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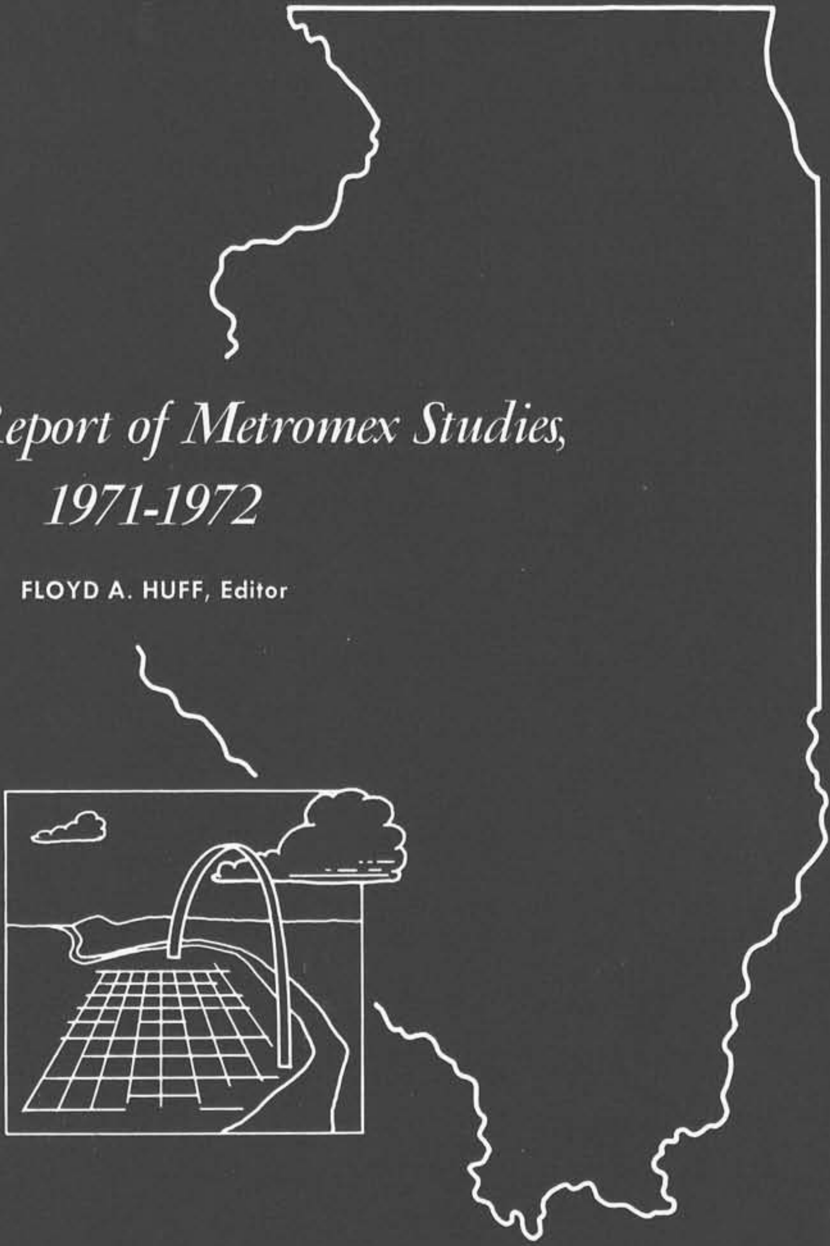
Summary Report of Metromex Studies, 1971-1972

FLOYD A. HUFF, Editor



ILLINOIS STATE WATER SURVEY

URBANA
1973

REPORT OF INVESTIGATION 74

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Summary Report of Metromex Studies, 1971-1972

FLOYD A. HUFF, Editor

Title: Summary Report of Metromex Studies, 1971-1972.

Abstract: Metromex is a large-scale investigation of inadvertent weather modification in an urban area, sited at St. Louis. Analyses to date from 2 years of data collected in the 5-year Metromex field program are summarized in this report. It includes extensive climatological-statistical analyses of rainfall and severe weather events and partial analyses for various atmospheric studies for which data are as yet limited. The 2-year results provide evidence that rain, thunderstorms, and hail maximize at locations 10 to 15. miles downwind of the urban-industrial region. These locations had more storms that were more intense, lasted longer, and produced greater amounts of rain and hail. Results also show that the atmosphere modified by heat and various emissions in the urban area does move up to levels where it can affect clouds and that the urban-modified atmosphere acts to invigorate convective storms and to increase the efficiency of precipitation events. Data and conclusions in this 2-year report provide a variety of information on urban effects on weather not obtainable in existing literature.

Reference: Huff,.Floyd A., Editor. Summary Report of Metromex Studies, 1971-1972. Illinois State Water Survey, Urbana, Report of Investigation 74, 1973.

Indexing Terms: Atmospheric chemistry, climatology, cloud physics, hydrology, inadvertent weather and climate change, meteorology, rainfall, severe weather, weather modification.

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GLOSSARY

Urban 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 within the network study area, as determined with respect to wind conditions just prior to the event. For some of the studies, specific definitions for potential and non-potential conditions were established, as given in the text. Two commonly used definitions are:

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 the urban areas of St. Louis and/or Alton-Wood River, as determined by the wind flow in the lower 850 mb of the atmosphere.

Downcity

A term used to describe a location where the low-level air has been exposed to modification from urban factors in its movement across the city.

Downstorm

A term used to describe a location that was downwind in relation to storm motion as opposed to low-level wind flow.

Hailstreak

An area of continuous hail having space-time continuity and representing at the surface an entity of hail produced in a storm.

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 Period

Discrete periods with at least 2 peals of thunder heard per 15 minutes, that were separated from other thunder periods by 1 hour or longer of no thunder.

Synoptic Weather Categories Used

Air Mass (AM) — A storm in which no large-scale trigger mechanism is discernable, and convective activity is disorganized and scattered.

Squalls, lines or systems (SQ) — Mesoscale systems of convective rainfall not directly associated with a surface front. Storms occur in organized lines or clusters and are frequently intense and widespread.

Frontal Zone — Storms producing precipitation within 50 nautical miles of a surface front: cold (CF), warm (WF), or stationary (SF).

Pre-Frontal and Post-Frontal Zone (PF) — Storms producing precipitation between 50 and 150 nautical miles ahead of (warm side) or behind (cold side) a surface front.

Low Pressure Center (Low) — A low center so near the network that frontal choice is not possible. These are infrequent in summer.

SUMMARY REPORT OF METROMEX STUDIES, 1971-1972

Floyd A. Huff, Editor

INTRODUCTION

Background

Metromex is a multi-agency research program involving an investigation of inadvertent weather modification at St. Louis (Changnon et al., 1971). The general program goals are: 1) to study the effects of urban environments upon the frequency, amount, intensity, and duration of precipitation and related severe weather; 2) to identify the physical processes of the atmosphere which are responsible for producing the observed urban weather effects; 3) to isolate the urban factors which are causing the observed effects; and 4) to assess the impact of urban-induced inadvertent weather changes upon the wider issues of society.

Major research goals of the Water Survey's participation in Metromex include studies of:

1) Severe local weather phenomena in summer so as to describe the temporal-spatial relationships of these events in the St. Louis area with special reference to their relationships under varying synoptic weather conditions
2) Raingage and radar data to assess the magnitude and location of urban-related precipitation changes with specific references to time-space analyses of rainfall and synoptic weather analyses
3) Upper air data with specific reference to the alterations of the boundary layer flow induced by the urban area and the possible effects of this alteration upon storm dynamics
4) The urban aerosol (with regard to both its size distribution and chemical constitution) with emphasis on its relation to removal processes and its importance to cloud microphysics
5) Atmospheric tracers involving placement of a tracer chemical into convective storms, and analysis to determine the time-space distribution of the tracer at the surface after its interaction with the precipitation process

Field operations were initiated in June 1971 and are scheduled for 5 summers, 1971-1975. Research support for Water Survey activities comes from three sources: the State of Illinois, National Science Foundation (GA-28189X and GI-33371), and Atomic Energy Commission (AEC-1199). Several organizations are now involved in Metromex research, and these include the other original participants, University of Chicago, University of Wyoming, and Argonne National Laboratory. This report was partially sponsored by the above NSF and AEC grants and by NSF GI-38371.

Purpose and Scope of Report

The purpose of this report is to summarize findings to date from analyses of data collected in the 1971-1972 field operations. Information is provided on the various types of field measurements and observations being made and the types of analyses being performed. Where possible, tentative conclusions are presented to assist in planning field and analytical programs for the remainder of the 5-year project, and for the use of those who may have an immediate need for information on urban effects which is not obtainable from existing literature. This report is restricted primarily to climatological-statistical analyses. Another report will cover detailed analyses of several interesting case studies utilizing surface, low-level, and upper air data.

Major emphasis has been placed on analyses of rainfall and severe weather events (thunderstorms and hail), since the dense surface networks of raingages and hailpads have provided a much greater quantity of data to date on these weather events than has been possible to obtain with the aircraft measurements, pilot balloons, radar observations, and other types of measurements. However, all phases of the program in which the Illinois State Water Survey participated are discussed. Much of the analyses incorporates data for the 2-summer period, but in a few cases results are limited to one year because analyses were incomplete at the time of report preparation.

The text of the report has two major parts, each with several contributions from project leaders. Part 1 concerns studies involving surface data measurements in Metromex. It includes a related hydrologic study made possible by the existing Metromex program. The second part incorporates all studies involving atmospheric measurements above the ground level. This is followed by a general summary and conclusions from all of the studies and a list of previous papers on Metromex.

This report has resulted from the cooperation of all staff members involved in the Metromex program. Each contribution is authored by the principal analyst involved in the particular study, but numerous assistants contributed to the work in each case. The report was prepared under the general direction of Stanley A. Changnon, Jr., Head, Atmospheric Sciences Section. Floyd A. Huff, analysis supervisor on NSF-GA-33371, was responsible for organizing, editing, and assembling the report. J. L. Ivens edited the final manuscript and J. W. Brother supervised the artwork.

Facilities and Instrumentation

Facilities and instrumentation used in the 1971 operations have been described in detail in *1971 Operational Report for Metromex* (Changnon, 1971). Surface instrumentation was expanded considerably in 1972. Types and location of most equipment are shown in figure 1.

The raingage and hailpad network of 1971 was extended downwind from St. Louis and Alton-Wood River to include an additional 1700 square miles with 1 gage per 81 square miles. Gage spacing in the extension is 9 miles compared with 3 miles in the basic research circle of 2200 square miles centered in St. Louis. This extension allows a better definition of the rainfall distribution at longer distances which may still be under the urban influence. Altogether, 243 raingages were operated in 1972.

In addition to the two raindrop spectrometers installed in 1971, six more were designed, built, and installed by the Water Survey in locations shown in figure 1. The network of rainwater collectors for total storm precipitation was expanded from 60 sites in 1971 (see *1971 Operational Report)* to 80 stations within the rectangle shown in figure 1. Aerosol and sequential rainwater sampling equipment was operated at the three sites identified in the figure. The 7-station hygrothermograph network of 1971 was found to be inadequate for mesoscale weather analyses, and was expanded to the 25 stations shown in figure 1. The wind recording network is also shown.

Upper air observations, used in conjunction with urban airflow studies, utilized three additional radiosonde stations with the pibal network in 1972. There was a minor reduction in the number of pibal stations. The 1972 upper air network is also shown in figure 1. The radar data from both the FPS-18 (PPI) and the TPS-10 (RHI) were recorded digitally in 1972 at the Pere Marquette base station.

References

Changnon, S. A., Jr., F. A. Huff, and R. G. Semonin. 1971. *Metromex: an investigation of inadvertent weather modification.* Bulletin American Meteorological Society, 52:958-967.

Changnon, S. A., Jr. 1971. *1971 operational report for Metromex.* A compilation of reports from cooperating research groups in the 1971 program prepared by the Illinois State Water Survey. 93 pp.

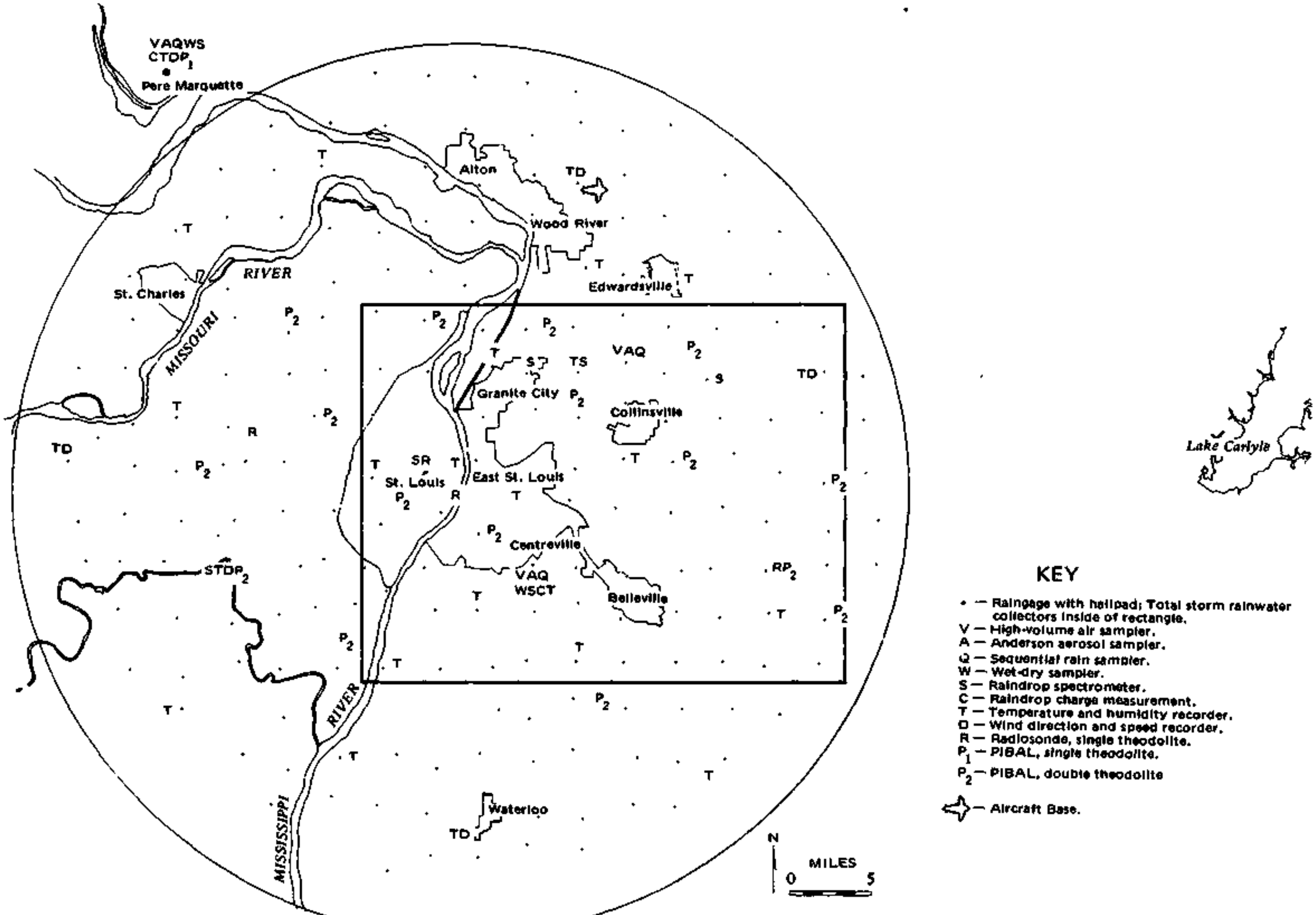


Figure 1. Equipment and facility sites for Metromex

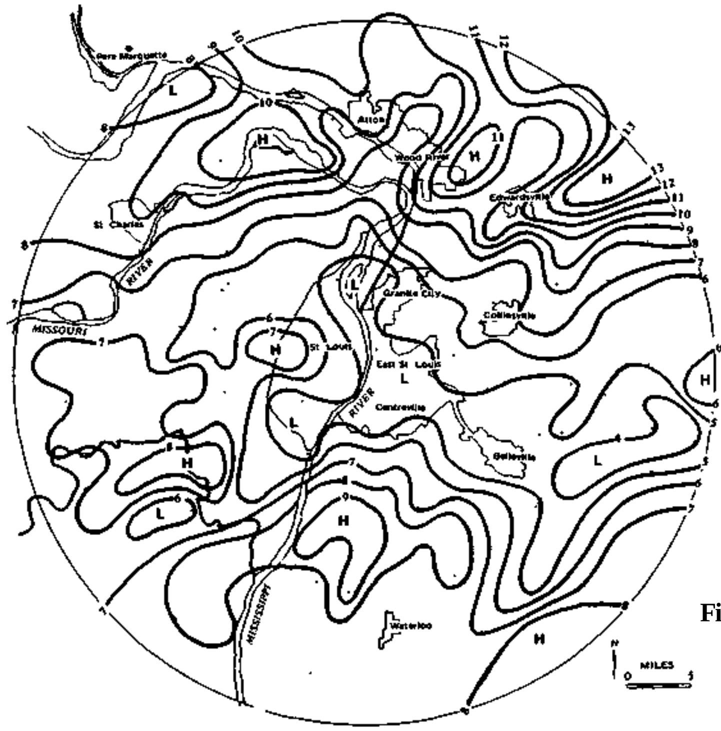


Figure A-l. Summer rainfall in 1971, in inches

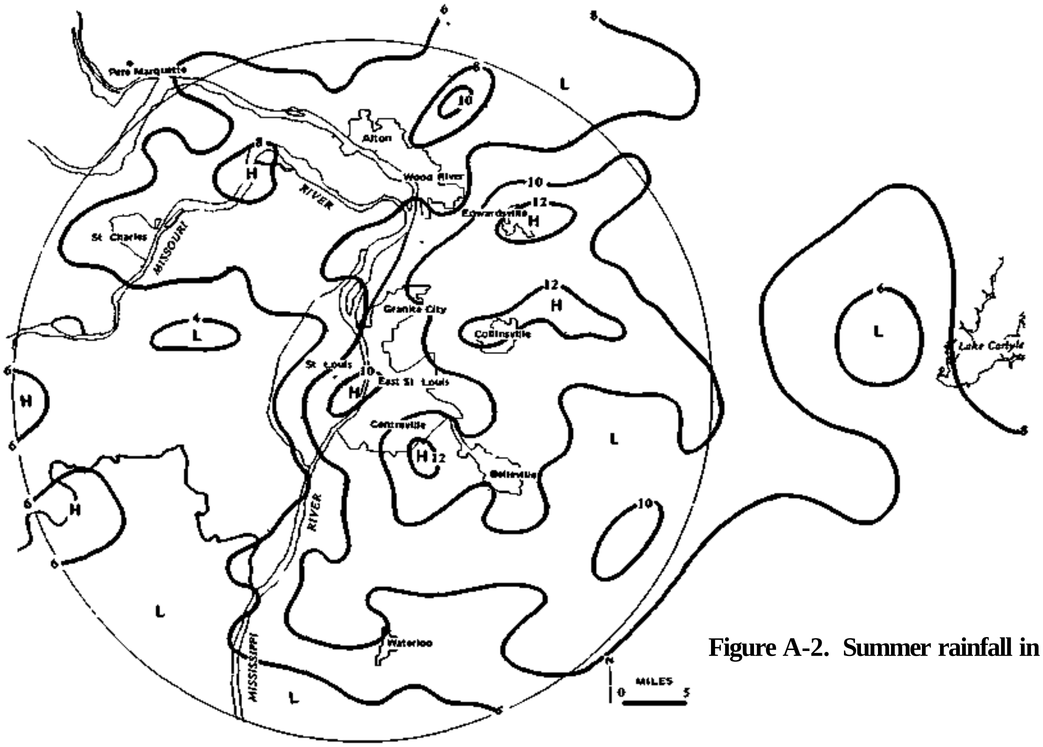


Figure A-2. Summer rainfall in 1972, in inches

PART 1. SURFACE STUDIES

A. 1971-1972 STUDIES OF MONTHLY, SEASONAL, AND STORM RAINFALL

F. A. Huff and E. E. Schlessman, Jr.

Introduction

The distributions of monthly and seasonal rainfall, occurrences of measurable rainfall, and heavy rainstorms were determined for the 1971-1972 operational periods on the Metromex network. This was done: 1) to establish the *location and intensity of potential urban effects on the regional rainfall* with more precision than was possible in the earlier climatic study of Huff and Changnon (1972a), 2) to investigate *potential urban-induced increases in the number of rain events*, and 3) to ascertain *to what extent urban effects are present when the natural rainfall is relatively heavy.* The Huff-Changnon climatic study had indicated the possibility of a major contribution to the downwind rainfall from urban-related modification of relatively heavy storms.

Analyses were performed to obtain information on differences in the rainfall distributions 1) on days of potential urban effects (based upon wind analyses) and days of no potential effect, 2) when the prevailing surface winds were from various directions prior to onset of rain, and 3) with storms of different synoptic types. The diurnal distribution of rainfall was investigated to search for preferred times of urban effect, and, hence, assist in isolating the major causes of urban-related differences in the rainfall distribution. Also, the 1971 and 1972 rainfall distributions were compared with wet, dry, and moderate distributions revealed by the earlier climatic study to assist in efforts to isolate the causes of urban-related effects. The natural variability within the network was analyzed in an effort to separate natural and urban-related effects on the large differences found between upwind and downwind areas in the 2-summer sampling period.

Monthly and Seasonal Rainfall Distributions

Figures A-l to A-3 show total rainfall patterns on the Metromex network for the summers of 1971 and 1972, and for the two summers combined.

Summer 1971. The June-August pattern for 1971 (figure A-l) was similar in shape to the dry-season pattern found by Huff and Changnon (1972a) in climatic analyses of the St. Louis area based on 1941-1968 data. However, the range of rainfall between highs and lows in the 1971 pattern was considerably greater than the climatic average for dry summers. The climatic pattern for dry seasons consists of a W-E high across the Alton area, another W-E high of slightly lesser intensity in the Waterloo region, and a W-E low extending across and well downwind of the urban area of St. Louis. The similarity between the 1971 and the climatic pattern is encouraging since summer 1971 was a dry season. Average rainfall for the network was 7.22 inches, or 63% of normal, based on long-term normals of the National Weather Service.

Monthly patterns for summer 1971 (not shown) indicated a major high in the rainfall pattern for June located about 5 miles east of Edwardsville. During July, three major highs were located a few miles NW and NE of the Alton-Wood River region, and east of Wood River. In August, a very dry month, the maximum rainfall was recorded at the southern extremity of the network near Waterloo.

For comparison purposes, 1971 summer rainfall was analyzed on the basis of only the climatic stations of the National Weather Service used in the Huff-Changnon climatic study. Again, it was encouraging to find that the basic features of the summer pattern obtained with the dense network of Metromex were present in the climatic network data. Possible causes of the dry-season pattern in the St. Louis region are discussed by Huff and Changnon (1972a).

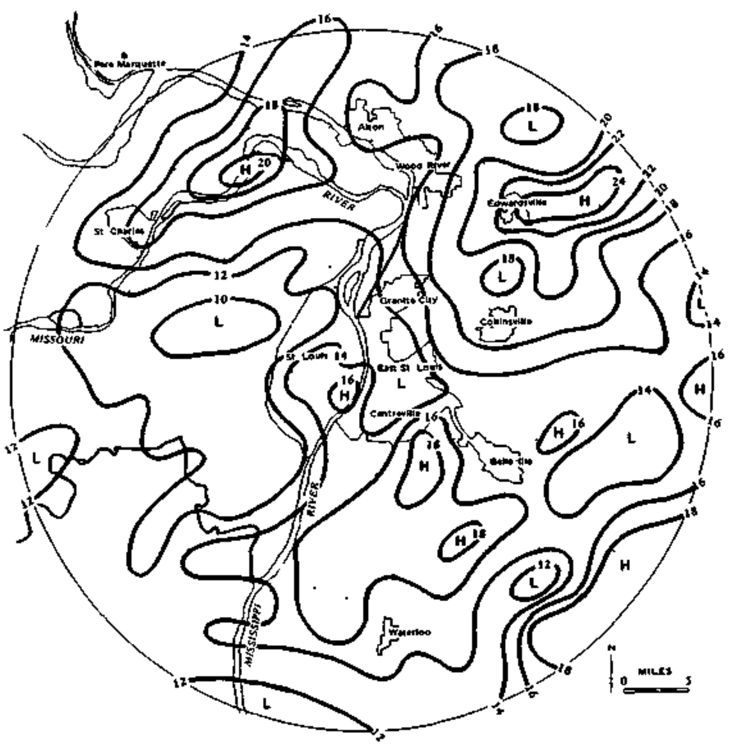


Figure A-3. Total summer rainfall for 1971-1972, in inches

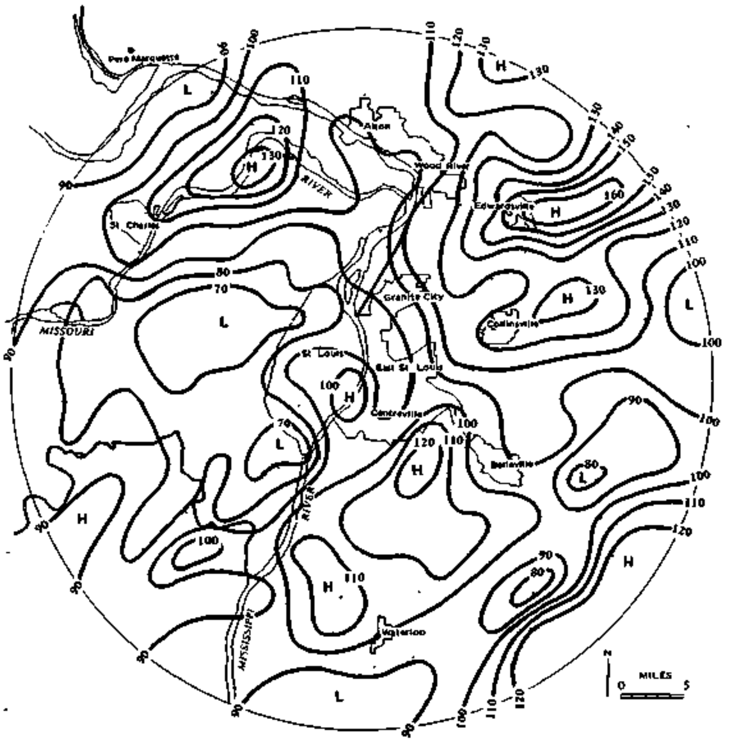


Figure A-4. Percent of network mean rainfall for summers of 1971-1972

Summer 1972. Figure A-2 shows the pattern of summer rainfall in 1972. The network average was again below normal, but not as much as in 1971. The June-August network average was 7.86 inches, or 69% of the long-term normal. However, the 1972 pattern was similar to the pattern for *moderate summers* obtained by Huff and Changnon (1972a) rather than the dry-season pattern. The moderate pattern is characterized by highs located NE of St. Louis in the Edwardsville region and SE of the city in the vicinity of Centreville, and by relatively heavy rainfall extending NE, E, and SE of the city for approximately 25 miles. The moderate pattern has major lows south of Waterloo, and W to NW of St. Louis. The 1972 pattern was very similar to the climatic mean pattern for moderate summers, except for the high NE of St. Charles in figure A-2.

The 1972 summer pattern of figure A-2 was controlled to a large extent by above-normal rainfall in August which averaged 3.60 inches (104% of normal) in the network area. June was much below normal with a network average of 1.38 inches (32% of normal), and July averaged 2.88 inches (80% of normal). The August and seasonal patterns were very similar in the distribution of highs and lows. This August control of the 1972 summer pattern accounts for its similarity to the typical pattern for moderate rather than dry summers.

Combined Summers 1971-1972. The rainfall totals for the summers of 1971-1972 were combined, as shown in figure A-3. The 2-year pattern had its major high east of Edwardsville in a region which would frequently lie downwind of both St. Louis and Alton-Wood River. With northeasterly storm movements, the high region would be downwind of St. Louis. With storm movements from the WNW, the high would be downwind of Alton-Wood River.

A secondary high was located in the bend of the river, NE of St. Charles. This location is a potential breeding region for convective storms, since it is in the hot, moist bottomlands of the Missouri River and not far from the heat-moisture source of the Mississippi lowlands. Also, a region of moderately high rainfall occurred north of Waterloo.

The major low center in the 1971-1972 rainfall distribution was west of the city with an extension eastward from the city (figure A-3). Overall, the 2-year pattern corresponded quite closely in distribution of highs and lows with the climatic pattern for dry summers. Since the 1971-1972 network average was only 66% of normal, a relatively close correspondence with the dry pattern is to be expected, provided that the previous climatic analyses revealed a reliable climatic anomaly. The 1971-1972 results are encouraging in this respect, and support the earlier climatic findings which motivated our rainfall studies in Metromex.

When monthly rainfalls for 1971-1972 were combined, they showed a major high in the Edwardsville region in both June and July. During August, a weak high was located in the Edwardsville region, also, but the major highs were located near Collinsville and between Centreville and Belleville. The high located NE of St. Charles in the river bottomlands was present also in all three months, but was strongest in July, normally the hottest month of the summer. A major low was located west of the city in both July and August, but it was nearly eliminated in the 2-year pattern for June. The secondary high in the Waterloo region was present in all three months, but had minor shifts in location.

Rainfall Variability in 1971-1972 on Metromex Network

Figure A-4 shows the pattern obtained from plotting the percent of the network mean rainfall at each raingage, based upon combined summer totals for 1971-1972. This map provides a measure of comparative magnitude of the rainfall centers. The percentages were obtained by merely dividing the raingage amount by the areal mean and multiplying by 100.

Centers of high and low rainfall in figure A-4 show that the major high in the Edwardsville area had amounts that exceeded the network average by over 60% during the 2-summer period. The bottomlands high NE of St. Charles had rainfall in excess of 30% of the network mean. Other highs SE of St. Louis received over 20% more than the areal average. The major low area west of St. Louis had amounts that were less than 70% of the network average. Thus, differences exceeding 90% occurred between the areas of heaviest and lightest rainfall.

An obvious question that is not possible to answer at this time is whether the positive departure of over 60% in the Edwardsville area resulted entirely from urban effects. It is doubtful, on the basis of climatic studies in this area and at 7 other large U. S. cities by Huff and Changnon (1972b), that such a large positive departure would be produced solely from modification of rain processes by the urban environment. In view of the negative departures of over 30% west of the city and positive departures of over 20% in the SE corner of the network, it is more likely that the Edwardsville high could be reflecting an urban-related difference of 20 to 30% during the 2-summer period.

Figure A-5 shows the areal pattern obtained by calculating the percent of urban mean rainfall recorded at each raingage in the summers of 1971-1972. The urban mean is based on 8 gages in the St. Louis urban area. This method of comparison was used in the climatic studies to obtain estimates of the magnitude of urban effects. Figure A-5 shows that the rainfall in the Edwardsville area was over twice that experienced in the central city. However, the bottomlands high NE of St. Charles and the high at the extreme southeastern part of the network had amounts over 40% greater than the immediate urban area. The urban area had approximately 20% more rainfall than the upwind low. Again, it is difficult to comprehend an urban mechanism that would double the rainfall in a region that is downwind a considerable part of the time (but not all the time) of two potential urban modifiers of the rainfall processes (St. Louis and Alton-Wood River).

Clarification of the causes for this extremely large variation in the regional rainfall pattern will require additional data collection and more comprehensive analyses of these data. However, it was thought that some indication of the part that natural variations may have contributed could be obtained by examining the departures from long-term normals of summer rainfall at National Weather Service stations within and near the 222-gage research network. This was done and the results are illustrated in figure A-6. This pattern of percent-of-normal rainfall was constructed from the pattern of normals for the long-term stations applied to the rainfall map of figure A-3.

Figure A-6 shows that Edwardsville, near the center of rainfall maximization for the 1971-1972 period, was the only long-term station exceeding its normal. The largest negative departure, less than 60% of normal, extended across the southern part of St. Louis and ESE to the edge of the network. Average percentage for the network was 66, approximately equivalent to the rainfall for the St. Charles high in figure A-3. Now, if the departures from the network average of 66% of normal represent sampling vagaries (natural variations) in the 1971-1972 distribution (figure A-3), the urban area mean (8 gages) can be normalized by multiplying the urban mean by the ratio of 66 to average percent of normal. The Edwardsville high can be normalized for sampling variations by the same procedure. When this is done, the 2-summer normalized rainfall is 20 to 30% higher in the Edwardsville region than in the urban area of St. Louis. This appears to be a more reasonable magnitude of urban-related differences.

Huff and Changnon (1972a) have suggested that the dry-period pattern results primarily from urban-related suppression of rainfall in and downwind of the city in such periods. However, the patterns in figures A-3 and A-6 indicate much greater differences between highs and lows than found in the dry-season average pattern that was based on 1941-1968 data. The large negative departure SW of St. Louis in figure A-6 is in a location that is unlikely to suffer frequent suppression from air traverse across the city during rainfall.

Possibly a substantial contribution to the large negative departure resulted from fewer and less intense convective systems developing in the Ozarks located SW-WSW of the city and moving into the area SW and W of the city. In any case, from information available at this time, the large differences in figure A-3 cannot be completely assigned to urban-related effects on the rain processes.

Figure A-5. Percent of mean rainfall at St. Louis for summers of 1971-1972

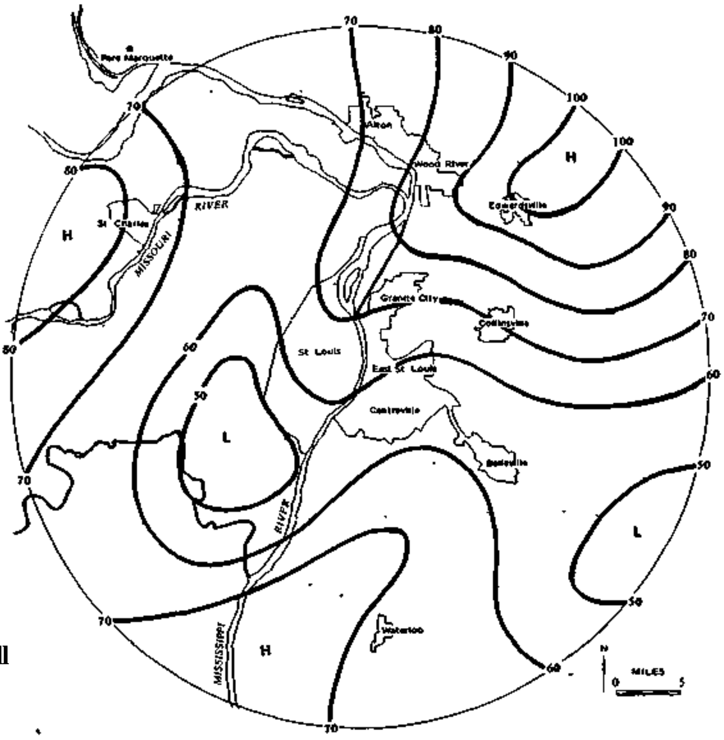


Figure A-6. Percent of normal rainfall during summers of 1971-1972

Frequency of Measurable Rainfall

Calculation was made of the number of occurrences of measurable rainfall (≥ 0.01 inch) at each raingage during network storms in 1971-1972. This was done to search for evidence that the urban environment causes an increase in the number of rain events, which in turn could be the primary cause of urban-induced highs in the rainfall distribution in and/or downwind of the city.

Results of this investigation are summarized in figure A-7 which shows the total number of rain occurrences in the 2-summer period of 1971-1972. From the distribution shown, there is no strong evidence of a substantial increase in the number of rain events from urban-induced effects. Although there is a distinct high in the network pattern in the Edwardsville-Collinsville region, where the 2-summer maximum rainfall occurred (figure A-3), there are highs of equivalent magnitude in nearly all directions from the city. Similarly, the regions of low occurrences are well scattered about the network.

Thus, figure A-7 portrays a rather random pattern of high and low frequencies, and provides no support for the hypothesis that the primary effect of the urban environment is to increase the number of rain occurrences from initiation of clouds and/or intensification of non-precipitating clouds. This does not imply that this process does not occur; it merely indicates that if this effect is present it is not readily apparent in the end-product, the frequency of surface rainfall events on days when rainstorms are recorded in the network.

Distribution of Heavy Rainstorms

The areal distribution of storm rainfall amounts of 1 inch or more was determined for the 2-summer period. Results are summarized in figure A-8. The most frequent occurrence of these heavy storms was recorded just E and NE of Edwardsville, and therefore corresponds closely with the major center of total rainfall for the two summers. Thus, this region not only received much above average rainfall with respect to the remainder of the network in 1971-1972, but also experienced a much greater percentage of heavy storms. The 10 occurrences NE of Edwardsville in figure A-8 exceeded the number in any other high center by 67% (10/6). There were several secondary highs of 6 occurrences, most of them east of the Mississippi in the area which is most frequently downwind from the city.

The bottomlands high NE of St. Charles was not as pronounced in the 1-inch storms as in the total rainfall pattern. If this is a primary breeding region, it is quite conceivable that maximum intensification of these storms would frequently occur a few miles downwind, possibly even in the Edwardsville area with westerly flow. In any case, evidence from the 2-year sample indicated that the downwind rainfall maximization is well correlated with the frequency of heavy storms, and indirectly suggests that intensification of existing storms is strongly related to the creation of the Edwardsville high.

The next step in this particular analysis was to determine the percentage of total summer rainfall for 1971-1972 that occurred in heavy storms having 1 inch or more of precipitation. This percentage distribution, presented in figure A-9, shows that over 60% of the total rainfall at the center of the major high east of Edwardsville occurred in the heavy storms. This is the highest percentage for any area within the 222-gage network. Similarly, most stations in the region of lowest rainfall (W of St. Louis in figure A-3) had less than 20% of their total rainfall in the heavy storms. In general, the regions of highest percentages were associated with seasonal rainfall highs. The percentages maximized in the Edwardsville-Collinsville area, where the intensity and areal extent of the rainfall highs were greatest.

Results of the analyses illustrated in figures A-8 and A-9 suggest that intensification of existing storms is a major cause of the seasonal highs in the rainfall pattern for summers 1971-1972. In turn,

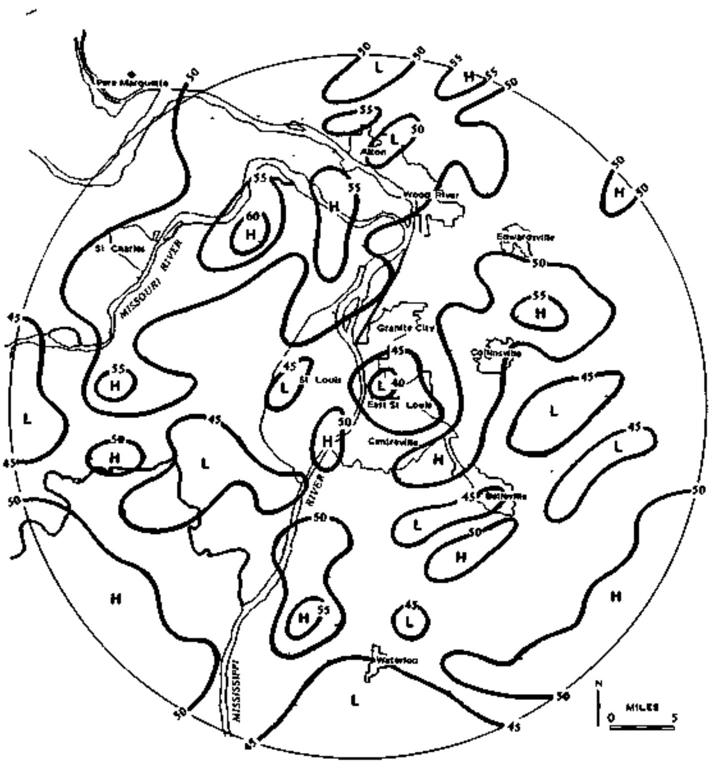


Figure A-7. Frequency of measurable rainfall in 1971-1972

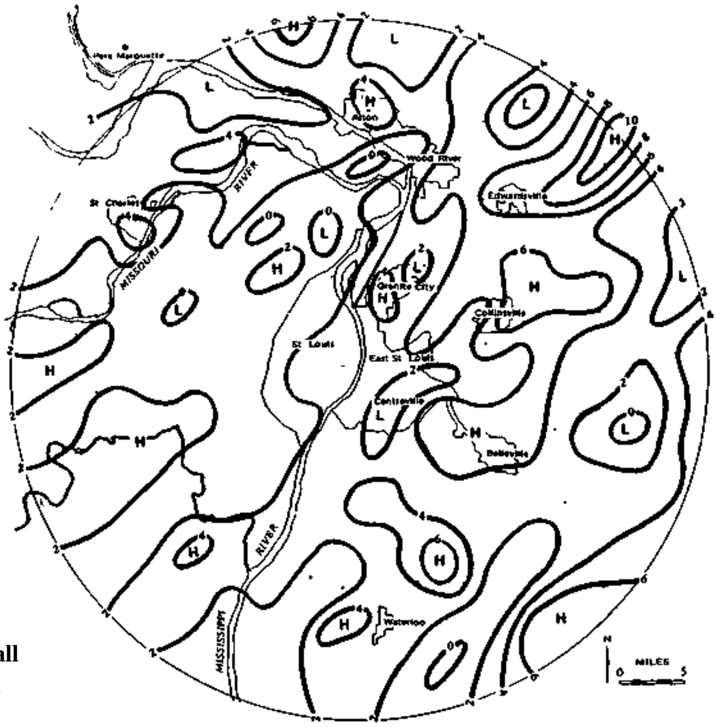


Figure A-8. Number of storms with rainfall ≥ 1.00 inch during summers of 1971-1972

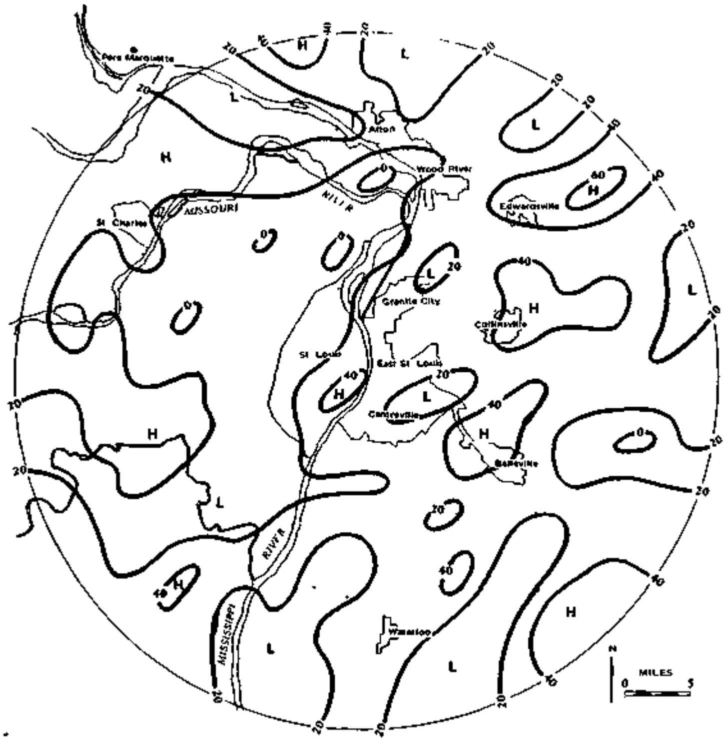


Figure A-9. Percent of **total rainfall occurring with storms ≥ 1.00 inch during summers of 1971-1972**

this indicates an urban-intensification mechanism applied to naturally occurring storms, provided that the Edwardsville-Collinsville high is wholly or partially related to urban modification of the natural rain processes. The 1971-1972 findings with respect to the relation between potential urban effects and heavy rainstorms are in agreement with findings in the climatic study of 8 major cities in the U. S. (Huff and Changnon, 1972b).

Weekday-Weekend Occurrences of Rainfall

The. frequency of rainfall occurrences on the Metromex network was determined on weekdays and weekends. More frequent rainfall on weekdays would be indicative of an aerosol involvement in the urban effect on rainfall because of greater industrial activity during the Monday-Friday period. Such evidence was found in the climatic study for St. Louis (Huff and Changnon, 1971a).

Tabulations for 1971 indicated that 76% of the rainy days occurred on weekdays compared with a normal expectancy of 71%. This agreed with the earlier climatic findings. However, in 1972, only 69% of the rainy days were on weekdays. For the 2-summer period, 72% occurred on weekdays, only slightly above the expected average of 71%. Thus, the 2-year total provides little evidence of a substantial difference in weekday-weekend frequencies.

Rank Score Tests

A rank score test was applied to the 2-summer data over the network to investigate further the presence of any trend for major rainfall centers to be strongly related to the frequency of relatively high storm rainfall. In this test, a score of 10 was assigned to the highest ranked point rainfall, 9 to the second ranked, and continuing down to a score of 1 for the 10th ranked amount. The frequency with which each gage was among the top 10 storm rainfalls and the total rank score for each gage were then determined.

The frequency of occurrences among the heaviest 10 storm amounts indicated a rather random distribution over the network, although the Edwardsville region did have one of the higher frequencies and the low west of St. Louis was in an area of minimum frequency. However, the total rank score, a measure of the position of the station among the 10 highest ranked values when it qualified, showed a pattern closely related to the total rainfall pattern of figure A-3. Thus, the highest rank scores of between 65 and 75 occurred in the Edwardsville region. The lowest scores which ranged from 0 to 20 were located in a W-E band extending from W and NW of St. Louis across the city and ESE to the edge of the network, very similar to the W-E band of low rainfall in figure A-3. Secondary highs were located in the Waterloo region and the extreme southeastern part of the network, again similar to the pattern of figure A-3. Also, the secondary rainfall high-located NE of St. Charles in figure A-3 had a corresponding high rank score of 45-50 at its center.

The analysis of rank scores provides evidence that the major rainfall highs are closely related to a tendency for storms to maximize in these areas with above-average frequency, particularly network storms of relatively heavy intensity. However, this above-average tendency for maximization does not imply a frequent occurrence, since the 134 storms in the 2-summer period give a maximum possible rank score of 1340 (rank 1 in all storms). The maximum rank score was only 74, at Station 51 in the center of the Edwardsville high of figure A-3. This station was among the top 10 in rainfall amounts in only 10 of the 134 storms. The maximum frequency on the network was 12 occurrences at two stations in the extreme southeastern part of the network.

Rainfall on Potential 'Effect' and 'No-Effect' Days

Another phase of the rainfall analyses involved grouping the seasonal amounts according to rain days classified as potential *effect* and *no-effect* days (see definition in Glossary). During 1971-1972, 39% of the rain periods were classified as potential *effect* cases.

The classification into potential *effect* and *no-effect* storm situations represents an initial attempt at separation. Obviously, some storms may have been placed in the potential-effect group as a result of heavy natural rainfall, unaffected by the urban environment, occurring in the designated effect area. Conversely, urban effects could have been present in some of the no-effect cases, but were not of sufficient intensity to overshadow heavy natural rainfall outside of the designated effect area. Results of analyses based on this division of rainstorms are presented as a first approximation of rainfall distributions occurring on days of potential-effect and no-effect from the urban environment. Further refinements will be presented later in Section F on rain-cell analyses.

Figure A-10 shows the rainfall distribution in the 30 potential-effect storms during summer 1972. The pattern compares very closely with the total rainfall map in figure A-2. This suggests that the total rainfall pattern was controlled largely by rainfall on these potential-effect days.

Analyses of the percentage of total summer rainfall occurring in potential-effect storms in 1972 showed values ranging from 40 to 88% on the network. In the Edwardsville high of figure A-2, 65 to 70% of the summer total occurred in these storms. In the Collinsville high, 70 to 88% of the total rainfall was recorded on these days. In the Centreville-Belleville high, the percentage average was 73%. However, the moderate high in the bottomlands NE of St. Charles, which would normally be upwind when the Edwardsville-Collinsville-Belleville area is downwind, also had 70 to 80% of its summer total in the

Figure A-10. Total rainfall, inches, on potential effect days, summer 1972

potential-effect storms. In the major low areas of figure A-2, the percentage in potential-effect storms ranged mostly from 50 to 70%. Thus, the 1972 rainfall distribution does show evidence of a contribution from urban effects to the relatively heavy rainfall centers east of the Mississippi River. That is, the percentage of total summer rainfall occurring in potential-effect storms in the downwind areas is greater, on the average, than experienced at those stations outside of the potential-effect region.

A more reliable estimate of the rainfall differences in potential-effect storms is provided in figure A-11 which shows the rainfall distribution for the two summers combined. The major high is in the Edwardsville area and corresponds very closely with the major high in the total rainfall pattern of figure A-3. In general, there is close correspondence between figures A-3 and A-11.

Calculations of the total percentage of 1971-1972 rainfall in potential-effect storms at individual gages were made. These showed 65 to 75% of the total rainfall in these storms in the Collinsville-Edwardsville region of relatively heavy rainfall, and 40 to 60% in the major region of relatively low rainfall W and SE of St. Louis. Thus, these 2-summer results support those for the 1972 rainfall distribution discussed above; that is, a much higher percentage of the total rainfall in the major high centers east of the Mississippi occurred on those days when this region was in the potential-effect area.

For comparative purposes, figure A-12 has been included to show the rainfall distributions on those days with no apparent urban effect during the summers of 1971-1972. In general, the rainfall on the network is considerably less in these storms. A high still persists in the Edwardsville area in the absence of any apparent urban effect. However, the major high in the research circle shifted to the SE part of the network.

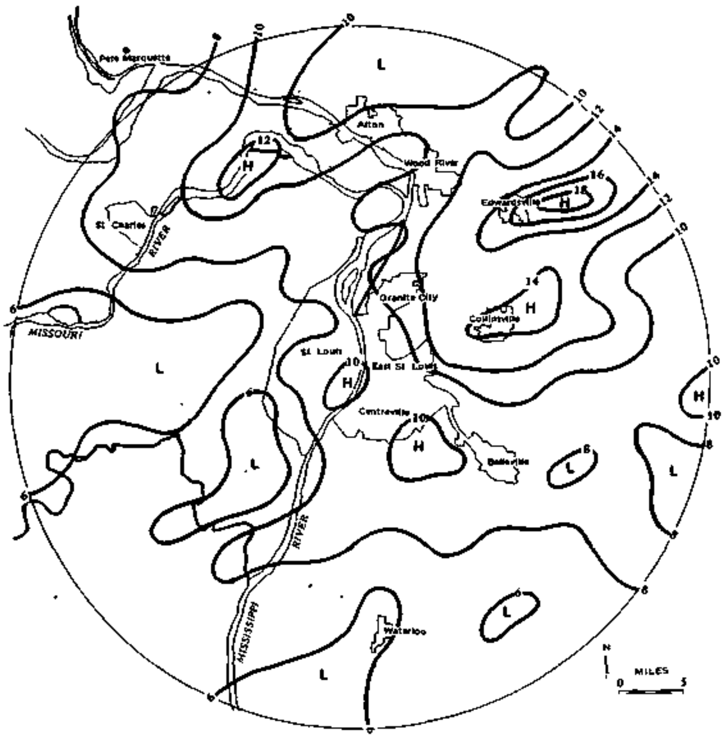


Figure A-11. Total rainfall, inches, on potential effect days during summers of 1971-1972

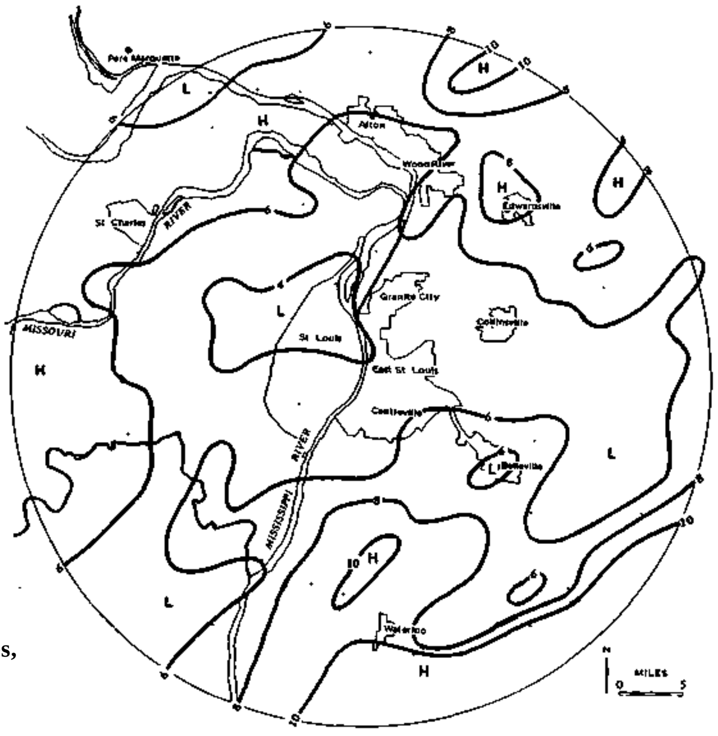


Figure A-12. Total rainfall, inches, on potential no-effect days during summers of 1971-1972

A region of relatively light rainfall extends from west of St. Louis through the urban area, and eastward to the edge of the network in figure A-12. The no-effect pattern for the two years is quite similar in distribution characteristics to the climatic pattern for dry seasons obtained by Huff and Changnon (1972a) and closely matches the 1971 and 1971-1972 distribution patterns of figures A-l and A-3. This finding further supports the earlier climatic analyses which suggested that the absence or suppression of significant urban effects during dry summers may be primarily responsible for the climatic pattern obtained for such periods by Huff and Changnon.

Relation between Wind Direction and Seasonal Rainfall

The 1971-1972 data were stratified by prevailing wind direction at the surface level. Wind directions were grouped into four quadrants, and the rainfall was assigned to the quadrant from which the prevailing wind was blowing for 3-6 hours prior to the onset of rain. The time averaging depended upon the existing wind speeds. Wind directions were based on observations at Lambert Field and Scott Field (Belleville).

The amount of summer rainfall was greatest with winds from the northwesterly quadrant (280-360 degrees) in 1971 and with winds from the southwesterly quadrant (190-270 degrees) in 1972. In the region of heaviest rainfall in 1971 near Edwardsville (figure A-l), over 50% of the summer rainfall occurred with winds from the northwesterly quadrant. A more normal situation occurred in 1972 when winds from the southwesterly quadrant were most frequently associated with rainfall.

Calculations were made of the average percent of the total summer rainfall that occurred with winds from the southwesterly quadrant in 1972. An average for 23 stations within the 11-inch isohyets east of the river (figure A-2) showed 59% of the summer total with these winds. A similar average of 23 stations within the 5-inch isohyet west of the urban area showed 55% of the summer rainfall associated with winds from 190 to 270 degrees. The difference in percentage between the upwind and downwind regions was only 4%, and this is considered too small to make any strong inferences regarding the relationship between these prevailing winds and favorable conditions for urban effects on the rain processes. At the center of the major highs in the Edwardsville and Collinsville regions, however, approximately 70 to 75% of the seasonal rainfall occurred with winds from the southwesterly quadrant, so that a favorable situation for urban effects likely occurs with S-SW-W winds in that region.

During summer 1972, only a very small portion of the rainfall was associated with prevailing winds from the northwesterly quadrant prior to onset of rain. The largest amount in the Edwardsville-Collinsville region was 1.34 inches, near the center of the Collinsville high in figure A-2. This was only 10% of the summer total. Within the major high in the Edwardsville region, only 1 to 2% of the summer total occurred with prevailing winds from the northwesterly quadrant.

Winds from the northeasterly quadrant were also associated with only a relatively small percentage of the 1972 summer rainfall within the Edwardsville-Collinsville high. In the center of'the Edwardsville high, less than 5% of the summer total was associated with these winds. Within the 12-inch isohyet of the Collinsville high (figure A-2), approximately 17% of the summer total occurred with northeasterly prevailing winds.

Within the 5-inch isohyet in the low west of St. Louis, an average of 22% of the summer total occurred with prevailing winds from the northeasterly quadrant. However, in the center of this low area of rainfall west of St. Louis, in and near the 4-inch isohyet, 30 to 40% of the seasonal rainfall occurred with N-NE-E winds. This percentage is nearly equivalent to that occurring with the much more frequent winds from the southwesterly quadrant. The region of relatively heavy rainfall with winds from the northeasterly quadrant would frequently be downwind of St. Louis or Alton-Wood River, depending upon the wind direction within the quadrant. Thus, the location of this relatively high percentage suggests an association with urban-induced effects on the rain processes.

Next to the southwesterly quadrant, the heaviest rainfall over the network in 1972 was associated with prevailing winds from the southeasterly quadrant. However, the heaviest rainfall was again east of the Mississippi which would be upwind of both St. Louis and Alton-Wood River with these wind directions. Other analyses indicated that most of the rainfall with these wind directions occurred with squall lines and cold fronts moving across the urban area, so that an urban effect (if present) would have reacted on these storms and could have been instrumental in producing the heavier. rainfall east of the Mississippi. The southeasterly surface flow would also intensify convergence in these storms that usually move from W-NW.

Wind-Rainfall Relations on Potential 'Effect' and 'No-Effect' Days

An investigation was made of the summer 1972 rainfall distribution in potential-effect storms when the rainfall was grouped according to the prevailing surface wind direction. Winds from the southwesterly quadrant were associated with 53% of the rains on potential-effect days. As shown in figure A-13, major features of the pattern were very similar to the total rainfall map in figure A-2. Although the heaviest rainfall was in the Collinsville region rather than in the Edwardsville area, the major highs and lows are located in nearly identical regions in both figures. Furthermore, the Collinsville-Edwardsville differences were small (less than 0.5 inch between the two high centers).

Maps were prepared also to show the rainfall distribution for the prevailing winds from each of the four quadrants on the potential no-effect days in 1972. These included 42 of the 72 rain periods. Southwesterly flow again dominated, with 40% of the total rain periods having prevailing winds from 190 to 270 degrees. The southwesterly map (figure A-14) showed a high persisting in the Edwardsville area where slightly more than 3 inches of rainfall were recorded in the June-August period in potential no-effect storms. This is approximately 50% of the amount recorded in that area in the 30 potential-effect storms. In fact, the network region east of the Mississippi was a region of relatively heavy rainfall and the area west of it had comparatively light rainfall.

Several possible reasons for this no-effect pattern can be suggested, such as the existence of a climatic high east of the river with peaking in the Edwardsville region, deficiencies in the classification of effect and no-effect storms, and the vagaries of sampling in the 2-summer period. Further data collection and study will be needed to evaluate the pattern observed in the first two years of Metromex operations. However, with S-SW-W winds, the possibility of urban-induced effects NE and E of the river is certainly present, and the best explanation at this time (in the writers' opinion) is that an urban effect was very likely operating on some of the days classed as potential no-effect situations, and this effect is being reflected in the no-effect pattern of figure A-14.

Stratification of Seasonal Rainfall by Synoptic Storm Types

Summer rainfall for each summer and for the two summers combined was stratified according to several basic types of synoptic storms (see Glossary). These included rainfall associated with organized squall activity, cold fronts (frontal plus pre-frontal rains), stationary or quasi-stationary fronts with waves, and non-frontal unorganized air mass storms. Other types, such as warm fronts, low center passages, and occluded fronts, were too few for separate grouping.

During summer 1971, squall activity was the most outstanding synoptic type associated with the network rainfall. At individual gages, it was found that squalls accounted for 65 to 85% of the summer total rainfall. Figure A-15 shows the total rainfall in 1971 resulting from this storm type on the potential-effect days. The highest amount was east of Edwardsville and located where the total rainfall high for summer 1971 occurred. In general, the major features agree quite well with the summer pattern in figure A-l.

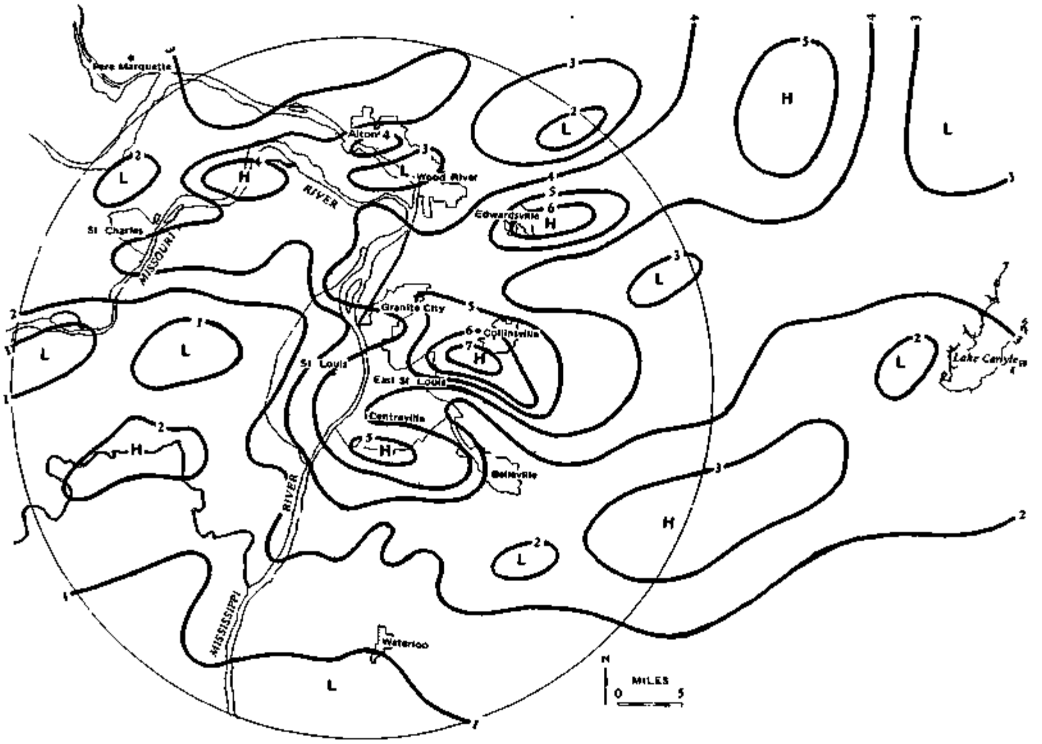


Figure A-13. Total rainfall, inches, on potential effect days during summer 1972 with winds from 190-270 degrees

The most important contributor to 1972 summer rainfall on the network was again squalls, with cold frontal storms ranking second. The major high center in the cold frontal storms was located near Edwardsville where the total rainfall for the summer was also highest on the network (figure A-2). In general, there was close correspondence between the cold frontal and total summer rainfall maps with respect to distribution characteristics.

The rainfall pattern associated with cold fronts on potential no-effect days in 1972 had the same type of pattern as discussed previously with the wind stratification. That is, the major areas of comparatively heavy rainfall were east of the Mississippi on the no-effect days as well as on the effect days. However, the rainfall amounts were much smaller in the no-effect storms.

The patterns of squall rainfall in 1972 showed major highs east of St. Louis on the potential-effect days with a maximum near Collinsville. The squall pattern for no-effect storms showed a rather random distribution of high rainfall centers, but the most intense were in the Centreville region and NE of Alton, that is, in areas that frequently are downwind of potential urban influences on the weather.

Although there were 28 rain periods associated with air mass storms in 1972, they contributed only a small portion of the network total rainfall in the June-August period. The pattern for potential-effect days showed a definite clustering of small high centers east of the river, whereas the no-effect pattern was much more random. This difference between effect and no-effect patterns suggests an urban-related intensification of these storms.

Table A-l shows the frequency of each major synoptic type associated with the network rainstorms during the summers of 1971-1972 combined, and the percentage of total network

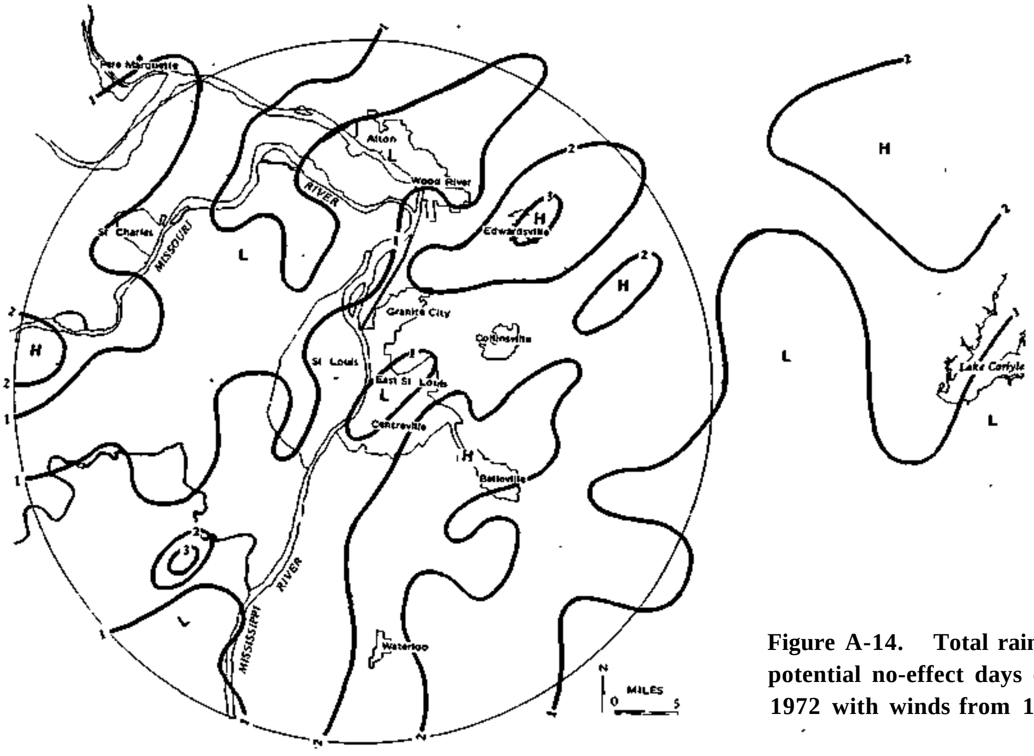


Figure A-14. Total rainfall, inches, on potential no-effect days during summer 1972 with winds from 190-270 degrees

Figure A-15. Total rainfall, inches, in squalls during summer 1971 rainfall associated with each type. Thus, air mass storms accounted for 42% of the storm occurrences, but only 10% of the total rainfall. Calculations were made of the percent of total rainfall associated with each synoptic type in the major high center in the Edwardsville region, the major low center west of St. Louis, and the secondary high NE of St. Charles in a potential breeding area for convective clouds. This was done to determine whether these outstanding anomalies departed significantly from the mean percentage distribution of rainfall according to synoptic type.

Table A-l. Distribution of Rainfall by Storm Type during Summers of 1971-1972

	Frequency of storms		Percent of total rainfall		
Storm type	Number	Percent of total	Network range	Median	Mean
Air mass	**55**	42	3-26	9	10
Squalls	**31**	25	39-75	59	59
Cold fronts	**21**	16	9-36	20	21
Stationary fronts and waves	16	12	3-22	10	9
Others	7	5			

Within the 22-inch isohyet of the Edwardsville high (figure A-3), 8, 60, 25, and 7% of the total rainfall occurred with air mass, squall line, cold front, and stationary front storms, respectively. Comparison with the median values of table A-l indicates that an above-average amount of rainfall associated with cold fronts was the largest departure from the network mean distribution. Within the 10-inch isohyet of the major low, percentages of 8, 58, 16, and 18 occurred with air mass, squall line, cold front, and stationary front storms. The only substantial departure was a +9% with the stationary fronts. The St. Charles secondary high showed very minor departures from the network medians for all synoptic types. Overall, the variations from the network percentage means in the major centers were within the limits of sampling variation that could readily occur in a 2-summer period.

Cold fronts and squalls accounted for 80% of the total network rainfall in 1971-1972. Within the region of the major high at Edwardsville-Collinsville (figure A-3) 85 to 90% of the total rain was associated with these two storm types. This was also the case in the secondary high regions in the bend of the river NW of St. Louis and in the Centreville-Belleville regions. In the major low area west of St. Louis, only 70 to 75% of the 2-summer total occurred with cold fronts and squalls.

