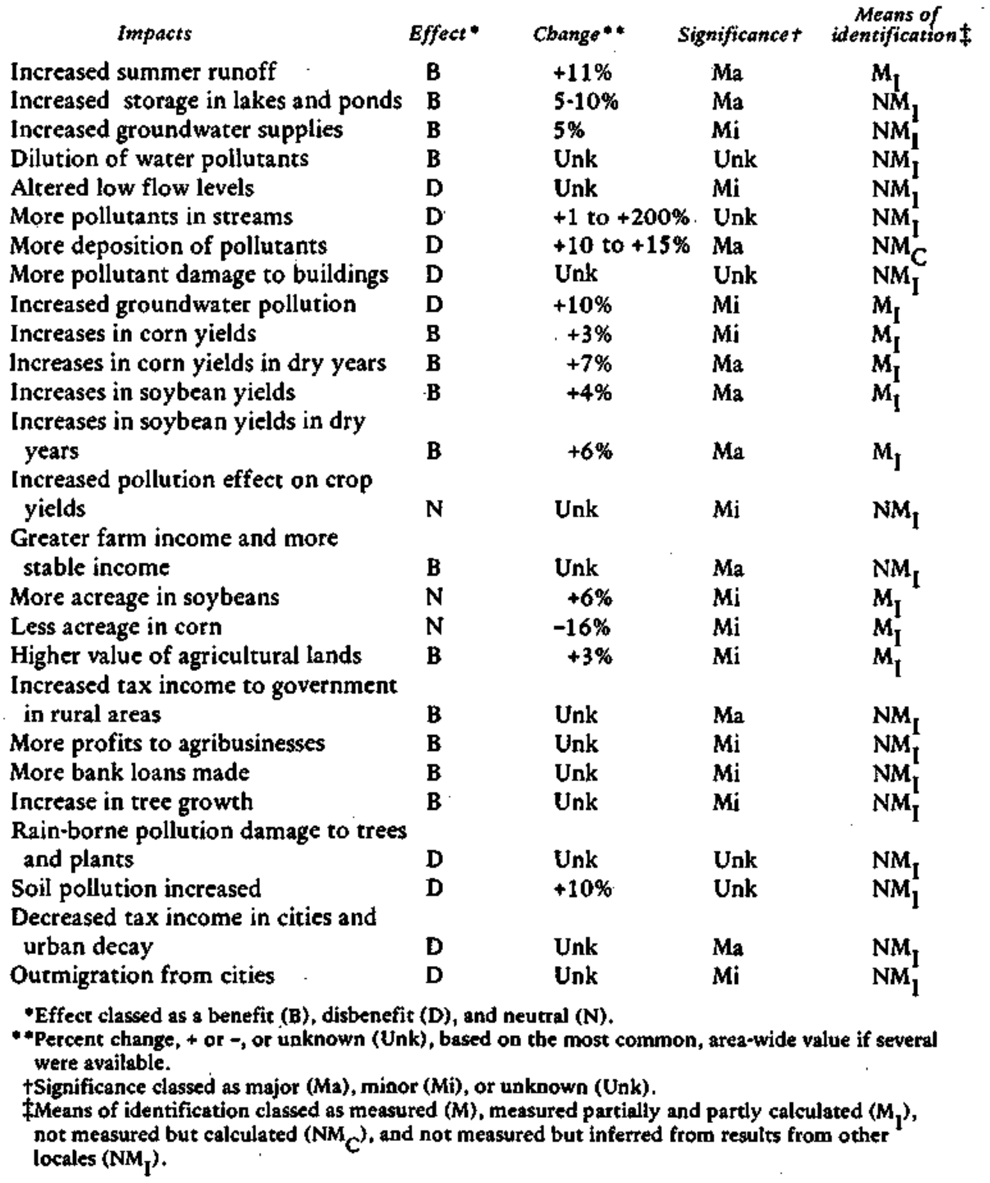
*Effect classed as a benefit (B), disbenefit (D), and neutral (N).

**Percent change, + or −, or unknown (Unk), based on the most common, area-wide value if several were available.

†Significance classed as major (Ma), minor (Mi), or unknown (Unk).

‡Means of identification classed as measured (M), measured partially and partly calculated (M_I), not measured but calculated (NM_C), and not measured but inferred from results from other locales (NM_I).

