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STUDIES OF URBAN AND LAKE EFFECTS ON SUMMER PRECIPITATION IN THE CHICAGO AREA

By

Stanley A. Changnon, Jr., David Brunkow,
Gregory Dzurisin, and Chin-Fei Hsu

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INTRODUCTION

Background

The Water Survey has performed extensive research over the past 25 years relating to 1) effects of Lake Michigan on precipitation processes and on the amount of precipitation over the lake; and 2) the influences of urban areas, and particularly St. Louis and Chicago, on precipitation (Changnon, et al., 1981). A recent 2-year (1976-78) project largely funded by the National Science Foundation (ENV77-15375) focused on a series of studies of Chicago, largely utilizing historical data from a dense raingage network in and around the metropolitan area (Changnon, et al., 1979). The results of that urban study indicated a summer season maximization of summer rainfall over the urban center and surrounding dense residental areas. It further showed, when storm motions were from the northwest, south, southeast, or east that a maximization of rainfall occurred over the urban center and generally over an area extending 40 km beyond the center of Chicago. However, the potential effect of the city on rainfall east and over Lake Michigan could not be investigated with the data available at that time. The METROMEX studies at St. Louis, which is a city with a similar summer climate, indicated a maximization of rainfall to the east of the city, ranging from 5 to 50 km east. Thus, a major unanswered question remaining after the 1976-1978 Chicago area study utilizing raingage network data was, "Does the Chicago urban effect/s on summer convective precipitation conditions extend eastward and appear over Lake Michigan?"

Another major area of urban influence studies at the Water Survey in the Chicago area has concerned the famed "LaPorte Anomaly." Climatological research in the 1960's culminated in a paper (Changnon, 1968a) which suggested that an area in northwestern Indiana, about 50 km east of the Chicago urban area, was the center of an anomalous and sizable increase of convective rainfall, thunderstorms, and hail. This was possible evidence of a possible sizable downwind effect in precipitation caused by a major metropolitan area, and it led to great scientific interest and to some controversy in scientific journals. In the most recent assessment of the precipitation data at LaPorte, Changnon (1980a) concluded that the isolated anomalous high rainfall at LaPorte had gradually disappeared during the 1960-1980 period. It was postulated that its disappearance was due either 1) to a broadening of the anomalous localized rainfall high into a larger area with a lesser peak in the rainfall at LaPorte making it more difficult to detect; or 2) to general shifts in atmospheric circulation that would tend to alter the degree of the urban effects, or to make the anomalous rain area shift and occur somewhere over Lake Michigan (and hence be undetected in the land-based climatological records). Thus, the disappearance of the LaPorte anomaly was another factor which motivated the current study.

The second area of long-term atmospheric interests has included study of lake effects on precipitation, and on defining the amount of precipitation over Lake Michigan (Changnon, 1968b). In a study utilizing raingage data from a water intake crib located 4 miles east of the lakeshore, Changnon (1961) concluded that the lake acted to diminish convection in the warm season, leading to a 20% decrease in summer rainfall 4 miles east of the Chicago lakeshore. Subsequent studies utilizing raingage data from islands in the northern end of

Lake Michigan also substantiated the expected 15 to 25% diminishment of summer precipitation by the lake in that area. The lake is relatively cool in summer and acts to stabilize the atmosphere (Gatz and Changnon, 1978). However, the actual precipitation distribution over Lake Michigan remains a continuing question, and additional data were desired.

Objectives

The above two scientific issues relating to major scientific interests of the atmospheric sciences group of the Illinois State Water Survey, could be addressed, for the first time, by a large volume of high quality digitized radar data. The Water Survey's HOT radar, with a 1.6-degree beam width and 10-cm wavelength, was operated for other northern Illinois research projects (CHAP, an urban rain forecast test, and for NIMROD, a study of thunderstorms and their downbursts) during the summers of 1977-1979. The resulting computerized radar data provided an excellent opportunity to study a large volume of summer precipitation data that encompass the rural areas upwind (west) of the urban and lake areas, over the Chicago urban area, and over the southern lake. These data were the basis for studying:

a) The distribution of precipitation over the lake east of Chicago and along the western shores to determine potential urban effects on the summer rainfall distribution; and

b) the overlake and land distribution of summer precipitation so as to better estimate lake influences and the average over-lake rainfall pattern; and

c) the processes by which the urban area and lake might be affecting summer precipitation.

The objectives of ascertaining whether and possibly how the urban influences acted to increase or decrease summer precipitation were addressed by analyzing the radar data along two avenues. First, we studied the precipitation patterns totaled by individual years, by the 3-year sample, by synoptic classes, by rainfall rate frequencies, and by storm motions. Second, we studied the characteristics of individual echo cells. Both of these studies were based on analyses of spatial differences between different land use areas (city center, suburbs, industrial areas, and rural) and different over-lake areas.

The third objective, discerning the general lake effects on summer precipitation, and particularly whether there was a systematic change eastward from the western lakeshore, was studied in a similar fash ion. The patterns of precipitation and of echo cells over the lake east of the non-urbanized area north of Chicago were compared with lakeshore and rural area precipitation and cells. Rainfall in zones (based on distance from the shoreline) were calculated and various rainfall expressions were compared with those of the shoreline. Characteristics of over-lake cells also were defined and compared to rural cells to help discern differences in atmospheric influences.

An important goal of both the urban and lake analyses of this study was to compare the Chicago findings with the exhaustive findings on urban atmospheric influences at St. Louis (Changnon, et al., 1981). Three issues are at stake in this comparison. One, are the local and downcity changes in summer rain at other cities of the same, lesser, or greater magnitude as those at St. Louis? Second, can this quantified change in rainfall be related to city size or to other factors? Third, are the causes for the rain changes now well established at St. Louis likely the same causes existing at other cities? Important to these issues is the belief that study of other data sets less complex than those developed at St. Louis can, through careful study (say of the time-space changes in echoes and rainfall employed this study), allow some insight as to causation for changes. By this process, these studies of Chicago and other cities could be sufficient to allow interpretation of the limited findings of Chicago by comparison with the more elaborate ones at St. Louis.

This issue of transferability of the St. Louis findings to other cities is a key one in the field of inadvertent weather modification (Robinson, 1977). The proposed objectives of this study do not presume to be a singular test of an explicit hypotheses as to how lake influences, or urban surfaces and emissions, act at Chicago to influence convective precipitation processes. However, the results which have been obtained, when 1) combined with the earlier Chicago and lake results (Changnon, 1980b), and when 2) compared and integrated (where appropriate) with the St. Louis findings (Changnon, et al., 1981) should shed light on the relative importance of the various urban influences on the atmosphere. In general, the information gained from this current study have helped sharpen the hypotheses about the causes of precipitation anomalies at cities.

The first major chapter addresses the data used and the analytical techniques employed. The next chapter addresses the rainfall totaled for various classifications and years, and the ensuing chapter presents results of the study of individual rain cells. The final chapter presents the major conclusions.

DATA AND ANALYSIS

Introduction

This project consisted of three major analytical tasks involving one large data set. The initial one concerned the radar data itself including the condensing, editing, and removing of ground clutter and glitches. This included red ucing the volume of data from 120 tapes collected in the field, to 5 rainfall grid tapes to serve as a convenient data base. This was a time consuming 6-month task for the 3-summer data sample, 1977-1979, but it yielded 87 discrete rain periods of usable corrected data.

The second task related to a "total analysis" of all of the rainfall totals and rain rate distributions in the 87 rain periods. This was based on every 3 (or 5) minute presentation of the total rainfall (and rate), generated for 4 mi^9 areas distributed evenly throughout northeastern Illinois and over Lake Michigan. These data were also sorted for various land use regions and over-lake zones. The data were classified according to synoptic weather conditions and rain motions. For these classifications, and the selected land use areas, rain totals and rain rate frequencies were accumulated to examine urban vs rural differences, lake vs urban differences, lake vs rural differences, etc.

The third major analytical effort related to the analysis of individual cells and their characteristics. A variety of statistics were generated for each cell (velocity, average rainfall intensity, area, total rain flux, duration, and location), and the cell statistics were sorted by synoptic types, and land use areas for studies to discern better the influences of the urban area and lake on the atmosphere.

Such analyses required a variety of data handling procedures and programs for the radar data, plus a series of definitions and selections of land use areas, rain events, cells, etc. The following text addresses these decisions and definitions, data manipulation techniques, and related analyses employed. The flow diagram for this data evaluation and adjustment including the two basic avenues of analysis is shown in figure 1.

Data

The data used in this study were collected by the HOT (Hydrometeorological Operational Tool) radar system operated near Joliet, Illinois, during the summers of 1977, 1978, and 1979. This radar has a 1.6° conical beam width with a 21-foot diameter antenna, and a sensitivity such that a 30 DBZ echo was detectable at 220 km range. The radar was operated in the summers of 1977, 1978, and 1979. This system was used to archive reflectivity measurements of storms which approached or tracked through the northeastern Illinois research area. The radar made 360-degree scans of the region within a 220 km radius of Joliet. Volume scan sequences were commenced at least once every 5 minutes (usually 3 minutes), and included elevation angles of 0.75, 2.1, 3.5, and 5.4 < degrees. High resolution data (224m x 1 degree) were digitally recorded in the spherical coordinate system of the radar. The radar output went to a TI980 computer system such that the data at all elevations were recorded on magnetic tape.

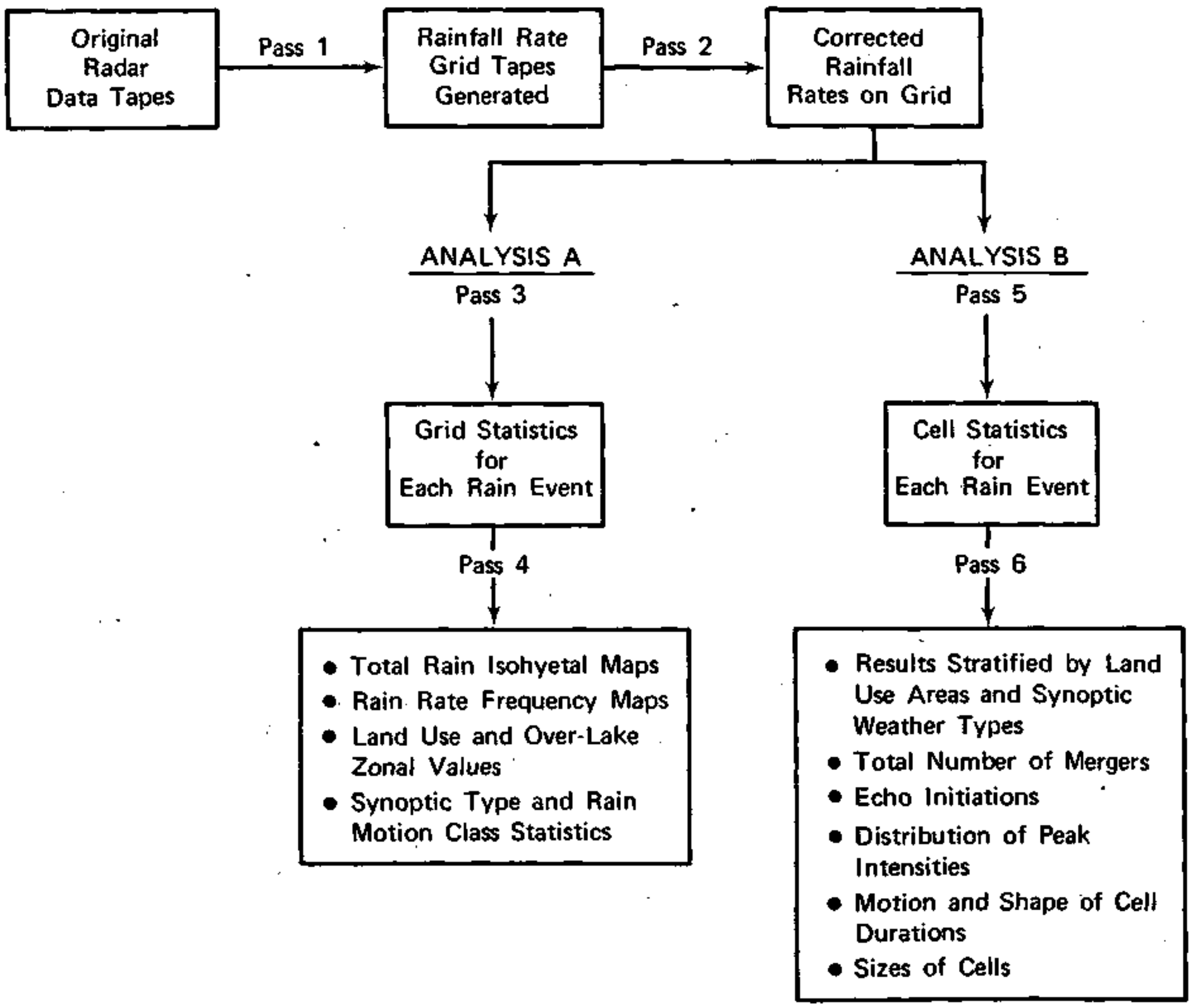

Figure 1. Data assessment and analytical approach used in study.

The first two passes (analysis) of the radar data (shown in figure 1) were designed to get the 1977-79 radar data into a corrected and useful format for the ensuing studies of near surface rainfall.

Pass 1. This pass was to translate the radar data originally collected by azimuth and range, into a cartesian or x-y grid.

The radar measurements were converted to rainfall rate estimates before the cartesian conversion, using the equation: $Z = 300\ R^{1.35}$ where Z is reflectivity in mm^6/m^3, and R is rainfall rate in mm/hr. The possibility of adjusting the radar-rainfall estimates with a spatially varying correction field derived from raingage measurements (Hildebrand, et al., 1979) was rejected due to the lack of raingages over the lake. This absence would cause data over the lake to be treated selectively differently from land data close to raingage locations, thus negating the validity of urban-lake comparisons. The standard range squared term was incorporated in the reflectivity calculation:

$$Z = \frac{C P_r R^2}{P_t} .$$

No further range normalization or stratification was used in this project. This was possible because the rain rates of interest were detectable at all ranges from the radar. Also, since the study was based on measurements made at 0.6 to 2.4 km AGL or less and at ranges less than 100 km, no significant range effects were expected, nor had any been observed in comparisons with raingage data (Hildebrand, et al., 1979).

The cartesian grid, which was the base for all of the analysis, was a 64 by 64 square with 3.2 km grid spacing. The limit of 4096 grid points was determined by the computer memory available. The 3.2-km spacing was required to cover a large enough area to permit a reasonable life history of many echoes to be established before they tracked beyond the urban and lake areas. Since the spatial resolution of the radar was generally much greater than that of the grid, simple averaging of the radar measurements about each grid point was used to determine grid values rather than a more complicated interpolation scheme. The study area was a square of 205 x 205 km, or 42, 010 km^2 (16,900 mi^2). The area included all of northeastern Illinois, portions of northwestern Indiana, and most of the southern end of Lake Michigan (see Fig. 2).

The main problems encountered in generating the grid in Pass 1 were ground targets close to the radar, and blockage of the 0.75° scan in parts of the northwest quadrant. These two problems were largely overcome by using a composite of the first four elevation scans, and use of two temporary 64 by 64 arrays. In one of the arrays, rainfall rates were calculated from the 0.75° scan only. For this array of data, ranges of 58 to 220 km were used and the remainder set to zero. The other array was a composite of the 2.1° scan values from 23.3 to 220 km, the 3.6° scan from 16.1 to 28.7 km, and the 5.5° degree scan from 9.4 to 20.6 km. The two arrays were combined by comparing each grid point of the first array with the corresponding grid point of the first array with the corresponding grid point in the second array, and retaining the larger of the two for the final composite grid. In this manner, grid points which were blocked on the 0.75° scan were effectively replaced by data from the 2.1° scan. At grid points close to the radar, data were taken from high elevation scans which had less contamination from ground clutter. The heights of the data points used ranged from 0.6 to 2.4 km AGL so the resulting grids were considered to be crude CAPPI (constant altitude planes).

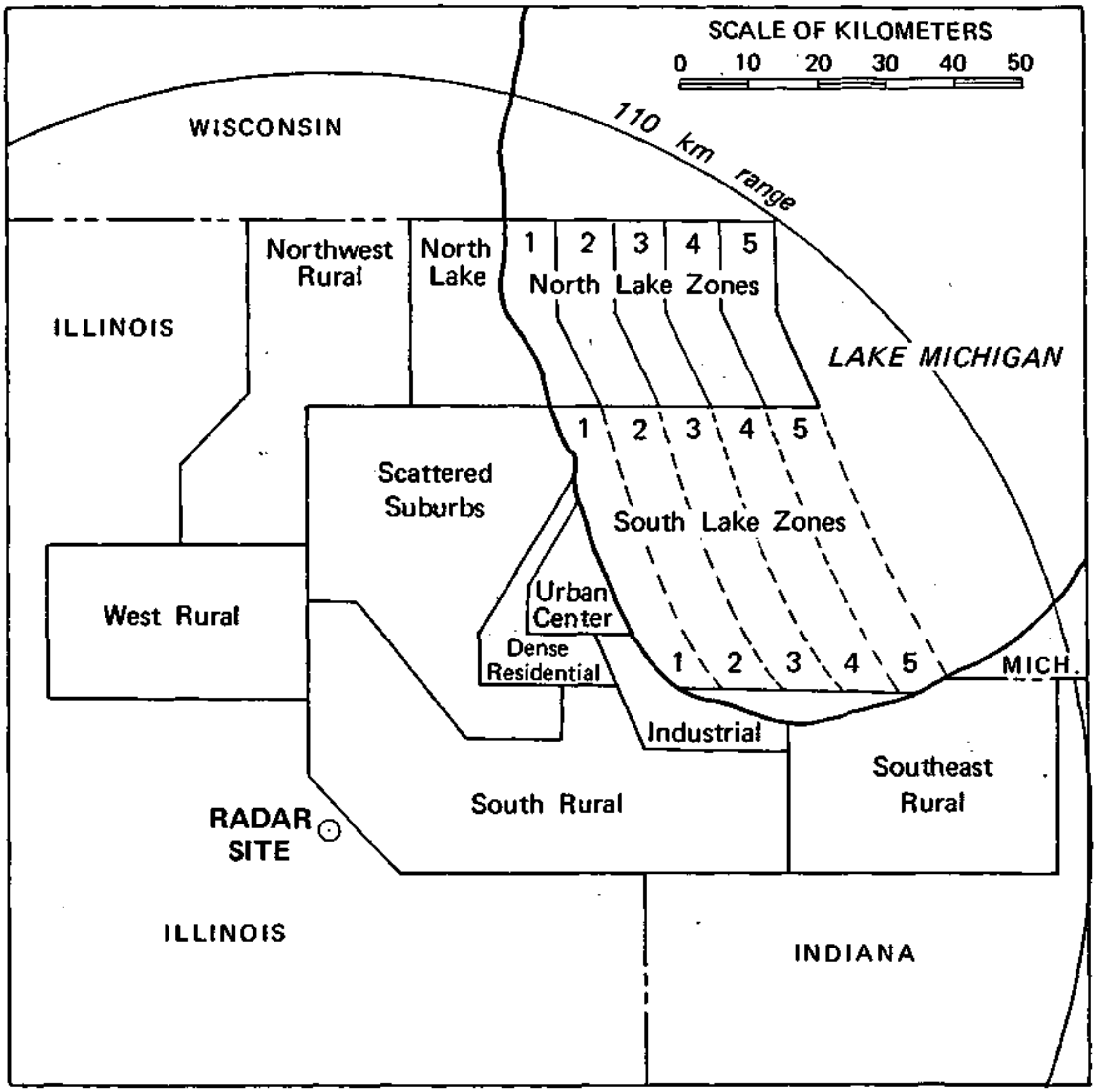

Figure 2. Land use areas and overlake zones defined for assessment of urban and lake influences on precipitation, and radar site. Study area is defined by the outer boundaries of this map.

At the end of Pass 1, the near surface rainfall rate grid existed for every 3 to 5 minutes. In this manner, the range and azimuth data stored during field data collection were transformed into a x-y cartesian format.

Pass 2. This pass consisted of a careful inspection by an analyst of the individual 3 to 5 minute "maps" of the rainfall rates. Using the interactive graphics presentation, two time adjacent patterns could be exmained simultaneously. The purpose of this final examination, in concert with the CAPPI presentations, was to discard scans or to eliminate areas of anomalous propagation or ground targets. Anomalous echoes related to atmospheric trapping, a particular problem related to lake-land relationships, had to be carefully detailed and eliminated. Raingage records of the individual rain periods were also utilized to help identify questionable anomalous propagation. As has been noted earlier, a dense raingage network was in operation during the summers of 1976-1979 (Changnon, et al., 1979). Areas chosen as anomalous propagation or as ground clutter were cleared from the record using an electronic pointer; either single points or rectangular areas could be cleared. After single points were cleared, they could optionally be recalculated based on the average of the four surrounding points.

The following analyses of the rainfall and rainfall rates were restricted to values over areas within 110 km (about 70 miles) of the radar. These areas of concentrated study are shown in figure 2.

Meteorological Classes. The corrected data resulting after Passes 1 and 2 were completed (Fig. 1), were divided into two meteorological units for study, "rain cells" and "rain periods." The definitions of these units are important.

A "cell" was defined from the sequences of 3- to 5-minute rain rate maps (as derived from Pass 2). It was defined by criteria asigned to identify echo formation and dissipation, and to treat echo splits or mergers during a cell's lifetime, somewhat in the manner used by Crane (1976).

Identification and tracking of a cell was a successive measurement (and tabulation) of various parameters of a cell during its life cycle. The parameters of the cells that were tabulated were: location from the radar, size, rate, volume, speed, direction and its present state of existence such as new growth, old echo, and echo split (or echo merger).

All echoes producing rates ≥ 4 mm/hr were displayed for each 3 minute (or 5 minute) map. This permitted the automatic removal of non-significant echoes. A cell was then identified as a completely enclosed entity of the ≥ 4 mm/hr isoline with an areal coverage of at least 2 adjacent grid points (~ 4 mi^2). The computer program permitted encircling of each potential cell at a given time, and the program then rejected any echo < 2 grid points in areal coverage. A second ensuing rain map (3 or 5 minutes later) was displayed adjacent to the first map. Again the potential echoes were encircled (and non-cells rejected).

With the two time consecutive maps on the screen, a match of the cells was made. The statistics of each cell were then recorded on computer tape. Then the next consecutive 3 or 5 minute map was displayed until the entire rain period ended. All cells were tracked in that matching fashion including those on the edge of the radar coverage. However, cells with durations of less than 9 minutes (apparent on 2 or more sequences) were not used in the analyses.

A cell that sometimes was in close proximity to another cell, each with their separate ≥ 4 mm/hr isoline, would merge and become one. This was known as a "cell merger." The opposite also occurred. A single cell would split and form two separate $\geq$ 4 mm/hr isolines. This was known as a "cell split." Cell splits and mergers were tabulated by the cell tracking program. The cell tracking effort required 9 months to complete. The number of cells defined appear in Table 1.

The other meteorological entity defined was the "rain period." A rain period was defined on a time and space scale, and basically is a discrete period of rain caused by a single synoptic scale (or mesoscale) weather disturbance. A rain period in the study area could consist of a single summer shower over a very small area, or broad rainfall over the entire 40,000 km^2 study area. Furthermore, there could be 2 or more rain periods occurring in the study area at a given time but as long as they were spatially separate at any given point by 1 hour of no rain and if each had a different rain-causing condition, they were separated.

The synoptic weather typing used followed earlier definitions (Changnon, et al., 1977) used for summer conditions. The three frontal types (cold, warm, and static), lows, and squall lines are easily envisioned and typed. Air mass storms are widely scattered and have no large scale synoptic causes. Squall zones were defined as less organized mesoscale convective events than squall lines, and were typically clusters or areas of echoes that developed, moved and dissipated in a some coherent fashion with some upper-air impulse evident.

The rain periods were also classed according to the principal motion of the rain system, not the individual cells. The motion was determined from study of maps of rain. The motions were classified according to 45-degree sectors including southwest, west, and northwest. These three motions incorporated the total radar sample of 87 rain events.

Table 1. Data Base Involved in the Study.

