ILLINOIS STATE WATER SURVEY
at the
University of Illinois
Urbana, Illinois

# CLIMATOLOGICAL ASSESSMENT OF URBAN EFFECTS ON PRECIPITATION

by

F. A. Huff and S. A. Changnon, Jr.
Principal Investigators

FINAL REPORT

PART I - SUMMARY AND CONCLUSIONS

National Science Foundation
Atmospheric Sciences Section
NSF GA-18781

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CONTENTS

## ILLUSTRATIONS



## TABLES

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# INTRODUCTION

A 2-year project involving extensive climatological analyses of urban effects on precipitation in and around eight major cities in central and eastern United States has been completed. The cities included St. Louis, Chicago, Indianapolis, Cleveland, Washington, Houston, New Orleans, and Tulsa. These urban areas were selected to represent different climatic zones, industrial complexes, geophysical sites (flatlands, valley-hills, large lakes), sizes of cities, and rate of growth in the 20th Centruy. The motivation for this research came largely from earlier results at La Porte, Indiana and Chicago (Changnon, 1968; Changnon, 1969a) which indicated urban-related rain, thunder, and hail increases downwind of Chicago and a few other cities.

Urban-induced changes in the natural precipitation could result from four potential modifications of the atmosphere. These include 1) atmospheric destabilizing from the output of the well established urban heat island, 2)modification of microphysical and dynamical processes in passing clouds through addition of condensation and ice nuclei from industrial discharges, 3) increase of low-level mechanical turbulence from urban-created obstructions to airflow, and 4) modification of the low-level atmospheric moisture content by additions from industrial-generated plumes emitted from stacks and cooling towers, along with changes in the natural evapo-transpiration process within the city resulting from the large percentage of impervious surface in central urban areas.

In the climatological study for each city, analyses were made initially of monthly and seasonal precipitation within a radius of 50 to 75 mi of the city, in order to establish whether any unusual values potentially related to urban effects appeared to be present. This was followed by analyses of weekday-weekend occurrences of precipitation (evidence of industrial-induced effect), number of precipitation days in various intensity categories, frequency of thunderstorm and hail days, thunderstorm rainfall amounts, and heavy rainstorm occurrences. Diurnal rainfall distributions, synoptic weather types, and wind climatology were studied also in cases where data were adequate and the analysis warranted. Thus, the objective was not only to identify any urban-related rain effect, but also to describe its characteristics in different seasons, under various meteorological conditions, and in the presence of different urban conditions.

Thorough study of the urban effect on precipitation conditions (inadvertent weather modification) should provide valuable information and guides to planned weather modification efforts. Results of the St. Louis study were instrumental in establishing an extensive field study of inadvertent weather modification in the St. Louis region which was initiated in June 1971 (Changnon, *et al*., 1971). A brief description of each city and reasons for its selection are provided in Table 1.

Table 1. Selected urban areas

| City | Urban description and reasons for selection |
|---|---|
| St. Louis | Relatively large midwestern city, located in and along Mississippi River Valley but subjected to possible topographic effects on storms moving from S-SW, humid climate experiences extremes of precipitation and temperature, highly industrialized, well situated for field experiments. |
| Chicago | Large industrialized city with lake effects, steel and heavy industry nuclei sources, dense urban recording raingage network available for past 20 years. |
| Cleveland | Industrial city subjected to lake effects, steel industry nuclei source, comparable to Chicago-La Porte situation. |
| Indianapolis | Moderate size city, located in very flat region (no topographic effects), moderate industrial development. |
| Washington | Large coastal city with little industrial development, eastern U. S. climate. |
| Houston | Large, industrialized, rapid-growth city, also petroleum refining center, close to Gulf and, consequently, warm, humid climate. |
| New Orleans | Coastal city with highly humid conditions, high average annual precipitation, warm Gulf Coast climate, modest industrial development. |
| Tulsa | Moderate sized city in flatlands of Great Plains, relatively rapid growth, major petroleum refining center, subjected to extremes of temperature and precipitation. |

Detailed descriptions of the results obtained for the 8 cities appear in Part II of this final report. The interested reader is encouraged to read that report for more detailed information on the many results obtained.

## METHODS OF ANALYSIS AND EVALUATION

### General Approach

Two basic types of precipitation analyses were employed in the monthly and seasonal evaluation of urban effects: 1) the usual expression of station precipitation values in inches, and 2) precipitation ratios, in which the precipitation (monthly or seasonal) at each station was divided by the average precipitation for the urban area. This simple normalization technique facilitated evaluation of time trends in urban effects, especially during periods of a climatologically generated upward or downward trend in precipitation extending throughout hypothetical effect and no-effect areas, as determined by a wind and storm motion climatology developed for each city. Furthermore, the ratios provide a simple measure of the magnitude of any urban-induced downwind effect.

In the time-trend analyses, 2- and 5-yr moving averages of monthly and seasonal precipitation were used to smooth out some of the year-to-year natural variability in the data, and this smoothing facilitates evaluation of any long-term trends. The moving averages, in conjunction with the ratios, were particularly useful in delineating potential urban effects in the precipitation time series for a given month or season.

As pointed out previously, earlier studies indicated urban-related increases in thunderstorm occurrences at Chicago and St. Louis (Changnon, 1969b) and sizeable increases in both thunderstorm and hailstorm frequencies in and around La Porte, Indiana, downwind of the south Chicago industrial complex (Changnon, 1968). Hence, similar investigations were undertaken at each city, based primarily upon comparative analyses of thunder-day and hail-day events. Point comparisons were made on a temporal basis for stations with long periods of quality records. Areal means were used to compare thunderstorm-hail frequencies upwind and downwind of each urban area.

At several cities, analyses were performed to determine possible urban effects on heavy rainstorms. If urban areas intensify or moderate naturally-occurring heavy storms, the frequency and magnitude of flood-producing storms will differ from those experienced in the surrounding region. In these heavy rainfall studies, comparisons were made of daily amounts equalling or exceeding 2.0, 2.5, and 3.0 inches.

Weekday-weekend relations between the frequency and intensity of daily precipitation were studied on a seasonal basis. If atmospheric particulates originating from urban-industrial sources have been instrumental in modifying the urban precipitation climate, differences between weekday and weekend occurrences would be likely because of a greater average output of particulates from industrial sources on weekdays. Various types of comparisons were made, but evaluation was based largely upon calculations of average ratios of daily precipitation on weekdays to that on weekends. These were used to normalize out differences between regional stations due to natural climatic differences and also, a known bias in that many cooperative observers tend to overlook occurrences of small daily amounts, such as 0.01-0.02 inch.

Limited synoptic studies were made at most cities to determine if apparent urban effects varied with types of storms. Because of time limitations, great effort required, and personnel limitations, these studies were restricted to the latest 5- or 10-year period for the season of maximum urban effect. Daily weather maps were used to identify the basic synoptic storm type associated with each precipitation day. Classifications used were frontal precipitation (with subgrouping by frontal type), squall lines, non-frontal air mass storms, and the approach and passage of major low centers. Since it was our intention to analyze the synoptic data in statistical terms, this simple synoptic classification was considered suitable for this purpose (although, not the most desirable grouping).

At several cities where data were adequate, an investigation was made of urban-effect differences on a diurnal basis. The diurnal distribution is useful in evaluating the presence of a heat-island effect, in the same manner that the weekday-weekend analyses help to identify a particulate effect.

At two cities (Cleveland and Washington) where special local problems existed, studies were made of the relationship between wind flow, synoptic type, and urban effect in selected 5-year periods. This type of analysis would have been helpful at other cities also, but was not possible with available funds, time, and personnel.

## Evaluation Techniques

As shown by Changnon and Schickedanz (1971), the final proof and scientific acceptance of inadvertent weather modification cannot and should not rest entirely upon standard statistical testing methods of historical data. Even before climatological analyses can be performed properly to identify urban-induced precipitation effects, a hypothesis on how the effect may be produced and where it should occur should be evolved. After a thorough climatological-statistical study is performed, any apparent urban effect should be verified further and physical causes investigated through field experiments designed to measure pertinent meteorological parameters controlling the cloud development and rain-producing processes. As mentioned earlier, such a program, Metromex, was initiated at St. Louis in summer 1971 partially as a result of findings in this climatological study.

In this report we are concerned only with the climatological phase of urban research which identifies the possible existence, general magnitude, and approximate location of apparent urban-induced effects on the regional precipitation. In so doing, we decided in the planning stages of this research that analyses would be performed on all precipitation factors for which climatological data were available and which, conceivably, could be affected by urban environmental factors. The combined weight of the evidence evolving from these varied analyses would then dictate our conclusions. It was agreed that considerable reliance would be placed upon spatial pattern analyses to determine the existence (or absence) of an urban effect and to alleviate interpretation problems that could arise from occasional non-representative data that might be undetected by the data evaluation procedures.

It was further decided that standard statistical testing would be applied in those analyses where it was considered applicable and useful as an evaluation guide. However, complete reliance on statistical testing was not considered acceptable. For example, randomization techniques cannot be applied properly in urban precipitation analyses since the urban effect is uncontrollable, and the factors which cause the effect are either unknown or the degree to which they are present is unknown at the start of an urban climatology study. This eliminates the usual treatment vs. non-treatment comparisons that are useful in planned weather modification where the non-treatment data serve as the control.

Another statistical problem encountered at all eight cities investigated is the lack of sufficiently long records and adequate station density to determine satisfactorily the statistical significance of apparent abnormalities in the precipitation distribution in urban areas. An urban effect, if present, would have existed to some degree over the entire period of record at most urban-area stations, and, thus, there is no proper base or norm for evaluating time changes. This problem of inadequate weather data in American cities has been described as a principal reason that urban effects on weather and precipitation specifically have gone largely unnoticed in the United States (Changnon, 1969a).

Finally, there is considerable question on the part of the authors as to the strict applicability of standard statistical tests in evaluating the significance of small precipitation abnormalities in a regional pattern which may be very real but tests as statistically insignificant. It is doubtful that rain events can be treated as a series of random numbers, since these events are certainly not truly random. Consequently, the same care should be exercised in interpreting statistical test results as in evaluating the implications of all other types of analyses employed in studies such as described here. The reader is referred to the paper by Changnon and Schickedanz (1971) for a more complete discussion of statistical problems and applications in urban-effect studies, and also to Part II of this final report for the evaluation techniques used at each city.

## Data Used

The primary source of precipitation data at all cities was the climatological records published by the Environmental Data Service of NOAA (formerly U. S. Weather Bureau). At some cities, such as St. Louis and Chicago, analyses were aided greatly by precipitation stations operated by local governmental agencies. Wind data used in the research were obtained from NOAA published data. Synoptic analyses were made from daily synoptic weather maps prepared by NOAA.

A major problem in the urban studies was to evaluate the reliability of available precipitation records in the study area. At St. Louis, it was possible to make a visit to all stations in the region where an urban effect was indicated, in order to evaluate the capabilities and interests of the paid and cooperative observers at the precipitation stations. Stations with questionable records in the Chicago, New Orleans, Houston, and Indianapolis areas were also visited. However, funds were not available to visit and inspect the questionable stations in all 8 cities. As part of other business trips, we were able to visit the NOAA stations at Houston and New Orleans where we received assistance in evaluating the quality of precipitation records in these areas.

Another method employed to minimize observational records involved review of station histories to ascertain changes in observer and/or location of each station and any change in precipitation distribution at a station following such changes. If any questionable change was discerned, all or part of the record was eliminated from the various analyses. Otherwise the record was accepted since elimination of all stations with observer and/or site changes would have made spatial pattern analyses impossible. As mentioned earlier, we depended upon regional groupings and pattern analyses to help us avoid pitfalls one might encounter in point comparisons of precipitation properties.