Figure A-16 shows the total 1971-1972 rainfall associated with the combination of squalls and cold fronts. Comparison of this map with figure A-3 demonstrates the major control exerted on the total rainfall distribution by these two storm types. Basically, the distribution patterns of figure A-3 and A-16 are nearly identical with respect to location of major centers of heavy and light rainfall. With only 8% of the total rainfall in the Edwardsville high of figure A-3 associated with unorganized air mass storms, any substantial contribution from urban effects to this primary high must have been associated with frontal or organized non-frontal squall activity.

Diurnal Distribution of Summer Rainfall

The diurnal distribution of summer rainfall for 1971-1972 was studied to obtain information on whether the potential urban effects tended to be more pronounced during certain periods of the day. If so, this would provide indirect indications of the involvement of combinations of diurnal and urban heat outputs in the urban-induced effects on the downwind rainfall.

The first step in this analysis was to divide the day into two periods, 0800-2000 CST and 2000-0800 CST. The first period includes the hours of maximum diurnal heating and most of the daylight hours. The second period incorporates most of the night hours, the hours of maximum diurnal cooling, and the period when the urban heat island is most pronounced. Figure A-17 shows the percentage of the 2-summer rainfall occurring in the maximum heating period, 0800-2000 CST.

Figure A-17 shows a definite difference in the percentages in the areas east of the Mississippi that are most frequently downwind of the urban areas, and the region west of St. Louis which is infrequently downwind of the urban centers in rainstorms. Thus, percentages exceeding 70% encompass St. Louis and the Collinsville-Edwardsville areas, east and NE of St. Louis and in the region of maximum summer rainfall in 1971-1972 (figure A-3). Percentages range from less than 50% west of St. Louis to over 75% in the East St. Louis-Collinsville area.

Thus, the large differences between the area west of St. Louis (usually upwind) and the St. Louis-Collinsville-Edwardsville area suggest that a combination of natural diurnal heating and urban effects are related to establishment of the center of apparent maximization of urban-induced rainfall E and NE of St. Louis. As hypothesized by Huff and Changnon (1972a), this could result from earlier initiation of convection in the urban area as natural diurnal heating is superimposed on the urban heat island which maximizes in the early morning hours, and/or increased convection in the late forenoon and afternoon from the urban heat and/or aerosol output superimposed on the normal diurnal heating.

Figure A-17 shows a high center in the bend of the river NE of St. Charles, and this is quite reasonable since convection in this hot-moist region should be well correlated with maximum diurnal heating. The high in the extreme northwestern part of figure A-17 is in a bluffs area where rainfall is likely to be favored most during the period of peak diurnal heating. Similarly, the high percentages in the southwestern part are in a region of rough terrain, where coincidence of maximum diurnal heating with the hill effect is favorable for rainfall initiation or intensification.

Next, the diurnal rainfall distribution was examined in more detail by calculating the frequency of rainstorms and the total amount of rainfall by 3-hour periods during the 1971-1972 summers. Briefly summarized, the 1971 patterns of 3-hourly rainfall indicated any urban-induced effect on the regional rainfall was strongest in the 1200-1500 period. The center of heaviest rainfall was located in the Edwardsville-Collinsville area at that time. Pattern analyses showed a secondary period of maximization in the hypothesized major effect region in the late evening (2100-2400 CST), but the reason for this maximum, if urban-related, is not clear at this time. In this period, a major high in the rainfall occurred east of Alton-Wood River, and this could have resulted from a regeneration or stimulation of early evening activity in and upwind of the primary urban regions. As indicated earlier, the early afternoon maximization in the major effect area could be related to a combination of natural diurnal heating and urban thermal output. Also, the urban intensification may have occurred in this period because conditions are most favorable in late forenoon and early afternoon for development of convective activity in feeder regions, represented by the Missouri-Mississippi confluence region and the Ozark foothills SW of St. Louis.

Examination of the 3-hourly maps for 1971 did not provide evidence of urban-related increases in rainfall during the early morning hours. If any effect was present, the pattern would suggest a suppression rather than a stimulation effect, since relatively light rainfall was recorded in the hypothesized major effect area during this period of the day. The area of lightest rainfall in the network extended ENE, E, and ESE of St. Louis in the period from 0000 to 0600 CST.

Examination of 3-hourly data for 1972 generally support the 1971 observations, except that ±e 3-hour period of maximum rainfall shifted from 1200-1500 to 1500-1800 CST. For the two summers combined, the heaviest 3-hourly rainfall period was 1500-1800 CST, and the rainfall pattern for this period is shown in figure A-18. The most pronounced highs, in which total rainfall equalled or exceeded 5 inches, were located within the urban area and east of the Mississippi where urban effects would most commonly occur because of low and middle-level wind patterns. The heaviest 3-hour amounts, which

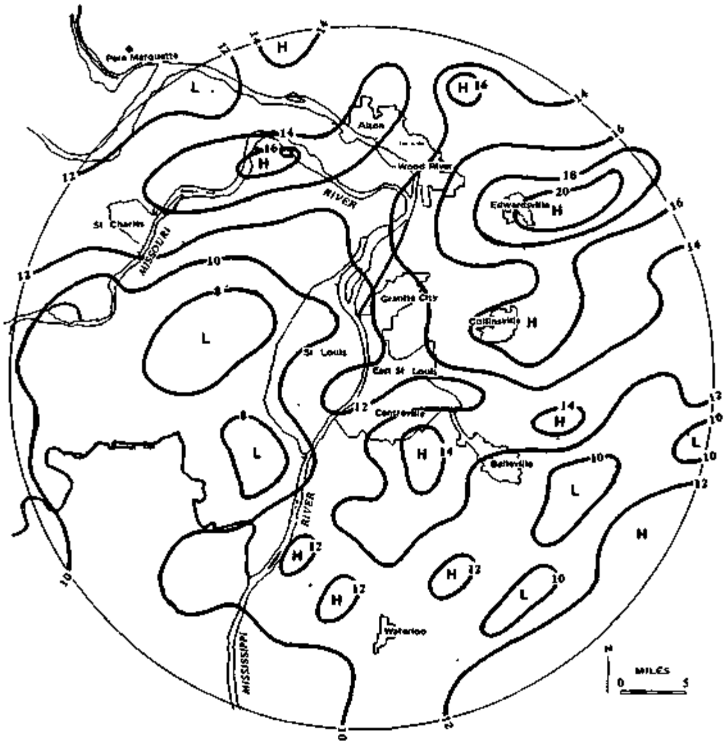


Figure A-16. 1971-1972 total summer rainfall, inches, with squalls and cold fronts

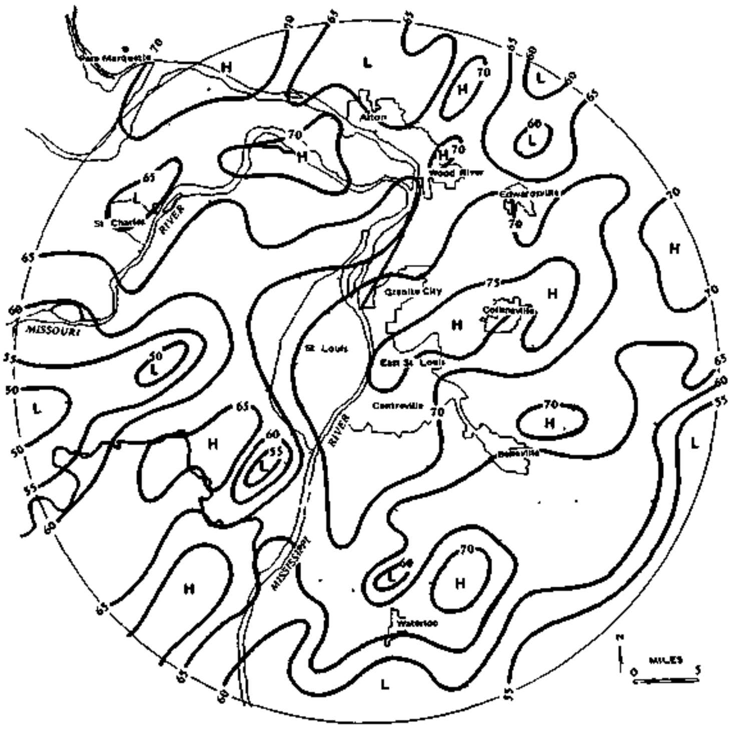


Figure A-17. Percent of total rainfall in storms beginning between 0800 and 2000 CST during summers of 1971-1972

Figure A-18. Total 2-summer **rainfall,** inches, **during 1500-1800 CST**

exceeded 6 inches, were in the Centreville-Belleville region and coincided closely with the potential urban-induced high identified by Huff and Changnon in their earlier climatic study. Highs also were located in the Edwardsville-Collinsville regions, and the Edwardsville high correlates well with the 2-summer total rainfall pattern in figure A-3. Minor highs were located in the lowlands between St. Charles and Alton and in the hills SW of the city.

In the Centreville-Belleville high of figure A-18, 40 to 50% of the total 2-summer rainfall occurred in the 1500-1800 period, and over 30% of the regional total was recorded during this 3-hour period in the Edwardsville-Collinsville region. As indicated earlier, this pattern of diurnal distribution suggests a maximization of urban enhancement of rainfall in the afternoon hours.

Table A-2 provides additional information on the diurnal distribution in the 1971-1972 period. In this table, the percent of the total 2-summer rainfall is shown for each 3-hour period at selected locations. These include regions where urban enhancement is indicated, potential breeding areas for convective clouds outside of the urban region, the region of minimum rainfall west of St. Louis, and a high observed in the extreme southeastern part of the network.

Except for the region of minimum rainfall west of St. Louis, all selected regions show an afternoon maximum. The region of the major low shows a maximization in the 0600-0900 period, and this may be related to the nocturnal thunderstorm phenomena of the warm season. Huff (1971) and Huff and Changnon (1972b) have shown that, on the average, the diurnal maximum of summer rainfall occurs during the 3 hours ending at 0400-0600 CST at the Lambert Airport station which is NW of the city and usually upwind, and in southwestern Illinois which is normally downwind and beyond the urban-effect region of St. Louis. A secondary maximum was found in the climatic distributions in the middle to late afternoon, when the primary maximum occurred over most of the Metromex network in

Table A-2. Diurnal Distribution of 1971-1972 Summer Rainfall, in Percent of Total Rainfall

Station and location	Percent of total 2-season rainfall for 3-hour periods 00-03	03-06	06-09	09-12	12-15	15-18	18-21	21-24
Wood River to Edwardsville and eastward								
47	3	8	14	7	17	26	12	13
50	6	4	10	5	23	30	11	11
51	5	6	8	5	23	31	8	14
Mean	4.7	6.0	10.7	5.7	21.0	29.0	10.3	12.7
Bottomlands to Alton and northeastward								
29	5	8	12	5	15	27	16	12
20	5	6	18	8	21	22	13	7
12	7	5	15	6	23	19	13	12
Mean	5.7	6.3	15.0	6.3	19.7	22.7	**14.0**	10.3
St. Louis Urban Area								
96	2	7	15	8	11	27	7	23
113	3	6	13	10	8	44	6	10
131	4	8	15	5	9	**44**	7	8
Mean	3.0	7.0	14.3	7.7	9.3	38.3	6.7	13.7
East St. Louis to Collinsville and eastward								
115	2	5	10	9	6	31	16	21
101	3	7	6	4	28	23	13	16
103	2	14	8	5	24	20	18	9
Mean	2.3	8.7	8.0	6.0	19.3	24.7	15.7	15.3
Centreville to Belleville								
133	3	7	13	8	3	49	9	8
151	2	8	8	8	15	47	7	5
153	3	6	8	12	21	29	15	6
Mean	2.7	7.0	9.7	9.3	13.0	41.7	10.3	6.3
Hills SW of St. Louis								
159	2	17	14	7	12	29	9	10
176	2	12	18	7	14	32	11	4
191	4	10	10	3	34	24	9	6
Mean	2.7	13.0	14.0	5.7	20.0	28.3	9.7	6.7
Major Low West of St. Louis								
91	7	10	24	8	12	17	13	9
92	3	11	26	8	10	16	11	15
93	3	9	23	3	8	30	10	14
Mean	4.3	10.0	24.3	6.3	10.0	21.0	11.3	12.7
SE High								
202	5	15	8	10	25	19	14	4
222	6	24	11	3	24	14	9	9
Mean	5.5	19.5	9.5	6.5	24.5	16.5	11.5	6.5

1971-1972. However, at the downtown station of the National Weather Service, the early morning and afternoon maxima were approximately equal in the climatic mean distributions. The more pronounced afternoon maximum occurring in the city diurnal distribution is quite likely related to urban influences.

Since the summers of 1971-1972 were well below normal in total rainfall, we may be observing a primary cause of the seasonal dryness in the diurnal distributions throughout the network; that is, the absence of the early morning maximum at most stations. Table A-2 does indicate a weak secondary maximum, but mostly in the 0600-0900 period. The climatic studies showed that the normal diurnal minimum occurs in the late forenoon. The earlier observation from the 1971 data of a possible early morning suppression of rainfall by the urban region may be a characteristic of dry summers. This, of course, must await more data for verification.

Summary and Conclusions

The summer rainfall distribution for 1971, a very dry season, agreed very well in its major features with the long-term dry season pattern found by Huff and Changnon (1972a) in their urban climatic studies. The 1972 summer pattern closely resembled the moderate-summer pattern of Huff and Changnon, and this resulted from dominance of the seasonal distribution by relatively heavy August rainfall and very light June and July rainfall. The 2-summer distribution, in which the network average was only 66% of normal, had a typical dry-season pattern with a dry zone extending W-E across St. Louis, major regions of relatively high rainfall NE and NW of the city, and a secondary high region S of the urban area in the Waterloo region.

The 2-summer pattern showed the heaviest rainfall in the Edwardsville region, NE of the city, which from wind analyses, was frequently downwind of the Alton-Wood River industrial complex in 1971 and the St. Louis urban area in 1972. Thus, this pronounced high is likely related to urban environmental effects from both urban sources. A secondary high NW of St. Louis in the lowlands of the Missouri and Mississippi Rivers may have been associated primarily with convective development in the heat-moisture source.

The 1971-1972 gradient of summer rainfall between the major downwind high (Edwardsville-Collinsville region) and primary upwind low (west of St. Louis) was much greater than found in the earlier climatic studies. Considering the normality of seasonal rainfall in the two summers and the magnitude of other unaffected highs and lows in the network distribution, it is estimated that the urban effect may have resulted in a 20 to 30% increase in rainfall in the Edwardsville-Collinsville region in 1971-1972.

Calculations were made to search for evidence of more frequent occurrences of measurable rainfall associated with the potential urban-induced highs during 1971-1972. Although a distinct high in the frequency pattern was found in the Edwardsville-Collinsville region, there were highs of equivalent magnitude in nearly all directions from the city, and the distribution appeared to be almost random. Thus, it was concluded that evidence for urban-induced increases in rainfall occurrences is not readily apparent in the 2-summer distribution pattern of measurable rainfall occurrences.

Study of the distribution of heavy (≥ 1 inch) rainstorms was made to investigate possible intensification of rainstorms by urban environmental effects. Results indicated that intensification of existing storm systems was a major cause of seasonal highs in the 2-summer rainfall pattern. Provided that the Edwardsville-Collinsville primary high was wholly or partially related to urban effects, this indicates that an urban-intensification mechanism applied to naturally occurring storms is instrumental in producing urban-related increases in summer rainfall. This agrees with the earlier climatic findings of Huff and Changnon. Other analyses (rank score tests) indicated an above-normal tendency for heavy storms to maximize in the Edwardsville region.

Rain days were divided into potential *effect* and *no-effect* situations, on the basis of low-level wind analyses and the location of maximum storm rainfall. Results indicated that a much higher percentage of the total rainfall in the major high centers, located east of the Mississippi, occurred on those days when this region was in the potential-effect area. In the Edwardsville-Collinsville region, 65 to 75% of the total 2-season rainfall occurred in the designated potential-effect storms. The no-effect pattern for 1971-1972 was very similar to the dry-season pattern in its distribution characteristics. This indicates that the absence of urban effects, or possibly urban suppression of rainfall during dry summers, may be primarily responsible for the climatic pattern of dry seasons, as suggested by Huff and Changnon (1972a).

Relations between prevailing surface winds prior to the onset of rain and the distribution characteristics of the resulting storm rainfall were investigated. In summer 1971, rainfall was greatest with winds from the northwesterly quadrant, and the region of the major network high near Edwardsville (figure A-l) would have been frequently downwind of the Alton-Wood River industrial complex. Over 50% of the rainfall in the Edwardsville high was associated with winds from WNW-W-NW directions. A more normal situation occurred in 1972 when winds from the southwesterly quadrant were most frequently associated with network rainfall. Over 70% of the summer total in the major highs in the Edwardsville and Collinsville regions were associated with these winds which would have placed the high areas frequently downwind of the urban area of St. Louis.

The summer rainfall data were stratified according to synoptic storm types to investigate the possibility that the urban effect was more pronounced with certain types of storm situations. During summer 1971, squall activity was the most outstanding synoptic type associated with the rainfall. The major features of the squall pattern of rainfall agreed quite well with the overall summer distribution shown in figure A-l. The most important contributor to 1972 summer rainfall was again squalls followed closely by cold frontal storms. In general, there was close correspondence between the summer total rainfall, squall, and cold frontal patterns. Although air mass storms (non-frontal) accounted for 42% of the storms in 1971-1972, they produced only 10% of the network rainfall, compared with 59% from squall lines, and 21% from cold fronts. No proof was established that the urban effect is primarily restricted to action in specific storm types. However, the above statistics indicate that any urban-induced excess accumulates mostly in organized systems (fronts and squalls).

The diurnal distribution of rainfall was studied to obtain information on whether the potential urban effects tended to be more pronounced during certain periods of the day. The 1971-1972 summer rainfall was divided first into two 12-hour periods, 0800-2000 CST which includes the maximum diurnal heating period, and 2000-0800 CST which encompasses the maximum cooling period. During the maximum heating period, much larger percentages of the 2-summer total rainfall occurred east of the Mississippi, which is most frequently downwind, compared with the most frequent upwind areas west of the river. Percentages exceeding 70% encompassed the St. Louis-Collinsville-Edwardsville area, with a range from less than 50% west of the urban area to 75% in the East St. Louis-Collinsville region. This distribution pattern suggests a combination of natural diurnal heating and urban effects related to establishment of the center of maximum rainfall E and NE of St. Louis in 1971-1972.

Analyses of 3-hourly rainfall amounts for 1971-1972 showed an afternoon maximization in the high rainfall centers east of the Mississippi. For the 2-summer period, 40 to 50% of the total rainfall in the Centreville-Belleville region occurred in the 1500-1800 period, and over 30% of the total was recorded in this period in the Edwardsville-Collinsville region. With equal hourly distributions, only 12.5% of the total should occur in this 3-hour period. This afternoon maximum in the hypothesized major effect area may be related to a combination of natural diurnal heating and urban thermal-aerosol outputs, and/or conditions favorable for development of convective activity in upwind feeder regions, represented by the Missouri-Mississippi confluence northwest of the city (hot, humid lowlands) and the Ozark foothills southwest of the urban area.

Examination of 3-hourly rainfall maps for 1971-1972 did not provide evidence of urban-related increases in rainfall during the early morning hours. If any effect was present, the patterns would suggest a suppression rather than a stimulation effect, since relatively light rainfall was recorded in the region east of the Mississippi during this period of the day.

During the relatively dry summers of 1971-1972, the diurnal distribution was abnormal with respect to time of rainfall maximization. Climatic studies have shown a primary maximum in the early morning and a secondary maximum in the afternoon. Absence of the primary maximum in the early morning (nocturnal phenomena) may be a characteristic of dry summers.

References

Huff, F. A. 1971. *Distribution of hourly precipitation in Illinois.* Illinois State Water Survey Circular 105. 23 pp.

Huff, F. A., and S. A. Changnon, Jr. 1972a. *Climatological assessment of urban effects on precipitation at St. Louis.* Journal of Applied Meteorology, 11:823-842.

Huff, F. A., and S. A. Changnon, Jr. 1972b. *Climatological assessment of urban effects on precipitation.* Illinois State Water Survey for National Science Foundation Grant GA-18781. Final report, Part II. 237 pp.

B. APPLICATION OF FRONTAL CLIMATOLOGY BY DIGITAL TECHNIQUES TO PROJECT METROMEX

G. M. Morgan, Jr., R. C. Beebe, and D. A. Brunkow

Introduction

Field research projects by necessity are carried out over a limited number of years. It is very unlikely that any of these years, the individual months that make them up, or the entire block of years and months covered by the field operations will be "typical" in the sense of constituting a sample representative of any other period of similar length.

Two years of measurement of precipitation at very fine scale (discussed in Sections A and F) have substantiated the downwind enhancement of precipitation which had been detected in data from the much coarser climatological network. Because measurements with the fine-scale network are not available for the years prior to the start of the field project, the representativeness of the observed patterns cannot be assessed. It is necessary to establish the similarity of simultaneous patterns of other measurables, such as surface winds, temperatures, moisture, and so on, to those of previous time periods, in order to argue for the representativeness of the new measurements. To this end, for example, the rainfall patterns based on the climatological network have been determined and evaluated for the periods of fine-scale network operations (Section A). Another element for which historical records are available is the surface front.

The surface front is a powerful device in weather analysis and forecasting, but it is not generally used as a basis for describing climate. As an additional set of climatic parameters for categorizing field operation periods, frontal frequencies for the entire North American Daily Weather Map have been determined for all months of the 10-year period 1961-1970 and for June, July, and August of 1971 and 1972. The entire year has been done for the 1961-1970 decade because it is anticipated that this will find applications in several other Water Survey research activities. For Metromex applications, only the three summer months are considered here.

The frequencies of occurrence of fronts (cold, warm, stationary, and occluded), squall lines, high pressure centers, and lows have been determined for 60x60 nautical mile (nm) squares for each Daily Weather Map. Only the stationary frontal frequencies will be discussed here.

For the examination of single months, the basic 60x60 square has proven too small; the distributions have a very uneven, noisy appearance. For this reason, the box size has been increased by combining the basic 60x60 boxes to yield box sizes of 180x180 and 300x300 nm.

Initial Results

Figure B-l shows the 10-year (1961-1970) average frequencies of stationary fronts for August, based on the 60x60 grid. There is considerable detail on this map, and such detail may be significant. Figure B-2 is the map of stationary frontal frequencies for the single month of August 1971, based on the 60x60 grid; much of the detail observed here is due to the small sample size. Figure B-3 displays the same map as B-2, but with a 180x180 grid. A further increase in grid size to 300x300 nm yields the smoother pattern of figure B-4. This is believed to be a desirable and appropriate level of smoothing for the examination of single months, so both the 10-year averages and the single months have been processed on that basis.

The 10-year maps of stationary frontal frequencies for the grid of 300x300 nm are shown for the three summer months in figures B-5, B-6, and B-7. In general, there is a pronounced belt of maximum frequencies through the middle of the continent, with a nearly E-W orientation. The region of this belt can be considered as one where southward surges of cold air tend to stall out. To the north of this belt lies cold air and to the south warm air. One would expect that the greatest frequencies of convective rains and squall systems would occur to the south of this band or, conversely, that convective rains would be infrequent for some distance north of it.

This expectation is consistent with the observations at St. Louis in 1971 and 1972. Both years were below normal in precipitation during the June-July-August period, with the only moderately wet months being July of 1971 and August of 1972. The shape of the total precipitation patterns for summer in these two years was strongly related to the rainfall patterns of June 1971 and August 1972. These showed very strong downwind rainfall maxima and these maxima dominated the summer distributions. The stationary front distributions for each month (figure B-8 to B-12) show the high concentration band running through St. Louis or to the south of it in all months except the months of June 1971 and August 1972 when it was well to the north of the St. Louis area. The frequencies in the maximum band were generally higher in the two downwind-effect months, indicating also greater sluggishness in the cold air penetrations.

Interpretation of the frequency distributions of the moving frontal systems is less straightforward and requires further study. A more complete investigation of the relationship between rainfall at St. Louis and the position of the stationary frontal maximum will also be pursued.

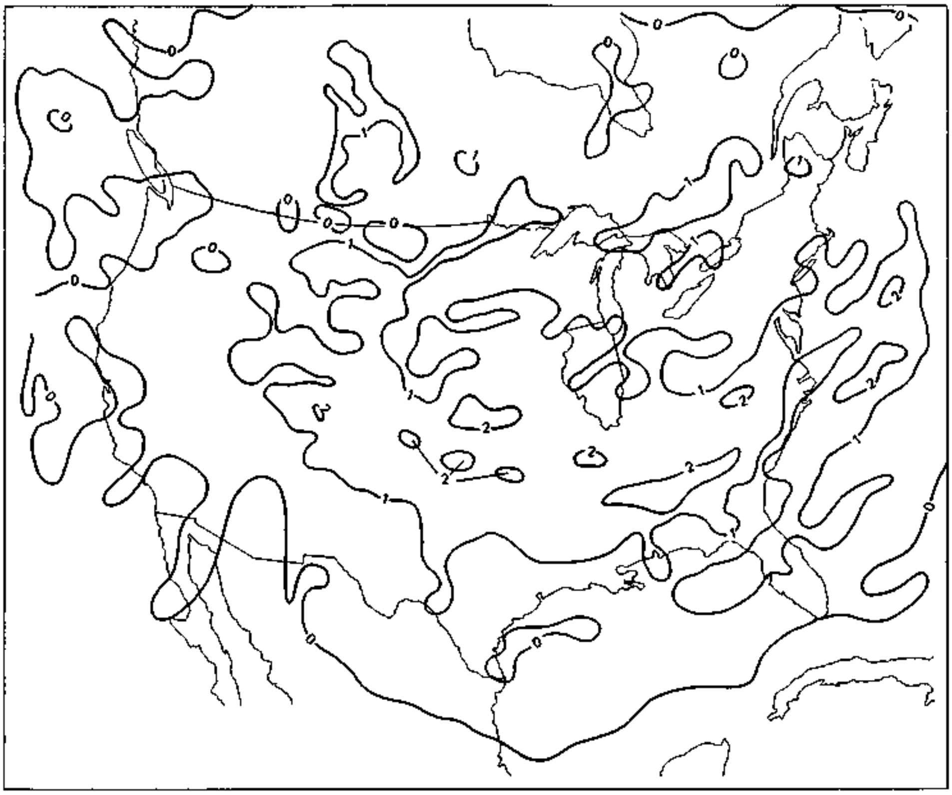


Figure B-l. Average annual frequency of stationary fronts in August (days), 1961-1970, 60x60 nm grid

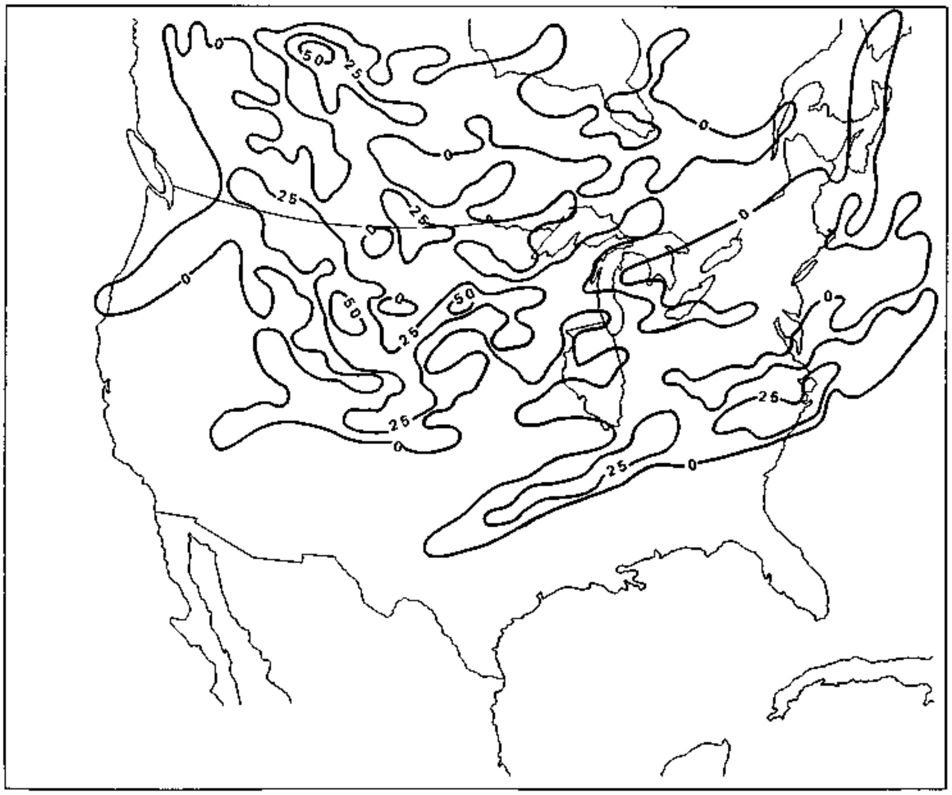


Figure B-2. Frequency of stationary fronts (days), August 1971, 60x60 nm grid

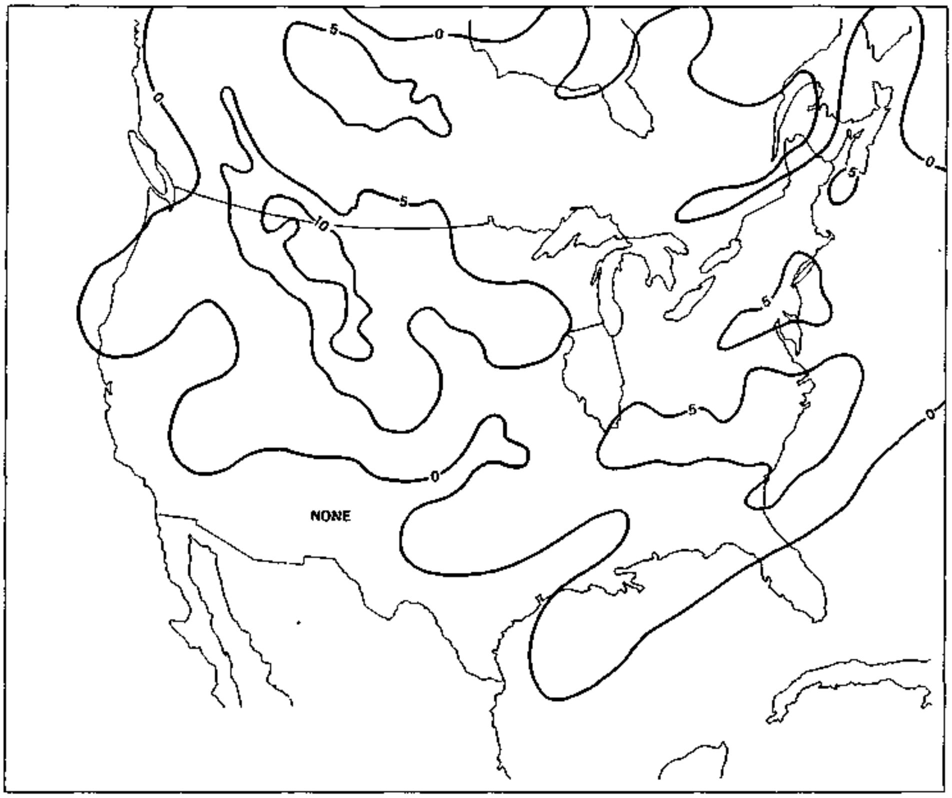


Figure B-3. Frequency of stationary fronts (days), August 1971, 180x180 nm grid

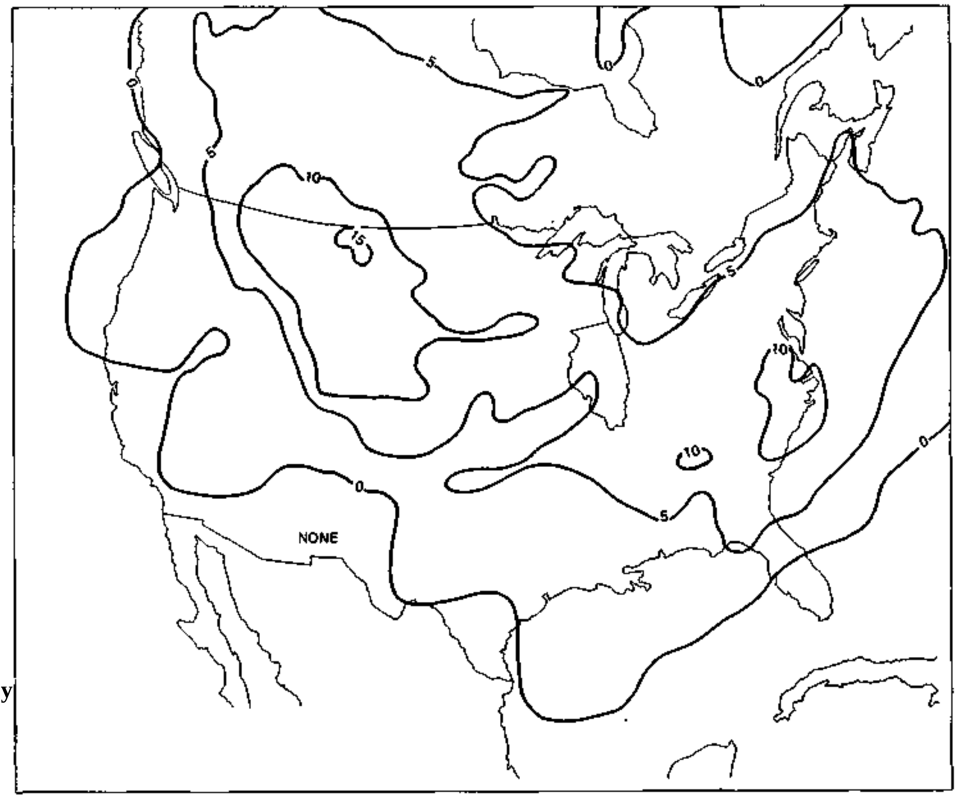


Figure B-4. Frequency of stationary fronts (days), August 1971, 300x300 nm grid

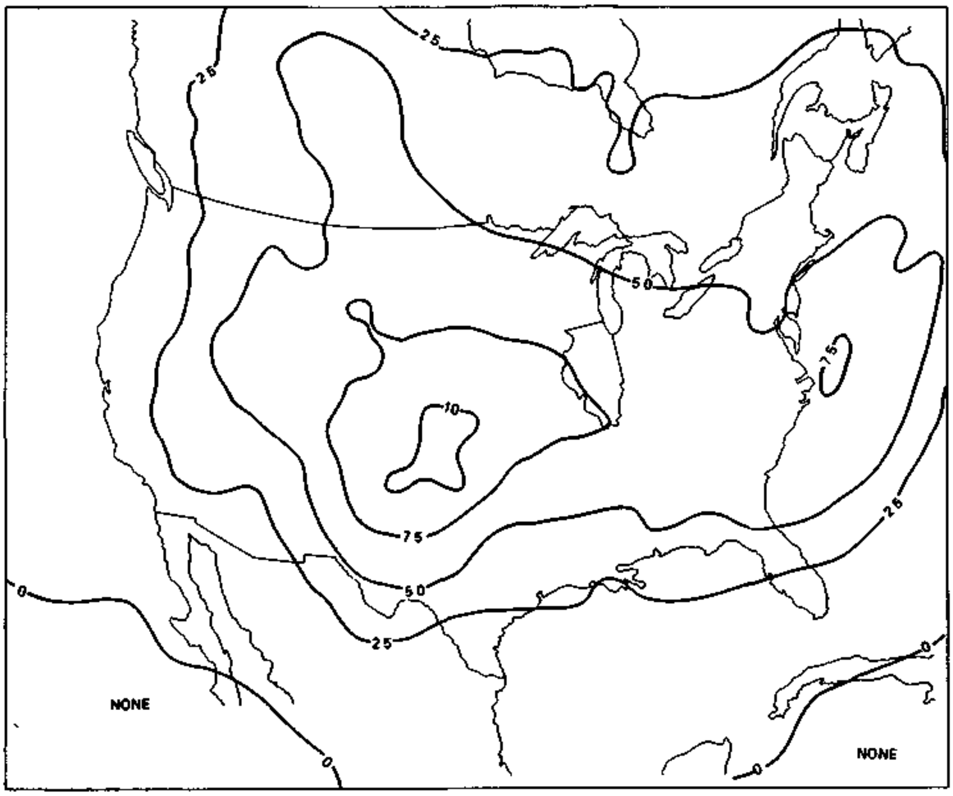


Figure B-5. Average annual frequency of stationary fronts in June (days), 1961-1970, 300x300 nm grid

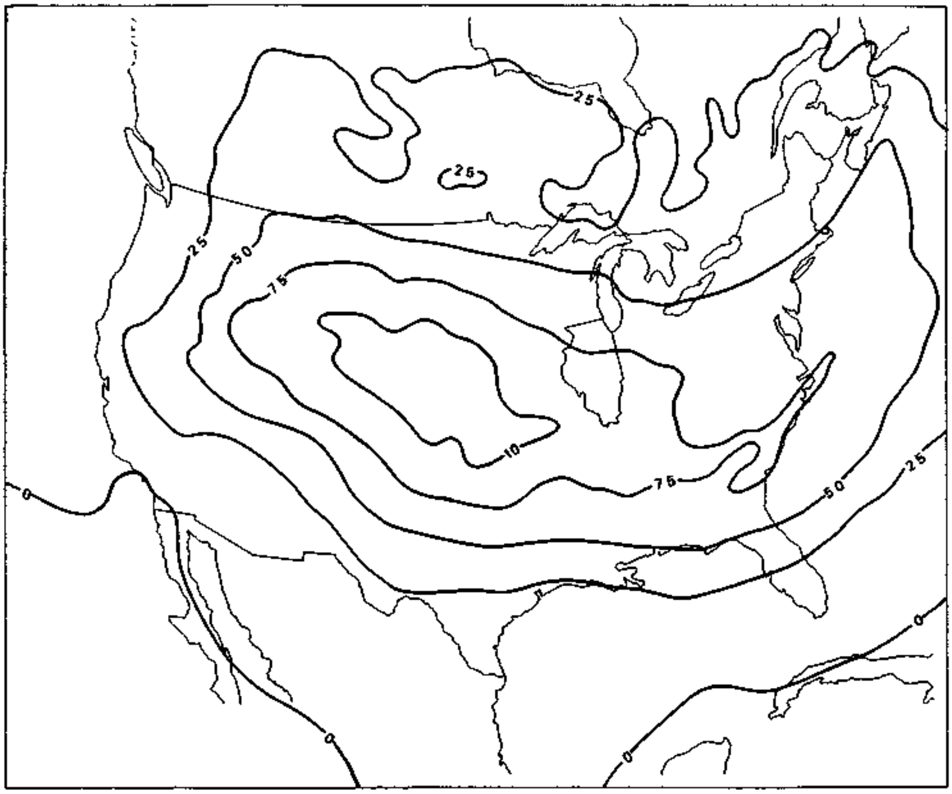


Figure B-6. Average annual frequency of stationary fronts in July (days), 1961-1970, 300x300 nm grid

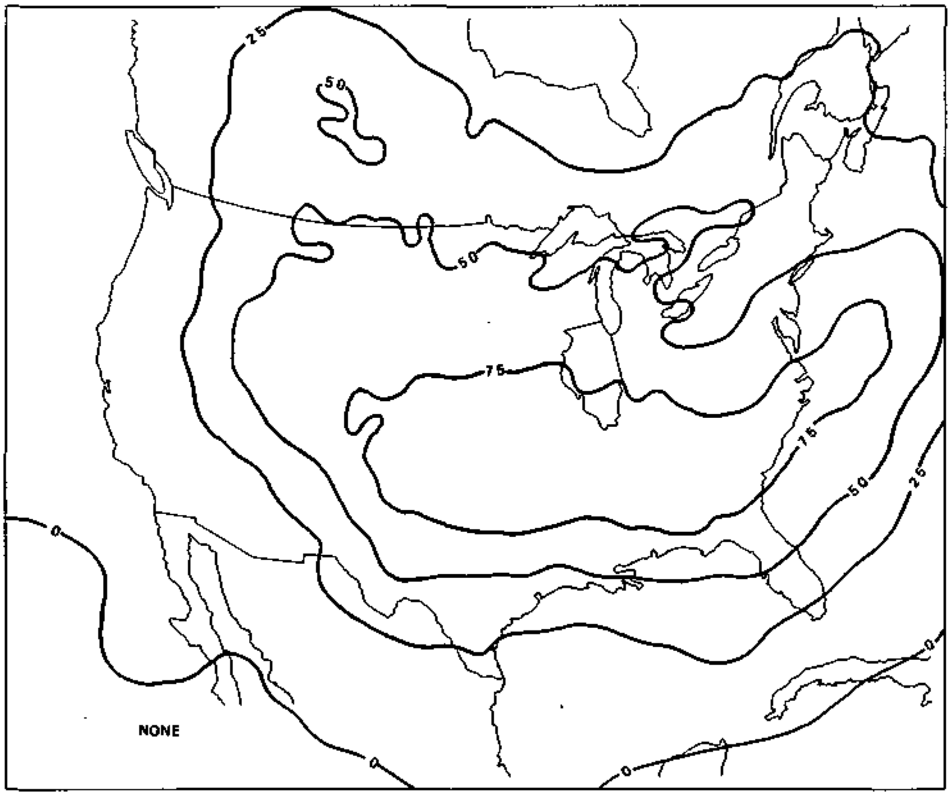


Figure B-7. Average annual frequency of stationary fronts in August (days), 1961-1970, 300x300 nm grid

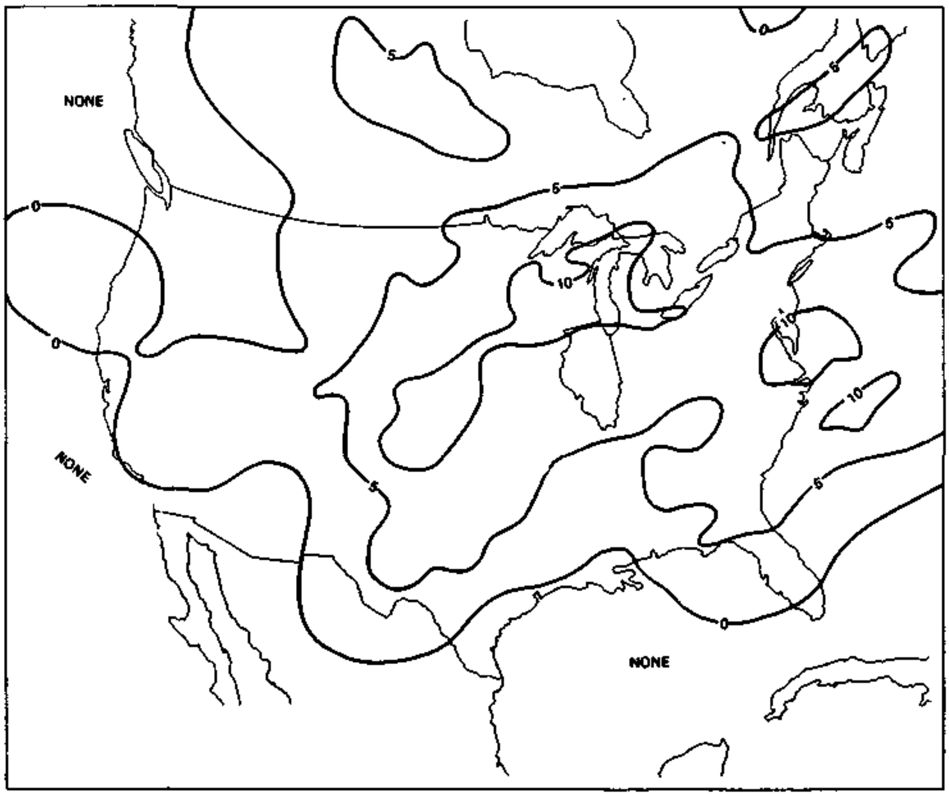


Figure B-8. Frequency of stationary fronts (days) in June 1971, 300x300 nm grid

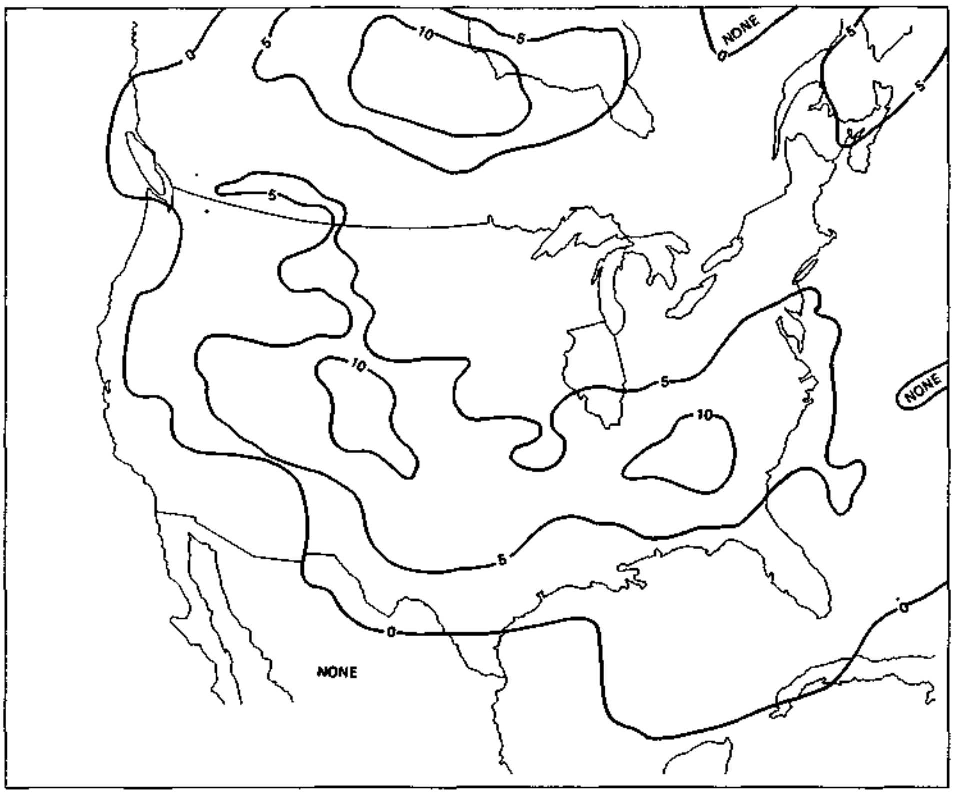


Figure B-9. Frequency of stationary fronts (days) in June 1972, 300x300 nm grid

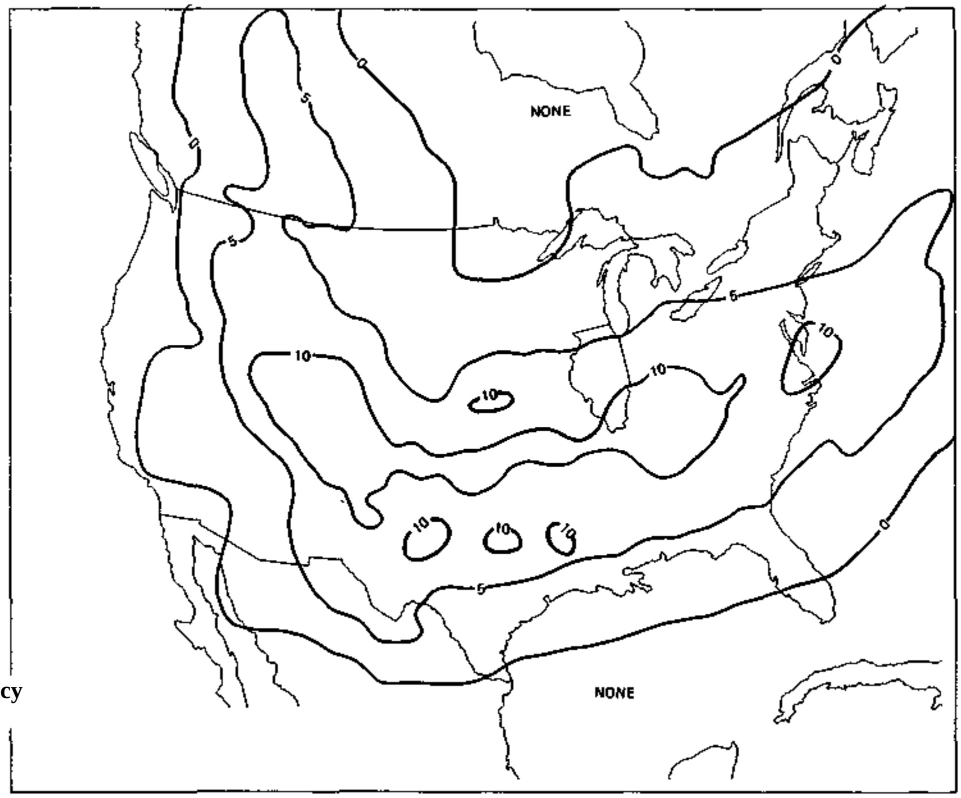


Figure B-10. Frequency of stationary fronts (days) in July 1971, 300x300 nm grid

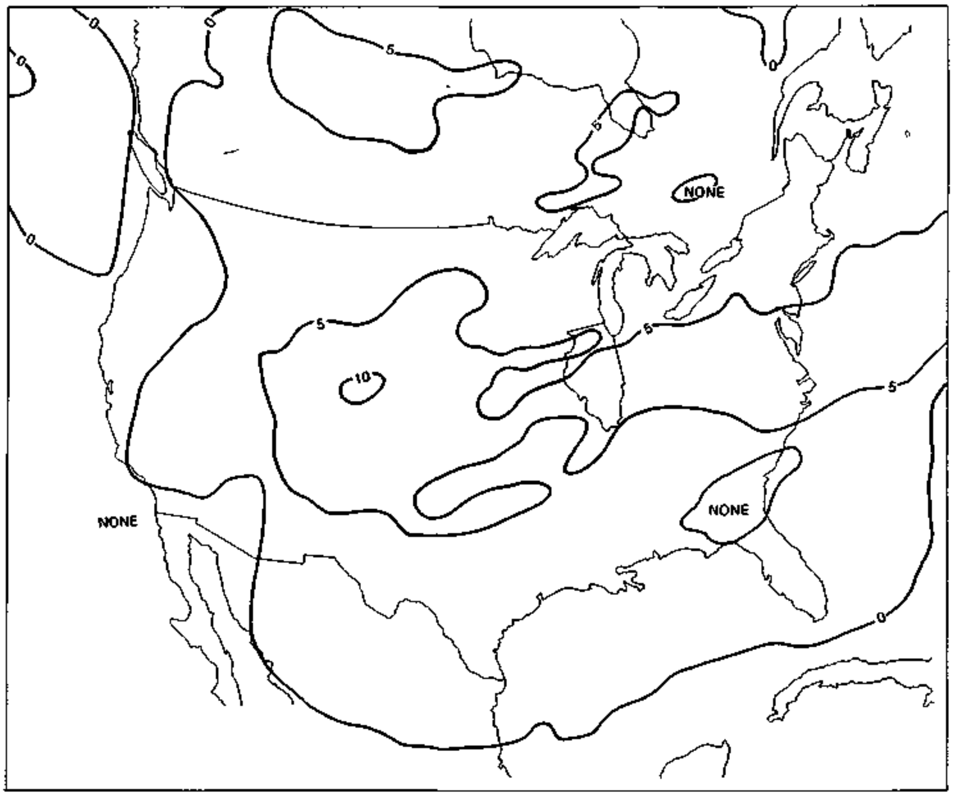


Figure B-ll. Frequency of stationary fronts (days) in July 1972, 300x300 nm grid

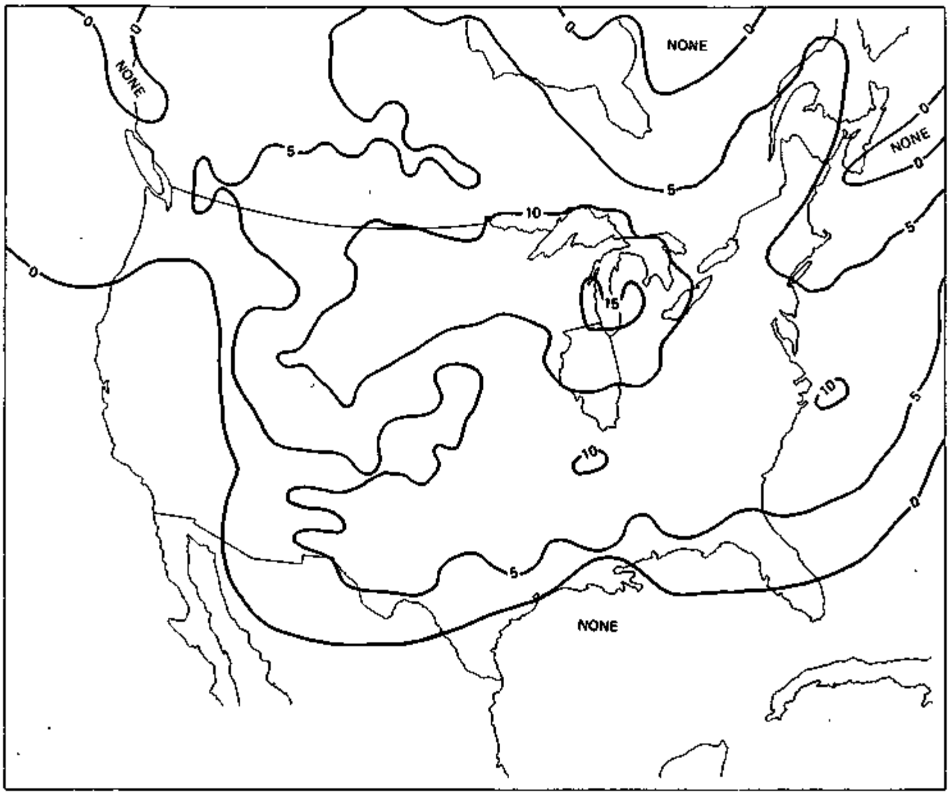


Figure B-12. Frequency of stationary fronts (days) in August 1972, 300x300 nm grid (see figure B-4)

C. SYNOPTIC AND RELATED STUDIES

G. M. Morgan, Jr., and R. C. Beebe

Introduction

Synoptic weather analysis serves two main purposes on Metromex. It produces data for a synoptic climatology on urban effects, and supports case study explorations into the causes of urban effects. First, daily analyses were carried out to determine the synoptic feature most directly responsible for each rain event during the 3-month field operations at St. Louis each summer. Individual rain events were then classified as *"urban effect"* and *"no effect"* (see Glossary). The frequency distribution of effect and no-effect events stratified by synoptic types was studied to detect any tendency for either class of event to occur preferentially with certain synoptic types. The value in this research approach lies in the fact that each synoptic category corresponds to a complex model of dynamic processes, or a model of the environment, within which the rain event occurs.

The summer months are notorious among weather analysts and forecasters for the difficulty to recognize conventional synoptic features such as surface fronts. Fronts tend to be weak and poorly defined in summer and frequently become stationary through the center of the country. Frontal displacements are generally slow and not sustained. Because of these difficulties in analysis, some cases must be submitted to extremely careful, hour-by-hour analyses, which are labeled "case studies," in order to establish with reasonable confidence the synoptic entity responsible for the rainfall. Similar detailed synoptic case studies are carried out as part of larger case studies involving all measurements made in Metromex.

Synoptic Classification Studies

The following synoptic categories, as defined in the Glossary, have been considered in classifying rain events: frontal zone including cold (CF), warm (WF), and stationary (SF); squall line (SQ); air mass (AM); pre-frontal (PF); and low pressure center (Low).

The results of two years of classification of rain events by synoptic type are contained in tables C-l, C-2, and C-3. The first column in each table is the overall partitioning of each type of event by synoptic categories, irrespective of the intensity of rainfall. The following columns show the frequencies for only those events whose maximum rainfall accumulation (highest gage total in network) equaled or exceeded the amount in the column heading. This method of classifying rain intensity provided a convenient means of identifying stable and unstable (TRW,RW) types of rain and separating storm periods according to general level of network intensity.

From table C-l, it is apparent that during the summers of 1971-1972 air mass storms were the most frequent occurrence on the network, followed by squalls and cold fronts. Table C-2 shows that air mass storms were the most frequent on effect days, followed by squalls. However, squalls dominated in those cases with relatively heavy maxima, especially when the network maximum was 1 inch or more. Table C-3 shows that air mass storms were most frequent also on no-effect days, followed by squalls and cold fronts. However, in those storm periods having maxima of 1 inch or more, squalls again were the dominant type.

Table C-4 was obtained by dividing the values in table C-2 by those in table C-l; that is, table C-4 shows the percentage of total storm periods that were effect cases in each intensity class for each synoptic type. From table C-4, it is seen that the overall percent of rains classified as effect storms (bottom row of table) increases steadily as more intense rains are considered. This is emphasized by recasting some of the data in the form of table C-5, which shows the percent of effect and no-effect rains occurring in each indicated intensity class. Effect rains show higher percentages in all intensity classes (note the cumulative character of the breakdown employed) than do no-effect rains.

Table C-l. Distribution of Rain Events by Synoptic Category and Maximum Point Rainfall for All Cases

Synoptic type	All rains*	Number, for events whose network maximum point rainfall equaled or exceeded given amounts *(inches)* 0.25	0.5	1.0	2.0	3.0
CF	19	12	9	5	1	0
SF	10	8	6	4	1	0
WF	4	2	2	0	0	0
SQ	32	24	22	19	8	2
AM	45	22	17	7	0	0
PF	10	8	6	3	1	0
Low	3	0	0	0	0	0
Total	123	76	62	38	11	2

* Difference in total rains between this table and table A-l resulted from combining several separate rain events used in table A-l into a single event for the above analysis.

Table C-2. Distribution of Rain Events by Synoptic Category and Maximum Rainfall in Effect Cases

Synoptic type	All rains	Number, for events whose network maximum point rainfall equaled or exceeded given amounts *(inches)* 0.25	0.5	1.0	2.0
CF	5	5	4	3	0
SF	5	4	3	2	0
WF	2	1	1	0	0
SQ	14	14	14	12	6
AM	19	10	7	3	0
PF	6	6	5	2	1
Low	2	0	0	0	0
Total	53	40	34	22	7

Table C-3. Distribution of Rain Events by Synoptic Category and Maximum Rainfall in No-Effect Cases

Synoptic type	All rains	Number, for events whose network maximum point rainfall equaled or exceeded given amounts *(inches)* 0.25	0.5	1.0	2.0
CF	14	7	5	2	1
SF	5	4	3	2	1
WF	2	1	1	0	0
SQ	18	10	8	7	2
AM	26	12	10	4	0
PF	4	2	1	1	0
Low	1	0	0	0	0
Total	70	36	28	16	4

Table C-4. Percent of Rain Events in Effect Class Grouped by Maximum Rainfall Intensity and Synoptic Type

Synoptic type	All rains	Percent, for events whose network maximum point rainfall equaled or exceeded given amounts *(inches)* 0.25	0.5	1.0	2.0
CF	26	42	44	60	
SF	50	50	50	50	
WF	50	50	50		
SQ	44	58	64	63	75
AM	42	46	41	43	
PF	60	75	83	67	100
Low	67				
Total	43	53	55	57	64

Table C-5. Percent of Effect and No-Effect Rains with Intensities of the Indicated Class

	All rains	Percent, for events whose network maximum point rainfall equaled or exceeded given amounts *(inches)* 0.25	0.5	1.0	2.0
Effect	100	75	64	42	13
No-effect	100	56	40	23	6

Examination of tables C-1 through C-3 shows that the synoptic category which dominates is the squall line. When the lighter intensity rain events have been removed from the sample, squall lines are the major source of rainfall. That is, the *heavier rains in the St. Louis area during June, July, and August were produced mostly by squall systems during 1971-1972.* At the same time, removing the lighter rain events resulted in an increase of the percentage of squall events which meet the "effect" criterion, thus indicating that the effect squalls produce more rain than no-effect squalls. Similar comments apply to some of the other synoptic categories, but the samples are too small in the higher rain intensity classes for these categories to promote confidence in the interpretation.

Mixing Depth Analyses

An examination of one year's data (Beebe and Morgan, 1972) suggested that the mixing depth, a quantity found useful in air pollution forecasting, was related to the occurrence of urban-effect rains at St. Louis. With two years of data now available, this relationship appears valid.

> The mixing depth was determined from the mid-day sounding taken at Gateway Arch, except on weekends when it was estimated from the surrounding soundings and surface data. The entire sample could not be utilized in studying the effect of the mixing depths. It was required that the precipitation episode begin after 1130 CDT, the time of the Arch sounding, to insure that the sounding was not affected by the precipitation itself. The mixing depth calculation was considered representative until the time subsequent to the sounding at which the surface temperature had fallen 8 F below the maximum temperature recorded by the Arch hygrothermograph. Precipitation events beginning after this time were not taken into consideration. This was to eliminate those events which occurred after the nocturnal inversion had developed to a depth of more than 150 meters above ground

level, at which point the city and industrial heat and pollution sources would be definitely cut off from the free atmosphere. [This cutoff at 8 F was arbitrary because of the lack of precise guidance from previous studies; data collected at St. Louis that are now being prepared for study will later allow a better understanding of this point.] Another precaution taken to eliminate rain interference was to consider only the first rain event subsequent to the time of the sounding in cases of two or more events per day. Table C-6 gives the results for the 2-year sample.

Table C-6. Distribution by Mixing Depth of Effect and No-Effect Rain Events

			Mixing depth *(meters)*				
	O-SOO	**6-1200**	**12-1800**	**18-2400**	**24-3000**	**> 3000**	**Total**
Effect	1	3	2	6	8	6	26
No-effect	3	4	8	3	4	4	26
Total	4	7	10	9	12	10	52
% Effect	25	43	20	67	67	60	50

The bottom row of the table shows the percent of rains in each mixing depth category which have been classed as effect rains. Mixing depths greater than 1800 meters seem to favor the downwind enhancement of precipitation. This and the relationship between effect rains and the more intense squall systems tend to relate the urban effect to cases with strong instability and free mixing from the lowest air layers to cloud base.

Reference

Beebe, R. C, and G. M. Morgan, Jr. 1972. *Synoptic analysis of summer rainfall periods exhibiting urban effects.* Preprints, Conference on Urban Environment, Philadelphia; AMS, Boston, pp. 173-176.

D. METROMEX THUNDERSTORM STUDIES FOR 1971-1972

Stanley A. Changnon, Jr.

Introduction

One of the primary goals of Metromex was to measure the thunderstorm frequency in the St. Louis area so as to learn whether it was altered by urban-industrial factors, and, if so, under what synoptic weather conditions these alterations were produced. Such a goal necessitated several point measurements of thunderstorm occurrences within the study area of 52-mile diameter centered on St. Louis.

This section of the report deals with space and time information on the occurrence of thunderstorms, as measured at 7 sites in the area during the June-August periods of 1971 and 1972. Some of the basic data are presented including the dates of thunder at each site. The frequencies of thunderstorms in the network, classified by geographic position, are presented for individual days, months, and season. Results on the time and duration of thunderstorm activity are presented along with information on the synoptic weather types associated with the thunder occurrences.

Instruments and Data

Historical data (Huff and Changnon, 1972) from a few observational locales in the St. Louis area had shown the existence of a summer season (June-August) increase in and downwind of St. Louis of 3 to 4 thunder days per year, on the average. These data sites were not spatially sufficient to cover the circular study area of Metromex. Since the audibility of thunder is normally 5 miles, several independent observation stations were needed with spacing of 10 miles or more apart.

Regular 24-hour observations of thunderstorm occurrences were available from Lambert Field (a National Weather Service first-order station), Scott Air Force Base (Air Weather Service Base), and Waterloo, Illinois (a NWS cooperative weather observer). After the field program operational base was established at Pere Marquette State Park (PMQ), 30 miles northwest of St. Louis, 24-hour weather observations were maintained at that site during June-August of 1971 and 1972. Thus, 4 sites with quality observer data were available. These are shown on figure D-l along with their 5-mile-radius circles of audibility.

However, other measurements were needed to fill area gaps and to give measurements along a WSW-ENE line (preferred storm motion) and in the upwind, city, and downwind areas. Therefore, instruments to automatically record thunder were designed and built for these 3 general locales. The facility at each site consisted of 1) a lightning detector (and chart recorder) used to initiate system operation (set at a level to begin before thunder was audible), 2) a rectangular array of 4 microphones, and 3) a multi-channel tape recorder (and associated electronics) which recorded, at high data rate speeds, the time and sound of thunder as received on each microphone. This type of installation furnished analog records of lightning activity and tapes on which thunder was recorded. The multi-recordings of thunder from the microphone array when plotted against time allowed determination of the direction from which the thunder arrived.

These remote instruments were labeled "thunder detectors," and were designed and built largely as a graduate student project. They were completed, installed, and operational by 12 July 1971. Their installation sites are shown in figure D-l. Many of the thunder detector results reported herein are based solely on the lightning and thunder (yes or no) occurrence data obtained in July-August 1971 and in June-August 1972. Difficulties in the multi-microphone operations and in the ensuing directional analysis have limited study of these data to a few days of 1972 for which exhaustive analyses of interesting rain situations are in progress.

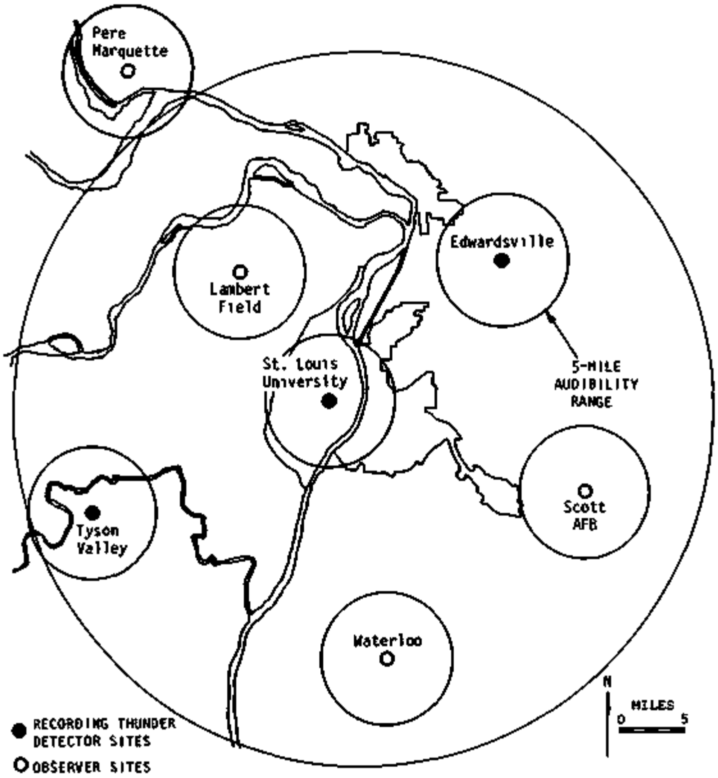


Figure D-l. Thunder observation sites **in 1971-1972**

Thus, the data available for study and presentation in this report are those from 7 sites, with 4 sites being manned by observers and 3 sites consisting of automatic lightning and thunder detectors. These data allow spatial and temporal definition of the frequency of thunderstorms.

Spatial Results on Thunderstorm Occurrences

The dates of thunder at the 7 locations and for the network in 1971 and 1972 are listed in tables D-l and D-2, respectively. These are the basic thunder data used in much of the analysis. All that is accurately known about thunder at the 4 observer sites is yes or no per calendar day, although hourly observations indicate those hours when thunder was heard. The thunder data from the detector sites are more detailed indicating accurately the times and frequency of lightning and thunder. These detector data were used to define "thunder periods" (see Glossary).

The number of thunder periods for the two seasons, counted after the thunder detectors started operation on 12 July 1971, are shown in table D-3. The number of periods at St. Louis University (SLU) and at Tyson Valley (TYV) were almost identical, but Edwardsville (EDW), located 10 miles 'downstorm' from the St. Louis area, had 50% more thunder periods.