	Number of rain periods				Hours of
	1977	1978	1979	Total	Data
Total rain periods[1]	80	64	40	184	
Total rain period in radar sample	1	12	23	36	259.2
Partial period in radar sample	34	9	8	51	222.3
Total periods studied	35	21	31	87	481.5
Synoptic Types with Rain Periods					
Cold front	7	3	5	15	65.5
Squall line	9	4	3	16	97.5
Squall zone	6	8	13	27	184.5
Air mass	4	3	3	10	34.0
Stationary front	6	2	7	15	84.5
Warm front	2	1	0	3	13.0
Low	1	0	0	1	2.5
Motion of Rain Events					
Southwest	5	6	15	26	
West	22	11	2	35	
Northwest	8	4	14	26	
Squall Areas					
Heavy rains	2	7	9	18	
Light rains	20	7	16	43	
Total	22	14	25	61	
Number of Rain Cells					
Total	322	601	728	1,651	
Cold front	74	67	89	230	
Squall line	44	45	114	203	
Squall zone ,	110	286	337	733	
Air mass	11	35	29	75	
Stationary front	76	103	109	288	
Warm front and other class	7	65	50	122	

[1]Based on data from large raingage network.

Another type of data unit was studied. It used the same rain periods and the basic synoptic classifcations, but with three different categories: squall line, squall area, and isolated (air mass type) cells. In this analyses, isolated cells retained the air mass definition. These three data divisions were used because each one had separate identifiable and very different convective characteristics, each unique unto themselves. The isolated echo conditions typically had light intensity cells and widely scattered cells. The lines were a group of echoes with definite linear characteristics. Some were intense, well organized and covered a wide area. Finally, the squall area class comprised typically semi-organized groups of cells which were often intense cells. There were 10 isolated cell periods, 12 line periods, and 61 squall area periods.

Line storms were defined as nearly solid lines and only the echoes encompassing the line were recorded. All residual echoes beyond the line were excluded. Study of the squall lines indicated two distinct subtypes. One was the "typical" line with intense echoes, existing several hours and traveling great distances (> 75 miles in length) and usually oriented NE-SW. There were 12 of these. The second type of line occurred more often and was less intense than the other type, being 20 to < 100 miles in length, with shorter lifetimes and shorter distances of travel. These assumed various orientations and several of these small lines sometimes existed simultaneously.

The third group were called "squall areas." They included some squall lines and most of the squall zones, static fronts, warm fronts, and cold fronts. The 61 squall areas were subdivided for later study into two classes: heavy and light intensity rainfall producers. Rain periods were defined by a function of rainfall amount and areal extent, and on a sliding scale, shown below, to qualify for the heavy class.

Number of Grids	Percent of Area	Total Rainfall at Grid Points (mm)
4096	100.0	≥ 3
2048	50.0	≥6
1024	25.0	≥12
512	12.5	≥24
256	6.25	≥48
128	3.12	≥96

Light rain periods were those which did not qualify as heavy. There were 18 heavy and 43 light squall areas (Table 1).

Table 1 presents other statistics on the basic data base involved in the study. Shown are various statistics relating to the number of rain periods in each year and for the total 3-year sample; the number of rain periods with various synoptic types; and the number of rain periods with various motion classes. The numbers of rain cells for each synoptic weather type and year are also shown.

Climatic Representativeness. The normality of the data sample in such a "climatological type" of study is important. The total number of rain events in the area, based on the large dense raingage network is shown in Table 1. There were 184 summer rain periods in the area in the 3 years sampled (based on raingage network data). The total sampled by the radar was 87, much less than the total. This resulted for two reasons. Many of the rain events were small events and inconsequential rain producers (cases where the radar was not operated). There also were periods when major power outages or radar problems eliminated opportunities for data collection.

To obtain an estimate of the sampling adequacy of the radar data, the radar statistics for the three summer (1977-1979) for various land use areas (see Fig. 2) were compared with the values obtained from the raingage network. In this case, the raingage network values represent the total summer rainfall. Table 2 presents the radar values and the raingage network values for the 3 summers, and their ratios indicate the percent of the total rainfall sampled. For example, the radar sampled a total of 72.3 cm for the urban city center, as compared to 89.2 cm for this area detected by the raingage network. Their ratio indicates that the radar sampled included 81% of the total rainfall in this area. The total area value shown reveals that the radar sample incorporated 70% of the total summer rainfall throughout the entire area.

Analyses

As noted earlier, the analyses were based on the rainfall rate grids developed for each 3- to 5-minute pass of the radar generated after Passes 1 and 2 (Fig. 1). There were two basic analysis followed, labeled A and B on figure 1.

Analysis A. This began with Pass 3 through the data base. The individual grided maps were accumulated for each rain period. For each rain period, the total rainfall was computed at each of the grid points. The rainfall rates at each grid point, and for each 3- to 5-minute sample, were also recorded. The rates were categorized into four classes (2 to 6 mm/hr, 6 to 12 mm/hr, 12 to 25 mm/hr, and > 25 mm/hr). These were counted and the number occurring in each of these four classes was retained at each grid point and for each rain period. Thus, a rain period lasting a hour at one grid point (with 3-minute sampling, or 20 samples) might have 11 counts at 2 to 6 mm/hr, 4 counts of 6 to 12, 0 counts of 12 to 25, and 5 counts of > 25 mm/hr. The result of Pass 3 (Fig. 1) was to have, for each rain event, the total storm rainfall pattern and the rainfall rate frequencies.

The next pass (Pass 4) in Analysis A (Fig. 1) consisted of calculating values from a variety of groupings of the individual rain events (including their total rainfall and their rainfall rate frequencies, each available for each rain event). These calculations yielded two products. One was a computer-derived isohyetal map for any classification desired (year, motion, or storm type). The other consisted of mean rainfall values for various land use areas and over-lake zones. Maps and area mean values (of total rain and of rain rate frequencies) were developed for the various synoptic weather types, , for the three rain motion classes, and for individual years.

Table 2. Comparison of Radar-Indicated Summer Rainfall (cm) and Gaged Rainfall, by Land Use Areas, for 1977-1979.

Land Use Areas	Radar	Raingage Network	$\frac{\text{Radar}}{\text{Gaged}}$ x 100
Urban (City Center)	72.3	89.2	81%
Dense Residential	60.9	88.9	69
NW Residential	67.1	84.1	80
Scattered Suburbs	62.3	88.8	70
West Rural	60.2	84.8	71
NW Rural	65.2	83.4	78
North Lake	54.3	78.1	70
South Rural	53.8	81.0	67
Southeast Rural	42.3	58.2	73
Area Total	56.8	81.1	70%

Various land use and over-lake zones were choosen for areal analyses to discern influences of land areas and lake surfaces. Prior studies of the rainfall in the Chicago area (Changnon, 1980b) had defined the major land use areas in and around the city. The urban areas were defined largely on density and type of buildings and on amount of impervious surfaces. At St. Louis, it was found that the areas with concentrated industry or with relatively dense multi-story buildings and impervious surfaces were areas that- had the greatest influence on the atmosphere for affecting cloud and precipitation development (Changnon, et al., 1981). The earlier studies of the Chicago regional rainfall using the dense raingage network data were based on the same areas in and around the city shown in figure 2. Principal regions of land use are the urban center, dense residential, two suburban areas, the industrial area, and a series of surrounding rural areas.

The North Lake rural area, located north of the Chicago suburban area (Fig. 2), is one where lake effects on land area rainfall are possible. It is also designated as a useful comparative "control" area for the urban center and dense residential areas.

The Northwest Rural and West Rural areas (Fig. 2) are considered "control" areas for the city and/or lake areas because of the predominance of westward motion of precipitation systems (Table 1). The South Rural and Southeast Rural areas are at times, control areas, depending on storm motion, and at other times areas potentially affected by storms that have crossed the urban and/or lake areas.

The study of over-lake precipitation was based partially on qualitative interpretations of various rainfall patterns. A quantitative regional analysis was also pursued. A series of 10 over-lake zones were defined, as shown in figure 2. The shapes of each zone was basically a mirror image of the outline of the western lakeshore. Vertical lines were drawn 5 miles (8 km) apart and out from the shore. A series of five such lake zones (each 5 miles wide) were defined east of the North Lake rural area and labeled the "North Lake Zones." These zones are east of the rural areas north of Chicago and their values should represent conditions over the lake and largely unaffected by urban influences. A comparable set of "South Lake Zones" to the east of Chicago (Fig. 2) have the potential of reflecting precipitation influences of the city.

Several comparisons were made to estimate urban and lake influences. The North-Lake zonal values, North Lake, and Northwest rural values were compared to obtain estimates of the lake effects, including those on land (North Lake versus Northwest rural), and those over the lake (the 5 zonal values versus the Northwest Rural values) as the "control." Similarly, the South Lake zonal values were compared with the North Lake values to estimate the extent of urban influences extending eastward from the city. In this sense, the North Lake zonal values were considered a control for the South Lake zonal values.

The total rainfall values and rainfall rate frequencies for these various land use and over lake zones were compared for the synoptic types and storm motion classes. Statistical tests were applied using two parallel regions. For example, the northwest rural values could be compared with the west rural control values; the north lake with the urban values and the north lake zones with the south lake zones. These six areas formed two east-west parallel tracks of rainfall, as based on the individual 87 rain events.

<u>Analysis B</u>. This analysis (Fig. 1) focused on the" individual rain cells derived from the radar data. The first pass through the data (Pass 5) was based on the 3- up to 5-minute grids for each rain period. The grided display

of echoes, displayed for time adjacent portrayals, was used to identify cells with time. This effort was based on an echo tracking program developed for the Chicago Hydrometeorological Area Project (Huff, et al., 1978). The echo tracking program is in a statistical format and makes decisions on echo acceptance (area) or rejection. The analyst inspected the sequence of accepted echoes on the 3-minute grided displays, and then made decisions for matching cells over time. At the end of each rain period, the characteristics of the cells were stored within the computer. At the end of "Pass 5" analyses, each definable cell from the 87 rain periods had been calculated. As shown in Table 1, there were 1,651 cells defined in the 3-year sample. The cells in one storm could not be clearly identified and were not included in the analysis.

Pass 6 (Fig. 1) consisted of a series of analyses of the cells. Based upon its position within the grid, each cell was classified as to three general land use occurrences. These were: 1) rural only, 2) lake only, 3) urban only, or 4) various combinations (rural and urban, rural, urban, and lake, and urban and lake, or lake-rural, etc.). The various echo characteristics including their peak intensity, their size, and duration were investigated for the synoptic types. In addition, the number and placement of mergers between cells and echo splits were analyzed. Mergers of cells were found in the St. Louis studies to be greater over and such beyond (east) of the city, and related to greater convective activity and heavier rainfall (Changnon, 1976).

Since the studies of the radar-determined cells was aimed at discerning more about the causation and the atmospheric processes affected by the city and lake, the cells, generally within the synoptic types, werre further analyzed, based on three classes (air mass, squall line, and squall areas) of different convective organization. Within the 61 squall areas, the cells were subdivided according to whether the rain was heavy or light.

Another study of the rain cell data, was related to squall lines. Study of the 16 squall line periods showed two basic classes. One was very well organized and intense, and the second consisted of less organized cells and short lived. Cells in each type were investigated separately.

RAINFALL FINDINGS

Annual Totals

Figure 3 presents the summer total rainfall maps for the 3 summers and for the total of the 3-summer period, 1977-79. Figure 3a is the isohyetal pattern for the summer of 1977. This shows as an area of relatively high rainfall (> 7 cm) extending from just north of the radar site eastward across the city into southern Lake Michigan. There are isolated highs over the city and at locations 10 to 30 km east of the city. Lows in the 1977 rainfall pattern are shown to the south, northwest, and over the portions of the lake.

The summer 1978 rainfall pattern (Fig. 3b) shows a east-west oriented maximum from northwest of Chicago eastward through the city and 40 km east of the city over the Lake. Other maximums lie to the northwest and to the southeast of the radar center. These were due to a single major rainstorm on 25 June 1978 (see Fig. 16). Low rainfall areas exist in the extreme northwest and two areas over Lake Michigan, one parallel to the shore and the other encompassing much of the northeastern lake area.

The summer 1979 rainfall pattern (Fig. 3c) reveals the heaviest rainfall areas occurred in a series of zones extending from the west and northwest suburbs across the city and eastward over the southern end of Lake Michigan. Low rainfall essentially existed through the upper part of the lake (and within the study area).

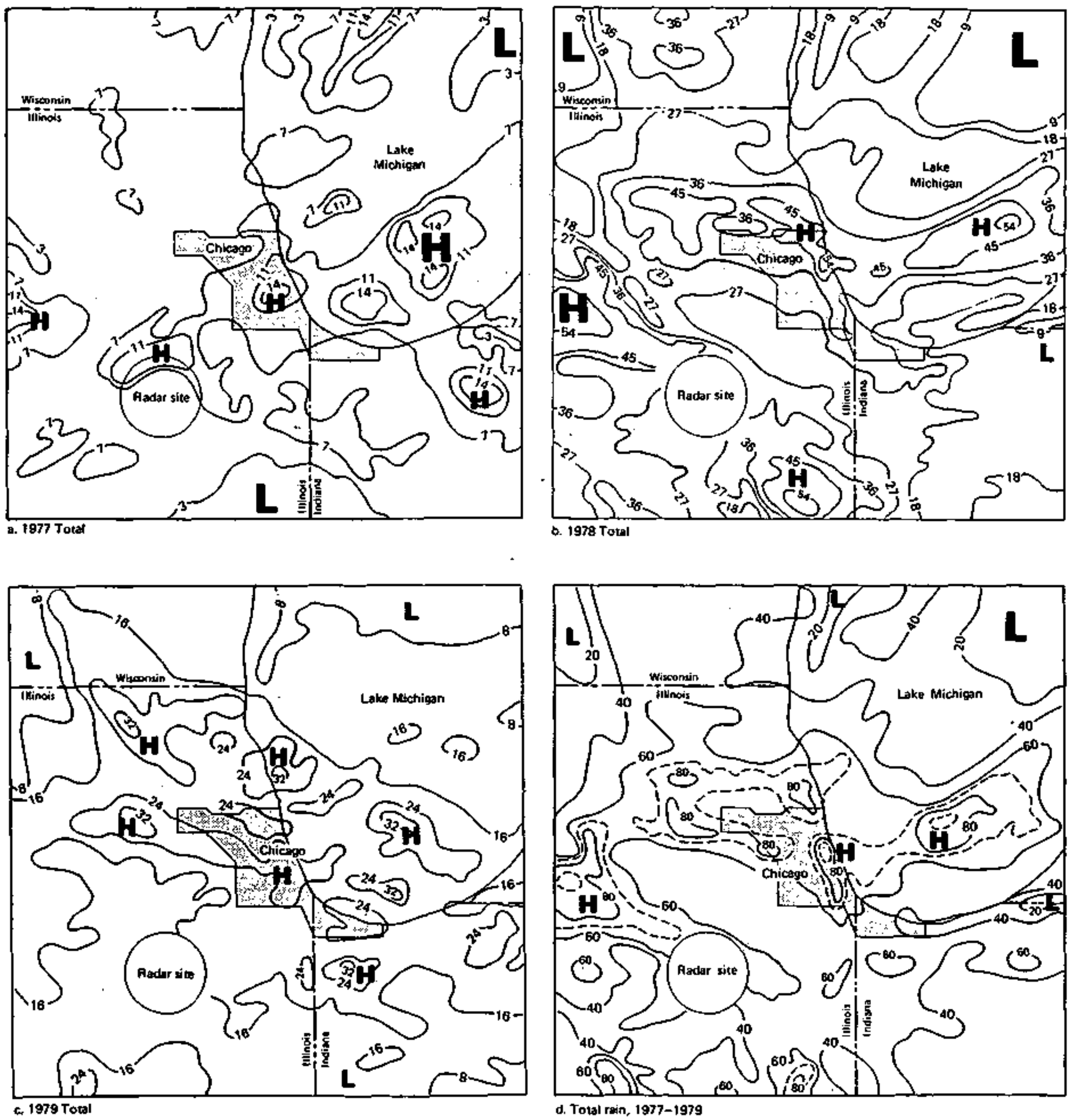

Figure 3. Total rainfall, in centimeters, for 1977 summer, 1978 summer,' 1979 summer, and the 3-summer total.

The 3-summer total precipitation pattern appears in figure 3d. Isohyetals are drawn for each 20-cm interval, except for the 70-cm interval used to help define the heavier rainfall zone. Inspection of the pattern reveals a major rainfall high that begins in the northwest rural area and spreads eastward across the city and into the southern end of Lake Michigan. Within this zone of > 60 cm, one finds four general areas of heaviest precipitation. One lies in the West Rural area; another occurs (> 80 cm) in the suburban area northwest of the city; a third are the highs along the lakeshore over the urban center and dense suburbs; and a fourth is in the south lake area from 15 to 40 kilometers east of the city.

Since this east-west maximum contains highs in the rural control area as well as over the city and over the lake, it is difficult to make definitive conclusions about urban or lake effects. Other important features shown in the 3-year rainfall pattern (Fig. 3d) are the two lows over the north lake area, one parallel to the lake and just a few miles off the lakeshore, and another located 20 miles and beyond-east of the shoreline. Other low rainfall areas appear in the extreme northwest and southeast.

The important aspect of these features shown on 3-year pattern relates to the persistent features on each of the 1-year maps. Those major features found on each of 3 summer maps, and which appear to be more locally representative (and possibly locally induced), are as follows:

1) a maximum over the city center and north suburbs;

2) a maximum over the lake directly east of the city beginning at 15 km and extending out 50 km (30 miles) with maximum value comparable to the urban maximum value;

3) a narrow, north-south oriented low rainfall area lying 5 to 15 km (3 to 10 miles) off shore north of the city; and

4) a low over the lake to the northeast beginning about 30 km east of the lakeshore and continuing eastward.

All other major features shown in the 3-summer isoheytal map (Fig. 3d) are a result of an excessive high or low rainfall value in just one or two summers. For example, the high northwest of the radar is largely due to heavy rainfall in June 1978. The heavy rainfall over the northwest rural and far suburban areas (west of the city) are result of moderately heavy rainfall in those areas in 1978 and again in 1979 (but with none there in 1977).

The total rainfall over the various land use areas (Fig. 2) and the five over-lake zones (north plus south combined) are shown in Tables 3 and 4. These reveal several interesting features including the fact that the city center with 723 mm has the peak value. Secondly, the total rainfall in the five lake zones diminishes steadily eastward across the lake, 597 mm in zone 1 to 486 mm in zone 5. The over-lake average, based on all 5 zones, of 531 mm is lower than all land areas except for the Southeast Rural (Table 3) which has a value of 423 mm. Of course, the Southeast Rural area could be influenced by lake effects tending to diminish the rainfall (Changnon, 1971).

Rain with Synoptic Weather Types

The 3-summer total rainfall for the primary synoptic weather types are shown in Tables 3 and 4 for the various land use areas and over-lake zones. As with the rainfall analysis (Changnon, 1980b), the squall line values show a marked maximization over the city and suburbs, with much smaller values in the rural areas. In addition, as shown in Table 4, the squall line values over the lake are much smaller than the urban values. The other synoptic types provide differing results. There is no clear indication in the cold front, warm and

Table 3. Area Mean Rainfall Values (mm), 1977-79.

Storm Class	City Center	Dense Residential	Indus-trial	Northwest Residential	Scattered Suburbs	North Lake	Northwest Rural	West Rural	South Rural	Southeast Rural
Total Rain	723	609	524	669	623	543	652	600	538	423
Squall Lines	301	240	166	238	201	98	166	128	129	92
Warm & Station-ary Fronts	101	91	94	111	97	105	115	69	84	82
Squall Zones	221	186	213	203	209	280	257	292	230	176
Air Mass	7	12	4	9	4	4	3	3	3	3
Cold Fronts	93	80	47	108	112	56	111	108	92	67

stationary front, or squall zone values of a singular urban maximum. The air mass results suggest an urban-related maximization with higher urban values, as shown in Table 3.

The over-lake values (Table 4) reveal a variety of interesting findings. A general eastward rainfall diminishment is found in the warm fronts, stationary fronts, squall zones, and air masses. However, with the cold front situations, there is an eastward diminishment out through zone 3 (15 miles), and then a slight increase east of that.

To further examine for possible urban influences on precipitation, the squall line data were studied. Urban influences are suggested in the squall line tabular values of Table 3, and in the St. Louis research, squall line rains were found susceptible to urban influences (Vogel and Huff, 1978). The isohyetal maps for the squall line rainfall in each summer are presented in figure 4. Figure 4a shows the 1977 squall line rainfall. It indicates a distinct maximum over the city with a band extending eastward 25 miles (40 km) over the lake. Other rain highs are scattered throughout the area including one over the northern portion of the lake. The 1978 map (Fig. 4b) shows an east-west zone of heavier precipitation (> 8 cm) extending across the city and out over the lake. Generalized lows in the rainfall pattern are shown over the lake north of this peak into the south-east. The 1979 squall line rainfall (Fig. 4c) shows an east-west oriented maximum beginning west of the city with a peak over the city and assemblage of high areas extending across the southern lake area.

The 3-summer map of squall line rainfall appears in figure 4d. It reflects the features shown in each of the 3 summers, with a maximum beginning over the northwest suburbs, becoming greatest over the city center, and a maximum extending eastward over the lake out to 30 miles (50 km). The pattern

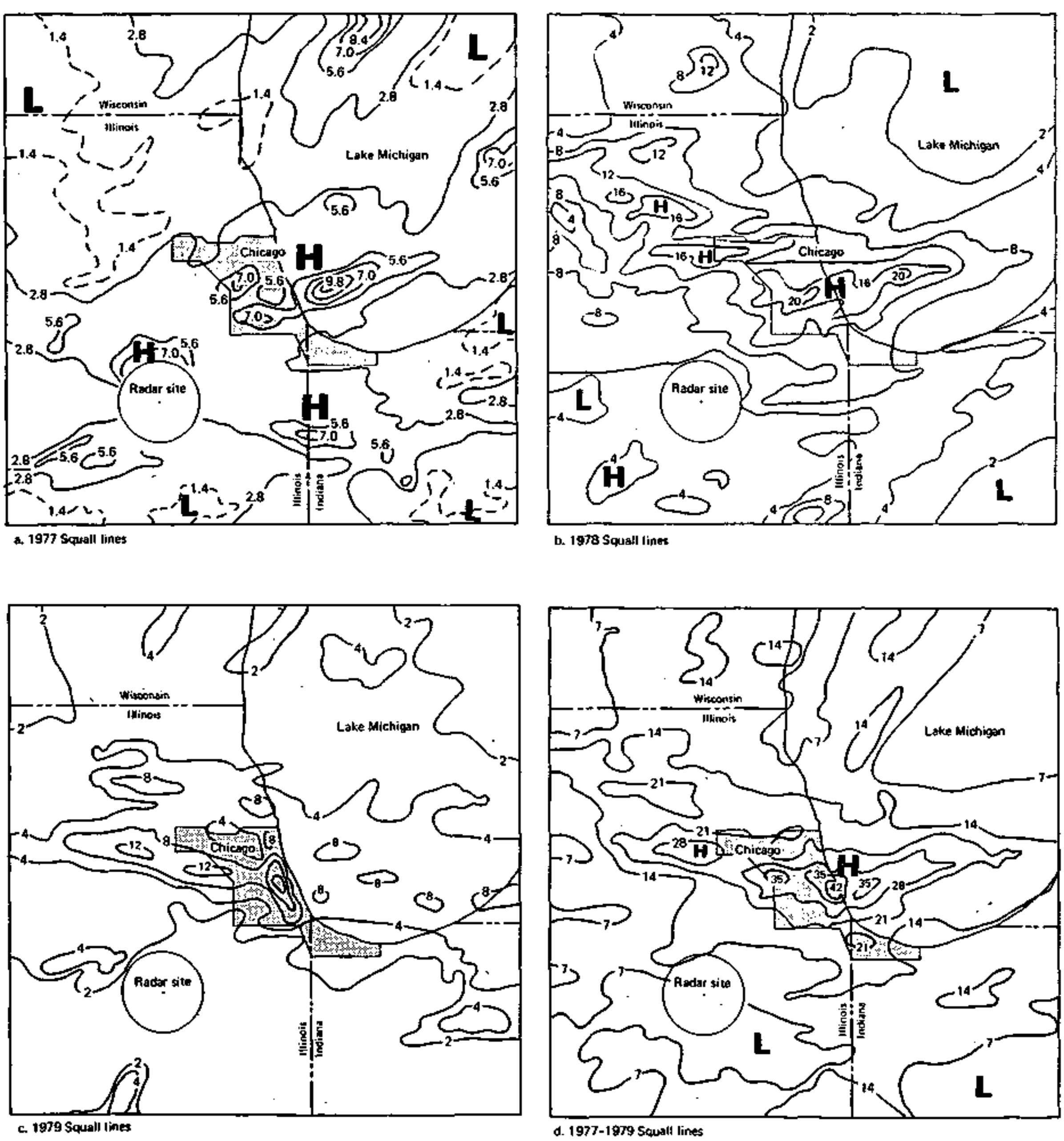

Figure 4. Total squall line rainfall for the summers 1977, 1978, 1979 along with total summer squall line rainfall for 1977-79, in centimeters.

also shows the tendency to have a low approximately parallel to the lakeshore and just east of the shore; a moderate rain high east of that, and then a major low farther eastward over the lake. In this sense, the squall line results reflect the major features found in the 3-summer total rainfall. The squall line rainfall comprises between 20 and 40% of the summer precipitation in much of the study area (Tables 3 and 4). If one substracts the squall line values from the total rain values, the general regional rainfall pattern over the land shows highest values in the rural west with steadily decreasing values eastward to the southeast rural, and with little semblance of urban high.