Table C-16. Impacts of More Total Summer Rainfall and Pollutants



Impacts	*Effect**	*Change***	*Significance†*	*Means of identification‡*
Increased summer runoff	B	+11%	Ma	M_I
Increased storage in lakes and ponds	B	5-10%	Ma	NM_I
Increased groundwater supplies	B	5%	Mi	NM_I
Dilution of water pollutants	B	Unk	Unk	NM_I
Altered low flow levels	D	Unk	Mi	NM_I
More pollutants in streams	D	+1 to +200%	Unk	NM_I
More deposition of pollutants	D	+10 to +15%	Ma	NM_C
More pollutant damage to buildings	D	Unk	Unk	NM_I
Increased groundwater pollution	D	+10%	Mi	M_I
Increases in corn yields	B	+3%	Mi	M_I
Increases in corn yields in dry years	B	+7%	Ma	M_I
Increases in soybean yields	B	+4%	Ma	M_I
Increases in soybean yields in dry years	B	+6%	Ma	M_I
Increased pollution effect on crop yields	N	Unk	Mi	NM_I
Greater farm income and more stable income	B	Unk	Ma	NM_I
More acreage in soybeans	N	+6%	Mi	M_I
Less acreage in corn	N	−16%	Mi	M_I
Higher value of agricultural lands	B	+3%	Mi	M_I
Increased tax income to government in rural areas	B	Unk	Ma	NM_I
More profits to agribusinesses	B	Unk	Mi	NM_I
More bank loans made	B	Unk	Mi	NM_I
Increase in tree growth	B	Unk	Mi	NM_I
Rain-borne pollution damage to trees and plants	D	Unk	Unk	NM_I
Soil pollution increased	D	+10%	Unk	NM_I
Decreased tax income in cities and urban decay	D	Unk	Ma	NM_I
Outmigration from cities	D	Unk	Mi	NM_I

*Effect classed as a benefit (B), disbenefit (D), and neutral (N).

**Percent change, + or −, or unknown (Unk), based on the most common, area-wide value if several were available.

†Significance classed as major (Ma), minor (Mi), or unknown (Unk).

‡Means of identification classed as measured (M), measured partially and partly calculated (M_I), not measured but calculated (NM_C), and not measured but inferred from results from other locales (NM_I).

impacts (71%) are listed as a local disbenefit. The total for the disbeneficial impacts is 34, or 59% of all the local impacts. This suggests a net disbenefit to the area resulting from the urban-induced precipitation anomaly, and as expected, the preponderance of the major disbenefits (12 of 17) relate to the heavier rains.

Table C-18 is a presentation of impacts for specific groups, the public, and the scientific community generally beyond St. Louis. These are all beneficial and 7 of the 10 are classed as having major value. The scientific knowledge generated by METROMEX, in both basic and applied scientific areas, is seen to represent a major national impact.

The study of the impacts suggested a considerable regional difference within the effect area of about 3108 km^2 (1200 mi^2). This difference seemed to relate to the major physiographic

Table C-17. Summary of the Frequency of Impacts in the St. Louis Area Sorted by Type of Effect and Their Significance

Effect	*Major*	*Minor*	*Unknown*	*Totals*
Thunder, lightning, and higher winds				
Benefit	0	1	1	2
Disbenefit	2	1	1	4
Neutral	0	0	0	0
Totals	2	2	2	6
Hail and related winds				
Benefit	0	2	0	2
Disbenefit	1	4	0	5
Neutral	0	1	0	1
Totals	1	7	0	8
Higher rain rates and more rainstorms				
Benefit	0	0	0	0
Disbenefit	12	3	1	16
Neutral	0	0	0	0
Totals	12	3	1	16
More total summer rainfall and pollutants				
Benefit	7	6	1	14
Disbenefit	2	3	4	9
Neutral	0	3	0	3
Totals	9	12	5	26
All impacts				
Benefit	7	11	2	20
Disbenefit	17	11	6	34
Neutral	0	4	0	4
Totals	24	26	8	58

Table C-18. Impacts of Overall METROMEX Results and Knowledge Extending to Groups beyond St. Louis

Impact	*Effect**	*Significance***
Information for weather modification industry	B	Ma
Information for improving urban weather forecasts	B	Ma
Basic new knowledge of atmospheric processes	B	Ma
Data for planned weather modification experiments	B	Ma
Information on network design and project operations	B	Mi
Information and data for numerical modeling	B	Mi
Setting of atmospheric research priorities	B	Ma
Prediction of urban anomalies elsewhere	B	Mi
Better understanding of climate change	B	Ma
Useful information to energy-concerned federal agencies	B	Ma

*Effect classed as a benefit (B), disbenefit (D), and neutral (N).
**Significance classed as major (Ma), minor (Mi), or unknown (Unk).