Table D-l. Dates of Thunder in Summer 1971*

Site	June		July	August
Pere Marquette	2,7,10,12,13,14,15,29	4,10	13,14,18,23,28	11,14,21,25
Lambert	2,7,10,11,12,15,20,21,22,23,29	4,10	13,14,18,23,28	10,11,14,15
Scott AFB	2,7,8,10,11,12,13,14,15,18,29,30	4,10	13,14,15,18,19,28	9,14,21,25
Waterloo	10,11,12,13,19,29,30	10	13,14,23	14,21,25
Tyson Valley			14,15,18,19,28	5,8,14,21
St. Louis U.			13,14,15,18,19	9,10,11,14,21,23
Edwardsville			13,14,15,18,19,23,28	4,11,14,21,25

Days with thunder in network

	Total number
June 2,7,8,10,11,12,13,14,15,18,19,20,21,22,23,29, and 30	17
July 4,10,13,14,15,18,19,23, and 28	9
August 4,5,8,9,10,11,14,15,21,23, and 25	11
Total	37

*** Dates based on midnight-to-midnight definition**

Table D-2. Dates of Thunder in Summer 1972

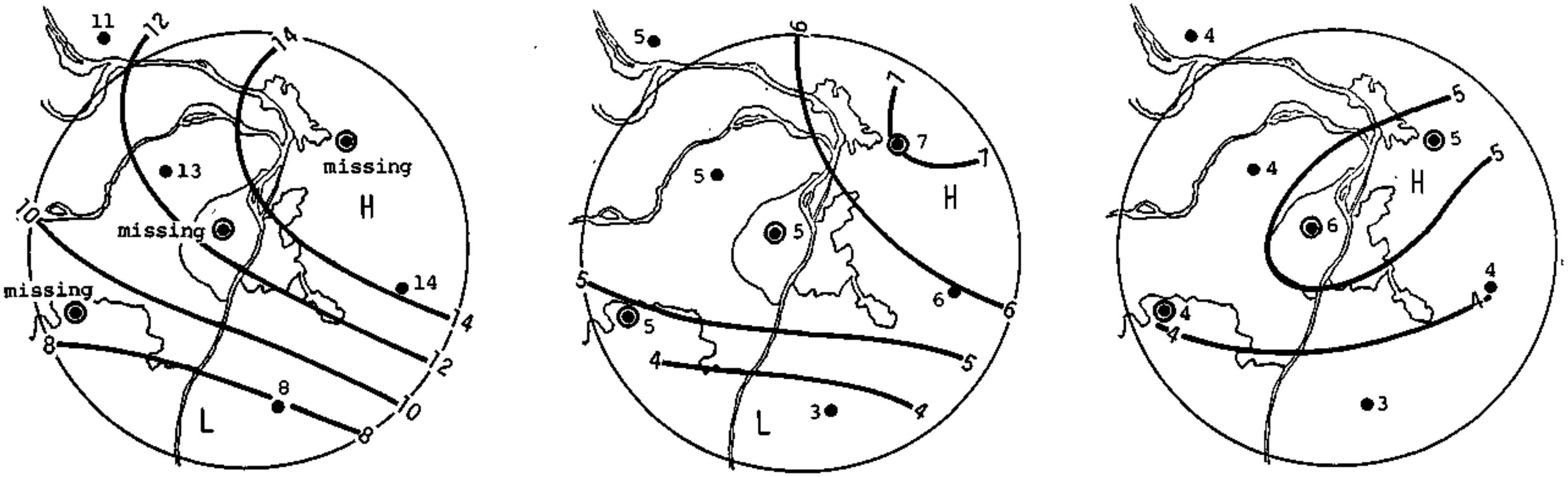
Site	June	July	August
Pere Marquette	9,13,14,19,24	2,15,18,26	2,3,6,11,12,14,25
Lambert Field	4,9,14,19,24,28	2,15,18,26	2,3,11,12,19,21
Scott AFB	9,10,14,19	1,9,10,15,17,26	2,3,11,19,20,21,22,23
Waterloo	5,19,27	1,10,15,18,19,26,27	2,3,12,19,22
Tyson Valley	9,14,19,27,28	1,10,26,27	2,3,12,14,22
St. Louis U.	9,10,14,19,27,28	1,2,9,10,26	2,3,6,11,21
Edwardsville	9,14,19,24,25,27,28,29	1,2,9,10,26	2,3,6,11,12,19,20,22,23

Days with thunder in the network

	Total number
June 4,5,9,10,13,14,19,24,25,27,28, and 29	12
July 1,2,9,10,15,17,18,19,26, and 27	10
August 2,3,6,11,12,14,19,20,21,22,23, and 25	12
Total	34

The number of thunder days per month at the detectors and at the observer stations are also shown in table D-3. The two largest totals are at the two downstorm locales, Edwardsville (EDW) and Scott Field (SAFB). Figure D-2 portrays the patterns of thunder days for the 6 summer months. July 1971 is 'split' to separate the periods with and without detector data. In 4 of the 6 months, the highest values came at 1 of the 2 possible downstorm locations (SAFB and EDW), and in the other cases it occurred at Waterloo and St. Louis, and not at the 3 locations west of St. Louis. An unmistakable city and downwind increase in thunder appears to have occurred in every month sampled, and this is reflected in the 1971 and 1972 seasonal maps of figure D-3. The total thunder-day map (figure D-3) reveals the distinct downstorm maximum at EDW, and leaves little doubt that there was a localized effect on thunderstorm frequencies, increasing it by 3 to 4 days per summer. This agrees closely with the earlier climatic results.

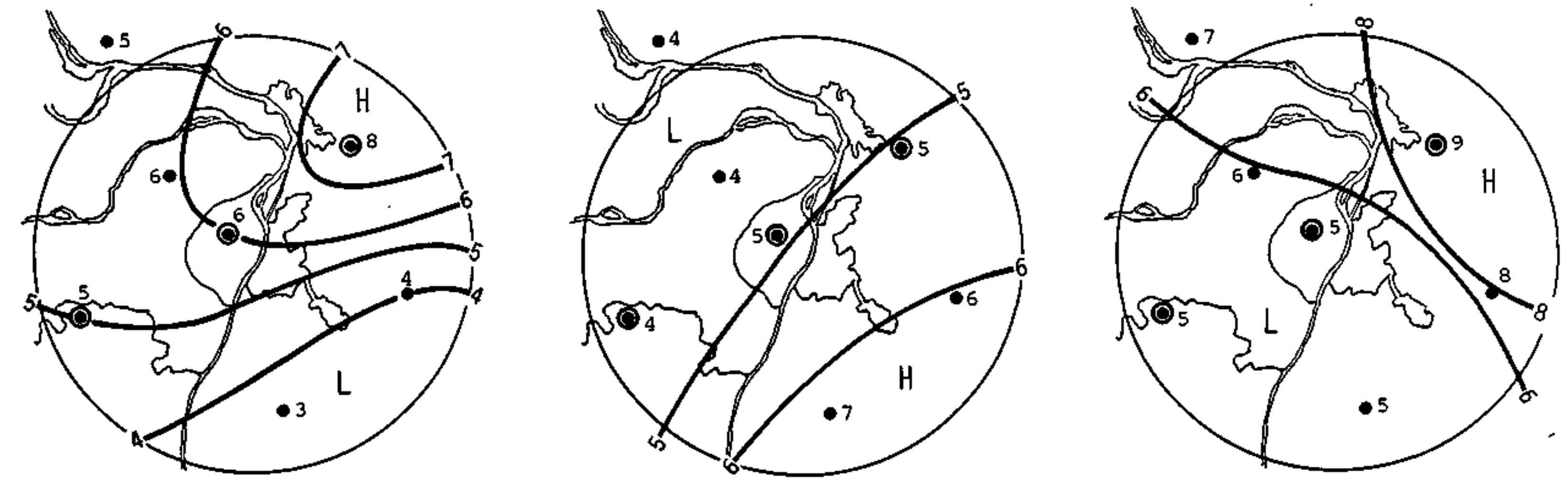
Times of thunder occurrences from the 4 thunder observer sites were sufficiently accurate to allow their identification by various periods of the day (nearest 1 hour), and the detector data gave exact temporal information. The thunder occurrences at each point could be and were classified as to



JUNE - 11 JULY 1971

12 - 31 JULY 1971

AUGUST 1971



JUNE 1972

JULY 1972

AUGUST 1972

Figure D-2. Monthly isoceraunic patterns, 1971-1972 their occurrence with each of the synoptically defined rain-producing entities (rain period; see Glossary) that passed through or developed within the network. There were 61 rain periods in 1971 (41 had thunderstorms) and 72 rain periods in 1972 (38 had thunderstorms).

Table D-3. Frequency of Thunder Days and Periods in 1971-1972

	1971		1972			
	12-31 July	Aug	June	July	Aug	Total
			Thunder days			
Pere Marquette	5	4	5	4	7	25
Lambert	5	4	6	4	6	25
Scott AFB	6	4	4	6	8	28
Waterloo	3	3	3	7	5	21
Tyson Valley	5	4	5	4	5	23
St. Louis U.	5	6	6	5	5	27
Edwardsville	7	5	8	5	**9**	**34**
			Thunder periods			
Tyson Valley	6	4	6	5	6	27
St. Louis U.	5	5	5	7	7	29
Edwardsville	10	8	8	7	11	44

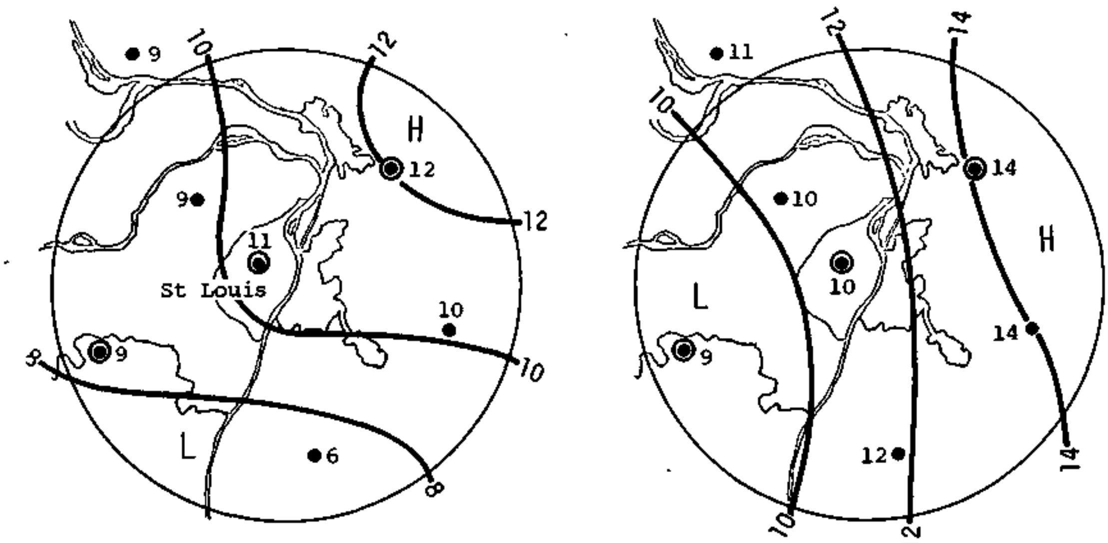
The regional distribution of thunderstorms for each period was classified as being "east only" (occurrences only at EDW and/or SAFB), "west only" (occurrences only at PMQ and/or TYV), "widely scattered" (at 2 or more locales and not the two previous definitions), or "widespread" (at all 7 sites). The resulting frequencies for the summers of 1971 and 1972 appear in table D-4. Differences in the east-only and west-only frequencies allow a crude estimation of the magnitude of the urban effects on thunderstorm frequencies per storm system. The 2-year, west-only frequency (11 periods) is considered indicative of the likelihood of isolated regional activity due to natural causes. The difference between east-only and west-only, or 9 rain periods with thunderstorms, suggests that the urban-industrial effects led to the development of thunderstorms in 9 rain systems in a 2-year period.

Table D-4. Rain Periods with Thunder, Classified as to Placement of Thunder in the Network

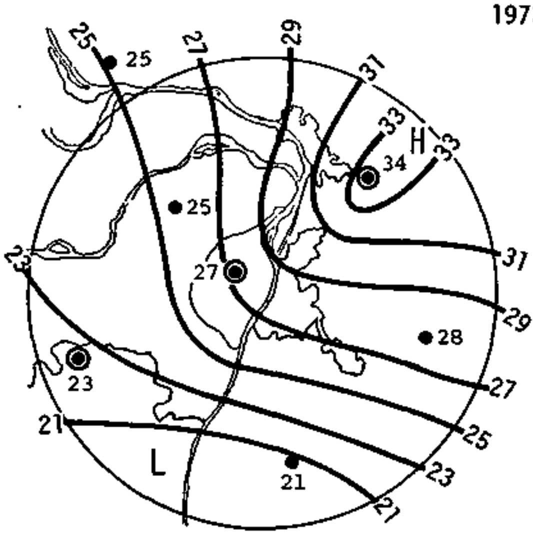
	Number for each type of thunder pattern within the network				
	Widespread	Widely scattered	West only	East only	Total
1971	8	17	6	10	41
1972	5	18	5	10	38
Total	13	35	11	20	79

Temporal Results on Thunderstorm Occurrences

Only the thunder detector data were used in the detailed temporal analyses of thunder. These analyses included investigations into the diurnal frequency distributions and the durations of thunder periods.



1971 1972



JULY-AUGUST 1971 & JUNE-AUGUST 1972 TOTAL

Figure D-3. Isoceraunic (thunder-day) patterns for 1971-1972

During the 2-year data period (12 July-31 August 1971 and 1 June-31 August 1972) thunder occurrences during 5 minutes or more in each clock hour were counted at each site. Tyson Valley (TYV) had 105 clock hours with thunder, St. Louis University (SLU) had 106, and Edwardsville (EDW) had 173 hours.

The number of hours with thunder in each 3-hour period (0000-0300 CDT, 0301-0600, etc.) were summed and used to construct figure D-4. There is little difference between the diurnal distributions at TYV and SLU, and the EDW frequencies for the period 1500 to 0300 CDT are much like those of SLU and TYV. The increase in thunder frequency at the downwind site, EDW, exists from 0300 to 1500 CDT with a maximum difference from 0600 to 1200 CDT. This closely supports earlier climatic findings (Changnon, 1969) which showed urban effects on thunderstorm frequencies were most pronounced in the late nocturnal, morning, and early afternoon hours.

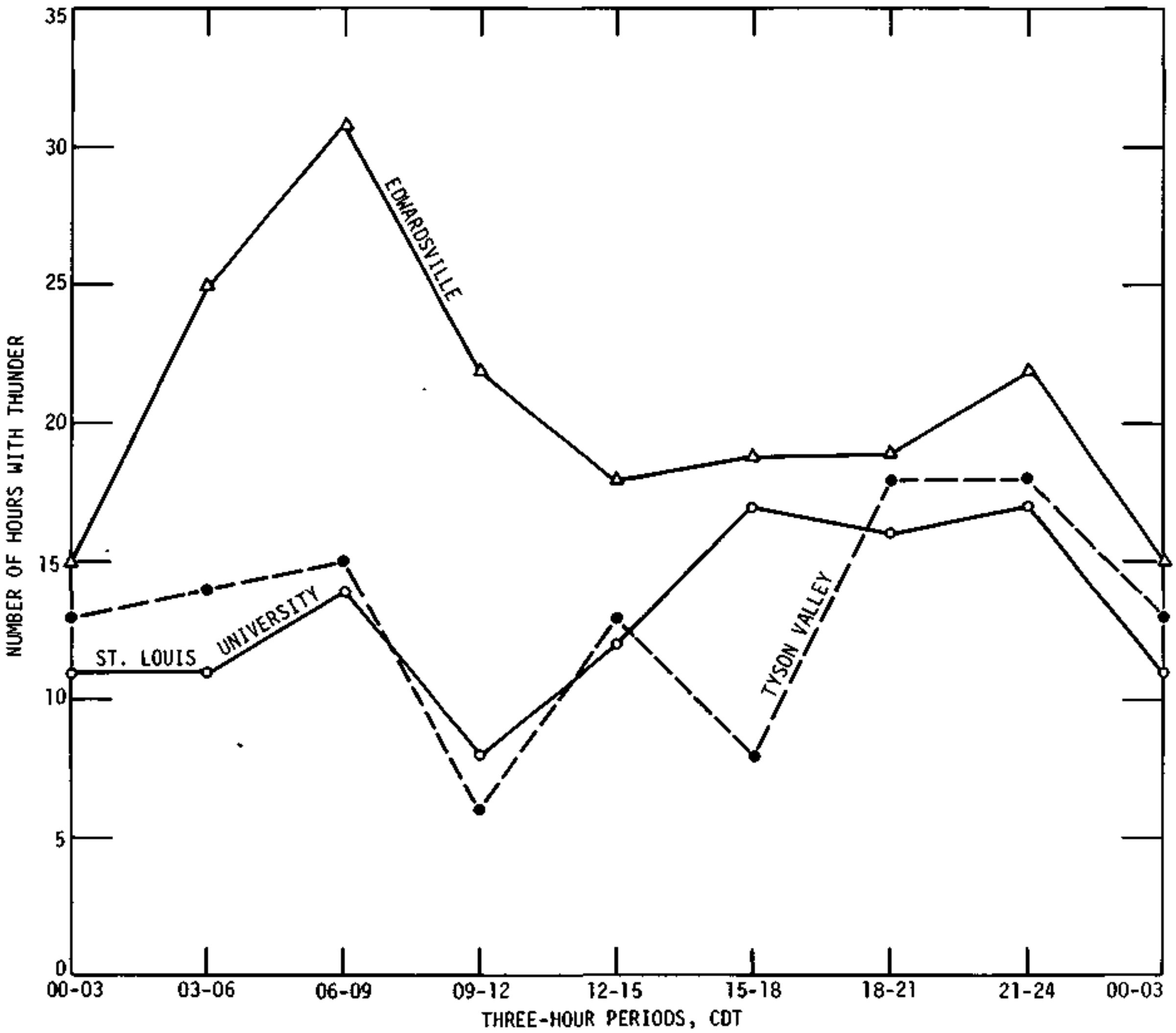


Figure D-4. Diurnal distributions of thunder (hourly occurrences) by 3-hour periods at thunder detector sites, July-August 1971 and June-August 1972

Distinct periods of thunder at each site also were defined, as mentioned earlier, and the numbers of these thunder periods at each detector have been shown in table D-3. Many more thunder periods occurred at EDW than elsewhere. The average and median duration values for the thunder periods at each site are shown in table D-5. The medians are the more 'stable' values for comparison. The medians show a tendency for the thunder to persist longer (5 to 10 minutes) at the downwind site than over the city (SLU) or upwind (TYV) of it. Thus, the many more clock hours with thunder (figure D-4) downwind of St. Louis (EDW) are a function of both longer thunder durations and more thunder periods, but are mostly due to the greater frequency of thunder periods.

The thunder period durations were ranked and plotted on probability paper (figure D-5) to examine further for differences. The values for TYV and SLU both fit a straight line, but they differed in that SLU had greater extremes (somewhat more likely to have shorter and longer durations) than TYV. The 44 values from EDW did not fit a straight line distribution on the log-probability graph. EDW distributions departed from the 50% probability (median) with a slope like (but greater than) that of the other stations for the longer durations. However, EDW also had more short durations, resulting in a different slope below the median. Thus, 2% of the time, a thunder period duration at EDW will be 10 minutes or less, compared with 20 and 29 minutes at SLU and TYV, respectively.

Table D-S. Average **and Median Durations of Thunder Periods at Thunder Detectors, 1971-1972**

	TYV	SLU	EDW
Number of thunder periods	27	29	44
Average, minutes	137	176	184
Median, minutes	131	125	136

The analysis of the 1971-1972 temporal information on thunderstorms, based on the quality detector data, reveals several distinct differences at the downwind (EDW) site. It had much more total time with thunder and this was related largely to many more (50%) thunder periods there and, to a lesser extent, to slightly longer thunder periods. However, the periods of thunder at EDW also achieved greater extremes of duration more often than those at the other sites.

Synoptic Weather Conditions with Thunderstorm Activity

An integral part of the severe storm studies involved the analysis of synoptic weather conditions at the time of thunderstorm activity in the network. Such analysis helps demonstrate the condition(s) during which urban-related enhancement of thunderstorms occurs. The synoptic analysis for thunderstorms was performed on the basis of their occurrence with the discrete summer rain periods, each with its distinguishable synoptic weather classification. Four basic summer weather classes have occurred with thunderstorms at St. Louis. These are air mass, squall line, frontal, and pre-frontal (see Glossary).

The results of these analyses appear in table D-6. Comparison of the 1971 and 1972 values for the widespread or scattered class does not show great differences between years, indicating collection of a reasonably good sample for this class. However, the west-only and east-only values are less frequent and differ greatly between the two years, showing the need for more data.

Table D-6. Areal Distribution of Thunderstorms during Network Rain Periods in 1971-1972 Sorted by Synoptic Weather

Synoptic class	Widespread or scattered			West only			East only			Totals		
	1971	1972	71-72	1971	1972	71-72	1971	1972	71-72	1971	1972	71-72
Frontal zone	7	6	13	1	1	2	6	1	7	14	8	22
Pre-frontal zone	2	3	5	1	0	1	0	0	0	3	3	6
Squall	13	9	22	3	1	4	0	2	2	16	12	28
Air mass	3	5	8	1	3	4	4	7	11	8	15	23
Totals	25	23	48	6	5	11	10	10	20	41	38	79

Comparison of 2-year totals for the west-only class, presumed to represent the natural distribution, with the 2-year east-only values, which should reflect urban effects, indicates: 1) the east-side increase is notable during air mass conditions (11 to 4) and in frontal zone conditions (7 to 2), and 2) there may be a thunderstorm decrease on the east side in squall situations (2 to 4). Nearly 50% (11 of 23) of all air mass thunderstorm periods were cases with thunderstorms *only on the east* (EDW and/or SAFB), whereas 30% of the frontal zone cases (7 of 22) were east-only cases.

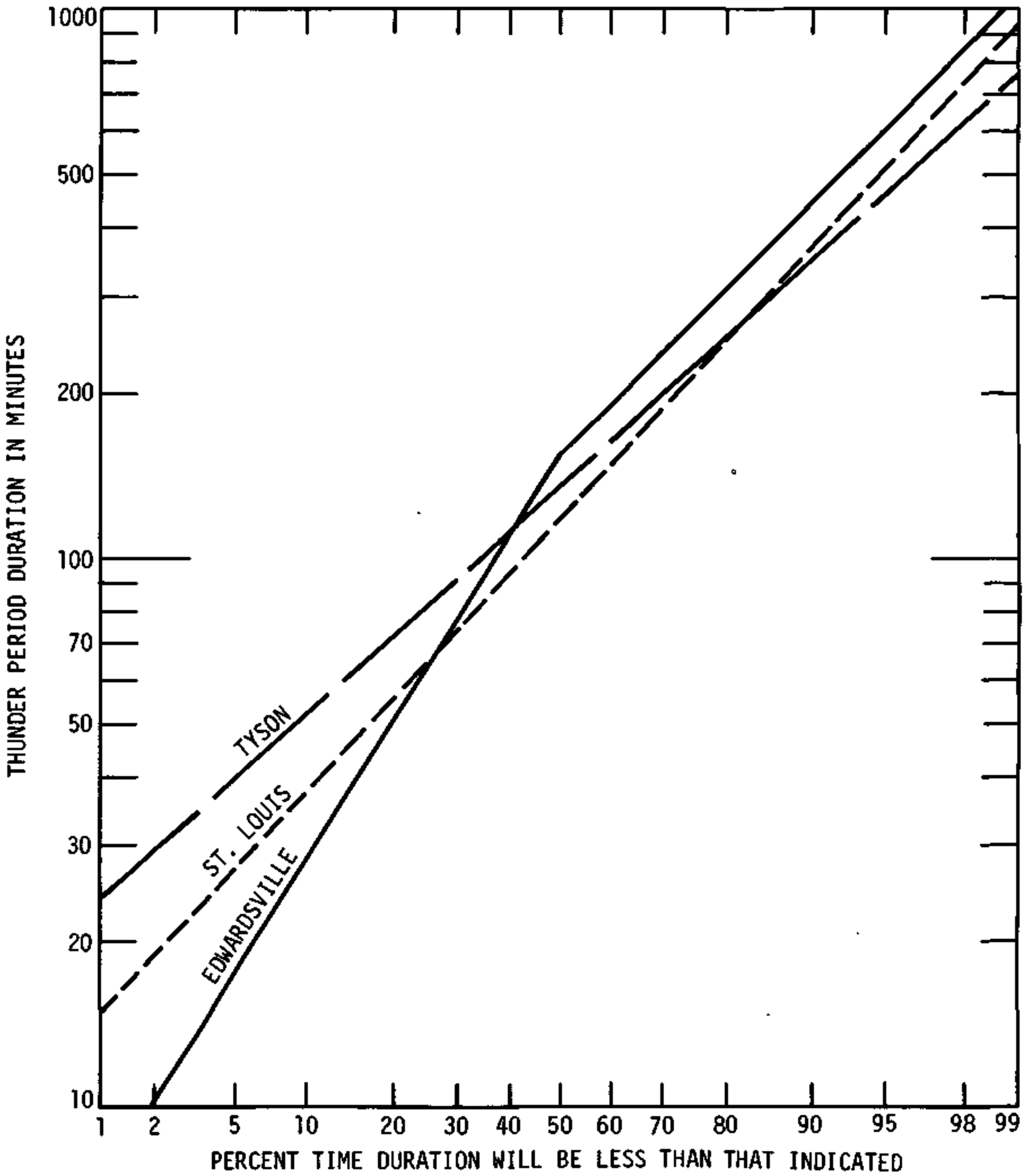


Figure D-5. Probabilities for durations of thunder periods at thunder detector sites

Conclusions

The 1971-1972 studies of thunderstorms in the St. Louis area have shown a downcity increase in the number of thunderstorm days, number of discrete thunder periods, and durations of thunder periods. The downcity summer increases were:

Number of thunderstorm days — 3 to 4 (+30%)
Discrete thunder with rain periods — 4 to 5 (+13%)
Individual thunder periods — 8 to 9 (+50%)
Duration of thunder periods — 5 to 10 min (+7%)

The increase in thunder occurrences occurred primarily between 0300 and 1500 CDT with a maximum increase between 0600 and 1200. The synoptic weather studies indicated that thunder initiation related to the city occurs most often in air mass (non-frontal) conditions, and is also quite prevalent in frontal zone (±50 miles of a front) conditions.

Many of the 1971-1972 results agreed closely with those determined from earlier climatic studies that used scantier data. The amount of west to east increase in thunder days and the morning maxima were re-affirmed in the 1971-1972 results. These results also revealed a need for additional data in the future. Included in this is a need to obtain viable thunder data for 3 or 4 locales farther downwind of the study area.

References

Changnon, S. A. 1969. *Urban-produced thunderstorms at St. Louis and Chicago.* Preprints, 5th Severe Local Storms Conference, Chicago; AMS, Boston, pp. 95-99.

Huff, F. A., and S. A. Changnon. 1972. *Climatological assessment of urban effects on precipitation at St. Louis.* Journal of Applied Meteorology, 11:823-842.

E. METROMEX HAIL STUDIES FOR 1971-1972

Stanley A. Changnon, Jr.

Introduction

Another major goal of the Survey's Metromex effort was to measure and study hail in the circular study area around St. Louis so as to determine whether its characteristics and frequency were altered by urban-industrial factors, and if altered, under what types of atmospheric conditions the alterations occurred. Areal-temporal delineation of hail in a 2200-square-mile area necessitates a large number of hail sensors since hail is such a small-scale phenomenon (Changnon, 1970).

This portion of the 2-year summary report concerns the space-time information derived for hail, as measured at 222 sites in the circular network during the summers (June-August) of 1971 and 1972. Some of the rather basic data are presented, including the dates, times, and locations of each hailfall. The spatial distribution of hail is presented on the basis of point and hailstreak frequencies according to rain periods, days, and total season. Characteristics of hailstreaks from "urban-effect" and "no-effect" raincells are compared to evaluate differences in their hailfalls (number of stones, point durations, etc.) and in their diurnal distributions. Finally, synoptic weather conditions associated with the hail-producing rain periods are examined to determine those conditions when apparent urban-related hail increases existed.

Instruments and Data

Hail data were obtained primarily from 222 hailpads, with one at each recording raingage site in the network. Each hailpad is a 1-ft^2 polystyrene pad wrapped in aluminum foil and held horizontally in a metal frame (Changnon, 1969). The number and sizes of hailstones can be determined per hailfall and the energy imparted is calculated. Time of hail (and duration) at each site is obtained from the adjacent recording raingage, so modified that the hail falls into the bucket causing a "spike" on the chart for each stone (Changnon, 1966). Added hail information is obtained from observers and field personnel. Hailpads were changed by field personnel within 24 hours after each storm to minimize conflicts arising from repeated hailfalls at a point. Much of the hail analysis was based on these point data.

To study hailstorms, each hailfall per day was plotted on a rain period base map. By temporal analyses, involving radar and rainfall data, "hailstreaks" were determined as defined in the Glossary (Changnon, 1970). For each hailstreak, its area and duration were determined along with average point values of number of hailstones (by sizes), duration, and energy, and the associated rain entity. To be classed in the "urban-effect" category, a hailstreak had to be produced by a raincell after the cell either developed or passed over the St. Louis or Alton-Wood River urban-industrial areas.

The basic hail data from the 1971-1972 period are summarized in table E-l. There were 26 days with hail, 10 in 1971 and 16 in 1972. These dates also are network "rain periods." The synoptic weather conditions with each of these 26 events are also shown in table E-l. The 4 types (pre-frontal, frontal zone, squall, and air mass) are defined in the Glossary.

The times of the hail periods in the network are shown, along with maximum hailstone size per period, and the number of points with hail separated according to whether they fell in the western half or eastern half of the network. The table also lists for each date or storm period the number of hailstreaks in the urban-effect raincells and those in no-effect raincells. Average daily point energy (ft-lb/ft^2) values based on values in the "effect" and "no-effect" hailstreaks are shown.

Table E-1. Summary of Hail Data

Storm date	Network period of hail time(CDT) Begin	Network period of hail time(CDT) End	Synoptic weather type*	Largest hailstone diameter *(inch)*	Number of points with hail West only	Number of points with hail East only	Hailstreaks classed by urban effect** E	Hailstreaks classed by urban effect** NE	Average point energy (ft-lb/ft^2) E	Average point energy (ft-lb/ft^2) NE
1971										
6/2	1417	1427	SQ	1.0	0	2	1	0	0.2456	0
6/11	1550	2259	SQ	0.8	5	15	13	4	0.3601	0.0643
6/14	1446	1510	FZ	0.9	0	2	2	0	1.8312	0
6/15	1415	1419	PF	0.4	0	1	0	1	0	0.0041
7/4	2035	2045	SQ	0.5	0	2	1	0	0.0135	0
7/14	0152	0935	SQ	1.0	9	2	3	6	0.1542	0.0657
7/18	0803	0922	SQ	0.5	0	2	2	0	0.0047	0
7/23	1443	2036	PF	0.5	4	1	3	2	0.0006	0.0018
8/21	1214	1226	AM	0.3	0	3	0	1	0	0.0005
8/23	1647	1658	AM	0.5	0	1	1	0	0.0042	0
1971 Totals					18	31	26	14		
1972										
6/9	2015	2215	FZ	2.3	9	0	0	6	0	0.0152
6/14	1910	1935	FZ	0.7	0	4	3	0	0.0791	0
6/19	2055	2352	SQ	0.8	1	17	10	1	0.0574	0.0161
6/27	2228	2306	PF	1.7	2	0	0	3	0	5.0607
6/28	0340	0735	FZ	0.4	1		0	2	0	0.0030
7/17	0415	0520	FZ	0.5	0		2	1	0.0075	0.0075
7/26	1627	1816	PF	0.7	4		2	4	0.2459	0.1181
8/2-3	2320	0044	SQ	1.0	7		3	4	0.5227	0.0130
8/3	1359	1805	FZ	1.0	0	11	8	2	0.6109	0.0089
8/6	2032	2123	AM	0.8	0	4	2	0	0.0336	0
8/11	1520	1845	SQ	1.0	2		2	4	1.7443	0.0339
8/12	1022	1126	AM	1.0	0		2	3	0.4449	0.4014
8/19	1505	1728	AM	1.5	1	11	2	5	1.3477	0.2501
8/20	1410	1416	SQ	0.5	0		1	0	0.1555	0
8/21	1645	1803	SQ	1.8	5	11	9	3	0.7597	0.8365
8/23	1250	1256	FZ	0.2	0		1	0	0.0006	0
1972 Totals					32	75	47	38		
2-Year Totals					50	106	73	52		

*** SQ = squall, FZ = frontal zone, PF = pre-frontal, and AM = air mass**

**** E = 'Effect' hailstreaks; NE = 'No-Effect' hailstreaks**

Thus, for a given day such as 19 June 1972, we see that hail fell in the network between 2055 and 2352 CDT, producing hailstones as large as 0.8-inch in diameter. This hail was with a squall situation and hail fell at 18 locations, with 17 of these in the eastern half of the network. There were 11 hailstreaks defined, with 10 in rain cells classed as potential effect. The average point energy in the effect hailstreaks was 0.0574 ft-lb/ft^2, compared with 0.0161 ft-lb/ft^2 in the no-effect hailstreak.

Spatial Distribution of Hail

Examination of table E-1 shows that on 9 of the 26 hail days, hail fell only from potential urban-effect cells, generally in or downstorm (east) of the city. The 5 days when hail fell only from no-effect cells can be considered as the background frequency due to natural causes. The difference between these two categories (9-5) indicates a 4-day or 80% increase in hail days due to urban effects.

On the other 12 days, hail fell from both effect and no-effect cells. Comparison of these "both-type" days also suggests hail enhancement related to urban factors. The number of no-effect streaks on these 12 days exceeded the effect streaks on 6 days (50%), so that no difference is indicated. However, on these both-type days, there were 59 effect hailstreaks (an average of 5 per period), compared with only 39 no-effect streaks (an average of 3). This suggests a 67% enhancement of hail entities in effect cells during conditions when hail production was widespread and partly due to natural atmospheric causes.

The frequency of hailstreaks on days with effect only or no-effect only hailstreaks was much lower. The average number of no-effect hailstreaks was 2.5 and the average of effect streaks was 1.6. Basically, these results suggest that hail-producing conditions on the both-type days were more favorable than those on the single type (effect or no-effect) days.

The number of hailfalls at each of the 222 points during 1971-1972 was plotted, and an isofrequency pattern developed (figure E-l). This shows 3 distinct highs: one downwind of the two urban-industrial areas (the major hail high), one just SE of St. Louis, and one in the 2-river floodplain NW of St-Louis. Large areas west of St. Louis had no hail. The long-term point average for St. Louis is 0.4 days per summer (2 in 5 years). This 2-year pattern definitely suggests localized urban enhancement of hailfalls and possible localized orographic-moisture related enhancement. The urban effect is supported further by the number of west and east point values in table E-l, which shows 50 hailfalls in the western half of the area and 106 in the eastern half. The 2-year frequency pattern is also markedly similar to the crop-hail insurance loss pattern for the 1948-1967 period (Changnon, 1972) which has its maximum losses where the 5-day value appears on figure E-l.

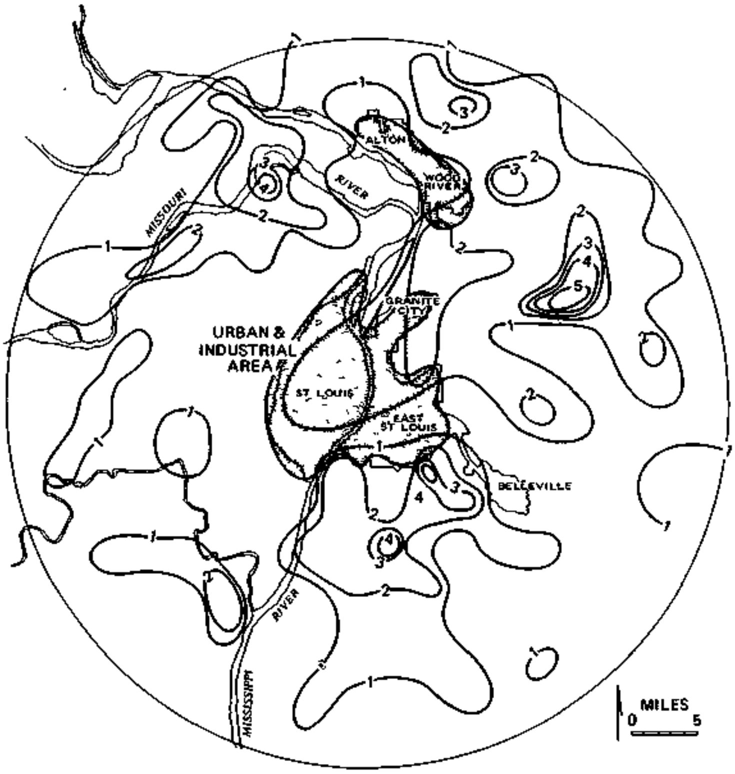


Figure E-l. Point frequencies of hail in 1971-1972

Hailstreak and Hailfall Characteristics

Further analysis of potential urban-related differences in hail at St. Louis concerned a comparison of urban-effect hailstreaks with those classed as unaffected.

As previously defined, the urban-effect hailstreak had to be produced from a raincell that developed or passed over the St. Louis or Alton-Wood River urban-industrial areas. This definition, coupled with the directions of raincell motions sampled in 1971-1972, revealed that all "effect" hailstreaks occurred downstorm (NE, E, or SE) of these two areas, and fell within less than 50% of the circular network. Furthermore, on any given hail day, raincell motions remained generally uniform (±20°), and the effect hailstreaks always occurred in less than 30% of the study area, resulting in an areal sampling bias in favor of no-effect raincells and their hailstreaks. Even with this 3:1 areal sampling bias, the number of effect hailstreaks exceeded the no-effect number, 73 to 52 (40% more), as shown in table E-2.

Table E-2. Comparison of Effect and No-Effect Hailstreaks and Hailfalls, Summers 1971-1972

	Effect	No-effect	Ratio, E/NE
Number of hailstreaks	73	52	1.4
Average hailstreak duration, minutes	15.1	12.7	1.2
Average hailstreak area, mi^2	6.6	5.7	1.2
Median hail energy, $ft\text{-}lb/ft^2$	0.0551	0.0091	.6.1
Average point number of hailstones by sizes (diameters)			
≤ 1/8 inch	43	30	1.4
1/4-1/2 inch	12	4	3.0
1/2-3/4 inch	6	3	2.0
≥ 3/4 inch	1	0.5	2.0
Total	62	37.5	1.7
Average point rainfall (inch) with hail	0.70	0.63	1.1
Average point hailfall duration, minutes	3.6	3.6	1.0

The average duration of urban-effect hailstreaks was 15.1 minutes, 20% greater than that of the no-effect hailstreaks, and the area size difference was comparable, 0.8 mi^2 or 20% larger. The typical hailstreak size in rural central Illinois is 6.9 mi^2 (Changnon and Towery, 1972). The single greatest difference between effect and no-effect hailstreaks was in their energy (stone size and ice volume plus wind) values, with the median energy of effect hailstreaks being six times greater than that of no-effect streaks. This sizeable difference is reflected in the average point frequencies of the hailstones. However, the average point hailfall durations were identical, 3.6 minutes, and the average point rainfall amounts occurring with the hailfalls were similar.

In summary, the values in table E-2 show that urban-industrial effects probably led to the production of 40% more hail entities in storms than could be expected to occur naturally, and the potential urban-effect hail volumes are greater (last longer and are bigger), yield many more hailstones and thus greater impact energy (damage potential), and are accompanied by more rainfall. They do move at the same speeds (equal point durations).

Temporal Distributions

The times of occurrence of the 73 urban-effect hailstreaks and the 52 no-effect hailstreaks were sorted and counted according to clock hours. Their hourly frequencies were summed by

3-hour periods to compare their diurnal distributions (figure E-2). Both achieved maximums in the 1500-1800 CDT period with secondary maximums in the 2100-2400 CDT period. In all 3-hour periods except these two, the frequencies of the two classes did not differ markedly. However, during the two peak 3-hour periods, there were notably more occurrences of hailstreaks of the potential urban-effect class. For instance, in the 1500-1800 CDT period, the urban-effect streaks resulted in 28 hourly occurrences, compared with only 12 hours with occurrences of no-effect streaks.

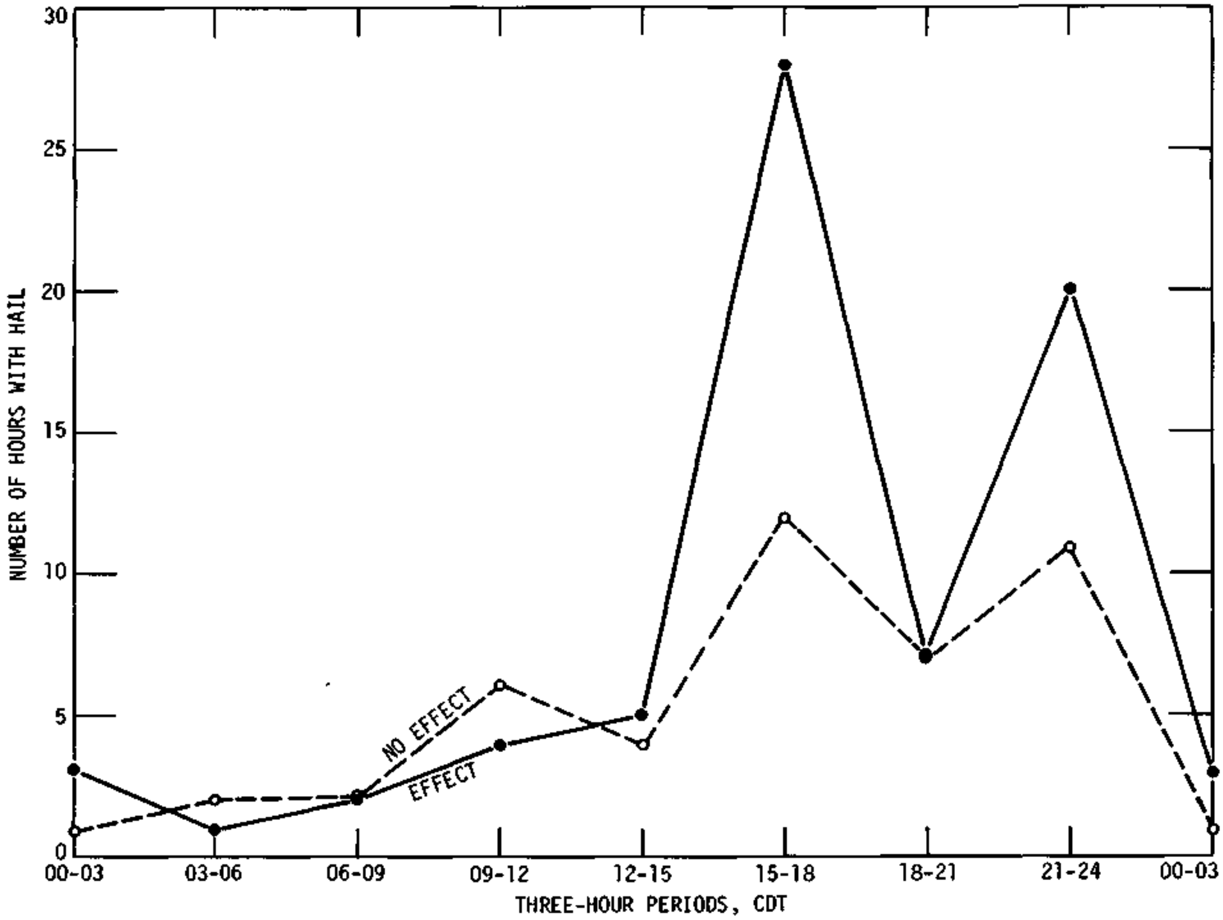


Figure E-2. Diurnal distribution of hours with hailstreaks, by 3-hour periods, 1971-1972

The periods of hail within the 26 rain periods with hail (table E-l) varied considerably, ranging from 4 minutes up to 7 hours and 9 minutes (11 June 1971). However, the hail period does not mean in all cases that hail was falling continuously, it just defines the time of first hail and the time of last hail. The average duration of these hail periods in the network was 2 hours but, as noted, the range of values was quite great.

Synoptic Weather Conditions with Hail

The type of synoptic weather existing during each rain-hail period is shown in table E-l. Four types were defined and the frequency of hail periods with each (table E-3) was 10 with squalls (lines and zones), 7 with frontal zones (cold and stationary), 5 with air mass conditions, and 4 with pre-frontal zone conditions. The number when large hailstones (≥ 1 inch) were produced, as shown in table E-3, was 10, and half of these came with squalls, but 1 or more occurred in all the 3 other weather types. These large stones fell from urban-effect rain cells in 8 cases.

Table E-3. Synoptic Weather Types and Hail Conditions

				Number of hail periods	
Weather type	Number of hail periods	Number when ≥ 3 hailstreaks occurred	Number of hail periods with stone diameters ≥ 1"	Hail only in urban-effect raincells	Hail only in no-effect cells
Squall	10	6	5	4	0
Frontal zone	7	4	2	3	2
Pre-frontal zone	4	3	1	0	2
Air mass	5	2	2	2	1
Totals	26	15	10	9	5

Fifteen hail periods occurred when hail was relatively widespread, as defined by 3 or more hailstreaks. As shown in table E-3, these periods occurred with all weather classes. Four of these 15 periods had large numbers of hailstreaks (≥ 10 per period), indicating considerable atmospheric instability. Three of these were with squall conditions and one with a frontal zone. Hail fell from both urban-effect and no-effect raincells, but in all 4 cases, the number of potential urban-effect hailstreaks exceeded the no-effect number (13 to 4 on 11 June 1971; 9 to 3 on 21 August 1972; 10 to 1 on 19 June 1972; and 8 to 2 on 3 August 1972). These results on widespread hail periods and on the placement and frequency of hailstreaks indicate urban effects in hail exist in quite unstable squall conditions and lead to 300% or greater increases in the number of hailstreaks and large hailstones downwind of St. Louis.

A comparison of the last two columns in table E-3 substantiates this conclusion. Listed are the numbers of hail periods when hail occurred only in urban-effect raincells and only in no-effect cells. The no-effect frequencies can be considered to represent the natural frequency without urban effects. The effect frequencies then allow some estimation of the synoptic weather types associated with urban effects on hail production. The most pronounced difference is in the frequency for squall conditions. Some possible increases are found also in frontal zones and air mass types, and a decrease is found in pre-frontal zones. However, the number of cases is small in all types, indicating the results must be considered quite tentative.

A comparison was made of mixing depths prior to the periods with hail only in effect cells and only in no-effect raincells. The average depth was 1900 meters on the effect days, compared with only 900 meters on the no-effect days. This suggests that there was a decided difference in the ability of surface heating and emissions to reach cloud base on effect cases of hail.

Summary

The study of hail days, hailfalls, and hailstreaks in 1971-1972 definitely indicated urban enhancement of the number of hail days, number (and area) of hailstreaks, and in the intensity of hail (stone sizes and energy). This occurred primarily in the maximum hail incidence periods, 1500 to 1800 CDT and 2100 to 2400 CDT when urban-effect hail was > 200% more than experienced in the natural distribution. Over the 2-year period, the downwind increases produced by the urban-effect storms were:

Number of hail incidences — 200%
Number of hail days — 80%
Number of hailstreaks — 20%
Number of large (≥ 1/2-inch diameter) hailstones — 250%
Impact energy of hail — 600%

The typical urban-related hailstreak was larger, longer-lived, produced (per unit area) more hailstones, greater impact energy, and was associated with heavier rainfall than were the hailstreaks which were not related to urban-effect raincells. The hail results for 1971-1972 were generally in good agreement with those found in previous climatic studies (Huff and Changnon, 1972). The 26 hail periods in 1971-1972 were associated with 4 types of summer weather. In general, urban enhancement of hail (either to produce hail only downwind of the city or to increase the number of hailstreaks and the intensity of hail in periods of widespread hail) occurred most often in squall conditions but also was apparent in frontal zone and air mass conditions.

References

Changnon, S. A. 1966. *Note on recording hail incidences.* Journal of Applied Meteorology, 5:899-901.

Changnon, S. A. 1969. *Hail measurement techniques for evaluating suppression projects.* Journal of Applied Meteorology, 8:596-603.

Changnon, S. A. 1970. *Hailstreaks.* Journal Atmospheric Science, 27:109-125.

Changnon, S. A. 1972. *Can weather modification usefully augment the water resources of the humid midwestern United States?* Proceedings of International Symposium on Water Resources Planning, Mexico City, pp. 1-32.

Changnon, S. A., and N. G. Towery. 1972. *Studies of hail data in 1970-1972.* Illinois State Water Survey for NSFGA-16917. Final report. 27 pp.

F. USE OF SURFACE RAINCELLS IN EVALUATING INADVERTENT RAIN MODIFICATION

Paul T. Schickedanz

Introduction

Although much information can be gleaned from studies of storm and hourly rainfall amounts, a more definitive measurement in time and space is necessary to pinpoint the precipitation characteristics that are being altered by the urban-industrial complex. These altered characteristics can be determined by isolating individual raincells and determining their history as to initiation, movement, maximization, duration, size, and total rain production. The chief advantage of this technique is that the isolation of raincells provides several cell parameters that are more directly related to the physical processes involved than is the integrated areal value in which the physical characteristics are often masked. The chief disadvantages are that the technique requires a considerable amount of data reduction and analysis and that the analysis can be subjective. However, for the Metromex program, definitions and procedures have been initiated which have reduced the amount of effort and subjectivity involved (Schickedanz, 1972, 1973).

In this report, the analysis of surface raincells is used 1) as a *descriptive tool* for demonstrating the magnitude, structure, and characteristics of the urban-industrial influence on rainfall, and 2) as an *investigative tool* for exposing and explaining causes of the altered precipitation characteristics.

Rationale for the Raincell Approach

Under favorable conditions, individual updraft areas within a thunderstorm develop into units of convective circulation. These units can be detected on a radar scope and are defined as regions of localization of convective activity within the thunderstorm (Byers and Braham, 1949). There may be more than one cell during a storm period, each of which may be independent or dependent of surrounding cells in the storm. During the period of the storm, each cell may be in different stages of development at any one time. The stages of development for a cell are 1) the cumulus stage characterized by updrafts in the cell, 2) the mature stage characterized by both updrafts and downdrafts in the cell, and 3) the dissipating stage characterized by weak downdrafts throughout the cell (Byers and Braham, 1949).

> The initial occurrence of precipitation at the surface marks the end of the cumulus stage (10-15 min) and the beginning of the mature stage which coincides with the initial appearance of the downdraft, aloft. As the rainfall continues throughout the mature stage of the cell, the horizontal extent of the downdraft increases in lower levels until it extends over the entire storm cell. The rainfall is often quite heavy during this stage, and the heaviest amounts usually occur prior to the maximization of the downdraft area. The maximization of the downdraft and the corresponding increase of the rain area marks the end of the mature stage (15-30 min) and the beginning of the dissipating stage. During this stage, the surface rain area contracts while the rainfall degenerates into light intermittent precipitation which lasts an indefinite length of time.
>
> In the Thunderstorm Project (Byers and Braham, 1949) it was found that the surface rainfall pattern under a thunderstorm follows closely the arrangement of cells, and reflect, to a considerable extent, the various stages of development. In Metromex, small, isolated precipitation areas in the surface rainfall patterns (that generally reflect conditions within the cells aloft) which are characterized by closed isohyets of high intensity gradients are designated as *surface raincells.* Cells from rain showers

as well as those from thunderstorms were investigated. The underlying assumption of the Metromex raincell analysis was that *changes which occur in the surface raincell parameters (in the vicinity of urban-industrial sources) are broadly indicative of urban-industrial induced changes in the clouds aloft.* Thus, the analyses of surface raincells in the vicinity of urban-industrial complexes yields insight into the physical processes involved.

Analytical Procedure for Surface Raincell Analysis

The Metromex program has provided a unique set of data for the evaluation of raincells because of the density (9 mi^2 /gage) and the size (~ 2000 mi^2) of the network. When the first summer of data became available in the fall of 1971, it was decided to develop an analytical procedure that would limit the amount of subjectivity involved in classifying raincells and expedite the data reduction process, so that large numbers of raincells over the large network could be handled efficiently and systematically. Although this procedure is largely objective, subjectivity is difficult to eliminate in this type of analysis.

An areal mapping of rainfall amounts for small time increments (such as 5 minutes) provides a map for each increment for which rainfall entities can be isolated and tracked from map to map. This eliminates the need to manually examine and compare raingage traces for similarities in order to isolate and track rainfall entities. Also, the procedure aids the comparison of the rainfall data with radar data because radar data are usually depicted in plan view (PPI) for various increments of time.

On the basis of prior experience in the reduction of raingage charts, it was concluded that a 5-min increment on a 24-hr raingage chart is the smallest time period for which rainfall amounts can be extracted with a high degree of accuracy. Since the advantage of the areal mapping is lessened considerably unless the 5-min amounts can be extracted automatically, they were digitized directly from the raingage charts and entered on punch cards through the use of a Model 3400 X-Y Digitizer (Autotrol). These digitized amounts were filed on magnetic disk storage and then processed by the IBM 360 computer so that a printout of 5-min rainfall rates was obtained. These were plotted on base maps and isohyets were constructed on each 5-min map in order to trace the rainfall entities between successive time intervals. In the analysis of the 1972 data, the procedure was modified so that the plotting of the 5-min rates was performed by the computer, and the data were plotted in terms of symbols which represented the various isohyets used.

From the 5-min isohyetal maps, a determination of which rainfall entities constitute a raincell must be made. In some cases, the determination is clear-cut because the rain entity is separated from the general rain system by no rainfall. On the other hand, many rainfall entities are imbedded within the rain system, and identification of the raincell is much more difficult. In these cases, the rainfall is represented by the concentration of rainfall in small areas of high intensity.

On the basis of these considerations, the following definition of a raincell was made: *A raincell is a closed isohyetal entity within the overall enveloping isohyet of the storm system; that is, it defines an isolated area of significantly greater intensity than the system-enveloping isohyet. When raincells develop apart from the multi-cellular storm system, the system-enveloping isohyet will not be present, and the single cell is uniquely defined by the separation between rain and no rain.*

In order to apply this definition, it is necessary to apply a size restriction on the area, an intensity restriction on the rainfall rate, and a time restriction on the initiation and dissipation of cells. These restrictions include:

1) A cell cannot envelop more than 1/3 of the area of the underlying isohyet of the storm
2) A cell can be delineated by rainfall rate when the difference between its smallest point value and the base isohyet equals or exceeds 0.75 in/hr

3) In order for a cell to initiate, it must be present for a time period greater than 5-min, and in order to dissipate it must be absent for a time period greater than 5-min.

These definitions and procedures provide a semi-objective method of cell delineation. Additional details concerning the mechanics of raincell analysis are given by Schickedanz (1972).

Once the raincells are defined on the 5-min maps, various raincell parameters are determined for each cell including: mean rainfall, area, duration, maximum rain/5-min, maximum area/5-min, mean path length, mean path velocity, maximum point rainfall, and minimum point rainfall. For the 1971 data, this phase was programmed on a Wang calculator, but for the 1972 data it was programmed on the computer. Thus, the only phase of the raincell analysis remaining to be computerized is the time-consuming process of cell identification, and this work is in progress (Schickedanz, 1973).

The basic data for raincell analysis are the 5-min rainfall amounts which are determined from 24-hr recording raingage charts. The chief limitations in the extraction of these amounts are 1) errors due to chart reading and 2) missing data due to raingage outage time.

Chart Reading Errors. Errors in determining 5-min amounts are due to human mistakes and the precision with which 5-min amounts can be determined for a given chart size, width of pen trace, and lag in the instrument. Jones and Sims (1971) have ascertained that for 6-hr charts a 1-min interval is the smallest interval for which amounts can be determined with a reasonable degree of confidence. However, in determining "line averages" along lines of raingages, Jones and Sims indicate that a 2-min interval is required because of timing inaccuracies. The 1- and 2-min intervals on a 6-hr chart correspond to 4- and 8-min intervals, respectively, on a 24-hr chart.

The amount of error involved in using 5-min amounts depends on how the data are used. When an areal mapping of 5-min amounts is made, considerable smoothing of the data occurs in the contouring process, and it is believed that in this case 5-min amounts are reliable. In addition, the human error factor is reduced because the processing is performed with the Autotrol X-Y digitizer. However, a statistical evaluation has not been performed on the errors in chart reading, and the limits of these errors are uncertain at the present time.

Missing **Data.** Missing data occur in analysis because of raingage outage time due to gear stoppage, pen failure, non-operational gages, and human error. In fact, during 1-10 June 1971 and 1-12 June 1972 the amount of missing data due to non-operational gages was so large that raincell analysis could not be performed. Also, on weekly charts timing inaccuracies will not permit extraction of 5-min amounts, so data from these charts are considered as missing in the raincell analysis. However, these charts are necessary for the determination of the proper date and time of each rainfall occurrence.

There was also a large amount of missing data due to clock stoppage in 1971 and 1972. Most of the clocks were cleaned and repaired during the winter to improve the data quality for 1973. It is believed that' the human error has been reduced to a minimum by the automatic processing.

The net effect of the missing data problem is three-fold. First, some small cells may go undetected. Secondly, cells which would normally be considered as single cells, in the presence of missing data, may be considered as multiple cells. Thirdly, the duration, area, and path lengths of cells may be greater or less depending on the location of the missing data. This is a problem in case studies, but not a serious one for comparison of effect and no-effect cells made with a large sample of cells.

There is one other difficulty. Many of the cells are not completely contained within the network, and the analyses that follow are restricted to complete cells. This creates discontinuities in the cell data along the boundaries. This problem is a subject for future investigations.

Analysis Plan

Overall, the analysis plan is to compare statistically the various cell parameters of those cells altered by the urban-industrial complex and those not affected by the urban-industrial environment. This is a difficult problem because of the uncertainty of many factors involved in the delineation of these "effect" and "no-effect" cells. The statistical and design considerations and the method of delineating effect and no-effect cells are described here.

Statistical and Design Considerations. The statistical assessment of inadvertent precipitation modification is an evaluation problem somewhat similar to that in planned weather modification, but there are problems inherent in the inadvertent case that do not exist for randomized, planned, weather modification experiments.

> The chief problem in evaluating inadvertent changes is that the treatment (urban) effect is not assigned at random to the experimental unit. Even if randomization is disregarded, there is the difficult fact that the treatment effect is uncontrollable, and the factors which cause the treatment effect are either unknown, or the degree to which they are present is unknown (Changnon and Schickedanz, 1971). This consideration eliminates the usual treatment vs non-treatment (seeded vs non-seeded) comparisons that are so useful in planned weather modification where the non-treatment data serve as the control.
>
> Another consideration in evaluating inadvertent modification is that the target area for the precipitation increase or decrease is unknown. In planned weather modification, the location of the treatment is known and the target area is thus determined *a priori*. Also, since the seeding is often assigned at random, the most valid and useful comparison is seeded vs non-seeded data and the exact boundary of the target area is not as critical as when the comparison must be based on a target vs non-target comparison. Therefore, assumptions must be made regarding how the urban complex acts as a treatment agent (roughness, increased aerosols, and added heat) in order to delineate apparent target (effect) and control (no-effect) regions.

Since the lack of randomization is unavoidable in inadvertent rain modification evaluation, the approach will be that of "data analysis" (Fleuck, 1971). *In this approach, the final proof and acceptance of inadvertent modification of precipitation does not rest entirely upon statistical evidence and results from tests of hypothesis. The test statistic will be treated as an informative summary statistic and is to be clearly distinguished from the concept of the test statistic as a strict accept-reject rule.* Thus, the flexibility of attack and the willingness to study things as they are, rather than as they, hopefully, should be, are stressed.

Thus, the Metromex raincell analysis must proceed with the knowledge that the treatment effect is not assigned at random. Therefore, the definition of target (effect) and control (no-effect) area in the sections that follow may not be completely rigorous. However, there is a great wealth of "approximate" knowledge (Tukey, 1962) available from the analysis of the Metromex raincell data, because of the well-designed field instrumentation program (Changnon, 1971). This knowledge yields invaluable information which can be used as a broad basis for establishing the causes and effects of inadvertent precipitation modification.

Delineation of Effect and No-Effect Cells. The delineation of effect and no-effect cells is complicated by the uncertainty of the source of treatment agents and the manner in which they are transported and interchanged with cells aloft. Because of this uncertainty, several stratification methods have been used with the 1971-1972 data which only approximate the true "effect" and "no-effect" cells. However, by studying the various stratifications, speculation can be made concerning the most likely sources, and their potential contributions can be explored.

> First, a composite plume was constructed for each rain day. In order to construct the plume, the urban-industrial complexes shown in figure F-l .were assumed to be sources of additional heat, nuclei, and moisture (treatment agents) to the atmosphere. The most divergent winds from the surface to 700 mb during the 12 hours prior to the onset of precipitation were used to define areas where probable treatment agents were transported over the research circle. Examples of the heat-nuclei plume for 18 June 1971 are

shown in figure F-l and are designated as the wind plume. This is not a conservative plume, and most likely, certain no-effect cells have been classified as effect cells.

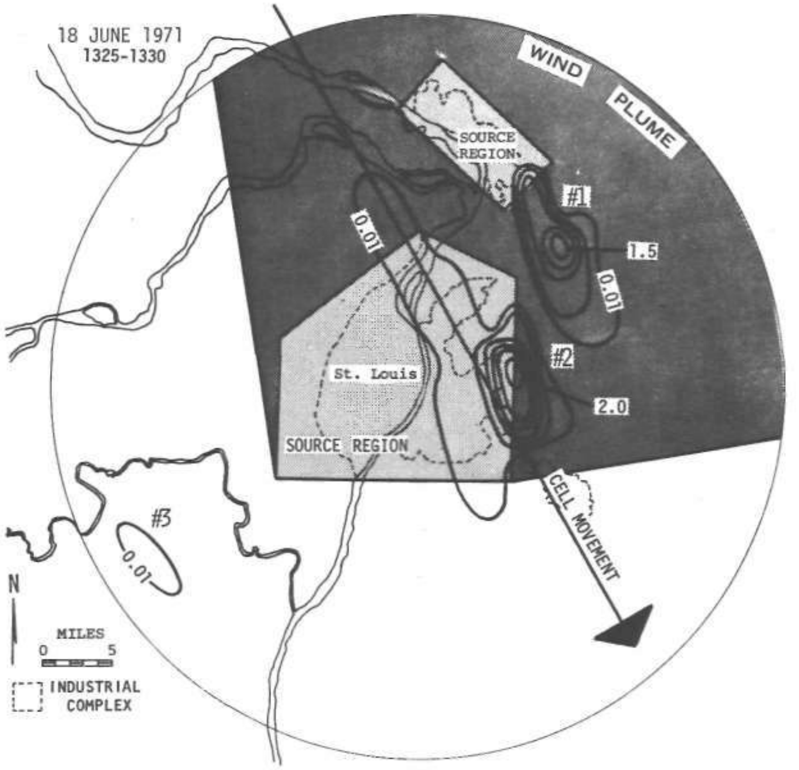


Figure F-l. Areal extent of the wind plume and associated raincells on 18 June 1971

Since the wind plume overestimates the number of effect cells, several other stratifications were made in order to separate effect cells from no-effect cells. The urban-industrial area of St. Louis was added to the Belleville area as shown in figure F-2 and designated as the L plume (city plume). The Wood River-Alton area, which has a dense concentration of coke plants, steel mills, and petroleum refining plants, was considered to be primarily a nuclei source and is designated as the W plume, the nuclei plume. The urban area of St. Charles was labeled as the C plume. Combinations of CWL and WL were also formed (figure F-2).

In an attempt to determine the areal spread of these treatment agents, two other stratifications were made. Whenever the areas of W and L were within the wind plume, they were designated as the *major plume.* The area outside the major plume, but within the wind plume, was designated as the *minor plume.* Comparisons of the major and minor plumes with the *control plume* yield indications of the potential areal spread of the treatment agents (heat, moisture, and nuclei).

In addition, there are two areas which are non-urban related, but which were considered as potential sources of heat and moisture. These are the bottomlands NE of St. Charles in the northwestern part of the network and the extension of the Ozark Plateau in the southwestern part of the network. These areas were designated as the bottomlands plume (B) and the hill plume (H) and are shown in figure F-3. These plume stratifications were made to separate the topographical and marine influences from the urban-industrial influences.

In the first-order stratification analysis, all cells which were within a given plume during their life history were designated as effect cells. All cells outside of the area of a given plume were considered no-effect cells, even though they may have been classified as effect cells for the other plumes. Comparisons were then made between effect and no-effect cells. In the second-order stratification analysis, all cells

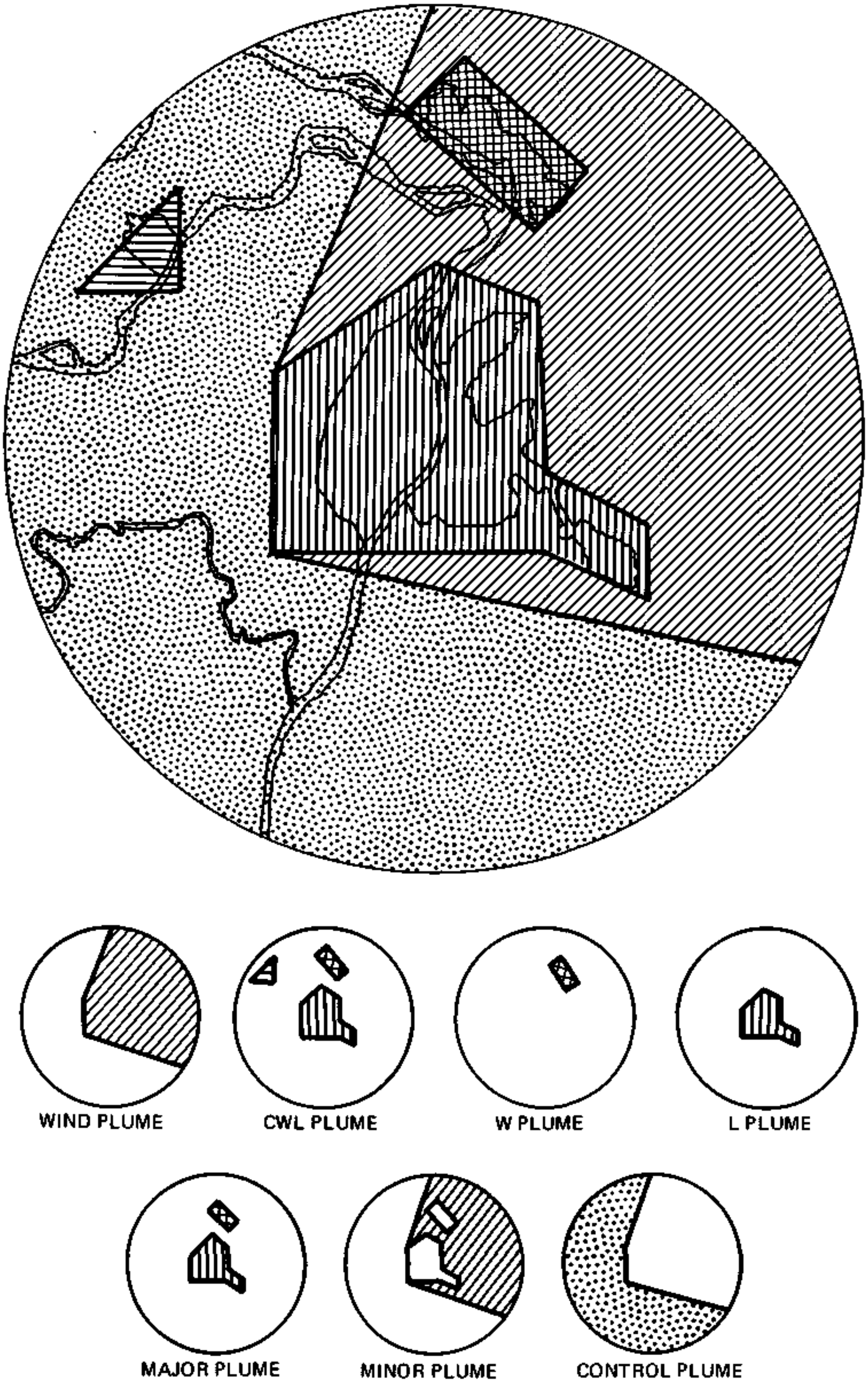


Figure F-2. Various plume stratifications used in the delineation of the effect and no-effect cells outside the wind plume (control plume) were designated as no-effect cells and compared with the effect cells of the various plumes.