The thunder-day and hail-day data used were gleaned largely from unpublished U. S. Weather Bureau station records for the 1901-69 period. The only source of thunderstorm and hailstorm data considered reliable with any evaluation are the records made at first-order stations of the U. S. Weather Bureau (now NWS) where trained weather observers have been on duty 24-hours a day. Unfortunately, within a mesoscale area with a radius of 60 miles centered on these 8 cities only a few stations have existed. Cooperative substations organized under Weather Bureau auspices are much more numerous, but are manned by volunteer observers who make daily measurements of temperature and rainfall, and who are asked to report weather conditions including hail and thunder. Some believe that thunder and hail data from these substations are questionable, mainly since the observers may miss an occurrence at night, or because the observers may be sufficiently busy or disinterested in the daytime to not note or list their occurrences. However, an elaborate technique of evaluating substation thunder-day and hail-day data was employed to evaluate all the records of substations around the 8 cities so as to establish those with quality records.

The reader will note that periods of records used in the various analyses at a given city and between the various cities are not always consistent. This difference arises because the length of reliable records of various precipitation events is not consistent. Furthermore, pattern analyses were restricted primarily to the last 15 to 20 years of the sampling period because these periods were ones of greatest station density. In the rainfall analyses, data for the 19 31-6 8 period were used when available and acceptable. For point comparisons used in the severe weather studies, data for the 1901-68 period were used in some instances. Our basic analysis principle with respect to data utilization was that all reliable records would be used for each analysis undertaken, rather than discard useful data in some cases to keep all analyses on the same time basis.

More exhaustive descriptions of the data employed for each of the 8 cities are contained in Part II of this final report.

## RESULTS OF 8-CITY ANALYSES

Specific atmospheric measurements of urban effects on weather that may extend considerably above the ground level and thereby lead to alterations in precipitation processes do not exist in historical records. Thus, evaluation of an urban effect on surface precipitation is difficult and is left to indirect statistical and circumstantial evidence. Assumptions must be made that: 1) any urban effect reacts on the local atmosphere so as to produce changes in surface precipitation conditions over and/or downwind of the urban complex (with downwind defined by the motions and durations of rain-producing elements crossing the urban complex), 2) that precipitation conditions in the area surrounding the urban and downwind potential effect area are representative of the climatic background (no effect), and 3) urban effects on precipitation lead to temporal increases detectable during the period of climatic records. Data from the basic effect and no-effect areas, whether analyzed on a regional, temporal, or point-to-point basis, become the basis for examining spatial and/or temporal changes in precipitation at a city. Unfortunately, pattern analyses, a primary standard climatic analytical tool, are difficult to test statistically, and yet lend themselves to meaningful urban rainfall investigations. Statistical tests of regional and point differences can also be applied on the basis of the above three assumptions. The various effect and no-effect areas defined for the various cities are described in Part II of this final report.

### St. Louis

A detailed climatic study was made of urban effects in the St. Louis area, based on long-term records of precipitation, severe local weather events (thunderstorms, hail, heavy rainfall), and related weather conditions within a radius of 50-75 mi of the central city. Major emphasis was placed upon the 1941-68 period when the most satisfactory distribution of raingaging stations was in operation. Analyses were made of: total precipitation on a monthly and seasonal basis; the frequency and intensity of daily rainfall; frequency of thunderstorms, hail, and severe rainstorms; thunderstorm rainfall amounts; weekday-weekend occurrence of precipitation (evidence of industrial-induced effects); diurnal rainfall distributions; possible differential urban effects in wet and dry periods; and, the relationship between urban effects and synoptic weather conditions.

Results of the various analyses led to the conclusion that the urban-industrial area of St. Louis definitely affects the distribution of precipitation in and downwind of the central city. Evidence of a localized increase in total seasonal precipitation was found in all seasons, but was strongest in summer. The center of the urban-induced high is located at Centreville only 8-10 mi ESE of the center of the city (Fig. 1). The background outlines the hypothetical major and minor effect areas, along with two control (no-effect) areas. A possible intensification of cloud updrafts over the city from the heat island, resulting in an accumulation of water aloft, followed by a rapid release of accumulated water as the intensifying source disappears east of the city is suggested by the St. Louis spatial pattern. Seasonal time-trend analyses indicated an intensification of the urban-induced high with progressing time, particularly during the last 10-15 years of the sampling period. The Centreville (CEN) trend is shown in Fig. 2, based on rainfall ratios of CEN to two long-term stations in the central city.

Spatial analyses of monthly precipitation patterns showed the strongest evidence of an urban effect in May, June, July, and August. Indications were that rainfall was being intensified both in and downwind of the city in July. Time-trend analyses of monthly precipitation (April-September) also indicated that the downwind high was intensifying with progressing time.

Analyses were performed to separate the natural and urban components of summer rainfall in the St. Louis region. Results indicated that the urban-induced increase averaged approximately 10% in the downwind effect area during the 1941-68 period with values at individual stations ranging from 6% to 15%.

Analyses of urban effects in relatively wet, dry, and moderate summers in the 1941-68 period indicated that urban-effect mechanisms for increasing rainfall downwind of the city were most effective in wet summers. In the dry summers, the average pattern suggested an urban-induced suppression effect on the naturally-occurring rainfall.

Studies of daily precipitation and heavy rainstorm occurrences indicated that urban-effect mechanisms were most active in increasing rainfall in the downwind area on days when the natural rainfall was of moderate to heavy intensity. Diurnal analyses indicated that the urban intensification is greatest during the afternoon peak of diurnal heating. Analyses of weekday-weekend relations in the warm season revealed a statistically significant greater frequency of rain occurrences per weekday than per weekend day in the major effect area east of the city. Furthermore, this major effect area averaged 11% more rainfall on weekdays than the surrounding region, compared with 4% greater on weekends. Thus, the weekday-weekend differences provide strong evidence that the downwind high is related to man's activities rather than the result of local topographic effects.

Synoptic analyses indicated that the summer rainfall high is the results primarily from a strong tendency for rain from cold front storms to maximize there. A less pronounced trend was found for squall-line storms to maximize in the area of major urban effect.

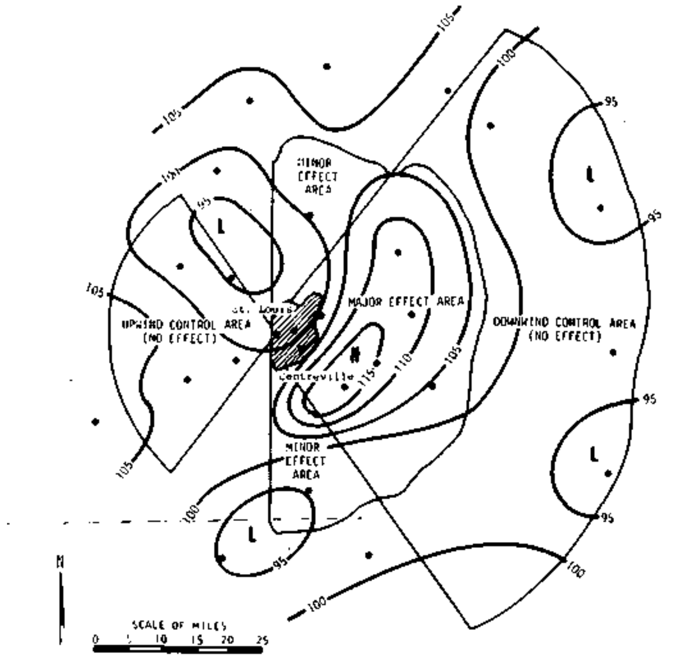



*Figure 1. Average rainfall ratio pattern at St. Louis, 1949-68*

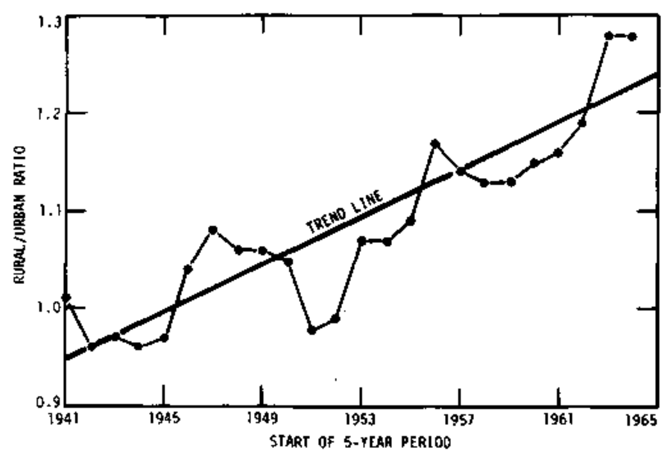



*Figure 2. Time trend of Centreville summer rainfall ratios*

Studies of the frequency of thunderstorm days indicated an urban-induced increase in and immediately downwind of the central city (Fig. 3). This apparent urban effect occurred primarily in summer and intensified with progressing time beginning in the 1940's. The greatest relative frequency of urban-isolated storms existed in the morning hours, suggesting that thermal input from the city is a major causative factor.

Areal analyses of hail-day occurrences (Fig. 4) showed a downwind high in the same general area as the urban-induced rainfall maximum (Fig. 1), but with both farther downwind than the thunder high (Fig. 3). The distance lag between the urban-induced thunderstorm and hailstorm highs would be expected in view of the normal time lag from development of thunderstorms until intensification to the hail stage occurs.

Overall, the results of the St. Louis climatic analyses showed varying degrees of summer season increases over but largely downwind of the city in all forms of precipitation. Downwind located summer changes in the 1941-68 period included: 1) average seasonal rainfall (area = +10%, point differences = +6 to +15%); 2) average wet season rainfall (point differences = +11 to +18%); 3) average dry season rainfall (point differences = -5 to -9%); 4) area average moderate (≥0.25 inch) rain days (+8%); 5) area average heavy rainstorms (+31%); 6) weekday (vs. weekend) area rain-day averages (+13%); 7) point differences in average afternoon rainfall (43%); 8) average thunder-day frequencies (point differences = +20 to +25%); and 9) area average hail-day frequencies (+35%). The summer increases in the downwind area in area-average rainfall, rain-day frequencies on weekdays, thunder-day frequencies, and hail-day frequencies were all statistically significant to 1-tail probabilities ≤0.02. In addition, all forms of pattern analyses supported positive departures in the downwind area. The simultaneity of all these positive aberrations in a single area located adjacent to and downwind of St. Louis reflects a coherence that, although not statistically testable as a combination of positive events, together become very strong circumstantial evidence of the presence of urban effects on summer precipitation.

The reader is referred to the paper by Huff and Changnon (19 72) for a detailed description of the St. Louis study.

## Chicago

Seasonal spatial analyses provided evidence of an urban-induced increase in summer rainfall in the La Porte (LPT) region, 25-35 mi downwind of the South Chicago-Gary industrial complex. This region experienced 17% more rainfall than the Chicago urban area (average of Midway Airport and city station) in the 1949-68 period, and 13% more in the 1959-68 period, as indicated in the precipitation ratio maps of Fig. 5. A secondary summer high is located in the central part of the city but could be related to a slight climatic ridge located west of the city rather than urban effects.

