CITIES CAN MODIFY RAINFALL -- A NEW CONCEPT

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INTRODUCTION

Several climatic studies during the past 100 years have shown that cities develop their own special internal climate, being warmer and less windy than rural areas. A few key climatic studies of the past 10 years found that cities may also produce effects on clouds and precipitation that extend several miles out from the city. Unfortunately, these challenging discoveries could not define adequately the true magnitudes, in time and space, of these precipitation anomalies because the desired records in and around most American cities are too sparse or just not available. They also could not specify how these complex atmospheric processes were being altered, but the possibility brought a new dimension to weather modification.

As a result, METROMEX (METROpolitan Meteorological EXperiment) was established in 1971 at St. Louis, a representative American city, to identify and describe the weather anomalies produced by that city. The anomalies under primary study, summer rainfall and severe storms, were those hardest to delineate and to explain. Their explanation also requires delineation of most other urban anomalies including those for temperature, moisture, winds, and aerosols. Summer thunderstorms and rainfall have been found to be increased up to 25% over areas from 800 to 3000 km^2, and hailstorms are increased in both severity and frequency by 300 and 80%, respectively.

CITY WEATHER AND CLIMATE

A major means whereby man has affected weather has been through his urban environment. More than 700 years ago (1273) the London urban complex had achieved a size such that it produced a recognizable effect on its local weather, at least in terms of reduced visibility and increased temperature (Chandler, 1965).

The increased tempo of urbanization that began 200 years ago with the industrial revolution has led to relatively significant local and mesoscale changes in the weather in and near urban locales (Peterson, 1969; Landsberg, 1970). Since urban areas first proliferated in Europe, considerable scientific attention has been directed to this problem in the European area during the last 100 years (Kratzer, 1956; Chandler, 1968). Now that major urban-industrial complexes are prevalent in many countries, worldwide attention to this problem has grown rapidly in the last 20 years, and the development of megalopolises in the United States during the past 30 years has brought with it increasing public and scientific awareness of the degree and, in some cases, the seriousness of urban effects on mesoscale weather and climate.

More intensively than any other comparable-sized part of the earth's surface, cities are converters of energy and matter, and their products directly affect the heat budget, moisture budget, and exchange of mass in the atmosphere. Consequently, the changes in weather wrought by urbanization encompass all major surface weather conditions. The list of elements or conditions affected includes the contaminants in the air, solar radiation, temperature, visibility, humidity, wind speed and direction, cloudiness, precipitation, atmospheric electricity, severe weather, and certain mesoscale synoptic weather features. Obviously, the degree of change in any of these elements at any time depends upon the areal extent of the urban-industrial complex, its types of industry, its juxtaposition to major water bodies and topographic features, time of day, season of the year, existing weather conditions, and climate. Urban areas often act as mechanical barriers to airflow, even retarding the forward motion produced by cities can be shown by urban solar radiation which 1) is decreased by cities much more in the winter than in the summer; 2) is decreased on weekdays; and 3) is decreased more in the morning than in the afternoon (Mateer, 1961).

Figure 1 shows the long-term changes in frequencies of smoke-haze days at several Illinois cities. These visibility-related data are descriptive quantitative indices of the march of urbanization and are unique because they are the only type of pollutant data collected continuously since the start of the 20th Century. They are useful in illustrating how man's input of visible particulates from combustion processes has changed dramatically. Chicago, the only major city in the group, was the first to show a sizeable increase. The moderate industrial cities of Moline, Springfield, and Peoria also show sizeable increases beginning in the 1930's, whereas the only small non-industrial city of minimal 20th Century growth, Cairo, has had no great temporal increase in smoke-haze day frequencies. These data show the existence of dramatic shifts and reflect the localized nature of visible smoke pollutants in this humid continental climate.

Urban effects on weather can be categorized as obvious, or easy to measure; and subtle, or hard to measure. The obvious effects of urban areas on weather first noted many years ago include such things as decreased visibility (McCormick and Ludwig, 1967), reduced winds (Pooler, 1963), and increased temperature (Clarke, 1969). Table 1 summarizes these effects. The visibility within a city varies considerably as particulates released from different land uses (residential, commercial, industrial) have been shown to vary sizably (Bunyard and Williams, 1967).

In a major urban complex the visibility is more frequently restricted than in rural areas, and this has come from the smoke, other contaminants, increased fog, and various photochemical additives like smog. The temperature within a small (10,000 population) to a large sized urban area is generally higher at any given time of the day or season than it is in rural areas because the most radical urban-produced change is in the heat balance. This results because the city produces more heat through combustion, stores more heat in its structures, and it gains heat because there is less evapotranspiration in cities than rural areas. The temperature effect has been well recognized and reasonbly well measured for 50 years because its direct measurement, at least at the surface, is easily accomplished. Recently, the vertical extent of the daytime urban heat island has been shown to extend

2000 or more feet up (Braham, 1972), and also to extend downwind as a "thermal plume" (Clarke, 1969); Changnon and Semonin, 1975). Urban areas often act as obstacles to decrease winds and alter their direction near the surface (Chandler, 1965), to increase turbulence and vertical motions in their immediate areas (McElroy, 1969), and to create in light wind conditions a localized rural-urban circulation pattern (Ackerman, 1973).