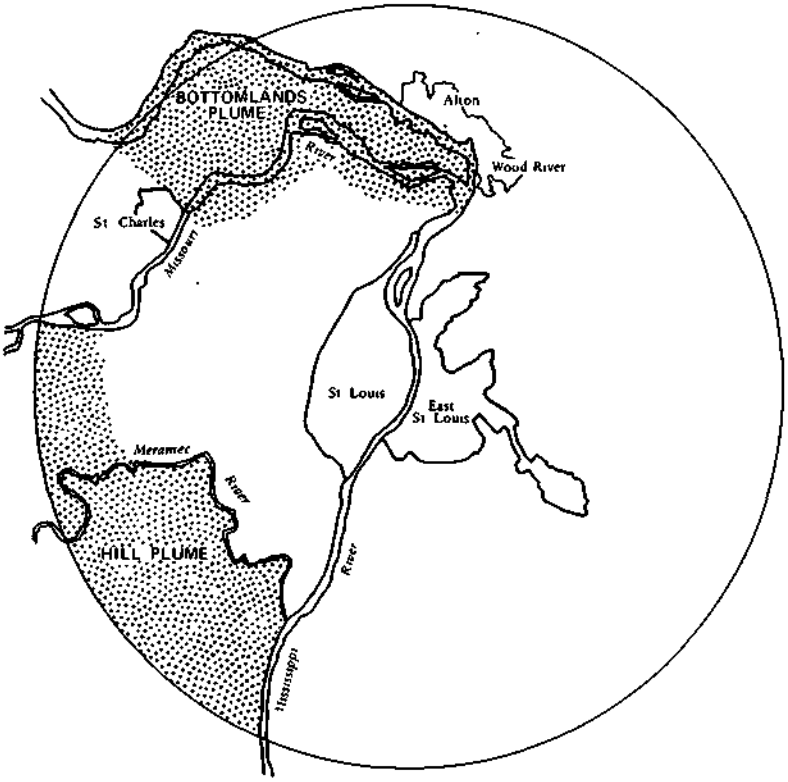


Figure F-3. Plume areas of the hills and bottomlands

In the third-order stratification analysis, the solo area concept was used. That is, the cells were stratified into those cells (effect) which were only in a particular plume area of W, B, L, or H. Cells which never occurred in these plume areas were considered to be no-effect cells (control). This control is considered to be the most representative area of the no-effect cells and was compared with all other plume areas (W only, B only, L only, and H only). In addition, various combinations of the W, B, L, and H areas were formed, and these included the nuclei-bottomlands (WB), the city-hill (LH), and the city-bottomlands (LB) combinations.

First- and Second-Order Stratification Analysis

The cell parameter means for the effect and no-effect comparisons during summer 1971 are shown in figure F-4 (first-order stratification analysis). For every stratification and every cell parameter, with the exception of minimum rain for the L-plume stratification, the effect means were greater than the no-effect means. The largest differences between the effect and no-effect cells occurred with total and maximum areal extent; the smallest differences occurred with duration, maximum rain, minimum rain, mean path length, and mean path velocity. [Note: The *maximum area* represents the maximum 5-min areal extent, and the *maximum rain* and *minimum rain* represent the high and low 5-min areal averages, respectively, of the cell during its lifetime.]

The t-test parameter was computed for these samples and the results are depicted in figure F-5. The parameters of area and maximum area had the largest t-values, followed by those for mean and total

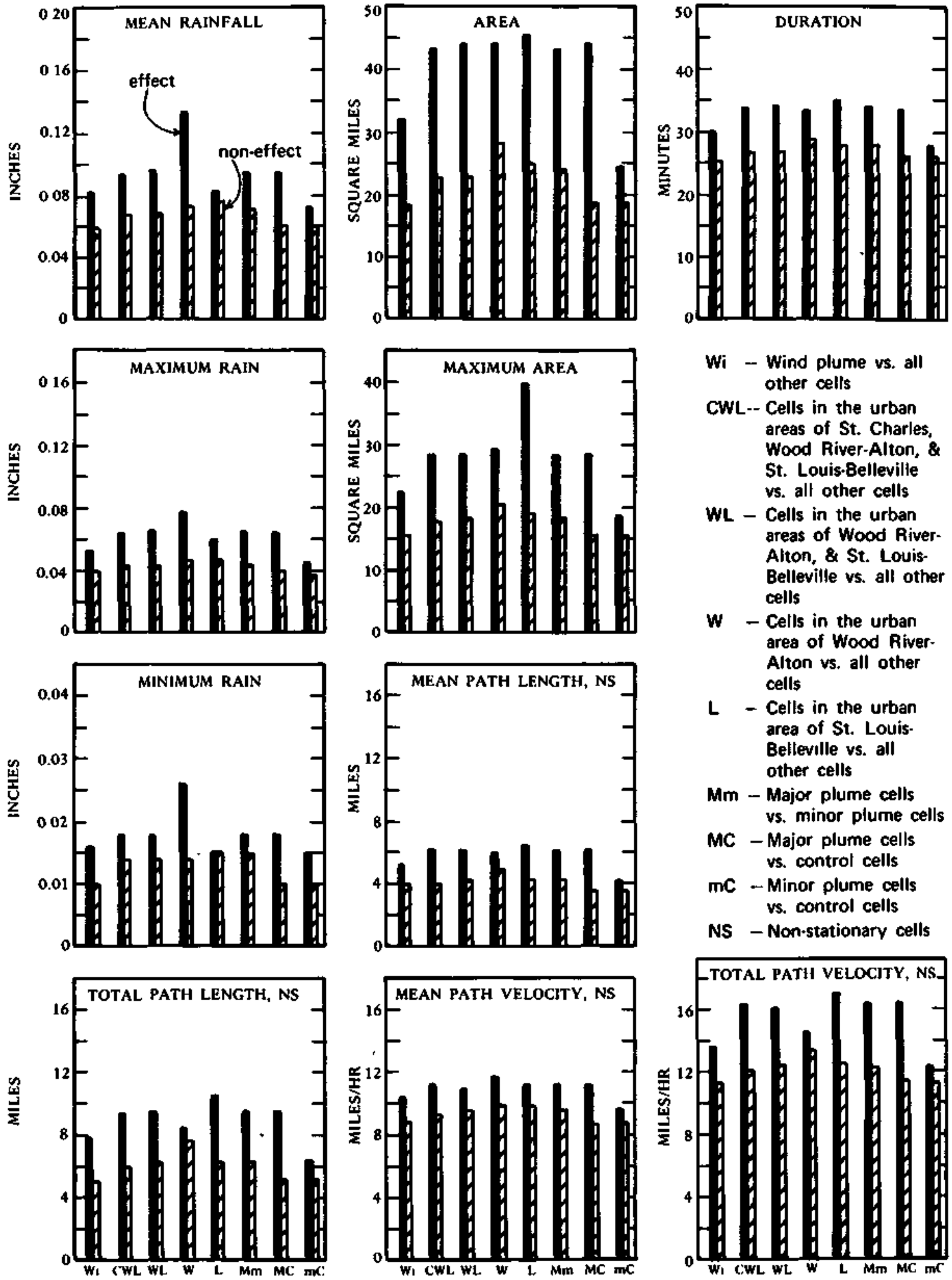


Figure F-4. Cell parameter means for the effect and no-effect comparisons according to the first-order stratification analysis, summer 1971

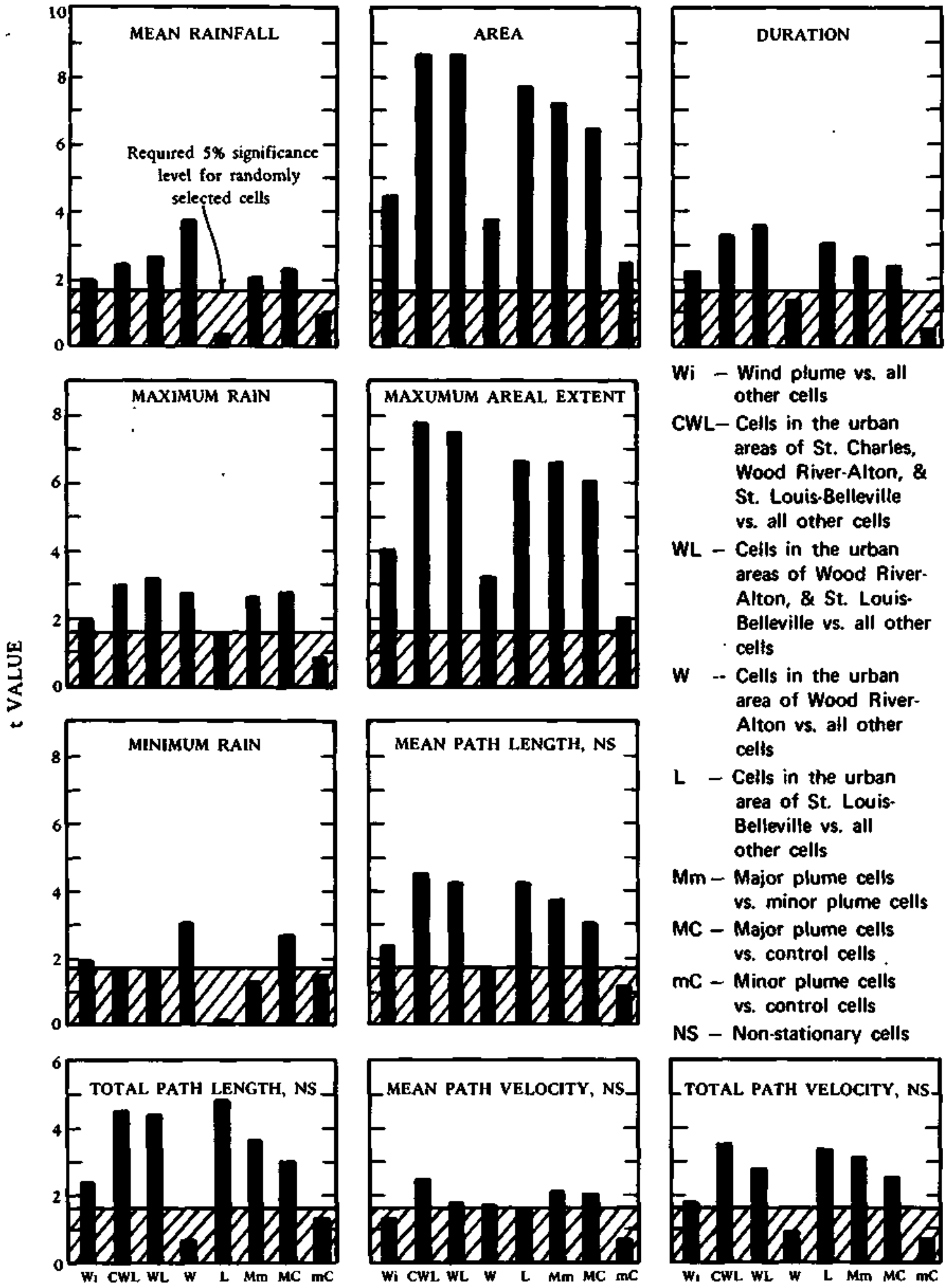


Figure F-5. The t-values for the effect and no-effect comparisons according to the first-order stratifications analysis, summer 1971 path lengths. The duration, maximum rain, minimum rain, and cell velocity had considerable smaller values of t, although all were positive and approached values that would be significant if these were random comparisons. According to the stratifications, the CWL, WL, and L plume comparisons, along with major vs minor and major vs control comparisons, provide the largest t-values.

The conclusion that can be drawn from figures F-4 and F-5 is that those cells designated as effect had considerably greater rainfall, areal extent, duration, path length, and velocity than the cells labeled as no-effect. Also, the large t-values between major and minor cells, and the small t-values between minor and control cells strongly suggest that the urban effect is limited in areal extent, and the modification of the precipitation processes occurs relatively close to the source regions.

However, there are at least two problems with the analysis as it was performed. First, the potential heat and moisture sources in the hills and bottomlands have not been considered. Secondly, the no-effect cells include cells which are considered effect cells for some of the other stratifications, and thus some of the features are masked.

In regard to the first problem, comparisons were made according to the B (bottomlands) and H (hill) plume stratifications and the results are tabulated in table F-1. The average, areal extent, and duration of rainfall within the cells were greater in the bottomlands and hills than in their corresponding control areas. In general, the hills had larger t-values than the bottomlands. The message from table F-1 is clear: the bottomlands and hill regions cannot be discounted and must be included in order to have a valid analysis.

Table F-1. Comparison of Effect and No-Effect Cells for the Bottomlands and Hill Stratifications, Summer 1971

	Average rain *(inches)*	**Areal extent** *(mr)*	**Duration** *(mm)*	**Maximum rain** *(inches)*	**Maximum area** *(mi^2)*
		Bottomlands (B)			
Mean, effect	0.088	37	32	0.062	25
Mean, no-effect	0.076	29	29	0.048	21
t-values	*0.86*	*2.35*	*0.98*	*1.52*	*2.12*
		Hills (H)			
Mean, effect	0.117	41	35	0.071	27
Mean, no-effect	0.075	29	29	0.048	21
t-values	*2.26*	*2.55*	*1.51*	*1.78*	*2.44*

In regard to the second problem, namely, the masking of the comparison by the placement of the effect cells from other stratifications into the no-effect sample, comparisons were made with the no-effect cells from the wind plume. The use of these cells as a control was based on the fact that the wind plume tends to overestimate the influence of the urban-industrial areas, and thus the non-plume area is relatively free of urban effects. The chief disadvantage of this control is that it will include some effect cells from the bottomlands and hill stratifications. The t-values resulting from comparisons of effect cells of the various plumes with the no-effect cells of the wind plume are listed in table F-2.

The results are indeed striking, for if these were random comparisons, all t-values would be significant with the exception of average rain for the L plume. The area factor (total areal extent and maximum area) had the largest t-values and this appears to be the most sensitive indicator of the effect. Even though the comparisons for the H and B stratifications are masked by the presence of some effect cells in the no-effect sample, the hills and the bottomlands are seen to be important factors. The small differences in t-values between the CWL and WL plumes suggest that C is of little importance in the analysis. Thus, for the third-order stratification analysis, the CWL plume was not considered and the C (St. Charles) cells were placed into the control sample (see figures F-1 and F-2).

Table F-2. The t-Values for Effect and No-Effect Comparisons with the No-Effect Cells from the Wind Plume as the Overall Control, Summer 1971

	Average rain	Areal extent	Duration	Maximum rain	Maximum area
W plume	3.45	6.31	2.69	3.12	5.85
L plume	0.72	6.53	2.96	2.31	5.81
H plume	2.46	5.97	2.73	2.45	5.09
B plume	1.84	5.15	2.40	2.26	4.52
WL plume	2.63	6.49	3.08	2.95	5.89
CWL plume	2.53	6.46	2.96	2.87	5.97

The first- and second-order stratification analyses were useful for giving general indications of the influence of urban, industrial, and topographical factors on the various cell parameters. However, the third-order stratification analysis is believed to be the most valid approach to the evaluation problem. Therefore, the first- and second-order stratification analyses were not performed for the 1972 data, and emphasis has been placed on the results of the third-order stratification analyses for both years.

Third-Order Stratification Analysis

The comparisons discussed here are designed to eliminate bias as completely as possible in a non-randomized experiment. In addition to the plume areas of L, W, H, and B, combinations of these areas such as W-B and L-H will be considered. The underlying motivation is that those cells which have a double exposure to the treatment effect (i.e., cells which occur in hills and city both) may be the heaviest rain producers. Since changes in the cell parameters are being used to indicate the magnitude of the effect, the discussion and results of the various stratifications are presented on a parameter-by-parameter basis. Also, this type of presentation facilitates the discussion of the physical implications of the modified cell parameters.

All references to 1971-1972 data in the discussions and tables of results refer to data from summer 1971 and from June and 1-20 August 1972. The analysis of the July data was not complete at the time of this report. A notable exception is the initiation data which does include data from all 3 summer months in 1972.

Cell Volume. Insofar as the ultimate economic benefit of enhancement or suppression of cell rainfall by the urban environment is concerned, the rain volume is the most important cell parameter. This parameter represents the total rain production by the cell and is an integrated measure of the other cell parameters, as well as an integrated measure of the various atmospheric conditions which produced the cell. Results for the comparison of effect and no-effect cells (control cells) are listed in table F-3.

> For the 1971-1972 data, the percentage differences ranged from 19 to 261% with the greatest differences occurring with the W, L-H, and the W-B plume stratifications. (A note of caution must be exercised at this juncture because of the smaller sample sizes associated with these double-area stratifications compared with the others).
>
> Cells which occurred in more than one treatment area, and those which occurred in the Wood River-Alton area produced the most rain. The city cells produced more rain than the hill cells, but much less than the cells which moved across both the city and the hills. The small value of t for the B stratification indicates that the cells in this area are relatively unimportant unless they occur both in the bottomlands and in the Wood River-Alton area.

Table F-3. Comparison of Rainfall Volume from Effect and No-Effect Raincells

	L	*W*	*H*	*B*	*L-H*	*W-B*	*Control*
			1971				
Sample size	117	30	32	60	9	17	281
Mean, acre-feet	219	409	190	116	466	444	97
Increase, %	126	322	196	20	380	358	
t-value	*3.6*	*4.0*	*1.8*	*0.5*	*3.9*	*4.8*	
			1972				
Sample size	86	25	13	35	2	1	231
Mean, acre-feet	400	424	187	215	192		166
Increase, %	141	156	13	29	16		
t-value	*3.4*	*2.2*	*0.2*	*0.7*	*0.1*		
			1971-1972				
Sample size	203	55	45	95	11	18	512
Mean, acre-feet	296	416	189	152	416	462	128
Increase, %	131	225	48	19	225	261	
t-value	*4.7*	*4.2*	*1.2*	*0.7*	*2.8*	*4.1*	

It is of interest to compare these mean control values to those obtained in earlier studies for unmodified raincells. In the Thunderstorm Project, Braham (1952) obtained a mean value of $1.24 \mathrm{x} 10^{8}$ kg or approximately 100 acre-feet for the total rain volume. Huff and Schickedanz (1970) obtained a median value of 110 acre-feet for raincells on a dense network in southern Illinois. When we consider that different techniques were used to delineate the raincells, the agreement of the control values with these previous values is quite good. This agreement lends support to the validity of using the described control in the various comparisons.

Average Rainfall. This parameter represents the average rainfall (rainfall depth within the cell) and as such is also a measurement of the intensity of storm rainfall. By itself, it does not represent the overall efficiency of rain production as does the cell volume, but it can yield physical insight into how the large differences in cell volume occurred. If the percentage increase in rainfall depth is as large as some of the cell volume increases, then the increase could be detrimental to farming and other interests. That is, an increased rainfall depth over a small area could cause heavy runoff, resulting in soil erosion and local flooding. The results of the comparison of effect and no-effect raincells according to average rainfall are listed in table F-4.

For 1971-1972 data, the largest percentage increases occurred with the W and W-B stratifications. The smallest percentage increase occurred with the B stratification and the size of the t-value implies that the bottomlands do not have an influence on rainfall intensity. Thus, the percentage increase in the W-B stratification was either due to the presence of the cells in the Wood River-Alton area or to a delayed response-action of factors in the bottomlands. The percentage increase for the L stratification is 19%, and much smaller than the increase for W. The corresponding value of t would indicate that the average rainfall is only slightly altered by the city. Thus, rainfall intensity apparently contributed very little to the overall increase in rainfall production of the L cells, whereas intensity was indicated to be a major contributer to the increase in rain production of the W cells.

The greater change in intensity of the cells in Wood River-Alton as opposed to those in St. Louis is supported by several other analyses in this report, notably the maximum rain/5-min, cell history, and the moving-stationary analyses. These analyses and the analyses of the areal factor (areal extent and maximum area/5-min) suggest that different physical processes were involved in the production of rain in the two regions.

Table F-4. Comparison of Average Rainfall from Effect and No-Effect Raincells

	L	*W*	*H*	*B*	*L-H*	*W-B*	*Control*
			1971				
Sample size	117	30	32	60	9	17	281
Mean, inch	0.08	0.14	0.12	0.07	0.13	0.14	0.06
Increase, %	20	118	76	8	98	124	
t-value	*1.2*	*3.6*	*2.4*	*0.4*	*1.9*	*3.2*	
			1972				
Sample size	86	25	13	35	2	1	231
Mean, inch	0.11	0.11	0.08	0.12	0.04		0.09
Increase (decrease), %	**19**	20	(9)	35	(54)		
t-ualue	*1.1*	*0.7*	*-0.2*	*1.3*	*-0.06*		
			1971-1972				
Sample size	203	55	45	95 -	11	18	512
Mean, inch	0.09	0.12	0.10	0.09	0.11	0.14	0.07
Increase, %	19	65	37	17	47	89	
t-ualue	*1.5*	*2.9*	*1.6*	*1.0*	*1.0*	*2.6*	

Total Areal Extent. This parameter is of considerable interest because a substantial contribution to increased rain production by the urban environment could result from spreading the rainfall over a larger than normal area. If this is the major source of urban enhancement, the increased rain production is less likely to cause local flooding and soil erosion, and in general provides a very beneficial effect of rainfall processes. The results of the comparison of effect and no-effect cells are listed in table F-5.

Table F-5. Comparison of Total Areal Extent of Effect and No-Effect Raincells

	L	*W*	*H*	*B*	*L-H*	*W-B*	*Control*
			1971				
Sample size	117	30	32	60	9	17	281
Mean, mi^2	40	34	31	25	75	51	17
Increase, %	**85**	56	**44**	**18**	248	135	
t-ualue	*6.5*	*3.5*	*2.5*	*1.4*	*7.7*	*5.7*	
			1972				
Sample size	86	25	13	35	2	1	231
Mean, mi^2	45	38	37	29	66		23
Increase, %	95	65	60	27	186		
t-ualue	*6.3*	*3.2*	*2.5*	*1.8*	*3.1*		
			1971-1972				
Sample size	203	55	45	95	**11**	18	512
Mean, mi^2	42	36	33	27	73	54	22
Increase, %	90	61	48	21	231	**144**	
t-ualue	*9.0*	*4.4*	*3.4*	*2.1*	*8.4*	*6.6*	

For the 1971-1972 data, the largest percentage increases and the largest t-values for areal extent occurred with the L-H and W-B stratifications. This could result from a double treatment effect, or simply that cells which have path lengths long enough to allow occurrence in both areas will naturally have larger cell areas. If the increase in area for L-H cells is due to a fortuitous positioning of L and H areas, then the total areal extent and the mean path length should be highly correlated. However, the correlation coefficient between total areal extent and mean path length is only 0.60 for the L-H stratification which indicates that only 36% of the variation in area is explained by path length. This would indicate that certainly not all of the increase in the area of the L-H cells is due to a fortuitous positioning of the H and L areas.

The L stratification had the next largest percentage increase in cell area and also had a larger t-value than the W-B and H-L stratifications. This indicates that the cells in the city had a larger percentage increase in area than did the cells in the industrial area of Wood River-Alton. The greater change in areal size of the city cells as opposed to those in Wood River-Alton is supported by several other analyses in this report, notably, maximum rain/5-min, cell history, and the moving-stationary analyses. These analyses and the analyses of the rainfall intensity factor (average rain and maximum rain/5-min) suggest that different physical processes were involved in the two regions.

It is of interest to *speculate* on the physical causes for the greater change in total areal extent of the city cells. It is conceivable that the primary effect of the urban-heat island may be to produce a dynamic effect on the cloud structure. A dynamic effect should produce higher cloud tops. According to data collected in the Thunderstorm Project (Byers and Braham, 1949), the higher the cloud, the greater the horizontal extent. This would likely increase the areal extent of the downdraft, and since the rainfall begins with the onset of the downdraft at the surface, there should be a corresponding increase in the area of the surface rainfall. This horizontal cloud explosion had been demonstrated by Simpson and Wiggert (1971) in the dynamic seeding of single clouds in Florida. In fact, it was demonstrated in the Florida experiments that it was probably the high wind shear in the later part of the 1968 experiments that inhibited seeded rain production by preventing or reducing the horizontal expansion of the cloud body (Simpson and Wiggert, 1971).

The above tentative explanation is based strictly on the observations of cell rainfall at the surface, and it is recognized that an entirely different explanation may be forthcoming when the detailed studies of the radar, rain drop, and aircraft data are completed. This explanation is merely offered as one possible reason for the increased areal extent of the city cells.

Duration. This parameter is of interest because urban enhancement of rain production may be related to extension of rainfall over a longer period of time than normal. The results of the comparison of effect and no-effect cells according to duration are listed in table F-6.

Table F-6. Comparison of Rainfall Duration from Effect and No-Effect Raincells

	L	*W*	*H*	*B*	*L-H*	*W-B*	*Control*
			1971				
Sample size	**117**	30	32	60	9	**17**	281
Mean, min	32	31	28	28	58	37	26
Increase, %	**22**	**19**	5	5	119	**41**	
t-ualue	*2.2*	*1.2*	*0.3*	*0.5*	*4.3*	*2.1*	
			1972				
Sample size	86	25	13	35	2	1	231
Mean, min	35	**31**	28	30	35		28
Increase, %	26	**11**	1	8	24		
t-ualue	*2.3*	*0.7*	*0.1*	*0.5*	*0.4*		
			1971-1972				
Sample size	203	55	45	95	11	18	512
Mean, min	34	31	28	29	54	42	27
Increase, %	24	15	3	6	97	53	
t-ualue	*3.2*	*1.4*	*0.2*	*0.6*	*4.0*	*2.7*	

The duration of cell rainfall was increased in every stratification with the largest increases occurring with the L-H and the W-B stratifications. These large increases in duration were expected because of the longer path lengths required in order for a cell to be present in two areas.

The next largest percentage increase and largest t-values were associated with the L stratification. The fact that the percentage increase was greater for the city cells than the cells in Wood River-Alton lends support to the concept that the primary effect is intensity enhancement in the industrial region. That is, since the cells in the industrial area produced more rain than the city (St. Louis) cells, had shorter durations, and smaller areal sizes, the areal and time intensity would need to be correspondingly greater.

Maximum Rainfall/5-min. This parameter is actually the maximum 5-min areal average during the lifetime of the raincell, whereas the average rainfall is the areal average over the lifetime of the cell. Since this parameter is closer to an instantaneous areal rainfall measurement than the average rainfall, it should be more representative of a rapid increase in areal intensity than the average rainfall. The results for the comparison of effect and no-effect raincells according to maximum rainfall/5-min are listed in table F-7.

Table F-7. Comparison of Maximum Rain/5-Minutes from Effect and No-Effect Raincells

	L	*W*	*H*	*B*	*L-H*	*W-B*	*Control*
			1971				
Sample size	117	30	32	60	9	17	281
Mean, inch	0.05	0.08	0.06	0.05	0.09	0.09	0.04
Increase, %	38	92	65	22	32	128	
t-ualue	*1.9*	*2.6*	*2.8*	*0.8*	*2.2*	*2.9*	
			1972				
Sample size	86	25	13	35	2	1	231
Mean, inch	0.08	0.09	0.07	0.08	0.03		0.06
Increase, %	42	55	25	42	41		
t-ualue	*2.2*	*1.7*	*0.6*	*1.6*	*0.4*		
			1971-1972				
Sample size	203	55	45	95	11	18	512
Mean, inch	0.7	0.08	0.07	0.06	0.08	0.10	0.05
Increase, %	40	73	40	27	69	106	
t-ualue	*2.8*	*3.0*	*1.6*	*1.4*	*1.4*	*2.7*	

For the 1971-1972 data, the largest percentage increases occurred with the Wand W-B stratifications. The smallest percentage increase occurred with the B stratification and the size of the t-value suggests that the bottomlands do not have a significant influence on rainfall intensity in the immediate area, at least. The percentage increase is greater for the W stratification than it is for the L stratification. This indicates again that the rainfall intensity contributed less to the overall rainfall production for the L cells than it contributed to the rainfall production for the W cells. The rainfall increases for the L-H and W-B stratifications are again relatively large and suggest that the double treatment effect may have produced the heaviest rainfall intensities.

These results are very similar to those obtained for average rainfall and suggest that the maximum rain/5-min and the average rainfall are correlated. For 1971 data the correlation coefficients between the two parameters were found to be 0.80 (64% explained variance) for the L cells, 0.84 (71% explained variance) for control cells, and 0.97 (94% explained variance) for the W cells. Thus, the correlation coefficients are nearly the same for control and L cells and higher for W cells.

These correlation coefficients lend support to the concept of a rapid increase in areal intensity of the W cells. That is, a rapid increase in the areal rainfall intensity in a short time (indicated by the duration and the maximum rain/5-min) would tend to make the maximum rain/5 -min more representative of the overall areal average of cell rainfall. Another indication that the rainfall intensity was not changed greatly in St. Louis is provided by the fact that the correlation coefficients for the L and control cells are nearly the same.

Maximum Area/5-min. Since this parameter is closer to an instantaneous measurement of area than the total areal extent, it should be more representative of the rapid expansion in areal size. The results from the comparison of effect and no-effect rain cells according to maximum rain/5-min are listed in table F-8.

Table F-8. Comparison of Maximum Area/5-Minutes from Effect and No-Effect Raincells

	L	*W*	*H*	*B*	*L-H*	*W-B*	*Control*
			1971				
Sample size	117	30	32	60	9	17	281
Mean, mi^2	27	24	23	20	41	32	17
Increase, %	57	38	37	18	137	86	
t-ualue	*6.0*	*2.8*	*2.8*	*1.8*	*5.6*	*4.8*	
			1972				
Sample size	86	25	13	35	2	1	231
Mean, mi^2	22	21	25	18	33		17
Increase, %	34	26	51	9	97		
t-ualue	*4.2*	*2.0*	*2.9*	*0.9*	*2.3*		
			1971-1972				
Sample size	203	55	45	95	11	18	512
Mean, mi^2	25	22	24	19	39	32	17
Increase, %	47	33	41	15	131	90	
t-ualue	*7.4*	*3.4*	*4.0*	*2.0*	*6.5*	*5.7*	

For the 1971-1972 data, the L-H and W-B stratifications produced the largest percentage differences. This suggests that the double treatment effect may have produced the largest areal sizes. The L stratification produced the next largest percentage increase and the largest t-value. This indicates again that the city cells had a larger percentage increase in area than the cells in the Wood River-Alton area.

The results are very similar to those obtained for total areal extent and suggest that the maximum area/5-min and the total areal extent are correlated. For 1971 data, the correlation coefficients between the two parameters were found to be 0.91(83% explained variance) for the W cells, 0.91 (83% explained variance) for the control cells, and 0.83 (69% explained variance) for the L cells. Thus, the correlation coefficients are nearly the same for the control and W cells and lower for the L cells. These correlation coefficients lend support to the concept of a rapid expansion in areal size; that is, a horizontal expansion of the area at a point along the path of the cell movement may tend to destroy the relationship between the two parameters. Another indication that the change in area size was not as large for the W cells as it was for the city cells is provided by the fact that the correlation coefficients for the W and control cells are nearly the same.

Mean Path Length (Moving Cells). This parameter is a measure of the distance which the center of a rain cell moves during its life history. This may not be representative of the actual cell movement in some instances because of horizontal growth along the axis of cell movement. The results of the comparison of effect and no-effect raincells according to the mean path length are listed in table F-9.

As with total area, duration, and maximum area/5-min, the largest percentage increases occurred with the L-H and W-B stratifications, and the next largest increase occurred with the L stratification. Thus, the longer path lengths of the St. Louis city cells can most likely be attributed to the greater areal expansion and to the longer duration of the city cells as opposed to the cells in Wood River-Alton.

Table F-9. Comparison of Mean Path Length from Effect and No-Effect Raincells for 1971 (Moving Cells)

	L	*W*	*H*	*B*	*L-H*	*W-B*	*Control*
Sample size	75	23	19	35	8	17	124
Mean, mph	5.7	4.7	4.8	4.4	8.2	6.2	4.0
Increase, %	44	18	21	11	107	57	
t-ualue	*3.2*	*1.1*	*1.2*	*0.8*	*3.9*	*3.0*	

Mean Path Velocity. This parameter is most likely the least reliable of the parameters insofar as comparisons between the various stratifications are concerned. Since mean path velocity is a ratio of the path length to the cell duration, there are several combinations of these two parameters which can give similar values in different stratifications. For example, in the L stratification a small value of velocity may be obtained by a larger value of duration and a short path length, whereas in Wood River-Alton a small value of velocity may be obtained by a small value of duration and a short path length. These would give similar velocity values for the cells in the two areas, but the physical processes involved could be greatly different. The results of the comparison of effect and no-effect cells according to mean path velocities are given in table F-10.

For the 1971 data, the effect velocities are greater than the control velocities in every instance; however, the percentage changes are smaller than for any of the parameters previously investigated. The corresponding t-values are also small. Note that the velocities for the city cells and Wood River-Alton are nearly the same, although the path lengths and durations were different, and the physical processes were most likely different in the two stratifications.

Table F-10. Comparison of Mean Path Velocity from Effect and No-Effect Raincells for 1971 (Moving Cells)

	L	*W*	*H*	*B*	*L-H*	*W-B*	*Control*
Sample size	75	23	19	35	8	17	124
Mean, mph	10.4	10.3	10.0	10.1	9.8	10.9	9.4
Increase, %	11	10	7	7	4	17	
t-ualue	*1.2*	*0.6*	*0.4*	*0.6*	*0.2*	*1.0*	

Supplementary Analyses

One of the problems alluded to in the section on data limitations was that of cells not completely contained on the network. Because of this problem, all of the analyses were based on cells that were completely contained on the network. The analysis of complete cells, only, presents the possibility that the data may be biased toward the effect cells. This bias may occur because St. Louis is located in the center of the research circle, and has the greatest opportunity to sample the heavier, longer-moving raincells. Another problem which has been alluded to often is that of separating the urban effects from the hills, bottomlands, and other confounding factors. The two analyses presented in this section are designed to investigate the possibility of bias and to study the urban effect without the confounding factors of the hills and bottomlands.

Moving-Stationary Analysis. In this analysis, the cells were partitioned into moving and stationary cells. Thus, if there is a bias toward the urban area sampling more of the longer moving cells, the stationary cells provide a method of investigating the urban effect free of this bias. The results of the comparison of effect and no-effect cells partitioned according to moving and stationary cells are listed in table F-11. [Note: Although raincells are herein designated as stationary, it is quite possible that the cells aloft are, in fact, non-stationary. The density of gages will not permit the determination of moving cells with very short path lengths as opposed to stationary cells.]

Table F-11. Comparison of Cell Parameters from Effect and No-Effect Raincells According to Moving and Stationary Cells during Summer 1971-1972

	Control mean	Change expressed as percent of control *L*	*W*
Stationary cells			
Sample size	280	73	13
Volume, acre-feet	34	90	15
Average rain, inches	0.05	9	39
Total area, mi^2	**11**	32	2
Moving cells			
Sample size	232	130	42
Volume, acre-feet	242	76	120
Average rain, inches	0.10	5	39
Total area, mi^2	36	60	20

In the control sample, there were more stationary cells than moving cells, whereas in St. Louis (L) there were more moving cells than stationary cells. This fact in itself does not necessarily indicate bias toward longer moving cells in the city, because the city may have caused some cells to move that would normally have been stationary. In addition, the fact that the cells moved does not indicate that they were the longer moving ones. Thus, the most significant feature of table F-11 is that there was a 73% increase in rainfall volume for the L stationary cells. Certainly, these cells were not biased, since they initiated and dissipated in the vicinity of the city. There was also an increase in rain volume for the Wood River-Alton (W) stationary cells, but it was much smaller than the increase for the W moving cells.

Comparison of the area and average rainfall parameters for the L and W cells again supports the concept that two different physical processes were involved in the L and W regions. That is, the greatest change in the W cells occurred with rainfall intensity, whereas the greatest change in the L cells occurred with areal extent. These differences were even more pronounced than they were for the samples with the stationary and moving cells combined.

Life History of Cells. In order to investigate changes in the raincells as they pass through the urban-industrial treatment regions of St. Louis and Wood River-Alton, the cells were partitioned into the periods before, during, and after their presence in the treatment region. Each cell did not have to go through all three cell periods in order to be included in the analysis. However, each cell had to have at least a before-during period combination, or a during-after period combination in order to be included. This partitioning of the cell history provides a method of determining whether the maximum effect occurs in the urban-industrial region or immediately downwind. Also, any confounding effects from the hills or bottomlands would be in the "before" and "during" periods, thus making the comparison more conservative. The results of the comparison between the three periods are listed in table F-12.

According to comparisons in table F-12, the average rain and total area of raincells were greater after the apparent treatment period than before. For L cells, the percentage increase was 28 and 17% respectively for average rain and total area. These increases were true for both W and L cells and provide strong evidence of an urban effect on raincells. Also, the average rain and total areal extent were greater during treatment than prior to treatment. Note that for the L cells the area parameter was increased the most during the treatment period (39%). This is additional evidence that area was a more important parameter than the average rainfall for the L cells.

Table F-12. Comparison of Life History of Raincells before, during, and after the Apparent Treatment Effect, Summer 1971*

Parameter	*L*	*W*
Changes, during compared with before, %		
Average rain	3	68
Total area	39	27
Changes, during compared with after, %		
Average rain	-19	22
Total area	19	-14
Changes, after compared with before, %		
Average rain	28	38
Total area	17	48

*** Sample sizes are small in these comparisons because of the number of partitions required. The sample sizes are 14, 24, and 15 for L, and 10, 17, and 10 for W, respectively, for the before, during, and after periods.**

For the L cells, the area was greater during the apparent treatment period than after (19%), indicating that there tends to be a decrease in areal extent after cells have been in the L source region. Even with this decrease, the area is still larger than it was before the treatment period (17%). The average rainfall is less during treatment than after (-19%), indicating that there is little difference in the total volume (mean x area) of rainfall in the "during" and "after" periods.

For the W cells, the average rain was greater during treatment than after treatment (22%) indicating that the rainfall intensity tends to decrease after cells have passed through the W source region. Even with this decrease, the average rainfall after treatment was still 38% greater than before treatment. Again, the area is less during treatment than after (-14%) indicating that there is very little difference in the total rain volume (mean x area) in the "during" and "after" periods.

These results indicate that the treatment effect endures for an indefinite length of time beyond the period of treatment. Because of the small sample sizes in the various partitions, more years of data are required to substantiate this result.

Analyses of Cell Initiation

A raincell analysis provides useful information concerning the areas in which cells tend to initiate. For example, it is useful to show whether cells tend to initiate more in the vicinity of urban sources of heat, moisture, and nuclei than in other regions. In addition, because of potential effects associated with hills and bottomlands upwind of the urban-industrial regions, mentioned previously, it is important to determine whether cells tend to initiate more in these areas also.

The number of times that each gage was included in a cell initiation during each summer month of 1971-1972 was tabulated and mapped. These tabulations were also mapped for the 2-month periods of June, July, and August 1971-1972 and for all 6 summer months combined. The various maps were then subjected to trend surface analysis in the manner described by Schickedanz (1973) to determine which initiation maxima were significant at the 5 and 10% levels.

The initiation areas significant at the 5 and 10% significance levels are shown in figures F-6, F-7, and F-8 for the three 2-month periods. The inner and outer isolines represent the 5% and 10% levels, respectively. For June 1971-1972, there are initiation areas in the vicinity S of the city which is ENE of the hills. There are also significant initiation areas in the vicinity of Wood River-Alton, Granite City, and in the bottomlands W and NW of St. Louis. For July 1971-1972, there are two prominent initiation areas S and SE of the city. There are also smaller ones E of the city and in the bottomlands. However, there are none in the city or in the Wood River-Alton area. For August 1971-1972, the initiation areas S of the city are prominent, but there are also initiation areas E of the city, in the city, and other small initiation areas over the Metromex study region (figure F-8).

From the individual monthly maps, counts were made of the number of times that a gage was included in an initiation area for the 5 and 10% significance levels. The numbers of counts over the 2-year period are shown on figure F-9 for the 10% case. The prominent areas are 1) the maximum S of the city and E of the hills, which indicates that in 4 out of 6 months there were gages included in a 10% initiation area; 2) the area immediately N of Granite City and S of Wood River-Alton, which also includes the count of 4; and 3) the area in the bottomlands. There are other isolated areas including the one immediately E of Wood River-Alton.

The protrusion of the initiation region southeast of the city into the city proper suggests that part of the initiation may have been due to the city. Similarly, the initiation areas between Granite City and Wood River-Alton might be attributed to either, since both are sources of industrial effluents. Likewise, the initiation maximum in the bottomlands may have been influenced by the Portage de Sioux power plant which is located approximately at the center of the initiation area. In addition, some of the initiation maxima are in locations such that the hills and bottomlands could be contributing factors. [Note: Metromex personnel have noted on several occasions the formation of cumulus clouds in the areas of Wood River-Alton and Portage de Sioux. A photographic example of such cloud development is shown by Henderson and Duckering (1972).]

From a survey performed by Venezia and Ozolins (1966) and from information provided by Metromex personnel, all known industries were plotted on a base map. This is not a complete inventory of industries, but many of the major industries could be located in this manner. From this base map, the fossil fuel steam electric plants, petroleum refining plants, and the major chemical plants were derived and superimposed on figure F-9. The results are shown in figure F-10.

The band of 3 initiation maxima southeast of the heavy industries in St. Louis and East St. Louis should be noted. The size and shape of this band corresponds roughly to the size and shape of the heavy industries. Can this preferred initiation area be attributed to the industries in St. Louis? If one assumes the cell speed to be 15 mph (average cell speed was 10 mph, table F-10) and the duration of the cumulus stage of cloud development to be 15 min, then it is possible for building cumulus clouds to move approximately 4 miles or more prior to the occurrence of precipitation. The distance between industries and initiation areas is 5-6 miles in figure F-10. Thus, it is not inconceivable that clouds could begin forming over the industrial areas and move downwind where the initiation of surface raincells would correspond to the beginning of the mature stage and to the onset of the downdraft at the surface.

To complicate the situation further, and to indicate the difficulty in evaluating the initiation maps, the hills and the bluffs (sharp changes in elevation of 150-250 feet) were superimposed on figure F-10, with the results shown on figure F-ll. It is indicated on figure F-ll that the isoline of 1 approximates the region of the bluffs and that 2 of the 3 maxima lie on the bluffs. Furthermore, 2 of the 3 maxima lie ENE of the hills. Thus, we have two more possible explanations

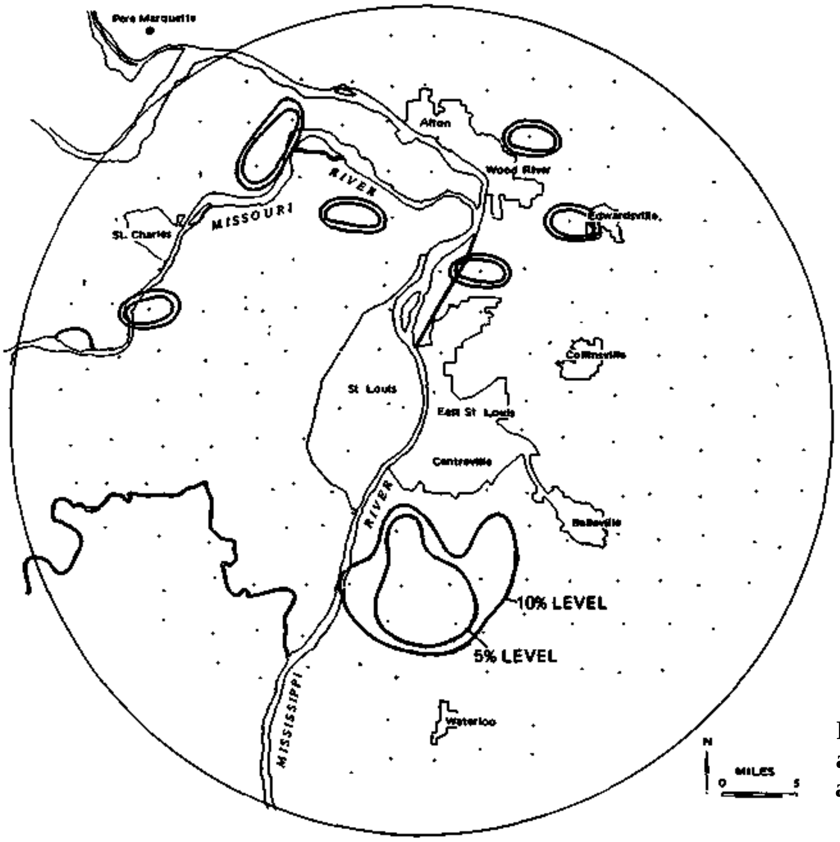


Figure F-6. Significant initiation areas as determined by trend surface analysis for June 1971-1972

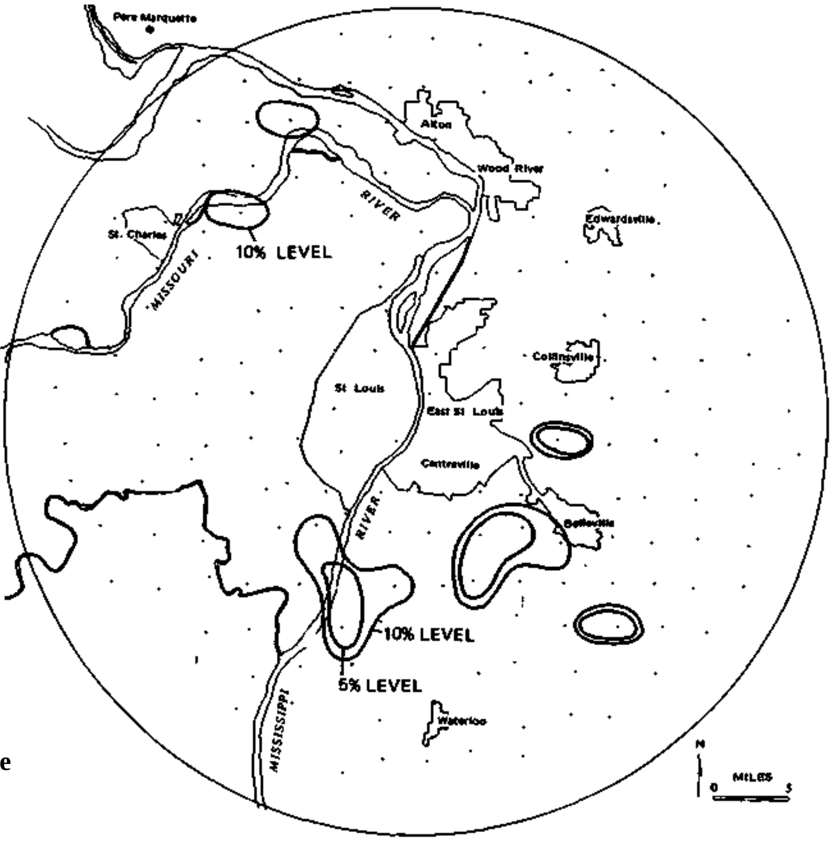


Figure F-7. Significant initiation areas as determined by trend surface analysis for July 1971-1972

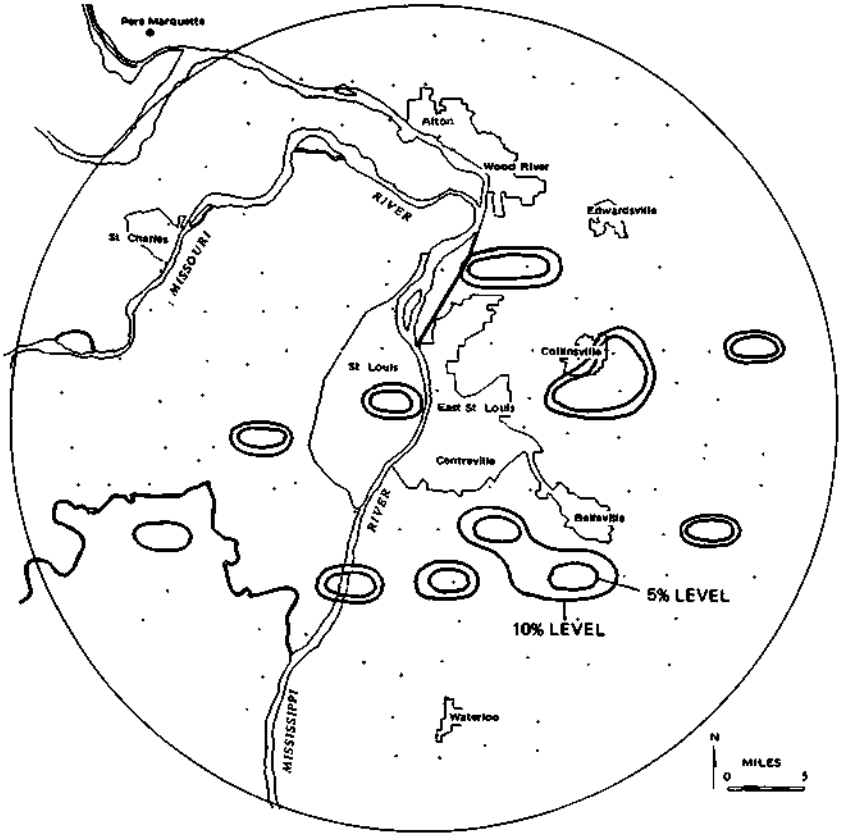


Figure F-8. Significant initiation areas as determined by trend surface analysis for August 1971-1972

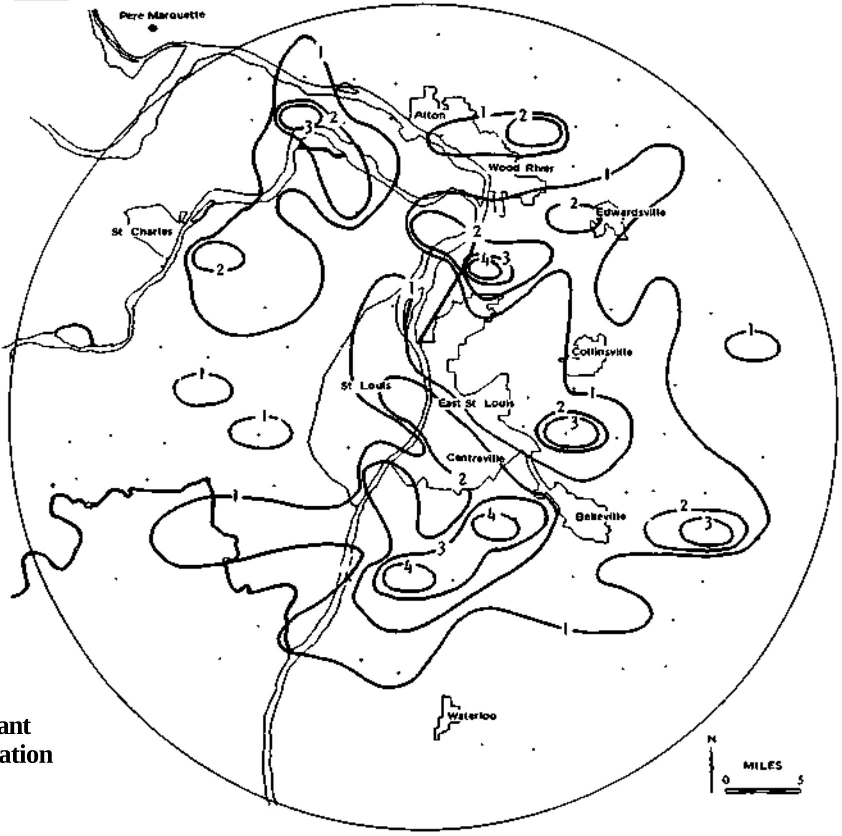


Figure F-9. Number of times each gage was included in a 10% significant initiation area on the monthly initiation maps for summers 1971-1972

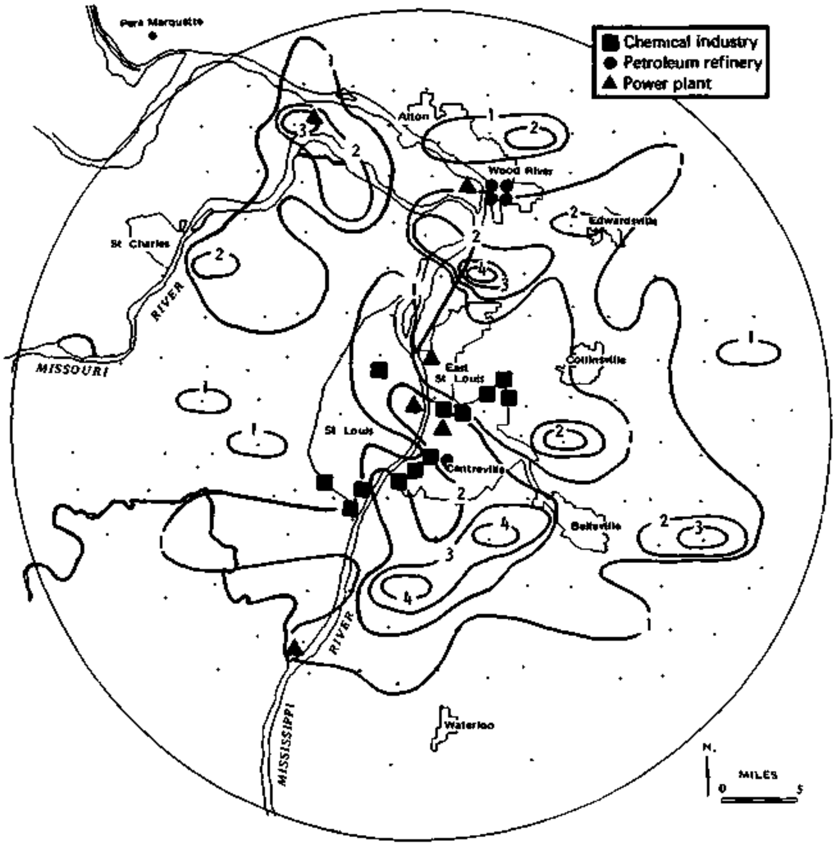


Figure F-10. Relation between locations of major industrial operations and number of times each gage was included in a 10% significant initiation area during 1971-1972

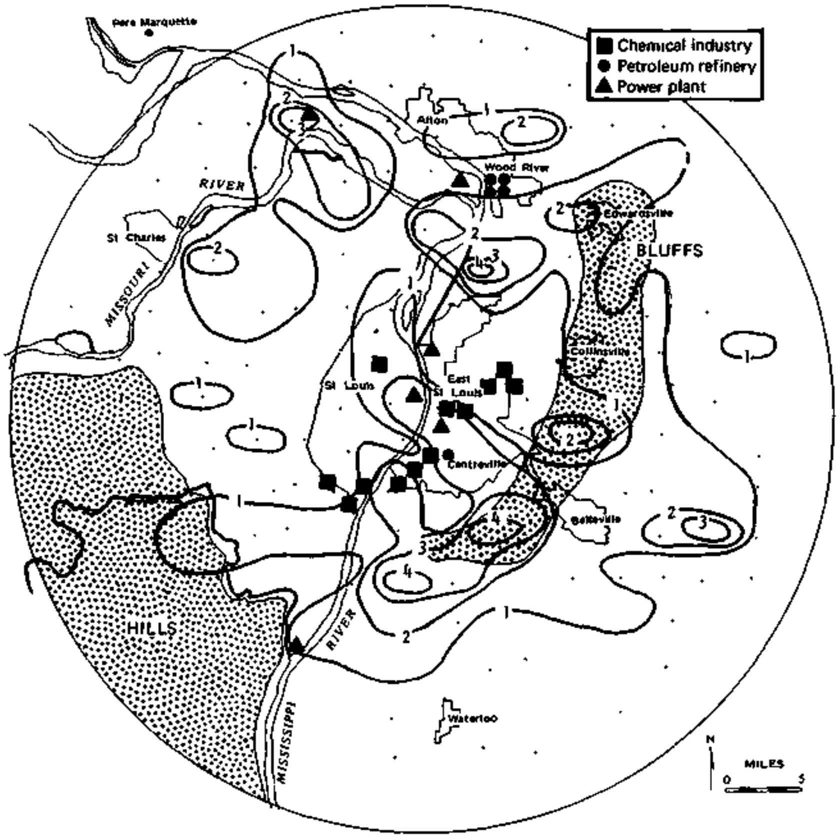


Figure F-11. Relations between locations of major industrial operations, hill region, and bluffs and number of times each gage was included in a 10% significant initiation area during 1971-1972 for the initiation maxima. It is quite possible that all three factors (industries, hills, and bluffs) contributed to the initiation maxima. The industries, hills, and bluffs are also shown in figure F-12 in conjunction with the 5% significance initiation areas instead of the 10% ones.

Since it is conceivable that the initiation maxima could have been produced by the industries, the following question is raised. Are the numbers of cell movements from northwest to northeast sufficiently large to lend support to this concept? The direction of cell movements for the summer of 1971 are shown on figure F-13. The preferred direction of cell movement is toward the ENE. However, there are 54 occurrences of cell movements in the sector from 110 to 170 degrees. The maximum of cell movements toward the ENE supports the concept that the hills are a contributing factor, whereas the number of occurrences in the 110 to 170 degree sector support the concept that industries are the contributing factor.

It is of interest to consider the initiation maximum immediately north of Granite City in view of the information in figure F-13. With the preferred cell movements indicated on figure F-13, cells in this preferred initiation area had ample opportunity to be influenced by the city as well as Wood River-Alton. Furthermore, the Granite City initiation center is frequently upwind of the seasonal rainfall maximum in the Edwardsville area (see Section A), so that intensification of these initiated cells with time could contribute substantially to production of the Edwardsville seasonal rainfall maximum. In order to investigate these factors further, future studies will include the identification of each cell in the various maxima, and a description of the wind environment of each.

Summary and Conclusions.

Analyses of the 1971-1972 raincell data have provided a substantial amount of information and knowledge that will be useful for future determination of the precise causes of inadvertent precipitation modification.

According to Byers and Braham (1949), the surface rainfall pattern under a thunderstorm follows closely the arrangement of cells, and reflect, to a considerable extent, the various stages of development. In Metromex, small isolated precipitation areas in the surface rainfall patterns, characterized by closed isohyets of high intensity gradients, are designated as surface raincells. The underlying assumption of the raincell analyses is that changes which occur in the surface raincell parameters in the vicinity of urban-industrial sources are broadly indicative of induced changes in the cloud precipitation processes. Thus, the analyses of surface raincells in the vicinity of urban-industrial complexes yield insight into the physical processes involved.

Because of numerous problems involved in a non-randomized experiment on inadvertent precipitation modification, the analysis plan chosen was that of "data analysis." In this approach, the final proof and acceptance of inadvertent modification does not rest entirely upon statistical evidence and results from tests of hypothesis. The test statistic is treated as an informative, summary statistic and is to be clearly distinguished from the concept of the test statistic as a strict accept-reject rule.

The data analysis approach is used to compare the various parameters of cells hypothesized to be in regions where they could potentially be altered by the urban environment with those cells not altered by the urban environment. The delineation of these effect and no-effect cells is complicated by the uncertainty of the source of treatment agents and the manner in which they are transported and interchanged with cells aloft. Because of this uncertainty, several stratification

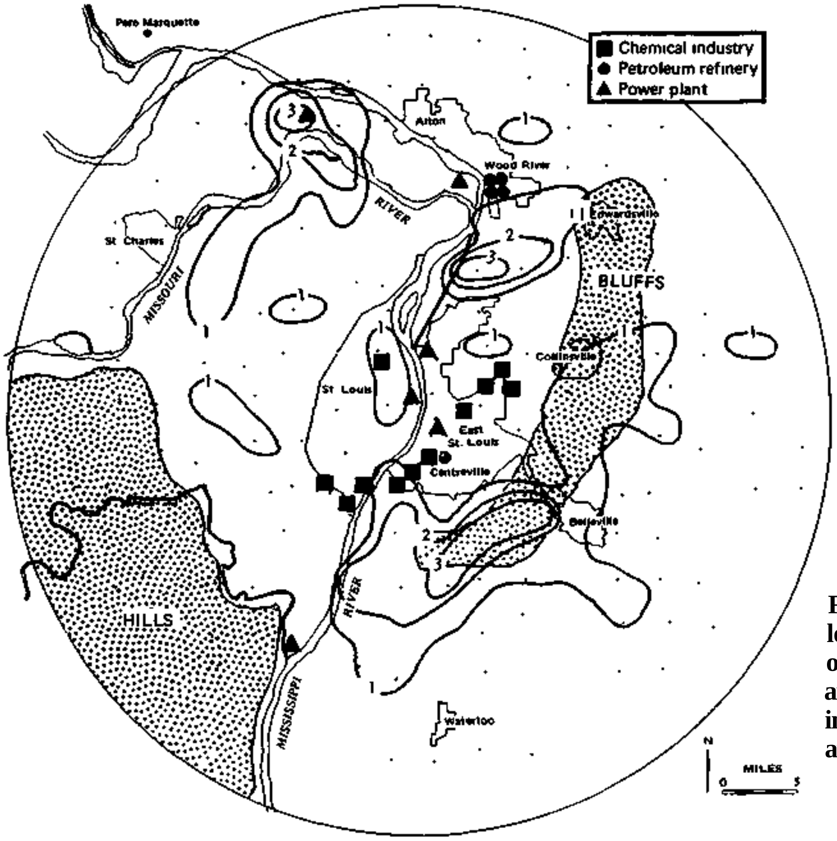


Figure F-12. Relation between locations of major industrial operations, hill region, and bluffs, and number of times each gage was included in a 5% significant initiation area during 1971-1972

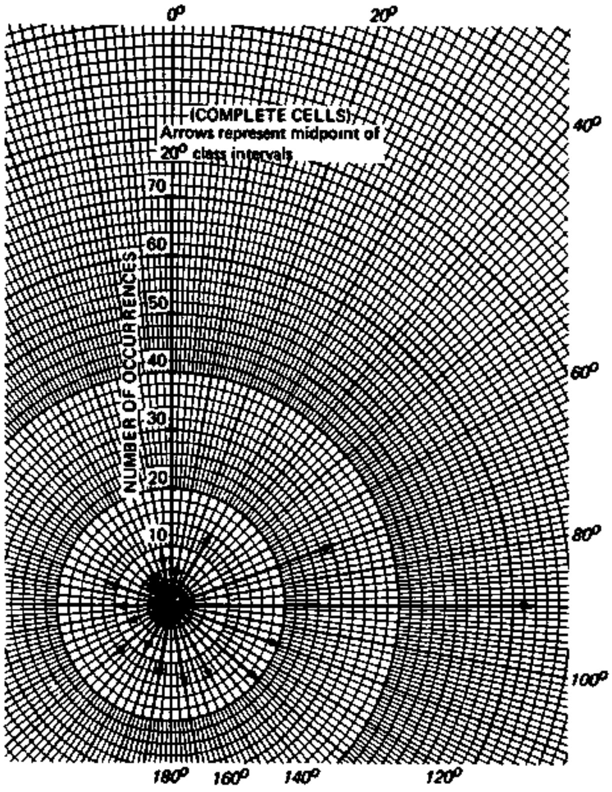


Figure F-13. Direction toward which raincells moved during summer 1971 methods were used which only approximate the true effect and no-effect cells. However, by studying the various stratifications, speculation can be made concerning the most likely sources, and their potential contributions can be explored. For all comparisons, the basic comparison statistic was the percent difference between the effect mean and the no-effect mean (control). In addition, the t-statistic was computed and used as a summary statistic, but not as a strict accept-reject rule.

The major results and conclusions derived from the various stratification analyses are listed below:

1) For cells that occurred in the *urban-industrial region of St. Louis-Belleville,* the rainfall volume was 131% greater than for cells in the control sample. The increases in average rainfall, areal extent, and duration were 19, 90, and 24%, respectively. The increase in rainfall volume was present in both stationary and moving cells. With the exception of rainfall volume, the parameter with the next greatest percent increase was areal extent. It was found that the areal extent was the largest while the cells were in the city, less after the cells had been in the city, and least prior to the time the cell reached the city.

2) For cells that occurred in the *industrial region of Wood River-Alton,* the rainfall volume was 225% greater than for cells in the control sample. The increases in average rainfall, areal extent, and duration, were 65, 61, and 15%, respectively. The increase in rainfall volume was present in both stationary and moving cells. With the exception of rainfall volume, the parameter with the next greatest percent increase was maximum rain/5-min. It was found that the average rainfall was the greatest while the cells were in the Alton-Wood River region, less after the cells had been in the region, and the least prior to the time the cell reached the region.

3) For cells that occurred in the *bottomlands region,* the rainfall volume was 19% greater than in the control sample. Of all hypothesized treatment regions, this region had the smallest percent differences and the smallest t-values.

4) For cells that occurred in the *hill region,* the rainfall volume was 48% greater than in the control sample. The increase in average rainfall and areal extent was 37 and 48%, respectively, but only 3% for duration.

5) For those cells receiving a *double treatment effect,* the rainfall volume was greater than with any other stratification (with the exception of Wood River-Alton). For cells which *crossed both the hills and St. Louis-Belleville,* the rainfall volume was 225% greater than in the control cells. For cells which *occurred both in the bottomlands and Wood River-Alton,* the rainfall volume was 261% greater than in the control sample. These cells also had the longest path lengths and durations, and the smallest sample sizes. Thus, no firm conclusion can be drawn without more years of data; however, the size of the t-values would indicate that these differences will be present in future years also.

6) The most frequent *initiation area* was approximately 6 miles southeast of the largest industries in the St. Louis and East St. Louis area. This initiation area is also located approximately 10-11 miles east of the hills and lies in the vicinity of the bluffs on the east side of the river. It is very probable that all three factors (hills, industries, and bluffs) contributed to the preferred initiation area. Other prorninent initiation areas were located in St. Louis, at Granite City, in Wood River-Alton, and in the vicinity of the Portage de Sioux power plant. Whether the above-mentioned sources were in fact the cause of the various preferred initiation areas awaits further investigation.

7) There is an indication that the treatment effect endures for an indefinite length of time beyond the period of treatment, but that the treatment effect is limited in areal extent, and thus the *modification of precipitation processes occurs relatively close to the urban-industrial regions.* This indication was based on analyses of 1971 data only, and more data must be analyzed before a firm conclusion can be made.

8) There are strong indications that the *physical processes* involved in the modification of raincell parameters in the St. Louis region were different from the physical processes in the Wood River-Alton region. The explanation of these differences must await the completion of the detailed studies of radar, rain drop, and aircraft data.

Overall, there is very strong evidence that the cell parameters have been altered by the urban-industrial environment. In some of the analyses, the differences between effect and no-effect raincell parameters are so great, and the sample sizes are so large, as to leave little doubt as to the reality of these differences. However, in certain stratifications — notably the double treatment area, cell history analysis, and the moving-stationary stratifications — additional data must be collected before confidence can be placed in the results. Many additional analyses are planned such as 1) synoptic, 2) time of day, 3) wind duration and speed, and 4) elapsed time prior to the maximization of cell rainfall.

Acknowledgment. Appreciation is expressed to Marion Busch who performed most of the computer analyses, assisted in the development of computer programs, and supervised various other critical analyses.

References

Braham, Roscoe, R., Jr. 1952. *The water and energy budgets of the thunderstorm and their relation to thunderstorm development.* Journal of Meteorology, 9(4).

Byers, H. R., and Roscoe R. Braham, Jr. 1949. *The Thunderstorm.* U. S. Weather Bureau, Government Printing Office, Washington, D. C, 287 pp.

Changnon, Stanley A., Jr. 1971. *1971 operational report for Metromex.* A compilation of reports from cooperating research groups, prepared by the Illinois State Water Survey. 93 pp.