The squall zone rainfall pattern for 1977-1979 is presented in figure 5d. This shows a very localized and minor maximization over the city center and industrial area with generally low rainfall in the western part of the metropolitan area. A high rainfall area extends from northwest of the radar site through the radar center on to the southeast. This was produced by heavy squall zone rainfall in that area on 25 June 1978 (Fig. 16), also reflected in total summer rain pattern (Fig. 3b). Another interesting feature in the squall

Table 4. Area Mean Over-Lake Rainfall Values (mm) for 5-Mile Wide (8 km) Zones, 1977-79.

	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Average of all Zones
Total Rain	597	553	511	506	486	531
Squall Lines	165	155	142	132	115	142
Warm and Stationary Fronts	110	108	96	91	87	98
Squall Zones	241	228	208	200	187	213
Air Mass	2	2	1	1	1	1.4
Cold Fronts	78	55	56	69	77	67

zone isohyetal pattern is a high located 15 to 40 miles east of the city and containing localized highs > 35 cm. Another feature found in the squall zone precipitation pattern, and one common to that of the squall lines, are the two lows over the lake, one parallel and adjacent to the lakeshore to the north and a generally large low area beginning 20 miles east of the lake shore and extending eastward. The high over the North Lake area and extending just offshore (north of Chicago) is due to locally heavy squall zone rainfall in one year, 1979.

In summary, the more permanent fixtures shown on the squall zone rain patterns of the 3 summers are similar to those of the squall lines: 1) localized highs over the city and the industrial area; 2) a high east of the city over extreme southern Lake Michigan; and 3) two low rainfall areas over the lake, to the north and northeast of Chicago.

Rain Motion Results

The principal reason for examining rain motion was to investigate whether the urban-related maximums in rainfall were aligned with the basic motion of storms. In general, the localized effects to increase or decrease rainfall should align themselves with the motion of rain events, as in St. Louis (Changnon, et al., 1981). Figure 5 presents the 3-summer total rainfall pattern based on classifying the rain periods into southwest motion, west motion, and northwest motion categories.

The southwest motion (Fig. 5a) shows a maximum over the city and industrial area with an area of increased rainfall extending towards the east-northeast (in the expected direction) with a maximum of 30 cm over the southern

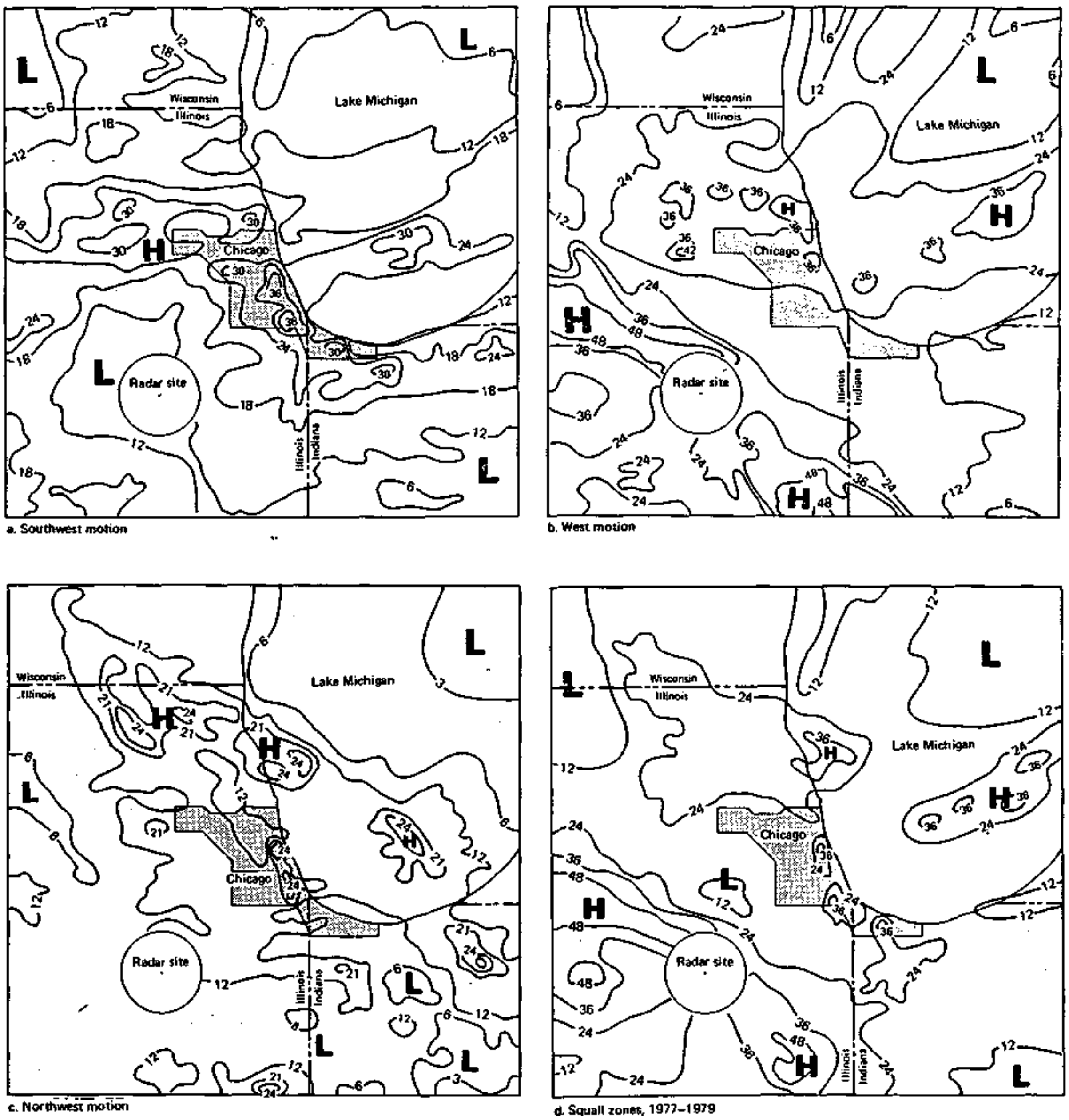

Figure 5. Total summer rainfall associated with rains moving from southwest, west, and northwest, and with squalls zones, in 1977-1979, in centimeters.

lake area. The pattern is indiscriminate elsewhere. The maximums northwest of the city are due to locally heavy rainfall in 1979. Rainfall decreases rapidly northward from the apparent urban-related maximum to 6 cm over the lake.

The west motion isohyetal pattern (Fig. 5b) incorporates a major maximum resulting from heavy rains northwest and southeast of the radar on 25 June 1978. However, more persistent year-to-year features of these rain events were the highs found over the city and northwest of the city, along with those over the lake (≥ 36 cm) extending out 40 miles due east of the city, as hypothesized. Also found in the west motion rain patterns of each summer are the two over-lake lows with values less than 12 cm.

The 3-summer isohyetal pattern based on storms moving from the northwest is shown in figure 5c. A series of maximums are aligned northwest-southwest, beginning in the rural areas northwest of Chicago and extending out over the southern lake area. Also shown are very small localized highs over the city. Another interesting feature is a high over northwestern Indiana, and one potentially related to the urban and/or lake effects. Considering the storm motion and the major land use features, the major highs of the northwest storms would not appear to be related to urban effects, other than possibly the one to the southeast of the city in northwestern Indiana.

In summary, urban effects are suggested in that localized urban highs appear in the motions from all three basic directions. However, only with the southwest and west motions is there a relatively clear indication that urban-related maximums extend eastward from the urban highs and over southern Lake Michigan. Another interesting feature is that the low rainfall trough found just to the east of the lakeshore, well north of the city appears only with the storms from the southwest and west. It is not a distinct feature in the northwest motion pattern. The results agree well with the St. Louis results (Changnon, et al., 1977) which showed urban influences most pronounced in west and southwest rain motion situations, and less prevalent in northwest motion cases.

Monthly Rainfall Study

To further understand and interpret the climatic aspects of the 3-summer sample, and to examine for possible lake and urban influences, the rainfall data were assembled by months. The resulting monthly total rainfall patterns appear in figure 6.

June is normally the area's wettest month (10 cm yearly average, or 30 cm in 3 years). The values (Fig. 6a) show June was the wettest of the 3 summer months during 1977-79, and the amount of rain sampled was at or above normal in many portions of the study area. The heavy June rainfall to the west and southwest of the radar was dominated by the heavy rainstorm on June 25, 1978 (see Fig. 16). Otherwise, the pattern shows a series of highs ($\geq$ 45 cm) scattered from west-northwest of Chicago eastward across the city, and then on across south-central Lake Michigan. There are also localized highs over Gary and the city's center, suggesting urban-industrial influences (particularly with no comparable highs north of the city). The high rainfall extending east of the city also may reflect an extension of urban influences. Notable lows in the rainfall pattern exist over the lake north of the urban high and along the southeastern lakeshore.

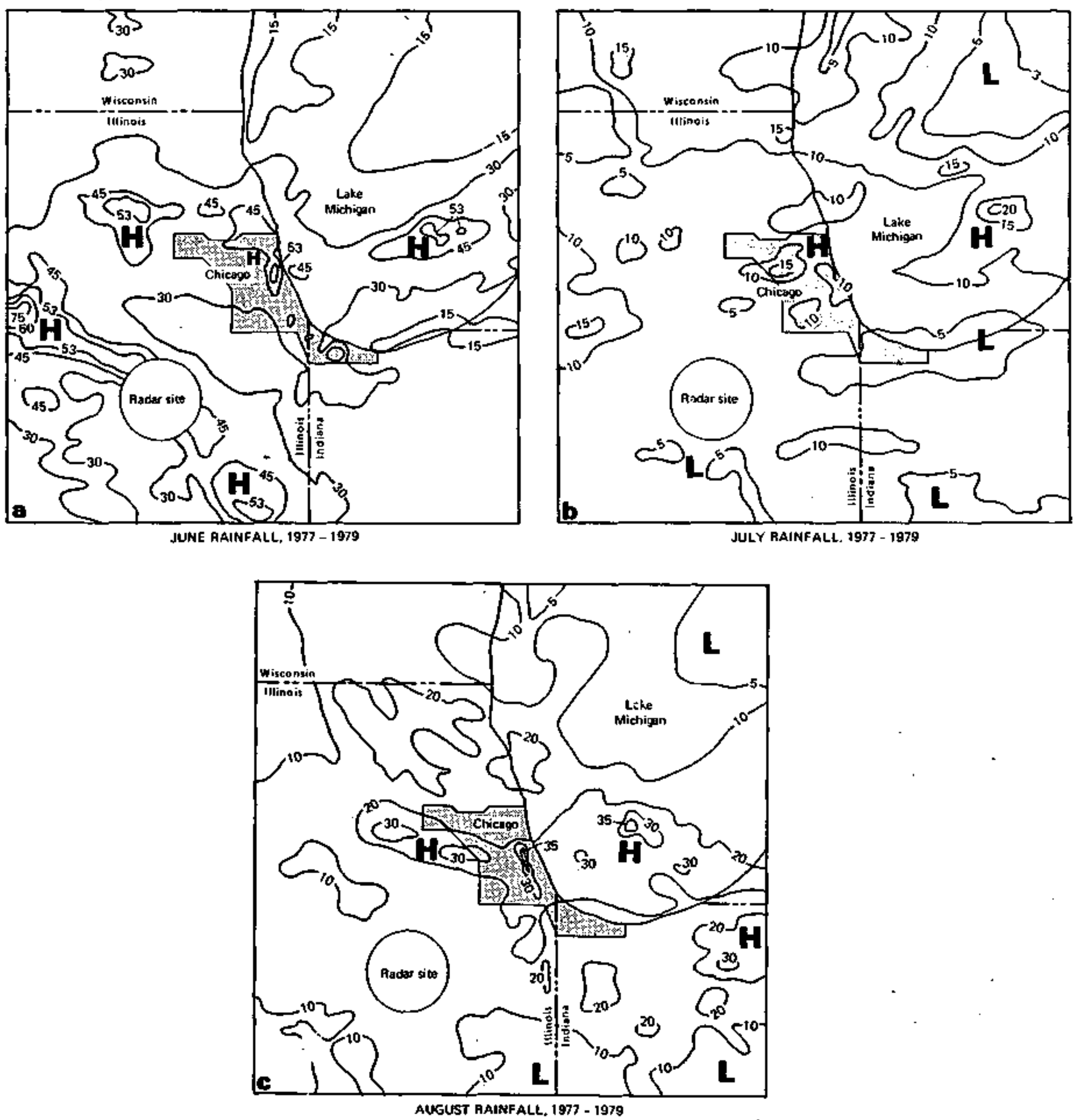

Figure 6. Total monthly rainfall, in centimeters, for 1977-79.

The July rainfall pattern (Fig. 6b) is more random than June. Comparison of July with June and August patterns reveals July was the driest month, a normal circumstance. Normal rainfall in July in this area is about 8 cm (24. cm in 3 years), so the sampled July totals for 1977-79 reflect below normal rainfall conditions. Areas of heaviest rain (≥ 15 cm) are found over the city, over the rural areas well west of north of Chicago, and over the lake. The most notable large-scale features in July are the three lake-related lows including 1) one parallel to the land just east of the lakeshore (Wisconsin); 2) one farther east and broader over the center lake; and 3) one along the southern lakeshore. In general, the July pattern reveals strong lake influences but with little suggestion of any urban influences.

The August rainfall pattern (Fig. 6c) differs from that of June and July. The normal August rain is about 8.5 cm (25.5 cm in 3 years), indicating that the 1977-79 August totals were generally near to below normal. The August pattern (Fig. 6c) features an east-west maximum extending from the rural area just west of Chicago eastward across the city, and on across extreme southern Lake Michigan. Localized highs (≥ 30 cm) exist in this band and also in northeast Indiana at LaPorte. A city high of > 35 cm is indicated, and another high (> 35 cm) is found east of the city. These may reflect urban influences. Lake lows north of the urban high match those found in the other two months.

In summary, urban influences on the rain patterns are suggested in June and August, but not in July. Apparent lake-related lows in the rainfall patterns are found in all three months with a trough just east of the lakeshore (north of Chicago) and then a broader and lower rainfall area that begins about 20 miles beyond the western shore.

Rainfall Associated with Varying Degrees of Convective Activity

The rainfall produced by convective storms, sorted into three classes reflecting varying degrees of organization and convective activity (well organized intense lines are one extreme and disorganized isolated cells are the other), was compared on a land use basis, to examine further for urban and lake influences.

The rain pattern produced by lines (nearly solid, well organized linear arrays of cells) reveals an east-west maximum (defined by $\geq$ 7 cm) from rural areas west of Chicago, eastward across Chicago and on across southern end of Lake Michigan (Fig. 7a). Within this broad east-west high are localized highs of $\geq$ 21 cm over the northwest suburbs and the city center. Urban influences are suggested.

The less well organized, non-linear but strong convection defined by 61 squall areas produced a rainfall pattern (Fig. 7b) that also exhibits an east-west maximum. It extends from the rural areas of Chicago eastward across the city and across southern Lake Michigan. This maximum band is centered farther north than that of the organized lines (Fig. 7a). The pattern for the squall areas shows a major maximum to the west and southeast of the radar due to the extreme rainfall on June 25, 1978 (see Fig. 16). If this anomalous event is excluded from the pattern, the important features that remain are the $\geq$ 60 cm values a) in the city and north suburbs (inland and along the lake shore), and b) east of the city in Lake Michigan. There is a strong suggestion of urban enhancement of rainfall amounting to 10 to 20 cm over the city and extending well east of Chicago over the lake. The organization of the highs parallel and along the lakeshore may reflect urban and lake influences. Lake effects on

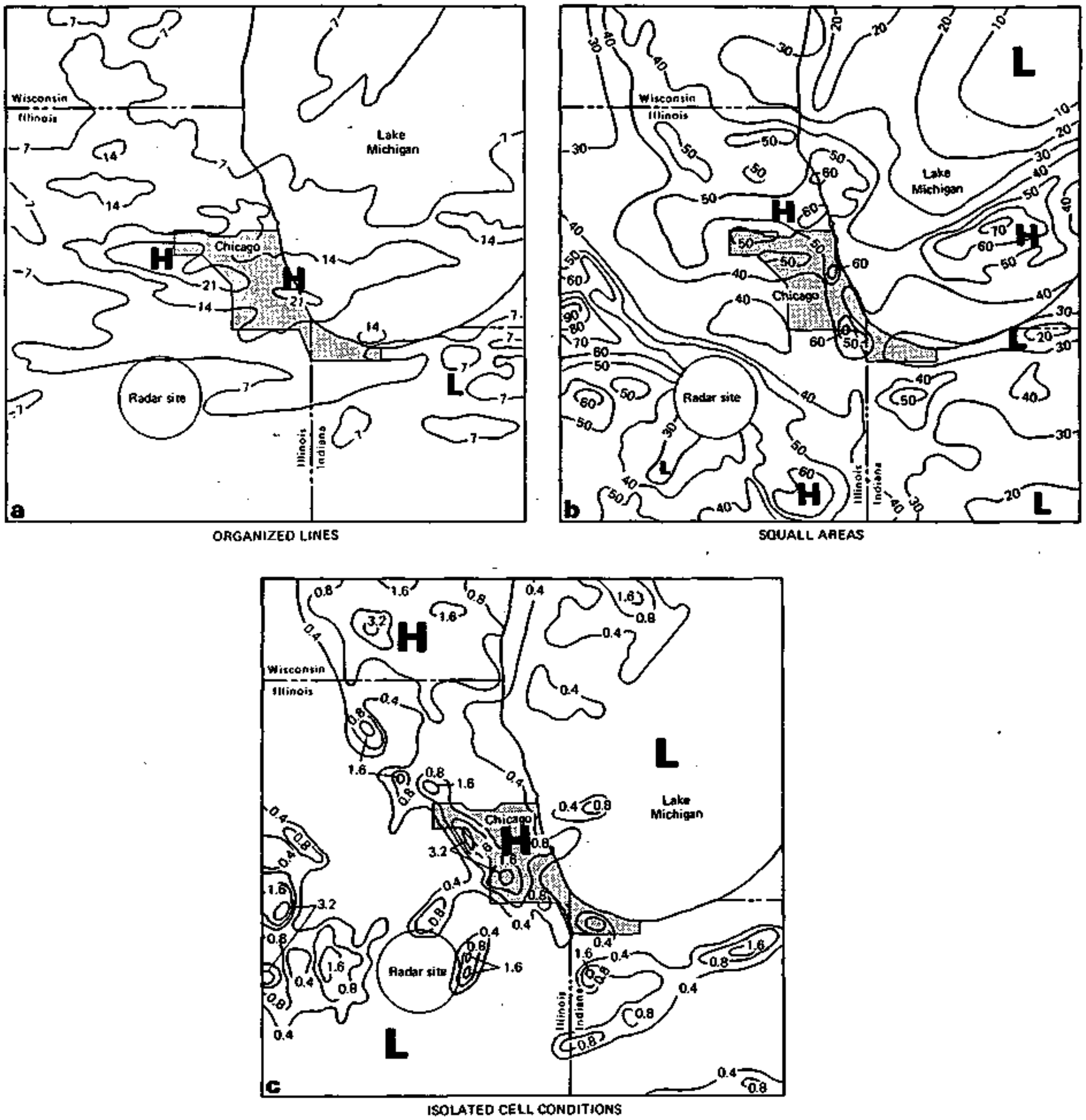

Figure 7. Total summer rainfall during 1977-1979 with different convective conditions, in centimeters.

precipitation processes are also revealed with decreases in squall area rainfall occurring just east of the northern lake shore north of Chicago. In general, there is a strong suggestion of a major interaction of lake and urban influences in the distribution of rainfall produced by semi-organized convective situations.

The isolated, weakly organized and often less intense convective cases produced the rain pattern of figure 7c. The three summers and 10 such rain periods are an inadequate sample for these isolated events. Regardless, the pattern does suggests a band of enhanced rainfall generally parallel to the lake shore and located 5 to 20 miles inland from the shore. This may result from the influence of lake breezes which may assist in the formation and/or intensification of isolated convective showers. The highest values, ≥ 3.2 cm, are found in the city and elsewhere to the north and west of the city. Urban effects under these conditions are not too evident from the pattern.

Table 5 shows for the 3 levels of convection the area mean rainfall values for 11 land use areas in and around Chicago (see Fig. 9 for areas). The City value ranks first in the Line and Squall Area classes, and second in the Isolated Cells (where Inner Residential ranks first). Order of the area values reveals that the city, inner residential and outer residential achieve first, second and third ranks in the lines and isolated cells. In the squall areas, these three metropolitan areas achieve ranks 1, 4, and 5. Collectively, the results suggest the existence of urban influences, under all types of convective activity. Comparison of the City mean values under each convective class with the average of respective control (NW Rural, North Lake, and West Rural) reveals greatest differences (> 75% increases in City) exist with the lines and isolated cell conditions. The difference in squall areas was about 10%.

Table 5. Area Mean Rainfall, cm, 1977-79 for Varying Convective Conditions.

Areas	Lines	Squall Areas	Isolated Cells
NW Rural	10.1	48.2	0.4
North Lake	6.9	44.7	0.4
West Rural	7.9	47.0	0.4
Outer Suburbs	15.2	42.0	0.5
Inner Residential	16.1	39.1	1.1
City Core	18.5	51.6	0.7
Industrial	10.2	38.6	0.3
South Rural	7.6	36.7	0.3
Southeast Rural	6.8	32.1	0.3
Lake	7.2	30.8	0.2

(1)See Fig. 9 for areas; lake area is all zones shown on Fig. 9.

Frequencies of Rainfall Rates

Tables 6 and 7 present area mean frequencies of various rainfall rate classes and based on the 3-summer total sample. The area mean number in the City Center for rainfall rates of 2 to 6 mm/hr was 301, as compared to 377 in the Southeast Rural area. Examination of Table 6 for the over-lake zones (north and south combined, Fig. 2) shows that these low rainfall rates were relatively frequent over the 5 zones over the lake. The average of all zones of 390 incidences for 2 to 6 mm/hr rates, was in excess of that over the City Center (301) as well as those of all the other land use areas (Table 6). This suggests an enhancement of low rainfall rates over Lake Michigan. Examination of the heavier rainfall rates, such as those > 6 mm/hr, shows a very different distribution. For example, the City Center average frequency is 347 and the over-lake average is 249 (Table 7).

Comparison of the various rainfall rate frequencies shown in Tables 6 and 7 for the various land use areas and lake zones suggests that light rainfall rates are most frequent over the lake and the higher rainfall rate are most

Table 6. Area Mean Frequencies of Various Rainfall Rates, 1977-79.

Rate Distribution	City Center	Dense Residential	Indus-trial	NW Suburb	Far Suburb	North Lake	NW Rural	West Rural	South Rural	Southeast Rural
2-6 mm/hr	301	298	316	303	310	384	345	304	300	377
> 6 mm/hr	347	310	275	332	291	272	300	245	254	172
12-25 mm/hr	105	86	81	111	85	68	81	72	69	38
> 12 mm/hr	184	155	125	184	156	116	148	139	127	71
> 2 mm/hr	649	608	574	635	600	656	641	547	551	551
6-12 mm/hr	163	155	150	148	138	156	152	105	126	100
> 25 mm/hr	78	68	143	73	70	47	66	67	58	325

Table 7. Area Mean Frequencies of Various Rainfall Rates for Over-Lake Zones.

Rate Distribution	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Average of all Zones
2-6 mm/hr	384	406	404	394	362	390
> 6 mm/hr	296	271	234	229	217	249
12-25 mm/hr	86	67	55	55	52	63
> 12 mm/hr	144	116	99	100	94	111
> 2 mm/hr	681	678	639	623	579	640
6-12 mm/hr	152	155	134	128	123	138
> 25 mm/hr	57	49	44	44	42	47

frequent over the land. Comparison of the total number of rainfall rates (> 2 mm/hr) of the City Center (shows a mean of 649) with the averages of all the five lake zones (a mean of 640) shows only 9 incidences less. This indicates it rained as often over the lake as over the city. The results therefore suggest that lake effects act to decrease rainfall rates. Comparison of the City Center and the dense Residential values with values from the rural areas shows an urban enhancement of the heavier rainfall rates. This helps make the urban-vs-lake differences greater.