The more subtle, less recognized weather changes wrought by urban areas include alterations of humidity, cloudiness, precipitation, snowfall, and severe weather. The possible alterations in these phenomena appeared to extend beyond the city although climatic studies on limited available data could not well specify the locale or causes. These changes could be related to 1) the thermal-induced upward motions of air (Changnon, 1969), 2) increased vertical motions from mechanically induced turbulence (Braham, 1971), 3) urban increased cloud and raindrop nuclei (Hobbs et al, 1970), and/or 4) industrial increases in water vapor (Changnon, 1968). Major questions that have been raised about these changes concern 1) the reality of the urban rain changes, 2) how the changes were made, 3) the effect of the findings on planned weather impact, and 4) the possible larger-area climatic changes.

This paper will focus on the challenging subject of urban-industrial effects on clouds and precipitation. One climatic investigation in the Chicago area made a singular impact on the issue of inadvertent rainfall modification, and this and other relevant climatic research and limited field experiments are reviewed. The controversies related to this subject are then treated, and this is followed by a description of a major field project that resulted.

TABLE 1

WEATHER CHANGES RESULTING FROM URBANIZATION

	Average Changes Expressed as Percent or Magnitude of Rural Conditions		
	Annual	Cold season	Warm season
Contaminants (Volume)	+1000%	+2000	+500
Solar Radiation (Langleys)	-22%	-34	-20
Tempeature (°F)	+2°	+4°	+1°
Humidity (Relative)	-6%	-2	-8
Visibility (Frequency)	-26%	-34	-17
Fog (Frequency)	+60%	+100	+30
Wind Speed (mph)	-25%	-20	-30
Cloudiness (Frequency)	+8%	+5	+10
Rainfall (Amount)	+14%	+13	+15
Snowfall (Amount)	±10	±10	-
Thunderstorms (Frequency)	+16%	+5	+29

URBAN EFFECTS ON PRECIPITATION

Most findings on this subject prior to 1971 resulted from climatic investigations using historical weather (largely rain) records in and around cities. Amounts and frequencies of rainfall on a variety of time (daily to yearly) and space (point and area) scales were studied most intensively.

A review of research in the United States concerning the modification of precipitation by urban areas reveals that study was quite meager before 1969 (Changnon, 1969). The lack of attention until 1969 to the inadvertent man-made modification by urban-industrial areas, study of which could provide valuable information and guides to planned modification efforts, is surprising.

The lack of research apparently resulted from the lack of uniform historical rain records, a lack of raingages in our urban areas, a lack of instrumentation to make airborne measurements, and difficulty in separating effects produced by gage-exposure variation, natural climatic variations, orography, and major water bodies. Evaluation of these changes was as difficult as that for an operational planned weather modification project.

The 1968 reporting of the LaPorte precipitation anomaly (Changnon, 1968) drew great attention and focused national interest on the subject of urban effects on precipitation. The LaPorte records were startling with sizeable (>30%) increases in warm season rainfall, days with moderate to heavy rainfall, thunderstorms, and hailstorms. These had developed largely during the 1930-45 period in northwestern Indiana, located downwind of the Chicago-Gary complex. The pattern based on numbers of heavy (≥ 2 inch) daily rainfalls for 1949-68 shows this high at LaPorte (Fig. 2).

The interest generated by the LaPorte anomaly led to intensive climatic studies of other American cities (Huff and Changnon, 1972a; Sanderson, et al., 1973; Eichenlaub and Bacon, 1974). In general, relatively strong evidence of urban effects was found in the precipitation distributions for St. Louis, Chicago, Cleveland, Detroit, and Washington. Evidence was weak or nonexistent at Indianapolis and Tulsa. Urban rain effects at Houston and New Orleans could be identified only in summer rainfall of air mass origin. The urban effect appeared to be more pronounced in summer than in winter and usually maximized 50 to 35 mi downwind of the city center. However, effects were identified within the city also at Chicago, Detroit, Washington, Houston, and New Orleans. Table 2 summarizes results for the summer.

A condensation of the thunder and hail results for 8 cities is also shown in Table 2. Six cities had thunder increases ranging from 10 to 42% above the surrounding values. The maximum hail increases ranged from 67 to 430%, and all were found significant at the 0.01 probability level.