Changnon, Stanley A., Jr., and Paul T. Schickedanz. 1971. *Statistical studies of inadvertent modification of precipitation.* Preprints, International Symposium on Probability and Statistics in the Atmospheric Sciences, Honolulu; AMS, Boston.

Henderson, Thomas J., and Donald W. Duckering. 1972. *A summary of operations conducted by Atmospherics Incorporated.* Fresno, California; report prepared for Illinois State Water Survey, 26 pp.

Huff, Floyd A., and Paul T. Schickedanz. 1970. *Rainfall evaluation studies.* Illinois State Water Survey for NSF Grant GA-1360. Final Report, Part II. 224 pp.

Flueck, John A. 1971. *Statistical analyses of the ground level precipitation data.* University of Chicago for NSF Grant GA-20470. Final Report, Part V. 294 pp.

Jones, Douglas M. A., and Arthur L. Sims. 1971. *Climatology of instantaneous precipitation rates.* Illinois State Water Survey for Contract F19628-69-C-0070. Final Report. 44 pp.

Schickedanz, Paul T. 1972. *The raincell approach to the evaluation of rain modification experiments.* Preprints, 3rd Conference on Weather Modification, Rapid City, S. D.; AMS, Boston, 336 pp.

Schickedanz, Paul T. 1973. *A statistical approach to computerized rainfall patterns.* Preprints, 3rd Conference on Probability and Statistics in Atmospheric Science, Boulder; AMS, Boston.

Simpson, Joanne, and Victor Wiggert. 1971. *Florida cumulus seeding experiment: numerical model results.* Monthly Weather Review, 99(2):87-118.

Tukey, John W. 1962. *The future of data analysis.* Annals of Mathematical Statistics, 33(1).

Venezia, R., and G. Ozolins. 1966. *Interstate air pollution study phase II project report, II: air pollutant emission inventory.* U. S. Department of Health, Education, and Welfare, Cincinnati, Ohio, 50 pp.

G. SURFACE MEASUREMENTS OF CONDENSATION NUCLEI AND RAINDROP DISTRIBUTIONS

Robert Cataneo

Condensation Nuclei Measurements in 1971

During 1971 condensation nuclei measurements were made at the Pere Marquette base station for the period June-August. The data were taken at ground level with a Gardner Associates small particle detector, type CN. The measurements were made hourly at one level of supersaturation (~ 250%).

Average nuclei values per tens of degrees wind direction at Pere Marquette are shown in figure G-l for the 3-month period. There is an obvious increase in nuclei counts in the southeast quadrant which is in the direction of the industrial complex in the St. Louis area. There is little doubt that the concentration of particulate matter produced by the urban-industrial complex is significantly above background rural levels, and is detectable at a distance of at least 25 miles (Pere Marquette).

Raindrop Distributions in 1972

Since climatological data in the St. Louis area indicate downwind increases in rainfall, the microphysics of the precipitation processes are likely altered. To investigate this possibility, raindrop distributions were measured in the St. Louis region. The distribution of raindrop spectrometers is shown in figure G-2.

At this time, data from two of the eight sites have been analyzed; these are at the Centreville (CEN) and Pere Marquette (PMQ) sites. The CEN location is within the area of apparent urban-induced increases in precipitation (Section A), whereas PMQ is sufficiently far from industrial areas to be considered rural. At these two locations, Joss spectrometers were utilized to determine the raindrop distributions. These devices were purchased commercially and function by converting the momentum of a raindrop impinging upon a sensor surface to drop size. At the remaining sites, in-house manufactured devices that operate on a similar principle were used.

During Metromex operations in 1972, raindrop data collected on 10 days at PMQ and 14 days at CEN were analyzed and compared; this provided a total of 275 five-minute rain samples at PMQ and 422 at CEN. The total number of drops at intervals of 0.1-mm diameter is shown in figure G-3 for all drops combined. If these totals are divided by the number of 5-minute samples, the average number of drops per 0.1-mm diameter interval results and is demonstrated in figure G-4. The data indicate an obvious difference in the distributions; the PMQ data show a much larger concentration of drops although the average rainfall rate for that site is approximately 1/2 that of CEN. The radar reflectivity (Z) values also reflect the distribution differences; this parameter is approximately 5-fold greater for CEN. This is expected since Z is dependent on drop diameter to the sixth power and figures G-3 and G-4 reveal consistently greater numbers of the larger drop sizes for CEN.

On three rain days, data were collected at both PMQ and CEN; this allowed a comparison of drop spectra for similar rain periods. Figures G-5 and G-6 compare average raindrop distributions for both locations for certain average rainfall rates. With the exception of figure G-5d, these individual comparisons agree with the general results shown in figures G-3 and G-4, indicating greater drop concentrations at PMQ for similar rainfall rates.

On the basis of the data analyzed to date at these two locations, it is concluded that the downwind, urban-affected location (CEN) has fewer, larger raindrops for similar rainfall rates, as well as generally higher rainfall rates, than the site at PMQ.

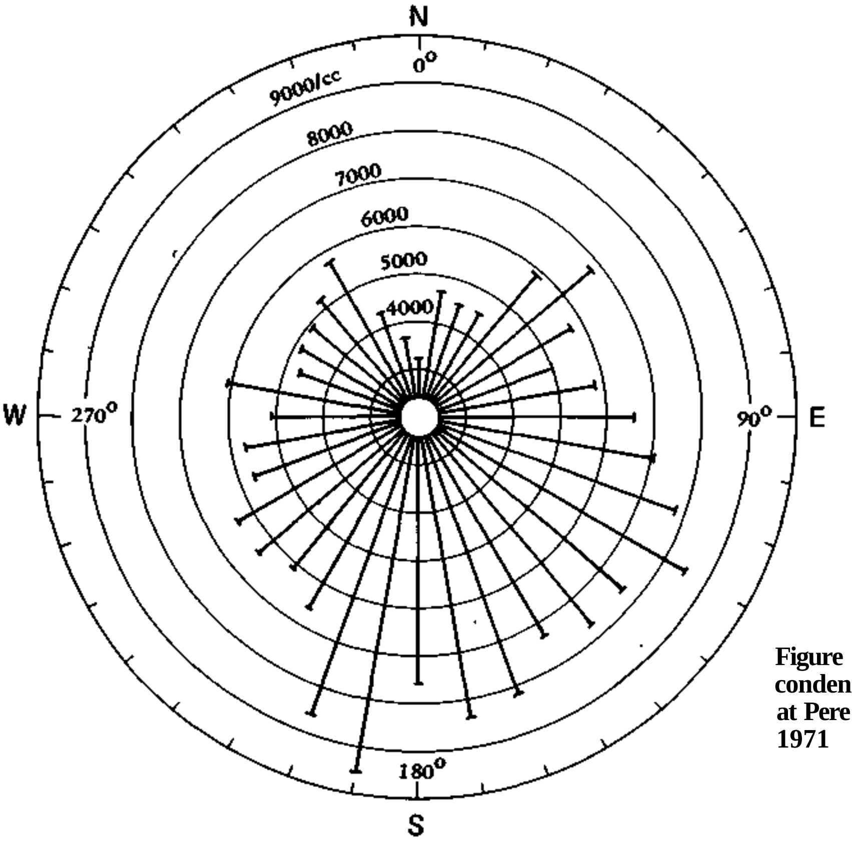


Figure G-1. Relation between surface condensation nuclei and wind direction at Pere Marquette during June-August 1971

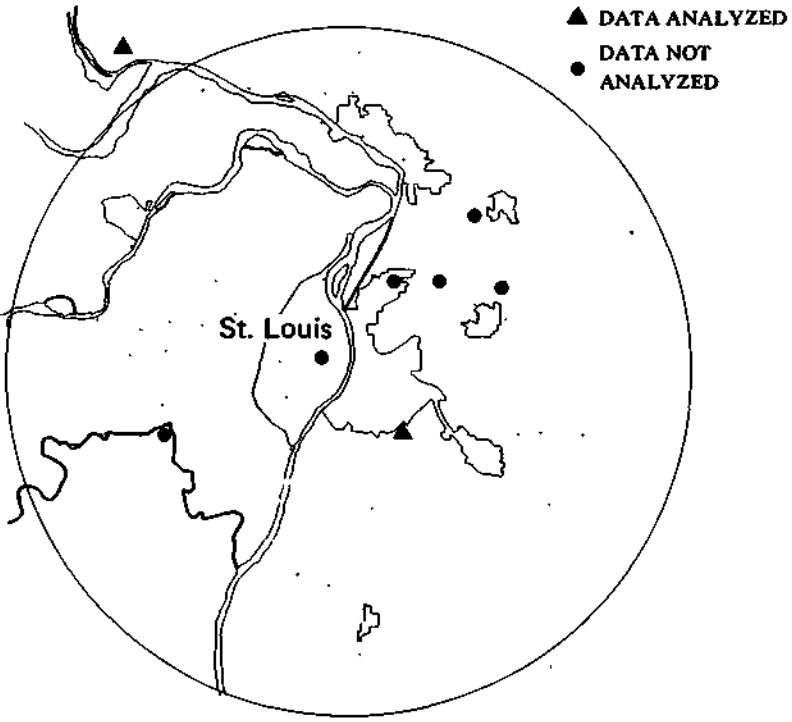


Figure G-2. Raindrop spectrometer locations in 1972

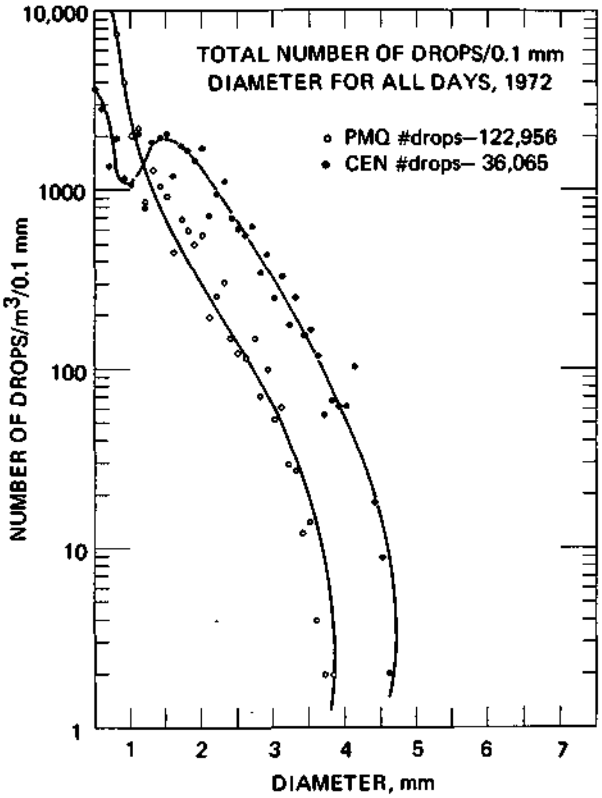


Figure G-3. Number of drops and drop diameters at PMQ and CEN in 1972

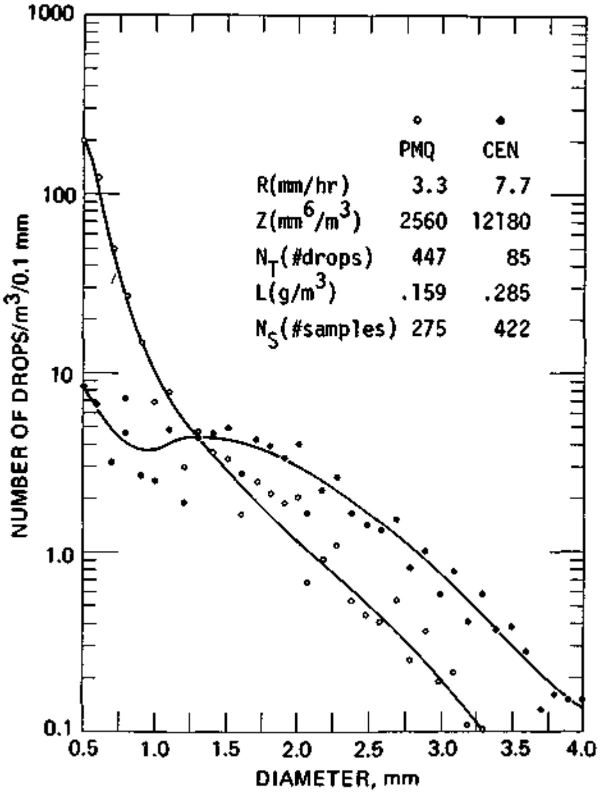


Figure G-4. Average raindrop distributions at PMQ and CEN for all days during 1972

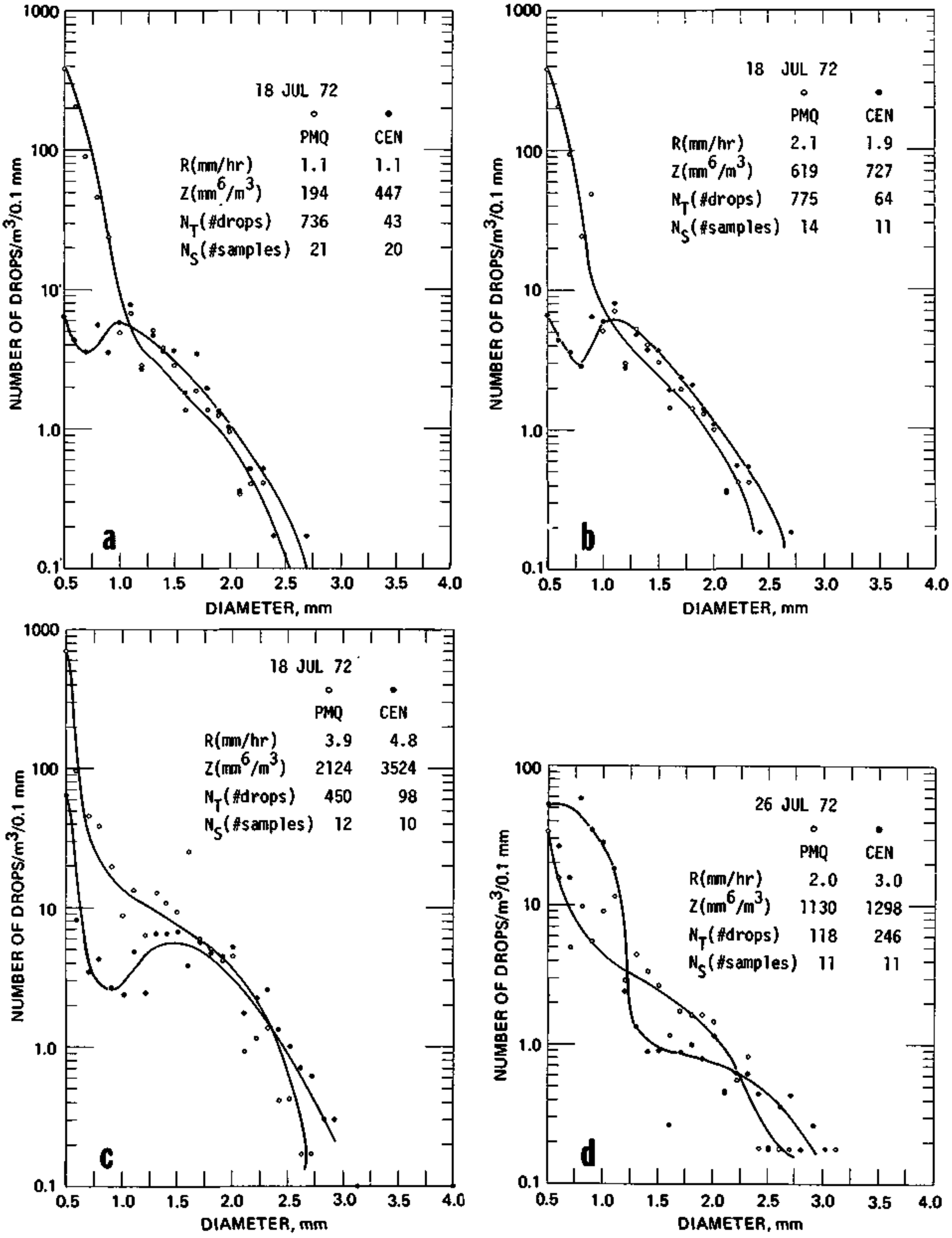


Figure G-5. Average raindrop distributions at PMQ and CEN for similar rainfall rates, on given dates in 1972

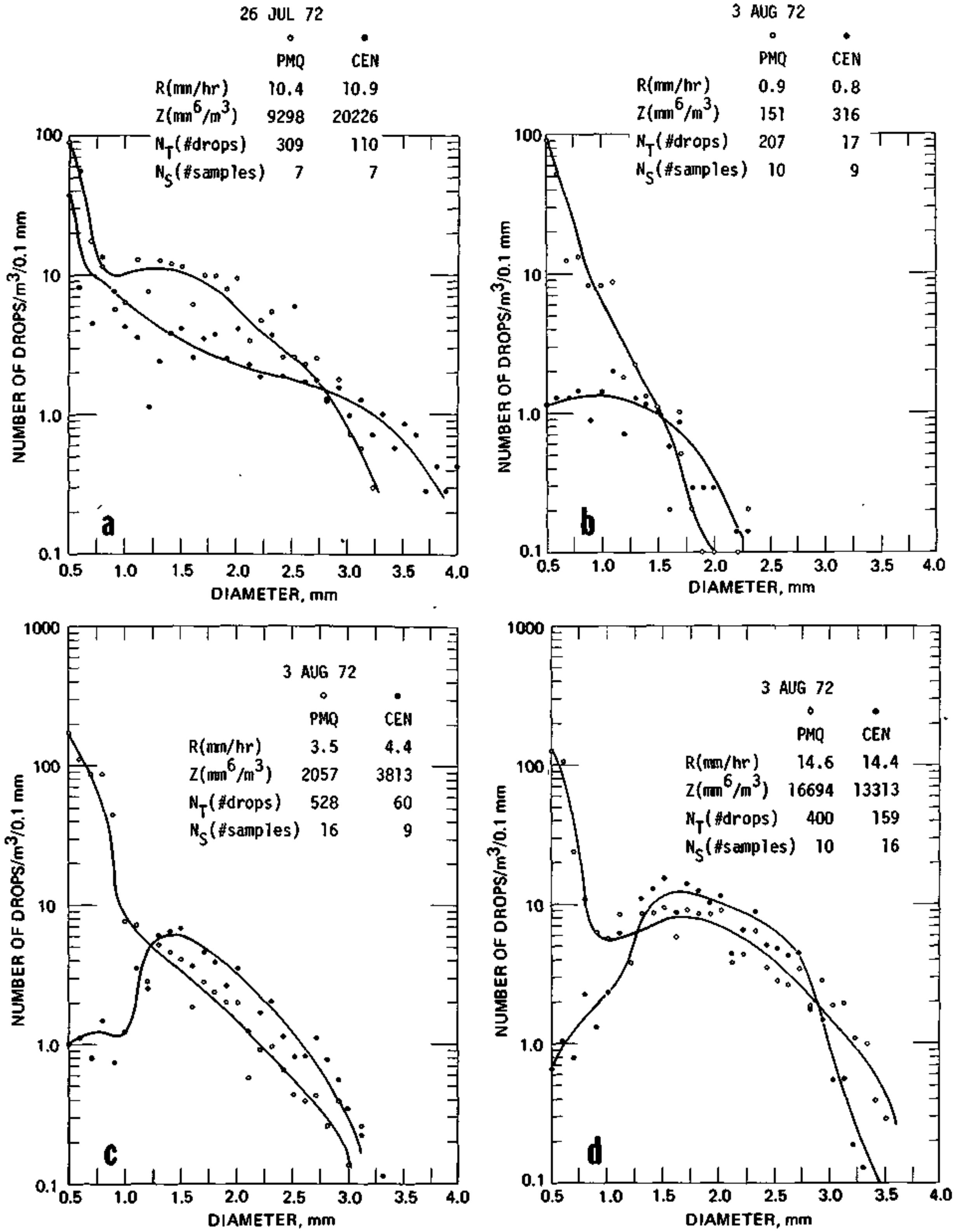


Figure G-6. Average raindrop distributions at PMQ and CEN for similar rainfall rates, on given dates in 1972

H. METROMEX SURFACE WINDS

Douglas M. A. Jones

Introduction

The surface network of wind-measuring equipment especially installed for Project Metromex consisted of six instruments. These were sited as shown on figure H-l and were generally on the perimeter of the Metromex research circle. No location changes were made between 1971 and 1972.

The wind recorder at the Pere Marquette (PMQ) radar headquarters was a Bendix-Friez Aerovane system with electric synchronous strip chart drive. Occasional missing records were caused by failure to change the chart and malfunction of the inking system of the recording pens. The speed and direction sensor was located approximately 15 feet above the crest of the ridge on which the radar antennas were located. The northwest-southeast orientation of the ridge would tend to bias the recorded wind directions toward the axis of the ridge to an unknown extent, and the crowding of streamlines rising over the ridge would tend to increase the recorded wind speed above ambient by approximately 5%. Although there are no obstructions to the wind field about the sensor, the site was surrounded by heavily wooded and lower hills. The sensor was sited on the highest hill within Pere Marquette State Park.

The wind recorder at the Alton Civic Memorial Airport used a speed sensor consisting of a beaded-rim, truncated-cone, three-cup design whose rotation was translated into a proportional dc voltage through an attached generator. The voltage was recorded as speed-equivalent in analog form in miles per hour (mph) on a mechanical clock-driven strip chart moving at 3 inches per hour. Starting speed of the cups was about 1 to 2 mph and recording accuracy was ±1 mph.

The wind direction was sensed by a wind vane approximately 3 feet in total length whose position was detected by 8 electrical contacts fastened to the vane shaft. The brush and contact arrangement was such that shorting contact was made between two adjacent direction contacts when the wind direction was between them. Thus, the intermediate directions as well as 8 points of the compass were indicated by the 8 event-recording pens that write on the strip chart recorder used for both speed and direction. The two sensors were mounted on a mast approximately 12 feet above grade. No obstacles taller than the recorder housing at 4 feet height were closer than 300 feet to the wind instrument. Data were lost occasionally because of clock failure, low voltage (12 v dc) to the direction recorder, or failure of the ink supply to the 9 recording pens.

The wind instrument at the Nagel Farm was sited in a clear, flat area with the closest obstacle an east-west railroad embankment approximately 100 feet to the south. The area was open in all other directions for at least 300 feet with a grove of trees to the east at that distance. The instrument is a duplicate of the Alton system and subject to the same data losses.

The Waterloo wind set was sited on a very slight prominence surrounded only by lawn to the north and corn or soybean fields to the south. A small fruit tree was growing approximately 30 feet southeast of the wind instrument. All other obstacles were less than half the height of the sensors at approximately 15 feet. This installation was a duplicate of the Alton installation.

A wind set was sited at the Weiss Airport in the Meramec River Valley southwest of downtown St. Louis. The instrument was located about 30 feet west of the north-south runway and had no obstructions within 300 feet of the site. The area is relatively protected since the airport is located in a wooded valley. No particular wind direction would appear to be favored, however. The instrumentation was a duplicate of the Alton equipment with the sensors about 12 feet above grade.

The sixth wind set was installed at the Spirit of St. Louis Airport in the flat flood plain of the Missouri River west of downtown St. Louis. The edge of the river valley was in the distant south with no obstructions within 500 feet of the instrument. The sensors were about 12 feet above grade. The equipment was a duplicate of the Alton wind set.

Data Collection and Results of Analyses

The operational period for the wind sets was from mid-June until 1 September 1971 and from 1 June until 1 September 1972, except for the PMQ equipment which was operated year-round after mid-June 1971. Full abstraction of the data was limited to the summer months of June through August of both years. The abstraction of the data was patterned after the procedure in use at the St. Louis station of the National Weather Service, i.e., hourly values of speed and direction averaged over the period from 10 minutes before the hour until the hour. Results for the six months analyzed are summarized in the following paragraphs.

June 1971. All stations indicated a predominantly southerly component to the winds recorded during the month, although there was considerable dispersion toward easterly and westerly components in this southerly flow. PMQ was the only station indicating some northerly winds. Wind roses have been plotted in figure H-l with the roses centered on the station locations. The recorder at Waterloo was installed too late in the month to establish average wind directions.

Wind speeds averaged between 4 and 9 mph with the highest wind speeds of 16 to 18 mph measured at PMQ and Alton, from northerly directions.

July 1971. The recorder at Weiss Airport was inoperative during most of this month and its record is not shown.

The wind directions shown in figure H-2 for July 1971 were confused, with strong northerly and southerly winds at PMQ and northerly and southeasterly winds at Alton and Nagel. Waterloo and Spirit of St. Louis indicated somewhat of a predominance of southerly flow. The highest wind speeds were measured at Alton and **PMQ** at 22 to 24 mph.

August 1971. All of the stations were in operation during August 1971. The patterns of wind direction from these stations show both north and south directions predominating at PMQ north-northeast and south at Alton, north-northeast at Nagel and Waterloo, south-southeast at Weiss, and southwest at Spirit of St. Louis. However, at all stations the northerly winds were the strongest measured. The wind roses for August 1971 are shown in figure H-3.

June 1972. The wind roses for June 1972 are shown in figure H-4. Alton and Nagel had north-northwest winds and PMQ had north-northeast winds of some noteworthiness. The winds at Spirit of St Louis had no predominate direction. The predominate wind at Weiss was from the west-northwest and at Waterloo was from the southwest.

July 1972. The predominate wind direction at all stations in July was from a southerly quadrant as shown in figure H-5. All stations except Weiss had a westerly component. Weiss had a southeasterly component.

August 1972. The predominate wind direction at all stations in August, as in July, was from a southerly direction as shown in figure H-6. The peculiar omission of the south wind at PMQ Spirit of St. Louis, and Alton raises the question of bias on the part of the person extracting the data from the charts. The bias seems to occur at the primary points of an 8-point compass, i.e., 0, 45, 90, 135, 180, 225, 270, and 315 degrees.

Discussion

The wind set at Nagel averaged a state of calm winds approximately 40% of the time during the summer of 1971. During 1972, the June average was 30%, July 18%, and August 4%.

Such protracted periods of little wind movement seem unreasonable even though the Nagel site is somewhat sheltered. The 4% calm average in August 1972 seems to be more normal. In contrast, the recorders at PMQ, Waterloo, and Alton in much more exposed sites rarely experienced calm conditions.

In general, the two years of wind direction data do not show a trend which would indicate that a particular site was biasing winds blowing over it, except in the case of Weiss in August of both 1971 and 1972. The Weiss data do not agree with the surrounding stations in indicating a southwesterly wind, but showed a southeasterly wind instead. The expected biasing in direction at PMQ and Nagel did not appear. The Nagel instrument may have been insensitive, but this seems to have been corrected during summer 1972.

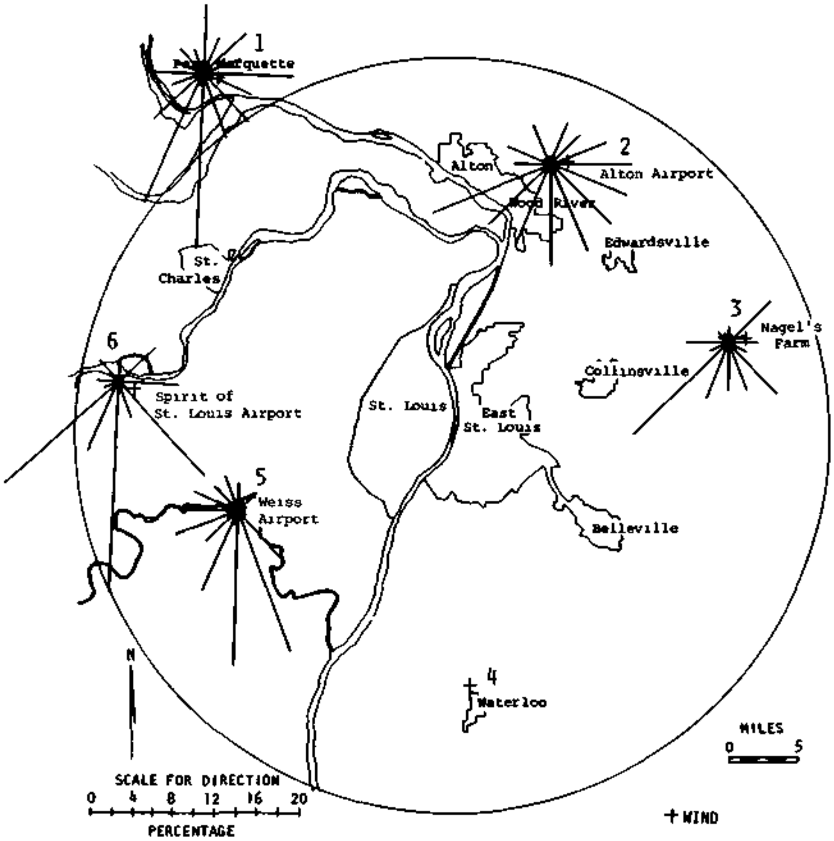


Figure H-l. Locations of wind stations and wind roses for June 1971

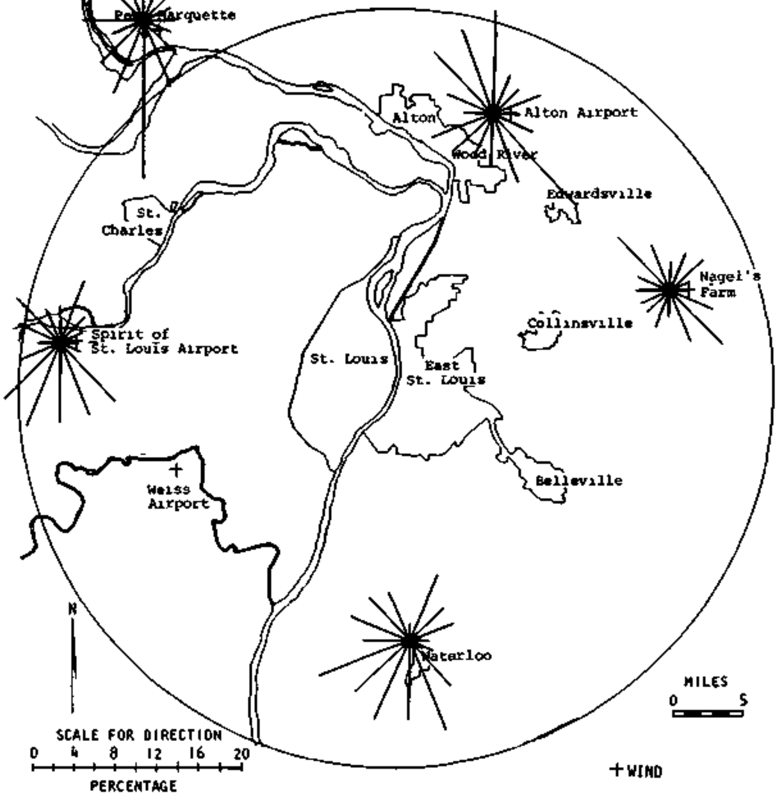


Figure H-2. Wind roses for July 1971

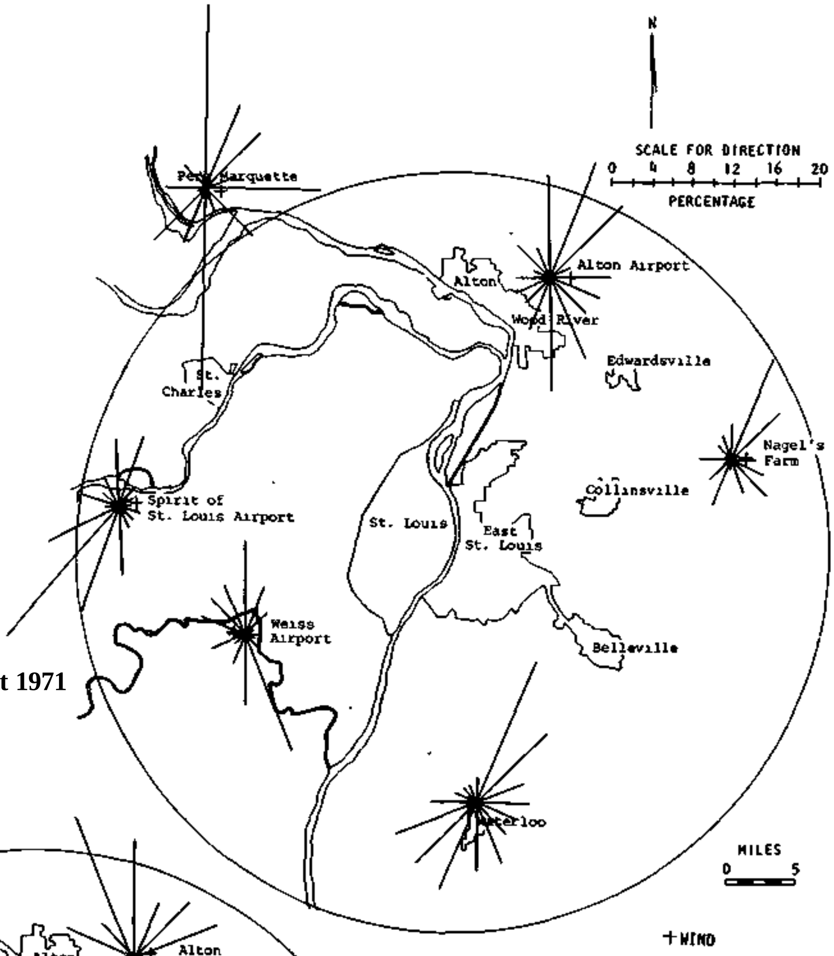


Figure H-3. Wind roses for August 1971

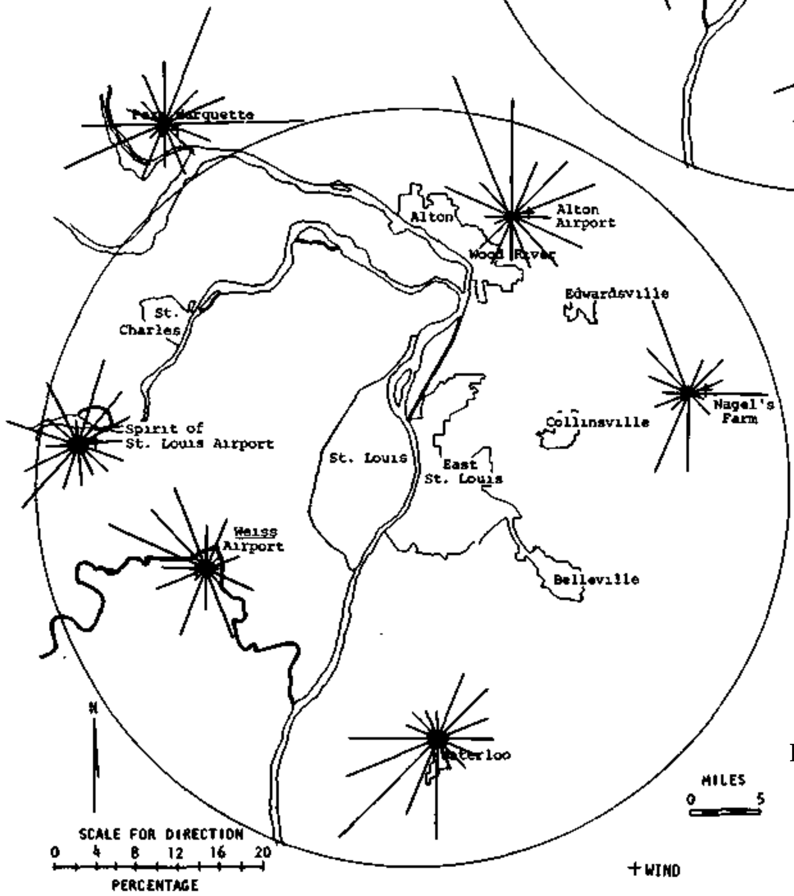


Figure H-4. Wind roses for June 1972

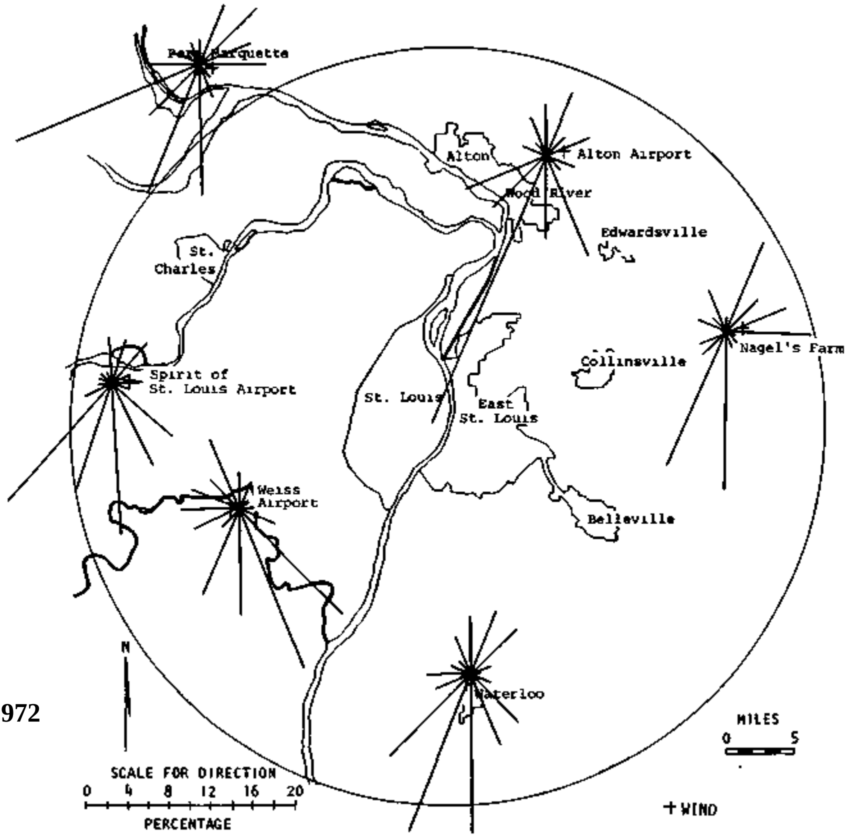


Figure H-5. Wind roses for July 1972

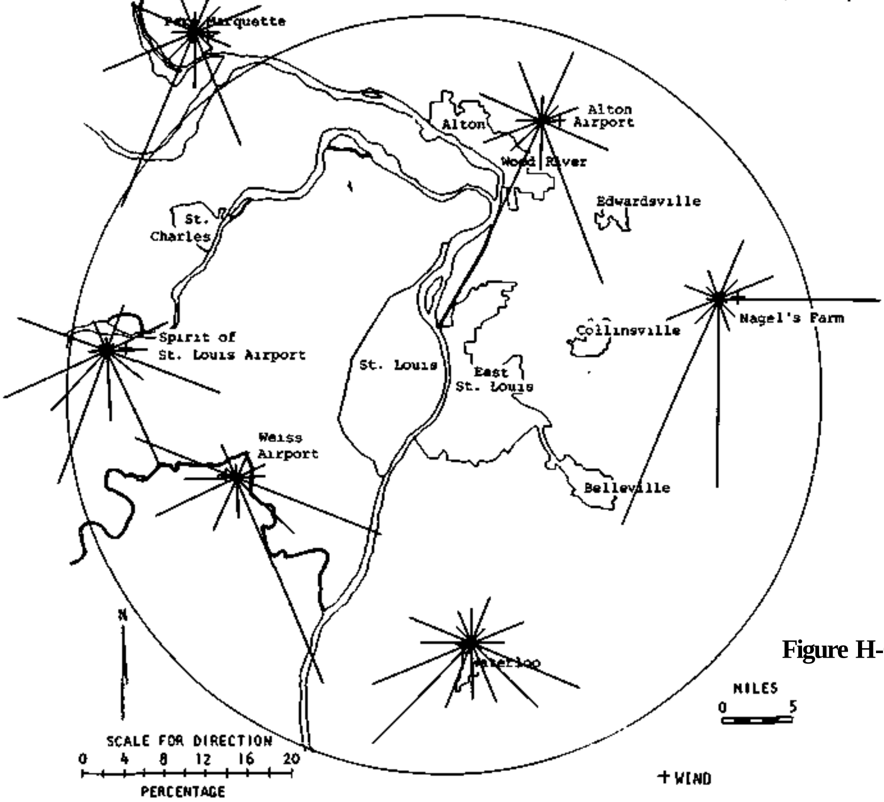


Figure H-6. Wind roses for August 1972

I. NETWORK SURFACE TEMPERATURE AND HUMIDITY

Douglas M. A. Jones

Sampling Network and Instrumentation

Surface temperature and humidity were recorded by hygrothermographs in standard Cotton Region shelters in both 1971 and 1972. Seven sites were in operation for the Metromex network during the summer of 1971. Used for these were five hygrothermographs manufactured by WeatherMeasure, Inc., and two manufactured by the Bendix Corporation. The WeatherMeasure instruments had a bi-metal temperature sensor and a hair bundle humidity sensor, which recorded onto a combined chart with 168-hr duration. The nearly logarithmic indication of humidity obtained from the hair-length changes was converted to nearly linear recording by a set of cams in the humidity linkage. The Bendix Corporation instruments used a bourdon tube for a temperature sensor and a harp of hairs as the humidity sensor. Except for these two differences the two types of instruments are similar.

Twenty-five hygrothermograph instruments in Cotton Region shelters were in operation during part or all of the summer of 1972. These sites are shown on figure 1-1. Seventeen of these instruments were of WeatherMeasure manufacture and 8 were Bendix instruments. Both types of instruments are capable of a recording accuracy of ± 1 F for temperature and ±2½% for humidity.

In 1971 the instruments were not sufficiently checked to insure accurate recordings. Hence, the 1971 data have been used only for studies involving limited inter-instrument comparisons. During the summer of 1972, a comparison with a sling psychrometer reading was made at the time of each chart change. These comparisons have been used to prepare corrections in temperature and humidity for the data reduced from the original recordings. Summer 1972 data from the 25 sites have been extracted from the charts and the corrections made. These corrected data have been punched into cards for machine calculation of the dew point temperature for each hour at each station. The data have been used in the special case studies of particularly interesting storms recorded during the summer.

Analysis

The temperature data at 3-hourly intervals from the hygrothermograph network of summer 1972 have been averaged for each station by months. In general, the 3-hourly temperature fields in the three months differ only in the temperature values; the patterns are the same. Only 17 sites had complete records during June and July, since the other 8 sites were not instrumented until late July. Hence, the greatest detail of pattern is to be found in the August data, and two hours from that month have been chosen to illustrate the patterns found in the research circle. These are the mean pattern for 0600 CDT (figure 1-1) representing the hour of transition between nocturnal radiational cooling and solar insolation, and the mean distribution for 1500 CDT (figure 1-2) representing the hour of maximum solar insolation.

August Mean Temperature Field at 0600 CDT. The greatest contrasts in temperatures between the urban complex and the surrounding rural areas (10.6 F) occur at dawn, as has been noted by other investigators. The measuring site at the Gateway Arch had the highest minimum temperature of 72.2 F. The coldest temperature (61.6 F) was measured at two rural sites, one at the Machens siding in the Missouri-Mississippi floodplain and the other south of the city of

Collinsville. A third cold spot was found south of St. Louis along the Mississippi River. The radar headquarters site in Pere Marquette State Park (PMQ) exhibits the expected reversal of temperature between day and night in comparison with plain or valley locations; the hill temperature remains relatively warm at night and relatively cool during the day. It will be noted that the river valley stations (Weiss Airport and Spirit of St. Louis Airport) were relatively warm at 0600 CDT.

August Mean Temperature Field at 1500 CDT. The difference between the warmest and coldest temperatures measured at 1500 CDT was 6.2 F. The urban heat island is still very much in evidence (figure 1-2), but the warmest temperature measured was at Spirit of St. Louis Airport in the Missouri River Valley. The Machens siding had a maximum temperature nearly as warm. This station had the greatest range in temperature of all measuring sites, 25.8 F.

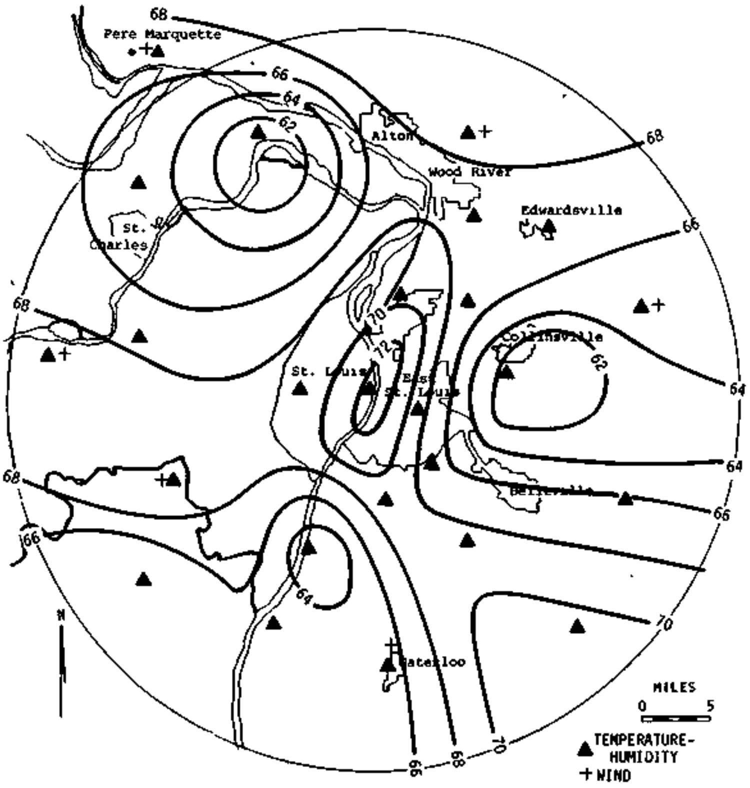


Figure 1-1. Mean temperature field at 0600 CDT for August 1972

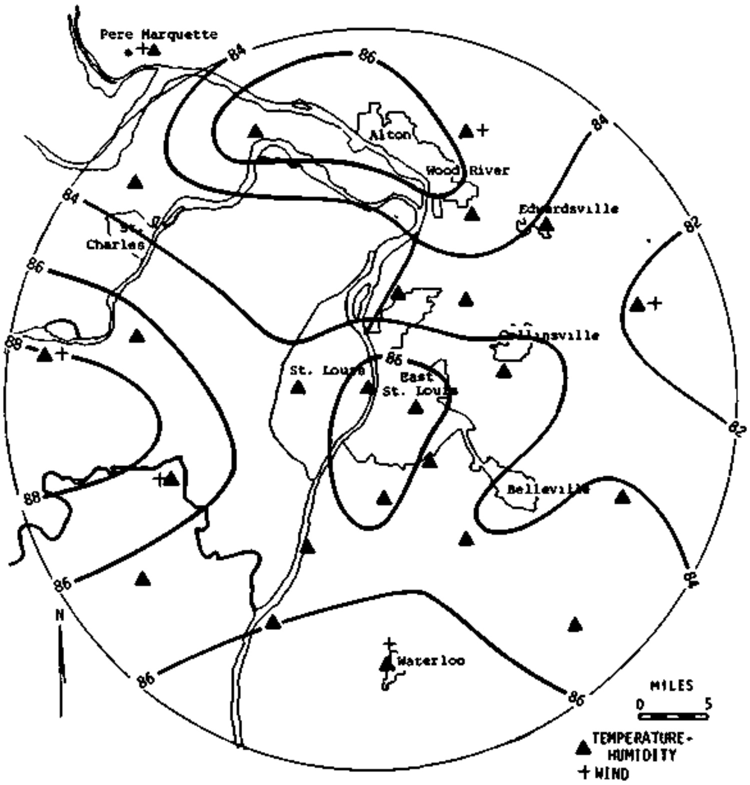


Figure 1-2. Mean temperature field at 1500 CDT for August 1972

J. RELATED STUDY OF URBAN EFFECTS ON SURFACE AND GROUNDWATER QUALITY

F. A. Huff

Introduction

In an earlier study of very limited data, evidence was found of an urban effect on runoff volume downwind of St. Louis (Changnon and Huff, 1972). Some evidence was found also that shallow groundwater aquifers were experiencing increased pollution in the downwind region. This would result most likely from a combination of increased scavenging of atmospheric particulates related to urban augmentation of rainfall, along with an increasingly polluted atmosphere with passing time. However, available data were inadequate and the quality of this data too questionable to make reliable conclusions. It was concluded that the water-supply pollution problem needed attention.

Consequently, in summer 1972, a small-scale pilot study was undertaken in conjunction with the Metromex field program to explore further the hydrologic implications of urban effects. The presence of a dense raingage network, a rainwater chemistry program, and tracer experiments made the pilot study possible at a minimum cost of equipment and personnel. Chemical analyses of water samples were limited to those being made with an atomic spectrometer in conjunction with rainwater chemistry studies sponsored by the Atomic Energy Commission.

In this pilot study, 6 wells in the shallow groundwater region were selected for routine sampling and chemical analysis of water. A small watershed of 22 mi^2, Canteen Creek, is located in the region of maximum urban effect on precipitation in the St. Louis area and was selected for a study of possible urban effects on surface water supplies. Figure J-l shows the location of the 6 well sites and the stream water sampling station.

This study was undertaken with a view to establishing a more comprehensive research program based upon knowledge and experience gained in the pilot study. Initial results of the pilot study are discussed here.

Well Water Analyses

Weekly water samples were obtained from the 6 wells during the June-August period. Locations 1,3, and 6 in figure J-l are very shallow, low production wells. Those at sites 2, 4, and 5 are used by industry and have relatively high production rates. Wells 4, 5, and 6 are in highly industrialized areas; wells 2 and 3 are in rural areas; and well 1 is near but not in the highly industrialized Wood River area.

To date, analyses have been made of lithium, sodium, and zinc concentrations in the water samples, and the pH of the samples. Lithium is an inert tracer released by aircraft in conjunction with certain Metromex atmospheric studies described in Section N of this report. Results are summarized in table J-l which shows weekly medians and their range in the June-August period, along with the total summer rainfall in the vicinity of each well. A relatively wide variation in medians is apparent between sites and the week-to-week range of concentrations at a given well was also highly variable in most cases. With regard to lithium, the medians were relatively low at the two rural sites, wells 2 and 3, compared with wells 4, 5, and 6 in the highly industrialized area of East St. Louis-Granite City. This indicates a possible external source of lithium from industrial activities in the St. Louis region. The lithium concentrations in the rural area wells (2 and 3) were comparable with the stream water concentrations which

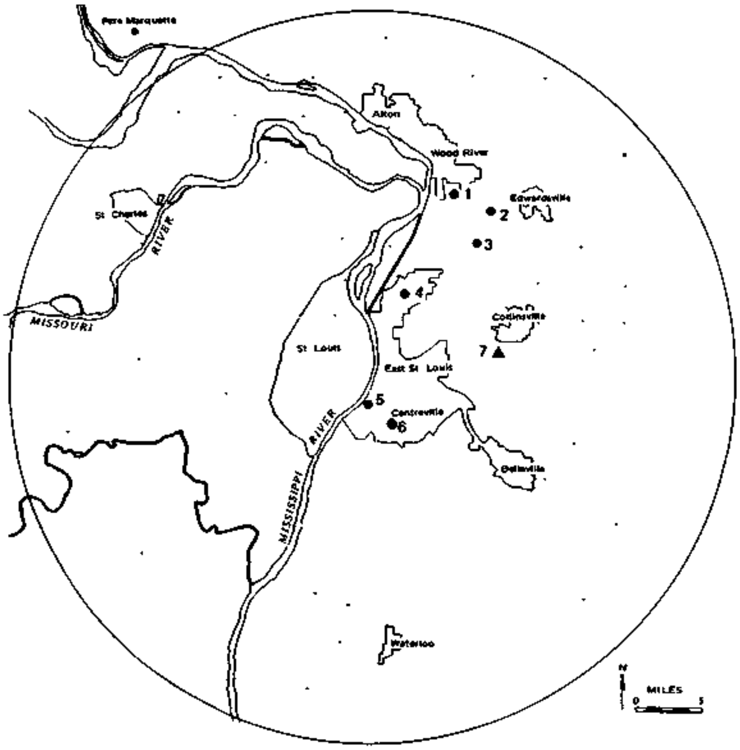


Figure J-l. Location of well water and stream water sampling sites

Table J-l. Median and Range of Weekly Well Water Concentrations, June-August 1972

Station	Li (ppb)	Na (ppm)	Zn (ppm)	pH	June-August rainfall (inches)
1	7.2 (3-11)	55.5 (40-58)	0.04 (.01-.08)	9.1 (8-10)	8.04
2	3.0 (2-9)	6.5 (6-7)	0.01 (0-.07)	7.5 (7-8)	10.41
3	7.9 (3-14)	13.5 (6-41)	0.21 (.01-.29)	8.6 (7-10)	11.25
4	22.9 (22-35)	12.5 (11-39)	0.01 (.01-.03)	7.3 (7-8)	9.50
5	29.1 (28-40)	24.0 (23-39)	0.01 (0-.05)	7.2 (7-8)	9.86
6	26.7 (5-36)	40.5 (12-49)	1.04 (.01-3.60)	7.5 (7-9)	9.35

had a median of 9.8 ppb at the Canteen Creek site (station 7 in figure J-l). The lithium released as an atmospheric tracer was not of sufficient concentration to be detected in the groundwater aquifers.

Two of the three lowest median concentrations of sodium occurred at the two rural area wells. No distinct trend was noted for the median values of zinc and pH to vary between the rural and the highly industrialized areas. No significant trend in concentrations was apparent between the shallow, low production and the high production wells.

Stream Water Analyses

Routine weekly samples were taken on Canteen Creek (figure J-l) from 9 June to 14 September. Occasionally, special samples were taken when rain was expected in the watershed area, and/or when tracer releases were scheduled. Unfortunately, in several of the special cases, rain on the network did not extend over the small watershed. Also, because of communication and scheduling problems, only part of the tracer releases were preceded and followed by stream water sampling.

Within limits of the data for 1972, it appears that the natural lithium concentration in the stream changes significantly following heavy rainfalls because of the dilution effect. For example, approximately a 100% decrease from 5.4 ppb to 2.6 ppb was noted following the 2.76-inch rainfall of 3 August. Aircraft tracer releases were made on this day, but any tracer reaching the stream was apparently insignificant compared with the dilution effect on the natural background concentration resulting from the heavy rainfall and associated runoff.

Stream water samples were taken preceding and following an aircraft tracer release on 18 July. Only light rainfall, 0.03 inch, occurred on the Canteen watershed on the tracer release day. The lithium concentration increased slightly from 9.7 ppb on the 17th to 10.5 on the 19th, and decreased to 9.5 on the 21st. Average concentration for July was 9.9 ppb with a range from 5.4 to 11.2 on 11 sampling days. Another aircraft tracer release was made on 11 August, but unfortunately stream water samples were taken before the rainfall and tracer release but not following the rain period.

From the limited 1972 summer data analyzed to date, it is tentatively concluded that the dilution effect from rainfall of moderate to heavy intensity eliminates the capability to detect small amounts of rainwater tracer reaching the stream. Detection of the tracer may be possible in very light rains.

The time distributions of lithium, sodium, and pH for Canteen Creek are shown in figure J-2 for June-August, along with the storm rainfall distribution. The time distributions of lithium and sodium have similar patterns that show a general increase in concentration from late June until late July during a period of relatively light rainfall. Then a relatively steep downward trend in concentrations takes place and continues until early August, when a reversal to a sharp increase occurs. The downward trend was accompanied by two heavy rainstorms of 1.41 and 2.76 inches. The lithium concentration shows another reversal to a downward trend in mid-August in a period of above-normal rainfall. In general, increases in concentration occurred during periods of light rainfall and runoff. Reversals took place when heavy rainfall was followed by above-normal runoff which resulted in greater dilution of atmospheric and surface contaminants reaching the stream.

The pH curve in figure J-2 is relatively flat and does not show a strong relationship with rainfall. An increase in alkalinity occurred during the relatively dry period of late June and July, and was followed by a decrease during the heavy rains of late July and early August. However, the alkalinity increased again during the moderate to heavy rains later in August and reached its observed maximum in late August during and following a relatively wet period.

Calculations were made of the mean, median, and range of concentrations (Li, Na, Zn) and pH values, based on observations for 23 days in the June-August period. When more than one measurement was made on a day, the daily mean was used in the above calculations. Results are summarized in table J-2.

As pointed out earlier, the median summer concentration of the atmospheric tracer, lithium, in stream water was comparable to the concentrations in the rural area. Comparison of tables J-l and J-2 shows that the median concentration of sodium in stream water was greater than found in 5 of the 6 wells sampled. Similarly, the stream water zinc concentration exceeded that found in 5 of 6 wells. In general, the stream water pH was lower than the well water values. The higher concentrations of sodium and zinc in the stream water indicates surface sources of these water contaminants in the Canteen Creek watershed.

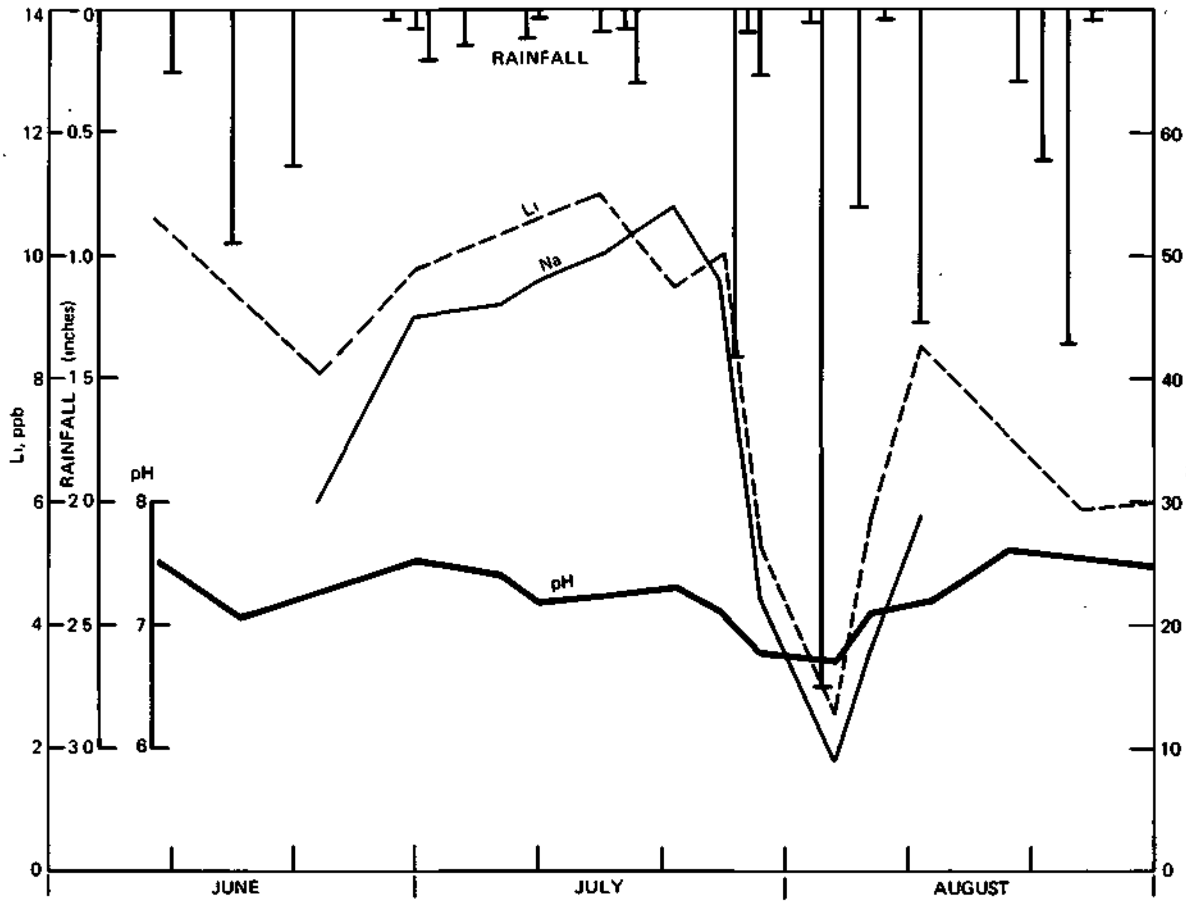


Figure J-2. Time distribution of sampling elements

Table J-2. Daily Concentrations in Canteen Creek Stream Water during June-August 1972

	Mean	Median	Range
Lithium *(ppb)*	8.8	9.8	2.3 -11.5
Sodium (*ppm*)	39.4	45.5	8.0 -54.5
Zinc *(ppm)*	0.13	0.10	0.02- 0.63
pH	7.2	7.2	6.5 - 8.0

Conclusions

A more comprehensive research program is needed to ascertain urban effects on surface water and shallow groundwater aquifers. More frequent sampling and more extensive chemical analyses of these water supply sources are required. This should include chemical analyses for the more common water pollutants, such as nitrates, sulfates, and chlorides. Multiple sampling of stream water in a number of rainstorms of various intensity, duration, and type should be included.

Weekly measurements at a sufficient number of wells to sample the various types of groundwater recharge must also be an integral part of the study. The inert tracer (lithium) being used in Metromex atmospheric studies has very limited application in the hydro logical study discussed here.

Reference

Changnon, S. A., Jr., and F. A. Huff. 1972. *Hydrologic implications of inadvertent weather modification.* Paper presented at the 53rd Annual Meeting, American Geophysical Union, Washington, D. C, April.

PART 2. ATMOSPHERIC STUDIES

K. METROMEX RADAR STUDIES

David Brunkow and G. M. Morgan, Jr.

Purpose and Scope

In the St. Louis Metromex Project, radar is used primarily as a complement to or extension of the raingage network. It is expected that comparative radar-rainfall studies over the network will yield information with which to determine 1) whether or not the radar can supplant some or all of the raingages in future field programs, and 2) whether or not the radar can be utilized in lieu of the gages in areas outside of the network. The radar, at the very least in a qualitative sense, shows in real-time where it is raining and how the rain system is evolving. This makes it an essential part of short-term operational forecasting and decision making required for the field project.

At the same time radar is being utilized to study the development of storms, their water budgets, vertical growth rates, and other aspects of cloud dynamics. Another important application is in radar-climatological studies aimed at revealing regions of preferred echo development, intensification, and decay in the urban region. Radar echo analyses are also useful in defining urban-effect and no-effect storms and studying the time and space differences between these "target" and "control" storms.

Technical problems resulted in only a small amount of radar data being collected in 1971. These problems were largely overcome in 1972, and a large amount of important data were collected with two sets. Emphasis to date has been in developing the computer techniques and methods to perform the massive data analyses required and to provide analytical output useful for the urban studies.

Radar Equipment

Two radars, a PPI and an RHI, were operated from field headquarters at Pere Marquette. The PPI radar is an FPS-18, 10-cm wavelength, of 1 megawatt peak power. The antenna is an NCAR 12-foot diameter dish mounted on a pedestal. The antenna has been modified to operate at 5 revolutions per minute with fixed elevation angle under strong wind conditions. This antenna will be replaced by the summer of 1974 with a new 20-foot diameter antenna and pedestal under an NSF equipment grant.

The signal from the FPS-18 radar is processed in an analog signal integrator of 100 gates which is described by Silha and Mueller (1971). The processed signal is recorded on magnetic tape for later display and elaboration. In 1971, one azimuthal scan out of four was recorded (one recorded scan every 45 seconds) as well as photographed from a display scope. In 1972, data from this radar were recorded only every 2.5 minutes.

The RHI radar is a 3-cm TPS-10 which has seen long service in radar-hail research at the Water Survey. In 1971, the TPS-10 was operated primarily in a manual mode, for control of aircraft operations in support of the precipitation tracer studies (Section N). The display scope was photographed (16 mm film) continuously. For 1972 Metromex operations, the normally fast scan-rate was reduced to one 22.5 elevation cycle/sec and 1.0 /sec azimuth. The radar signal was fed into the FPS-18 integrator on a time-sharing basis and recorded on the same tape with the 10-cm data.

Sample Results for FPS-18

The recorded FPS-18 data taken to date are intended primarily for radar-rainfall studies, and for display in support of case studies. The first step for the case studies was creating a contoured display of the computerized data. Figure K-l shows a series of such contour plots for the rainfall episode of 11 August 1972. The radar was not calibrated for these plots, but the outer contour in each frame corresponds roughly to a reflectivity level of 30 dbz and the interval between successive contours is 6 db.

The FPS-18 contour display program was adapted from one supplied by Dr. P. Eccles of the National Center for Atmospheric Research (NCAR), Boulder, Colorado. All contouring of the FPS-18 radar data was carried out on the NCAR Facilities Division computer.

Another important development was the ability to track radar cell motions by digital computer. A technique for doing this for isolated echoes has been accomplished. It requires that cells be delimited manually. This is done by roughly defining the area of interest from line printer outputs. The computer then calculates the center of mass, the actual area covered with echo, velocity of center of mass, and growth rates averaged over the preceding 5, 10, 15, 20, and 25 minutes. Thresholds are automatically established so that all the above parameters are recalculated with an effective gain reduction of 3, 6, 9, 12 db, etc. The centroid locations are then plotted on the St. Louis base map as shown in figure K-2. This case occurred between 1400 and 1620 CDT on 20 August 1972. The area enclosed within two threshold contours is plotted as a function of time in figure K-3. Figure K-4 shows contour maps at six different times during the same 1400-1600 CDT period. The new cell developments A and B on the contour maps show as peaks on figure K-3..

This simple approach has the advantage of being faster and more objective than comparable hand work. The simplicity leads to low cost. The computation and plotter time for this case cost about $15.

Sample Results for TPS-10

The display and examination of 3-dimensional radar data as furnished by the TPS-10 is one of the major problems common to Metromex and other Survey radar-oriented research. This has been nearly solved with the development of computer programs which perform the following:

1) Constant altitude radar display (CAPPI)
2) Vertical sections in arbitrarily oriented planes
3) Determination of the distribution with height of the mass of precipitation in the storm
4) Calculation of the total liquid water mass of storms
5) Calculation of the volume vs height and total volume of the radar echo

Examples of the manipulation of 3-dimensional digital radar data from the TPS-10 are shown in figures K-5, K-6, and K-7. Figure K-5 shows a pair of constant level displays, commonly known as CAPPI displays, at 10,000 and 20,000 feet above ground at 1801 CDT on 11 August 1972, within the box outlined on figure K-l a. Figure K-6 shows three vertical cross sections of the same storms at approximately the same time as figure K-5. The horizontal projections of the planes of the cross sections are the lines A—A', B—B', and C—C in figure K-5a.

Figure K-7 represents the distribution with height of radar detectable liquid water. The reflectivity, Z, has been converted to M, the liquid water content, through the relation $M = 2.6 \times 10^{-3} Z^{0.6}$ and integrated in 0.5-km thick layers over the entire area of figure K-5, and these values plotted as a function of height. The integral over height of these values gives the total mass of radar-detected water in the box. Total mass is given in figure K-7 for each of the curves.