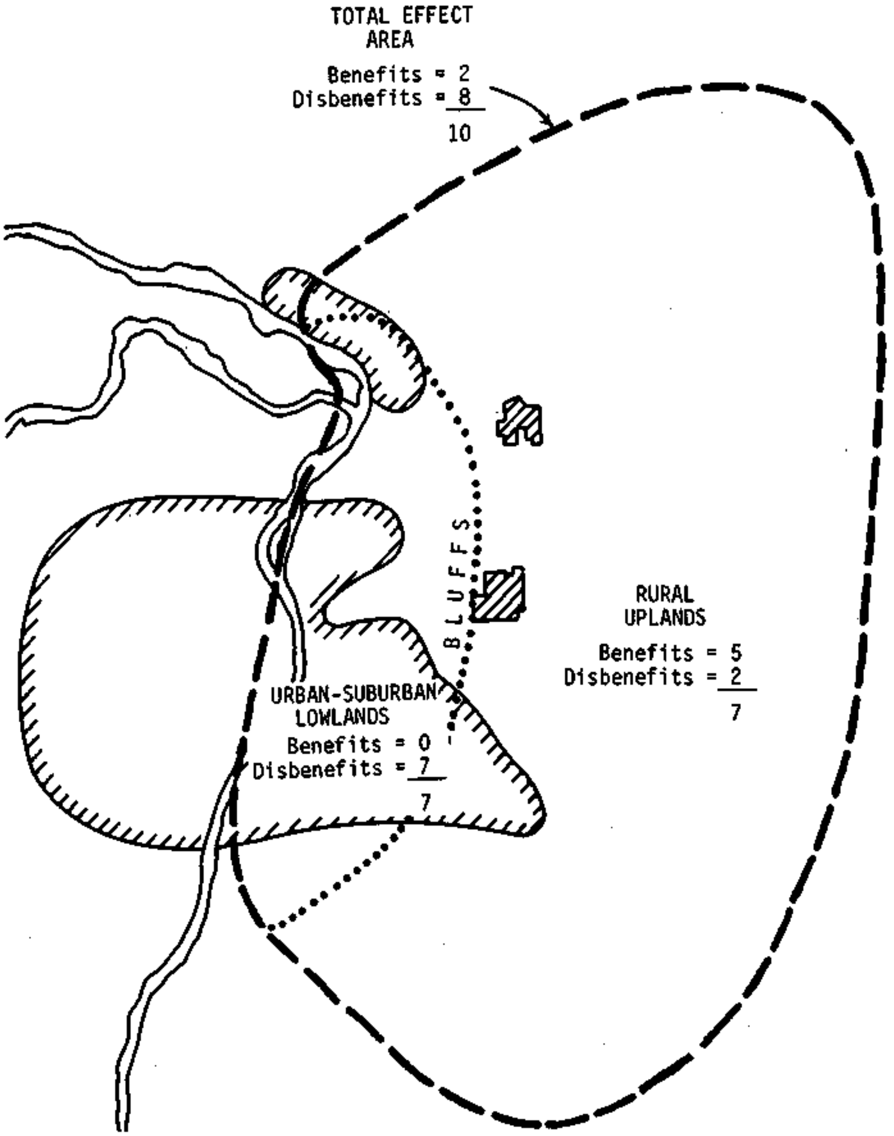


Figure C-12. The number of major impacts classed as a benefit or disbenefit in the urban-suburban lowlands, the rural uplands, and those impacting on both areas (total effect area)'

and land use differences. A schematic map of the effect area in figure C-12 shows the frequency of major impacts in each of the two major areas and the number that affected both or all of the effect area.

In the urban-suburban floodplain area no major impacts were classed as beneficial and all seven were disbenefits. Addition of the 10 area-wide impacts to this area results in 2 beneficial and 15 disbeneficial impacts. In the rural (agricultural) uplands there were 7 major impacts but 5 were benefits. Addition of the area-wide 10 impacts results in 7 beneficial major impacts and 10 disbenefits. Clearly, the urban-induced rain anomaly is generally disbeneficial in the floodplain and has mixed benefits and disbenefits in the uplands.