In summary, rain, thunder, and hail-day increases were found at most cities investigated, and these increases occurred in the largest cities. The results indicated that a critical size (> 1,000,000 population) or urban area must be reached before an urban area affected rain and 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 bases

(New Orleans as opposed to Chicago), a part of the increase was apparently due to thermal and dynamic effects of the city on weather, as well as locally generated aerosols serving as active cloud and/or ice nuclei.

TABLE 2

Maximum Increases (URBAN-RURAL DIFFERENCE) in Summer Rainfall and Severe Weather Events and Areas of Occurrence

	Rainfall		Thunderstorms		Hailstorms	
	Percentage	Location*	Percentage	Location*	Percentage	Location
St. Louis	+15	b	+25	b	+276	c
Chicago	+17	c	+38	a,b,c	+246	c
Cleveland	+27	c	+42	a,b	+ 90	c
Indianapolis	0	-	0	-	0	-
Washington,D.C.	+ 9	c	+36	a	+ 67	b
Houston	+ 9	a	+10	a,b	+430	b
New Orleans	+10	a	+27	a	+350	a,b
Tulsa	0	-	0	-	0	-
Detroit	+25	a	Not studied			

*a = within city permimeter, b = 5 to 15 miles downwind, c = 15 to 40 miles downwind.

RELATED CONTROVERSIES

The great interest shown, both by the public and scientific community in the 1968 LaPorte results, eventually led to scientific controveries relating to the reality of that anomaly and to the even larger question, "Can man inadvertently alter precipitation by a significant (10% or more) degree?" The LaPorte and ensuing results of inadvertent cloud and rain changes essentially challenged those who did not believe in weather modification (by any means), and as a scientific issue, inadvertent rain modification represented a complex process and was difficult to clearly prove both as to its reality or its cause (Eichenlaub, 1972). Those who challenged the reported inadvertent increases did so on three general premises: 1) that records were faulty (observer or site problems), 2) that increases were not found universally, and 3) that the physical proofs of how the alterations occurred were lacking.

Changnon (1968) in the original LaPorte paper posed the question of reality for the anomaly, and concluded that faulty observer and site change explanations were not valid. Holzman and Thom (1970) used annual precipitation data for LaPorte to conclude that the rain change was due to systematic observer falsification of the records. Changnon (1970) challenged this by showing 1) how other nearby stations had experienced recent rain increases, 2) the LaPorte rainfall correlated with the smoke-day frequencies (an index of pollution) at Chicago, 3) that the increase in LaPorte hail days was supported by local increases in crop-hail insurance losses, and 4) that the LaPorte frequency of rain sorted by days of the week showed distinct differences between weekday and weekends. Figure 3 shows the pattern of slope values or time trend of summer rainfall in the Chicago-LaPorte area, wherein the rainfall of each station is individually regressed with time. The LaPorte value (upward trend) clearly fits within the regional values.

Ogden (1969) chose to test the hypothesis that the LaPorte anomaly was related to the Gary steel mill complex by examining the inland precipitation data around an isolated steel mill complex along the eastern coast of Australia. His results were conflicting. He found that the plant had affected annual rainfall by 5 to 15%, but he also claimed that the outputs (ice and condensation nuclei plus heat) were too small to affect rainfall totals "appreciably". Ogden also attempted to refute any relationship between the temporal distribution in LaPorte rainfall and industrial activity. This analysis was challenged by Changnon (1971b) who showed that the major fluctuations in the LaPorte precipitation were reasonably related to shifts in the national economy. This second controversy really did little to clarify the LaPorte issue.

The effect of industry on rainfall (Hobbs et al., 1970), based on an interesting field sampling effort with a climatic investigation, also were questioned. Elliott and Ramsey (1970) expressed doubt in the climatic analysis, the statistical treatment, and explanation involving added CCN, but their questions were answered with a reply that brought forth new rainfall results and more detailed information on CCN sources.

The next series of controversies on the subject of inadvertent precipitation modification largely concerned analysis of related geophysical data, as suggested by Seidel (1971). Hidore (1971) made an extensive analysis of river and stream runoff in and around the LaPorte area, and compared the time series of historical runoff data with those of precipitation at LaPorte and other area stations. He found runoff increases that related well with the LaPorte precipitation and supported the reality of the anomaly. Holzman (1971) questioned this result, but his conclusions "inadvertently" supported Hidore's and the reality of the local rain increase. The runoff results did much to resolve the reality of the LaPorte anomaly, but other environmental data were pursued in the relentless efforts to scientifically evaluate it.