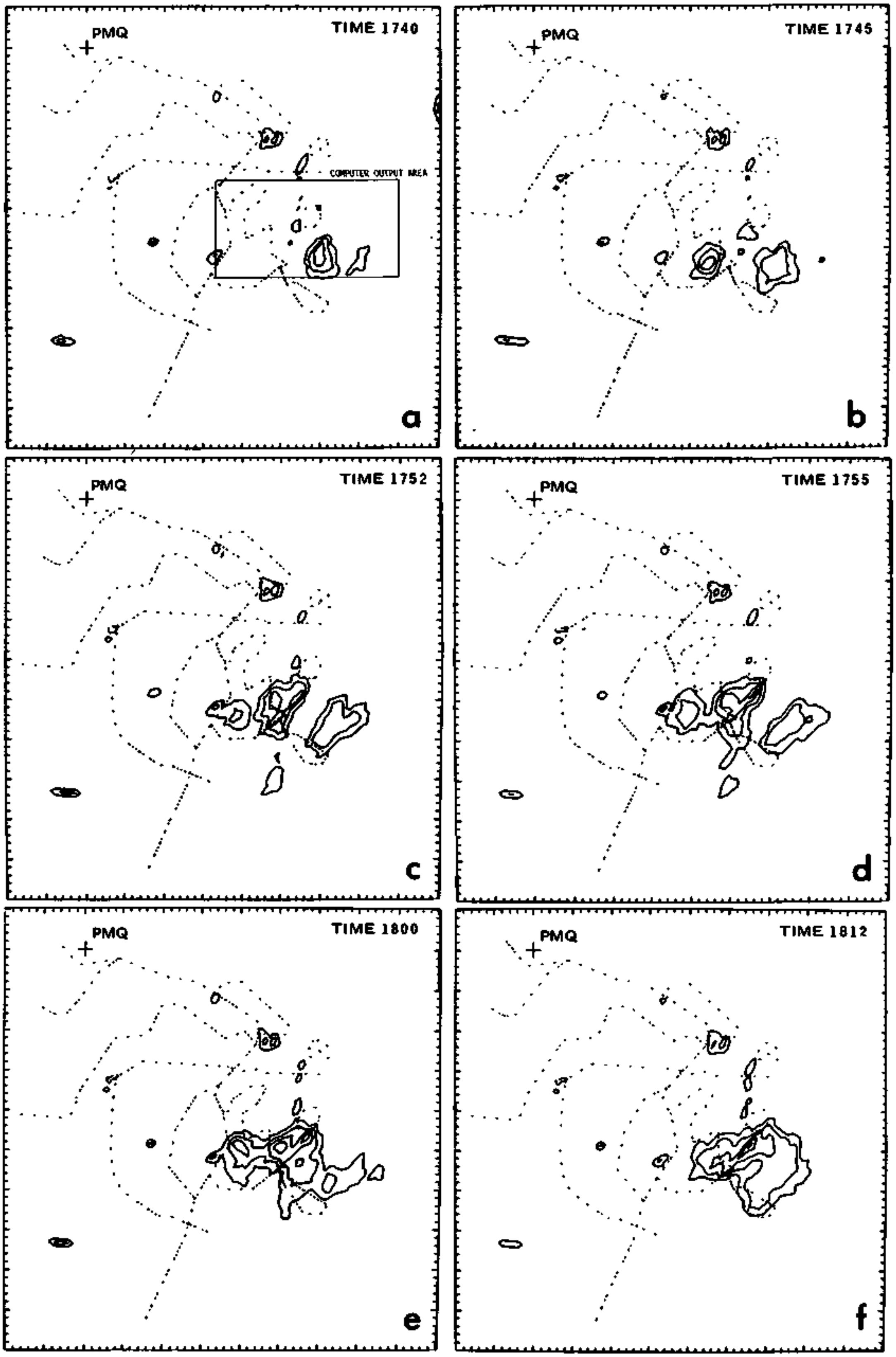


Figure K-l. Contour plots for FPS-18 on 11 August 1972

In a previous study (Morgan and Mueller, 1972) integrations of the TPS-10 data similar to those of figure K-5 were carried out by combined photographic, manual, and digital techniques totaling many days of work for a few minutes (real time) of data. With the fully digital procedures described here, the manpower time between the data and results is reduced to a few minutes.

References

Morgan, G. M., Jr., and E. A. Mueller. 1972. *The total liquid water mass of large convective storms.* Preprints, 15th Radar Meteorology Conference, Champaign-Urbana; AMS, Boston, pp. 39-40.

Silha, E. J., and E. A. Mueller. 1971. *Reflectivity-rainfall relationships and reflectivity variability observed with a hybrid video processor.* Research and Development, Report ECOM-0204-F, Army Signal Corps.

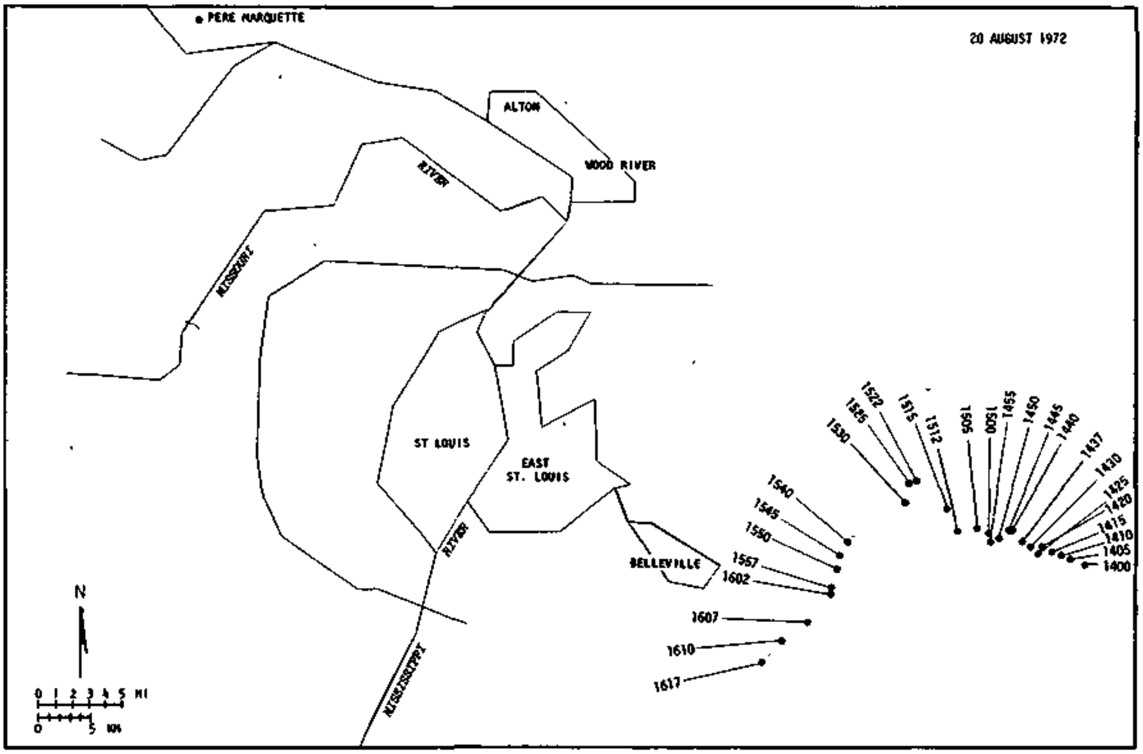


Figure K-2. Echo centroid track, 1400-1600 CDT on 20 August 1972

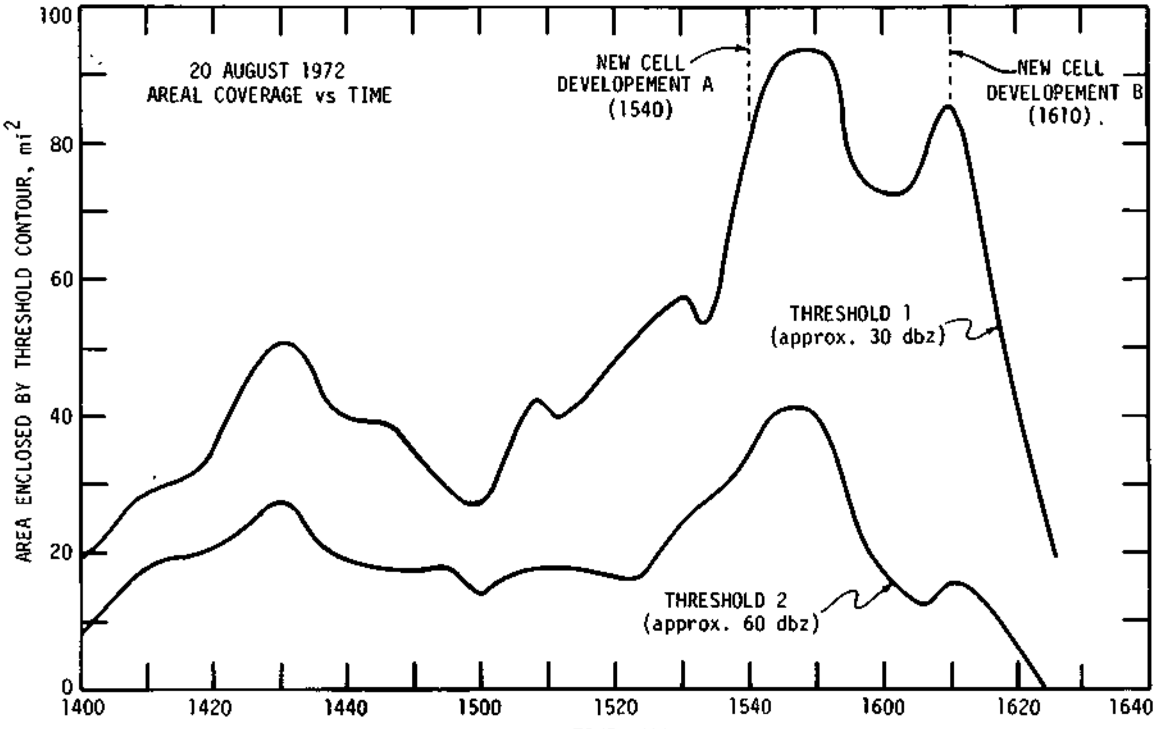


Figure K-3. Areas enclosed by two threshold contours as a function of time,
1400-1600 CST on 20 August 1972

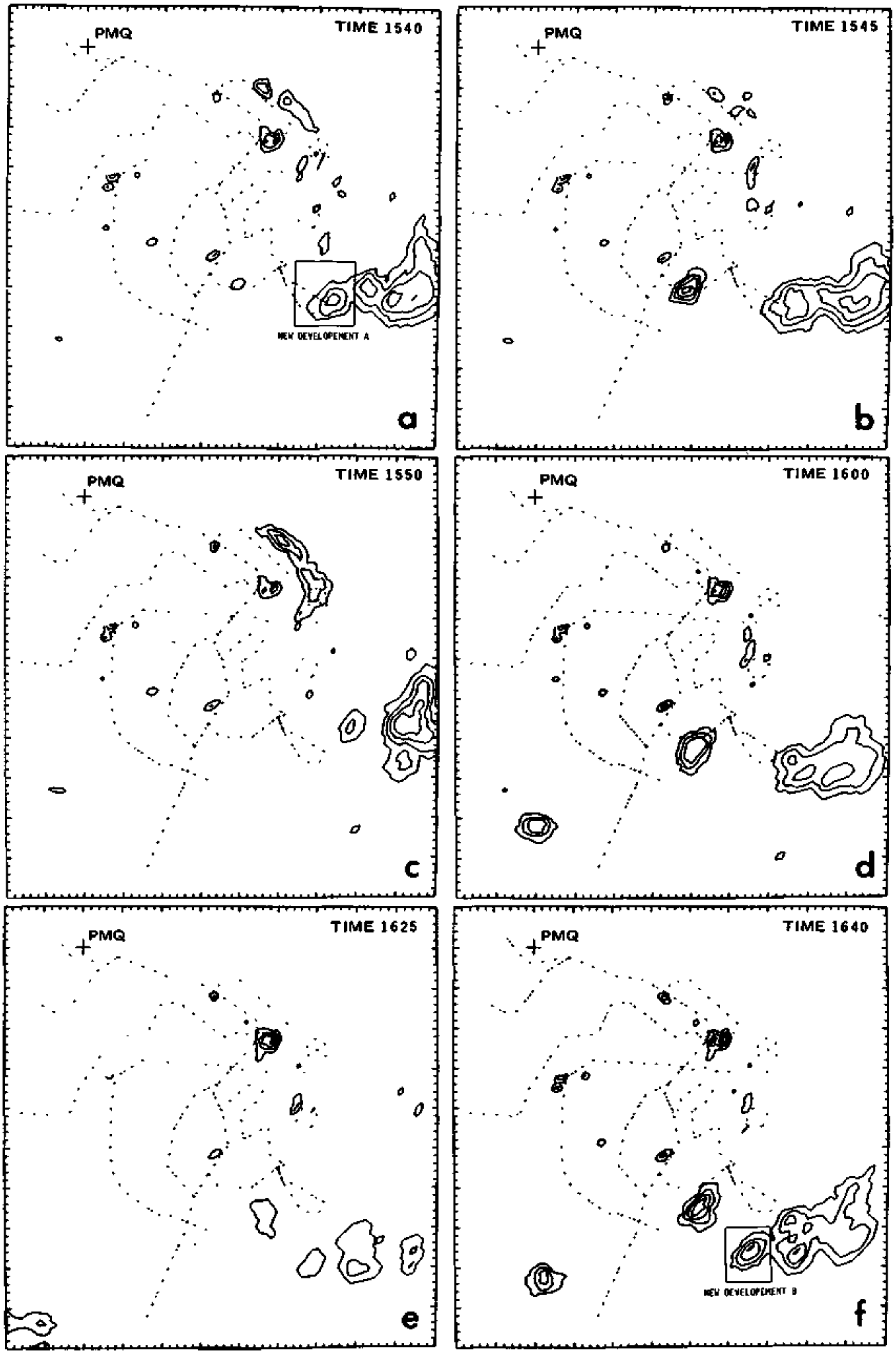


Figure K-4. Contour plots for FPS-18 on 20 August 1972

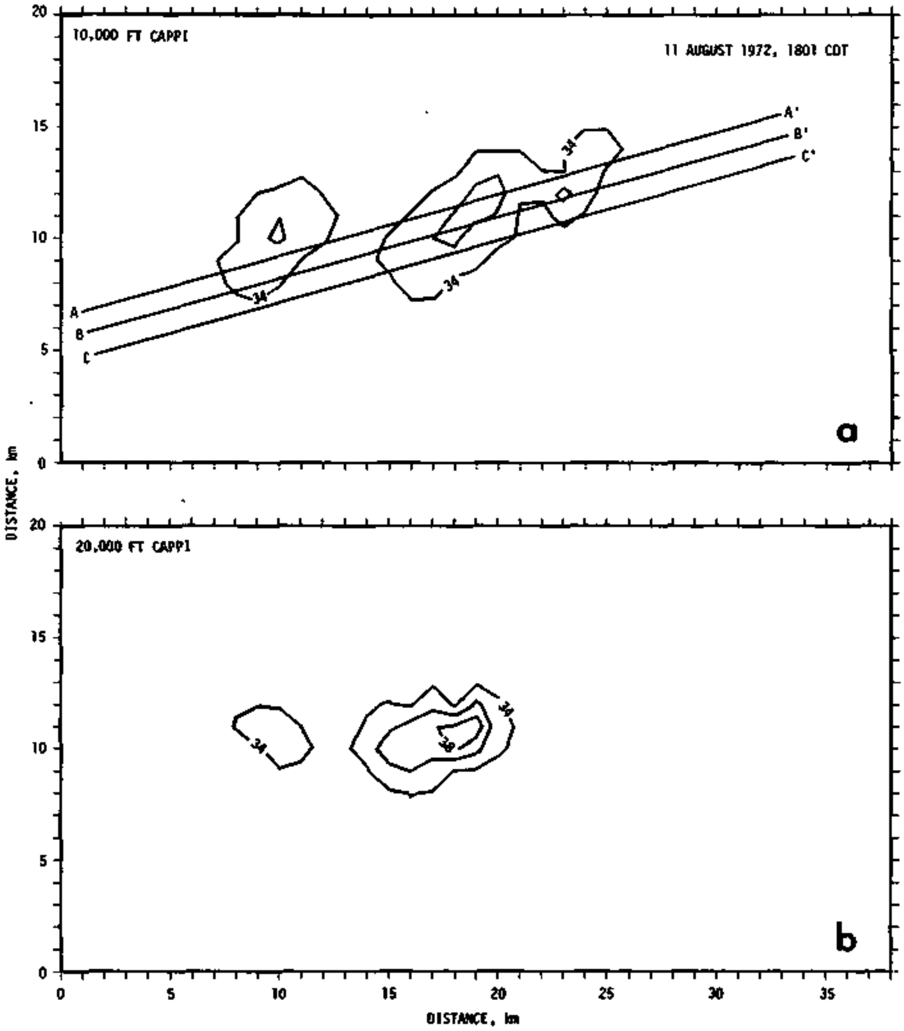


Figure K-5. CAPPI displays for 10,000 and 20,000 ft AGL,
1801 CDT on 11 August 1972
(Area of figures is box on figure K-la)

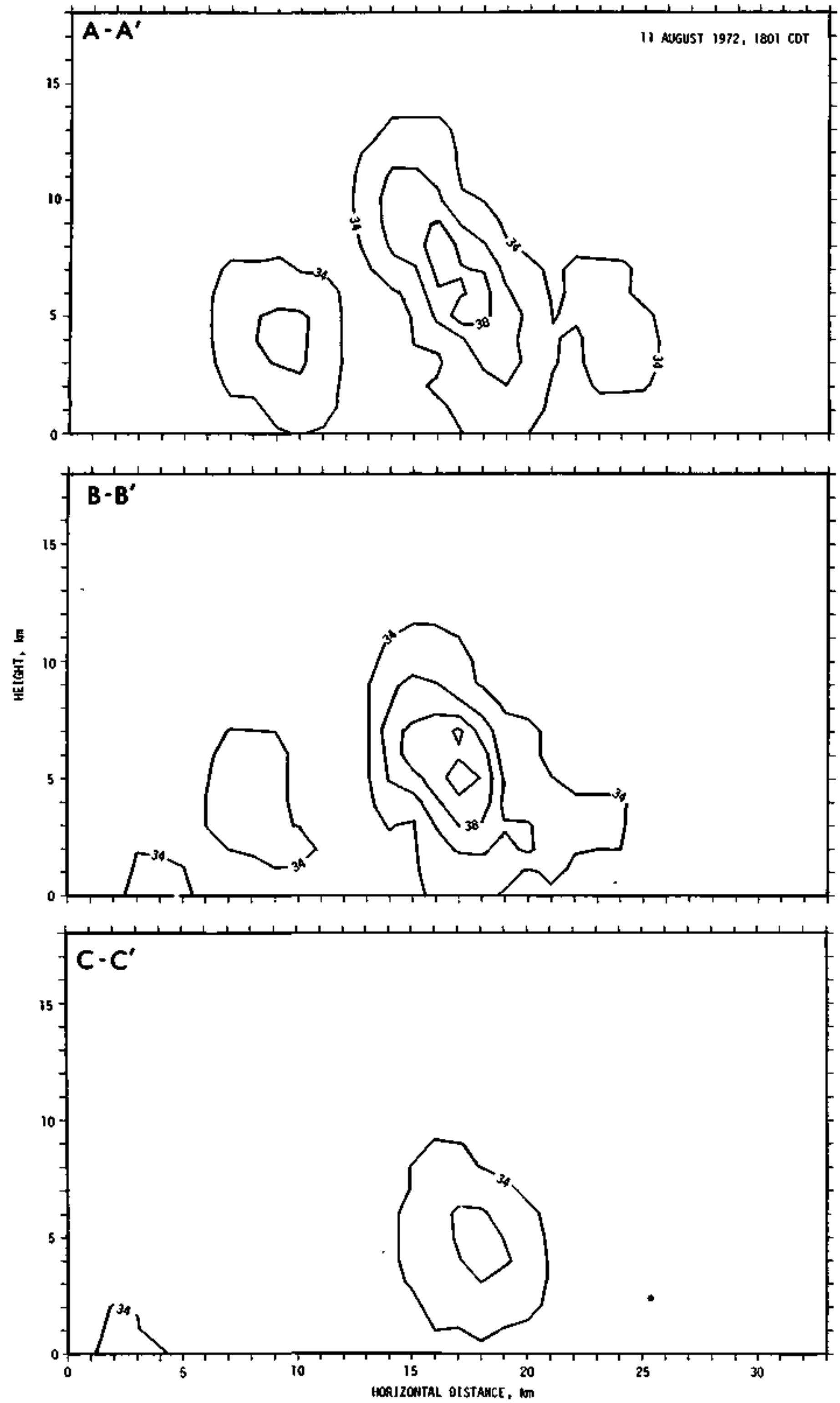
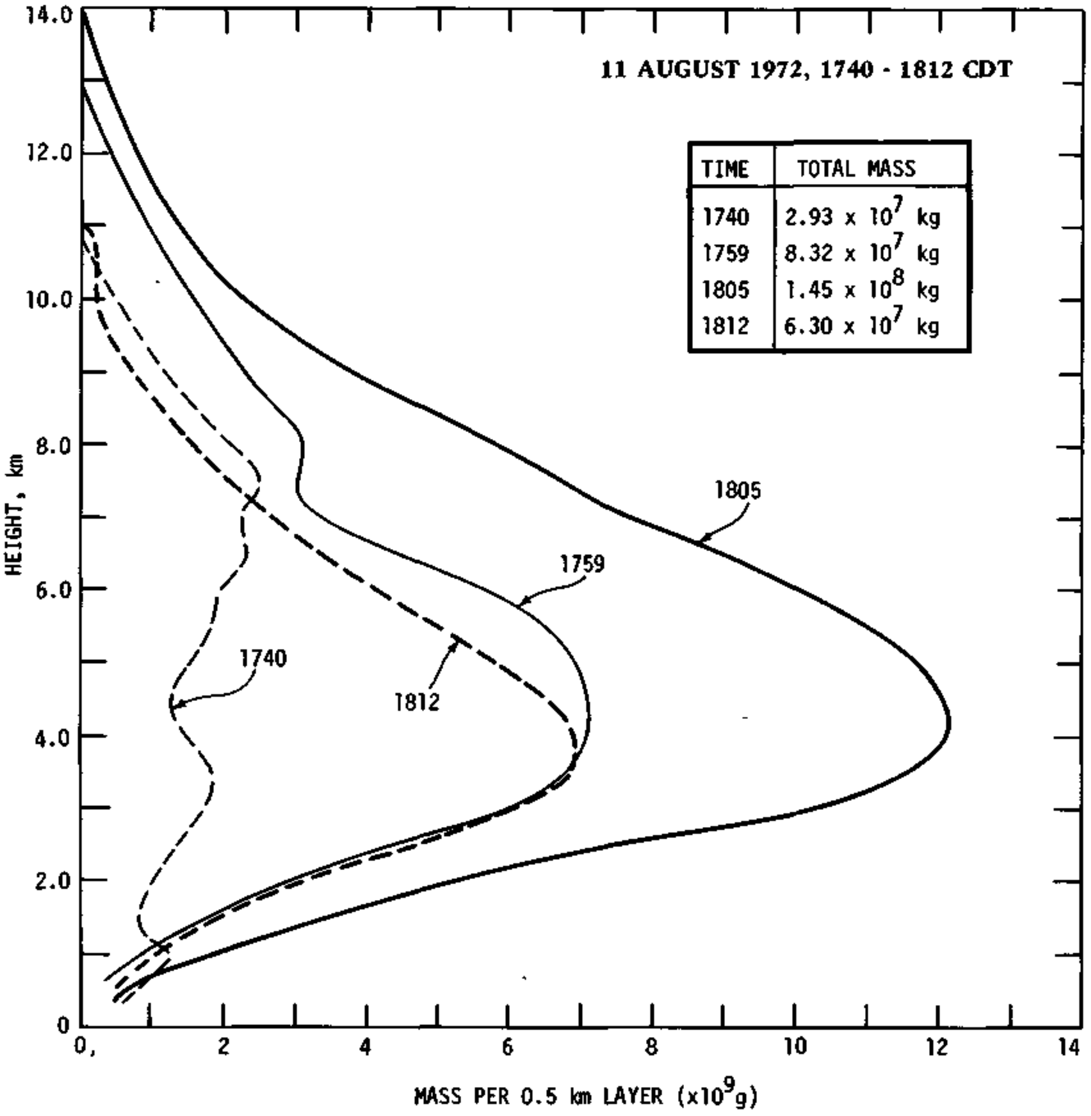


Figure K-6. Vertical cross sections through storm shown in figure K-5



TIME	TOTAL MASS
1740	2.93×10^7 kg
1759	8.32×10^7 kg
1805	1.45×10^8 kg
1812	6.30×10^7 kg

Figure K-7. Distribution with height of radar-detected liquid water at indicated times within area of figure 5 on 11 August 1972

L. RELATED STUDY ON QUANTITATIVE MEASUREMENT OF SURFACE RAINFALL WITH RADAR

F. A. Huff and A. L. Sims

Rainfall data from the large Metromex network and the 10-cm radar data (FPS-18) collected in conjunction with the Metromex program are being used in an effort to develop better techniques for radar measurement of areal mean rainfall. This is a continuation of earlier research at the Water Survey which was hampered by the lack of satisfactory radar equipment. The capability to measure rainfall quantitatively with radar with an accuracy approaching that of dense raingage networks would be a major asset in the evaluation of weather modification experiments and in hydrologic applications (flood forecasting, etc.).

Presently, methods and techniques to be used in this study are being developed. Computer programs are being developed to calculate the raingage-indicated and radar-indicated rainfall over specific areas of varying size and for varying times (time integration of rainfall). These processed data will then be used in evaluating the reliability and accuracy of radar for quantitative precipitation measurements. Evaluation of radar measurement capability in different types of precipitation and under various synoptic weather conditions will be incorporated in the study eventually.

Programs and techniques are being developed with 1972 data, but the research will continue concurrently with the Metromex program in the 1973-1975 period. This research is a most desirable undertaking made possible by the extensive data collection and analysis programs of Metromex.

M. THE AIRFLOW PROGRAM IN METROMEX

Bernice Ackerman

Purpose and Scope

The boundary layer program in Metromex has had two general goals: 1) to determine the extent and nature of the changes caused by the urban complex in the 3-dimensional dynamic structure of the layer in instances of both stagnation and large scale motion, and 2) to define the wind and thermodynamic fields in the layer for estimation of the urban plume and fluxes into convective systems.

The airflow measurements in 1971 were carried out by Argonne National Laboratory and emphasized the first goal. These have been described elsewhere (Ackerman, 1971). The 1972 airflow program was carried out by the Illinois State Water Survey. It was designed to provide data for both of these general goals with emphasis on the second. The specific objectives were:

1) To determine the evolution of the airflow and thermodynamic structure as convective cloud systems developed and moved through the metropolitan and adjoining areas, and to provide trajectory information for the analysis of tracer experiments.
2) To determine the streamlines and trajectories in non-rain situations for use in defining the urban "plume."
3) To determine if a nocturnal urban circulation develops during periods of well-established urban-rural temperature differences and the form and strength of such a circulation.

The daily operations were scheduled to serve one of the three objectives on the basis of the morning forecast of conditions in the network. The observations were basically the same with parameters such as station array, observation interval, etc., selected to optimize the experiment for the particular objective.

The field experiments involved the measurements of 1) mean winds in the lowest 2 km obtained from simultaneous pilot balloon observations from 7 to 9 locations, and 2) the vertical distribution of temperature and humidity to about 500 mb from 3 locations. Details of the methods used in the field observations are given below.

Field Operations

The 1972 field observations in the St. Louis area were carried out from 12 July to 11 August under the direction of the author. The wind measurements were obtained by double theodolite tracking of pilot balloons. The temperature and humidity measurements were made with standard radiosonde units and receivers.

The Air Weather Service of the U. S. Air Force assigned a unit of 26 men, including supervisory personnel, from the 6th Weather Squadron (Mobile) to carry out the pilot balloon and radiosonde observations. It also provided the standard equipment for both types of measurements, plus the vehicles necessary to transport personnel and equipment to observations sites.

The operations were based at Scott Air Force Base, Illinois, about 20 miles ESE of downtown St. Louis. All personnel, military and civilian, were housed on or close to the base. Daily weather briefings were provided by Base Weather, 7th Weather Wing, and by the Water Survey forecaster at Pere Marquette.

- During each operational period the observers were deployed to about 10 sites scattered in and around St. Louis. Three of these were permanent locations from which radiosonde balloons were released and tracked. The others, from which pibals were released and tracked, varied from operation to operation depending on the objective to be served. They were selected from 16 previously surveyed locations (figure M-l).

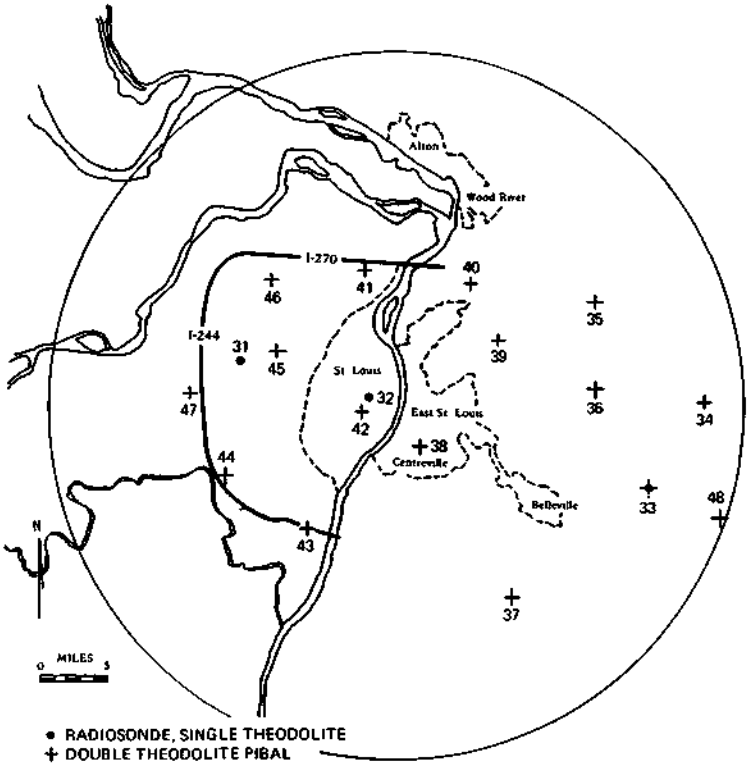


Figure M-l. Pilot balloon and radiosonde release sites

Pibal Siting. The pibal sites were carefully selected on the basis of a number of criteria, some scientific, some logistic.

a) Sites had to form an array such that experiments pertinent to the objectives could be carried out.
b) The area around each site should have, as much as possible, homogeneous surface conditions.
c) The baseline (distance between the observers) should be 2000 feet or longer.
d) The two observers should be able to see each other through their theodolites, and it should be possible to string telephone line between them without crossing walks or heavily traveled roads.
e) There should be no obstructions to the view of the balloon in any direction.
f) Personal safety of the observers must not be endangered in any way, and phone and toilet facilities must be within reasonable walking distance.
g) Equipment could be set up in a reasonable length of time.
h) The site must be within 1-hr driving time from Scott AFB (an AWS regulation).
i) Permission to use the property from the owner or the pertinent public official must be granted.

It was not always possible to meet all of these criteria. Those which were essential and had to be met were *a, d, f, h,* and *i.* Criterion *c* was met in all but three of the sites. The shortest baseline was about 1650 feet long, and the other two were over 1850 feet long. The longest line was 3600 feet.

The other criteria were met with varying success. The most difficult one to satisfy was *b*, particularly at sites in the city. In fact, even for criterion *a*, the locations, although suitable, were not always optimal.

When establishing the site, the survey team selected two suitable spots for theodolite "pads." They then measured off the straight line distance between the two with transit and tape and the difference in height with a stadia rod. With the baseline as the y axis, check orientation points were determined for each pad. The orientation of the baseline relative to true north was determined later from sightings on Polaris on clear nights.

Pibal Procedures. Almost all of the pibal sites were on unprotected public and private property, so that only small wooden ground stakes marking the theodolite locations were located permanently at the sites. The observers had to transport, set up, and then dismantle all equipment for each day's observations. This took roughly an hour at both the start and the end of the day.

Two observers composed a pibal "team," one at each theodolite. They were linked by a land phone line for communication. Into this line were hooked a tape recorder and a tone generator that was activated by a timer. These along with pertinent electrical connectors were packaged into a small attache case for convenience of transport and storage. The timing tone was set for a timing interval of 20 seconds and sounded for roughly 3 seconds. At the start of the tone the observers centered the balloon on the cross-hairs of the theodolite and kept it there until the tone ended. Then before changing the dial settings each observer, in turn, read the azimuth and elevation angles of the balloon (to hundredths of a degree) into their head phones for recording on magnetic tape.

Azimuth angles, as given, were in the coordinate system with y-axis parallel to the baseline. Rotation of the coordinate system to true north was accomplished in the data reduction. The observers were requested to orient their theodolites 360-180 by sighting on each other and checking orientation to the fixed markers. This was to assure that the theodolites were accurately placed and properly adjusted. They were also asked to check the alignment and level periodically during the operation.

At the end of each operation the verbal records from two balloon releases were transcribed. These were mailed to the Urbana office for immediate keypunching and computation of winds, and then returned. Although turnaround was two to three days, this did permit a satisfactory measure of quality control.

Radiosonde Siting and Procedures. The radiosonde sites were permanently located along a WNW-ESE line across the city (figure M-l). The criteria in establishing these sites were fewer and less demanding than those for pibal sites.

a) The locations were to be such as to provide approximately an east-west cross section across the city.
b) The equipment had to be permanently located in a building to which the observers could have 24-hr access.
c) The location had to be within 1-hr driving time of Scott AFB.

The eastern station was conveniently located at base headquarters, Scott AFB. The central location was situated at St. Louis University, in the center of the city. The western station was located in the far western suburbs at the Monsanto Research Park. Although it might have been desirable to have this station a little farther west, this was not possible because of the need to meet all of the above criteria. (On figure M-l, the dashed lines encircle the city of St. Louis and other urbanized areas, and the highway loop formed by 1-270 and 1-244 encloses most of the suburbs.)

Since primary interest was in the lower atmosphere, over-inflated 100-gram balloons were used. These resulted in bursting heights of about 500 mb, which was adequate for most of the objectives. During operations designed in support of convective shower studies, one sounding a day was taken to the tropopause. In some of the operations, the radiosonde balloon was tracked by a single theodolite.

Both radiosonde and pilot balloons were inflated for estimated rise rates of 2.5 meters per second (mps). Flow meters, rather than weights, were used in inflation because of the short time between the termination of one run and the start of the next and the difficulty of inflating the balloons in the open. Although inflation rates were assigned, and were adhered to as closely as possible, this was not an essential factor since the computations of winds are independent of the rise rate in both the double theodolite and radiosonde measurements. In fact, the rise rates computed in the double theodolite program provide valuable estimates of the vertical air motions in the boundary layer.

Data Reduction Techniques

Radiosonde. The reduction of radiosonde measurements is standard. Field reduction of the data was made immediately by the standard synoptic criteria. This was adequate for monitoring data quality. When used in analysis, these data were checked for errors and sometimes recomputed to obtain more detail of the vertical structure in the boundary layer.

One serious problem, as yet unsolved, concerns the humidity measurement. The radiosonde packages were of the type in which the humidity measurements are subject to both radiation errors and errors arising from poor ventilation. Estimates of the magnitudes of these errors have been given in the literature (Teweles, 1970; Morresey and Brousaides, 1970). Although consideration has been given to this problem, no standard solution has been decided upon, other than to use the guidelines given in these publications.

Pibal. The theodolite readings were computer processed to obtain winds. The computations are based on the methods described by Thyer (1962). The technique solves for location of the shortest distance between the rays from the two theodolites and estimates the most probable position of the balloon along the line joining the rays at this location. The average wind velocity for the layer between two successive reading times is provided by the difference between the balloon positions at those two times. The rate of ascent of the balloon is determined by the height difference.

The minimum distance between rays provides an estimate of the error in the calculated position of the balloon due to errors in the angles to the balloon. Thus, the technique provides a means of detecting sizeable errors in the theodolite readings and of correcting them. Prior to any analysis the data were first reviewed for obvious errors and then suitably corrected whenever possible.

Preliminary Results

Seventeen operational periods were completed during 1972. Table M-l gives the objectives served (as listed on page 113) and some of the design features of these operations. For the accuracy test, four teams set up along parallel baselines tracked the same balloon.

Analysis of several of these operations are currently in progress. Some of the features of the nocturnal circulation and the urban plume studies have been presented elsewhere (Ackerman, 1972, 1973). Also, a detailed analysis of two convective shower studies is being prepared for another report.

The nocturnal circulation and urban plume operations were carried out during fair weather, usually following a cool polar outbreak. The winds were generally light and the boundary layer capped with a subsidence inversion. Preliminary results from these studies indicate that the airflow can be significantly perturbed over the urban complex in the lower part of the boundary layer, and that this perturbation may. extend through much of the boundary layer if the convection is intense.

Table M-l. Objectives and Design of the Airflow Observations, 1972

	Objective 1 Convective showers	Objective 2 Urban plume	Objective 3 Nocturnal circulations	Accuracy test
Number	**6**	**4**	**5**	**2**
Times, CDT (approx)	**1400-1900**	**1220-1530 or 1400-1700**	**2140-0100** s	**0930-1130**
Number of sites				
Pibal	**7**	**8**	**8 or 9**	**1 (4 teams)**
Radiosonde	**3***	**3**	**3**	
Number of releases at each site				
Pibal	**8**	**8**	**8**	**6 (each team)**
Radiosonde	**5****	**1**	**2**	
Time between releases, min				
Pibal	**30**	**20**	**20**	**20**
Radiosonde	**60****		**90**	
Maximum height				
Pibal, km (approx)	**3.25**	**2**	**2 .**	**2**
Radiosonde, mb	**500****	**~400**	**600**	

* Radiosonde balloon tracked by single theodolite
** One release at central city location tracked to tropopause, therefore one fewer release and interval of 2 hours before following release

Example from Nocturnal Study. Figure M-2 shows the average winds over the network during the early part of the evening on one operational period, 17 August 1971.

> At 100 meters above ground, the perturbation in the general flow is manifested in changes in direction and speed around the city. It is strong enough to produce counterflow at the southwest edge of the city — against ambient flow of 2.5 to 3 mps. The perturbation is still in evidence at 350 meters but is greatly reduced in intensity. This wind field produced convergence of the order of 10^{-4} over the city in the lower 200 to 300 meters.
>
> The wind field changed radically during the next hour resulting in net divergence rather than convergence in the lowest layers. A similar change occurred on another evening also. These results suggest that the perturbation must be oscillatory in nature. A pulsation in the surface nocturnal wind field in London has been reported by Chandler (1960).

Analyses of Fair Weather Days. Figure M-3 shows the mean wind fields over the metropolitan area at two levels on 10 August 1972. The boundary layer convection was quite intense on this day with convective plumes or bubbles frequently reaching the inversion (1200 meters) and maximum updraft velocities as large as 4 mps. The streamlines tend to take on anticyclonic curvature upwind of the city and cyclonic downwind, the curvature decreasing with height. The flow patterns shown here resulted in net convergence over most of the urban complex of the order of 10^{-4} sec^{-1} at 150 meters AGL and $3\text{x}10^{-5}$ sec^{-1} at 400 meters AGL (550 meters MSL) in the presence of divergence of about 2 to $3\text{X}10^{-5}$ sec^{-1} at these levels over the upwind rural areas.

The results from the analysis of two fair weather days suggest the following:

1) The wind speed can vary by 20 to 30% and the direction by 20 to 25 degrees over the metropolitan area, and these variations may differ through the boundary layer.
2) The wind speed tends to vary little in the vertical through the mixed layer (figures M-4 and M-5). The directional shear in the boundary layer, also relatively small, is greater downwind from the city than upwind. The formation of an internal boundary layer is suggested by the development of a layer of veering winds in the lowest 100 to 200 meters over the city, in the presence of backing winds in that layer over upwind rural locations.

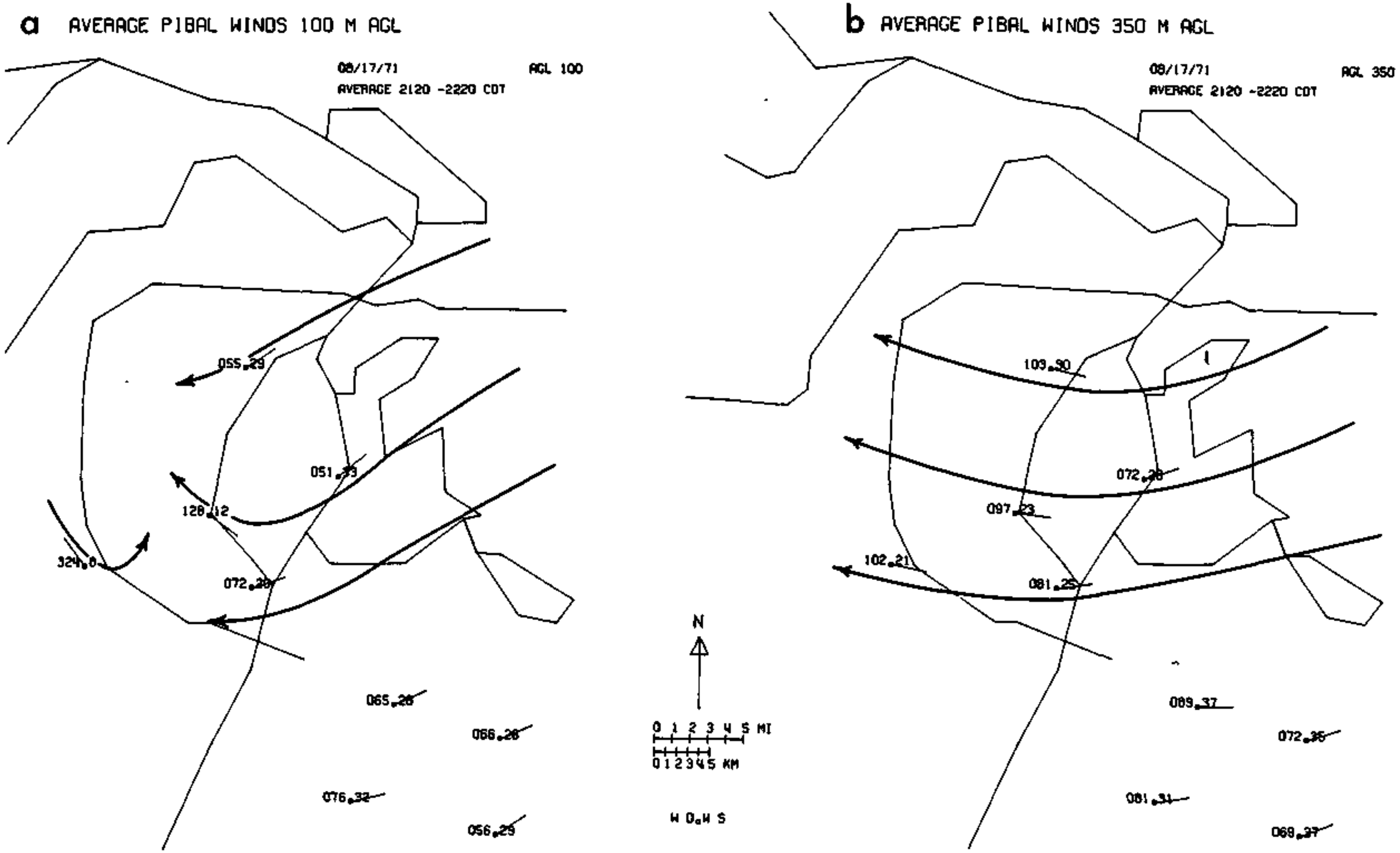


Figure M-2. Average winds during early evening on 17 August 1971 (Wind speed in mps is shown to right of the balloon position. The direction from which the wind was blowing is given on the left and is also indicated by the barb)

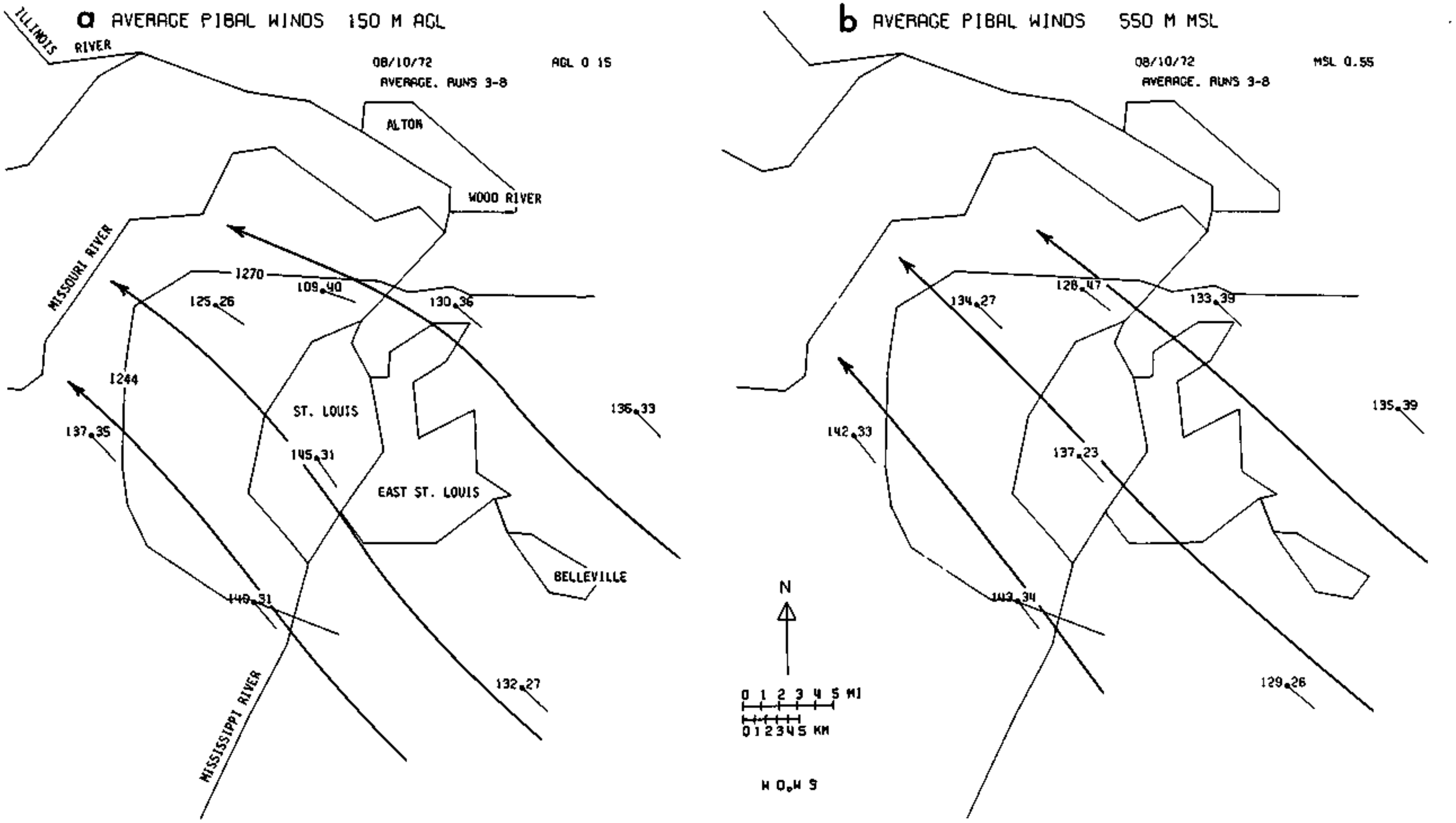


Figure M-3. Average wind field over St. Louis area, 1520-1730 CDT, 10 August 1972 (Symbols as in figure M-2)

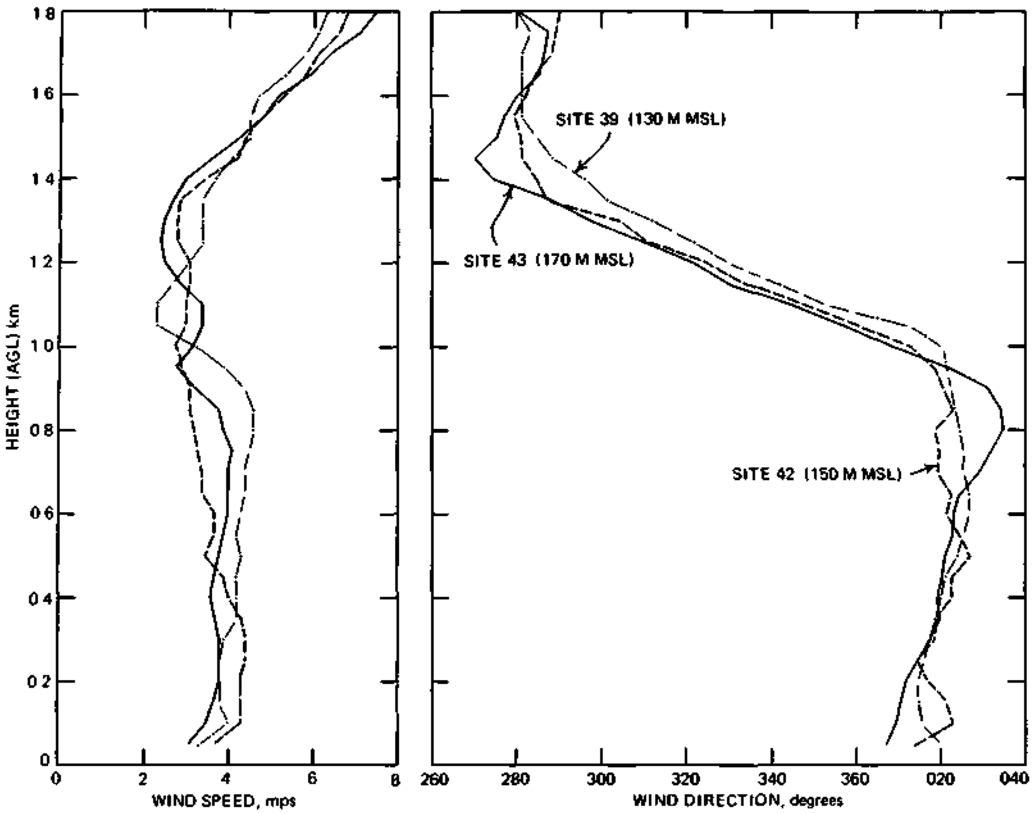


Figure M-4. Average vertical profiles of wind speed and direction for 1400-1700 CDT, 4 August 1972, from an upwind rural (site 39), a mid-city (site 42), and a downwind suburban (site 43) location

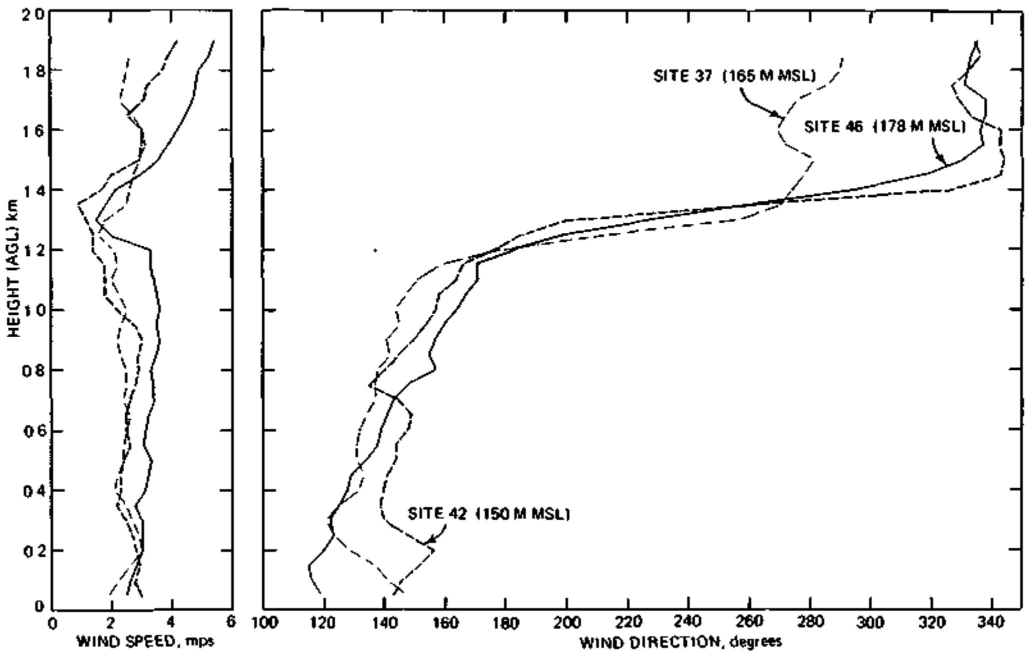


Figure M-5. Average vertical profiles of wind speed and direction, 1430-1730 CDT, 10 August 1972, from an upwind rural (site 37), a mid-city (site 42), and a downwind suburban (site 46) location

3) The height of a subsidence inversion (indicated by the zones of strong directional shear in figures M-4 and M-5) may vary over the area, but it may not necessarily be greater over the city. Synoptic influences seem to dominate, although strong low-level convection can modify the inversion layer locally.

4) Significant changes in wind direction and speed occur over short periods of time throughout the boundary layer (figures M-6 and M-7). These perturbations may result from local convection and/or shearing gravity waves along a surface of discontinuity. They could be induced locally or by a larger mesoscale phenomenon. On 4 August, when the convection was generally limited to the lowest 400 to 500 meters, the perturbation had longer periods and could be tracked across the network. On the 10th, the convection extended to the inversion. The periods of the perturbations were short and could not be tracked across the network. The air overlying a roughened surface, such as the central city site or a suburban area of considerable local relief, tended to be more severely perturbed than elsewhere (figure M-7). In addition, the intense perturbations and large updrafts extended later into the afternoon in the city.

These variations could be induced by synoptic, mesoscale, topographic, or urban forcing, but the observations suggest that at least some of them are locally produced.

Statistical Properties. The data from the two fair weather days were used in a simple statistical analysis of the time variations. The standard deviations of speed (oS), longitudinal and transverse components of the wind [oV(A),oV(N) respectively], and the standard vector deviation (oV) were calculated for each 50-meter level at each site, on each of the two days. These were then scaled by dividing by the average wind, in the case of wind speed by the arithmetic average of S, and in the case of the other variables by the magnitude of the vector average or resultant wind.

Although these statistics differed somewhat at the various levels, there was no indication of systematic changes with height. Therefore, the estimates for each 50-meter level in the boundary layer were averaged through the boundary layer to obtain a single value for the boundary layer for each site on each day.

The sites were divided into five types: rural locations upwind of the metropolitan area, mid-city, and suburban locations upwind of the metropolitan area, downwind of the primary city complex, and downwind of a significantly large suburban area. The data for sites of each type, for both days were pooled and the statistics averaged. Results are shown in table M-2.

Table M-2. Average Statistical Properties of Winds in the Planetary Boundary Layer on Two Fair Weather Days

	Rural	**Suburban**		**Suburban area, downwind of**	
Parameter*	**upwind**	**upwind**	**City**	**city**	**suburbs**
a, S	0.81	0.92	0.96	0.97	0.87
CV, S	0.23	0.25	0.30	0.28	0.24
o,V	1.26	1.35	1.54	1.46	1.34
CV, (V)	0.39	0.40	0.53	0.45	0.39
oV ( )	0.98	0.94	1.09	1.09	0.95
oV ($|\bar{V}|$ /	0.29	0.27	0.38	0.33	0.28
oV ( )	0.84	0.95	1.05	1.01	0.93
OV(A)/$|\bar{V}|$	0.26	0.26	0.38	0.31	0.25

* o = Standard deviation
CV = Coefficient of variation
S = Scalar wind speed
V = Vector wind velocity
V(A), V(N) = the longitudinal and transverse component of the wind, respectively
$|\bar{V}|$ = Magnitude of the vector mean wind

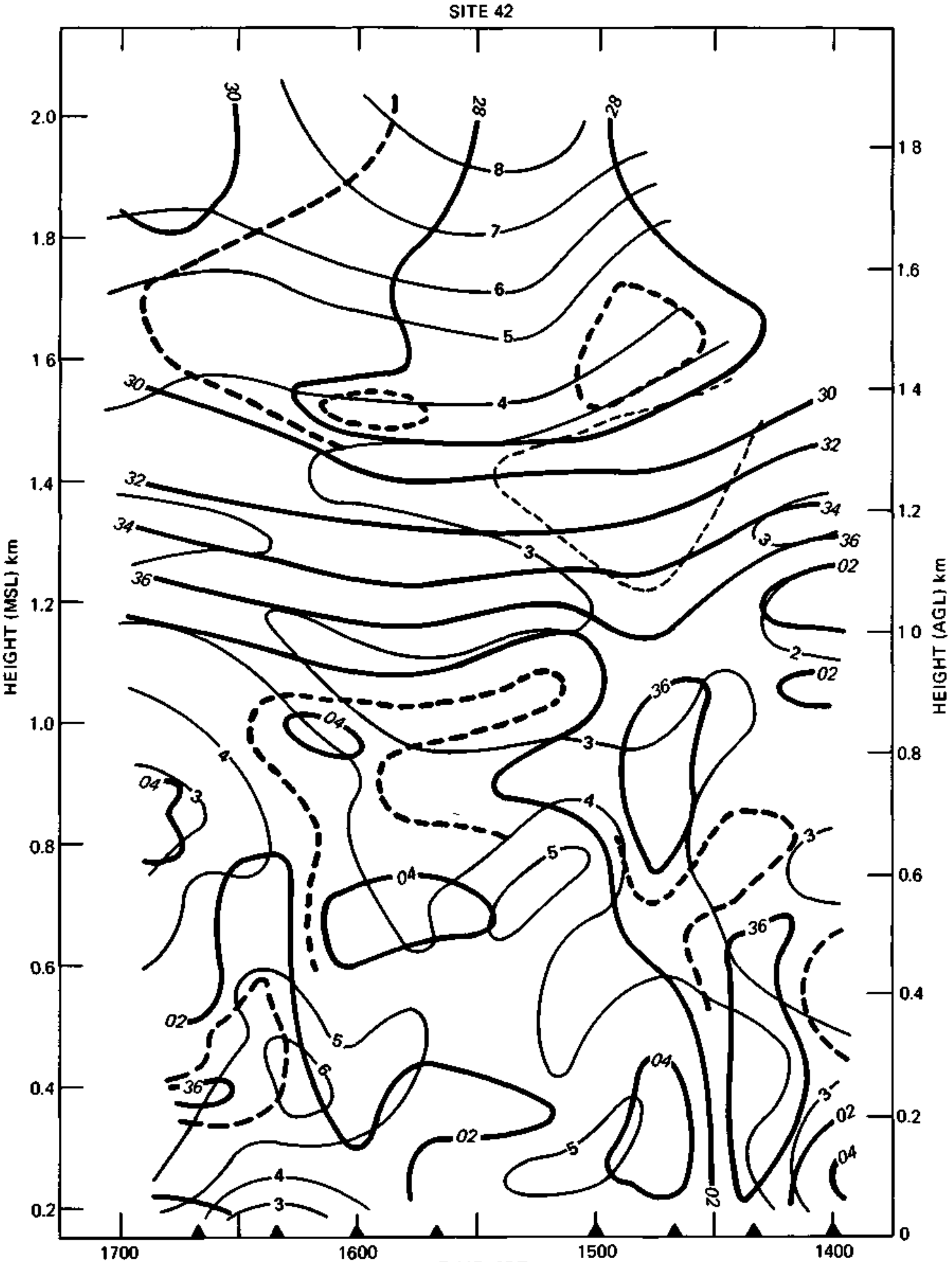


Figure M-6. Time section of wind speed and direction over site 42, a mid-city location, 4 August 1972 (Thin lines are isotachs labeled in mps, heavy lines are isogons, and arrows along abscissa indicate times of the balloon releases)

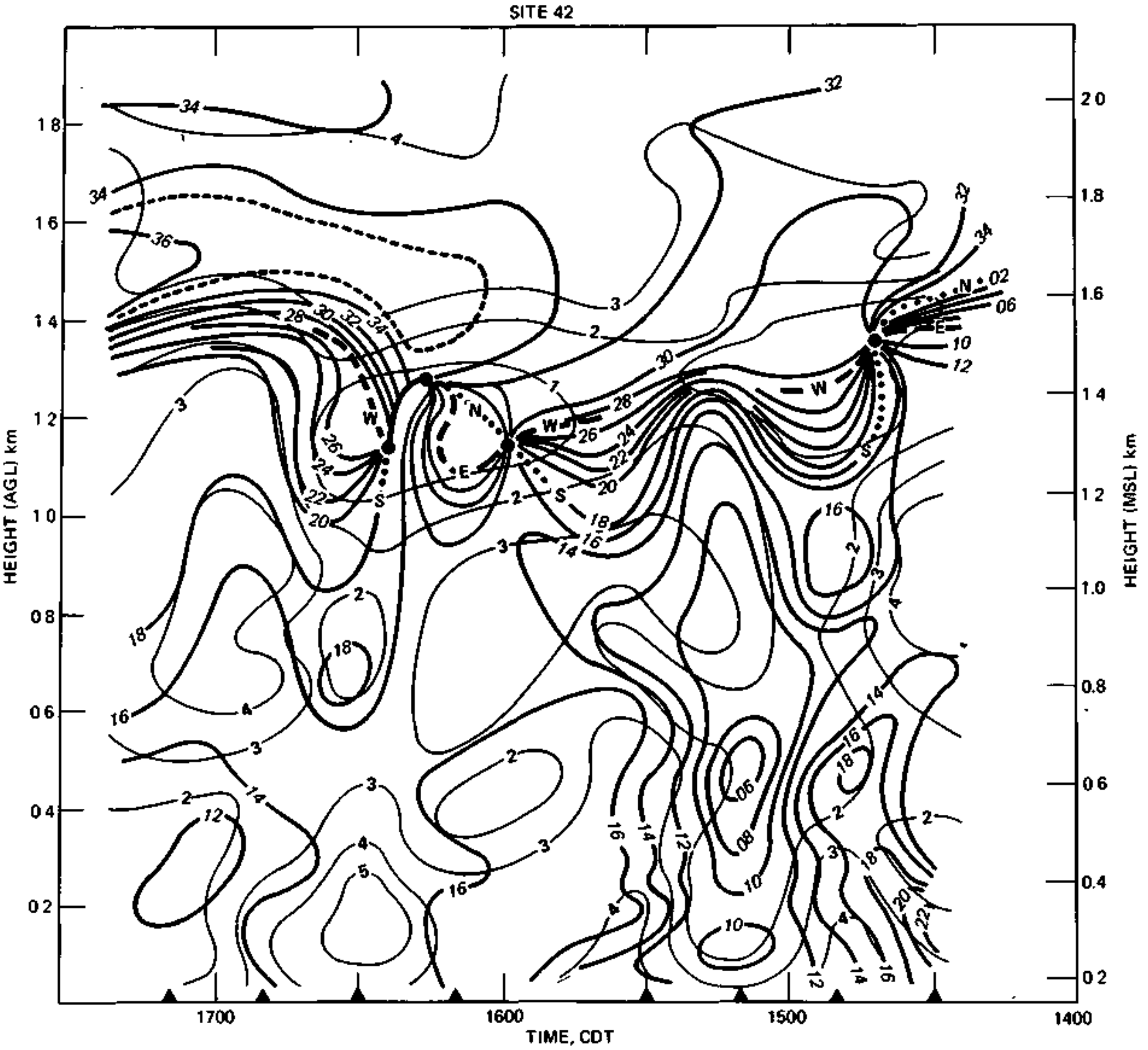


Figure M-7. Time section of wind speed and direction over site 42, a mid-city location, (See figure M-6 for details) on 10 August 1972

It can be seen from table M-2 that the standard deviations and coefficients of variation for all the wind parameters were larger at the city station than elsewhere. The standard deviations were larger at the city site than at rural sites by 11 to 25%, and the coefficients of variation were larger by 30 to 45%. At the suburban sites downwind of the city, the average statistics were larger than at other suburban or rural locations. In fact, the standard deviations of speed and of transverse component of the velocity. were equal to those in the central city.

There were negligible differences between the average statistics at the suburban sites upwind of the urban complex and those downwind of a suburban area. The average standard deviations of speed velocity and longitudinal component of the wind were smaller at the rural stations. However, division by the strength of the wind tended to equalize the statistics, and there is virtually no difference between the coefficients of variation of the various wind parameters at the rural and suburban sites except those downwind of the city.

This limited statistical analysis suggests that the planetary boundary layer of air overriding the central city is more turbulent than elsewhere in the nearby surroundings. Studies made of winds from towers have indicated that this was true for the surface layer (Graham, 1968; Bowne and Ball, 1970).

The air overriding suburban areas downwind of the city is almost as turbulent as that over the central city, perhaps because the turbulence generated over the city has not yet decayed. Although the rural area tended to have less intense wind fluctuations, the relative turbulence at suburban sites other than downwind of the city was about the same as at upwind rural locations.

References

Ackerman, B. 1971. *A field program to study the urban wind field.* *In* 1971 Operational Report for Metromex, pp. 14-21.

Ackerman, B. 1972. *Winds in the Ekman layer over St. Louis.* Preprints, Conference on Urban Environment, Philadelphia; AMS, Boston, pp. 22-27.

Ackerman, B. 1973. *Airflow over the metropolitan area of St. Louts.* Submitted for publication, Journal Air Pollution Control Association.

Bowne, N. E., and J. T. Ball. 1970. *Observational comparison of rural and urban boundary layer turbulence.* Journal of Applied Meteorology, 9:862-873.

Chandler, T. J. 1960. *Wind as a factor of urban temperatures, a survey in north-east London.* Weather, 15:204.

Graham, I. R. 1968. *An analysis of turbulence statistics at Fort Wayne, Indiana.* Journal of Applied Meteorology, 7:90-93.

Morresey, J. F., and F. J. Brousaides. 1970. *Temperature-induced errors in the ML-476 humidity data.* Journal Applied Meteorology, 9:805-808.

Teweles, S. 1970. *A spurious diurnal variation in radiosonde humidity records.* Bulletin American Meteorological Society, 51:836-840.

Thyer, N. 1962. *Double theodolite pibal evaluation by computer.* Journal Applied Meteorology, 1:66-68.

N. METROMEX CHEMICAL TRACER STUDIES

R. G. Semonin

Introduction

The identification of the sources and sinks of particulate pollutants in an urban-industrial region is essential for the complete understanding of the impact of man's activities on his environment. In particular, the removal of trace elements by precipitation from the atmosphere is a vital study area with implications to weather modification, air pollution meteorology, and ecosystem analysis, to name a few major applications. The industrial and urban wastes emitted to the atmosphere are of particular importance in the study of urban-induced alterations of the atmospheric properties conducive to the formation and continued production of precipitation.

The tracer chemical studies are directed toward the acquisition of knowledge concerning the interaction between simulated urban effluents and cloud and precipitation processes, as well as providing an insight into the internal motions of convective storms which transport and diffuse urban-industrial airborne waste materials.

Field Experiments

The field experiments were designed to examine the scavenging of sub-micron particles by precipitation and convective cloud processes. The 1971 experiments were designed to extend the techniques developed in the previous 2 years in central Illinois (Semonin, 1970), and to systematically approach the entire problem anew in the vicinity of a large metropolitan area. The field facilities offered by the cooperative Metromex research program (Changnon et al., 1971), relating to the interaction between the urban effluent from the St. Louis metropolitan area and the cloud and precipitation processes, presented a unique opportunity to enhance the scope of the scavenging research and to understand better the role of urban aerosols in altering precipitation.

The tracer chemicals (lithium and indium) were released from both ground level and from aircraft. The ground-level releases were used to simulate the emissions of materials from sources such as automobiles and small industries, whereas the aircraft releases were made in the area of the updraft of convective storms to examine the removal processes of precipitating clouds. Since the lithium tracer is very hygroscopic, the aerosol is almost immediately involved in natural cloud processes as a component of the available cloud condensation nuclei. The indium tracer, however, is non-hygroscopic and is attached to cloud and rain particles by entirely different mechanisms, namely, diffusion and impaction.

The tracers were released into the clouds by quite different techniques. The lithium was burned in a standard weather modification silver iodide generator, whereas the indium was released by burning pyrotechnic devices containing an indium compound. The equipment necessary for the tracer experiments was mounted on a light twin-engine aircraft (from Atmospherics, Inc.) which was directed to storms of interest by the Metromex radars. The aircraft crew would look for the updraft associated with an observed precipitation cell and then initiate the tracer release. Either or both of the tracers could be released during a particular experiment.

The simulation of ground sources of contaminants was accomplished with a high-pressure generator (also used for cloud seeding) burning a solution of lithium in a manner similar to the techniques employed on the aircraft. The burner was located on a high building to represent better the effluent from a low-level stack. During 1971, the ground releases were carried out in cooperation with a local industry which allowed the material to be injected in the stack of their plant at a point behind the electrostatic precipitator.