Figure 8 presents patterns based on the frequency of rainfall rates in the light category (2-6 mm/hr), and the moderate to heavy category (> 6 mm/hr) for the 3-summer period. The pattern for the light rainfall rates (Fig. 8a) shows a major high (point values > 360 incidences) stretching from southeastern Wisconsin out across southern Lake Michigan and into northwestern Indiana. Localized highs of 420 incidences are found along the lake shore extending outwards 15 to 20 miles. Similar highs are shown in northeastern Indiana. However, comparable highs of 422 or more incidences of light rains are found in the northern portion. The incidences decrease eastward over the lake to values less than 240. This suggests some lake influences to enhance the light rainfall rates, as shown in Tables 5 and 6, although the pattern does not establish lake effects too clearly. The lower lake rainfall (Fig. 3d) and lesser rate incidences beginning 25 miles east of the shore, suggest a suppression of rain activity.

The pattern based on the higher rainfall rates, those > 6 mm/hr shows an east-west high in the northwestern suburbs through the city center and extending over southern Lake Michigan. This pattern reflects the dominant features for the total rainfall pattern (Fig. 3d).

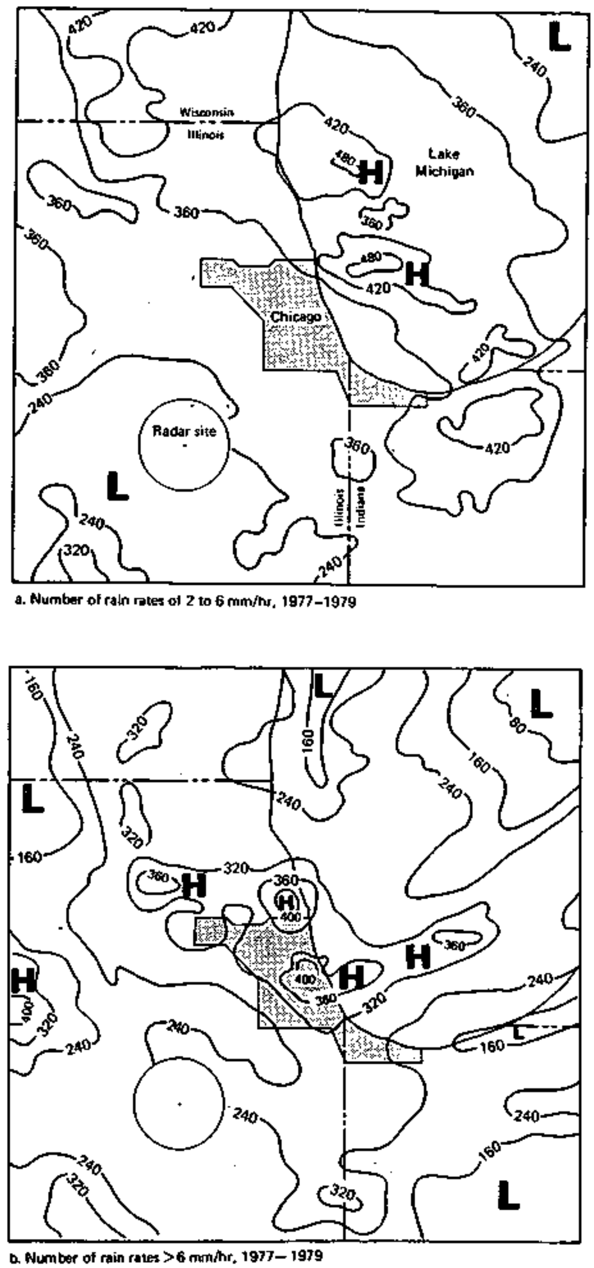

Figure 8. Frequency of light and moderate to heavy rainfall rates during summers of 1977-1979.

Evidence of Urban and Lake Effects

The preceding assessments of total rainfall and frequencies of rainfall rates, classified by synoptic types and rain motion, and for the total 3-year period, reveal certain persistent, year-to-year features in the isohyetal patterns. The 3-year sample provides evidence that in the stronger convective situations the precipitation is enhanced over the center of Chicago, and that this enhancment extends eastward 30 to 40 miles, depending on synoptic types and rain motions. The results also suggested that the lake acts to diminish rainfall over and just east of the shore line to the north of the area with urban influences. This section further examines these potential urban and lake effects using regional rain values.

Table 8 presents the results for the two sets of five zones over Lake Michigan. As noted in figure 2, these five zones were divided to form a series of "north lake zones" and "south lake zones." This is based on the hypothesis that the north lake values are east of rural areas and are generally indicative of non-urban effects (lake effects only), whereas those over the south lake zones potentially represent both urban and lake effects. The values for total rainfall in these two sets of 5 lake zones appear in figure 9, and comparison of these shows marked differences in magnitude and west-to-east trends. The north lake (uneffected) zonal values show a general west-east decrease although Zone 2 is higher than Zone 1, reflecting the pattern differences noted in figure 3. The south lake values are much higher in all categories (zone 1 north lake vs. zone 1 of south lake, etc.). The south lake zonal values show a west-east decrease out through zone 3, then an increase reflecting the maximums found in that general area east of the city (Fig. 3).

Table 8. Over-Lake Zonal Rainfall Values East of Chicago and East of Rural Area, 1977-79.

		North Lake Zonal Averages, mm (east of rural area)					South Lake Zonal Averages, mm (east of Chicago)				
	North Lakeshore	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
Total Rain	543	507	527	424	360	273	660	572	571	608	634
Squall Lines	98	87	83	79	67	47	226	205	186	177	163
Squall Zones	280	221	200	214	217	216	272	270	201	177	144
Cold Fronts	55	43	37	31	24	15	104	69	74	101	120
					Rain Rate Frequencies						
2-6 mm/hr	384	408	428	417	388	327	369	392	397	399	385
> 6 mm/hr	272	244	256	211	191	140	233	282	251	255	271
> 25 mm/hr	47	45	46	33	24	16	67	52	53	59	60

The rainfall rate frequencies shown on Table 8 vary considerably between the north and south lake zones, and these differences are portrayed in figure 10. This comparison of the north and south lake values for the light and for the moderate to heavy rainfall rates shows interesting differences. Also shown on figure 10 are the values upwind (west) of the over-lake zones.

Let us first consider the light rainfall rates displayed in the upper portion of figure 10. The rural and city values of South Lake curve are comparable indicating no relative west-east effect; however, east of the city the frequency of light rainfall rates increases dramatically reaching a peak in zones 2, 3, and 4 (5 to 20 miles east of the city). The North Lake profile of light rates differs. The North lakeshore value (384) indicates an enhancement of light rainfall rates relative to that in the Northwest (upwind) Rural area (to the west), with continued eastward enhancement of light rainfall rates, reaching a peak over lake zone 2, followed by rapid eastward decrease to 327 in zone 5.

The differences between the north and south lake values for the light rainfall rates tends to suggest some possible urban effect that acts to enhance the light rainfall rates farther east (25 miles) of the city than is found in the urban uneffected (north lake) area. Also, there is a probable enhancement of light rain rates along the lakeshore without the city.

The profiles for the moderate to heavy rainfall rates (Fig. 10, lower portion) shows a different outcome. Let us consider first the south lake values. The upwind rural value of 245 is much smaller than the near lakeshore (City Center) area, revealing urban enhancement of rain rates. Farther east, a major decrease occurs in lake zone 1, followed by a slight increase eastward in these heavier rain rates. The north lake profile is strikingly different, showing a diminishment along the lakeshore (lake effects may act to decrease), with a continuing decrease in the heavier rainfall rates eastward from the lake. Comparison of the north lake and south lake curves for the heavier rain rates helps demonstrate that the urban effect near the lakeshore overwhelms the lake tendency to diminish such rates. The urban effect apparently enhances, in general, the heavier rainfall rates east of the city so they are well above the control (north lake) values.

Table 9 presents the various regional values expressed as a percent of the average of the two upwind control values, Northwest plus West rural. In this table, the over-lake zonal values of the north and south are combined into one general set. This shows a 3-year urban value of 15 percent greater than the upwind controls, exactly comparable to that obtained in the prior study of raingage network data (Changnon, 1980b). Squall lines show the next to the largest urban percentage increase, exceeded only by the air mass value of 233%. The over-lake zonal values, in most instances, show a west-to-east decrease, except in the cold front values. Warm and stationary frontal rain values over the lake exceed those in the upwind rural controls.

The apparent urban effect leading to heavier rainfall extending over Lake Michigan was further investigated by expressing the south over-lake zonal values as a) percent of the City Center value, and b) as a percent of the West Rural values, considered a control area. The resulting two sets of percentages appear in Table 10. Comparisons with the City Center value shows the diminishment eastward in the squall lines and squall zones, but an enhancement (> 100%) above the city values in zones, 1, 4, and 5 with cold fronts. The profiles of the rainfall rates (Fig. 9) are reflected in the percentage values also shown in Table 10. Of interest are the percentages for the > 25 mm/hr rates. They

Table 9. Regional Rainfall Values Expressed as a Percent of the Average of the Northwest and West Rural Area Values.

Rainfall for all Storms	City Center	Dense Residential	Indus-trial	NW Suburb	Far Suburb	North Lake	South Rural	SE Rural
1977-79	115	97	84	107	99	87	86	70
Squall Lines	205	162	113	162	137	63	88	63
Warm & Stationary Fronts	111	100	103	122	107	115	93	90
Squall Zones	80	68	77	74	76	103	83	64
Air Mass	233	400	67	300	133	133	83	83
Cold Fronts	86	74	44	199	105	51	83	25
Rain Rate Frequencies, 1977-79								
2-6 mm/hr	93	92	97	93	95	118	92	116
> 6 mm/hr	127	114	101	122	107	100	93	63
> 25 mm/hr	116	101	213	109	104	70	87	49

	Over-Lake Zonal Values					
	1	2	3	4	5	5 Zone Averages
1979-79	95	88	81	81	78	85
Squall Lines	112	105	97	90	78	97
Warm & Stationary Fronts	121	119	105	100	96	108
Squall Zones	88	83	76	73	68	77
Air Mass	67	67	33	33	33	47
Cold Fronts	72	51	52	64	71	62
Rain Rate Frequencies, 1977-79						
2-6 mm/hr	118	125	124	121	111	120
> 6 mm/hr	108	99	86	84	79	91
> 25 mm/hr	85	73	66	66	63	70

Table 10. Over-Lake 3-Year Rainfall Values East of Chicago, as a Percent of Urban (City Center) Value and of West Rural Control Area Value.

Class	South Over-Lake Zonal Values as Percent of City Center Value					South Over-Lake Zonal Values as Percent of West Rural Value				
	1	2	3	4	5	1	2	3	4	5
Total Rain, 1977-79	91	79	79	84	87	110	95	95	101	105
Squall line rain	75	66	62	59	54	177	160	145	138	127
Squall zone rain	123	122	91	80	65	93	92	69	61	49
Cold front rain	111	74	79	108	129	98	65	70	95	113
All Rainfall Rates, 1977-79										
2-6 mm/hr	123	130	132	133	128	121	129	131	131	126
> 6 mm/hr	96	81	72	73	78	136	115	102	104	110
> 25 mm/hr	86	68	68	76	77	100	78	79	88	89

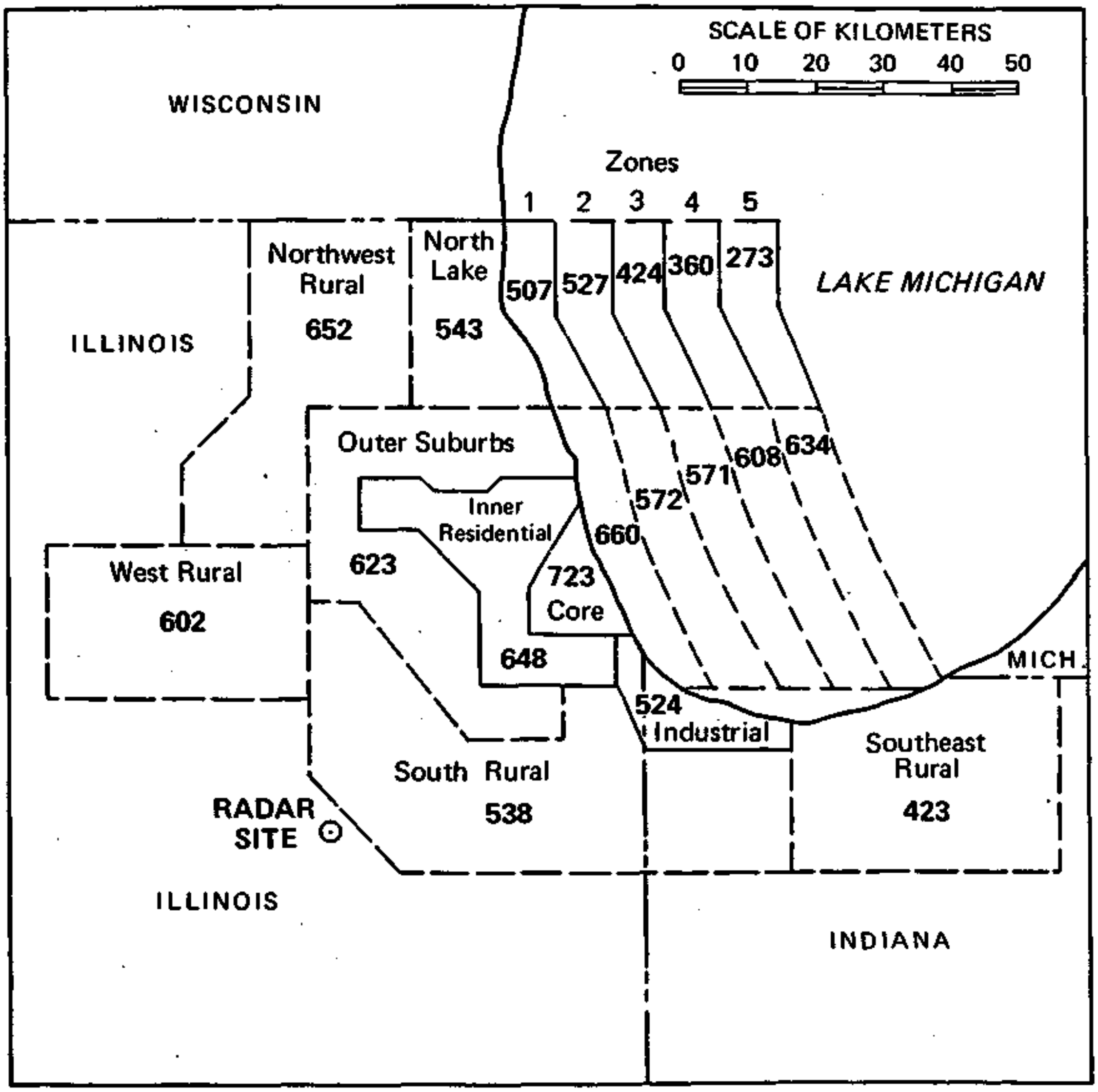

Figure 9. Area-mean total rainfall values (millimeters) for the summers 1977-1979.

diminish eastward from the City Center with a secondary maximization in zones 4 and 5. Expression of the zonal rate values, as a percent of the West Rural (control) values, also appear in Table 10. In general, rainfall rate frequencies, for both light and the moderate to heavy rates (> 6 mm/hr), are higher over the lake than in the west rural area, ranging from 2 to 36 percent. However, there are distinctly fewer rates > 25 mm/hr over the lake than in the upwind control. Inspection of the percentages for the rainfall with synoptic types (in Table 10) shows that in most instances, other than in squall lines, the over-lake values are less than the West Rural. Zones 2, 3, 4, and 5 had total rainfall in 1977-79 that was comparable to the rural areas with values ranging from 95 to 105 percent of the West Rural value. It is noticeable, however, that the squall line values are much higher than the West Rural value, ranging from 27 to 177 percent higher.

Further indication of lake influences on precipitation over the lake, and over the adjacent land area can be derived from the values of Table 11. Here the North Lake land values and those for the north over-lake zones for certain rainfall totals and rainfall rate categories are expressed as a percent of the Northwest Rural value considered an upwind control. The values for total rainfall for 1977-79 indicate a 17 percent diminishment over the North Lake, with a continued diminishment over the lake such that zone 5 (20 to 25 miles east of the lakeshore) received only 42% of the rainfall over the Northwest Rural area. Similar west-to-east decreases are shown with all synoptic types in the case of over-lake rainfall.

Comparison of the rainfall rate frequencies suggests a distinct enhancement (as shown in Fig. 10) of the light rainfall rates (2 to 6 mm/hr), both over the north lake and over the lake through zone 4. However, the moderate

Table 11. North Over-Lake and Adjacent North Lake Rural 3-Year Values Expressed as a Percent of Northwest Rural Control Area Value.

Class	North Lakeshore	North Over-Lake Zones 1	2	3	4	5
Total Rain, 1977-79	83	78	81	65	55	42
Squall Line rain	60	53	50	48	41	28
Squall Zone rain	109	86	78	83	84	83
Cold Front rain	50	39	34	28	22	14
All Rainfall Rates, 1977-79						
2-6 mm/hr	111	118	124	121	112	95
> 6 mm/hr	91	81	85	70	64	47
> 25 mm/hr	71	68	70	50	36	24

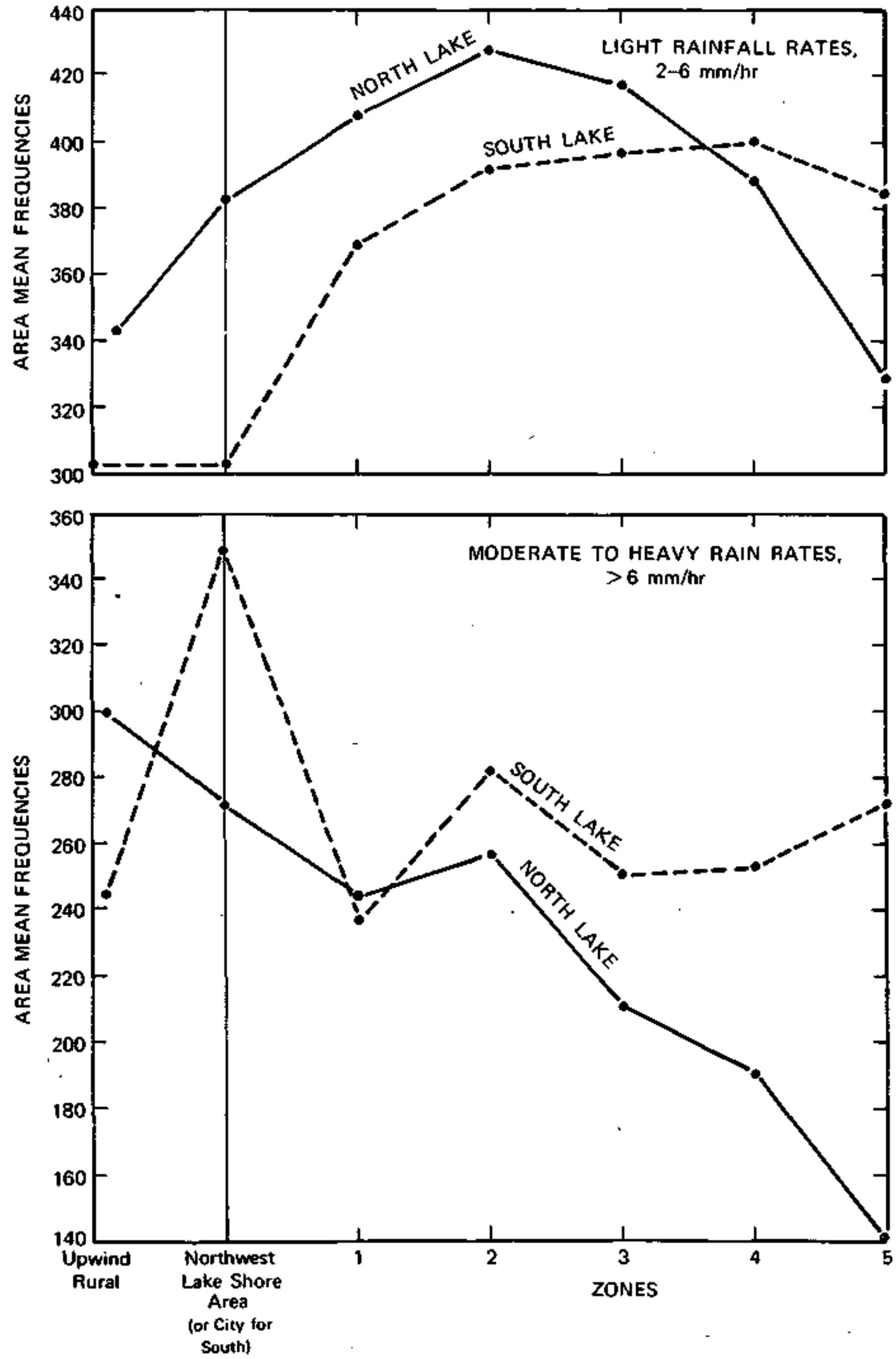

Figure 10. Profiles for west-to-east across the north lake and south lake areas (in zones depicted on Fig. 9) for total summer area mean rainfall and for light, and moderate-to-heavy rainfall rate frequencies.

(> 6) and heavy (> 25 mm/hr) rainfall rates (Table 11) both show marked decreased over the North Lakeshore and lake zonal values. Lake effects to decrease rainfall in moderate to heavy rainfall rates are clearly suggested by the values in Table 11. Values beyond 20 miles east are less than half of upwind control values. This is a greater diminishment than prior studies had estimated for the central portions of the lake (Changnon, 1968b). Patterns of rainfall in figures 3-7 furthermore indicate that this low is very distinguishable at 20 miles and continues to extend eastward to the edge of the study area which is more than 40 miles east of the western lake shore. Values of rain at 6 raingage stations along the eastern shore of Lake Michigan and for the 87 rain periods revealed an average of 34 cm which was 52% of the upwind control value and 63 percent of the North Lake land area.

Comparison of the rainfall total values including those for squall lines, squall zones, and cold fronts in Table 11, with those in Table 10 (percent of West Rural) also gives indications of the marked urban influences on the rainfall east of the city. The north over-lake rainfall values for 1977-79 differ dramatically, 78 percent down to 42 percent in zone 5. However, in the south lake, the values are 110 percent in zone 1, and 105% of the West Rural in zone 5. Similar comparisons for the squall lines show the marked influence east of the city with minor influence in squall zones, and no influence in cold fronts.

Statistical Assessment

The area mean total rainfall values were compared and tested to ascertain the statistical significance, if any, of their differences. The comparison was based on values of two parallel sets of three areas oriented west-east (along the prevailing motion of rain). Two rural areas well west of the lake and Chicago (Fig. 11) were chosen as control areas with their differences reflecting natural conditions. The next paired areas were the North Lake and City (Fig. 11) with differences in rain hypothetically reflecting urban influences. The final pair of areas were the North Lake and South Lake areas where it was hypothesized that differences were due to urban influences in the South Lake. Note that the two sets of areas were separated to provide a buffer zone. The City and South Overlake areas were considered "target" areas, whereas the three Rural and North Overlake areas were "control" areas. A target-control comparison method (Hsu, et al., 1981) was used to assess the significance of rainfall anomalies, if any, over the City and South Overlake. The basic data used for this analysis consisted of the storm total rains averaged over each of the 6 areas for the summers of 1977 to 1979.

Analyses of Area Rainfall. The duration of the 87 rain periods is shown in a stem-and-leaf display (Fig. 12a). The majority (inter-quartile range, or the box in Fig. 12) of the durations was between 3 to 9 hours with a median of 6 hours. Two storms had a relatively long duration, namely that of June 29, 1979 (20.75 hours), and that of June 25, 1978 (16.9 hours). Otherwise, the distribution of the storm durations was symmetric with slight truncation at zero, and was not significantly different from a normal distribution (P-value larger than 0.15 using the Kolmogorov-Smirnov test).

The stem-and-leaf displays for the beginning and ending times of storms (Fig. 12b and 12c) reveal that small modes existed in the evening and night, fewer storms began in the earlier morning, and even fewer ended in the earlier morning. In general, both distributions resembled a (circular) uniform distribution.