Harmon and Elton (1971) and then Ashby and Fritts (1972) both initiated ecologically-oriented studies based on analyses of tree rings in and around the LaPorte area. Harmon and Elton showed a weather-related anomaly in tree rings in the area that they ascribed to a "more favorable rainfall" climate resulting from a combination or urban effects on rainfall and of lake effects on weather. Ashby and Fritts concluded that trees in the area showed increasing effects of man-made pollution on growth. Their analysis of rainfall could only partially support a precipitation change because a 30% increase was too insignificant to be detectable statistically since their results showed that the precipitation variable could explain only about 25% of the total variability in tree ring size. Charton and Harmon (1973) turned the unclear tree ring results into a mini-controversy over the question of pollution (toxic) effects on tree growth, but as Fritts and Ashby (1973) pointed out, tree ring analysis to monitor climatic variations in a polluted area are limited, and in general the tree ring investigation neither strongly supported nor refuted the rainfall anomaly at LaPorte.

None of the studies stemming from the controversies was able to explain adequately the causes nor establish through measurement a systematic physical explanation for the anomalies at LaPorte or elsewhere. The best that could be offered in this area, using the limited historical and field data available, was to show that: 1) the LaPorte precipitation correlated moderately well with the Chicago frequencies of smoke-haze days which can be considered an index of potential condensation and ice nuclei (Changnon, 1970); 2) a 2-month rainwater-chemistry sampling program in the Chicago-LaPorte area showed a secondary downwind increase in pollutants that suggested their inclusion in the rain process (Changnon, 1971c); and 3) a simple time model involving the motions of surface materials to cloud base, storm ingestion and processing time, and cloud motions was developed to show that cumulus clouds affected in the Gary area would reach maturity in precipitation production in the LaPorte area.

METROMEX

Concern over the complex problem of urban effects on clouds, precipitation, and related severe weather finally led to a major investigation. METROMEX was the world's first major research-field program to attempt to clearly establish how, when, and where an urban area affects atmospheric behavior and especially precipitation. The large urban field effort sited at St. Louis began in 1971 and is being concluded in 1976. Eight research groups were involved.

The METROMEX field effort required installation of 1000 weather instruments to form 14 networks of weather instruments in a 5000-km^2 circular area centered on St. Louis. These networks, aided by several aircraft, measured all basic weather conditions. After 5 years of summer field operations, many urban-created anomalies at St. Louis have been defined.

The summer average air temperatures show the urban heat island in the St. Louis area exists in all hours. Its magnitude decreases from 6°C in the early morning to 2°C in mid-afternoon. The center of the heat island also elongates and envelopes the adjacent industrial area to the east during the day.

Under all types of sky conditions, there is a tendency for the humidity to maximize west of the city during the early morning. The city is often relatively dry and the afternoon moisture maxima are located over the river bottomlands (NW of St. Louis). The bottomland area is also one of the areas of preferred convective development that has been found. There often is an apparent relation between the localized warm and moist regions and the subsequent initiation of clouds and rain.

Average monthly surface winds in the summer often show systematic regional differences within the circular study area. The airflow above

St. Louis and environs is perturbed by the city on both rain and fair days. This perturbation often results in a zone of convergence over the city, extending through the first kilometer above the surface. This implies net upward motion through cloud base level, enhanced moisture inflow, and transport of city effluents into cloud systems. The wind measurements indicate significant reduction in speed downwind of the city at 500 m, and lowest average wind speeds directly above the urban area between 700 and 1200 m above the ground. Enhanced vertical exchange of momentum and non-uniform flux divergence through the lowest one or two km of the atmosphere is strongly suggested.

The air tends to be a little warmer (about $1^{o}C$) and drier in the first km or two over the downtown St. Louis area than over surrounding rural areas. In agreement with the higher temperatures and lower urban humidities, the lifting condensation level and the convective condensation level are higher over the city. The urban-rural differences in the latter agree well with differences in observed cloud base heights. The mixing depth also tends to be slightly higher over the city. Urban cloud bases are typically 300 to 600 m higher than those of rural clouds.

Analyses made of the dimensions of first radar echoes (first precipitation formation inside clouds) show the average bases are much lower over the urban area than over rural areas (Semonin and Changnon, 1974). This suggests the urban cloud achieves coalescence much more rapidly above cloud base than occurs over rural areas. The cloud base and echo base differences for urban and rural clouds show an anomaly related to urban-related temperature, moisture, and aerosol factors. The first echoes also indicated distinct differences between formation frequencies with various land uses. The urban-industrial areas had 50 to 70% more first echoes than nearby hill and bottom land areas and 100% more than other rural areas.

Mergers of radar echoes, an event frequently associated with the intensification of rainfall, occurred most often just east of the St. Louis urban area. This led to longer lasting more vigorous storms than merged storms elsewhere (Changnon, 1976). The coupling of cloud and rain initiation with a greater chance for merging and storm development is one of the first major explanations of how the St. Louis urban-industrial area produces local rainfall increases (Changnon, et al., 1976).