The precipitation (or dry fallout) samples were collected from a network of 80 sites downwind of St. Louis. The collectors were polyethylene bottles affixed to a farm fence post. Where possible, the samplers were located in proximity to recording raingages in order to derive other features of the storm rainfall.

Upon completion of a tracer mission, the samples were collected and transported to the laboratory for chemical analysis. The precipitation samples were immediately filtered to remove the insoluble fraction from the sample and the filtrate was analyzed by atomic absorption spectrophotometer methods. The insoluble portion of the sample was on a filter which was digested by various acid treatments. A dilution of the final acid solution was analyzed by atomic absorption in a manner similar to that for the soluble fraction.

The concentrations were used as input to a computer program which calculated the deposition of the various elements. These calculations were used to depict the areal and temporal variability of the materials deposited by the precipitation. Detailed studies of the patterns in conjunction with knowledge of the aircraft flight path allowed estimation of the contribution of the tracer to the total storm chemistry, as well as inferential information concerning the time required for the scavenging process to remove the tracer chemicals.

Aircraft Tracer Release

On 14 August 1971, a line of thunderstorms moved through the rainwater chemistry network from the NNE. The tracer release aircraft of Atmospherics Inc. was directed to intercept a developing portion of the line near the north-central portion of the network. The aircraft crew ignited two acetone burners in the updraft area of a storm cell located near point A in figure N-l. The lithium release continued through a 60-min period beginning at 1240 and terminating at 1340 at the extreme southeast corner of the network. The flight track followed a weave pattern swinging from west to east below cloud base while drifting south with the convective line.

As shown in figure N-l, the northeastern maximum (A) was directly associated with the initiation of the tracer injection. The analysis of radar and raingage data indicated the subsequent movement and occasional intensification of the associated (treated) raincell as the entire line progressed southward across the network. It should be noted at this time, however, that the *intent* of the experiment was to treat the isolated cell which was encountered first and moved SSE. It is readily apparent that the storm system dynamics rapidly distributed the tracer material in an unexpected manner. Each of the observed deposition maxima appeared related to a relative maximum of the rainfall, but several were not a result of rain from the treated cell. There is a suggestion that the rainfall and lithium deposition maxima are slightly displaced, which may be expected since the tracer was released in a non-precipitating updraft area.

It is not possible to examine the deposition rate as a function of the rainfall rate. Estimates of the process time based on possible first rain at a sampling location were made for the various observed deposition maxima. These times ranged from nearly 10 min for the maximum associated with the initial tracer release, to 45 min for the maximum in the southwest corner of the network.

The flight path of the aircraft was constrained to approximately the southeast quadrant of the rainwater network and yet considerable tracer material appeared in the rainwater in the southwest quadrant. These results strongly suggest that the seeding of an "isolated" updraft in advance of a multicellular line of convective storms results in an exchange of the seeding material between the various cellular components of the system.

Ground Tracer Release

Tracer lithium was released through an industrial stack (shown in figure N-2) into a weak convective system which traversed the network on 14 July 1971. The lithium deposition pattern

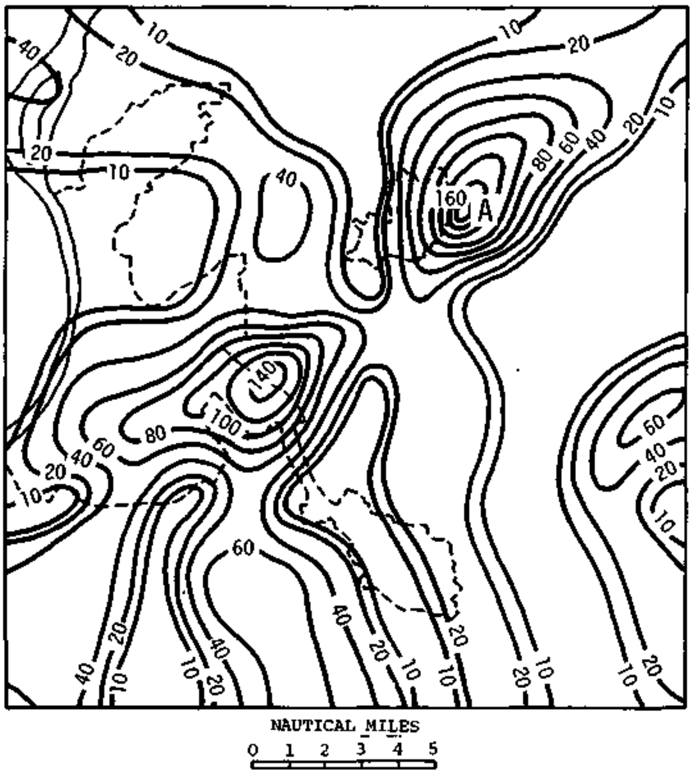


Figure N-l. Lithium deposition in picograms/cm^2 from tracer release on 14 August 1971

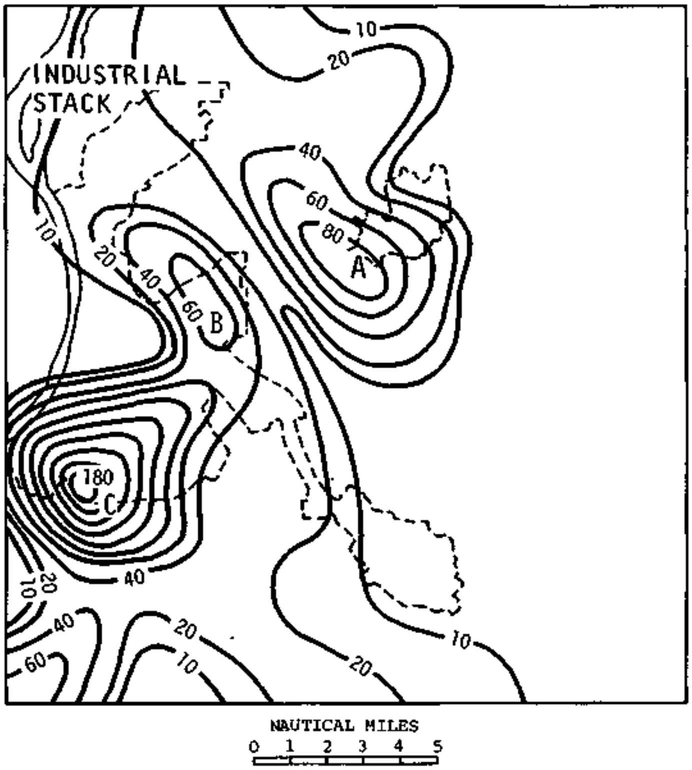


Figure N-2. Lithium deposition in picograms/cm^2 from stack release of tracer on 14 July 1971 is shown in figure N-2. The low-level winds varied from WNW through NNW during the 1.5 hr release of lithium. There is an obvious maximization of the lithium at a distance of approximately 10 miles downwind from the source. The deposition decreases further downwind to the east and southeast and is barely discernable above the background.

The detailed analysis of recording raingage data within the rainwater network reveals that the rain which yielded the lithium maximum in the north-central area (A in figure N-2) was the result of new raincell development at 1650 CDT or 50 min after the initiation of the release. The second smaller maximum (B in figure N-2) to the southwest of A, was associated with the merger of the first raincell with additional precipitation adverted from the north. The final and heaviest deposition, shown as C in figure N-2, was the result of intensification of the system as it became more organized and moved slowly across the network. The individual convective showers were imbedded within a continuous rain as the associated cold front drifted southward.

There was no apparent relationship between rainfall and the lithium deposition. This lack of correlation suggests that the convective activity was too weak to produce precipitation, but sufficiently active to concentrate the stack effluent.

While it is difficult to determine the precise history of the deposition pattern shown in figure N-2 since sequential time samples were not obtained, it is possible to estimate the minimum time required for the lithium to interact with the precipitation. The earliest rain that fell at the sampling sites that delineate the three maxima occurred 50, 65, and 75 min after the initiation of the tracer experiment. The mean low-level wind was approximately 15 knots during the experiment. The time required for the wind to transport the lithium to the raincell intercept point was 30, 25, and 35 min for deposition maxima A, B, and C, respectively. Therefore, the process time of the lithium in each of the raincells associated with the deposition pattern was 20 min for A, 40 min for B, and 40 min for C.

Summary

The preliminary results from the experiments conducted in the first 2 years of the Metromex project have also been summarized by Semonin (1972). The most important results from these experiments are enumerated as follows:

1) The almost total absence of lithium in non-tracer rainfall indicates its suitability as a tracer chemical.
2) The low-level releases of tracer lithium indicate that an urban-industrial aerosol of the proper physico-chemical properties can be processed by precipitating convective storms and deposited in the region of the observed climatic rainfall maximum in Illinois.
3) A target-control design for advertent weather modification of multicellular convective systems is not a sound approach unless the target and control are separated by at least 20 miles.

The final result from this aspect of the Metromex research program will not be known until the completion of the many years of field efforts because of the complexities of the complete chemical analysis of the samples and the detailed analysis of the surrounding meteorological conditions. In any event, these results will be of great value in the determination of the ability of the atmosphere to remove man-made materials and maintain an equilibrium value of pollutant particulates.

References

Changnon, S. A., Jr., F. A. Huff, and R. G. Semonin. 1971. *Metromex: An investigation of inadvertent weather modification.* Bulletin American Meteorological Society, 52(10):958-967.

Semonin, R. G. 1970. *Study of rainout of radioactivity in Illinois.* Illinois State Water Survey for AEC Contract AT(11-1)-1199. Ninth Progress Report. 55 pp.

Semonin, R. G. 1972. *Tracer chemical experiments in Midwest convective clouds.* Preprints, 3rd Conference on Weather Modification, Rapid City, S. D.; AMS, Boston, pp. 83-87.

O. pH MEASUREMENTS IN RAINFALL

R. G. Semonin

Introduction

The rainwater chemistry project within Metromex requires the collection of numerous precipitation samples over an area of 750 mi^2 to determine the spatial variability of several elements. Among these are the elements which are released into convective storms traversing the sampling network located immediately downwind of the St. Louis-East St. Louis metropolitan area.

During the summer of 1972, rainwater samples suitable for pH determination were obtained on 14 days. The maximum number of samples obtained from a given storm was 81 with lesser numbers available on the other days depending upon the degree of organic contamination in the sample. Subsequent to the pH measurement, the water sample was prepared for the chemical determination of many elements removed by the precipitation process.

Sample Acquisition and Handling

The samples were collected in plastic bottles within a network downwind of the city of St. Louis covering an area of 750 mi^2. Each of the sampling locations represented an area of about 9 mi^2. Within a short period of time after the cessation of rain (a few hours), the samples were removed from the field, immediately capped, and transported within 24 hours to Champaign, Illinois, for analysis.

Upon receipt of the samples in the laboratory, the container was weighed with its precipitation sample and a pH measurement was obtained. If the individual sample appeared to be contaminated with various organic materials (primarily bird droppings), as indicated by a visual inspection, the determination of pH was not made. The pH of contaminated samples was uniformly greater than 7. Although the samples deemed unfit for this analysis were discarded, the rain falling through trees and on man-made edifices would be so contaminated. Consequently, such natural phenomena may counteract the acid content of the precipitation and tend to neutralize it toward more alkaline values.

Results

The average pH at each of the sampling sites was calculated and is shown in figure 0-1. The values ranged from 4.26 to 6.82 resulting in a network average for all data points of 4.94. The average pH values shown in figure O-l are weighted by the total water in each of the individual samples.

It is difficult to identify any particular pattern associated with the known industrial areas within the network. There is a relatively low pH value near Granite City and in the southern East St. Louis area, but comparable values of pH are observed in the extreme southeast portion of the network in a rural environment.

Because of the natural abundance of CO_2 in the atmosphere, precipitation will become more acid as a result of the solubility of this gas. As an approximate measure, the pH of water falling through the atmosphere would be about 5.7 due to the formation of natural carbonic acid. Therefore, many of the values shown in figure O-l are more alkaline than the natural rainwater

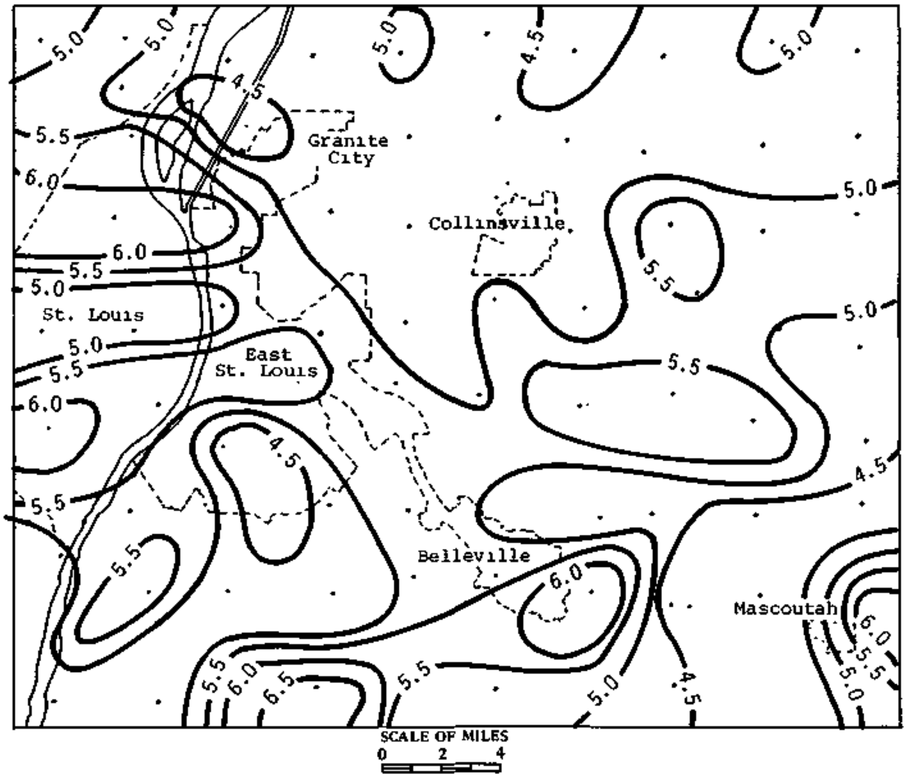


Figure O-l. Mean pH from 14 rain events during 1972 (Dots are sampling locations in chemistry subnetwork of Metromex research area)

without the addition of man-made effluents. In general, the remaining pH values after adjustment for CO_2 solubility would increase, but there are few areas in the network where the pH would be entirely accounted for by the natural acid content of the rainfall.

The average precipitation for the samples included in this analysis is shown in figure 0-2. The precipitation pattern (measured in milliliters) and the pH values shown in figure 0-1 show little resemblance and appear to be totally independent.

The deposition of the hydrogen ion can be deduced from the observations of the pH and the precipitation, and the mean values for the summer of 1972 are shown in figure 0-3. The resulting pattern appears to be dominated by the distribution of the pH values rather than by the rainfall. This, of course, may be expected since the pH, by definition, is proportional to the logarithm of the hydrogen ion concentration, whereas the precipitation parameter is linear.

Summary

The pH was measured in several storms during 1972 and average values of pH, precipitation, and hydrogen ion deposition were determined. These initial data indicate the mean pH over an area of 750 mi^2 is 4.94 and varied from 4.26 to 6.82. These values are not adjusted for the CO_2 saturation which would naturally acidify rainwater to a pH of 5.7. There does not appear to be a distinct correlation between the precipitation and the pH. Likewise, there appears to be no relationship between the areal pH pattern and the industrial areas of the St. Louis region.

These observations will be continued during the remaining years of the Metromex program to ascertain the effects of rainfall acidification on the quality of the soils in the rich agricultural areas in Illinois, and its possible destructive action on buildings and other man-made edifices.

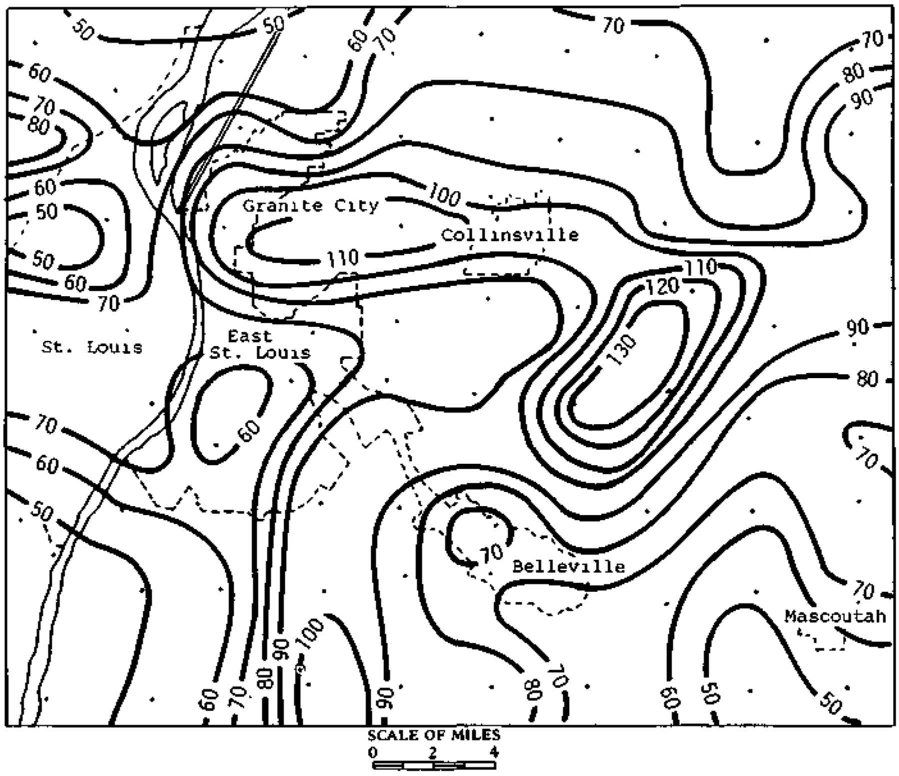


Figure 0-2. Mean rainfall (milliliters) of the 14 rain events with pH observations

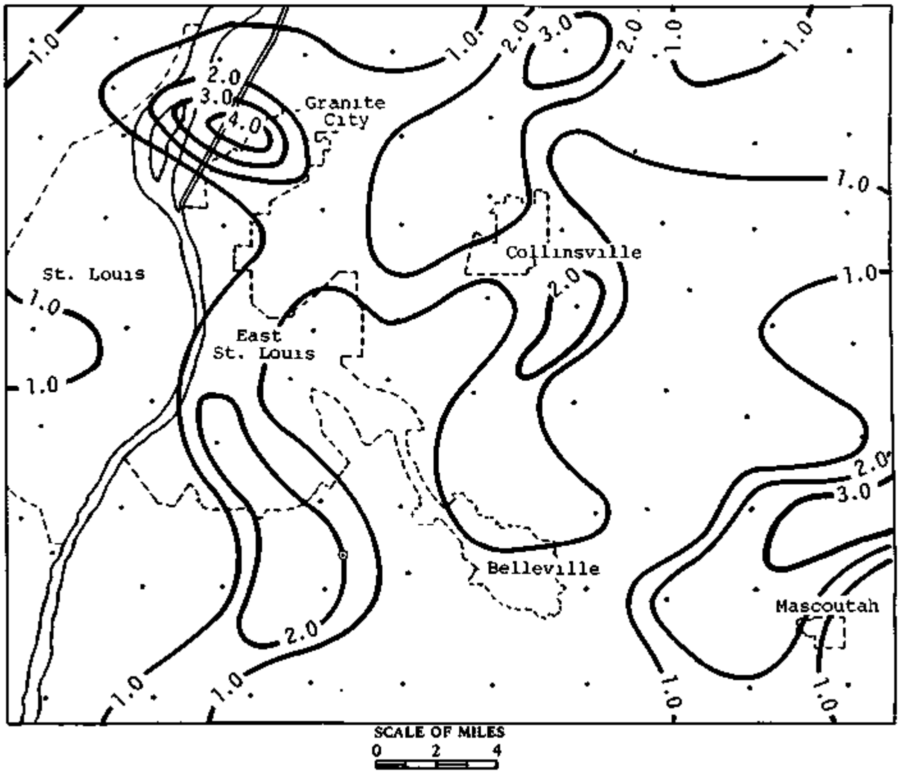


Figure 0-3. Mean hydrogen ion deposition (grams) calculated from pH and rainfall

P. SCAVENGING RATIO MEASUREMENTS

Donald F. Gatz

Introduction

The scavenging ratio is the ratio of a material's concentration in rain to its concentration in air. Specifically, the scavenging ratio, W, is defined by

$$W = k\rho/x \qquad (1)$$

where k is the concentration of a material in precipitation (µg/g), x is its concentration in air (µg/m^3), and p is the density of air, taken as a constant, 1200 g/m^3 (20 C, 760 mm Hg). [Note: This ratio has also been called the "washout ratio" (Goldsmith et al., 1963; Chamberlain, 1960), but that term is a misnomer, because the ratio is a relative measure of the efficiency of *all* scavenging processes — not only washout, which is usually defined to include only below-cloud scavenging mechanisms.]

Deposition in precipitation is one segment in the system of pathways by which airborne materials travel through the environment. Accurate assessments of *how much* material travels this way, and *how fast* it travels, are desirable, if not essential, for the accurate evaluation of pollution hazards or control strategies.

Scavenging ratios have been found to be relatively constant (varying by a factor of the order 10) for a wide variety of airborne materials (Engelmann, 1971). This makes them useful for prediction of deposition in precipitation when the scavenging characteristics of the material of interest have not been studied in detail. Unfortunately, this is all too often the case.

Even when the physical and chemical properties (e.g., particle-size distribution and solubility) of an aerosol are known, there is no general theory of scavenging yet available from which deposition at a point may be predicted. The scavenging ratio method for predicting precipitation deposition is.based on measuring or assuming values for W and x, from which k may be calculated (equation 1).

The objective of this work is to improve the scavenging ratio method for predicting deposition in precipitation. The first part of the work consists of the measurement of scavenging ratios for six elements, based on daily precipitation and air filter samples collected as part of the field observation program of Metromex. The detailed data on precipitation, cloud microphysics, and winds that are available from this program permit a search for relationships between daily scavenging ratios and meteorological parameters. The second part of the work consists of efforts to generalize the results to other materials, through measurements of the rain solubility and particle-size distribution of the elements for which scavenging ratios are measured.

The field sampling and sample analysis portions of this work were carried out in 1971, when the investigator was employed by Argonne National Laboratory. Interpretation of the results was performed primarily at the Illinois State Water Survey.

Sampling and Analysis Procedures

Rain samples were collected in polyethylene funnel collectors of 10-inch diameter; these drained into polyethylene bottles, and were positioned about 3 meters above ground level. The samplers were located at stations designated on the map in figure P-l as Pere Marquette, KMOX, Centreville, Tyson, and Coldwater Creek. They were visited daily to pick up samples and clean the funnels. Dry deposition samples were collected occasionally to provide information needed to correct the rain analyses for dry-deposited materials.

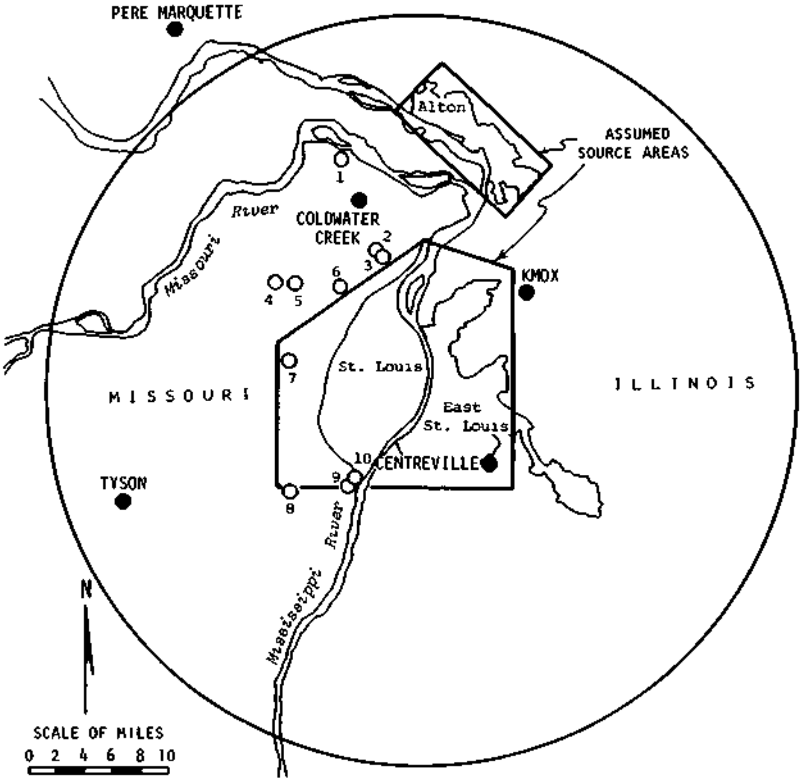


Figure P-1. Locations of rain samplers, urban plume sources, and network of St. Louis County Health Department

Filter samples were collected about 2 meters above ground level on 15-cm diameter Whatman-41 filter paper, by use of high volume (about 40 m^3/hr) positive displacement pumps. Filters were changed daily. Sample volumes were estimated from pressure drop measurements made at the start and end of each filter, calibrated against a precision rotameter-type flow meter. Sample volumes obtained in this way are considered accurate to ±5%. Filters were handled only with clean Teflon-covered forceps and were stored with the sample-side folded together in polyethylene bags until analysis.

Rain samples were filtered through 0.5-µm pore diameter, low-blank membrane filters to separate the soluble and insoluble components. After all of the liquid portion of each sample had passed through the filter and into a clean polyethylene bottle, the filtrate (soluble fraction) was removed from the filtration chamber and stored frozen until analysis. Care was taken to remove as much of the insoluble material as possible from the walls of the polyethylene sample bottle, by use of a stream of distilled deionized water from a squeeze bottle, and when necessary, a clean Teflon scraper. Less than 5% of the insoluble material was left in the bottles, by visual estimate. All water rinses and a final isopropyl alcohol rinse of the filter funnel were collected below the filter in a separate waste bottle and discarded.

Dissolution of the filter samples was carried out in a clean 100-ml Teflon beaker. A few drops of acetone were added to dissolve the membrane filter, and the sample was again dried, by low heat on a hot plate. Then 10 ml of concentrated HNO3 was added and the sample heated on the hot plate until the reddish-brown NO2 fumes disappeared. Ten ml of concentrated $HClO_4$ and 5 ml of concentrated HF were added carefully and heated to strong fumes of $HClO_4$. Another 5 ml of HF was added and the sample was again heated to strong fumes of $HClO_4$, followed by evaporation to reduce the sample volume to about 5 to 10 ml. This was transferred, with beaker washings, to a 50-ml volumetric flask, diluted to volume with distilled water, and transferred to a polyethylene bottle for storage until analysis.

The insoluble portions of the precipitation samples were analyzed for Cu, Fe, Pb, Mg, Mn, and Zn directly by aspiration of the sample into the air-acetylene flame of an atomic absorption spectrophotometer (Instrumentation Laboratory Model 353). Approximately 2 ml was needed for each element. A standard La addition was used to suppress interference in the Mg determination.

The same procedure was followed in the case of the soluble portion, except that in these samples Cu and Pb were first concentrated by a solvent extraction with dithizone into ethyl propionate (Sachdev and West, 1969).' After confirming that rain contains virtually no soluble Fe, no Fe analyses were performed on the soluble rain fractions.

The instrument response was read in absorbance units and converted manually to concentration with calibration curves constructed from analyses of standard solutions. The standards used with acidified samples were made approximately 10% acid with equal parts of concentrated HNO3 and $HClO_4$ to match the sample matrix. Standards for the extracted elements were prepared in water and underwent extraction in the same way as the samples. Single-element hollow cathode lamps were used as light sources for the analyses.

The air filter analyses were performed by using half portions of the collected filter samples. After removal of the outer ring of the filter (through which no air had passed), the filter was cut approximately in half with a clean surgical knife. The fraction analyzed is the ratio of the mass of the analyzed portion to that of the whole filter (without outer ring). Before weighing, care was taken to insure that the filter mass had stabilized for the ambient laboratory temperature and humidity conditions.

Except for the elimination of the addition of acetone (used to dissolve the membrane filter) the dissolution and analysis of the air filters followed the same procedure given earlier for the rain insoluble fraction.

Concentrations in Rain

Table P-l shows that mean concentrations of each of the elements are consistently higher (up to about 10 times) at the downwind stations close to the city (Centreville, KMOX, and Coldwater Creek) than at the more remote upwind stations (Tyson and Pere Marquette). This is true for both the rainfall-weighted and the arithmetic means. Concentrations of rainfall constituents usually decrease with increasing rainfall amounts, so the rainfall-weighted concentration would be expected to be smaller than the arithmetic mean. The results in table P-l are inconsistent on this point, although Pb and Mg are consistently just the opposite of the normally expected pattern. However, these results may be due to the small numbers of samples at most stations.

In assessing the influence of the urban area on the concentrations in rain, one should ideally divide his samples at each station into 1) those collected from rain systems that ingested air that had recently passed over the urban area and 2) those collected from rain systems that had not ingested such air. Because of the small numbers of samples at each station, however, it is not practical to do this with the 1971 data. A similar but somewhat less satisfactory procedure is to take the data from all stations and divide them in the same way. The results of such a data stratification, and a test of the significance of the observed differences using the student's t-test, is given in table P-2.

The two areas assumed to be the source(s) of the "urban plume(s)" are outlined in figure P-l. The direction of movement and the horizontal spreading of the plumes from these sources were estimated subjectively from available wind observations in the mixing layer. These consist of about 10 surface stations and low-level soundings at the Arch made by the NOAA Environmental Meteorological Support Unit (EMSU).

Table P-l. Rainfall-Weighted Mean and Arithmetic Mean Concentrations in Rain during 1971

	Concentration, µg/kg					
	Cu	Fe	Pb	Mg	Mn	Zn
*Centreville (n = 5)**						
Rainfall-weighted mean	7.2	640	55	303	10	73
Arithmetic mean	14.0	760	23	204	15	184
Its standard deviation	7.7	360	14	142	9	81
KMOX (n = 4)						
Rainfall-weighted mean	2.1	350	38	260	8	21
Arithmetic mean	0.6	610	12	212	4	47
Its standard deviation	0.6	310	12	84	2	28
Coldwater Creek (n = 4)						
Rainfall-weighted mean	10.	540	108	330	17	126
Arithmetic mean	6.1	330	58	256	10	67
Its standard deviation	5.0	328	51	120	8	58
Tyson (n = 3)						
Rainfall-weighted mean	0.9	**	23	46	6	**
Arithmetic mean	0.3		5	23	5	
Its standard deviation	0.3		5	13	3	
Pere Marquette (n = 13)						
Rainfall-weighted mean	1.5	210	10	103	7	9
Arithmetic mean	1.7	180	9	125	7	24
Its standard deviation	0.2	87	2	37	3	13

*** n is the number of samples at each station**
**** Contamination or error suspected**

The rain sample was designated to be *"downwind"* if it was located in the urban plume at the time of, or up to 1 hr prior to, onset of rain at the collecting stations. Otherwise, the sample was designated *"upwind."*

The concentrations in upwind rain are consistently less than in downwind rain, and the differences are significant at the 10% level for all the elements measured except Pb and Mn. However, the upwind data are biased toward the locations more distant from the city (13 of 18 observations were from Pere Marquette and Tyson), so the differences may reflect the effects of distance as well as urban or non-urban trajectory of the ingested air.

Table P-2. Comparison of Concentrations in Rain at 'Upwind' and 'Downwind' Stations

	Arithmetic mean concentration ± its standard deviation, µg/g		
	Upwind n = 18	Downwind n = 10	t-value*
Cu	0.0015 ± 0.0007	0.0088 + 0.0042	2.13
Fe	0.15 ±0.06	0.67 ±0.22	2.70
Pb	0.0070 ±0.0021	0.034 ±0.021	1.66
Mg	0.11 ±0.03	0.24 ±0.08	1.72
Mn	0.0061 ± 0.0021	0.011 ±0.005	1.02
Zn	0.026 ±0.011	0.13 ±0.05	2.47

• t-value for significance at 10% level = 1.71

Concentrations in Air

The mean concentrations x of the same six elements in air sampled on rain days at the various filter sampling sites are presented in table P-3. All filters collected on rain days were analyzed, even if rain was collected at only one station. The table shows that concentrations in air, like those in rain, increase from the more distant upwind locations to the downwind locations closer to the city. Again, the downwind concentrations are higher by factors of up to about 10. For each element except Pb, KMOX had the highest concentration, followed by Coldwater Creek, Tyson, and Pere Marquette. For Pb, the order of KMOX and Coldwater Creek was reversed.

Table **P-3.** Mean Concentrations **in Air on** Sampled **Rain** Days in **1971**

	Concentration, µg/m^3					
	Cu	**Fe**	**Pb**	**Mg**	**Mn**	**Zn**
*KMOX (n = 8)**						
Arithmetic mean	0.0297	1.13	0.476	0.463	0.043	0.294
Its standard deviation	0.0052	0.12	0.039	0.093	0.004	0.063
Coldwater Creek (n = 8)						
Arithmetic mean	0.0181	1.01	0.574	0.325	0.031	0.162
Its standard deviation	0.0059	0.11	0.157	0.036	0.005	0.071
Tyson (n = 8)						
Arithmetic mean	0.0020	0.52	0.314	0.157	0.017	0.064
Its standard deviation	0.0003	0.08	0.058	0.034	0.003	0.027
Pere Marquette (n = 14)						
Arithmetic mean	**	0.28	0.15	0.125	0.013	0.047
Its standard deviation		0.06	0.03	0.020	0.001	0.014

*** If 4 samples collected on dry days are included, the means at KMOX are: Cu, 0.0246; Fe, 1.13; Pb, 0.489; Mg, 0.397; Mn, 0.044; and Zn, 0.277 µg/m^3**

**** Cu undetectable on all filters**

For comparison, monthly and mean trace metal concentrations measured in the 10-station network of the St. Louis County Health Department during summer 1971 are given in table P-4. Station locations are shown in figure P-l. Agreement between the two networks is generally excellent. A possible discrepancy occurs in the case of Cu, where the Health Department concentrations are generally higher. As Hoffman and Duce (1971) have pointed out, however, brush wear on Cu armatures can be a significant source of Cu contamination on filter samples collected on the type of high-volume sampler used by the Health Department. This problem should be less severe in the samplers used in Metromex, since the motor that drives the vacuum pump was enclosed in a housing open only near the ground, while the filter paper was exposed at a height of about 2 meters.

Again, it is of interest to examine upwind-downwind differences in concentration, as an indication of the effect of the city on air quality. Table P-5 shows mean concentrations of the various elements (and standard deviations of the means) for all stations, divided into two categories that indicate whether the sampling site was upwind or downwind of pollution source regions (see figure P-l) during the sampling period. In this case, a sample was designated "upwind" if its collection station was in the urban plume for only 2 hr or less during its 24-hr collection period. All other samples were designated "downwind." As shown in table P-5, downwind concentrations are greater for each element, with significance at the 10% level or better for all elements except Pb.

Here again, the upwind observations are somewhat biased toward the more distant stations — 16 of 24 samples were from Tyson and Pere Marquette. In this case it was possible to compare concentrations at a single station when it was upwind and when it was downwind of the source regions. This has been done in table P-6 for the KMOX station. The total number of samples (12) is still not as large as would be desirable, but the results, though still preliminary, reveal some interesting variations from what was observed in the pooled samples.

For example, at KMOX only Cu and Mg have significantly (10% level) higher concentrations in the air from source regions. Many speculations about the causes of such occurrences are possible, but it now seems that the answer probably lies in the rather poorly known distribution of sources of the various elements in the St. Louis area.

Table P-4. Trace Metal Concentrations in Air during 1971 Measured by St. Louis County Health Department

		Concentration in air,, $\mu g/m^3$				
Station	**Month**	**Cu**	**Fe**	**Pb**	**Mn**	**Zn**
1	June	0.357	1.13	0.40	0.054	0.04
	July	0.235	1.58	0.80	0.031	0.00
	August	0.375	1.16	0.54	0.029	0.47
	Mean	0.322	1.29	0.58	0.038	0.17
2	June					
	July					
	August	0.130	1.87	1.76	0.052	0.67
	Mean					
3	June	0.022	1.11	0.85	0.072	0.09
	July	0.015	1.11	1.63	0.043	0.00
	August	0.070	1.78	0.79	0.042	0.56
	Mean	0.036	1.33	1.09	0.052	0.22
4	June					
	July	0.008	0.95	1.08	0.029	0.19
	August	0.041	1.70	1.48	0.045	0.03
	Mean	0.024	1.32	1.28	0.037	0.11
5	June	0.125	1.42	1.02	0.079	0.12
	July	0.079	0.99	1.11	0.015	0.00
	August	0.148	3.04	1.38	0.117	0.00
	Mean	0.117	1.82	1.17	0.070	0.04
6	June	0.025	1.26	1.40	0.067	0.12
	July	0.017	1.14	2.20	0.047	0.28
	August	0.029	1.96	1.38	0.070	0.41
	Mean	0.024	1.45	1.66	0.061	0.27
7	June	0.084	1.48	1.93	0.082	0.20
	July	0.034	1.25	3.14	0.013	0.00
	August	0.032	1.44	1.68	0.048	0.00
	Mean	0.050	1.39	2.25	0.048	0.07
8	June					
	July	0.033	1.07	2.88	0.029	0.20
	August	0.075	0.96	0.84	0.043	0.17
	Mean	0.054	1.02	1.86	0.036	0.18
9	June	0.101	1.33	0.64	0.056	0.11
	July	0.036	1.94	1.36	0.045	0.16
	August	0.062	2.47	0.66	0.039	0.00
	Mean	0.066	1.91	0.89	0.047	0.09
10	June	0.002	4.00	1.06	0.096	0.24
	July	0.034	2.38	1.28	0.042	0.09
	August	0.059	4.23	0.60	0.068	0.07
	Mean	0.032	3.54	0.98	0.069	0.13

Table P-5. Comparison of Air Concentrations between 'Upwind' and 'Downwind' Stations

	Arithmetic mean concentration ± its standard deviation, $\mu g/m^3$		
	Upwind n = 24	Downwind n=17	t-value*
Cu	0.0045+0.0013	0.021 ± 0.004	3.99
Fe	0.60 ±0.07	0.89 ±0.12	2.85
Pb	0.30 ±0.06	0.44 ±0.06	1.63
Mg	0.20 ±0.02	0.34 ±0.06	2.51
Mn	0.021 ± 0.003	0.034 ± 0.004	2.67
Zn	0.091 ±0.022	0.21 ±0.05	2.51

* t-value for significance at 10% level = 1.68

Table P-6. Comparison of Concentrations in Air at Station KMOX when it was 'Upwind' and 'Downwind'

	Arithmetic mean concentration ± its standard deviation, $\mu g/m$		
	Upwind n = 5	Downwind n = 7	t-value*
Cu	0.015 ± 0.003	0.032 ± 0.006	2.29
Fe	1.1 ±0.1	1.2 ±0.1	0.62
Pb	0.52 ±0.06	0.47 ±0.04	0.61
Mg	0.26 ±0.02	0.50 ±0.10	1.84
Mn	0.042 ± 0.004	0.045 ± 0.005	0.42
Zn	0.27 ±0.03	0.28 ±0.07	0.18

* t-value for significance at 10% level = 1.81

Scavenging Ratios

It is worthwhile to repeat that our emphasis has been on measuring *daily scavenging ratios,* based on daily measurements of concentrations in rain and air — not on the mean concentrations just reported (tables P-l and P-3). Furthermore, it should be understood that the arithmetic mean of daily scavenging ratios over the period of a month, say, is *not* equivalent to the ratio that would be computed from analyses of *monthly* air filter and precipitation samples collected at the same place. The arithmetic mean of daily scavenging ratios gives equal weight to each rain, regardless of amount, whereas a ratio computed from monthly samples weights the rain samples according to amount. The scavenging ratios and the concentrations in rain and air found in the literature are frequently this type of "rainfal-weighted" composite. It is of interest to compare scavenging ratios computed both ways from the same data.

Both types of scavenging ratios for Cu, Fe, Pb, Mg, Mn, and Zn from Metromex 1971 are presented in table P-7. The composite means range from about 1/4 to 3/4 of the respective arithmetic mean values for the various elements. This shows how the composite means are influenced by the heavier rains, which frequently have low k-values and hence, low scavenging ratios.

A comparison of mean scavenging ratios at a given station in the two cases when it is upwind and downwind of pollution sources is again the most desirable. However, the data are presently too few to yield anything meaningful at any one station, and we are forced to group the data from all five stations into upwind and downwind cases. Daily scavenging ratios were included only if both component measurements fell into the same class, i.e., upwind or downwind. The comparison given in table P-8 shows very small differences for all the elements, with no differences significant at the 10% level.

Tables P-7 and P-8 show some rather marked differences between scavenging ratios for the various elements. To examine these differences more carefully, tests for significance of the differences between means of each element pair were performed with the student's t-test. Because the test for upwind-downwind differences showed no significance, all samples were grouped together for this test. The computed t-values are listed in table P-9 and show that the scavenging ratio for Pb is significantly different from those of all the other elements determined, at the 1% level or better. In addition, the scavenging ratios for Mg and Mn were found significantly different at the 10% level.

Inspection of the scavenging ratio data suggested that some pairs of elements were positively correlated and others perhaps negatively correlated. To examine this possibility in a more quantitative way, correlation coefficients were computed for all pairs of elements. The results appear in table P-10. The pairs Cu-Mg, Cu-Mn, Fe-Mg, and Fe-Mn, had correlation coefficients greater than 0.80, and all were significant at the 5% level or better.

Table P-7. Arithmetic Mean and Rainfall-Weighted Mean Scavenging Ratios during 1971

	Cu	Fe	Pb	Mg	Mn	Zn
Arithmetic mean	724	979	147	1282	721	696
Its standard deviation	251	233	32	267	158	168
Rainfall-weighted mean	202	520	116	660	405	294
Number of samples	8	19	17	21	18	20

Table P-8. Comparison of Scavenging Ratios at 'Upwind' and 'Downwind' Stations

	Arithmetic mean ± its standard deviation		
	Upwind	Downwind	t-value**
Cu	540 (1)*	790 ±410 (5)	
Fe	870 ±450 (8)	930 ± 150 (8)	0.13
Pb	190 ± 70(7)	140 ± 70(7)	0.59
Mg	1200 ±380 (10)	1400 + 490(8)	0.26
Mn	840 ±280 (9)	520 ±210 (6)	0.78
Zn	970 ±330 (7)	710 ± 250 (9)	0.61

• Number of samples in parentheses

* * t-value for significance at 10% level ~ 1.76

Table P-9. Results of t-Tests for Significance of Differences between Mean Scavenging Ratios

	Scavenging ratio	t-values*				
		Cu	Fe	Pb	Mg	Mn
Cu	724					
Fe	979	0.62				
Pb	147	3.10	3.25			
Mg	1282	1.23	0.82	3.71		
Mn	721	0.01	0.88	3.36	1.69	
Zn	696	0.09	0.96	2.89	1.62	0.10

* t-value for significance at 10% level ~ 1.7, at 1% level ~2.8

Table P-10. Correlation Coefficient Matrix for Scavenging Ratios from All Stations in 1971

	Correlation coefficient				
	Cu	Fe	Pb	Mg	Mn
Fe	0.45				
Pb	−0.30	−0.31			
Mg	0.83	0.82	−0.13		
Mn	0.94	0.84	−0.24	0.50	
Zn	0.23	−0.20	0.34	−0.04	−0.01

In examining the possible causes of these relatively high correlation coefficients, it is useful to review what scavenging ratios and their correlations mean in physical terms. The ratios are computed from concentrations in air and precipitation measured near the ground. Actually, of course, the cloud "sees" a different concentration entering at its base, and the physical processes that remove particles from the air in the cloud act on that concentration of particles. The physical processes that remove particles from the air below the cloud act on the entire vertical concentration profile up to cloud base.

To reflect the actual physical processes taking place, scavenging ratios should take into account the vertical concentration profile from ground level to cloud base. However, obtaining vertical profiles is a difficult sampling problem, even in a research situation, and is completely impractical for operational use. Thus, if scavenging ratios are to be useful for prediction purposes, the necessary measurements must be conveniently made, i.e., at or near ground level. Ground-level concentrations will be useful in predicting wet deposition if they are a reliable index of concentrations in the layer below cloud base.

However, we must look more closely at the situation in examining relations between elements. If the scavenging ratio of element A is larger than that of element B, it can mean 1) that the scavenging efficiency for A is greater than that for B, or 2) that the estimate of concentration of A, XA. at cloud base, made with ground-level measurements, was disproportionately low, relative to the estimate of XB • As an example of the latter situation, consider two elements whose scavenging ratios are equal, based on measurements at cloud base. Now, however, suppose that the concentration of element C is constant with height from the ground to cloud base, while the concentration of element D decreases by a factor of 10 between the ground and cloud base. Then the estimate of the mean XD below cloud base, from a ground-level measurement, will be disproportionately high, relative to Xc. Because x is in the denominator of the scavenging ratio, the resulting W_D will be larger than Wc. Thus, if a given element's scavenging ratio is high relative to some other element, it can mean either that the first element is more efficiently removed from the air, either in cloud or below cloud, or that its estimated x is disproportionately low, relative to the second element. Conversely, a (relatively) low scavenging ratio means less efficient removal, or a disproportionately high estimate of X.

In general, a positive correlation between two variables indicates that large values of the two parameters tend to occur together and small values tend to occur together. In terms of the possible interpretations of correlations between scavenging ratios, positive correlations can indicate either 1) parallel variations of scavenging efficiency from rain to rain, or 2) parallel deviations between actual and estimated concentrations in air.

One possible explanation for a high correlation between scavenging ratios is that the two elements have similar particle-size distributions. The efficiencies of both nucleation collection and impaction are very dependent on the size of the collected particles, so that elements with very similar size distributions could have removal efficiencies that would vary in a parallel manner from rain to rain in response to varying updraft speeds, moisture, nuclei concentrations, and raindrop-size distributions of the precipitation systems.

Another possible explanation of highly correlated scavenging ratios is a common source. For example, industrial plants or power plants with high stacks could cause parallel deviations between ground-level concentrations and those for the sub-cloud layer for certain elements.

Both of these possible explanations find support in the literature. In heavily industrialized northwest Indiana, Nifong (1970) found that Fe, Mg, and Mn occurred predominantly on large (5-10 µm diameter) particles, and had common sources in the steel industry. Common sources were also found by Dams et al. (1971) for Fe-Mg-Mn in northwest Indiana but not for Cu-Mg-Mn. An association between Fe, Mg, and Mn may also be expected in the St. Louis area since there are steel manufacturing operations in the area. However, the measurements to confirm this expected association, and to determine whether one also exists for Cu-Mg-Mn are tasks for the future.

Relationships with Weather Parameters. For the 1971 data, a number of possible relationships between scavenging ratios and weather parameters were investigated. The parameters included were 1) rainfall, 2) atmospheric stability, and 3) synoptic rainfall type.

There is a well known inverse relationship between contaminant concentrations and rainfall amount. Thus, it might reasonably be expected that scavenging ratios would also vary inversely with rainfall amount. Correlation coefficients for scavenging ratios and corresponding rainfall amounts were computed and are given in table P-11. The correlation coefficients vary from -0.69 to 0.65, but because of the small number of data points and large variability, none is significant at the 10% level.

Relationship to stability was investigated by computing correlation coefficients between scavenging ratios and mixing depth as determined from the NOAA low-level sounding at the Arch, and by grouping the ratios according to whether the rain fell during daylight (unstable) or darkness (stable). The results (not shown) indicated no relationships between scavenging ratios and either stability parameter,

Table P-ll. Correlation Coefficients between Scavenging Ratios and Rainfall

	Correlation Coefficient Upwind	 Downwind	 Total
Cu		-0.69 (5)	-0.61 (6)
Fe	-0.44(8)*	-0.16(8)	-0.34(16)
Pb	0.27(7)	0.52(7)	0.37(14)
Mg	-0.13(10)	-0.38(8)	-0.24(18)
Mn	-0.41 (9)	-0.46 (6)	-0.38 (15)
Zn	0.65 (7)	-0.03 (9)	0.35 (16)

* Number of cases shown in parentheses

Table P-12. Correlation Coefficients between Scavenging Ratios and Percent Solubility

Element*	n	Correlation coefficient
Cu	8	−0.58
Pb	17	+ 0.23
Mg	21	−0.13
Mn	18	−0.42
Zn	20	+ 0.22

* Fe is not included because it is virtually 100% insoluble in rain

but the data set was very limited. This relationship should be investigated further when more data are available.

Relationships with Particle Parameters. Relationships between scavenging ratios and particle parameters offer a possible method of extending the present results to other aerosol materials. Thus, relationships between 1) scavenging ratios and solubility and 2) scavenging ratios and particle-size distribution were examined.

Solubility was suspected as a possible indicator of susceptibility to scavenging by nucleation collection. Thus, correlation coefficients for scavenging ratios and the soluble fraction of each element in individual rains were determined. The results are given in table P-12. The computed coefficients range from -0.58 to +0.23, but only Mn (correlation coefficient = -0.42) was found to be significant at the 10% level.

Analysis of Andersen impactor samples collected in 1971 are not yet completed, so we do not have primary information on particle-size distributions for the various elements in the St. Louis area. However, the literature contains information on particle-size distributions measured in other areas from which we may draw some tentative conclusions about the relationship between scavenging ratio and particle-size distributions. The large-particle preference of Fe, Mg, and Mn in northwest Indiana found by Nifong (1970) has already been mentioned. The same work showed Zn to occur primarily on the small-particle stages (≤ 1 Mm diameter) of the Andersen impactor, whereas Cu showed both large-particle and small-particle components, with emphasis usually on the latter. Others have published data on mass median diameter (MMD) for other locations. [Note: MMD is that-size for which half the total mass of a given element occurs on larger particles and half on smaller particles.] A partial summary of these data is given in table P-l 3. The data were also used to construct the graph shown in figure P-2 relating the rainfall-weighted mean scavenging ratios to particle size ranges reported in the literature. Although table P-9 shows only Pb to have a scavenging ratio significantly different from all the other elements, the graph shows steadily increasing ratios with increasing MMD for the various elements measured.

It is reasonable that scavenging ratios should increase with particle size over the approximate diameter range from 0.5 to 5 µm. Both nucleation and impaction are effective collection mechanisms in this size range, and the efficiencies of both increase with particle size (Fletcher, 1962).

Summary

Scavenging ratios for Cu, Pb, Fe, Mg, Mn, and Zn were measured during 1971. The observed values ranged from about 150 for Pb to 1280 for Mg. No significant upwind/downwind differences were found for scavenging ratios, although concentrations in both precipitation and air showed

Table P-l3. Literature Values of Mass Median Diameter for Selected Elements and Locations

Location	MMD(μm)					
	Cu	Fe	Pb	Mg	Mn	Zn
Cincinnati †	1.2	3.7	0.2*	4.5		
Cincinnati ‡	1.3	2.5	0.5		2.1	1.1
Fairfax, Ohio **t**		1.4	0.4*	7.2		
Philadelphia $	1.2	2.4	0.5		2.3	1.3
Washington, D.C. ‡	1.2	2.3	0.4		1.5	1.3
Chicago ‡	1.5	3.6	0.7		1.9	1.0
Denver ‡	1.6	2.5	0.5		1.8	1.6
St. Louis ‡	1.1	3.2	0.7		2.2	1.2

* Estimated
t Reference, Lee et al. (1968)
$ Reference, Lee et al. (1972)

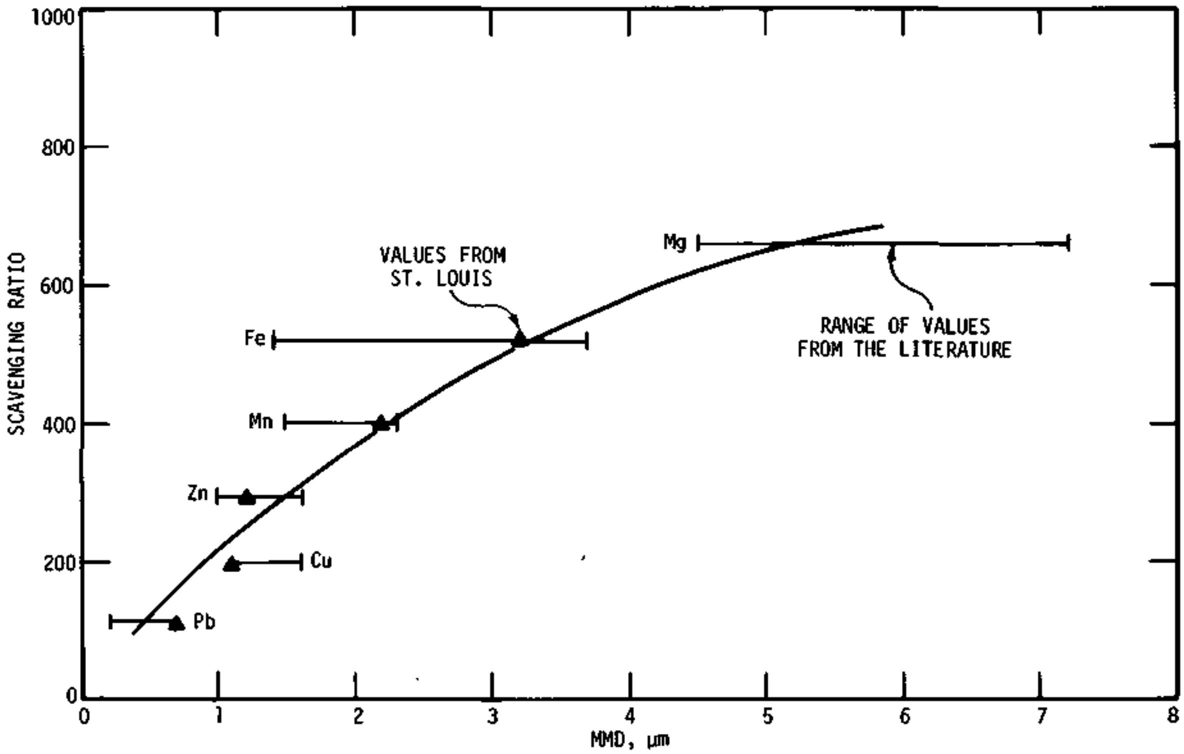


Figure P-2. Relation between rainfall-weighted mean scavenging ratios and particle size ranges

variations ranging up to about 10-fold. The ratio for Pb was significantly smaller than that for each of the other elements. In addition, plots relating scavenging ratio to literature values of MMD for the various elements show a continuous increase in scavenging ratio with particle size. Little or no relationship was found between scavenging ratios and any of the several meteorological or particle parameters examined, including atmospheric stability, rainfall amount, synoptic rain type, and solubility of aerosol materials in rain.

References

Chamberlain, A. C. 1960. *Aspects of the deposition of radioactive and other gases and particles. In* Aerodynamic Capture of Particles, Pergamon Press, New York, 200 pp.

Dams, R., J. A. Robbins, K. A. Rahn, and J. W. Winchester. 1971. *Quantitative relationships among trace elements over industrialized N. W. Indiana.* Nuclear Techniques in Environmental Pollution, Proceedings International Atomic Energy Agency Symposium, Salzburg, Austria, October 26-30, 1970, pp. 139-157.

Engelmann, R. J. 1971. *Scavenging prediction using ratios of concentrations in air and precipitation.* Journal Applied Meteorology, 10(3):493-497.

Fletcher, N. H. 1962. *The physics of rainclouds.* Cambridge University Press, 386 pp.

Goldsmith, P., H. J. Delafield, an'd L. C. Cox. 1963. *The role of diffusiophoresis in the scavenging of radioactive particles from the atmosphere.* Quarterly Journal of the Royal Meteorological Society, 89(379):43-61.

Hoffman, G. L., and R. A. Duce. 1971. *Copper contamination of atmospheric particulate samples collected with Gelman Hurricane air samplers.* Environmental Science & Technology, 5(11): 1134-1136.

Lee, R. E., R. K. Patterson, and J. Wagman. 1968. *Particle-size distribution of metal components in urban air.* Environmental Science & Technology, 2(4):287-290.

Lee, R. E., Jr., S. S. Goranson, R. E. Enrione, and G. B. Morgan. 1972. *National Air Surveillance Cascade Impactor Network II. Size distribution measurements of trace metal components.* Environmental Science & Technology, 6(12): 1025-1030.

Nifong, G. D. 1970. *Particle size distributions of trace elements in pollution aerosols.* Ph.D. Dissertation, The University of Michigan, Department of Meteorology and Oceanography. (Also available as Report 08903-8T, C00-1705-8, U. S. Atomic Energy Commission, Office of Research Administration, Ann Arbor.)

Sachdev, S. L., and P. W. West. 1969. *Concentration and determination of traces of metal ions.* Analytica Chimica Acta, 44:301-307.

Q. AIRCRAFT FILTER SAMPLING AND ANALYSIS

Donald F. Gatz

Introduction

Section P of this report pointed out that the ratio of the concentrations of any material in rain and air (the scavenging ratio) may depend on the vertical distribution of the material in the atmosphere. The prediction of concentrations in precipitation, based on measured scavenging ratios *and ground-level* concentrations in air, may be quite valid, but knowledge of the *vertical distribution* is needed to provide clues to the dominant physical mechanisms of particle collection and their relative and absolute efficiencies.

To provide a few samples collected aloft for comparison with surface concentrations, a program of aircraft filter collections over St. Louis was carried out during Metromex field operations in 1971. This was accomplished through the cooperation of scientists at Los Alamos Scientific Laboratory (LASL) with the use of an RB-57C sampling aircraft and flight crews of the 58th Weather Reconnaissance Squadron, U. S. Air Force. This team had extensive experience in the collection of filter samples by aircraft, including recent low-altitude flights in urban areas and in the vicinity of other pollution sources.

While the primary purpose of the aircraft sampling program was collection of filters for chemical analysis, a second analysis priority was particle-size determination from the LASL Scanning Electron Microscope (SEM). These determinations were planned for the filters collected aloft, and in addition, for filters of the same type exposed at ground level during the approximate period of sample collection aloft. With such a set of samples, it was possible to examine upwind/downwind differences, in addition to vertical differences in the particle size distribution and trace element concentrations.

A summary of the samples collected during July and August 1971 and a report of results obtained from the collected samples up to 1 February 1973 are presented in the following paragraphs.

Sampling Procedures

The sampling aircraft operated from Kirtland AFB, Albuquerque, New Mexico. On sampling days the aircraft flew to St. Louis, collected a single sample, landed at Scott AFB for refueling, and returned home. Eight sampling flights were scheduled, one each week between 8 July and 26 August 1971. Various operational difficulties altered the original schedule somewhat, but eight sampling flights were accomplished. This included sampling of one thunderstorm anvil in the Albuquerque area to determine the particle content of air that had been circulated through a thunderstorm.

While sampling in the St. Louis area, the aircraft flew along the flight path shown in figure Q-l, at an altitude of about 610 meters (2000 feet) above ground level, at speeds of about 103 mps (200 knots), for periods of one-half hour. Sampling was carried out with the LASL B-57 Particulate Debris Sampler on the RB-57C aircraft (for further description see Kelsey, 1971). The Kronisol-impregnated IPC-1478 filters used to collect the samples were loaded, unloaded, and handled by LASL or USAF personnel following their usual precautions to avoid contamination. Portions of each filter were removed for chemical and particle-size analysis by a standard procedure designed by LASL to insure that the portions removed are as representative as possible of that collected by the aircraft (Guthals and Smith, 1972). Sample volumes for the aircraft samples were estimated from the area of the sampler inlet, the aircraft speed, and the duration of the sample, corrected for a sampling efficiency of 0.554 (Kelsey, 1971). [Note: Sampling efficiency is defined as the actual mass-flow rate divided by the product of the free-stream air density, the aircraft velocity, and the area of the sampler inlet.]

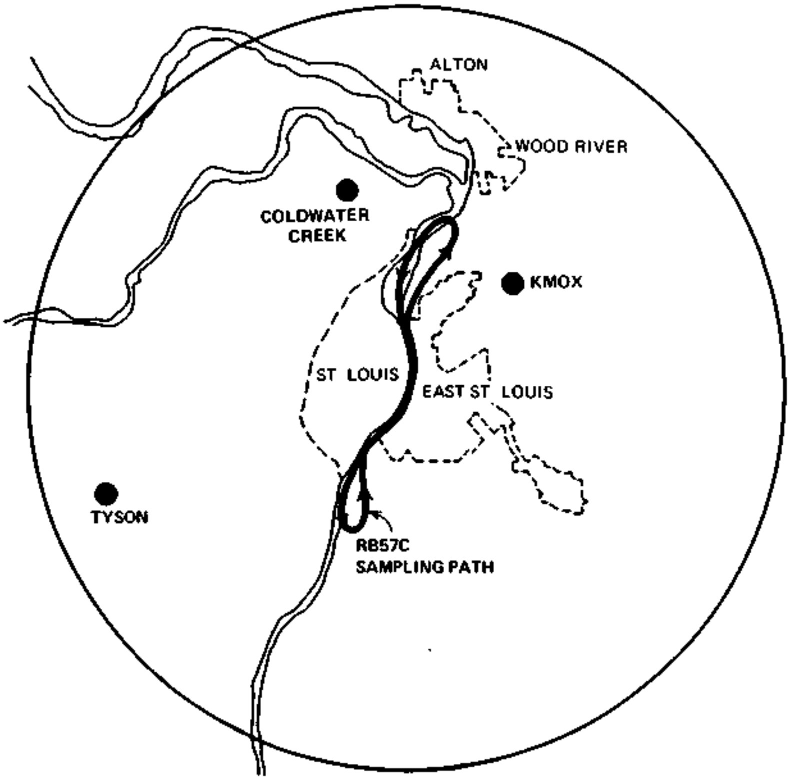


Figure Q-l. Flight path and ground-level sampling stations

On selected aircraft sampling days, ground-level samples were collected on IPC-1478 filters at three sites (Tyson, KMOX, and Coldwater Creek) shown in figure Q-l with use of high-volume (approximately 50 m^3/hr) positive-displacement pumps. Volumes for these samples were estimated from the pressure drop, read at the beginning and end of each sample and calibrated against a precision rotameter-type flow meter. Additional samples were collected for chemical analysis on 25-mm diameter, Whatman-41 filter paper. Collection times varied from 1.5 to 10 hours, bracketing the period of aircraft sampling.

Analysis Procedures

For particle-size analysis, a small portion of each filter sample was coated with either pure gold or a gold-palladium alloy. After coating, the filters were affixed to the SEM mounts with silver glue. A series of photographs was made of various portions of each filter at magnifications of 1000X. Particle-size determinations were made from the photographs, the particles being classified in radius ranges of 0.1-0.5 (µm, 0.5-1.0 µm, and so on up to 5.0 µm, and then in 2.5-µm classes up to the largest particle observed.

The procedure for chemical analysis of the filters consisted of wet-ashing the filter in a mixture of nitric, perchloric, and hydrofluoric acids. This was followed by trace metal analysis with atomic absorption spectrophotometry. Details of the procedure were given by Gatz et al. (1972). The elements Ca, Cu, Fe, Pb, Mg, Mn, K, Na, Zn, and others are detectable on the filters with this procedure.

Error Estimates

This section is included to provide the reader with perspective from which to judge whether the data justify the conclusions drawn. Unfortunately, the various uncertainties are difficult to quantify. Thus, the errors given are subjective estimates of the maximum error that may reasonably be expected. In slightly more precise terms, they may be viewed as approximately two to three times the expected standard deviation.

- Particle-Size Distributions. Errors in particle-size distributions may arise from three main sources: sample volume estimates, sampling procedures, and counting procedures. Incorrect sample volumes would affect the *position* (absolute error) of the distribution curve on the concentration scale, but not the *shape* (relative error) of the distribution. The various errors that are possible in the sampling and counting procedures could affect both the position and the shape (i.e., cause both absolute and relative errors).

The error in the aircraft sample volumes resulting from errors in measurement of inlet area and aircraft speed are expected to be well within 5%. Kelsey (1971) did not discuss the error in the determination of sampling efficiency, but examination of his data indicates that the error is perhaps 5 to 10%. Errors associated with sampling and counting are likely to be much larger.

Kelsey, for example, found that the velocity profile of air passing through the filter is "extremely nonuniform." Indeed, he shows that velocity varies by a factor of >4 across the face of the filter. Thus, error may be introduced if the small section of the filter selected for analysis is not representative of the entire volume of air sampled. According to Guthals (1972), this error has been minimized through long experience with the sampling system. Still, an error of 10 to 20% from this source may reasonably be expected.

Filter collection efficiency and its variation with particle size are additional sources of possible errors. Figure Q-2 shows collection efficiencies given in the literature as a function of particle size and face velocity for IPC-1478 filters impregnated with the organic adhesive Kronisol (dibutoryethyl phtalate). For the aircraft sampling at a speed of 103 mps (200 knots) at an altitude of 610 meters (2000 feet) above ground level, the face velocity was about 7.12 mps (1400 ft/min). Interpolating between the 5.08 mps (1000 ft/min) and 10.16 mps (2000 ft/min) curves in figure Q-2 gives collection efficiencies varying between about 70 and 95% for particles between 0.1 and 1 *µm* in diameter (based on spherical polystyrene latex particles). The collection efficiencies for particles larger than 1 µm are unknown.

In figure Q-2 the data of Stern et al. (1960) at 5.08 mps suggest that collection efficiency increases continuously with particle size. However, the data of Stafford and Ettinger (1971) for 10.16 mps suggest that efficiency may decrease somewhat with increasing particle diameter above 1 µm. Overall, on the aircraft filters, variation of collection efficiency with particle size is not likely to cause errors of greater than 25% in the size range with which we are dealing.

The ground-level samples, collected with face velocities of about 2.03 mps (400 ft/min), have collection efficiencies ranging from about 30 to 90% over the radius range 0.1 to 0.5 µm. Thus, the particle members in our smallest size category must be systematically increased by a factor of about 2 to be comparable to the aircraft filter results. For particles larger than *0.5-µm* radius, the two types of samples should have approximately the same collection efficiencies. Corrections for collection efficiency have not been applied to the size distributions presented in this section.