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Part D. General Conclusions

F. A. Huff and Stanley A. Changnon, Jr.

1. The major precipitation anomaly in the region from Granite City to Edwardsville is strongly related to urban effects, and there is no evidence of any significant topographic involvement. However, a secondary high in the bottomlands NW of St. Louis is related to topographic factors, although some urban effect is likely involved when low-level winds are from the SE. Another secondary high SE of St. Louis is apparently related to a combination of urban and topographic effects. A pronounced low WSW of St. Louis is in a region nearly devoid of urban effects, since it is rarely downwind of the urban-industrial area and is a part of the major low rainfall area that existed in 1971-1975.

2. In general, major features of the seasonal pattern were maintained throughout the five summers, and this provides strong evidence that the spatial pattern is not a transitory occurrence resulting from natural rainfall variability during the project period.

3. The Edwardsville anomaly was most pronounced in June, and relative to the rest of the network, was stronger in below-normal rainfall months. This is evidence that the weather modification (inadvertent) processes are at least as active in relatively dry periods as during normal or wet periods.

4. Analyses of individual rainstorms showed that the Edwardsville anomaly is produced largely by a relatively few storms (7% of total) which occur in organized storm systems producing relatively heavy rainfall in the surrounding area. These anomaly producers are most frequently squall lines in which convective elements move from the WSW or SW to produce traverses across the urban-industrial regions.

5. Analyses of the relationship between storm intensity (mean rainfall) and the network rainfall pattern showed that the Edwardsville anomaly is caused largely by heavy storms that produce amounts of 25 mm (1 inch) or more in the anomaly area. The Edwardsville anomaly is also evident to a lesser degree in moderate storms producing amounts of 12.5 to 25 mm (0.5 to 1 inch), but is missing in the network patterns associated with less intense storms. In fact, analyses indicated that nearly all of the rainfall excess in the center of the Edwardsville high is accounted for by the heavy storms. A pronounced maximum in both the frequency of heavy rainstorms and total rainfall production from heavy rainstorms was found in the Edwardsville area. However, the frequency of all storms (measurable rainfall $\geqslant$ 0.25 mm or 0.01 inch) in the Edwardsville area was slightly below the network average.

6. Analyses of heavy raincells in the network showed that the water yield from urban-exposed cells exceeds that from cells subjected to small-scale topographic influences, and both produce more surface water than the rural no-effect cells. Thus, the median water yield in urban-effect cells was 70% greater than in the no-effect cells and 28% greater than in the topographic-effect cells, which, in turn, had a median output that was 33% greater than the no-effect cells.

7. The heavy rainfall analyses also indicated that the additional water yield from the effect cells was produced primarily by inadvertent enhancement of the areal extent, and consequently, of the point duration of rainfall from these cells. Rainfall rates tended to be less in the modified than in the no-effect cells.

8. The heavy cells occurred most frequently in association with intense organized storm systems, particularly squall systems; moved most often from SW, WSW, and WNW; and initiated

most frequently in late afternoon in the St. Louis urban-industrial area. Thus, a typical urban-effect cell occurs within a squall line in late afternoon, is accompanied by thunder, moves from the WSW, grows in areal extent upon exposure to the urban environment, and maximizes ENE-NE of the urban-industrial area where its water yield is 70% greater than surrounding rural cells.

9. Comparison of spatial patterns in wet and dry months showed that the general features are maintained in dry, wet, and near-normal rainfall periods. In the center of the Edwardsville anomaly, rainfall in the three driest months was 40% greater than the network average, compared with a 10% excess in the three wettest months. This is another indication that the inadvertent weather modification processes induced by the urban environment are as active (or more so) in dry periods as in wet periods.

10. Analyses of the diurnal distribution of rainfall showed that the Edwardsville anomaly results from two periods of excessively heavy rainfalls. The first occurs in the afternoon (1400-1700 CDT) and is apparently related to maximum diurnal destablizing of the low levels of the atmosphere by the combination of solar heating and urban heat output. The second maximum occurs in late evening (2100-2400) and is believed to be associated with interactions between the urban heat island and atmospheric processes (nocturnal thunderstorm phenonemon). Heavy rainfall areas east of St. Louis are produced primarily by the afternoon rainfall maximum when up to 35% of the total summer rainfall was recorded in the eastern portions of the urban-industrial area.

11. Examination of the diurnal distribution of rainfall indicated that the urban environment exerts a stronger influence on the diurnal distribution than do the small-scale topographic discontinuities in the network.