The 1971-1974 summer rainfall pattern (Fig. 4) shows the rain fell heaviest just east of St. Louis. The lowest rainfall was recorded west of St. Louis and the Mississippi River in a region that is usually upwind of any urban-induced effects on the precipitation. The rainfall in the region northeast of St. Louis was over 30% greater than the network mean rainfall. The most frequent occurrence of storms producing 3-cm or more of rainfall existed just east of St. Louis. In this area, the 4-summer frequency was twice the network average of 8 occurrences. The rainfall maximum area is frequently downwind of either St. Louis or the Alton industrial area (see Fig. 4), depending upon storm movements. Results indicate that storm merging and intensification of existing storms is a major cause of the seasonal rain highs which are most prominent east of the Mississippi River.

Overall, more rainfall occurred in the late afternoon than during any other period of the day. For 1971-1974, the network averaged 24% of its total summer rainfall in the 1500-1800 CDT period. The most pronounced diurnal excess in this period occurred over the St. Louis urban-industrial area (Fig. 5) where 42% of the rainfall was recorded in three hours beginning at 1500. The outstanding late afternoon rain maximum in the St. Louis region reflects intensification of convection by the urban heating. The maximum in the next 3-hour period (1800-2100) is east of the city (Changnon, et al. 1976).

There is an apparent urban-related increase in thunderstorms of 25% (Fig. 4). However, it is localized within an area of 1000 to 2000 mi^2 east of St. Louis. The enhancement of electrical activity is greatest in the 1500-0300 CDT period. The St. Louis urban area also produces sizeable increases in hail activity (Fig. 4). This increase occurs 3 to 20 miles east of St. Louis and includes more days with hail, and when hail occurs, it is larger and more frequent in this area.

The rain and severe weather results have been interpreted according to the rain-producing synoptic weather conditions that existed during periods leading to the local anomalies (Vogel, 1975). The analyses suggest that the more intense synoptic situations are those existing when most of the rainfall increase occurs east of St. Louis, and that air mass storms are often effected but do not account for much of the substantial increases in rainfall.

Thus, distinct anomalies have been found in and around (generally east of) St. Louis in all weather conditions (temperature, humidity, winds, rain, and severe weather). The geographical and temporal aspects of these strongly suggest they are urban-related, and urban thermodynamic effects leading to the focusing of cloud and rain initiation areas in or near the urban area bring about storm merging and heavy rains on days with unstable atmospheric conditions.

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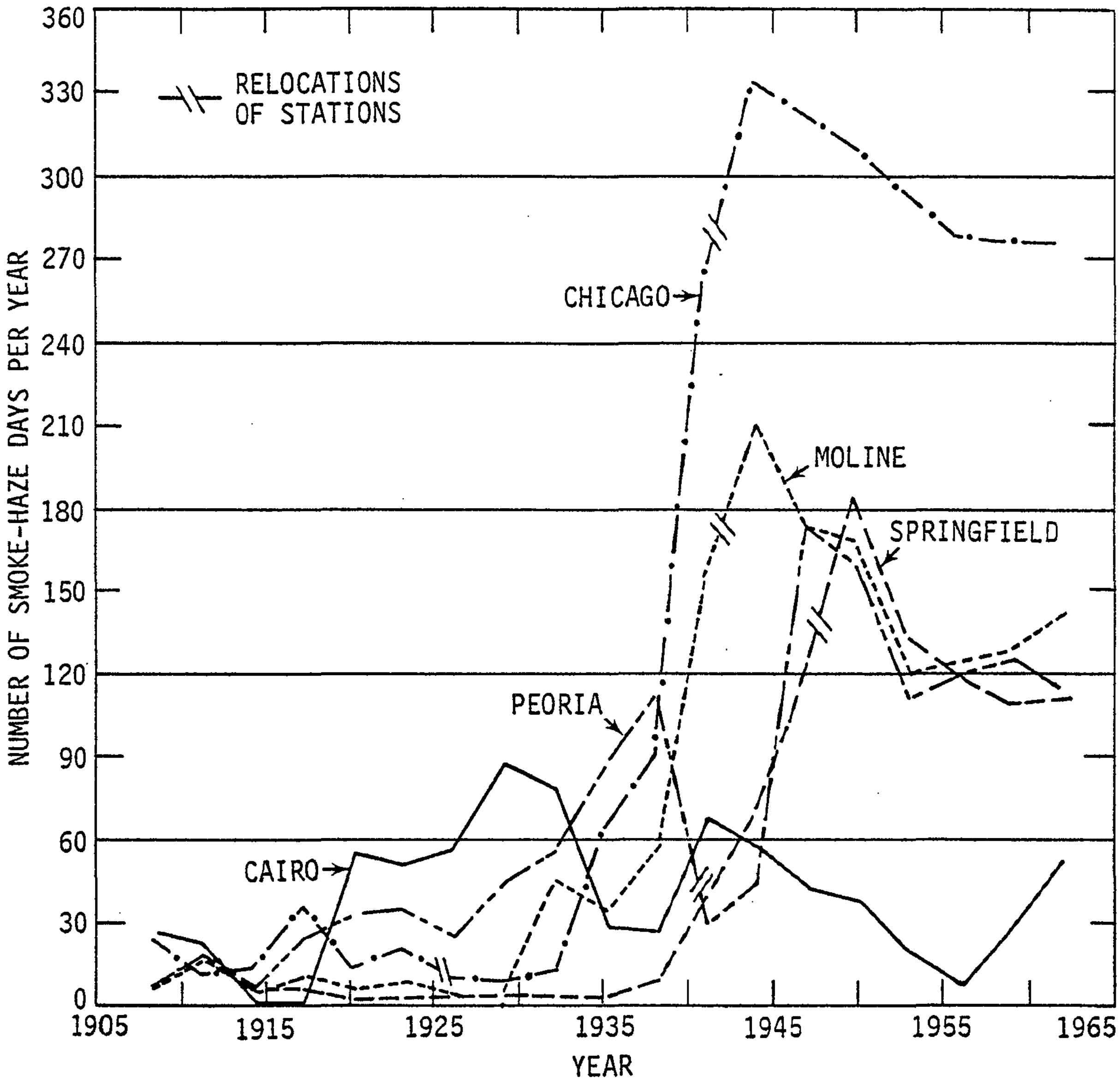