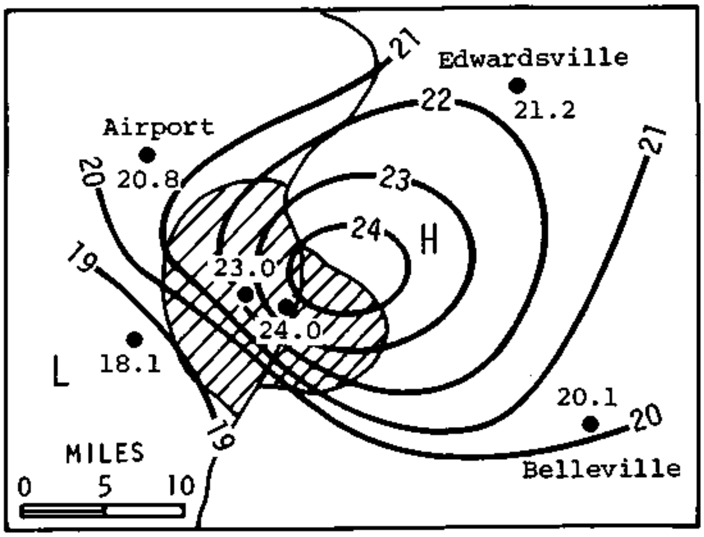



*Figure 3. Average number of summer thunder days in 1951-58*

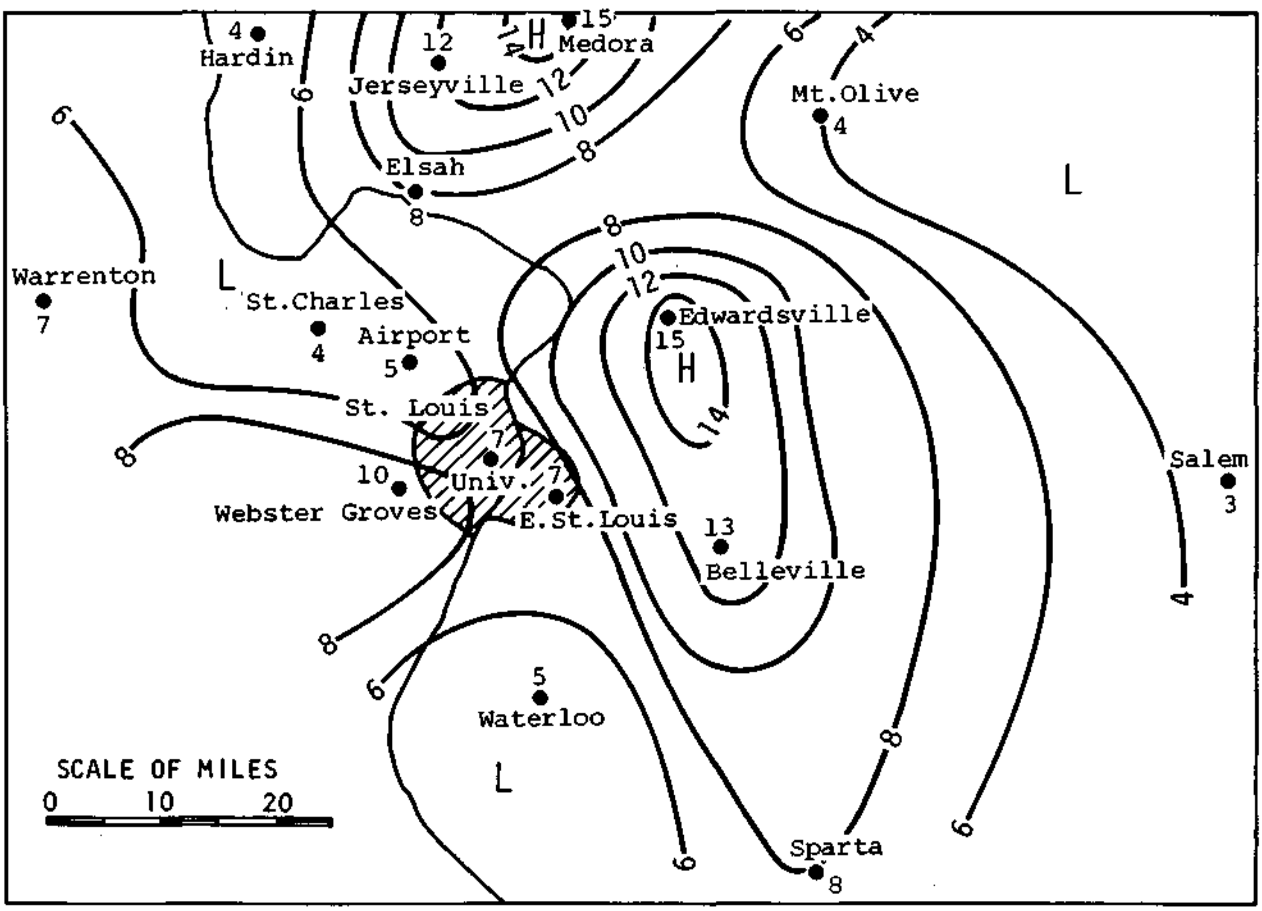



*Figure 4. Number of summer hail days at St. Louis, 1949-65*

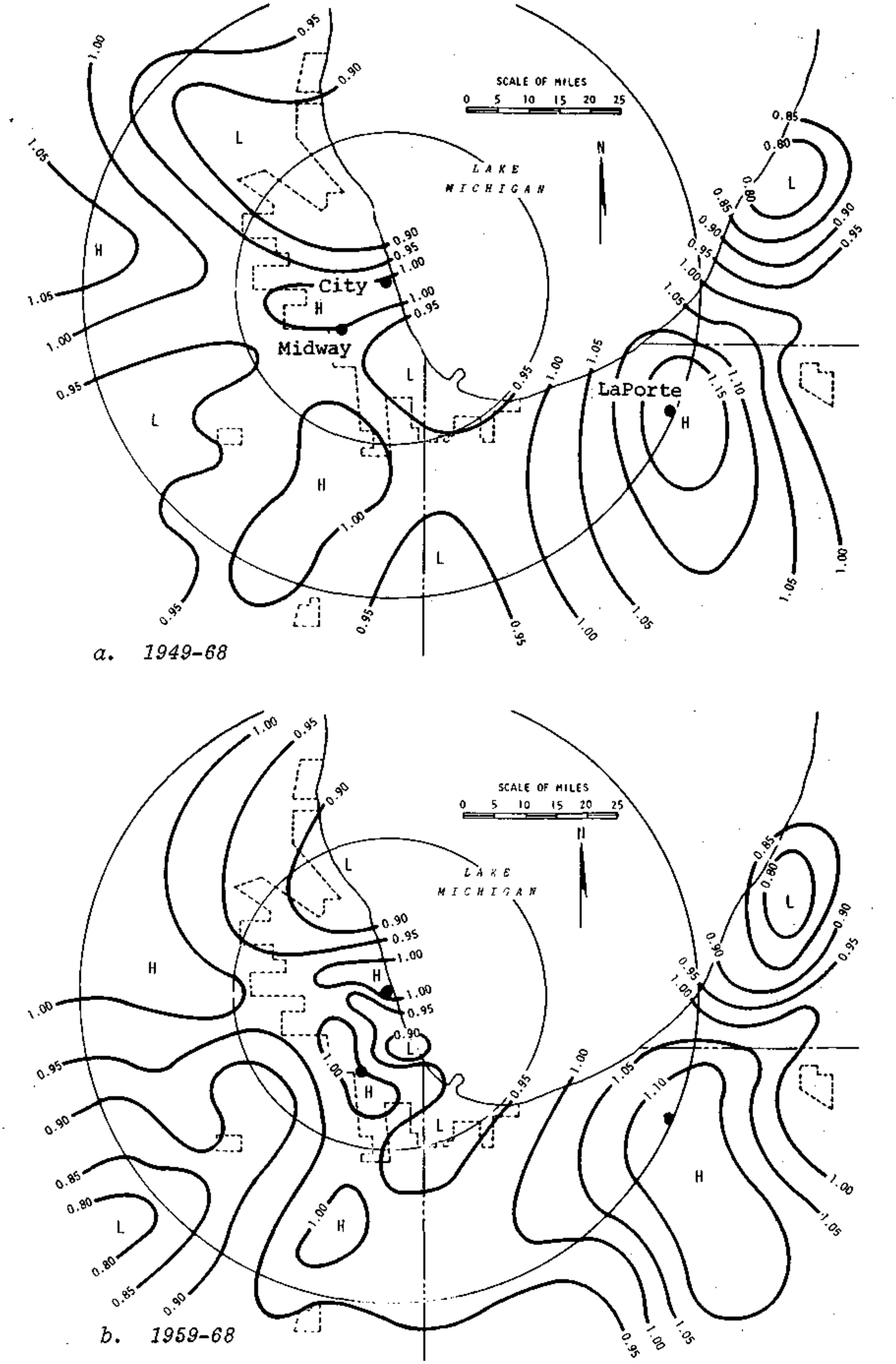



*Figure 5. Average rainfall ratio patterns in summer at Chicago*

As shown in Fig. 6, a pronounced, persistent winter high was found in the LPT region, in which the precipitation during the 1949-68 period averaged nearly 50% higher than at the two long-term Chicago urban stations, Midway Airport and the city station. Other analyses indicated a major portion of the excessive precipitation at LPT can not be explained by lake-effect storms.

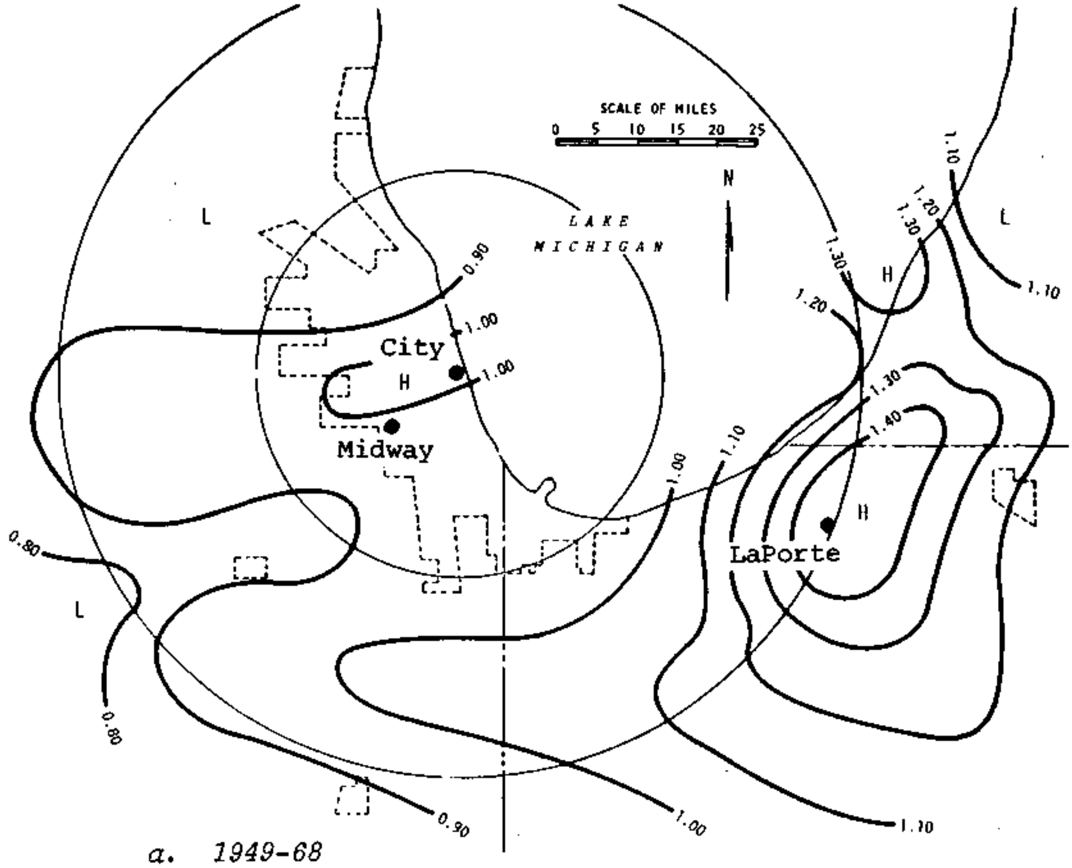
Spring spatial patterns indicated a LPT high averaging 26% more rainfall than the urban area during 1949-68. Fall patterns were similar to winter patterns with LPT averaging 47% more precipitation than urban Chicago in the 1949-68 period.