12. Increases in rainfall intensity rather than rainfall frequency are mostly responsible for the Edwardsville diurnal anomalies.

13. Analyses of 5-summer rainfall were made in 17 areas selected to represent various degrees of urban and topographic effects, plus a no-effect (control) area. Results indicated the urban enhancement reaches a maximum of 30 to 35% in the Edwardsville-Granite City region. The bluff effect was calculated to be approximately 14%, and the SW hills (Ozark foothills) apparently cause an increase of about 9%. The effect in the central city is about 10% and this increases to 22% in the heavily industrialized area east of the Mississippi.

14. Synoptically, the urban enhancement was found to occur largely in association with squall lines and cold fronts, particularly those in which convective elements moved from the SW quadrant across the urban-industrial complex. These two storm types accounted for less than 30% of the total rainstorms but produced over 60% of the network total rainfall. Squall zone and air mass storms which accounted for over 50% of the storm occurrences contributed very little (if any) to the urban-induced increases.

15. Mixing height analyses showed that the urban enhancement was largely generated in those synoptic situations in which the atmosphere was well mixed throughout a layer extending 3000 m (~ 10,000 feet) or more above the ground. The urban effect was most pronounced when a relatively deep mixing layer occurred in association with squall lines and cold fronts. Thus, the St. Louis urban-industrial complex appears to enhance intense, deep convective systems, whereas other weather systems contribute little, if any, to the urban anomaly.

16. Among various surface-wind and storm-motion combinations, the greatest rain producers were storms moving from the WSW with SE surface winds. This combination produced a maximum in the network pattern along a line from Granite City to Edwardsville in the region of maximum urban effect.

17. Analyses of potential differences between weekday and weekend rainfalls indicated that differences are non-existent or too small to be identified in the noise of the natural rainfall

variability during the five summers. Since major industries no longer close down for weekends, this finding is to be expected.

18. All thunderstorm properties appear to be enhanced by the urban-industrial area of St. Louis (thunder frequency, duration, intensity, etc.). Synoptically, the greatest enhancement occurs with cold fronts, warm fronts, and air mass storms, but increases are also detectable with squall lines and squall areas. Urban influences cause earlier development of thunder activity, but the enhancement is also evident at night over and NE of St. Louis, and this correlates well with a late evening rainfall maximum in the Edwardsville area. Increases in thunderstorm activity were found to maximize in June when the Edwardsville rainfall anomaly also is greatest. Although not as pronounced, thunder activity is also increased apparently by the Alton-Wood River industrial area.

Wind data reveal a 100% increase in the number of high gusts (⩾ 30 mph) to the east of St. Louis. There was no evidence from the 1971-1975 data on summer tornadoes of an urban effect on tornado frequencies.

19. The pattern of point hailfalls correlates excellently with the total rainfall pattern for 1971-1975, as do other hail parameters such as hailstone sizes and mean energy of hailstones. Moderate to large enhancement occurred in urban-exposed storms; this includes increases in point duration (40%), maximum stone diameter (22%), number of hailstones per unit area (36%), and mean energy (100%). Urban effects on hail activity usually appear near the time of maximum diurnal heating and continue into the night with maximization from 1800 to 2400 CDT. Synoptically, the urban effect appears to be most effective in squall lines and cold fronts, and least effective in air mass storms, which is in complete agreement with rainfall findings. In general, it appears that the urban environment intensifies updraft velocities but not updraft durations, since the urban influence is not apparent in the duration and size of hailstreaks but does enhance point hailfall properties in the region extending approximately 10 to 30 km (6.2 to 18.6 mi) downwind of the city.

20. During 1972-1975, the METROMEX Network was extended to the NE and E to investigate possible urban-induced enhancement of rainfall beyond the 42-km (26-mi) radius research circle. Results indicated that the urban anomaly does not extend beyond 80 km (50 mi) and is primarily restricted to within 40 km (25 mi) of the urban area. The greatest extension of the anomaly occurs in June when it is usually found 15 to 45 km (9 to 28 mi) from the urban center, but occasionally reaches 80 km (50 mi) NE of St. Louis. No indication of an urban-related decrease in rainfall was found beyond the urban-induced high.