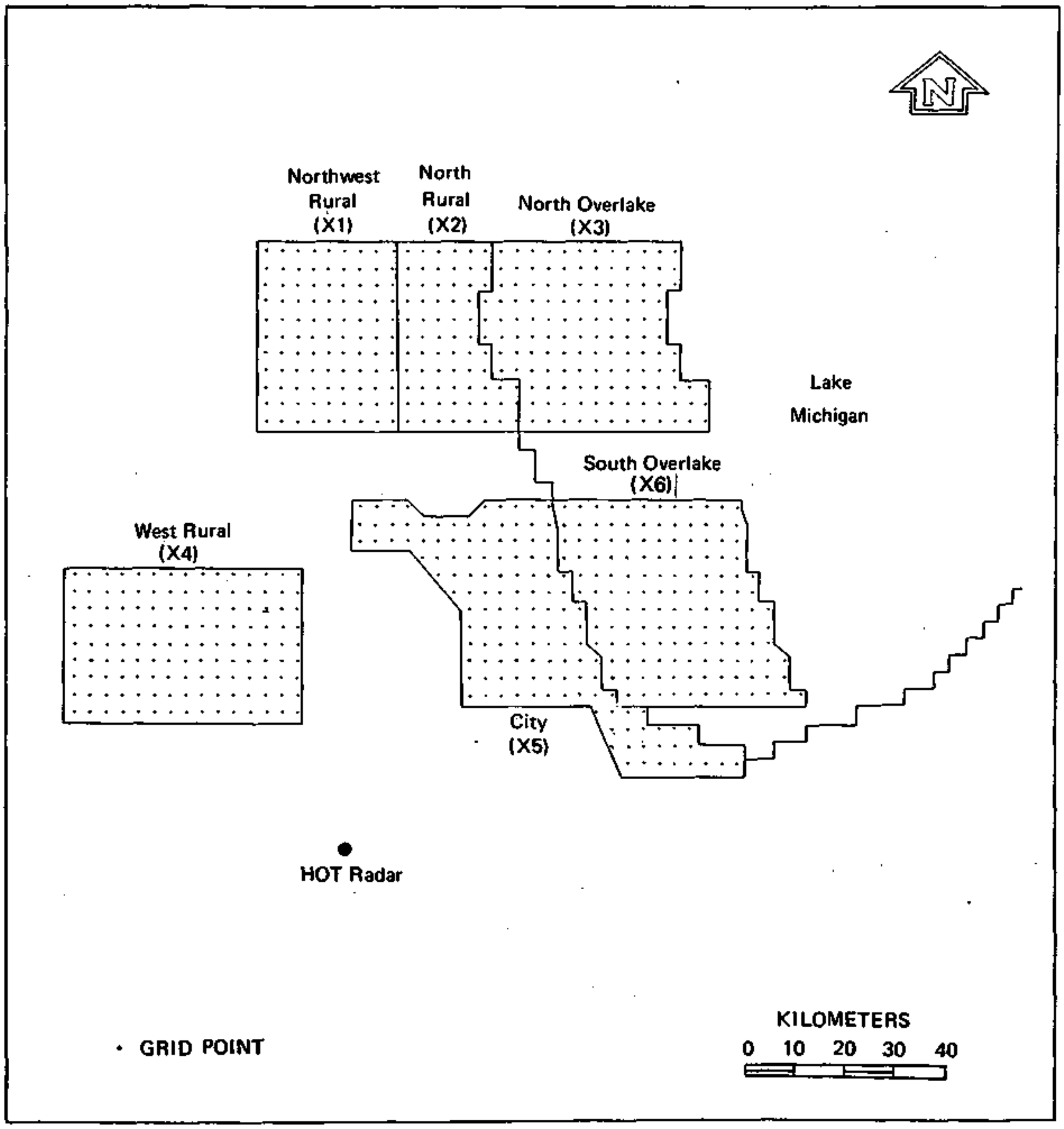

Figure 11. Areas used in the statistical study (dots are grid points).

a. Storm Duration

```
STEM LEAF                  #     BOXPLOT
  20 7                     1        0
  19
  18
  17 0                     1        !
  16                                !
  15                                !
  14                                !
  13 06                    2        !
  12 0129                  4        !
  11 0237                  4        !
  10 2                     1        !
   9 2455667               7        !
   8 111267999             9     +-----+
   7 000678                6     !     !
   6 022345789             9     *--+--*
   5 0227789               7     !     !
   4 03445567778          11     !     !
   3 11588                 5     +-----+
   2 1122345789           10        !
   1 002688                6        !
   0 4569                  4        !
     ----+----+----+----+
```

b. Beginning Time

```
STEM LEAF                  #     BOXPLOT
  22 001236                6        !
  21 47                    2        !
  20 5                     1        !
  19 07                    2        !
  18 002577                6        !
  17 1249                  4        !
  16 4557                  4     +-----+
  15 001344667             9     !     !
  14 44                    2     !     !
  13 0145588               7     !     !
  12 155567                6     *-----*
  11 0057                  4     !  +  !
  10 56                    2     !     !
   9 99                    2     !     !
   8 225688                6     !     !
   7 337                   3     +-----+
   6 79                    2        !
   5                                !
   4 99                    2        !
   3 05                    2        !
   2 4677                  4        !
   1 11456                 5        !
   0 357888                6        !
     ----+----+----+----+
```

c. Ending Time

```
STEM LEAF                  #     BOXPLOT
  23 1224489               7        !
  22 1555                  4        !
  21 022555999             9        !
  20 2345                  4     +-----+
  19 37                    2     !     !
  18 37899                 5     !     !
  17 012238                6     !     !
  16 479                   3     !     !
  15 349                   3     !     !
  14 1237                  4     *--+--*
  13 5                     1     !     !
  12 03889                 5     !     !
  11 00479                 5     !     !
  10 448                   3     !     !
   9 224778                6     +-----+
   8 44459                 5        !
   7                                !
   6 13                    2        !
   5                                !
   4 8                     1        !
   3 19                    2        !
   2 03689                 5        !
   1 00                    2        !
   0 135                   3        !
     ----+----+----+----+
```

Figure 12. Stem-and-leaf display of duration, and beginning and ending time of rain periods in 1977-79.

Simple descriptive rainfall statistics and a bar chart for each area are shown in figure 13. (The bar chart is similar to the usual histogram.) The City had the largest rain period mean rainfall (7.62 mm), South Overlake the second largest (7.26 mm); the three rural areas had compatible mean rainfall (in the 6-7 mm range); but North Overlake had noticeably less rain (5.44 mm). The medians had a similar ordering except that South Overlake had the maximum median rain (1.47 mm). Large skewness and coefficient of variation (C.V.) existed in all six distributions, but with smaller magnitudes in City and South Overlake. The bar charts show that there existed an extremely large observation in each Rural area and the North Overlake. The extreme was especially large (150.05 mm) in West Rural. These extremely large values contributed substantially to the large skewness (3.09-5.78) and C.V. (198-273) of the three Rural and North Overlake areas, when compared to City (2.22 and 176, respectively), and South Overlake (2.23 and 173, respectively). Since the maximum observation in each of these four distributions was relatively far away from the next largest value, the question was raised of whether or not it was in fact an "outlier." Examining the dates when the maximum rains occurred revealed they were all observed in one single storm, namely, that of June 25, 1978. Being very heavy with a duration of 16.9 hours, this particular storm was examined and special analyses conducted, as described later in this section.

a. Rain Amount. The mean areal rains in the two target areas were stratified by amount (Tables 12a and b). The frequency distributions of rain in the City and South Overlake were similar to each other. About 23% (20 rain periods) of the 87 periods did not rain over City or South Overlake. More

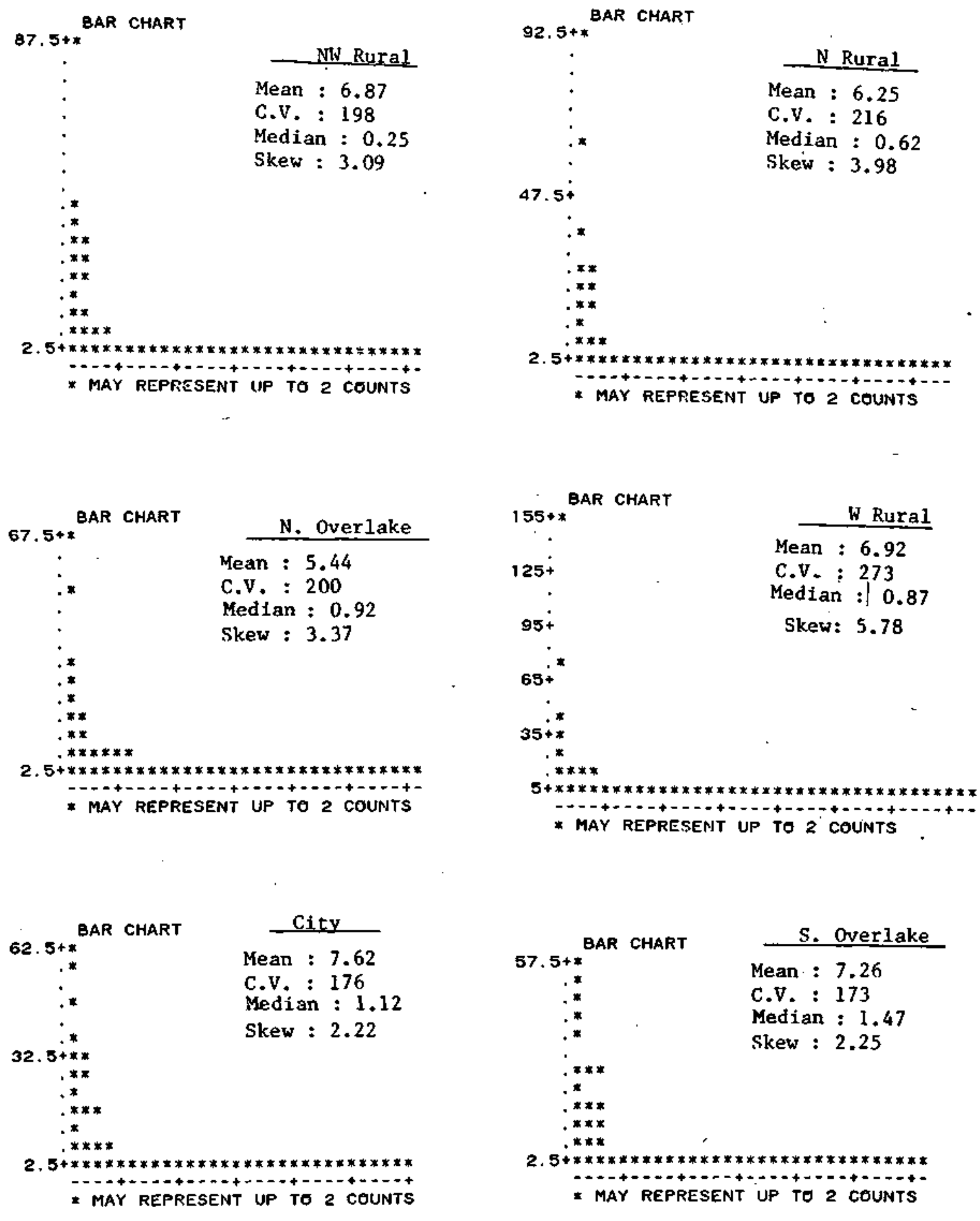

Figure 13. Stem-and-leaf display and descriptive statistics of areal rainfalls or millimeters, for 87 summer rain periods in 1977-79.

than 40% of the periods had a mean rain in the range of 0.26-12.50 mm (0.1-0.5 inch). There was one more rain period in the City than in South Overlake which had mean areal rain in the 25.00-50.00 mm category. In both target areas there were 2 periods with more than 50 mm of mean areal rains. They occurred, respectively, on June 11, 1978 (City), June 13, 1978 (South Overlake), and June 25, 1978 (City and South Overlake).

b. Synoptic Type. Each rain period was classified into one of the 9 synoptic types (Table 12). In both target areas, rainfall from the squall zone and squall line periods were heavier than those of the other types. Those from the stationary fronts also contributed to significant amounts of rain over City. For South Overlake, both the stationary front and cold front periods were also important sources of rains. The two largest rain periods were of squall zone and squall line types. The squall line periods occurred on June 11, 1978 over City, and on June 13, 1978 over South Lake. The heaviest squall zone period occurred on June 25, 1978, in both target areas.

c. Storm Motion. Another stratification of areal mean rainfall values in the two target areas was by amount and rain motion (Table 13) indicated that 40% of the rains came from the west, and 30% each came from the northwest and the southwest. Over the City, the number of periods which had rains of more than 12.50 mm (.5 inch) was 8 from the west, 7 from the southwest, and 3 from the northwest; however, one storm from the northwest had more than 50 mm of rain in City. The number of similarly heavy periods in South Overlake was 7 from the west, 6 from the southwest, and 4 from the northwest. Interestly, there were less zero-rain storms from the west in South Overlake than in City; while there were more zero-rain storms from the northwest and the southwest

Table 12: Rain Period Rainfall Stratified by Amount and Synoptic Type, 1977-1979.

City

Amount	AM	CF	LW	POSF	PRCF	SF	SL	SZ	WF	Total
	Synoptic Type (1)									
0.00	4	7	1	0	0	2	2	3	1	20
0.01- 0.25	2	1	0	0	0	3	0	5	1	12
0.26- 2.50	2	1	0	0	0	4	5	9	0	21
2.51-12.50	2	2	0	1	1	3	2	5	0	16
12.51-25.00	0	1	0	0	0	1	3	1	1	7
25.01-50.00	0	2	0	0	0	1	3	3	0	9
>50.00	0	0	0	0	0	0	1	1	0	2
Total	10	14	1	1	1	14	16	27	3	87
Percent	12	16	1	1	1	16	18	31	3	
South Overlake										
0.00	6	5	0	0	0	3	2	2	2	20
0.01- 0.25	2	1	0	0	0	2	1	4	0	10
0.26- 2.50	2	4	0	0	1	4	3	7	0	21
2.51-12.50	0	1	1	1	0	4	3	9	0	19
12.50-25.00	0	1	0	0	0	1	3	2	0	7
25.00-50.00	0	2	0	0	0	0	3	2	1	8
>50.00	0	0	0	0	0	0	1	1 (2)	0	2
Total	10	14	1	1	1	14	16	27	3	87
Percent	12	16	1	1	1	16	18	31	3	

(1) See text for explanation of abbreviations.

(2) Storm on 6/25/78.

Table 13. Rain Period Rainfall Stratified by Amount and Motion, 1977-1979.

City

Amount	Motion (from) NW	W	SW	Total	Percent
0.00	6	12	2	20	22.99
0.01- 0.25	6	1	5	12	13.79
0.26- 2.50	6	9	6	21	24.14
2.51-12.50	5	5	6	16	18.39
12.51-25.00	1	4	2	7	8.05
25.01-50.00	1	3	5	9	10.34
>50.00	1	1*	0	2	2.30
Total	26	35	26	87	
Percent	29.89	40.23	29.89		

South Overtake

Amount	NW	W	SW	Total	Percent
0.0	8	9	3	20	22.99
0.01- 0.25	2	4	4	10	11.49
0.26- 2.50	6	9	6	21	24.14
2.51-12.50	6	6	7	19	21.84
12.51-25.00	2	2	3	7	8.05
25.01-50.00	2	4	2	8	9.20
>50.00	0	1*	1	2	2.30
Total	26	35	26	87	
Percent	29.89	40.23	29.89		

* Storm on 6/25/78

in South Overlake than in City. The two heaviest rains (> 50 mm) over City were from the northwest (June 11, 1978) and the west (June 25, 1978); whereas the two heaviest periods in the South Overlake were from the southwest (June 13, 1978) and the west (June 25, 1978).

d. Target-Control Comparison. The correlation coefficients between rainfall in the 6 areas were high (Table 14). The smallest was .61 (between City and North Overlake). The rainfall values of the 3 rural areas were highly correlated, with the correlation coefficients in the range of 0.84-0.91. But the correlation between North Overlake and West Rural was relatively low (0.67), which might be attributed to the distance between them. The relationship between the City and South Overlake was strong, .85.

There are two distinct features about the correlation coefficients of the area rains. The first is that the correlation between the two target areas was larger than the correlation between any target-control pair. The second feature is that, for a fixed control, the correlation between it and either one of the targets was smaller than the correlation between it and any other control. For example, the correlation coefficient between X1 (control) and X5 (target) was 0.78; while the correlation coefficient between X1 and other controls was 0.91 (X2), 0.83 (X3), and 0.80 (X4). These results pointed out that the rains of the 6 areas could be classified into two groups in terms of correlation coefficients. The distributional characteristics of rains in the City and South Overlake were not totally "harmonic" with those of the 3 rural areas and North Overlake.

Two target-control comparisons were used for the City. First, it was compared with North Rural (X2), then with West Rural (X4). South Overlake (X6) was compared with the North Overlake (X3) and with West Rural (X4). A simple

Table 14. Correlation Coefficient of Areal Rains and Storm Characteristics, 1977-1979.

CORRELATION COEFFICIENTS / PROB > IRI UNDER HO:RHO=0 / N = 87

	DURATION	BTIME	ETIME	X1	X2	X3	X4	X5	X6
DURATION	1.00000	-0.16659	0.07545	0.45265	0.42105	0.43011	0.46960	0.47421	0.45491
	0.0000	0.1230	0.4873	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
BTIME	-0.16659	1.00000	0.12320	-0.16495	-0.12669	-0.17627	-0.24555	-0.17811	-0.14645
BEGINNING TIME OF STORM	0.1230	0.0000	0.2556	0.1268	0.2423	0.1024	0.0219	0.0988	0.1759
ETIME	0.07545	0.12320	1.00000	0.01931	0.06180	0.02528	0.00814	-0.10882	-0.05184
ENDING TIME OF STORM	0.4873	0.2556	0.0000	0.8592	0.5696	0.8162	0.9403	0.3157	0.6335
X1	0.45265	-0.16495	0.01931	1.00000	0.91241	0.83476	0.79794	0.78245	0.73602
NW RURAL	0.0001	0.1268	0.8591	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001
X2	0.42105.	-0.12669	0.06180	0.91241	1.00000	0.91138	0.75102	0.62687	0.73415
N RURAL	0.0001	0.2423	0.5696	0.0001	0.0000	0.0001	0.0001	0.0001	0.0001
X3	0.43011	-0.17627	0.02528	0.83476	0.91138	1.00000	0.66949	0.60598	0.66080
N OVERLAKE	0.0001	0.1024	0.8162	0.0001	0.0001	0.0000	0.0001	0.0001	0.0001
X4	0.46960	-0.24555	0.00814	0.79794	0.75102	0.66949	1.00000	0.74584	0.64955
W RURAL	0.0001	0.0219	0.9403	0.0001	0.0001	0.0001	0.0000	0.0001	0.0001
X5	0.47421	-0.17811	-0.10882	0.78245	0.62687	0.60598	0.74584	1.00000	0.85417
CITY	0.0001	0.988	0.3157	0.0001	0.0001	0.0001	0.0001	0.0000	0.0001
X6	0.45491	-0.14645	-0.05184	0.73602	0.73415	0.66080	0.64955	0.85417	1.00000
S OVERLAKE	0.0001	0.1759	0.6335	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000

ratio of rains was formed for each comparison. For example, R52 was the ratio of the rain of City divided by that of North Rural. Times series plotting of four simple ratios, R52, R54, R63, R64 are shown in figure 14a-d. The abscissa in the plots is the Julian date, the ordinate is the ratio. (Ratio with zero denominator was not plotted). A value larger than 1 indicated that target rain was larger than control rain. These plots reveal general patterns of the target-control relation as well as their evolution over time.

There was a minor cyclic pattern of R52 and R54 in 1977; a minor trend of R52, R54 and R64 in 1979, as well as R63 in 1977. In addition, a local minimum of R54 and R64 existed in July of 1977, which might be due to small sample size. The variation of R54 and R52 in 1978 was smaller than that of 1977 and 1979; similarly the variation of R63 and R64 in 1978 was smaller than that of 1977 and 1979. Otherwise, there seemed to be no other identifiable patterns.

The ratio calculated above is "simple ratio" in contrast to "double ratio" (DR), which is a ratio of two simple ratios. Two double ratios were formed, DR5241 (=R52/R41) and DR6341 (=R63/R41). Their time series plots are shown in figure 15a and b. The double ratio can be thought of as an adjusted simple ratio. For example, the relationship (R52) between City (X5) and North Rural (X2), if adjusted by the relationship (R41) between West Rural (X4) and NW Rural (X1), gives DR5241. The inclusion of this adjustment reduces inherent biases which might exist due to climatological differentials as well as geographical differentials between a target and a control. The double ratio is therefore a more desirable statistic than the simple ratio. From the plots (Fig. 15), it is clear that in only 3 months, August of- 1977, June of 1978,

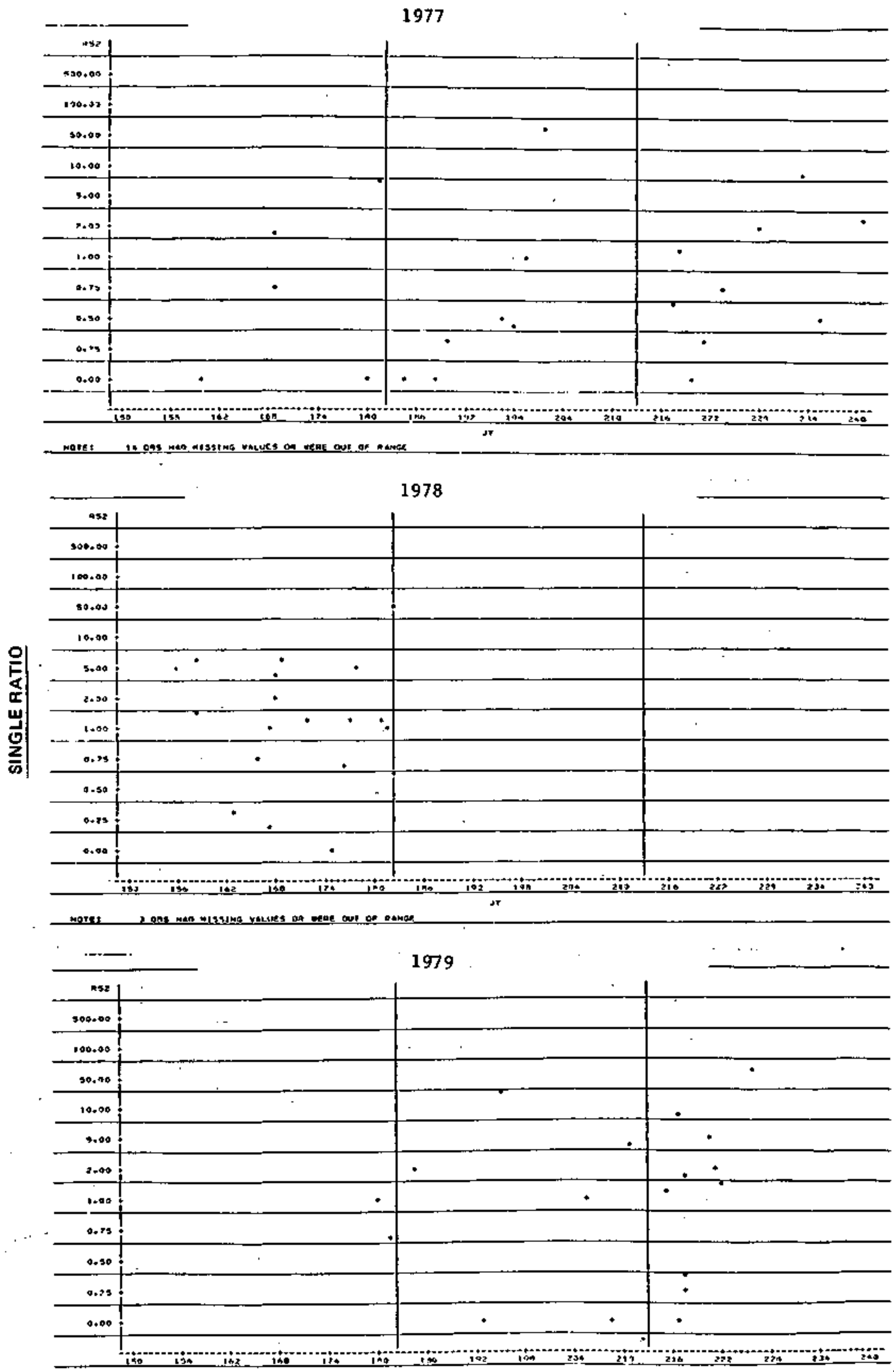

Figure 14a. R52, the single ratio of the city (X5) over north rural (X2).