FIGURE 1: Annual number of days with smoke-haze conditions at Illinois cities, as based on 3-year moving averages.

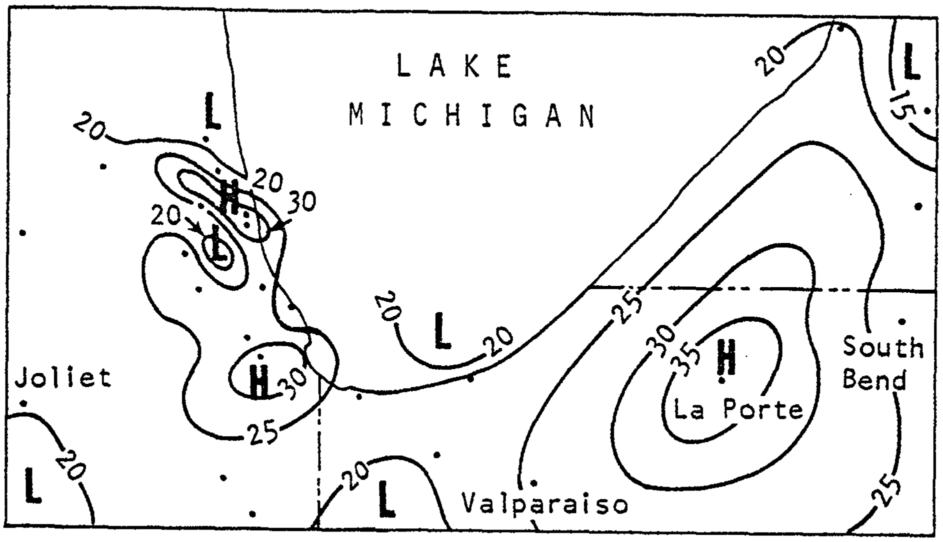


Figure 2: Frequency of heavy (≥ 2 inch) daily rainfalls in the Chicago-LaPorte area, 1949-68 period.