21. Assuming an urban enhancement, the three precipitation parameters investigated in this research occur in a logical spatial sequence. Thunder frequency shows a maximum within and immediately downwind of the urban area, whereas the maxima in surface rainfall and hailfall occur a few miles downwind of the central urban area and closely coincide with each other. Thunder would be the first observable product of convective stimulation by the urban environment as the development of convective clouds increased and, therefore, would be observed frequently within or slightly downwind of the city. The end-product of the enhancement (rain, hail) would involve a longer period of atmospheric processing, so that the effects would maximize at the surface later, and thus farther downwind than the thunder. Furthermore, air mass storms are a frequent occurrence and a major contributor to the thunder frequency maximum in the urban area. However, their influence on the rain enhancement pattern is very small, because their surface rain output is almost insignificant in comparison with that of organized storm systems.

22. The various analyses performed in compiling this report provide support for the general findings in earlier climatological studies of urban effects on precipitation at nine major cities in the

United States. These all suggested a strong dynamic input is involved in the rain enhancement processes that are stimulated by the urban environment.

The key climatic effects of the St. Louis studies are the increased cloudiness (up to 10%), the increased total summer rainfall (up to 30%), and increased severe storm activity (up to 100%). All are related to urban effects on the summer atmosphere. These increases occur over and just east of St. Louis in a 4000 km^2 (1544 mi^2) area.

23. Impacts on water resources of the more intense and polluted urban rains include more runoff (+11%), more local flooding (up to +100%), and more stream and groundwater pollution (+1 up to +200%). The findings relating to altered weather conditions reveal how to better design and execute midwestern weather modification experiments and operations; suggest use of seeding materials; show the potential for useful rainfall increases in summer dry periods; and show that man-induced summer rain increases may also result in more hail, stronger winds, and lightning.

24. Urban-altered precipitation results in a net local-area average increase of 3 to 4% in grain crop yields. This increase is reflected in the value of agricultural lands and in certain planting strategies used by local farmers. The urban-induced increases in severe storm activity lead to 100% increases in crop-hail losses, affecting farmers and the insurance industry. Various shifts of land values, crop planting strategies, and insurance purchases indicate some local perception of the anomaly and/or its local impacts. Delineation of those conditions when urban showers are triggered or when heavy rains result because of urban factors will lead to improvements in weather forecasting and water management for urban areas.

25. The city, as a whole, leads to most of the rain changes discerned, indicating there is no controllable way for urban planners to "design out" the problem. However, the wisest use of land from this viewpoint calls for agricultural land use, as opposed to suburban development, east of the city. The results on cloud and rainfall processes and subsequent deposition of urban-generated pollutants also relate to the missions of government agencies concerned with the environment and land use management. Certain findings focus on proper siting and controls of fossil-fuel power plants in industrial complexes so that large releases of heat and moisture are not concentrated in a small area.

26. A key question, as yet not totally answerable with the available impact information, is whether the various precipitation-related changes produced by a major city like St. Louis represent a net benefit or loss *when all factors are considered.* This study does suggest that the effect is likely a net disbenefit. As was shown in figure C-2, derivation of the social and economic values is very complex. Clearly, further research into the effects of pollutants on crops, the environmental impacts, social aspects including public attitudes, and the legal issues of inadvertent (urban) weather modification needs to be pursued to help derive an effective assessment of the impacts and the priorities that should be assigned to them.

27. At this time, results from METROMEX indicate that the urban rain alterations are due to an integration of effects from the entire urban complex and are not due primarily to one isolatable and controllable factor, such as a particular compound in the effluent from automobile exhaust or from a specific factory. Although the exact sources have yet to be identified, the St. Louis area sources of large condensation nuclei are of some importance. If the source can be found, a potential might exist for partially altering the "urban effect" on summer rainfall. However, it will be difficult to present a specific set of do's and don'ts for altering the urban effects on precipitation processes, *should they be deemed harmful.* METROMEX cloud and radar studies have shown that a large refinery complex produces demonstrable (100 to 200%), but very local, increases in convective clouds and the initiation of rainfall. These effects could be potentially minimized in future arrays of large industrial complexes.

28. Another major question that this impact analysis cannot answer is whether the urban-related cloud and rain alterations in and east of St. Louis are sufficiently harmful to deserve consideration in urban planning efforts aimed at wise land use. Assessment of the aggregate water resource impacts suggests that the net effect is a considerable economic disbenefit for the floodplain area east of St. Louis. Planners and decision makers could minimize this urban rain effect east of the city by 1) altering possible forcing functions (such as sources of large nuclei and industrial water released to the atmosphere), or by 2) attempting to minimize human settlements and improve water resource systems within the area which will suffer most from wet (rain) and dry deposition of pollutants, from more frequent flooding, erosion and silting, and from increased water pollution. In the area of effect to the east of St. Louis existing knowledge would suggest the best land use would be a grain-type agriculture. If water supply were a problem in an urban area, the area east of the city would be an excellent place for reservoirs.