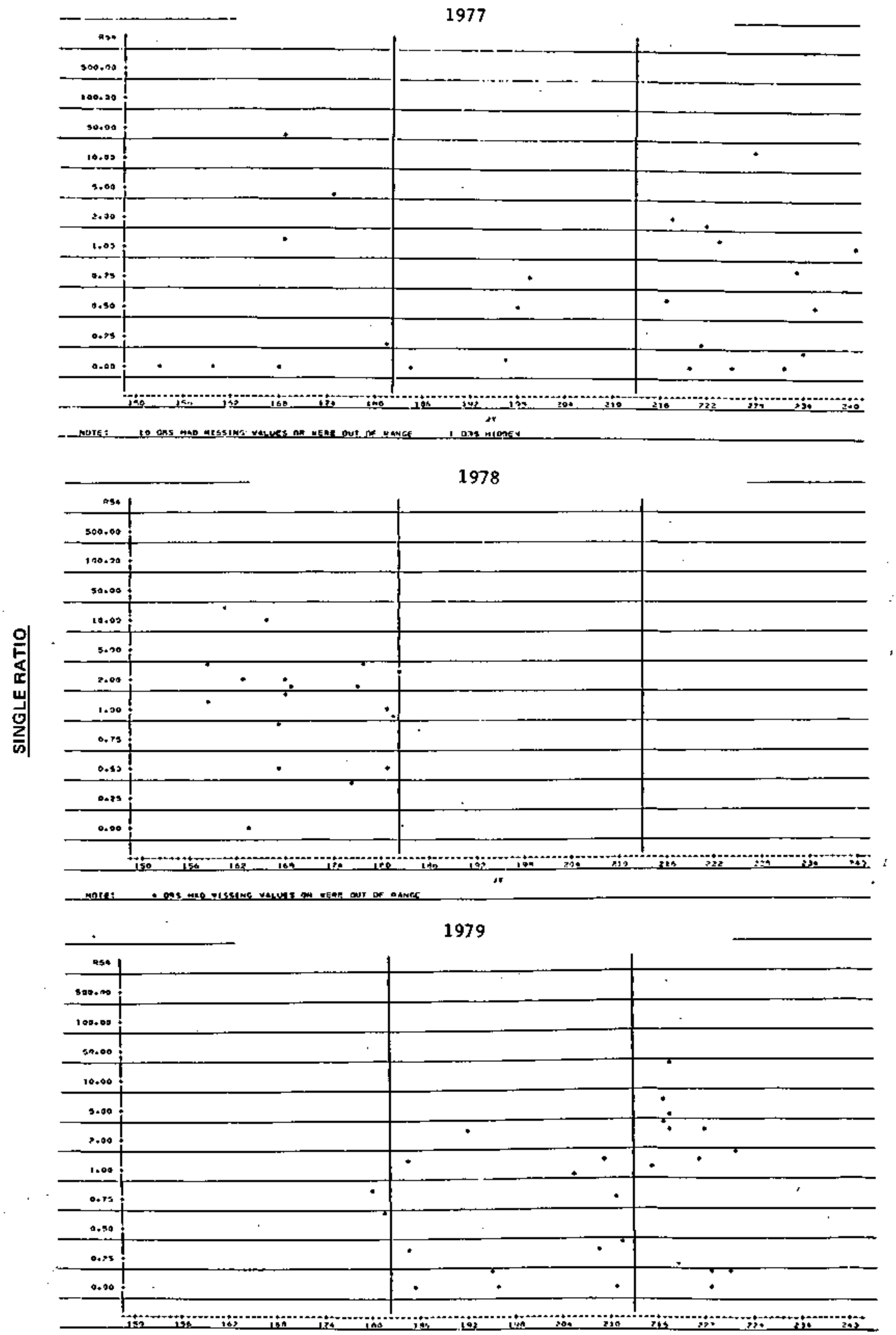

Figure 14b. R54, the single ratio of the city (X5) over west rural (X4).

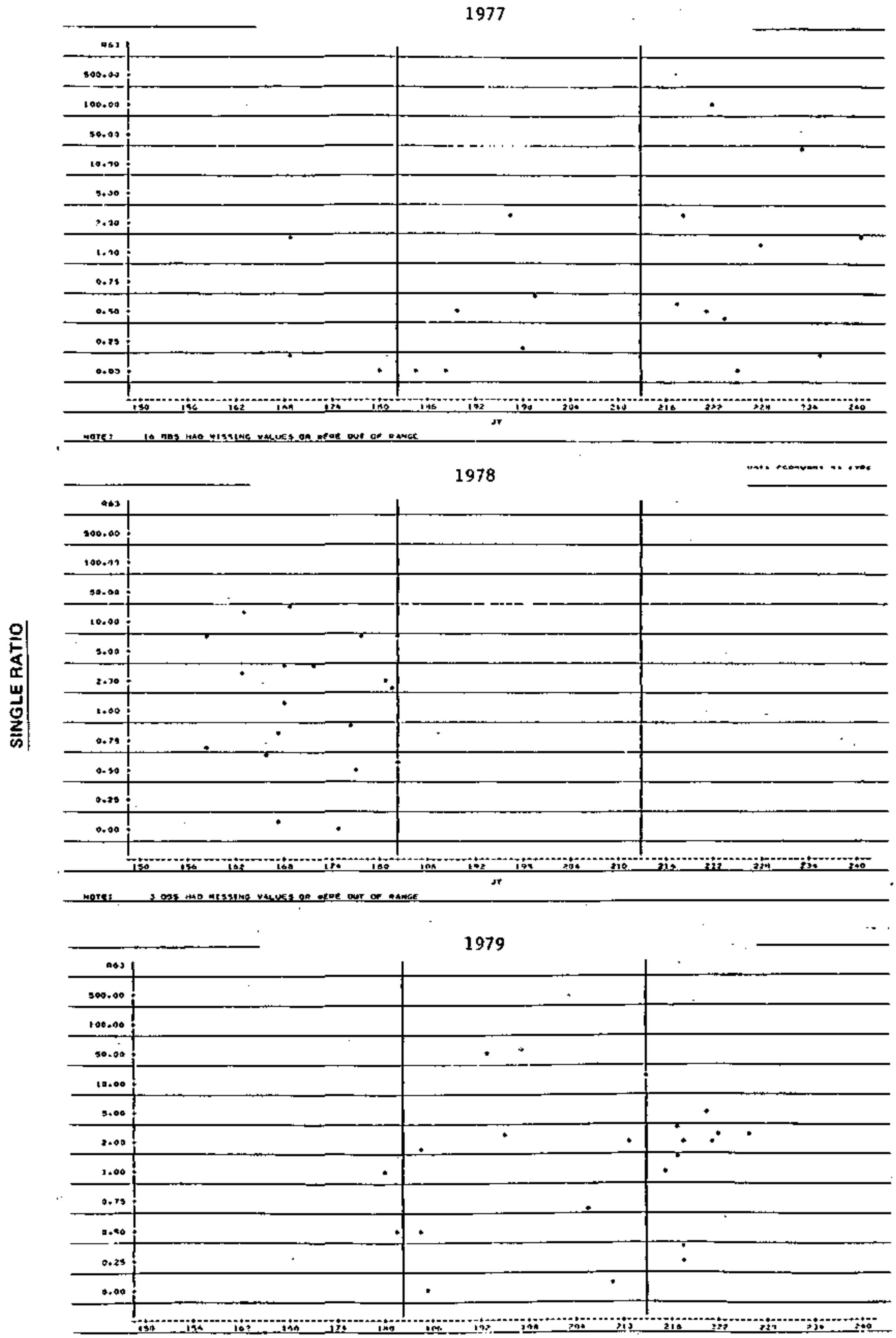

Figure 14c. R63, the single ratio of the south over-lake (X6) over the north over-lake (X3).

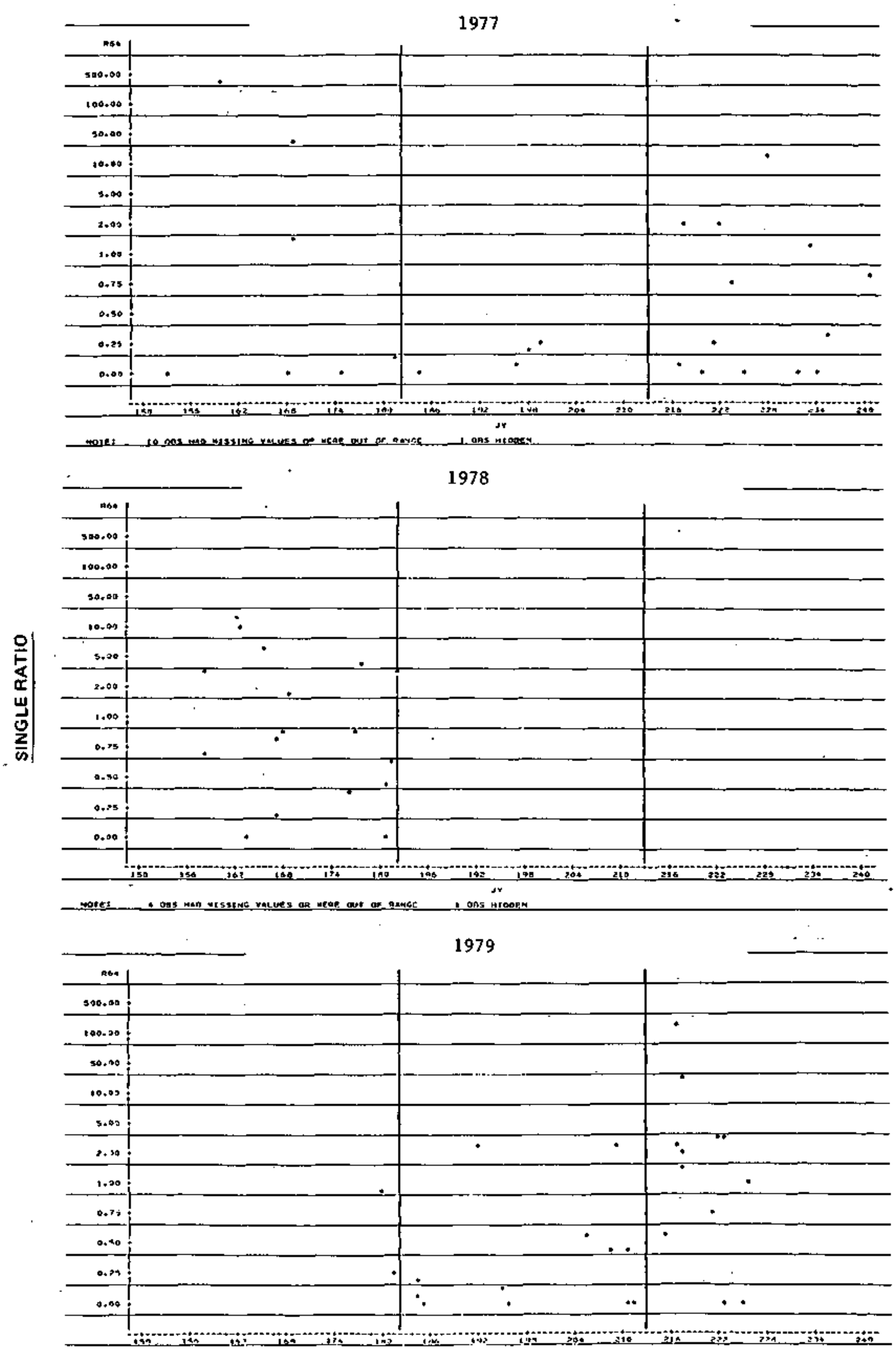

Figure 14d. R64, the ratio of the south over-lake (X6) over the west rural (X4).

and August 1979, the distributions of DR5241 and DR6341 showed a distinct pattern that their magnitudes were larger than 1.0; the majority of DR's in other months had magnitudes less than 1.0.

The above double ratio was computed from each rain period, hence its distribution had a relatively large variance. Another kind of double ratio was computed by first taking the average of rains from 87 storms for each area, and then computing the simple and double ratios as above. The DR thus calculated for 3 summers was 1.211 in the 5241 comparison, and 1.325 in the 6351 comparison. In other words, 21.1% more rainfall occurred over City when adjusted by the 3 controls; while 32.5% more rainfall occurred over South Lake when similarly adjusted.

To assess the statistical significance of these rain differences, re-randomization testing was carried out for each of the (averaged) double ratios. Only a brief outline of the procedure is described (see Hsu, et al. (1981) for more details). For either 5241 or 6341 comparisons, each re-randomization exchanges certain observations of target variable pairs, e.g., (X5, X2), with the same number of observations of control variable pairs, e.g., (X4, X1); and then re-calculates a new DR. The orientation of the variable pair, south-north in this example, was thus kept intact in the re-randomization procedure. The underlying logistic (null hypothesis) for this re-randomization testing is that if the City exerted no influence on the summer rainfall, then the distributions of both simple ratios (R52 and R41 in the example) would be identical, hence they can be pooled as though coming from a single distribution. Five hundred re-randomizations were performed. The number of (re-calculated) DR which were larger than or equal to the observed DR (1.211 in the 5241 comparison) was, by

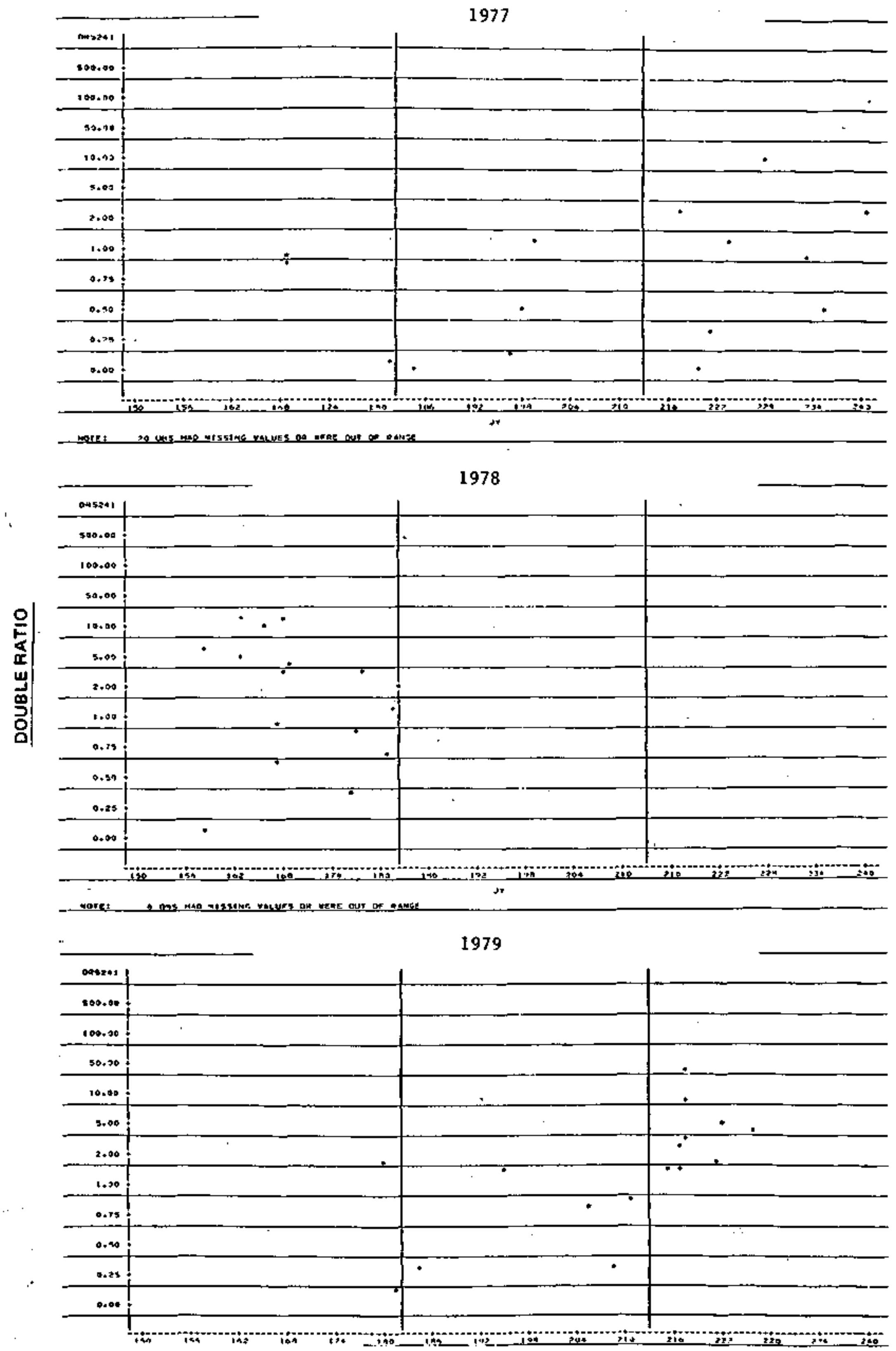

Figure 15a. DR 5241, the double ratio of R52 over $41.

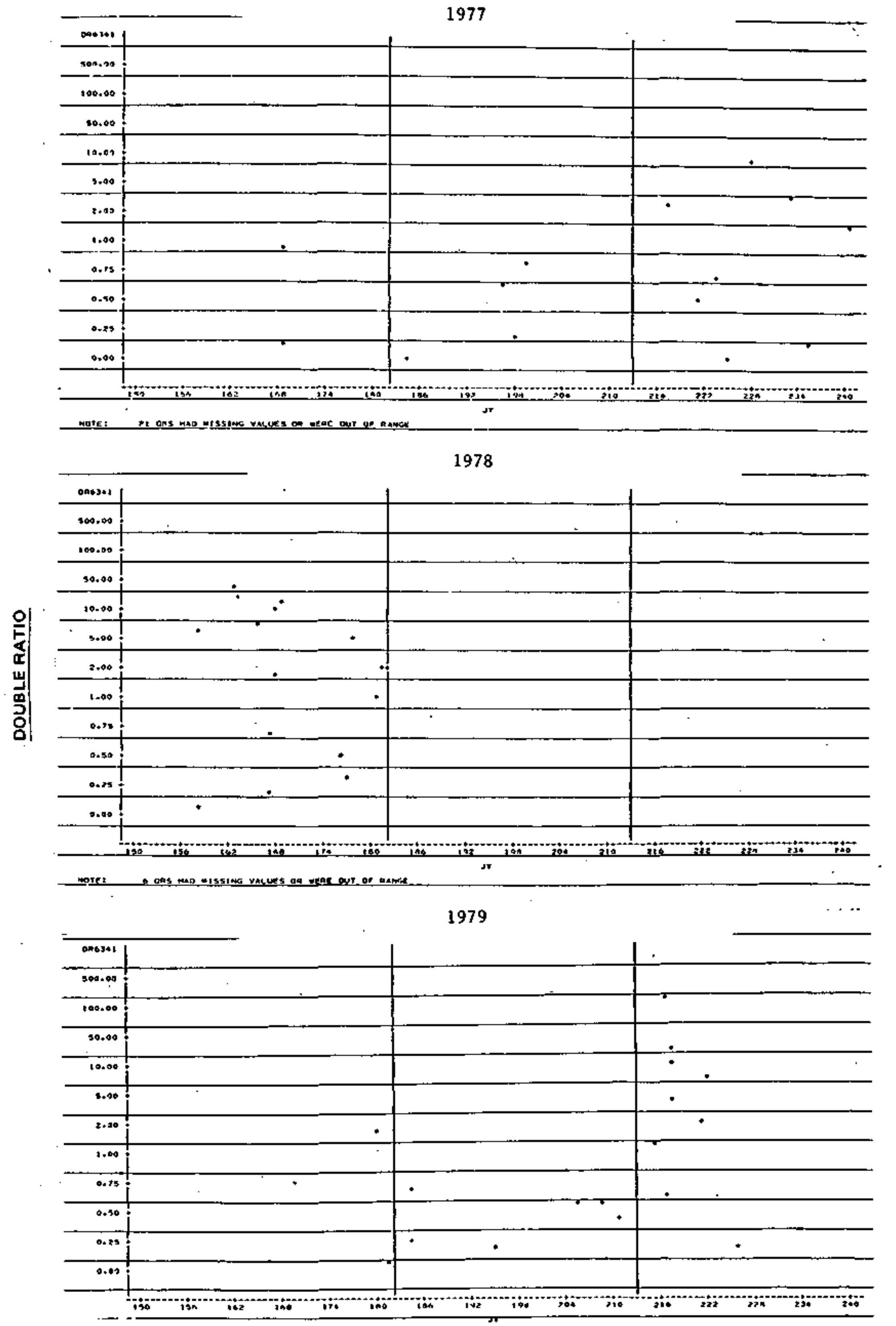

Figure 15b. DR 6341, the double ratio of R63 over R41.

definition, the P-value. The DR and its P-value, as well as other similar testing statistics and their P-values are shown in Table 15. The P-values of the four statistics did not indicate that City or the South Overlake had significantly more rain than the Controls.

Analyses Excluding the Storm of June 25, 1978. It was mentioned earlier that the areal rains of the storm on June 25, 1978 were extremely heavy. The differences between the maximum rain period and the second largest rain period were especially large in the four rural areas (Fig. 13). A statistical test to discern whether these extreme values were "outliers" was carried out using the following test statistic (Barnett and Lewis, 1978)

$$T = X_{(n)} / N\bar{x}$$

where $X_{(n)}$ D is the maximum observation, N is the total number of observations, and $\bar{x}$ is the mean of N observations. In using this test, an exponential distribution had been assumed for each of the six areal rains. This was fairly reasonable by looking at the bar charts in figure 13. For the 87 storms, the values of T for X1 through X6 were respectively .142, .167, .137, .249, .091, and .088. The first four T values were significant at 1% level (by extrapolating values in Table I of Barnett and Lewis, 1978). This test confirmed statistically that the rain period on June 25, 1978 was an "outlier" storm.

Furthermore, the isohyetal map (Fig. 16) of rainfall for this storm shows that there was a major high in the southwestern region. A band of minimum rainfall ran from northwest to southeast and separated the West Rural area from the other five areas. Motion of storm elements was studied and it revealed that the rain cells on June 25, 1978 had already released most of their rain

Table 15. Ratio-Differences and Their P-Values, 1977-1979*.