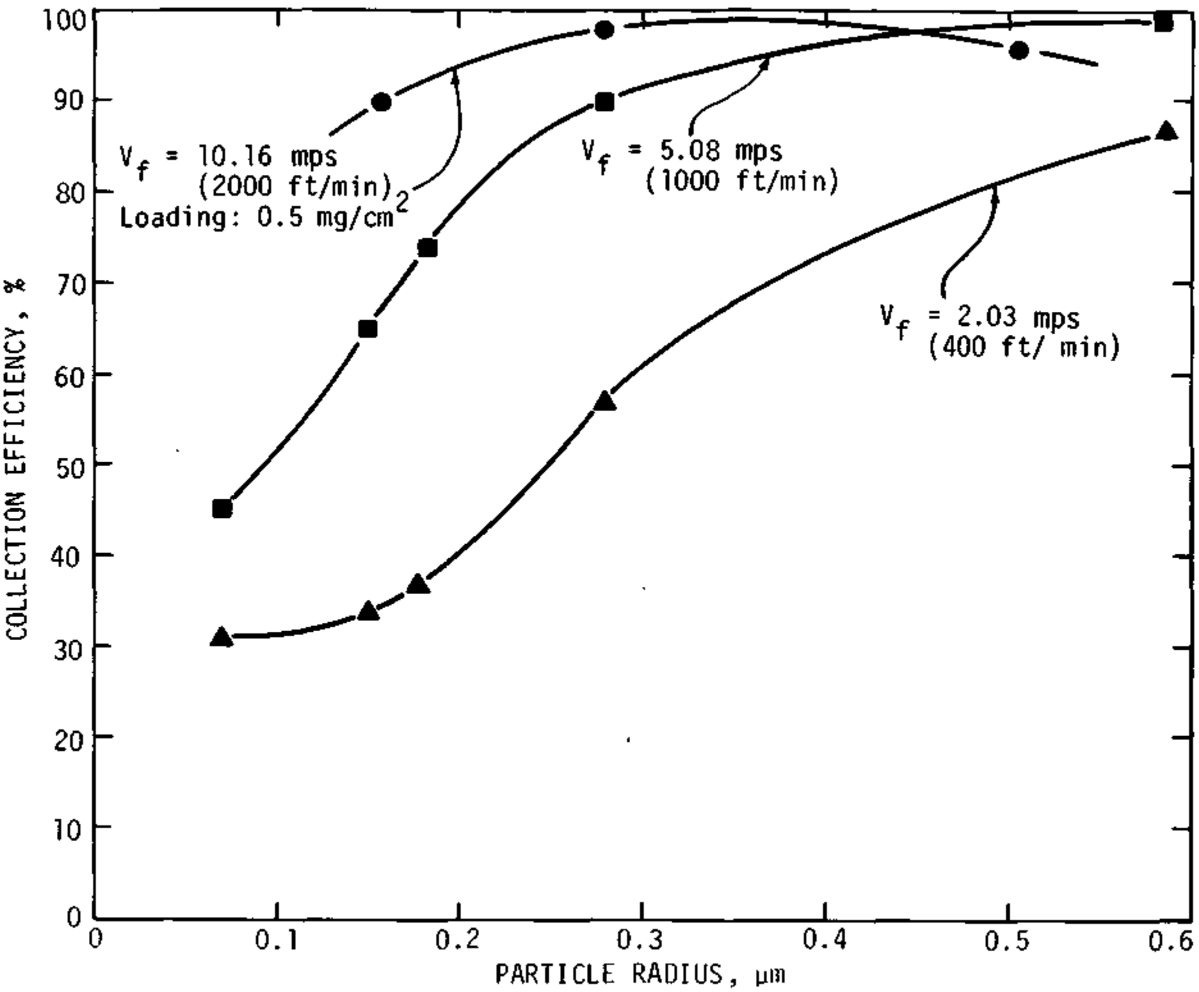


Figure Q-2. IPC-1478 filter collection efficiency as function of particle size and face velocity

Counting procedures are the probable source of greatest error. The IPC-1478 filter mat is made of viscose, having a thickness of 0.084 inch and a fiber volume making up 10% of the mat (Stern et al., 1960). Thus, the filter is a loose, and relatively thick, mat of fibers. The nature of the filter causes the collected particles to be distributed nonuniformly across the face of the filter, i.e., only where there were fibers to intercept them. This increases the danger that the SEM fields selected for photography may be biased toward those containing sharply focused, visible fibers and particles, and thus be unrepresentative of the filter as a whole.

By far the greatest potential source of error, however, arises from the inability of the SEM photographs to show the entire depth of the filter. Only the fibers and their collected particles near the surface are visible; particles collected deep within the filter mat go uncounted. The systematic errors introduced in this way undoubtedly range from 500 to 1000% and upward, and perhaps vary slightly with particle size.

With errors of this magnitude, one might question the usefulness of the particle-size data. Certainly the absolute concentrations determined have little relation to reality. This will be demonstrated later by comparison of these results to Junge's (1963) model for the size distribution of continental aerosols.

However, certain *relative* comparisons are valid. First, comparison of the number concentration and distribution shape among samples collected at the same face velocity should be valid, assuming no gross errors due to selection of fields for photography. Thus, ground-level samples may be compared among themselves, and the same is true for aircraft samples. Further, comparison of ground samples and aircraft samples is possible if differences in collection efficiency at each particle size are taken into account.

Chemical Analyses. Errors in reported concentrations may arise from errors in sample volume estimates or from analytical errors. Sample volume errors may be 20%, as previously discussed. With analytical errors included, the overall error is estimated at ±25%.

Results and Discussion

Ground-level and aircraft filters for 17 and 19 August 1971 have been analyzed for particle-size distribution, and a single aircraft filter collected on 13 August has been analyzed for trace metals in particulate matter.

Particle-Size Distributions. Figure Q-3 shows particle-size distributions near ground level and aloft on 17 August. All distributions show a severe departure from Junge's (1963) model for continental aerosols. This is undoubtedly due to the fact that the filter medium collects most particles too deep within the mat to be seen by the SEM. The deviation from the model appears to be least in the largest particles (about 5 to 10 µm radius).

Winds during the collection period were mostly NNE to E at about 2 mps, but were occasionally lighter and more variable in direction. With such winds, the station at the KMOX transmitter (see figure Q-l) would have been upwind of all major sources. The Coldwater Creek station would have been upwind of the St. Louis-East St. Louis source area, but downwind of the Alton-Wood River source area. Tyson would have been distantly downwind of all sources. The aircraft sampling track would have been over or downwind of sources at all times, with the possible exception of its southernmost extremity.

The observed distributions all had approximately the same shape (figure Q-3). The observed drop-off in concentration in the smallest size category on the ground-level samples is not seen in the aircraft sample, but this may be attributed to differences in collection efficiency resulting from differences in face velocity of the two sampling systems, at least for the KMOX and Tyson samples.

The number concentrations appear to have increased from upwind (KMOX) to intermediate (Coldwater Creek) to downwind (aircraft and Tyson). It is somewhat surprising, however, that the aircraft sample and the one collected at Tyson were so similar. After all, the aircraft sample was collected directly over, and immediately downwind, of major sources, while Tyson is at least 24 km (15 miles) downwind of any major sources. In view of the possible errors, however, one should probably not attach great significance to this result.

On 19 August, winds were from the S to SW at about 2 mps. All distributions (figure Q-4) again showed major departures from Junge's model, but the distribution shapes were again similar to each other, and they were similar to those found on 17 August. Sampling site orientations with respect to pollution sources were reversed, to a large extent, on 19 August. Tyson was upwind, Coldwater Creek upwind to intermediate, and KMOX downwind. The aircraft track would have been mixed, perhaps 1/3 upwind and 2/3 downwind.

Among the ground-level stations, number concentrations at KMOX were greater than at Coldwater Creek among particles smaller than 4-µm radius, as expected, but Tyson showed unexpectedly high concentrations below 2 *µm*. This result might be accounted for by the fact that this sample was the only one counted by the author, who is relatively inexperienced in particle identification and sizing. (All other samples were counted by an experienced spectroscopist — H. L. Smith of LASL).

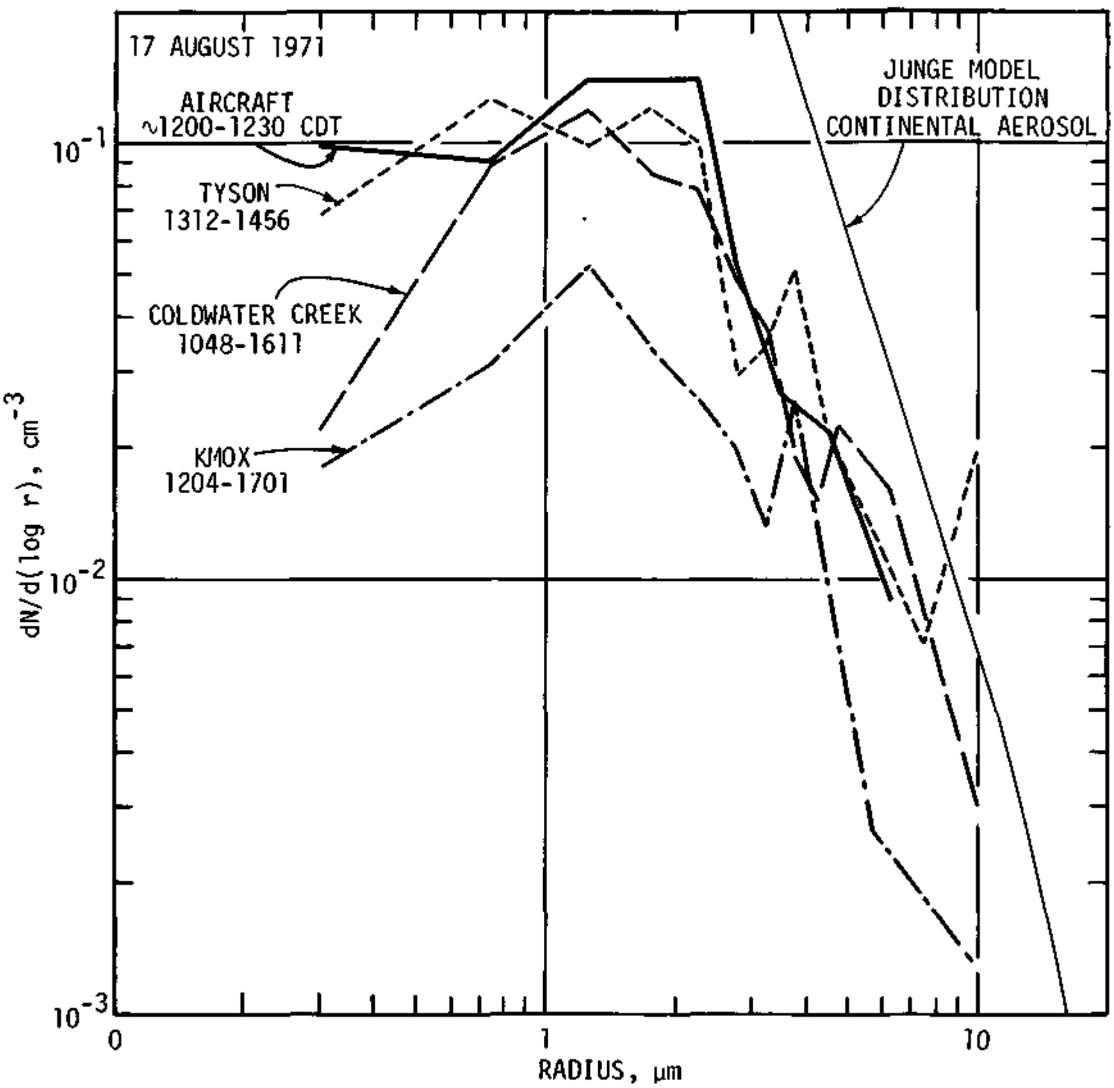


Figure Q-3. Particle-size distributions near ground level and aloft on 17 August

Chemical Analyses. One aircraft filter collected 13 August 1971 has been analyzed for trace metals. The results appear in table Q-l, along with comparative data from the St. Louis County Health Department. The St. Louis County samples were collected near ground level or rooftop level, and are mean concentrations for August 1971. Thus, they are not strictly comparable to the ½-hour aircraft sample collected at 610 meters above ground level. Nevertheless, the comparison serves as a rough indication of aircraft data quality. Table Q-l shows that concentrations measured from the aircraft filter correspond roughly to the highest monthly means at the St. Louis County stations.

The surface winds on 13 August were from the SE to SSE, with speeds between 0.9 and 2 mps at sampling time. The low-level sounding taken from the Arch at 1230 CDT indicated a mixing depth of 2070 meters with the average winds to that height from 170° at 1.4 mps. These data indicate a very limited horizontal air motion, which would allow greater than normal pol-

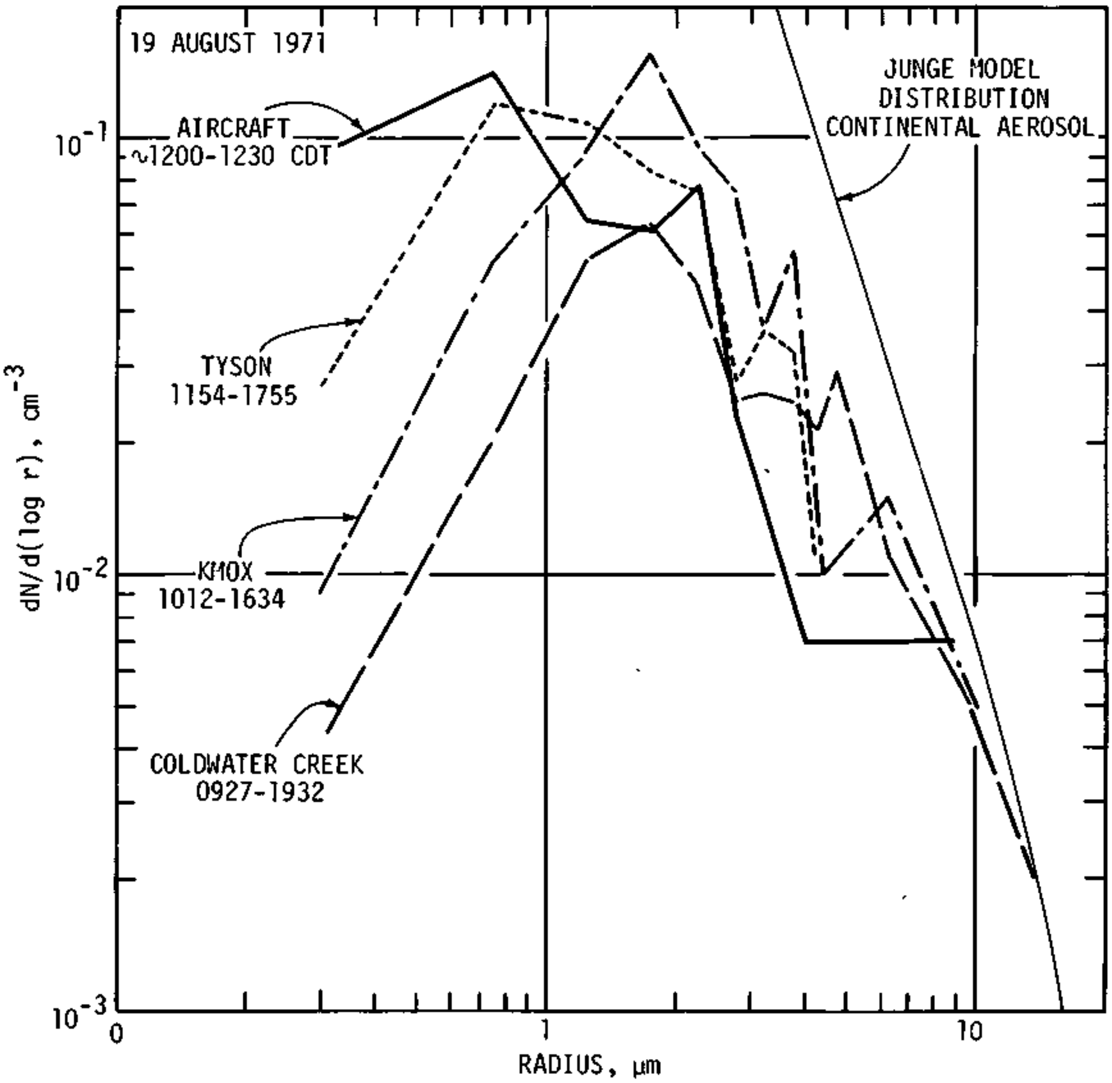


Figure Q-4. Particle-size distributions near ground level and aloft on 19 August

lutant concentrations to build up over the St. Louis area. Thus, the finding that concentrations at 610 meters correspond approximately to the highest monthly means among the St. Louis County surface stations is not at all surprising.

Conclusions

The usefulness of particle-size distributions determined from SEM counts of IPC-1478 filter collections are limited to relative comparisons between sampling locations. Such comparisons show that particle concentrations increase from upwind to downwind locations. No differences were apparent between particle concentrations at 610 meters above the surface and surface stations having the same orientation with respect to pollution sources. Concentrations of trace metals at 610 meters on 13 August 1971 appear to be reasonable in comparison with monthly means from St. Louis County surface stations, in view of the weather at sampling time.

Table Q-1. Trace Metal Concentrations from Aircraft Sample and Comparative Sample

	Cu	Fe	Mg	Mn	Pb	Zn
Concentration aloft, 13 August 1971, 2000 ft AGL, µg/m^3	0.139	5.53	4.54	0.198	1.87	0.583
Detection limit, µg/m^3	0.0008	0.03	0.004	0.003	0.004	0.007
St. Louis Co. Health Dept. Monthly Mean, August 1971, µg/m^3						
1* Sinks	0.375	1.16		0.029	0.54	0.47
2 State Farm	0.130	1.87		0.052	1.76	0.67
3 Chambers	0.070	1.78		0.042	0.79	0.56
4 St. Ann	0.041	1.70		0.045	1.48	0.03
5 Harold	0.148	3.04		0.117	1.38	0.00
6 Northland	0.029	1.96		0.070	1.38	0.41
7 SLCHD	0.032	1.44		0.048	1.68	0.00
8 T-4	0.075	0.96		0.043	0.84	0.17
9 Mt. St. Rose	0.062	2.47		0.039	0.66	0.00
10 ACIC	0.059	4.23		0.068	0.60	0.07

• Numbers refer to locations shown in the previous section on figure P-1

References

Changnon, S. A., F. A. Huff, and R. G. Semonin. 1971. *Metromex: an investigation of inadvertent weather modification.* Bulletin American Meteorological Society, 52:958-967.

Gatz, D. F., D. L. McCarthy, and M. R. Koors. 1972. *Filtration: its effect on the accuracy of rain water analysis by atomic absorption spectrophotometry.* Argonne National Laboratory Radiological Physics Division Annual Report, January-December 1971, ANL-7860, Part III, Argonne, 111.

Guthals, P. R. 1972. Personal communication.

Guthals, P. R., and H. L. Smith. 1972. Personal communication.

Junge, C. E. 1963. *Air chemistry and radioactivity.* Academic Press, New York, p. 124.

Kelsey, J. R. 1971. *Flight test report — LASL B-57, particle debris sampler.* Development Report, Sandia Laboratories Aeroballistics Division, SC-DR-71 0206, April.

Stafford, R. G., and H. J. Ettinger. 1971. *Efficiency of IPC-1478 filter paper against polystyrene latex and dioctyl phtalate aerosols.* American Industrial Hygiene Association Journal, 32:493-498, figure 11.

Stern, S. C, H. W. Zeller, and A. I. Schekman. 1960. *The aerosol efficiency and pressure drop of a fibrous filter at reduced pressure.* Journal Colloid Science, 15(6):546-562.

R. AIRCRAFT MEASUREMENTS AND OBSERVATIONS

Robert Cataneo

1971 Aircraft Program

In addition to its main priority of injecting tracer material into convective cells, the Piper aircraft from Atmospherics Incorporated (AI) made flights on fair weather days during 1971 to measure condensation nuclei, ambient temperature, and wet bulb depression at approximately 1300 feet AGL in an X-pattern flight path over the St. Louis area (figure R-l). Standard aircraft parameters were also measured. The data were recorded continuously on a strip chart recorder. These missions were carried out on 19 days during the 6-week period of aircraft operations.

Aircraft data analyses are summarized briefly in figures R-2 to R-10. The abscissa in each of these figures represents points along the flight path shown in figure R-l. Some observations and tentative conclusions relating to these figures are presented here.

1971 Condensation Nuclei Measurements at Flight Level

The condensation nuclei (CN) data reported here were taken with a continuous condensation nuclei counter. The relative humidity attained during measurements was approximately 350%, so it may be assumed that essentially all sub-micron particles are activated and counted with this instrument. One obvious value of the CN data obtained with the aircraft is for an attempt to delineate the urban effluent under varying meteorological conditions.

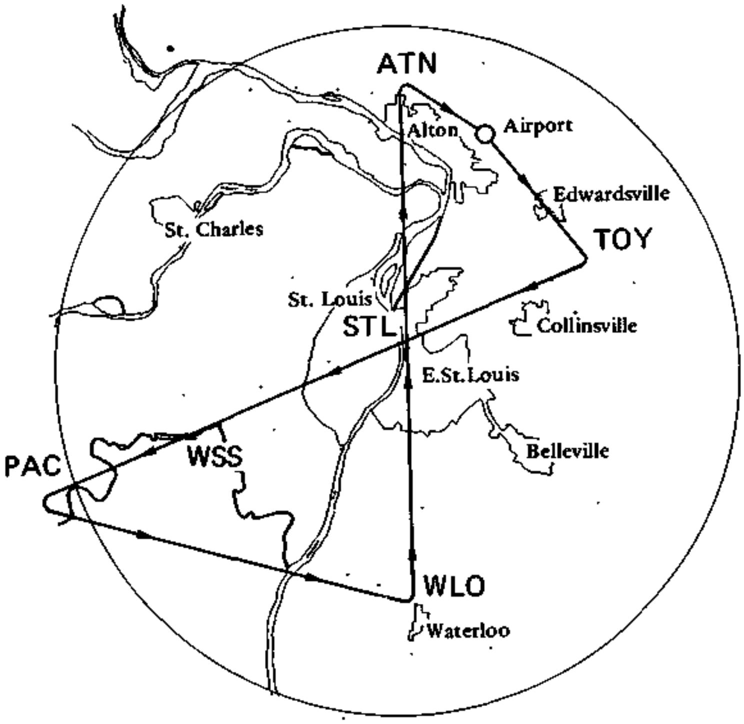


Figure R-l. Flight path on fair weather days during 1971

Figure R-2 shows the average CN values for the dates indicated. There were two regions of maximum CN values. One was located immediately across the Mississippi River from downtown St. Louis and was obtained as the aircraft was heading WSW from Troy (figure R-l). The other was a general increase from Waterloo to approximately 8 miles south of the downtown St. Louis area. Two distinct minima were found also; one was at Pacific located approximately 30 miles WSW of the Arch and the other occurred immediately north of Granite City. The Pacific minimum is not unexpected, nor is the general decrease from the Arch to that point; but, the marked decrease from approximately 3 miles south of the Arch to just north of Granite City is rather surprising. However, examination of heavy industrial area locations indicates a distinct lack of activity in this region (see figure R-7).

The following four figures depict the average CN profile under varying low-level wind conditions. The value at Pacific in figure R-3 appears to be consistent with the average wind flow on the three days examined. With northeasterly flow at low levels, the Pacific CN value was relatively higher, compared with surrounding readings, than on days with a different flow pattern (figures R-4 to R-6). This is reasonable in light of the position of this region with respect to downtown St. Louis on two days with NNW flow (figure R-4). The aircraft appeared to cross the urban plume as it tracked WSW reaching a minimum at Pacific. It is difficult to determine whether Pacific was in the urban plume; if so, then it was likely on the extremity of the plume in light of the low reading. However, there is little doubt that Pacific was well within the plume in figure R-3 with ENE flow and CN values very slowly decreasing from the Arch (St. Louis) to Pacific. The Pacific reading was an order of magnitude higher than the lowest readings. It should be noted that the values decreased rather sharply as the aircraft left Pacific heading ESE toward Waterloo, apparently indicating an extremity of the urban plume.

Figures R-5 and R-6 depict CN profiles obtained on three days with SSE-S winds and one day with a SW wind. Figure R-7 shows the areal distribution of industrial areas and major particulate sources which could be related to the CN distributions illustrated in figures R-2 to R-6.

Flight-Level Temperature Distributions in 1971

Ambient temperature at flight level was measured with a Rosemount probe. Flight-level temperatures averaged for five flights are plotted in figure R-8. Missing data on portions of cross-section flights on other days precluded their use. The data in figure R-8 have been corrected for differences in topography by use of a dry adiabatic lapse rate (1 C/100 meters). No attempt was made to correct for deviations in aircraft altitude from 1800 feet MSL; it is assumed that these deviations are random and are "averaged out" over a sufficient number of samples. Plotted also in figure R-8 are the temperature deviations along the flight path (figure R-l) from an average rural value of 22.7 C.

The data indicate an average positive temperature anomaly of 0.7 C in the urban area when compared to rural values; this is present in both the WSW and N legs of the flight track. It is very apparent that, for the data presented, the temperature at 1800 feet MSL increases as the urban area is approached, maximizes in this area, and then decreases as the area is left.

Wet Bulb Depression Analyses for 1971

Wet bulb depression was measured with an electronic psychrometer manufactured by Mee Industries. Wet bulb depression corrected for topography and averaged over five flights is shown in figure R-9. Topography corrections used were 1 C/100 meters for temperature, and 1 C/235 meters (moist adiabatic lapse rate) for wet bulb temperature. To properly assess possible moisture changes as the aircraft traversed the urban area, values for mixing ratio were calculated from ambient temperature and the corresponding wet bulb temperatures. Figure R-10 depicts these two variables with respect to location in the X pattern configuration shown in figure R-l.

> The WSW-ENE leg from Troy to Pacific does not indicate a marked difference in mixing ratio across the city as was obvious in figure R-8 with temperature; the minor perturbations are too small to be attributable to any particular source. The steady increase in mixing ratio going from south to north shows little resemblance to the corresponding temperature changes for the same periods, although there is an obvious decrease in moisture south and west of the urban region. If one accepts the temperature changes as being indicative of.an urban influence on these data, and there appears to be substantiation for this, then the dissimilarity of the temperature and mixing ratio traces precludes any obvious urban influence on the moisture field.

1972 Aircraft Program

The main 1972 mission of the AI aircraft during the 6-week period of 6 July to 15 August was, as in 1971, to inject tracer material into convection cells that passed over the rainwater collection network. Four additional priorities were included. These were: 1) to measure cloud bases over the urban area and the surrounding rural area to determine possible differences in the two; 2) to map updrafts in convective cells as to updraft speed, size, location, and duration; 3) to identify and locate major particulate sources in the St. Louis urban area; and 4) to determine general cloud structure characteristics in the region. The aircraft logged 44 flights during 1972 including five tracer missions. Two tracer materials were used during those missions, a solution of lithium chloride which was burned as an aerosol, and solid indium oxide flares.

Cloud Base Study

A total of 82 cloud-base measurements on 19 days were made by the AI aircraft to fulfill the first priority listed above. These have been plotted in figure R-11 and isopleths of equal cloud-base height have been drawn. The data strongly suggest the presence of higher cloud bases in the urban area when compared with rural values, the maximum difference being approximately 2000 feet. The times of observation ranged between 1300 and 1600 CDT, and the measurements were random with respect to time and place.

Updraft Study

Updraft measurements were made on 12 days and are plotted in figure R-12. Since there was no apparent pattern to the distribution, no isopleths are drawn. However, the following observations were made by the AI crew:

1) Most inflow locations, even in vigorous thunderstorm activity, gave the impression of small diameter areas with short duration inflow pulses.
2) Most significant inflow areas, observed and measured, were on the leading edge of squall lines with little activity on the trailing edge. Inflow on the rear of cumulus cells was found in systems that contained vigorous feeder clouds.
3) No significant inflow areas were found in weak or dissipating mature thunderstorms.
4) With few exceptions, there were no significant inflow areas at mid-levels of moderate to large cumulus cells. In those cases, inflow was evident very near the rising turrets and approximately 2000 to 3000 feet below cloud top.

Particulate Source Mapping

The locations of 25 major particulate sources in the Alton-St. Louis area are shown in figure R-13. With a few exceptions, all of the major sources are located along the Mississippi River. There is an obvious lack of major industry in an area between Granite City and Wood River.

Cloud Structure

It was observed by the AI crew that major differences exist between urban-affected and unaffected clouds. Further, these differences appear to be evident in the lower 2000 feet of cloud. At these levels, the urban clouds appear to be diffused, fractured, and without well-defined inflow areas. This appearance seems to be related to the type and concentration of particulates released by industries in "the area. The diffused cloud base may be the result of differing activation supersaturations required by the variety of particulate emissions.

It was noted that well-defined, solid bases existed on days when cumulus clouds developed totally above the top of the haze layer, where particulates were at background levels equivalent to those in the rural regions.

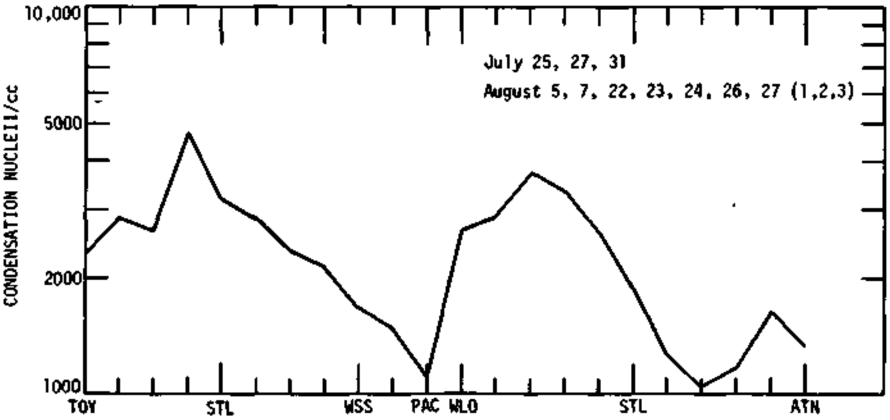


Figure R-2. Average condensation nuclei counts along flight path for dates indicated during 1971

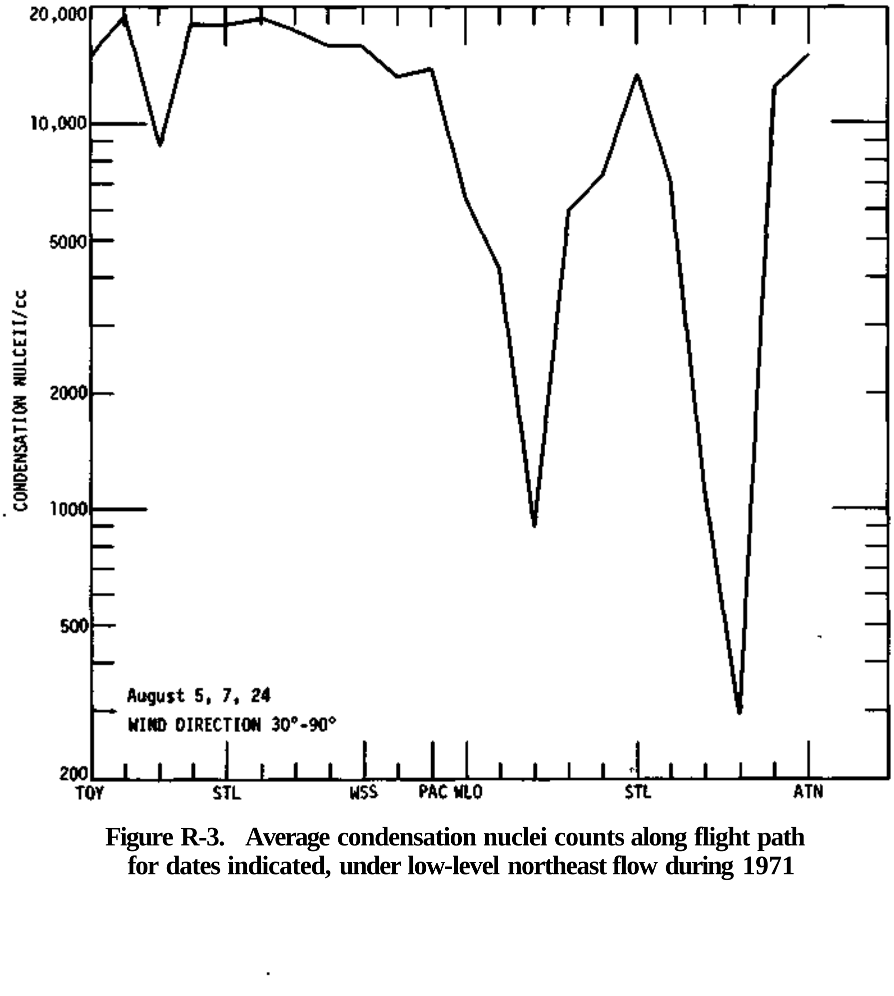


Figure R-3. Average condensation nuclei counts along flight path for dates indicated, under low-level northeast flow during 1971

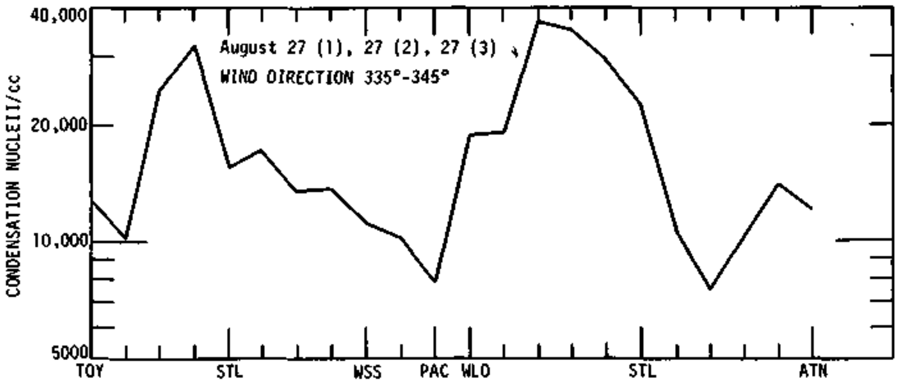


Figure R-4. Average condensation nuclei counts along flight path for dates indicated, under low-level north-northwest flow

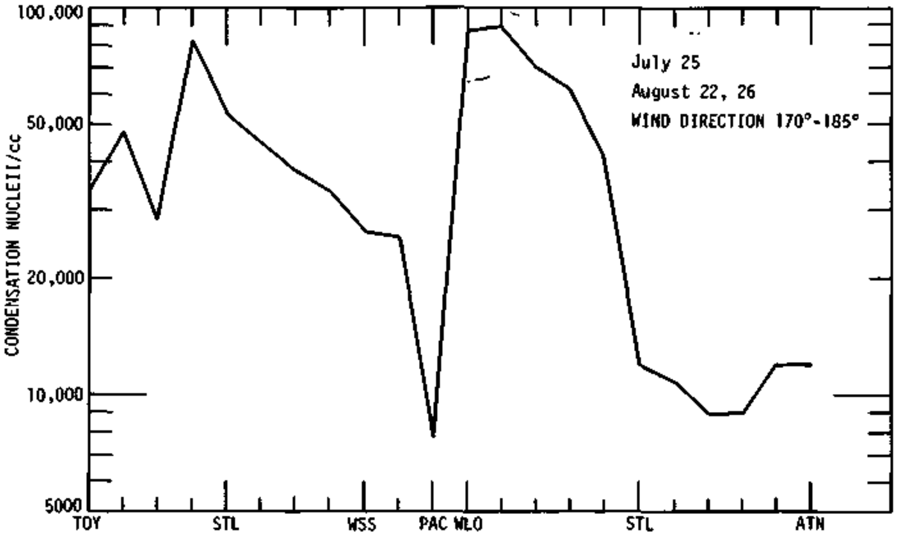


Figure R-5. Average condensation nuclei counts along flight path for dates indicated, under low-level southerly flow

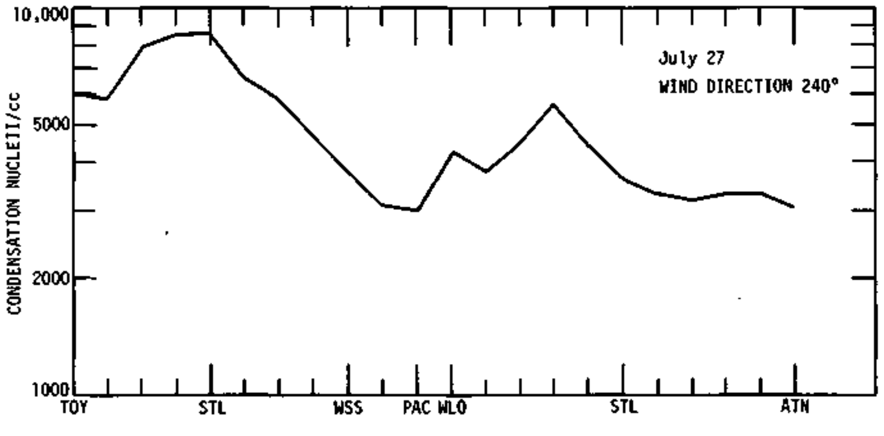


Figure R-6. Condensation nuclei counts along flight path for dates indicated, under low-level southwest flow

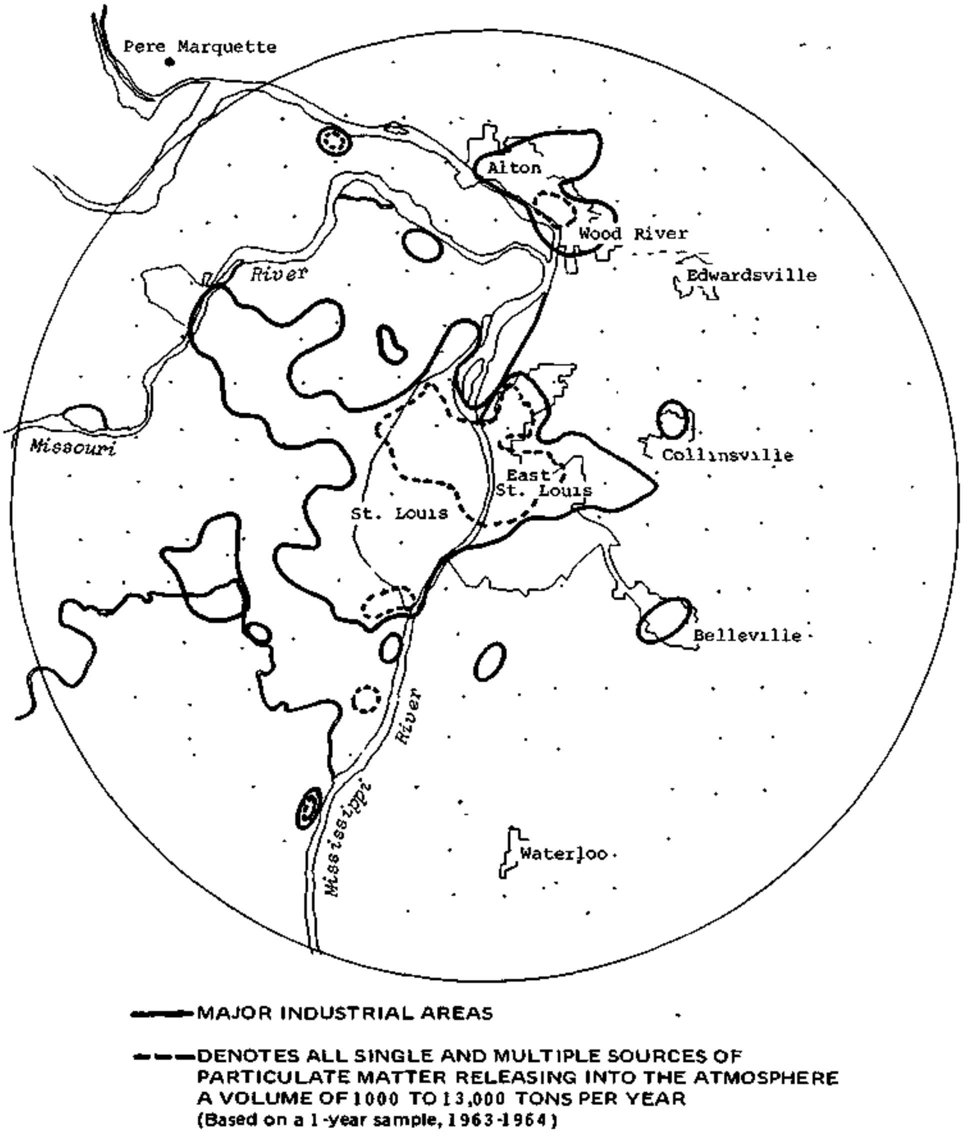


Figure R-7. Distribution of industrial regions and particulate sources in the St. Louis area

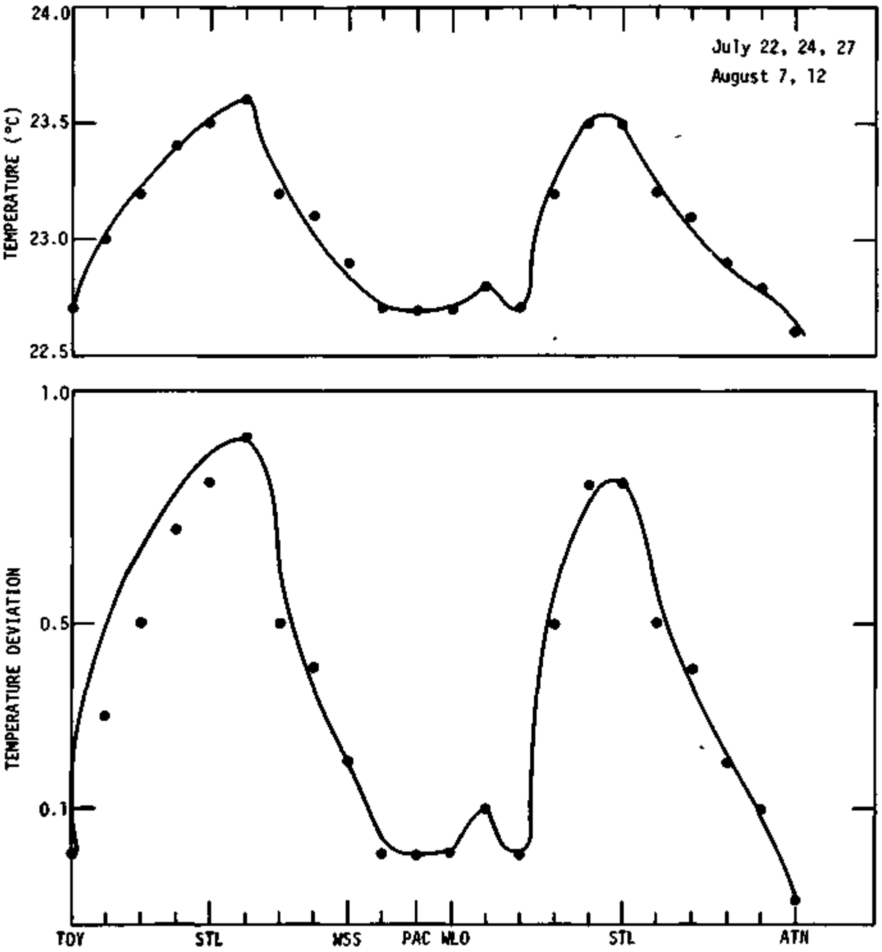


Figure R-8. Flight-level temperature with temperature deviation along flight path for dates indicated during 1971

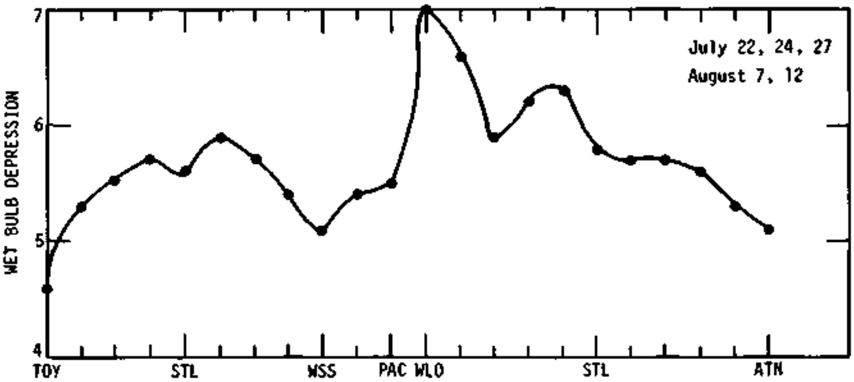


Figure R-9. Wet bulb depression along flight path for dates indicated during 1971

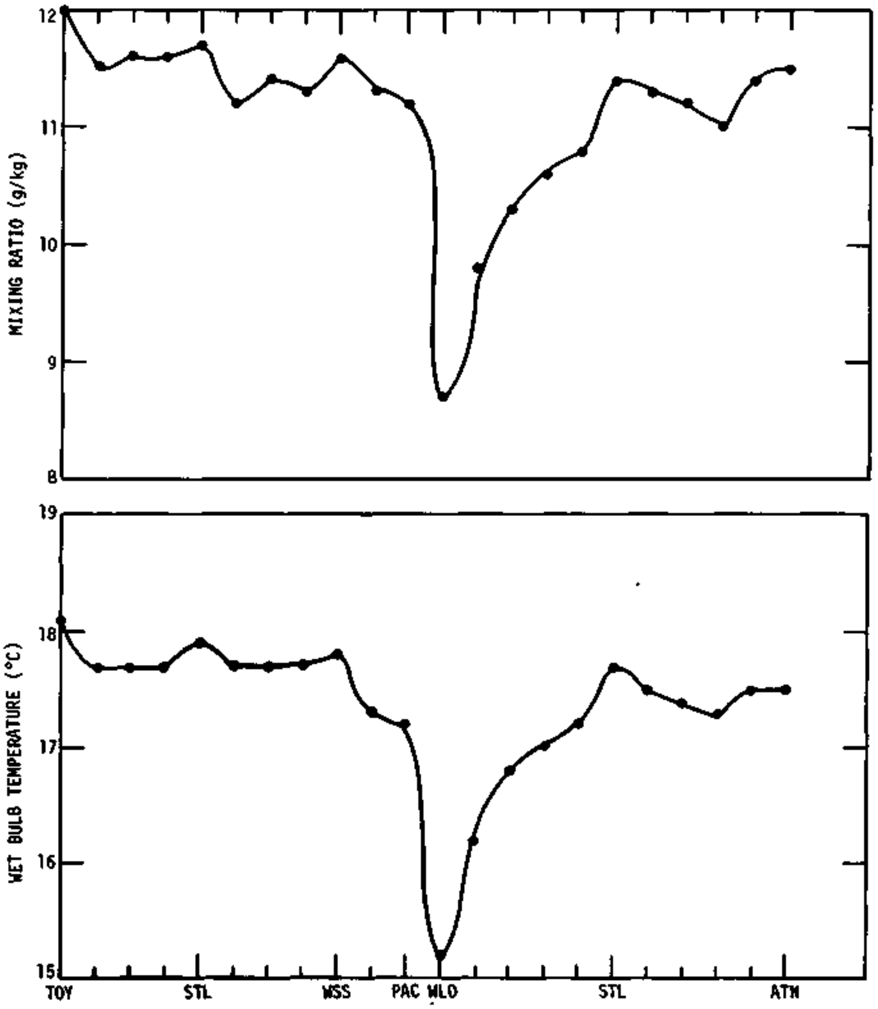
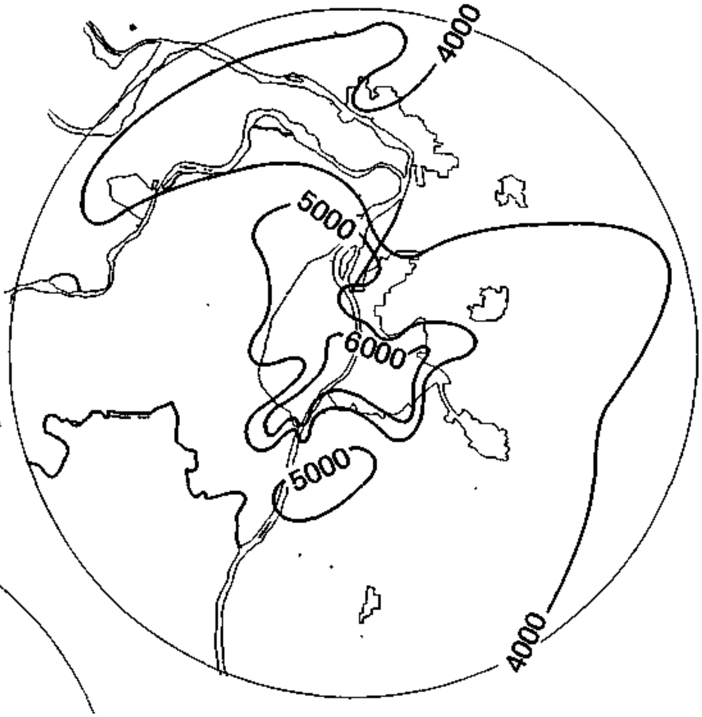


Figure R-10. Wet bulb temperature and mixing ratio along flight path during 1971

Figure R-11. [Right] Cumulus cloud base heights in feet above ground during 1972



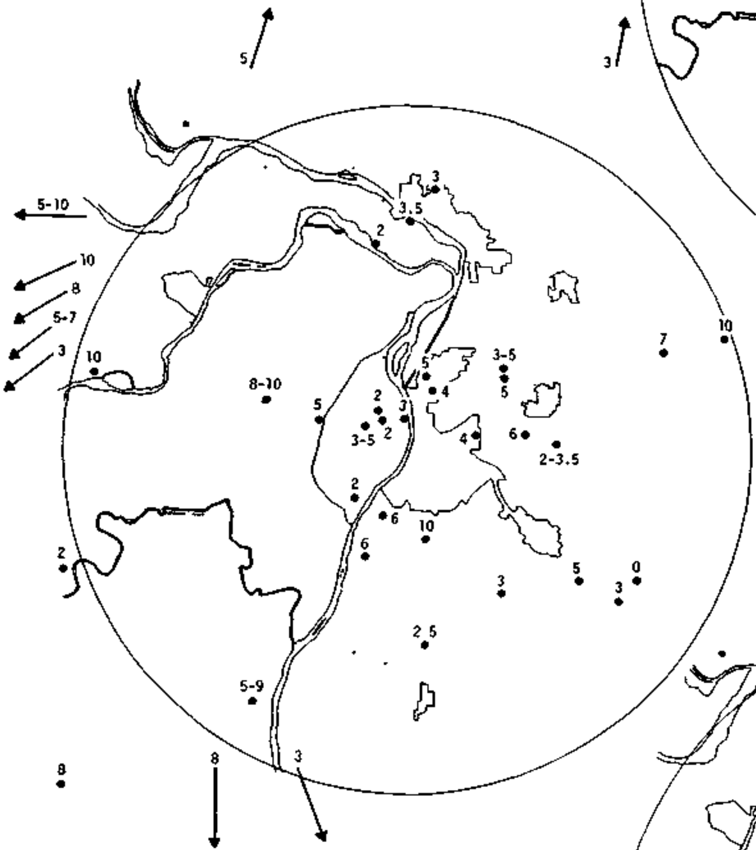
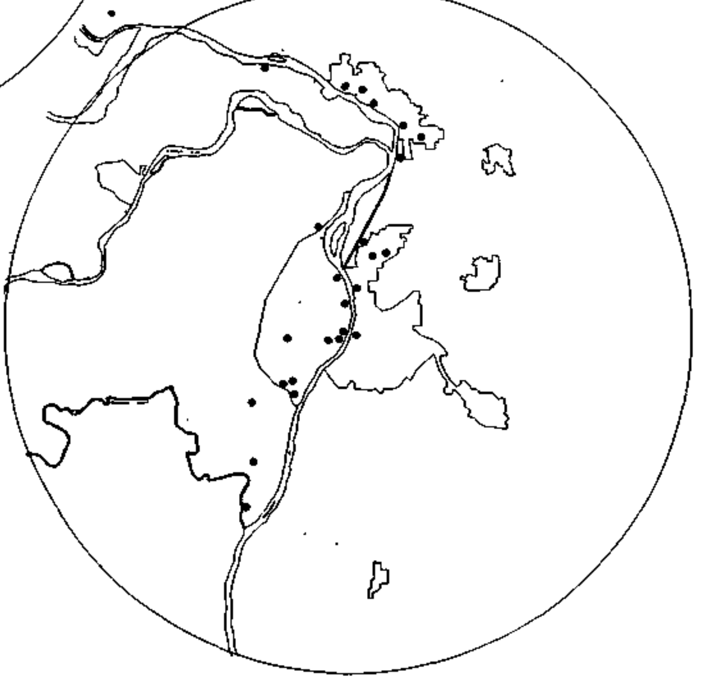


Figure R-12. [Above] Updraft determinations in hundreds of feet per minute made by aircraft during 12 days in 1972

Figure R-13. [Right] Major particulate sources in the St. Louis area as determined by Metromex aircraft



GENERAL SUMMARY AND CONCLUSIONS

Prepared by F. A. Huff

Seasonal and Storm Rainfall Studies

Summer rainfall was below normal on the Metromex network in both 1971 and 1972, and averaged 66% of normal for the 2-season period. The 1971-1972 pattern closely resembled the dry-season pattern established in earlier climatic studies. Various analyses indicated that the urban effect may have resulted in a 20 to 30% increase in rainfall in the downwind area in the vicinity of Edwardsville and Collinsville.

> Surface wind analyses indicated that urban effects could have been related primarily to the Alton-Wood River industrial complex in 1971 and to the St. Louis urban-industrial region in 1972. Studies of storm frequencies and intensities indicated that intensification of existing storm systems was a major cause of the rainfall highs in the 1971-1972 summer pattern, but little or no effect from network variations in storm frequencies was evident. This also agrees with earlier climatic findings for St. Louis and other cities.
>
> Analyses of diurnal distributions showed that most of the 2-season rainfall occurred in the daylight hours (0800-2000) which incorporate the maximum diurnal heating period. Furthermore, 30 to 50% of the total 2-season rainfall in the downwind highs occurred in the 1500-1800 CST period, indicating a strong possibility that these highs result to a large extent from urban effects (heat and/or aerosols) released during the period of maximum diurnal heating, when natural destabilizing of the lower atmosphere would favor more effective operation of the urban mechanisms. Other diurnal analyses suggest that the below-normal rainfall in 1971-1972 may have resulted largely from the general absence of a major diurnal peak of rainfall in the early morning hours, as shown by past climatic studies in the St. Louis region.

Synoptic Studies

Stratification of the 1971-1972 rain periods according to synoptic storm types showed that organized squall activity was the most important contributor to the 2-summer rainfall, and, along with cold fronts, was responsible for 80% of the total network rainfall.

> Synoptic climatology studies indicated that the frontal distributions during the 1971-1972 summers were generally conducive to the development of squalls in the network region. Non-frontal, unorganized air mass storms were the most frequent occurrence, but accounted for only 10% of the 2-summer total rainfall.
>
> A study of mixing depths in 1971-1972 storms indicated that depths exceeding 1800 meters favor the downwind enhancement of precipitation. This relationship and the fact that the heavier rains in 1971-1972 were produced mostly by squall lines tend to relate the urban effect to cases with strong instability and free mixing from the lower air layers to cloud base.

Thunderstorm and Hail Studies

The 1971-1972 analyses indicated a downcity increase in the number of thunderstorm days, number of discrete thunder periods, and durations of thunder periods. The increase in thunder occurrences occurred primarily between 0300 and 1500 CDT with a maximum increase between 0600 and 1200. City-related thunder initiations occurred most often in air mass storms, but were also quite prevalent in frontal zones.

Results generally agree with past climatic studies. Additional data are needed in the future, including data from 3 to 4 locations farther downwind of the present study area.

> A definite urban enhancement of the number of hail days, number and area of hailstreaks, and intensity of hail is indicated by the 1971-1972 data. This enhancement occurred primarily in the maximum hail incidence periods, 1500-1800 and 2100-2400 CDT.
>
> The hail-day increase was about 80%; the number of hailstreaks was increased by 20%; the number of large stones (½-inch diameter or more) was increased 250%; and the energy was increased 600%. The typical urban-related hailstreak was larger, longer-lived, produced more hailstones per unit area, had greater impact energy, and was associated with heavier rainfall than hailstreaks unrelated to urban effects.
>
> Results are in good agreement with past climatic studies. Urban enhancement of hail occurred most frequently in squall conditions, but was also observed in frontal zones and air mass storms.

Surface Raincell Studies

A total of 939 surface raincells have been analyzed to date in the 1971-1972 rainstorms. Analyses were performed to discern differences among *effect* and *no-effect* cells. Effect cells were defined as those which were exposed to potential urban or topographical effects, or combinations of the two types of effects. The no-effect cells were used for controls and comparisons to evaluate the magnitude of urban-related or topographic-imposed effects. The St. Louis urban-industrial complex and the Alton-Wood River industrial area were assumed to be potential sources of urban effects. The Ozark foothills SW of St. Louis and the bottomlands of the Mississippi-Missouri confluence (heat-moisture source) were considered potential sources of topographic effects. Comparative analyses were made between a number of raincell parameters, such as volume, mean rainfall, maximum rainfall, areal extent, duration, path length, and velocity.

> Overall, there is very strong evidence that the cell parameters were altered by the urban-industrial environment. In some of the analyses, the differences between the effect and no-effect cell parameters were so great and the sample sizes so large as to leave little doubt as to the reality of the differences. Relatively strong evidence was found also that the Ozark Hills and the Mississippi-Missouri bottomlands intensified exposed raincells beyond that expected from cells unexposed to these effects.
>
> Growth in areal extent was the parameter most strongly affected by the urban-effect cells in the St. Louis area, whereas cell mean rainfall (rain intensity) experienced the greatest effect in the Alton-Wood River area. However, all cell parameters were affected to some extent. The greatest change in cell parameters was found with those cells that were exposed both to the hill effect and the St. Louis urban effect. However, this sample was relatively small and additional data must be collected before strong confidence can be placed in the results.
>
> Indications were found that the treatment effect (urban or topographic) endures for a considerable period of time after exposure, but that the modification of the rain processes is limited in areal extent, so that the effects occur relatively close to the urban-industrial regions.
>
> Differences in urban effects on the various evaluation parameters indicate that the physical processes involved in the modification of raincell properties in the St. Louis region are different from those predominant in the Alton-Wood River area.

Surface Condensation Nuclei and Raindrop Measurements

Surface condensation nuclei measurements were made at Pere Marquette in 1971. Results showed an obvious increase in nuclei counts in the southeast quadrant in the direction of St. Louis.

There is little doubt that the concentrations of particulate matter produced by the urban-industrial complex is significantly above rural background levels and is detectable at distances of 25 miles or more.

Surface raindrop distributions were measured at 8 sites in 1972. From analyses performed to date on a rural station (Pere Marquette) and on an urban-affected station (Centreville), it appears that the urban site experiences fewer, larger raindrops for similar rainfall rates, as well as generally higher rainfall rates than the rural site. This difference was based on 10 rain days at Pere Marquette and 14 days at Centreville, so the results are considered a significant indication of an urban effect.

Surface Wind, Temperature, and Humidity

A surface network of six wind instruments has been installed especially for Metromex. These were operated from mid-June to 1 September 1971 and for the June-August period in 1972. Data abstraction consists of hourly values of speed and direction averaged over 10 minutes prior to the hour. No particular bias among the instruments has been found in the 2-year period.

During 1971, seven hygrothermographs were operated in the Metromex network, and this was increased to 25 in 1972. Questionable accuracy among the instruments has limited use of the 1971 data. All summer data for the 1972 instruments have been extracted and are being punched to permit machine calculation of hourly dew point temperatures. Monthly averages have been made at 3-hourly intervals for the 1972 network, and the patterns are similar for all months.

Initial analyses for August indicate that the greatest temperature contrasts between the urban complex and rural areas occur at dawn. The urban heat island was still very much in evidence in mid-afternoon, but was much less pronounced, with a maximum urban-rural difference of 6.2 F at 1500 CDT compared with 10.6 F at 0600 CDT.

Urban Effects on Surface and Groundwater Quality

In a related Metromex study, a small-scale investigation was undertaken to explore the hydrological implications of urban effects on groundwater and surface water sources downwind of St. Louis. Weekly measurements of water quality were made at six shallow wells and at a streamgage on a small watershed in southwestern Illinois a few miles east of the central city. A few storm sequential measurements of stream water were made also. Chemical analyses were limited to those being made in the atmospheric chemistry program (pH and mostly trace elements). Results indicate that a more comprehensive program is needed to ascertain urban effects on surface water and shallow groundwater aquifers, including chemical analyses of the more common water pollutants such as nitrates, sulfates, and chlorides. The number of well sites should be increased considerably. The inert tracer (lithium) used in Metromex atmospheric tracer studies has very limited use in hydrological studies.

Radar Studies

Technical problems resulted in only a small amount of satisfactory 10-cm PPI and 3-cm RHI data being collected in 1971. Problems were largely overcome in 1972, and a large amount of important data were collected with both sets. Emphasis to date has been in developing the computer techniques and methods to perform the massive data analyses required and to provide analytical output useful for a number of the urban studies.

Very satisfactory progress has been made in the programming for both the FPS-18 (10-cm PPI) and TPS-10 (3-cm RHI) data. For the FPS-18, a contoured display of echoes has been developed, and techniques for tracking radar cell motions by digital operations have been accomplished. The cell analyses provide information on movement, areal extent, and growth rates. For the TPS-10, the display of 3-dimensional radar data is nearly solved with the development of computer programs which provide constant altitude radar display, vertical sections in arbitrarily oriented planes, distribution with height of the mass of precipitation in storms, calculation of the total liquid water mass of storms, and calculation of volume vs height and total volume of the radar echo.

In addition to the above direct applications of radar to Metromex, the FPS-18 data are being used in conjunction with the raingage network data in an effort to develop better techniques for radar measurement of areal mean rainfall. This capability could be a major asset in weather modification experiments and in various hydrologic applications, if means for achieving a higher degree of reliability and accuracy can be developed than has been accomplished in the past.

Airflow Program

The two general goals are 1) to determine the extent and nature of the changes caused by the urban complex in the 3-dimensional dynamic structure of the boundary layer in cases of both stagnation and large-scale motion, and 2) to define the wind and thermodynamic fields in the layer for estimation of the urban plume and fluxes into convective systems. The 1972 field operations were carried out from 12 July to 11 August. Wind measurements from pibals and temperature and humidity measurements from standard radiosonde equipment were employed in the operational program. Observers were deployed at about 10 selected sites in and around St. Louis during each operational period; pibals were made at all 10 sites and radiosondes were employed at 3 locations.

During 1972, 17 operational periods were completed. Preliminary results from nocturnal studies indicate that the airflow can be significantly perturbed over the urban complex in the lower part of the boundary layer, and that this perturbation may extend through much of the boundary layer if the convection is intense.

Results from two fair weather days analyzed to date suggest that: 1) the wind speed can vary by 20 to 30% and the direction by 20 to 25 degrees over the metropolitan area, and these variations may differ through the boundary layer; 2) the wind speed tends to vary little in the vertical through the mixed layer, but the directional shear is greater downwind than upwind of the city; 3) the height of the subsidence inversion may vary over the area, but it may not necessarily be greater over the city; and 4) significant changes in wind direction and speed occur over short distances throughout the boundary layer and may be induced by synoptic, mesoscale, topographic, or urban forcing, but observations suggest that some are locally produced.

Chemical Tracer Studies

The tracer chemical studies are directed toward acquisition of knowledge concerning the interaction between simulated urban effluents and cloud and precipitation processes, as well as providing an insight into the internal motions of convective storms which transport and diffuse urban-industrial airborne waste materials.

The field experiments have been designed to examine the scavenging of sub-micron particles by precipitation and convective cloud processes. The tracer chemicals (lithium and indium) are released from both ground level and aircraft. Precipitation and dry fallout samples are collected from a network of 80 sites downwind of St. Louis, and chemically analyzed for the tracers and other atmospheric contaminants.

Preliminary results indicate that lithium is an excellent tracer chemical. The low-level tracer releases indicate that under favorable conditions an urban-industrial aerosol can be processed by precipitating convective storms and deposited in the region of observed climatic rainfall maximum downwind of the city. Results also indicate that a target-control design for advertent weather modification of multicellular convective systems is not a sound approach unless target and control are separated by at least 20 miles to eliminate effects from interchange of seeding agent between cloud systems.

pH Measurements in Rainfall

During summer 1972, rainwater samples suitable for pH determination were obtained on 14 days. The pH values ranged from 4.26 to 6.82 with a network average of 4.94 over the sampling area of 750 mi^2 in the rainwater chemistry sampling network. There does not appear to be a distinct correlation between precipitation and pH. Similarly, there is no apparent relation between areal pH patterns and the industrial areas of the St. Louis metropolitan region.

Scavenging Ratio Measurements

The objective of this study is to improve the scavenging ratio method for predicting deposition in precipitation. The first part of the study consists of the measurement of scavenging ratios for six elements, based on daily precipitation and air filter samples collected as part of the Metromex program. The second part involves efforts to generalize the results to other materials through measurements of the rain solubility and particle-size distribution of the elements for which scavenging ratios are measured.

Results to date are based upon 1971 data on scavenging ratios for Cu, Pb, Fe, Mg, Mn, and Zn at five stations. No significant differences were found in the scavenging ratios between upwind and downwind sites, although concentrations in both precipitation and air showed variations up to 10-fold. Little or no relationship was found between scavenging ratios and any of several meteorological or particle parameters examined, including atmospheric stability, rainfall amount, synoptic rain type, and solubility of aerosol materials in rain.

Aircraft Filter Sampling and Analysis

The scavenging ratio may depend on the vertical distribution of the material in the atmosphere. Knowledge of the vertical distribution is needed to provide clues to the dominant physical mechanisms of particle collection and their relative and absolute efficiences.

To provide a few samples collected aloft for comparison with surface concentrations, a program of aircraft filter collections was carried out in 1971 with an RB-57C aircraft in conjunction with the Metromex field program. Detailed analyses for flights on 17 and 19 August indicated that particle concentrations increase from upwind to downwind locations. However, no significant differences were apparent between particle concentrations at 610 meters above ground and surface stations having the same orientation with respect to pollution sources.

Aircraft Measurements and Observations

Condensation nuclei measurements were made at flight level in 1971. In general, locations of maxima and minima were quite logical. Flight-level temperature measurements in 1971 indicated an average positive anomaly of 0.7 C in the urban area compared with the rural surroundings. Wet bulb depression measurements did not indicate any obvious urban influence on the moisture field.

Aircraft measurements of cloud bases in 1972 strongly suggest the presence of higher cloud bases in the urban area as opposed to rural regions. Updraft measurements indicated that most inflow locations appear to be small-diameter areas with short-duration inflow pulses. The most significant inflow areas were on the leading edge of squall lines with little activity on the trailing edge. No significant inflow areas were found in weak or dissipating mature thunderstorms. With a few exceptions, there were no significant inflow areas at mid-levels of moderate to large cumulus cells; in these cases, inflow was evident near the rising turrets.

PUBLICATIONS ON METROMEX

Ackerman, B. 1972. *Winds in the Ekman layer over St. Louis.* Preprints, Conference on Urban Environment, Philadelphia; AMS, Boston, pp. 22-27.

Beebe, R. C, and G. M. Morgan. 1972. *Synoptic analysis of summer rainfall periods exhibiting urban effects.* Preprints, Conference on Urban Environment, Philadelphia; AMS, Boston, pp. 173-176.

Changnon, S. A. 1971. *1971 operational report for Metromex.* A compilation of reports from cooperating research groups in the 1971 program prepared by the Illinois State Water Survey, Urbana, 93 pp.

Changnon, S. A. 1972. *Can weather modification usefully augment the water resources of the humid Midwestern United States?* Proceedings International Symposium on Water Resources Planning, International Association Hydrological Sciences, Mexico City, 32 pp.

Changnon, S. A. 1972. *Field study of urban effects on precipitation and severe weather at St. Louis.* Illinois State Water Survey for NSF GA-28189X. Annual Report. 20 pp.

Changnon, S. A. 1972. *Urban effects on thunderstorm and hailstorm frequencies.* Preprints, Conference on Urban Environment, Philadelphia; AMS, Boston, pp. 177-184.

Changnon, S. A. 1973. *Inadvertent weather and precipitation modification by urbanization.* Journal Irrigation and Drainage Division, ASCE, pp. 27-41.

Changnon, S. A., F. A. Huff, and R. G. Semonin. 1971. *Metromex: an investigation of inadvertent weather modification.* Bulletin American Meteorological Society, 52(10):958-967.

Changnon, S. A., R. G. Semonin, and W. P. Lowry. 1972. *Results from Metromex.* Preprints, Conference on Urban Environment, Philadelphia; AMS, Boston, pp. 191-197.

Huff, F. A., and S. A. Changnon. 1972. *Climatological assessment of urban effects on precipitation at St. Louis.* Journal Applied Meteorology, 11:823-842.

Gatz, D. F. 1972. *Washout ratios in urban and non-urban areas.* Preprints, Conference on Urban Environment, Philadelphia; AMS, Boston, pp. 124-128.

Schickedanz, P. T. 1972. *The raincell approach to the evaluation of rain modification experiments.* Preprints, 3rd Conference on Weather Modification, Rapid City, S. D.; AMS, Boston, pp. 88-95.

Semonin, R. G. 1972. *Study of rainout of radioactivity in Illinois.* Illinois State Water Survey for AEC Contract AT(11-1)-1199. 11th Interim Progress Report. 11 pp.

Semonin, R. G. 1972. *Tracer chemical experiments in midwest convective clouds.* Preprints, 3rd Conference on Weather Modification, Rapid City, S. D.; AMS, Boston, pp. 83-87.