29. A third key question concerns whether there will be more urban weather modification in the future. The answer appears to be "yes" for several reasons. First, the population shift and growth is into urban centers and it appears likely that megalopolises such as the Boston to Washington corridor or the Chicago to Boston corrider will bring more and larger weather changes. It also seems likely that over the next 20 years fossil-fueled power plants will increase in and around cities and that automobile transportation will be sustained if not expanded. Another national activity that will induce more weather effects is the continuing thrust for economic and industrial expansion.

30. At this time little if anything is being done consciously by local or regional public officials to adjust to or to manage urban weather anomalies or their impacts. They have plenty of pressing problems such as crime and transportation, and inadvertent weather modification will not be addressed by public officials until 1) inadvertent weather modification and its impacts become greater and receive wider public awareness, 2) the public becomes concerned and believes action is needed, and 3) the public perceives that the matter is appropriate for some governmental agency.

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GLOSSARY

General Terms

Downstorm — A term used to describe a location that was downwind in relation to storm motion as opposed to low-level wind flow.

Downwind and Upwind — In this study *downwind* refers to areas in the path of air flow or storms that have crossed the potential effect areas (urban-industrial or topographic features) and *upwind* refers to areas not in the path of such potentially affected air or storms.

Effect (E) and No-Effect (NE) — Terms used throughout this study to categorize various meteorological events that would or would not have been exposed to modification by the urban-industrial areas (or topographic features) within the network study area, as determined with respect to wind conditions just prior to the event. For some studies, specific definitions for potential and non-potential conditions were established, as given in the text. For example:

Effect and No-Effect Hailstreak — A hailstreak produced by a raincell after the cell either developed or passed over the St. Louis or Alton-Wood River urban-industrial areas, or one not so produced.

Effect and No-Effect Rain Day or Rain Period — A rain day or period during which the maximum rainfall on the network occurred or did not occur in a region that was downwind of St. Louis and/or Alton-Wood River, as determined by the wind flow in the lower 850 mb of the atmosphere.

Hail Terms

Hailfall — **A** period of semi-continuous hail falling from a single storm passing over a point (hailpad site), and generally lasting only a few minutes but occasionally for 10 to 20 minutes.

Hail Period — Hailfalls associated with an objective rainstorm period.

Hailstreak — An area of continuous hail having space-time continuity and representing at the surface an entity of hail (hail cell) produced in a storm.

Rain Terms

Objective Rainstorm — A period of precipitation on the network identified with a given synoptic weather condition such as a cold front or a squall line, and separated from other periods by 20 miles and/or 1 hour between end and start times. There could be more than one such period in a day. (Also referred to as objective storm and objective storm period.)

Raincell — A closed isohyetal entity within the enveloping isohyet of a synoptic storm system consisting of one or more rainshowers or thunderstorms. Each shower or thunderstorm may be single or multicellular. In a multicellular storm system, the raincell incorporates an isolated area of significantly greater intensity than the system-enveloping isohyet. In isolated single-cell storms, the raincell is uniquely defined by the separation between rain and no rain.

Rain Period — An entity of rain (1 or more cells and/or areas of rain) in the network identified with a specific synoptic weather condition and separated in time and space from other entities having different weather conditions.

Thunder Terms

Thunder Day — A midnight to midnight period with thunderstorm occurrences defined by audible thunder heard by either thunder recorders or the thunder station observers.

Thunder Period — A period, as determined by thunder recorders, that had 2 or more peals in a given 15 minutes that was separated from other periods by 1 or more hours with no thunder. There could be more than one thunder period in a day.

Network Thunder Period — A period when 1 or more points in the network had thunder periods that exhibited a time and space coherence associated with an existing precipitation system. There could be more than one network thunder period in a day.

Thunder Rate Segment — **A** period having a constant thunder rate within 4 possible levels: *very light,* a frequency of 5 peals or less per hour; *light,* 6 to 11 peals/hr; *moderate,* 12 to 60 peals/hr; *intense,* more than 60 peals/hr. There could be more than one segment in a thunder period.