Analyses of heavy rainstorm occurrences (daily rainfall $\geq$ 2 inches) supported both the LPT anomaly and the secondary high over the urban area. The 14-gage urban network averaged 8-33% more daily rainfalls equalling or exceeding 2.0, 2.5, and 3.0 inches than 8 upwind suburban stations. LPT experienced 58-100% more occurrences than the suburban average and approximately 50% more than the city average. LPT had 38 days with two inches or more rainfall in the 1949-68 period compared with a maximum of 31 among city stations and 27 among suburban stations.

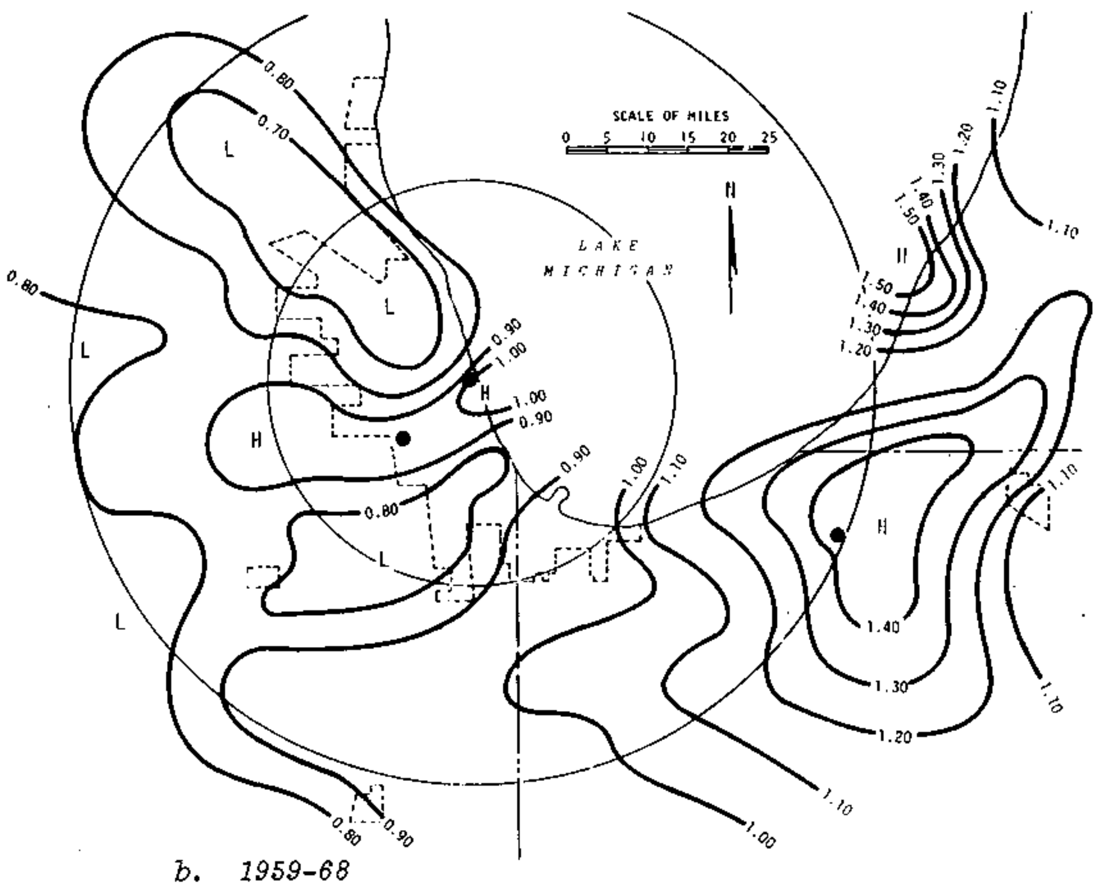
Time-trend analyses indicated that precipitation in the Chicago urban area has been increasing with respect to the surrounding region in all seasons during the 1931-68 sampling period employed in these analyses. This upward trend was not found at La Porte, although its average seasonal precipitation exceeds the city precipitation by relatively large amounts. Thus, LPT may have had its precipitation increased by urban-induced effects for a long period of time, but evidence from the trend analysis is that urban influences are being reflected more within the city as time progresses.

Analyses of daily precipitation grouped by intensity indicated that any urban-induced effect operates at all intensity levels. However, in the warm season, the urban effect appears to be more pronounced on days with moderate to heavy rainfall, whereas in the cold season the effect maximizes on days of relatively light precipitation. This apparent variation in inadvertent modification between seasons indicates a need to employ different seeding techniques in planned weather modification to optimize seeding effectiveness under different synoptic weather conditions. Thus, seeding effectiveness with summer mesoscale disturbances appears to be best on days favorable for moderate to heavy natural rainfall, whereas the large-scale winter systems are most likely to be favorably modified on days with light natural precipitation.

Analyses of weekday-weekend relations did not provide clearcut evidence of urban-induced effects resulting from greater particulate discharges into the atmosphere on weekdays in either the warmer or colder parts of the year. A rather strong climatological variation in weekday and weekend precipitation occurred throughout the sampling region in the 1949-68 period, and this produced background interference that would make small changes resulting from urban particulate discharges difficult to discern. However,




*a. 1949-68*




*b. 1959-68*

*Figure 6. Average rainfall ratio patterns in winter at Chicago*

there is some evidence that particulate discharges may be more favorable for precipitation increases on weekends in the major effect area, perhaps, due to an over-supply of cloud and raindrop nuclei on weekdays.

A limited study of diurnal relations in the 1964-68 period showed the maximum positive difference in hourly rainfall between city and upwind recording gage stations occurring during the 3-hour period of maximum diurnal heating, 1200-1500 CST. This supports findings in the St. Louis study, and indicates that the heat island effect superimposed on the natural diurnal heating is an important factor in producing urban-induced highs in summer rainfall patterns.

Synoptic weather analyses for summers in the 1959-68 period indicated that the major contribution to the downwind LPT high occurred in cold front storms. Initiation and/or intensification of air mass showers (non-frontal) over the urban area did not appear to be instrumental in producing the LPT high.

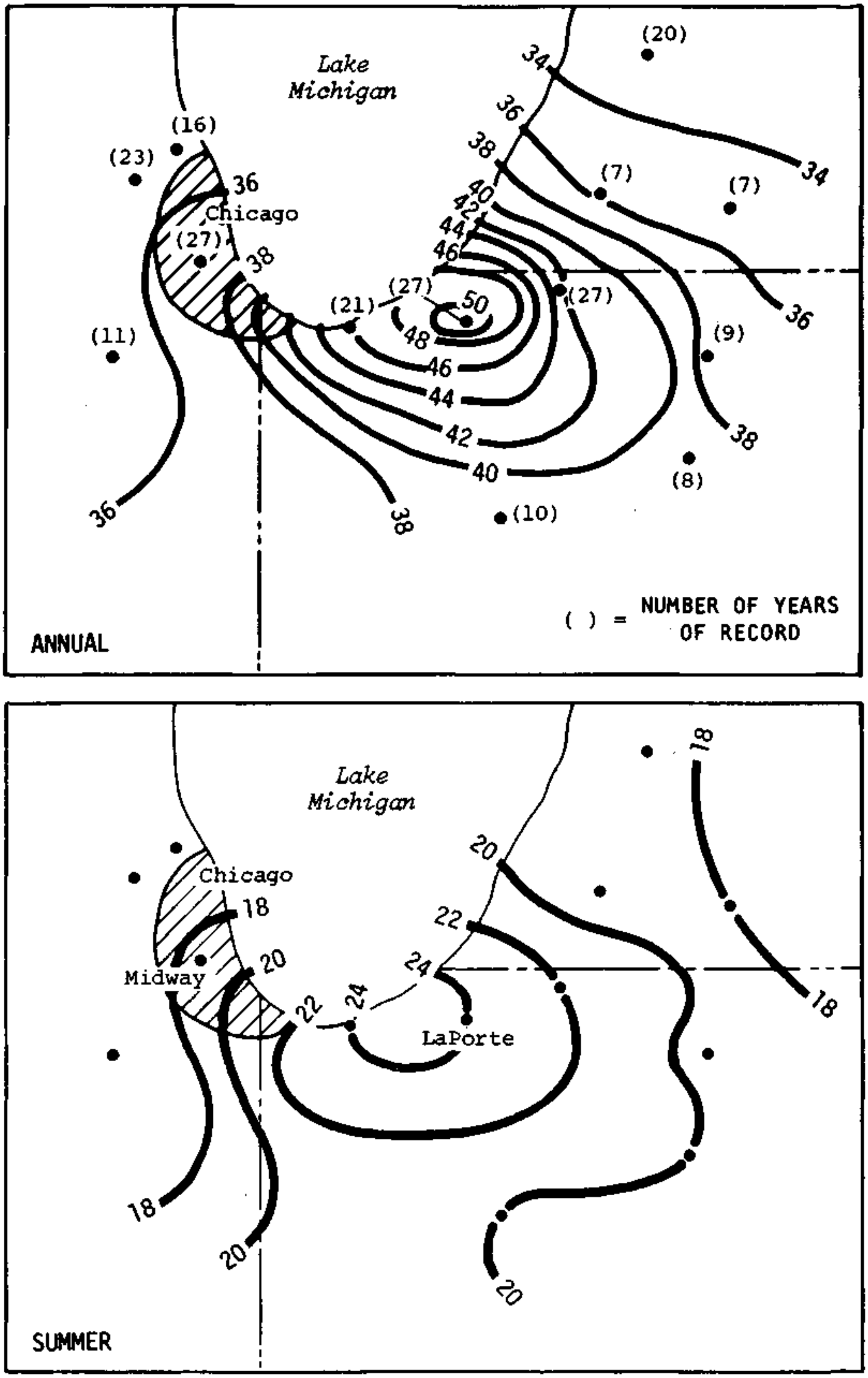
An earlier study by Changnon (1968) found that LPT had 38% more thunderstorms and 246% more hail days in the 1951-65 period than did surrounding stations. This pronounced increase in severe weather events is discussed in detail in the above reference and elsewhere (Changnon, 1969b). Inspection of Fig. 7 reveals the distinct maximization downwind of Chicago and also that the summer and annual numbers of thunder days in the city itself during recent years were higher than those in the rural areas west of Chicago.

## Indianapolis

Evaluation of urban effects on precipitation in the Indianapolis region was hampered by inadequate raingage density and lack of long-term concurrent records for existing stations in the immediate urban area. Within limitations of the data sample, no strong evidence was found of urban-induced effects on the spatial patterns of seasonal precipitation or in the seasonal time trends at individual stations. Daily precipitation analyses provided some evidence that urban effects were intensifying rainfall on days with amounts of one inch or more during summer within the city. However, this effect could not be substantiated in the winter analyses. Furthermore, studies of the frequencies of severe rainstorms with daily amounts of two inches or more, the majority of which occur during the warm season, did not provide evidence of a measurable urban effect on such storms. Stations with quality thunder and hail data revealed no increases, but again there were no stations with quality data in the immediate downwind area. However, it must be stressed that failure to identify urban effects at Indianapolis does not necessarily preclude their existence, since the data sample was not as adequate as that available for the St. Louis and Chicago studies described previously.

## Cleveland

Seasonal spatial analyses provided evidence of an urban enhancement of summer rainfall 25-50 mi east of the central city in the Chardon-Dorset region




*Figuve 7. Average annual and summer patterns of number of thunder days at Chicago-LaPorte area based on 1942-68 period*

and 25-35 mi SE in the Hiram-Ravenna region. Fig. 8 shows the summer rainfall ratio pattern using Cleveland Airport as the comparison point (ratio denominator). Isolation of the magnitude of this effect is complicated by physiographic features of the area, but comparisons between upwind and downwind stations indicated the urban enhancement is of the order of 5-15%. Indications of a spring enhancement similar in location and magnitude to the summer urban effect was found also.