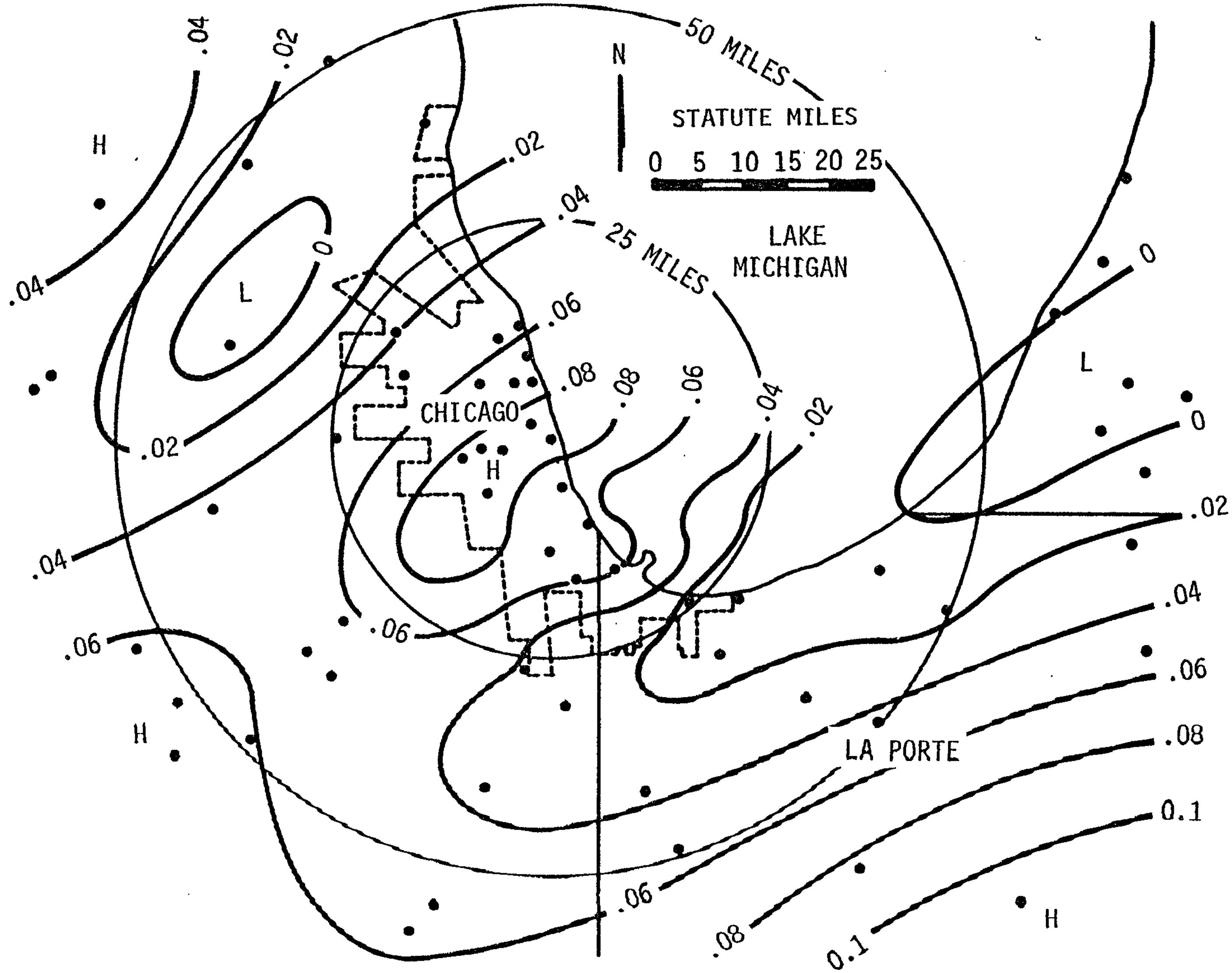
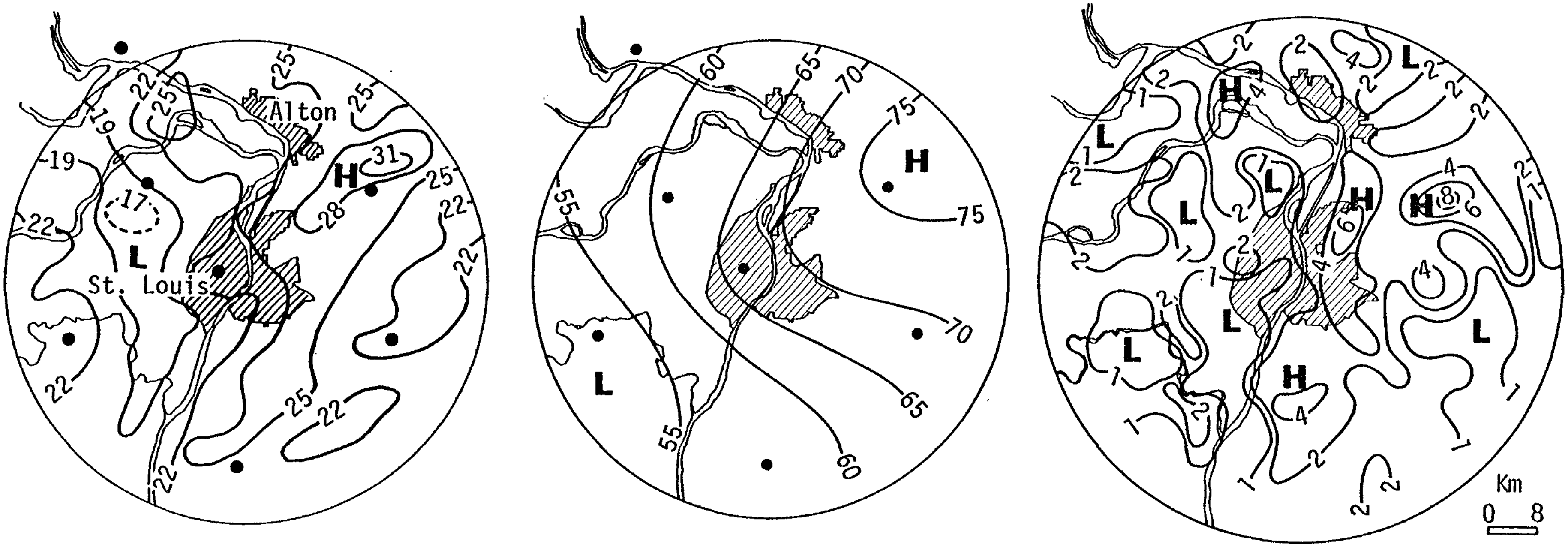


Figure 3: Trend pattern based on 5-year averages of summer rainfall, 1931-68.