	$\dfrac{\bar{T}_s \quad \bar{C}_h}{\bar{T}_h \quad \bar{C}_s}$	$\bar{T}_s - \bar{T}_h - \bar{C}_s + \bar{C}_h$	$\bar{T}_s/\bar{C}_s - \bar{T}_h/\bar{C}_h$	$\bar{T}_s/\bar{C}_h - \bar{C}_s/\bar{C}_h$
5241	1.211 (.174)	1.321 (.164)	.192 (.174)	.212 (.136)
6341	1.325 (.128)	1.770 (.140)	.257 (.132)	.328 (.080)
		Excluding 6/25/78 Storm		
5241	1.509 (.016)	2.448 (.012)	.450 (.016)	.499 (0.016)
6341	1.600 (.026)	2.655 (.026)	.477 (0.026)	5.29 (0.016)

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* = T_s: City (X5) or South Overlake (X6)

T_h: N. Rural (X3) or North Overlake (X2)

C_s: West Rural (X4)

C_h: NW Rural (X1)

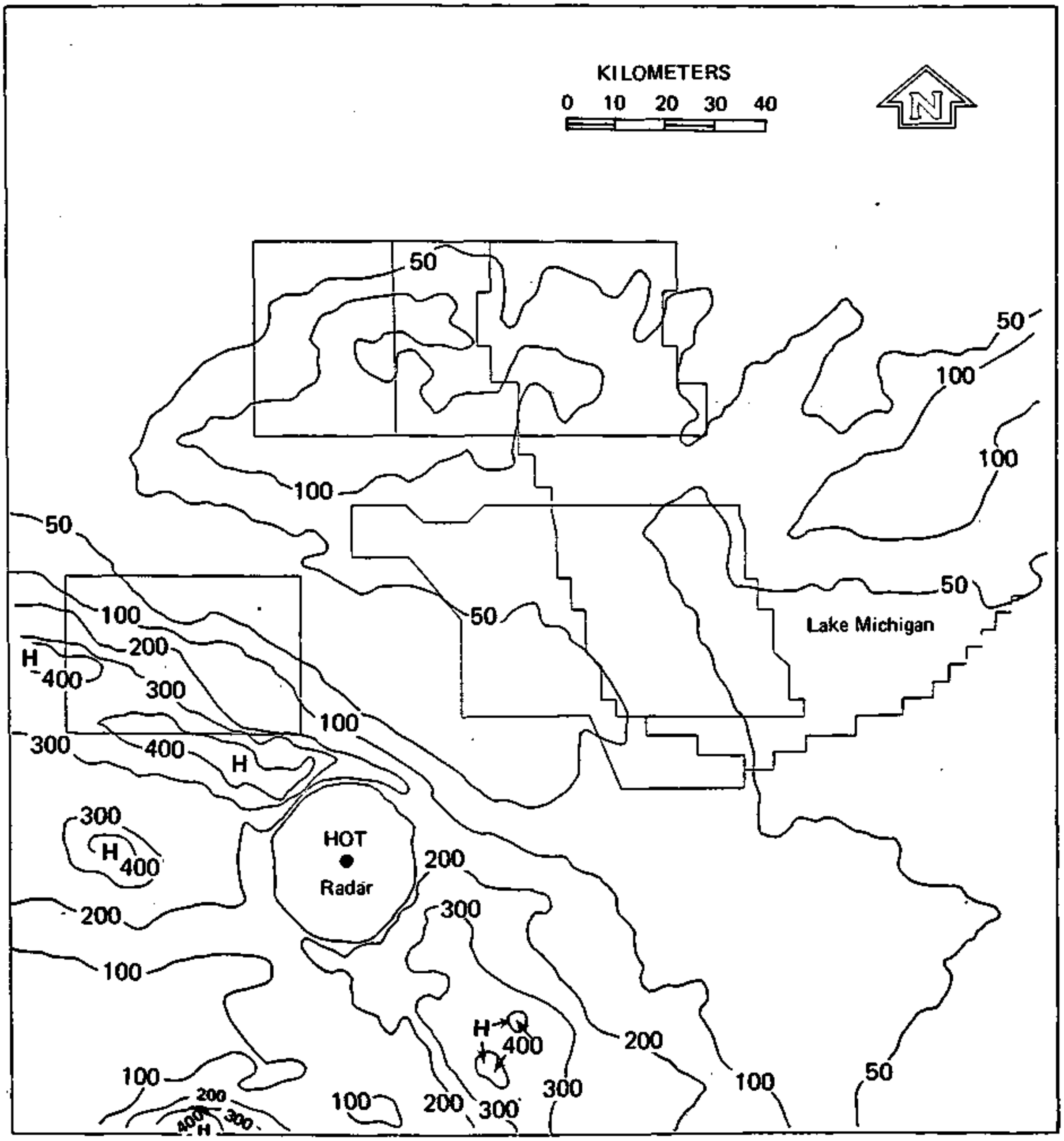

Figure 16. Total rainfall pattern of the rainstorm on 25 June 1978, in millimeters.

west to the City before passing over the urban and lake areas. The effect of City on this storm, if any, would be very difficult to establish using the target-control comparison because of the overwhelming magnitude of rain falling in the upwind area of City. For these reasons, statistical comparisons of these six areas for the 3 summers were conducted after excluding the rains of June 25, 1978.

The descriptive statistics of the six areas (Table 16) clearly indicate the changes in the characteristics of distributions after deleting the outlier storm. Comparison of results in Table 16, with figure 13 reveals the following changes occurred: 1) all 6 means were smaller, and 2) the coefficient of variation (C.V.) in the four control areas was decreased by 10% to 180-206. The C.V.s in all six areas were thus more homogeneous than those including the outlier storm (Fig. 13). Similarly, the skewness in the four control areas was reduced to 2.00-3.74, and was more compatible with those of the two target areas. Importantly, the C.V. and skewness of the two targets (calculated after deleting the outlier) were very close to those when the outlier was included, an indication that the distributional characteristics of the two targets were only slightly altered after deleting the outlier storm.

A similar re-randomization procedure was conducted for the outlier-excluded sample of 86 rain periods and the same test statistics were used. Results were shown in Table 15. All the statistics were significant at the 5% level. There were 50.9% more rain in City than the controls; and 60.0% more rain in South Overlake. If one is willing to accept the evidence presented earlier that the storm on June 25, 1978, had different characteristics than the other storms and thus must not be included in the statistical analyses, then

Table 16. Descriptive Statistics of Areal Rain, mm, 1977-1979, and Excluding the Storm on June 25., 1978.

NW Rural	N Rural	N. Overlake
Mean : 5.96	Mean : 5.27	Mean : 4.75
C.V. : 180	C.V. " 189	C.V. : 186
Median : 0.25	Median : 0.62	Median : 0.91
Skew : 2.00	Skew : 2.96	Skew : 2.96
W. Rural	**City**	**S. Overtake**
Mean : 5.26	Mean : 7.01	Mean : 6.70
C.V. : 206	C.V. : 174	C.V. : 171
Median : 0.79	Median : 1.06	Median • 1.41
Skew : 3.74	Skew : 2.17	Skew : 2.23

Table 17. Ratio-Differences and Their P-Values by Year.

		$\frac{\bar{T}_s \bar{C}_h}{\bar{T}_h \bar{C}_s}$	$\bar{T}_s - \bar{T}_h - \bar{C}_s + \bar{C}_h$	$\bar{T}_s/\bar{C}_s - \bar{T}_h/\bar{C}_h$	$\bar{T}_s/\bar{T}_h - \bar{C}_s/\bar{C}_h$
1977	5241	1.14 (.310)	.29 (.264)	.15 (.314)	.19 (.250)
	6341	0.86 (.618)	-.17 (.564)	-.21 (.624)	-.19 (.666)
1978	5241	1.12 (.414)	1.45 (.438)	.10 (.418)	.14 (.352)
	6341	1.08 (.442)	.53 (.492)	.07 (.442)	.10 (.420
1979	5241	1.46 (.108)	2.39 (.118)	.42 (.100)	.30 (.180)
	6341	2.16 (.036)	4.79 (.036)	.75 (.034)	.75 (.070)
			Excluding 6/25/78 Storm		
1978	5241	1.67 (.032)	6.31 (.024)	.55 (.046)	.70 (.020)
	6341	1.46	4.28	.38	.47

the comparisons indicated that the rains which occurred over City and its downwind area (South Overlake) were significantly more than those occurred in the upwind control areas during the summers of 1977-1979.

Analyses by Year. The time series plots of simple ratios and double ratios in figures 14a-d and 15a-b were values for each rain period. Differences of these ratios between years were discussed previously. For each year, rainfall anomalies over City and the downwind (South Lake) area, as well as their significance levels, were studied. Similar re-randomization procedures were applied to the storms of each year, using the double ratio and their derivatives as statistics. The results are shown in Table 17. There was more rain in City and South Overlake, when compared to the control areas, in each year except in one case. In 1977 there was less rain over South Lake than in the control areas. The differences of rain were in the 10% range in 1977 and 1978; but was more profound in 1979 — 46% in City and 116% over the Lake. The latter difference was significant at the 5% level.

If the storm on June 25, 1978, was excluded from the analyses, the differences were 67% more rain in City and 46% more rain over South Lake, with the former significant at the 5% level. The time series plots of double ratios revealed that in 1978 there were fewer smaller DR and more larger DR in the 5241 comparison (Fig. 15a) than in the 6341 comparison (Fig. 15b). On the other hand, the reverse was true in August 1979.

A look at the rain motion by year (Table 18) revealed that there was a change of motion from a majority of west in 1977-1978 to a majority of northwest and southwest in 1979. In addition, there were more squall zone storms (13) in 1979 than in 1977 (6) and 1978 (8). This might provide insight as to the shift of a significant rainfall anomaly from over City in 1978 to the South Lake in 1979.

Table 18. Annual Frequency of Storms by Storm Motion.

	Direction of Storm Motion			
	NW	SW	W	Total
1977	8[1]	5	22	35
	9.20[2]	5.75	25.29	40.23
	22.86[3]	14.29	62.86	
	20.77[4]	19.23	62.86	
1978	4	6	11	21
	4.60	6.90	12.64	24.14
	19.05	28.57	52.38	
	15.38	23.08	31.43	
1979	14	15	2	31
	16.09	17.24	2.30	35.63
	45.16	48.39	6.45	
	53.85	57.69	5.71	
Totals	26	26	35	87
	29.89	29.89	40.23	100.00

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(1)Year

(2)Frequency Percent

(3)Row Percent

(4)Column Percent

CHARACTERISTICS OF RAINCELLS

Introduction

The other major investigation of this project involved the study of characteristics of individual raincells. A raincell was defined as a single precipitation entity with one identifiable core. To be classed as a cell in the analytical procedure, a cell had to be ≥ 12 sq mi (3 contiguous grid squares); have a rain intensity of > 4 mm/hr; and exist for 15 minutes or more. This definition includes only a portion of all "radar echoes", and basically represents a class of rain-producing cells of a moderate to large class (Changnon, 1981). In other words, small, short-lived cells often detected by a radar were excluded from the analysis by this definition.

The approach to the study of raincells, with the belief that a 3-summer sample provided a large and representative sample, involved various frequency analyses. The characteristics of cells were studied on a land use basis and on a synoptic weather type basis in a manner used by Schickedanz (1974). In the land use analysis, only 3 major land use types were used. The urban class included the city shown on figure 11 (or the city core, inner residential, and industrial areas depicted in Fig. 9). The lake area included all of the lake in the square-shaped study area, and the rural area was the remaining portion of the study area which totaled 16,384 mi^2. As shown in Table 21, the rural area comprised 66% of the total study area, the lake 31%, and the urban area 3%.

Table 19 presents the frequency of raincells sorted by land use categories. The values are presented according to the sequence of land use areas the raincell crossed during its lifetime. For example, 1,013 raincells spent their entire lifetime only in the rural area, whereas 94 raincells began in the rural area and moved into the lake. Some 135 raincells spent a portion of their lives over the urban area. Table 19 reveals a wide variety of motion for these 135 urban cells. Table 19 also shows the average dura.tion (in minutes) of the centroid of the rain cells over the urban areas. Most urban durations typically ranged from 10 to 20 minutes.

Table 19. Number of Rain Cells Sorted by Land Use Categories and Based on Life History of Each Rain Cell.

Non-Urban Cells		Urban Cells		Average Duration (Min) Over Urban Area
Rural-only	1,013	Urban-only	14	18
Lake-only	378	Rural-to-urban	31	10
Rural-to-lake	94	Urban-to-lake	24	12
Lake-to-rural	31	Urban-to-rural	12	13
Sub-total =	1,516	Lake-to-urban	2	15
		Rural-urban-rural	23	10
		Rural-urban-lake	24	17
		Urban-lake-rural	3	38
		Urban-rural-lake	1	16
		Rural-lake-urban	1	6
		Sub-total =	135	

Table 20 presents the frequency of raincells for each of the seven synoptic weather types that occurred during the three summers. The prime producer of cells were the 27 squall zone rain periods which yielded 733 of the raincells. Fifty-nine of the squall zone cells existed during portions of their lifetime over the urban area. The total number of urban cells, 135 represented about 8% of the 1,651 total cells. The average number of cells per rain period (Table 20) shows that the synoptic weather type producing greatest number of raincells was a warm front followed by squall zones with 27 cells as an average. The number of cells produced by air mass conditions was much smaller.

Certain characteristics were determined for each of the raincells for use in the land use and the synoptic weather type comparisons. These characteristics included place of initiation of cells; mean cell motions (speed and direction) based on cell lifetime; its duration between inception and dissipation, the yield of water expressed as the total volume of water produced by the cell during its lifetime. Four cell characteristics were based on the cell's rain rate and size measured during each scan (every 3 to 5 minutes) of the radar of the cell. These instantaneous portrayals of the cells were used to calculate 1) the average instant rain rate and size (based on all radar scans), and 2) the peak (largest) instantaneous single value of rain rate and size any time during the life of the rain cell. Again, the averages of the instantaneous rate and size values of the cells was developed from all the values scanned during the lifetime of the echo.

Also determined was the geographical distribution of mergers of two or more rain cells. Prior research (Changnon, 1975) indicated that merging of cells in the St. Louis area was followed by increased rainfall rates. The

Table 20. Number of Rain Cells for Each Synoptic Weather Type.

Type	Total Cells	Average Number Per Rain Period	Cells Over Urban Area[1]
Squall lines	203	14	33
Squall zones	733	27	59
Cold fronts	230	15	15
Air masses	75	8	0
Stationary fronts	288	19	21
Warm fronts	109	36	7
Pre-cold front	13	13	0
Totals	1,651		135

(1) For partial or total lifetime of cell.

comparisons of rain cell characteristics were based on use of averages calculated from the total sample, either by land use areas or by synoptic weather types. There was no attempt to compare cell extremes, only their averages.

Raincell Characteristics Associated with Land Use Areas

Initiation of Raincells. The number of initiations of raincells for the three major land use categories is shown in Table 20. This shows that 72% of all the raincells initiated in rural areas, with 25% over the lake, and 3% over the urban area. Also provided in Table 21 are land area extents. Comparison of the percentages of the land area with those of the raincells reveals that

Table 21. Rain Cell Initiations by Major Land Use Areas.

Land Use Areas	Number of Cells	Percent of Total Cells	Land Areas Square Miles	% of Total
Rural	1,186	72	10,844	66
Lake	411	25	4,980	31
Urban	54	3	560	3
Total	1,651	100	16,384	100

the urban area had the frequency expected for its areal size, but that the lake area had fewer initiations than its areal size would have indicated, 25% of the cells vs 31% of the area. These statistics do not suggest a general urban enhancement of cells (as defined herein), but they do indicate a decrease in initiations of raincells due to lake effects. Braham and Dungey (1978) found an urban related increase in echo initiations using a 3-cm wavelength radar, but these were often less intense cells than defined in this Chicago study using a 10-cm wavelength radar.

Table 22 presents the average raincells values for the three major land use areas. Comparison of the averages reveals that the urban raincells were longer lasting, faster, and with greater intensification sometime during the lifetime (greater peak values of both rainfall rate and of size) than were the rural or lake cells. Conversely, the lake raincells were the least longest lasting, had the smallest total volume, lowest average rain rates and peak rates, but had the largest average size of the three classes of echoes. This indicates that a cell at any given time was a broader cell but with lower rates. Coupled with a short duration; the lake cell yields a low total volume of water. This agrees with general lake suppression of convective activity noted by Lyons and Wilson (1968).

Table 22. Average Rain Cell Values.

		Duration,	Speed,	Mean	Total	Rain Rate, mm/hr(2)		Size, in mi (2)	
	Number	Minutes	mph	Direction	Volume[1]	Average	Peak	Average	Peak
Lake-only	378	32.4	26.3	275°	224.4	39.3	54.7	82.3	137.8
Rural-only	1,013	36.8	25.4	284°	267.1	47.1	64.1	78.7	133.4
Urban	135	41.3	35.8	284°	249.7	41.4	66.6	70.4	147.1

[1] Multiply by 1500 to obtain volume in cubic meters.

[2] Values based on sizes at scan times, not lifetime of cells.

The rural raincells had the heaviest average rainfall rate and had the greatest yield of water, probably because they were slower moving. The data in . Table 22 suggests that urban influences caused raincells traversing the urban area to be intensified and to last longer than others. The results also suggest that lake effects act to diffuse echoes decreasing convective strength with less rainfall at any given instant (and hence over lifetimes) and shorter duration. In the net, the lake decreases the convective strength of cells.

The cell characteristics based on their traverses over various land uses were compared. The values for the 10 most frequent types (based on land use areas traversed) were compared and ranked. These ranks appear in Table 23. Rank 1 means either the fastest speed, the longest duration, the largest volume, etc. For example, the rural cells ranked 9th in speed (slow), 6th in duration, 3rd in total volume, etc. The ranks for each cell type shown in Table 23 were totalled and averaged to get an average cell score for each of the land use combinations. The results show that on the average, the cells that developed over Lake Michigan and moved over the rural areas to the south of the lake were the largest, and were moderately high ranked in all categories. The next two highest ranked classes of raincells were the Rural-Urban-Rural cells (typically moving from the north-northwest to the southeast), and the Rural-Urban-Lake cells. The R-U-R raincells were large and quite intense although low-ranked in total rain volume. The R-U-L raincells were faster and produced a larger volume of water (ranked second). The Rural cells were relatively long-lasting, and the Urban-Lake cells were biggest rain volume producers. Interestingly, the U-L and R-U-L cells (both traversing the urban and lake areas) were the two largest producers of rain. Conversely, the Rural-to-Urban and Urban-only raincells ranked quite low in most all raincell characteristics. In general, the results suggest a possible interaction of urban and lake influences that collectively enhance rain production. The

Table 23. Rank of Mean Values of Cell Characteristics.

Land Use Areas Traversed by Cells[1]	Number	Speed	Duration	Total Volume	Rain Rate Average	Rain Rate Peak	Cell Size Average	Cell Size Peak	Average Score
R	1,013	9	6	3	4	7	4	5	5.4
L	378	8	7	4	8	9	3	4	6.1
U	14	10	10	10	6	3	10	10	8.4
RU	31	7	8	6	9	10	9	8	8.1
RUR	23	5	2	7	1	2	2	2	3.0
RL	94	3	1	8	2	4	6	6	4.3
RUL	24	1	3	2	7	6	5	3	3.8
UL	24	2	5	1	10	5	8	7	5.3
UR	12	6	9	9	5	8	7	9	7.6
LR	31	4	4	5	3	1	1	1	2.7

[1] R = Rural
L = Lake
U = Urban

results further suggest that raincells developing over Lake Michigan, and that move on over the land, are effected considerably with enhancement of their size and rainfall rate.

Mergers of Raincells. The 3-summer sample included 851 mergers of 2 or more raincells, and the points of merger were recorded as being in the urban, rural, or lake areas. Their distribution is shown in figure 17. The urban area had a relatively high density of mergers as do the rural areas west and north of the city. The south lake area, beginning 6 to 10 miles east of Chicago, also has a relatively large number of mergers. These four areas of greater frequency of merging cells are where the 3-summer total rainfall is greatest (Fig. 3d). Of course, mergers are more apt to occur when there are more cells per unit area or larger cells. Regardless, prior research has shown that mergers of precipitation entities often yield heavy rains. Within the urban area, one also notes a concentration of mergers parallel to the lake and anywhere from 2 to 10 miles inland, suggesting lake influences.

The rural area had 521 mergers, 61% of the total mergers occurring within 66% of the study area. The lake area had 27% of the mergers (in 31% of the area). Importantly, the urban area had 12% of the mergers in only 3% of the area, as shown in Table 24. The quadrupling of mergers in the urban area, 3% area with 12% mergers, certainly suggests a major enhancement of cell interactions over Chicago.

Also shown in Table 24 is the frequency of all 852 mergers expressed as the number per square mile. That is, in each of the land use areas, the total number of mergers were divided by the area size. In the urban area, the merger

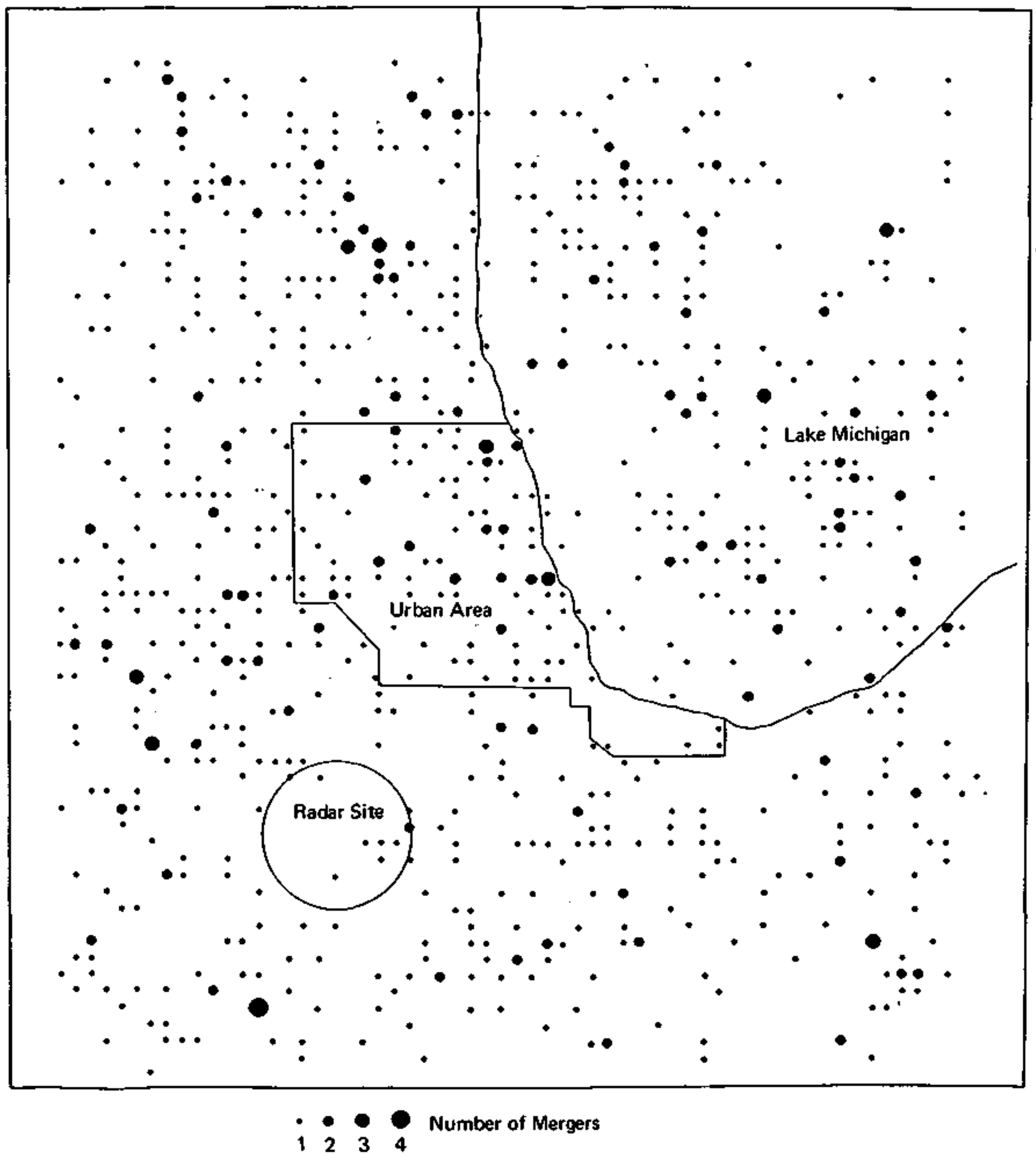


Figure 17. Frequency distributions of mergers of raincells for the summer 1977-1979.

Table 24. Frequencies of Raincell Mergers and Initiations.

	Mergers Squall Lines		Mergers Squall Zones		Mergers Cold Fronts		Mergers Stationary Fronts		Total Mergers	
	No.	%	No.	%	No.	%	No.	%	No.	%
Rural	68	49	283	64	68	65	38	60	521	61
Lake	38	28	120	27	28	27	15	23	230	27
Urban	32	23	41	9	9	8	11	17	101	12
	138		444		105		64		852	100

Average number of square miles per merger and per raincell initiation

	Urban	Lake	Rural
Initiation	10.4	12.1	9.2
Merger	5.5	21.7	20.8

frequency is 1 per 5.5 sq mi, much more frequent than the 21.7 value over the lake and 20.8 number per square mile over the rural area. Comparison of these numbers suggests a slight reduction in merger frequency, about 5% (21.7 - 20.8 ÷ 20.8) over the lake area, in relation to the rural area. The urban value of 5.5 is nearly 4 times the rural area value, further reflecting the potential of urban enhancement.

Raincell Characteristics with Various Synoptic Weather Types

Initiations of raincells were classified according to the five primary synoptic weather types and by the three major land use areas. The cell initiation frequencies are shown in Table 25 and the frequencies are also expressed as percent of the total cells with each synoptic type. For example, squall lines produce 136 raincell initiations in the rural area, and these represented

67% of the squall line initiations. This percentage can be compared with the percentage of area comprising the rural area, 66%, or equivalent in this situation.

By using the 31% of the study area in the lake, and comparing it with the initiation percentages in Table 25, one discovers that all synoptic weather types have lesser percentage values, ranging from 18% (stationary fronts), up to 30% (air mass). Obviously, the lake acts to suppress the initiation of convective activity under all rain-producing weather conditions.

The urban area comprise 3% of the total study area, and comparison of this value to those with the synoptic weather types on cell initiations reveals a significant increase in the squall line cells; 8% initiated in the city which is only 3% of the total area. Stationary fronts also showed some enhancement with a percentage of 4% as compared to 3% for area. Initiations of cells with squall zones showed no urban influence, and initiations with cold front conditions in the urban area were only 1% of their total, suggesting urban diminishment of initiations. Most of these results agree with those found at St. Louis which showed a general enhancement of cell initiations over the city (Changnon, et al., 1981), and with the greatest influence occurring in the well organized squall line and stationary frontal conditions.