Evidence of a more pronounced urban enhancement was found during winter in the Chardon area which averaged 30-40% more precipitation than the city in the 1954-68 period (Fig. 9). Examination of data for upwind stations with similar topography and/or distance from Lake Erie indicates the Chardon high is not primarily the result of lake or hill effects. This is further substantiated by a secondary winter high near Hiram, about 25 miles SE of the central city, where 20% more precipitation occurred than in the city (Fig. 9), and in a region which could be expected to reflect urban enhancement also. A downwind effect in fall similar to winter conditions was noted.

Analyses of daily precipitation grouped according to intensity provided evidence that the Cleveland urban downwind enhancement is most pronounced on days of moderate to heavy rainfall, similar to findings at St. Louis and Chicago. Warm season analyses of weekday-weekend relations provided little support for significant weekday-weekend differences in the frequency and intensity of daily rainfall (indicative of the industrial impact on the inadvertent modification of precipitation). However, cold season analyses did provide some evidence of greater intensification of natural precipitation from urban effects on weekdays compared with weekends.

From a study of surface winds and synoptic storm types on winter precipitation days in 1960-64, additional evidence was found to support a relatively pronounced urban-induced increase in precipitation in the Chardon region east of Cleveland. The dominance of SW to WNW surface winds in winter precipitation is most favorable for producing an urban high downwind of the central city.

Willoughby, a cooperative station located 5 miles downwind of Cleveland (Fig. 8), showed an average of five more thunderstorm days per year, which represents a 14% increase over the values expected. The summer values at Willoughby during the 1960-68 period were 25% greater than those elsewhere, and development of this anomaly began in 1960 (Fig. 10). The Cleveland City Station showed no increase in thunder, but it was terminated in 1940, and the only city-area station is at the Airport which is upwind of the urban complex; unfortunately, only Willoughby, located 5 miles NE of the urban area, defines the downwind increase in thunder activity. This station does not show a comparable increase in hail days. However, at St. Louis, the city-located station reflecting the major urban-related thunder-day increase there also did not indicate any hail-day increase.

Cleveland's potential effect on severe weather conditions is difficult to analyze because of the pronounced lake effects during the spring and fall seasons of major thunderstorm and hail activity. These lake effects tend to

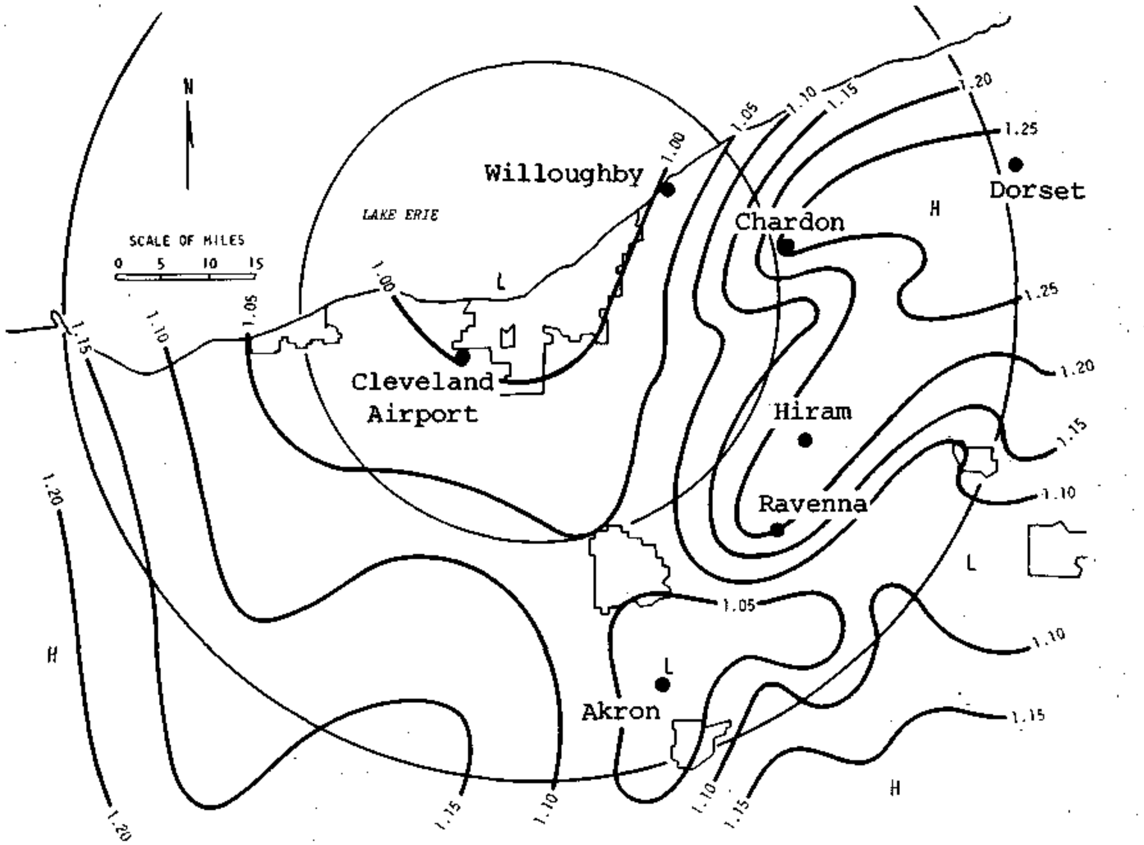



*Figure 8. Average rainfall ratio pattern at Cleveland, summer 1954-68*

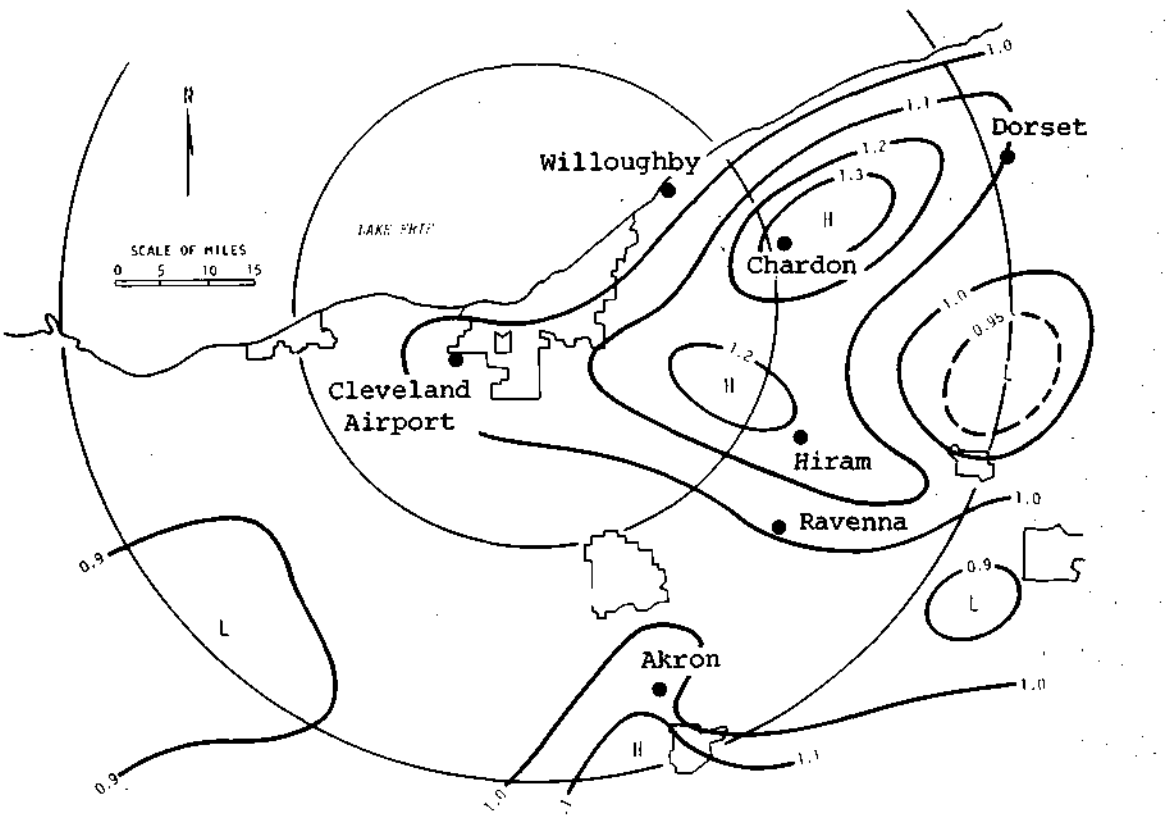



*Figure 9. Average rainfall ratio pattern at Cleveland, winter 1954-68*

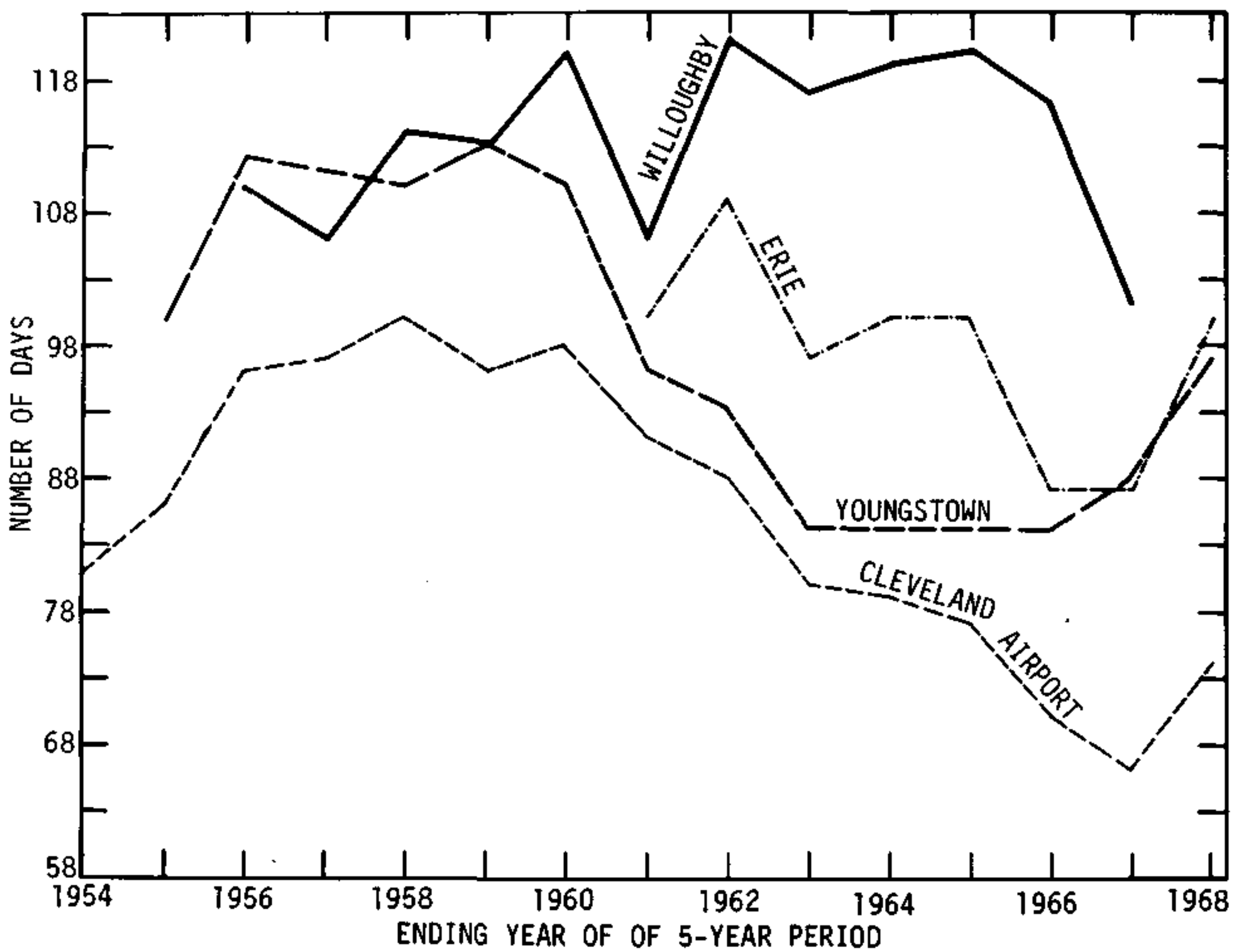



*Figure 10. Five-year moving totals of summer thunder days in Cleveland area*

mask any urban-related hail increase that exists, other than in summer. Hail-day increases were apparent in summer at Chardon and Hiram, located farther downwind of the urban center than Willoughby. These urban-related summer increases in hail-day frequencies began in the 1950's. Downwind hail-day increases in summer amounted to 80-100%. Severe weather results for Cleveland are quite similar to those obtained at Chicago and St. Louis. The pattern of increase found in all three locations consists of 1) greatest increases in the summer season, 2) the thunder and hail increases began in the 1947-60 period, 3) the thunderstorm increases are lower, percentagewise, amounting to 15-35%, than the hail increases which amount to 50 to 200%, 4) the thunderstorm increases occur over the city and/or immediately downwind and those over the city are not accompanied by hail increases, and 5) hail increases occur farther downwind.