Mean Rainfall, cm, 1971-1974

Total Thunderstorm Days

Total Hailfalls

Figure 4: Patterns of summer rainfall (1971-74), thunderstorms (1971-73), and hailfalls (1971-73) in the St. Louis METROMEX research circle.

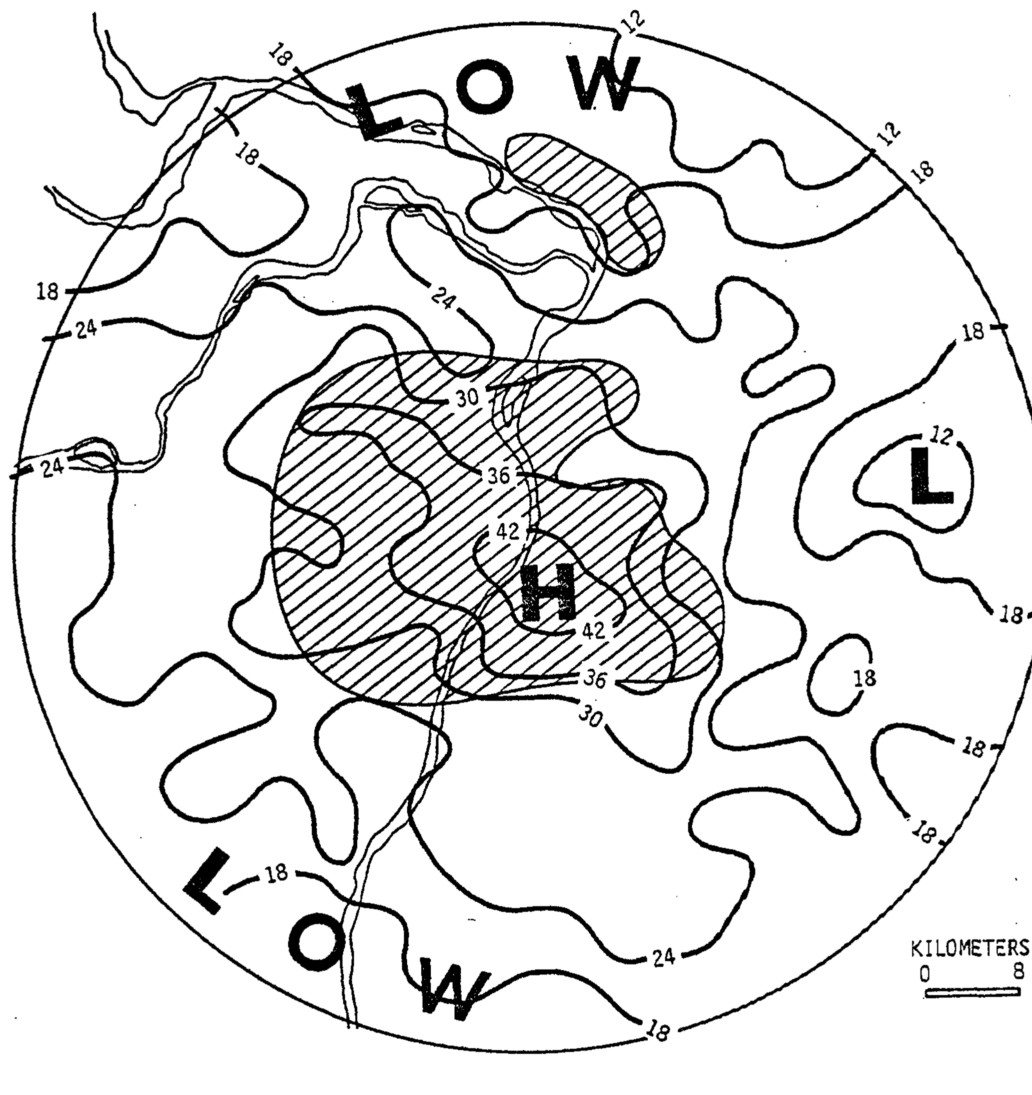


Figure 5: The isopercentile pattern of summer rainfall (1971-74) that occurred during the 1500-1800 CDT period in the St. Louis METROMEX research circle.