METROMEX INSTRUMENT SITES

ALN	Alton Civic Memorial Airport, IL	KMX	KMOX Field Site, IL
ARC	St. Louis Memorial Arch, MO	LVT	Livingston, IL
BCC	Belleville Community College, IL	MCH	Machens Field Site, MO
BHN	Brighton, IL	MDT	Millstadt, IL
BHS	Bunker Hill High School, Bunker Hill, IL	MRN	Marine Field Site, IL
BLL	Belleville, IL	MRV	Maryville, IL
BLV	Scott Air Force Base, IL	MTA	Mascoutah, IL
BVK	Beavercreek Field Site, IL	MVM	Mehlville, MO
BWM	Brentwood, MO	NDS	New Douglas Field Site, IL
CAH	Cahokia Airport, IL	NGL	Nagel's Farm Field Site, IL
CLV	Collinsville, IL	NWB	Newburg Field Site, MO
CKM	Cahokia Mounds, IL	OFN	O'Fallon, IL
CMB	Columbia, IL	OKV	Okawville, IL
CRV	Centreville, IL	PMQ	Pere Marquette State Park, IL
DRR	Doerr Field Site, IL	PTB	Pontoon Beach, IL
EDW	Edwardsville, IL	RCK	Rock Creek, MO
ELV	Ellisville, MO	RXS	South Roxana, IL
ESL	East St. Louis. IL	SCH	St. Charles, MO
FLO	Florissant, MO	SIE	Southern Illinois University-Edwardsville, IL
FNG	Fernridge, MO	SJB	St. Jacobs, IL
FRB	Freeburg, IL	SLU	St. Louis University Field Site, MO
FRM	SIU Experimental Farm, IL	SRX	South Roxana, IL
FSB	Fosterburg, IL	SSH	State School, Bellfontaine Neighbors, MO
FTP	Forest Park (in St. Louis)	STL	Lambert Field, MO
GDF	Godfrey, IL	SUS	Spirit of St. Louis Airport, MO
GRC	Granite City, IL	TYV	Tyson Valley, MO
GTS	Green Trails School, MO	VLM	Valmeyer, IL
GVR	Grover Field Site, MO	WBH	Weber Hill, MO
HES	Hamel Field Site, IL	WLO	Waterloo, IL
IMS	Imb's Station Field Site, IL	WSP	Weiss Airport Field Site, MO
KMM	Kimm's Farm Field Site, IL	WDR	Wood River, IL

ABBREVIATIONS AND ACRONYMS

acre-foot (feet)	ac-ft
Agricultural Research Service	ARS
Atomic Energy Commission	AEC
bushels per acre	bu/acre
Center for the Environment and Man	CEM
centimeter(s)	cm
Central Daylight Time	CDT
Chicago Area Program	CAP
condensation nuclei	CN
cubic meter(s)	m^3
degree(s) Celsius	°C
degree(s) Fahrenheit	°F
Energy Research and Development Administration	ERDA
Environmental Data Service	EDS
Environmental Protection Agency	EPA
Farmers Home Administration	FHA
Federal Aviation Administration	FAA
Federal Crop Insurance Corporation	FCIC
foot (feet)	ft
foot pound(s)	ft lbs
foot pound(s) per square foot	ft lbs/ft^2
Geostationary Environmental Satellite	GOES
gram(s)	g
hour(s)	hr
Housing and Urban Development	HUD
Illinois Power Company	IPC
inch(es)	in.
Internal Revenue Service	IRS
joule(s)	J

kilometer(s)	km
kilometer(s) per hour	km/hr
Massachusetts Institute of Technology	MIT
mean sea level	MSL
meter(s)	m
Metropolitan Meteorological Experiment	METROMEX
micrometer(s)	*µm*
mile(s)	mi
mile(s) per hour	mph
millibar(s)	mb
milligrams per liter	mg/l
millimeter(s)	mm
millimeter(s) per hour	mm/hr
million gallons per day	mgd
minute(s)	min
National Center for Atmospheric Research	NCAR
National Science Foundation	NSF
National Weather Service	NWS
parts per million	ppm
pounds	lbs
Research Applied to National Needs	RANN
Research Triangle Institute	RTI
square centimeter(s)	cm^2
square foot (feet)	ft^2
square kilometer(s)	km^2
square meter(s)	m^2
square mile(s)	mi^2
Soil Conservation Service	SCS
Southwestern Illinois Metropolitan and Regional Planning Commission	SIMRPC
U.S. Department of Agriculture	USDA