## Washington

Summer spatial patterns throughout the 1949-68 period indicated a distinct, persistent high in the rainfall pattern extending in a general SW-NE direction across the Washington urban area. This high decreased in intensity NE of Washington, then increased again to a still higher value in and NE of Baltimore, about 35 miles NE of Washington. This high was apparent in the latest 5-year period (1964-68), the 10-year period (1959-68), and the 15-year period (1954-68). Fig. 11 shows a rainfall profile for 1954-68 extending SW-NE across the area through the central part of urban Washington.

In the region of heaviest urban rainfall, the summer enhancement appeared to be of the order of 5-15% with an average of 10%. An urban-induced increase of approximately 5-10% was indicated in the winter, spring, and fall patterns in the region of maximum effect.

Time-trend analyses of seasonal precipitation were inconclusive. Analyses of the intensity and frequency of daily precipitation provided slight evidence that urban-induced increases in precipitation may extend to days with moderate to heavy rainfall, in agreement with earlier findings at St. Louis, Chicago, and Cleveland.

Study of the relationship between daily rainfall and prevailing winds in summer during the 1960-64 period provided relatively strong evidence of a heat-island effect on the urban precipitation. Concurrent synoptic studies suggested the most pronounced effect was associated with air mass storms', which are generally scattered in nature and areally unorganized.

A study of weekday-weekend relations at selected stations resulted in conflicting evidence regarding the existence or non-existence of a differential urban effect during the week when atmospheric particulate discharges would tend to be greater. No firm basis for a conclusion was established.

The spatial and temporal studies of thunder and hail data in and around Washington indicate that measurable but very localized increases in both events developed in the 19 36-45 period.

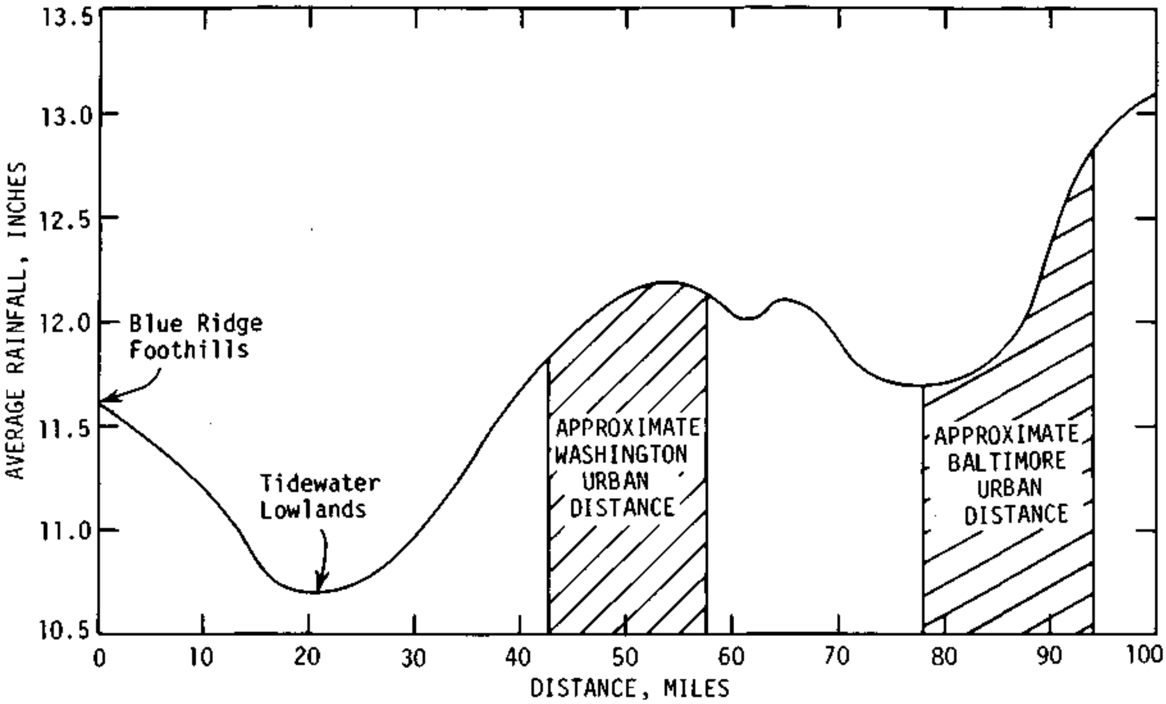



*Figure 11. SW-NE summer rainfall profile in Washington-Baltimore area, 1954-68*

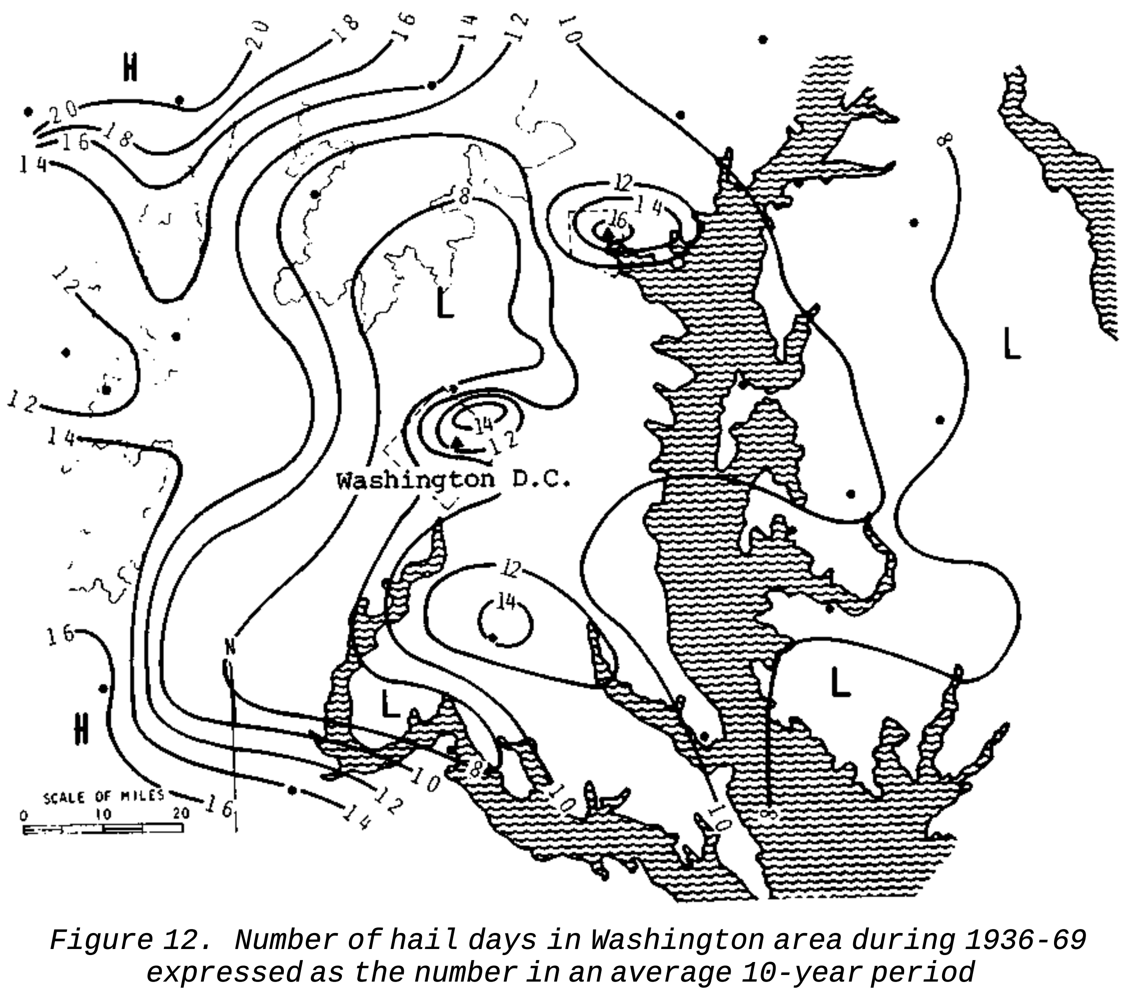



*Figure 12. Number of hail days in Washington area during 1936-69 expressed as the number in an average 10-year period*

Apparent urban-related increases are, on the average, greatest in summer (3 thunder days, 2 hail days), but the largest percentage increases occur in fall (47% in thunder days, 100% in hail days). The average annual thunder-day increases (6 days, or 19% of the expected value) are comparable to those found in St. Louis (5 days) and Cleveland (6 days). Annual hail increases (5 days per 10 years, or 55%) are sizeable, and thus are in agreement with those found at La Porte, St. Louis, and Cleveland. The localized nature and presence of hail highs at Washington and at Baltimore are reflected in Fig. 12.

Importantly, the thunder and hail increases at and immediately downwind of Washington indicate that non-industrial urban conditions (thermal effects and possibly vehicular exhaust particules) affect these mature aspects of convective activity. The increases are as great percentagewise as those found at industrial centers, and this may suggest that increases noted in industrial areas may not be directly related to industrial activity.

Houston

The general conclusion dictated from spatial analyses of total seasonal rainfall is that there is no reliable evidence of an urban precipitation effect during any season. This conclusion agrees with that of Kelly (1972), based on a study of annual and monthly rainfall in the Houston area. However, the presence of an urban effect is not precluded by the above findings. The sparcity of long-term precipitation data and natural climatic gradients of rainfall in the region make pattern analyses (basic to the Illinois study) a relatively weak evaluation tool under these circumstances.

Time-trend analyses for the 1954-68 period did provide weak evidence of an urban effect intensifying with time on the west side of the city during the warm season (May-September), when prevailing winds, industrial concentrations, and the urban heat island would favor such a development. However, this same west side trend was present in the cold season when the effect would have been expected east of the city with westerly-component winds prevailing. Overall, therefore, there is but little support for an urban effect in the time-trend analyses.

Examination of spring, summer, fall, winter, warm season, and cold season precipitation patterns for days with rainfall of one inch or more led to the conclusion that the evidence is insufficient to identify reliably the existence or non-existence of an urban effect on relatively heavy rain days. However, there is a suggestion of an urban intensification of these storms in winter about 25-45 miles E and NE of the urban center.

The basic conclusion from a study of weekday-weekend rainfall relations is the same as for the 1-inch rain days. That is, there is not adequate evidence from our 4-station analysis to prove satisfactorily the presence of a weekday-weekend differential effect resulting from urban environmental factors.

Diurnal and synoptic weather analyses performed for the 1964-68 period did indicate that there is an urban enhancement of non-frontal rainstorms within the city during the warm season. This increase in non-frontal rainfall is of the order of 8% in the May-September period and 17% in the June-August period.

Values of thunder days and hail days at the NOAA city station during the period of joint airport and city operations (1931-60) showed no trends, and the city averages for two periods analyzed do not vary. Inspection of the thunder-day averages of the Houston Airport, located on the south side of the city about 8 miles SSE of the city station, show that the thunder frequencies in the 1941-60 season represented a 10% increase over those prior to 1941. The 1941-60 thunder day average at the airport station closely matched the city station value. The association of the thunder-day upward trend at the airport in the late 1930's and the early 1940's and an increased frequency of smoke-haze days at the airport are indications of urban-industrial effects on thunderstorms. The rapid growth of industry southeast of Houston in World War II obviously led to an increase of smoke days in the area, indicating the possibility of sizeable releases of active cloud and ice nuclei to enhance rain and lead to thunderstorms.

A sizeable increase in hail days developed at the airport in the early 1950's (Fig. 13), about 10 years after the thunderstorm increase occurred. In the pre-effect period (1931-50) the airport average hail day frequency was 1.5, or only 25% of that at the city station. The hail-day increase at the airport led to an average of 6.5 days in 1951-60 which was comparable to the city average. This was a 400% increase in hail days at the airport.

The 10% thunder-day increase and the 400% hail-day increase at the Houston Airport, in and near where sizeable urban-industrial growth has occurred, do appear to relate to inadvertent effects. An increase in smoke-haze days at the Airport that closely matches the thunder-hail increases, and the lack of increases in thunder or hail days at the Houston city station or at Galveston support this conclusion.

## New Orleans

The presence of relatively strong climatic gradients in the urban region and scarcity of long-term climatic records outside of the city makes identification of any existing urban effects on daily and seasonal precipitation difficult to identify with a high degree of confidence. Based primarily on data for 1954-68, some evidence was found in the warm season rainfall patterns of an urban-induced increase in the northern part of the city. A possible suppression effect was suggested by the winter precipitation patterns.

Time-trend analyses of summer rainfall provided some evidence of an urban-intensified effect superimposed upon a climatic ridge extending northward through the city. No evidence of a changing trend was found in winter precipitation.

Weekday-weekend analyses for 1949-68 yielded evidence of a greater urban effect on the warm season rainfall on weekdays compared with weekends. The

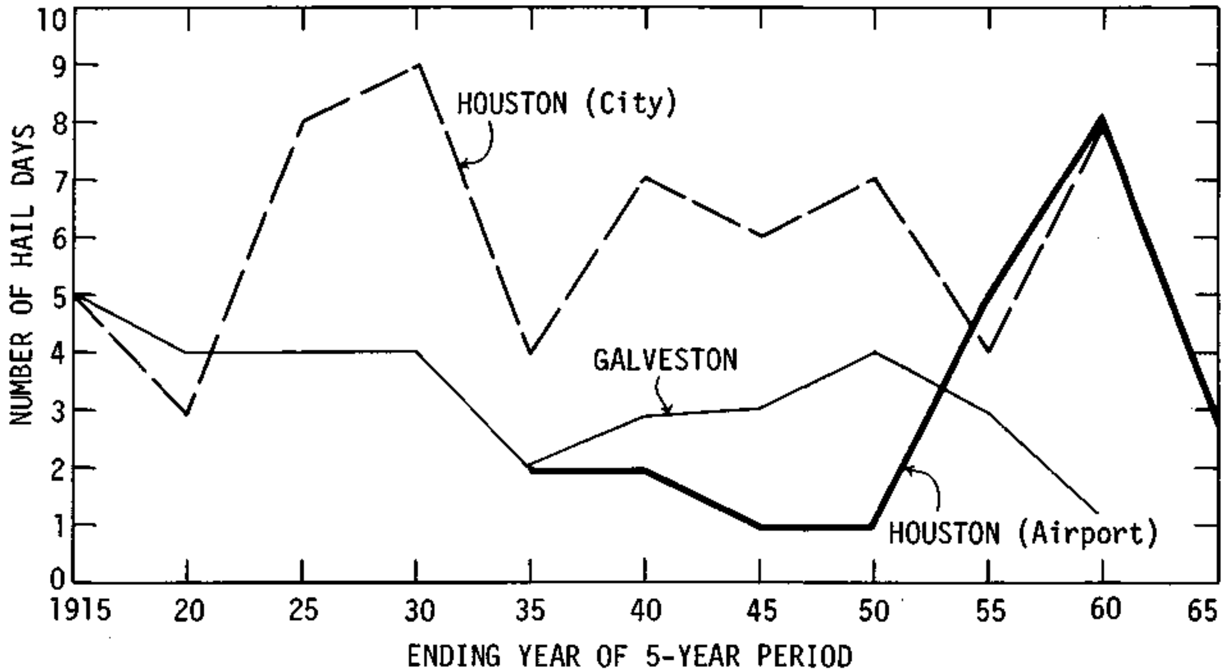



*Figure 13. Hail days at Houston City, Houston Airport, and Galveston City stations*

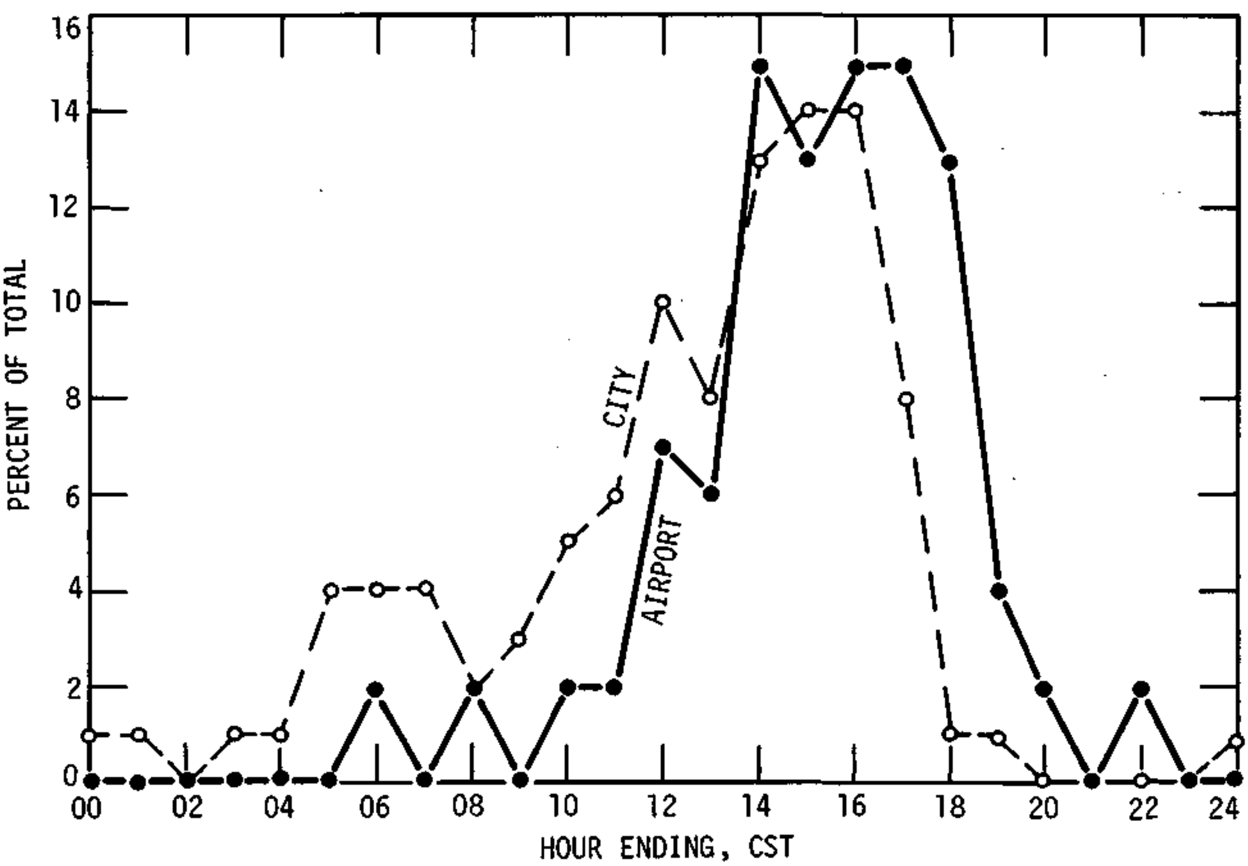



*Figure 14. Diurnal distribution of hours with thunderstorms in New Orleans area, 1961-64*

frequency of rainy days was greater on weekdays at all intensity levels of daily rainfall tested, but increases in total seasonal rainfall apparently occurred mostly on days with natural rainfall less than one inch. In the cold season, a possible weekday suppression effect was suggested by fewer occurrences and less precipitation on weekdays, and this effect appears to increase with increasing natural precipitation.

Synoptic analyses for 1964-68 indicated a possible increase of the order of 10% in summer rainfall on the north side of the city, associated with urban intensification and/or development of air mass storms.

Rather strong evidence was found showing recent urban-related increases in thunder days and hail days within the New Orleans urban area. These increases began in the 1960-65 period, and the 1961-69 values within New Orleans were greater than any there in previous years or those at surrounding stations in the 1961-69 period.

The thunder increase was most pronounced in the major convective season, May-October, and the NOAA city station increase in thunder days was 26%. The summer season increase was found to be significant at the 0.1-probability level. The increase occurred entirely with unorganized air mass storms, and, as shown in Fig. 14, resulted in more storms earlier in the day at the City than occurred at the rural Airport. This and other findings suggest that added heating from the city is a critical factor in initiating added convective activity over New Orleans.

Sizeable increases in hail days within New Orleans were found in both seasons, but the warm season increase was most pronounced. The increase in hail days at the NOAA city station was 100%.

## Tulsa

Spatial analyses of summer rainfall provided slight evidence of an inner-city high related to urban effects, but its existence is questionable because of the configuration of the natural climatic pattern in the Tulsa region. Also, no real basis for an urban effect could be discerned from winter spatial patterns. Trend analyses did not indicate any clearcut evidence of urban effects in the time distribution characteristics of seasonal precipitation, although an increasing summer rainfall enhancement in recent years is suggested.

Analyses of weekday-weekend relations did not provide strong evidence of urban effects related to particulate discharges from industrial sources. However, slight evidence was found that particulate discharges may lead to enhancement of light to moderate natural precipitation in the cold season. Evidence of urban effects on thunderstorms, hailstorms, and heavy rainstorms was not revealed in the various Tulsa analyses.

# OVERALL SUMMARY

In general, relatively strong evidence of urban effects was found in the daily and/or seasonal precipitation distributions for St. Louis, Chicago, Cleveland, and Washington. Evidence was weak or non-existent at Indianapolis, Tulsa, and New Orleans. Urban effects at Houston could be identified only in May-September rainfall of air mass origin. The urban effect appeared to be more pronounced in summer than in winter and usually maximized 10-35 mi downwind of the central city. However, effects were identified within the city also at Chicago, Washington, Houston, and New Orleans. Table 2 summarizes briefly results for the 8 cities in summer.

A condensation of the 8-city results of the thunder-day and hail-day analyses is shown in Table 3. Although various pattern and point-to-point temporal analyses were employed, the thunder results shown are for differences between a) the station with the greatest increase in thunder-day frequency, and b) the average frequencies for the same time period at two or more stations in the uneffected area upwind of the city. The percentage increase values were determined for the period from the start of the increase through 1969 (or until the record ended).

Six cities have thunder increases ranging from 13 to 47% above the climatic background, and three of these increases are highly significant (one percent probability due to random chance). All six were significant at a probability of 0.1. Only Tulsa and Indianapolis had no increase, and it is possible that an increase might exist at Indianapolis because the stations with quality data were sparse and poorly located with respect to the city and its immediate downwind area. The season of the maximum percentage thunderstorm increase was summer in all cities except Washington where the fall increase was slightly greater than the summer increase. Periods when the increases began spanned a 30-year period with those in Washington and Houston beginning in the late 1930's whereas those in New Orleans began in the early 1960's. However, four of the six urban thunder-day increases occurred in the 1936-50 period. All thunder-day increases were found to exist in the city proper with maximization either there, or within 10 miles of the city in 5 or 6 cities.

Efforts to evaluate the hail results from these eight cities required developing regional upwind area and downwind area means where possible. Regional evaluation eliminates the problem of great natural time-space variability of hail and minimizes the effect of an incorrect point record. The maximum area or point increases shown in Table 3 range from 90 to 350%, being much greater than the thunder increases. All the hail-day increases. were found to be statistically significant at the 0.01 probability level. The seasons of hail and thunder maximization were the same in all six cities, and again Tulsa and Indianapolis had no hail increase. Seasons when the maximization began seldom agreed exactly with those of the thunder, slightly preceding the thunder increases in three cities and following the thunder by

Table 2. Summary of urban effects on summer rainfall at 8 cities

| City | Observed Effect | Maximum Change Inches | Maximum Change % | Approximate Location |
|---|---|---|---|---|
| St. Louis | Increase | 1.6 | 15 | 10-12 mi downwind |
| Chicago | Increase | 2.0 | 17 | 30-35 mi downwind |
| Indianapolis (1) | Indeterminate | --- | -- | |
| Cleveland (2) | Increase | 1.4 | 15 | 25-50 mi downwind |
| Washington | Increase | 1.1 | 9 | Urban area |
| Baltimore (3) | Increase | 1.7 | 15 | Urban & northeastward |
| Houston (4) | Increase | 1.3 | 17 | Near urban center |
| New Orleans (4) | Increase | 1.8 | 10 | NE side of city |
| Tulsa | None | --- | -- | |

(1) Sampling density not adequate for reliable evaluation

(2) Estimated orographic effect subtracted, 27% greater than city

(3) 30-40 miles downwind of Washington - not included in original study

(4) Urban effect identified only with air mass storms - apparently little or no effect in frontal storms

a few years in the other three cities. The hail increases were found to occur farther downwind of the city than were the thunder increases.

In summary, thunder and hail-day frequency increases were found in six of the eight cities investigated, and these occurred in the six largest cities. In a very general sense, this result suggests that a critical size of urban area must be reached before an urban area can affect severe storm frequency. Since sizeable increases were found in a non-industrial city such as Washington, as well as in industrial cities with widely varying industrial basis (New Orleans as opposed to Chicago), one must conclude that a part of the increase is due to thermal and dynamic effects of the city on weather, as well as locally generated aerosols serving as active cloud and ice nuclei.

Statistically significant increases were found in two basically different climatic zones studied, the midwestern continental and the Gulf Coast marine climates, indicating that the urban effects were sufficiently sizeable to interact with the somewhat different convective conditions in these climates. Also the increases were always found to be greatest in the warm season, and generally the summer, (June-August).

The placement of maximization of the two events, thunder generally in the city and hail 15 to 25 miles downwind, suggests a logical convective sequence: an increase in convective activity over the city leading to the formation of thunderstorms within audible distance of the city center, and the evolution of these storms into hailstorms in the downwind area. The downwind hail highs corresponded closely with downwind highs in the seasonal rainfall patterns. The areas of increase in both thunder and hail are small, generally less than 1000 mi.

Although the percentage increases differed between thunder and hail, 20 to 40% versus 100 to 300%, respectively, these were nearly matched in the actual frequency of days. For example, at St. Louis the summer season thunder-day increase of 25% is an increase of 4 to 5 thunder-days per year, and the 270% average hail-day increase was 3 days (a total of 5 days) as compared to an upwind regional value of less than 2 hail days. Thus, the numerical magnitudes of the two increases were nearly identical but the lower frequencies of upwind, uneffected hail frequencies led to the greater percentage increases.

The increases in thunder and hail in and downwind of Cleveland, also a city with a site not unlike Chicago-La Porte, is considered further proof of the validity of the La Porte anomaly in thunder and hail.

Studies of the frequency of thunder occurrences by day-of-the-week did not provide any suggestion of a weekday increase, as opposed to weekend frequencies. However, in cities where the diurnal frequencies of thunderstorms could be ascertained (Chicago, New Orleans, St. Louis) the nocturnal frequencies of thunderstorms were those increased greatest. These findings help support the thermal heat effect explanation for the severe weather increases at the 6 cities. Limited synoptic weather analyses of the thunder increases at Chicago, St. Louis, and Cleveland indicated that they occurred most frequently either in air mass, isolated convective situations, or in cold frontal situations.

Table 3. Thunder-day and hail-day summary for 8 cities

THUNDER

| City | Maximum point increase, % | Season of maximum increase | 5-Yr period when increase began | Where(*) | Statistically significant[2] |
|---|---|---|---|---|---|
| Chicago | 38 | June-Aug | 1941-45 | City & 25 miles downwind | yes |
| Cleveland | 42 | June-Aug | 1956-60 | City & 10 miles downwind | yes |
| Houston | 13 | May-Sept | 1936-40 | City & 10 miles downwind | no |
| Indianapolis | 0 | --- | --- | ------ | --- |
| New Orleans | 27 | June-Aug | 1960-64 | City | no |
| St. Louis | 25 | June-Aug | 1946-50 | City | yes |
| Tulsa | 0 | --- | --- | ------ | --- |
| Washington | 47 | Sept-Nov | 1938-42 | City | no |

HAIL

| City | Maximum point or area increase, % | Season of maximum increase | 5-Yr period when increase began | Where(*) | Statistically significant[2] |
|---|---|---|---|---|---|
| Chicago (pt) | 246 | June-Aug | 1940-44 | 25 miles downwind | yes |
| Cleveland (area) | 90 | June-Aug | 1948-53 | 15-20 miles downwind | yes |
| Houston (pt) | 350 | May-Sept | 1951-55 | Area of industrial growth, 10 miles downwind of urban area | yes |
| Indianapolis | 0 | --- | --- | ------ | --- |
| New Orleans (pt) | 350 | May-Oct | 1950-54 | City | yes |
| St. Louis (area) | 276 | June-Aug | 1951-55 | 15-20 miles downwind | yes |
| Tulsa | 0 | --- | --- | ------ | --- |
| Washington (area) | 100 | Sept-Nov | 1936-40 | City & 15 miles downwind | yes |

(*) Where covers general area of increase, and downwind refers to area where majority of storms move after crossing the city, and distance (miles) refers to that from the city center to the point or area of maximization.

(2) From use of Binomial test and considered "yes" (significant) if probability was ≤ 0.01 that difference was due to random chance.

## IMPLICATIONS FROM URBAN STUDIES

At this point, it is appropriate to ask what has been learned from these eight urban studies that contributes to our understanding of weather modification, both planned and inadvertent. First, results of the St. Louis study were instrumental both in the initiation of Metromex, the major field study now underway in that city, and in planning the Metromex research program (Changnon, et al., 1971).

Results of studies for St. Louis, Chicago, and Cleveland provide strong evidence that the natural precipitation distribution in the Midwest can be altered by cloud treatment (inadvertent in the urban case).

Evidence was found that both thermal and aerosol inputs can lead to increased precipitation from existing storm systems. Overall, the evidence indicated that the thermal effect (heat island) may be the more important of the two stimulation factors.

It was very evident from our studies that when cloud treatment (uncontrolled) increases the surface precipitation on a monthly or seasonal basis, that the frequency of severe weather events (TRW, hail, heavy rainstorms) are also increased substantially. The stimulation of severe weather events appears most evident in data for the larger cities.

In general, whereas all intensities of daily rainfall appear to be increased by inadvertent weather modification in the vicinity of large cities, the most pronounced effect appears to be on those days with moderate to heavy natural rainfall. This implies that the urban modification is primarily a rain stimulation process in existing rain clouds, as opposed to initiation of rain from non-precipitating clouds. In turn, this implies an ability to significantly stimulate the ongoing rain process by seeding, even in relatively efficient rain-producing system.

Our studies indicate that the inadvertent modification is most pronounced in the warm season, although evidence of alteration in all seasons was found at some cities. This may be related to the tendency for the urban effect to be felt more in relatively heavy precipitation compared with light rain-producing storms. Thus, we have an implication from the inadvertent modification effects that warm season systems are most amenable to seeding treatment.

In general, the warm season rainfall increase maximized 10-35 miles downwind of the cities and corresponded closely with the hail peak. The TRW peak tended to occur over and slightly downwind of the city. This provides a first approximation of the average time and distance for cloud treatments to materialize and maximize their effects at the surface.

Evidence from the St. Louis study was that the inadvertent weather modification mechanisms reacted differently in wet and dry years, with indications of a suppression effect in dry summers. This raises a question which needs further study and consideration in planned weather modification, and implies that different technique of planned weather modifications may have to be evolved for different synoptic and climatic conditions.

The finding that heavy rainstorms are intensified by inadvertent weather modification (urban effects) has implications which should be given consideration in hydrologic problems, such as the design of urban and suburban storm sewer systems, and possible effects on replenishment of surface water supplies and shallow groundwater aquifers.

Agriculturally, there was some evidence compiled in the Chicago and St. Louis studies that crop production was increased in the region of the summer rainfall high downwind of these cities (Changnon, 1972). Since the increase only averaged 10%, the implication is that modest rainfall increases from planned weather modification may be economically valuable.

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Huff, F. A., 1972: Potential augmentation of precipitation from cooling tower effluents. Bull. Am. Meteor. Soc, Aug. (partially based on NSF-18781 research).

## ORAL PRESENTATION OF PAPERS UNDER NSF-18781
(in addition to above list which were originally oral presentations at scientific meetings)

Changnon, S. A., 1972: Urban Effects on Precipitation. Water Resources Meeting, American Society of Civil Engineers, Atlanta, Jan.

Huff, F. A. and S. A. Changnon, 1972: Hydrologic Implications of Inadvertent Weather Modification. American Geophysical Meeting, Washington, D. C, April.

Changnon, S. A., 1971: Realities of Urban Effects on Rainfall. Lecture, University of Pennsylvania, Philadelphia, April.

Changnon, S. A., 1971: Climatic Studies of St. Louis Urban Effects. Lecture, University of Wyoming, Laramie, May.

Changnon, S. A., 1971: Changes in Urban Climate. Lecture, Annual Gas Dispatches Forum, Highland Park, Illinois, October.

Changnon, S. A., 1971: Urban Effects on Climate. Lecture, Graduate Seminar at University of Minnesota, October.

Changnon, S. A., 1971: Analytical Techniques for Weather Anomalies. Lecture, Faculty-Student Geography Seminar, University of Minnesota, October.

## STUDENT EMPLOYMENT AND TRAINING

Timothy A. Lewis, Geography Department, University of Illinois, prepared his Ph.D. thesis in conjunction with research carried out under NSF-18781. The title of his thesis was "A Climatological Study of Thunder and Hail Day Patterns in and Around Seven Large United States Cities."

Three undergraduate students from the University of Illinois (Nancy Wallick, Nancy Thun, and Linda Schmidt) were employed part-time throughout the grant period. They were assigned primarily to routine statistical analyses of precipitation data.

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