In general, the distribution of raincell initiations by land use with squall zones showed very little influence of either the lake or the city. Cold fronts showed major effects from land use, with the lake value of 22% (versus 31% of the area), as well as the 1% urban value (versus 3% in entire area). Stationary fronts indicated lake-related diminishment of cell initiations, but with urban enhancement, as did squall lines.

Table 25. Frequency of Rain Cell Initiations by Major Land Use Areas and By Synoptic Weather Types.

	Rural		Lake		Urban		
	W	% of total	N	% of total	N	% of total	Initiation totals
Squall line	136	67	51	26	16	8	203
Squall zones	507	69	201	28	25	3+	733
Cold fronts	180	77	47	22	3	1+	230
Stationary fronts	225	78	53	18	10	4	288
Air mass	52	70	23	30	0	0	75
Totals	1,100	72	375	24	54	4	1,529
Percent of area	66		31	0		3	

The average characteristics of raincells crossing the urban area, and classified according to the four major synoptic weather types producing most urban cells (126 cells of the 135 urban total), are presented in Table 26. Comparison of the average characteristics of the 4 synoptic types reveals the following. Squall line cells that crossed over Chicago were relatively short-lived and slow moving, but with relatively large rainfall rates, sizes, and volume. Squall zone cells crossing the city were fast moving and yielded little total water at any given time and had low rates. Cold front cells crossing Chicago were long-lived and fast-moving but with large sizes (at any given instant) but with low rainfall rates and a low volume of rainfall produced during their lifetimes. Stationary front raincells crossing the city were long lasting with small instant size but with high rainfall rates and production of a large volume of water. In their rainfall production, the stationary frontal cells resembled those of the squall line.

These raincell characteristics are consistent with the values related to the initiations in Table 25. That is, the squall line and stationary frontal raincells that existed over the urban area were the major rain-producers (ranked 1 and 2 in volume, rain rate, and peak rain rate), and they also are the slowest of the four weather classes. The cold front cells over Chicago, which are indicated to have their initiations suppressed, produced the lowest volume of rain and moved the fastest, revealing internal consistency. The results of the speed, rain rate, and volume suggest that squall line and stationary frontal cells are the major producers of rainfall over the city, and that cold front and squall zone cells are lesser producers of rain over the city, on the average. Whether the differences reflect any urban influences is not discernible from the values in Table 26.

Values in Table 27 allow an interpretation of possible urban influences on characteristics of raincells under different synoptic weather conditions. The average cell values of the urban cells, sorted by synoptic types, were compared with those of rural cells. The resulting differences appear in Table 27. Study of these differences reveals that the squall line raincells of the urban areas were notably larger, faster moving, longer lived and much greater rain producers than were the rural raincells produced by squall lines. Urban enhancement is suggested by the differences in all cell characteristics. The urban raincells with stationary fronts were faster, longer lived and with much higher rainfall rates and volumes than their rural counterparts, but their areas, at any instance, were smaller on the average, than rural values. Again, urban enhancement seems evident. Conversely, the raincells over the urban area with squall zones showed slight decreases in duration and rainfall rates

Table 26. Average Values of Characteristics of Cells Over the Urban Area for Each Synoptic Weather Type.

Synoptic Type	Number of, Cells	Duration, Min	Speed, mph	Direction	Volume[1]	Rain Rate, mm/hr[2] Average	Rain Rate, mm/hr[2] Peak	Size, mi² (2) Average	Size, mi² (2) Peak
Squall lines	33	36	30	248°	302	57	87	88	141
Squall zones	59	37	33	283°	214	37	54	68	132
Cold fronts	15	46	37	257°	169	31	48	114	235
Stationary fronts	19	50	31	284°	340	47	74	46	74

(1)Volume value x 1500 = m^3.

(2)Size based at any given instant (period) of measurement (scan).

Table 27. Differences in Average Values of Characteristics of Urban and Rural Rain Cells, Sorted by Synoptic Weather Types.

	Difference, U-R						
Synoptic Type	Speed, mph	Duration, Min	Volume[1]	Rain rate, mm/hr[2] Average	Rain rate, mm/hr[2] Peak	Size, mi² (2) Average	Size, mi² (2) Peak
Squall lines	2	8	174	11	24	24	34
Squall zones	7	-3	-109	- 6	- 2	-28	-32
Cold fronts	13	5	-116	-18	-24	50	130
Stationary fronts	10	24	142	6	14	29	-48

(1)Volume value x 1500 = m^3.

(2)Size (mi^2) at any instant of scanning.

(average and peak), resulting in a lesser volume of rainfall (about a 30% decrease). In general, there is a suggestion that urban influences acted to decrease rainfall yield of squall zone raincells. Similarly, the urban raincells with cold fronts showed a mixture of influences. The cold front cells that crossed over the city were faster, lasted longer, and were larger than their rural counterparts; however their rainfall rates and yield of precipitation were markedly less than the rural cells.

The areal frequency of mergers for the major synoptic weather classes is shown in Table 24. The percentages for the urban area, in all synoptic types, exceed the areal extent of 3% in the urban area, indicating enhancement of cell merging over Chicago. The greatest percentages, or relative enhancements, occur with squall line and stationary frontal conditions. This agrees with the raincell initiation findings.

In summary, urban influences on the raincells acted, under squall line and stationary frontal conditions, to initiate cells, to cause mergers and to intensify them and their rain production. Conversely, a slight influence to diminish squall zone raincells is suggested for squall zones, with a stronger suggestion that the urban area acts to diminish precipitation rate and total volume of cold frontal cells and initiations.

Raincell Characteristics with Varying Degrees of Convective Organization

A third category of raincells was employed to discern possible urban influences. This related to classification of the rainfall by whether it was produced by nearly solid, well-organized lines of cells; by semi-organized groups of cells called squall areas; or by isolated unorganized cells. Table 28 presents the average raincell characteristics related to these three classes of varying convective organizations. One notes that their direction of motion varied considerably from west-southwest with lines, to west for squall area cells, and northwest for the isolated cells. The cells with the lines were short-lived, fast moving, and with high rainfall rates. Conversely, the isolated cells were slow moving, had low rainfall rates, small sizes and small volumes of rainfall produced. The squall area cells produced the highest average volume of water.

The averages of the convective conditions associated with the urban raincells were compared with those of rural raincells. The differences appear in Table 29. There were too few urban cells in the isolated category to make valid averages. Examination of Table 29 reveals that the urban cells were superior to their rural counterparts in every sense. The urban volumes were much larger, as were their rainfall rates and sizes. The squall area raincell comparison revealed that the urban cells were slightly longer lasting and faster moving with slightly higher average rainfall rates. However, their areas were smaller on the average, resulting in a smaller volume of rainfall. These results, which are in general agreement with those on synoptic weather types, suggest that the urban area exerts its greatest influence on raincells associated with well organized convective activity. In lesser organized activity such as found in squall areas, the urban effect appears to be mixed, possibly producing an increase in rainfall rate.

Table 28. Average Rain Cell Characteristics for Varying Convective Conditions.

	Number of cells	Duration, Min	Speed mph	Direction	Volume(1)	Rain rate, mm/hr(2) Average	Rain rate, mm/hr(2) Peak	Size, mi^2(2) Average	Size, mi^2(2) Peak
Lines	182	27.8	28.9	253°	183.2	47.3	65.9	68	112
Squall areas	1,363	39.8	26.7	282°	404.6	45.6	63.7	96	162
Isolated	75	29.1	22.1	298°	51.3	37.0	53.3	35	52

(1)Volume by 1500 = m^3.

(2)Sizes and rain rates at any instant of scanning.

Table 29. Differences in Average Values of Characteristics of Urban and Rural Rain Cells, Sorted by Convective Organization.

	Urban-Rural Differences						
	Duration, Min	Speed, mph	Volume(1)	Rain rate, mm/hr(2) Average	Rain rate, mm/hr(2) Peak	Size, mi^2(2) Average	Size, mi^2(2) Peak
Lines	+10	+1	+181	+14	+22	+21	+29
Squall areas	+3	+5	-160	+2	+8	-28	-39

(1)Volume by 1500 = m^3.

(2)Size (mi^2) at any instant of scanning.

SUMMARY AND CONCLUSIONS

This study had three objectives: 1) study of the distribution of summer rainfall over Lake Michigan east of Chicago and along the western shore to determine the presence and magnitude of urban effects; 2) study of the over-lake and shoreline rainfall patterns well away from Chicago to better estimate lake influences and actual over-lake rainfall values; and 3) investigate processes by which urban and lake effects might be altering summer rainfall.

To serve these objectives, precipitation data, as defined by a 10-cm radar for three summers, 1977-79, were utilized. After adjustment of the radar signal to point rainfall values, the radar values were used to estimate rainfall. Two basic investigations were made.

In one, various rainfall expressions for the entire area and on an event basis (rain period, monthly, and summer) were analyzed. The rain period, monthly, and summer rainfall analyses involved a) rainfall quantity, and b) rainfall rate. These were further studied by utilization of various land use areas and distances from lake shorelines, with rain periods further classified according to synoptic weather conditions, motions of rain, and degrees of convective organization.

The second broad area of study concerned individual raincells, the individual convective entities which typify surface rainfall patterns of thunderstorms and showers. The raincell statistics were also analyzed according to synoptic weather type, motion, and degree of convective" activity. Raincell characteristics were studied primarily to get better insight into the physical processes related to the lake and urban influences.

Since the research dealt with a large data sample and was hence more climatic and statistical than meteorological, the representativeness of the 3-summer (1977-79) sample was important, particularly as to whether it had sampled unique summer rainfall conditions which could affect the interpretation of the results. The radar data utilized was for 87 rain periods in the 3 summers which had sampled, on the average, 70% of the total 3-summer rainfall. The monthly and annual patterns of rainfall over the land areas appeared representative of long-term conditions, and agreed with the land rainfall patterns from the earlier raingage studies of the Water Survey (Changnon, et al., 1980). The monthly total rainfall patterns were representative of long-term conditions., although the July total rainfall in the sample indicated relatively dry conditions, whereas June and August totals sampled were near normal. Statistical investigations of the rain period durations, and the time of beginning of rainfall, revealed they were normally distributed and matched the general climatology. Hence, it was concluded that the 3-summer sample was generally representative of rainfall conditions in the Chicago area.

The persistent features found in the summer total rainfall maps of the three years are illustrated in figure 18. This includes three small highs over the city and close to the lake shore, and two other highs located 5 to 25 miles east of the city. Four areas of low precipitation were found in each of the three summer maps. These included two minor low rainfall areas along and just inland from the lake located north of Chicago and southeast of Chicago; a narrow north-south oriented low about 5 miles offshore; and a major low precipitation area located 25 or more miles east of the western "shoreline. The rainfall pattern north of Chicago shows a general west-to-east decrease beginning about 10 miles west of the western shoreline, eastward across the lake.

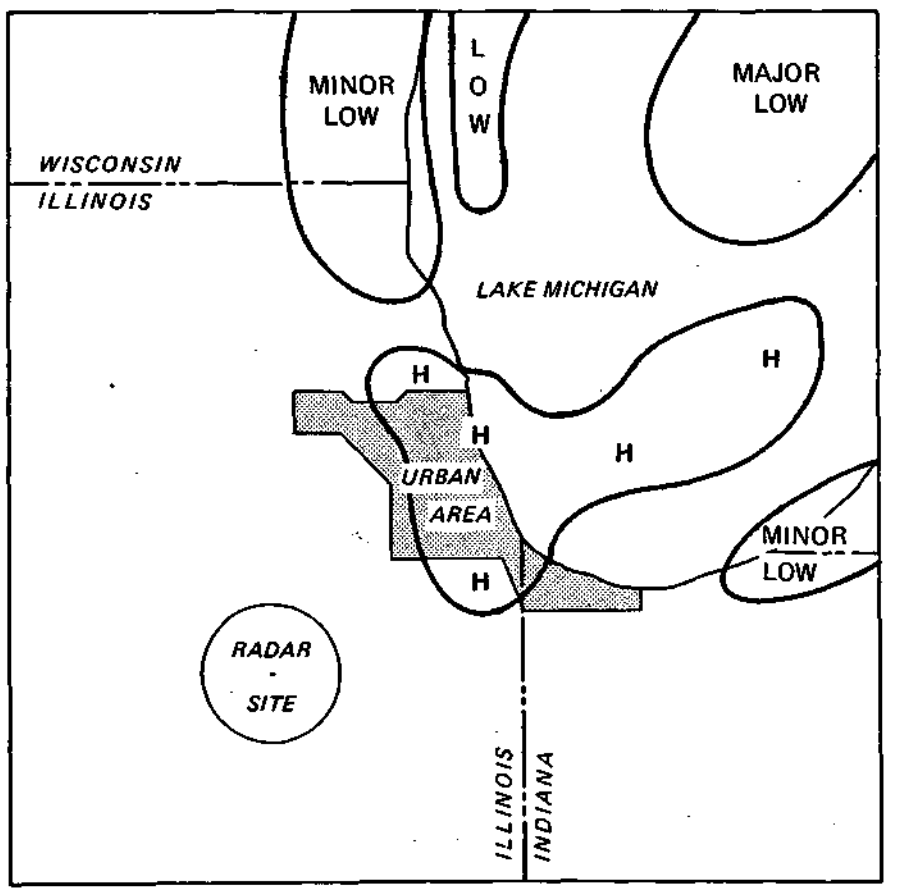


Figure 18. Persistent major features of the 3-summer rainfall patterns.

The 3-summer total rainfall maps for both June and August reveal major high rainfall areas over Chicago and extending eastward into southern Lake Michigan, suggesting urban influences on rainfall that begin over the city and extend eastward. However, the July rainfall pattern does not clearly show these apparent urban-related highs. In all three of the summer months, there are low rainfall areas parallel and just east of the western lakeshore, and then farther east over the central portion of Lake Michigan. Apparent lake-related rain lows appear on the western inland shoreline and along the south-eastern shore in both June and July. The August total rainfall pattern does not show these lake-related shoreline lows. It should be noted that lake temperatures, on the average, in August reach their maximum values with less lake stabilization of convection and hence lesser expected decreases of rain-fall in August than in June and July.

The analysis of total rainfall and rainfall rates for the seven major synoptic weather types that produced the 87 rain periods in 1977-79 revealed a major rainfall high over the city when squall line conditions occurred. This was in agreement with the earlier rain studies based on the dense raingage network in the area (Changnon, et al., 1980). Only very minor, if any, urban rainfall highs occurred with the other synoptic types although minor urban highs were associated with the air mass and squall zone conditions. The squall line rainfall pattern for the three summers produced a high in the northwestern suburbs, a high over the central city, and a high out to 35 miles east of Chicago and southern Lake Michigan. It also denoted the two major low rainfall areas in the lake north and east of Chicago. Importantly, the squall line rainfall pattern (based on 16 rain periods) largely controlled the configura-tion of the 3-summer total rainfall pattern. Without the squall line rainfall, the remaining rainfall pattern shows a general west-to-east decrease over both the land and lake area. The squall zone rainfall pattern did indicate a minor urban high with an over-lake rainfall high located 10 to 40 miles east of Chicago and the two notable lake low rainfall areas. All total rainfall patterns associated with each of the 7 synoptic weather types revealed a general eastward decrease in rain across the lake.

The studies of total rainfall classified according to rain motions (southwest, west, and northwest) revealed that the major features of the rain associated with southwestern motions were a high over the city (extending to the east northeast of Chicago) with the two low rainfall areas over the northern and eastern lake. The rainfall pattern with west motions of rain indicated a high in the rainfall pattern northwest of Chicago, one over the city, and another extending east from Chicago 40 miles across Lake Michigan. It too had the two major lake low rainfall areas, as found with the southwest motion. The northwest-moving rainfall (largely associated with cold fronts) indicated a high north-northwest of Chicago extending southeast across Lake Michigan with a minor high over the city and another high in northwestern Indiana. Interestingly, this pattern did not indicate the presence of the two major lake low rainfall areas. These results on motion agree in general, with those at St. Louis (Changnon, et al., 1978) which showed that the major urban highs and downwind high rainfall areas came with rainfall moving from the southwest or west, with lesser apparent effects on rains with northwesterly motion.

Urban Effects

These results and others were utilized to focus on potential urban effects, both over land and over the lake, and their possible causes. Basically, prior research has shown that major urban areas in summer, in the net, act to enhance convective activity through a variety of processes that include greater convergence over the city on certain days. These influences lead to more clouds, more convective activity, and intensification of existing convection.

The rain increase over the center of Chicago, based on the radar results from 1977-79, indicates an average increase of 15% when the urban value is compared with the average rainfall based on all the surrounding rural controls. This agrees exactly with the 1976-78 rainfall results obtained using a dense raingage network (Changnon, et al., 1980). Another comparison of the area precipitation was based on a 6-area statistical analysis using 3 rural areas (2 west of the city and 1 north), and one north over the lake, one being the city center, and the sixth an overlake area east of the city. Statistical comparisons of these areas revealed that the urban area had 21% more rainfall than expected, and the east overlake area (with potential urban effects) had 32% more than predicted by controls. Using double ratio tests and 500 rerandomizations, these differences were not shown to be significant. However, one excessive rain storm (June 25, 1978) was removed from the 87 rain period sample and six area values were again compared and tested. With this extreme event (outlier) removed, the city's 3-summer rainfall value was ascertained to be 51%

higher than predicted by the rural control areas, and the east overlake area was 60% higher. These were both statistically significant differences.

The apparent urban-related rainfall highs over Chicago and the overlake area east of the city (out to 40 miles) occurred in all three summers and in June and August and are apparent persistent features. The 1976 raingage network data also revealed the high over the city (Changnon, et al., 1980). Further support for the urban influence on precipitation relates to the overlake rainfall pattern when the rain periods were sorted by rain motion. In all cases, there is an urban "plume" of heavier rainfall stretching from Chicago downwind in the appropriate direction.

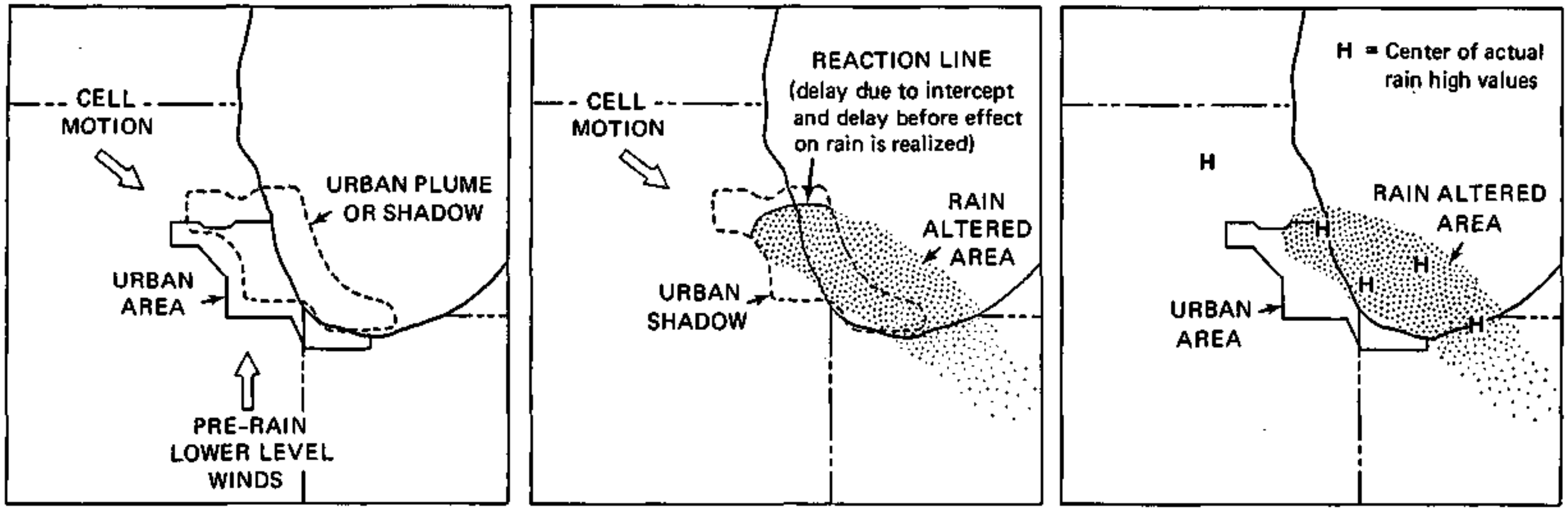
Important to the general definition of the urban influences is the fact that the squall line rainfall revealed an increase of 105% over the city with more than 50% increases (above rural controls) extending out 25 miles east of Chicago over southern Lake Michigan. Again, the apparent ability of the urban area to influence the generally well-organized convection of squall lines agreed with the findings from St. Louis (Changnon, et al., 1981). In general, the evidence of an urban influence on precipitation over the city and beyond it was well established by the persistence in the 3 years, its statistical significance, its location sorted by rain motion, and by its agreement with findings on squall lines at St. Louis. Now, let us examine the findings that help explain the causes of these urban influences on convective activity and hence on summer rainfall.

Among these findings is the enhancement of convective activity through the initiation of raincells under squall line conditions, and diminishment of convective activity in less organized conditions as reflected in decreased urban area initiation of cells (and rainfall) during cold front conditions. The

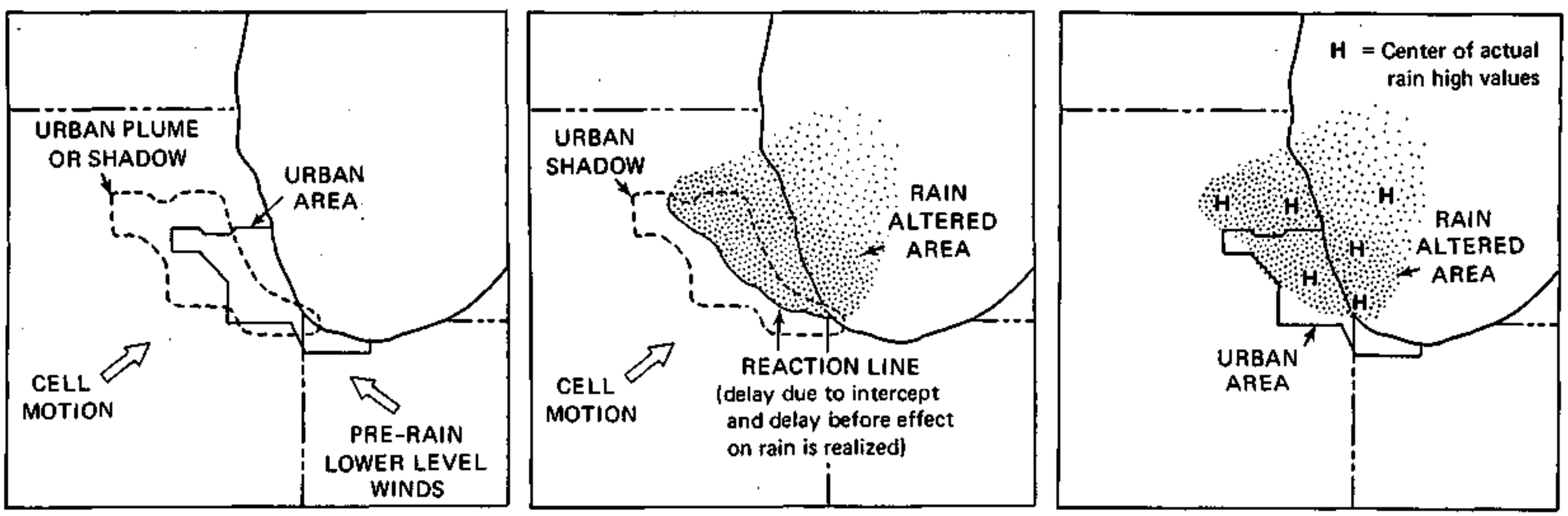
Chicago urban area also apparently enhances, as well as initiates, convective intensity in squall line and stationary frontal conditions with their raincells being larger, having heavier rainfall rates, and greater rainfall volumes than do raincells with other synoptic conditions over the city.

Interpretation of three sequential series of atmospheric motions is important in understanding and testing hypotheses about urban influences on the summer rainfall distributions. Research prior to the METROMEX field experiment in St. Louis attempted to define, on the basis of average cell motion, the potential areas of urban effect on rainfall (Huff and Changnon, 1973). These were later found by the detailed METROMEX investigations to have been correctly postulated. Hence, a similar development of hypothesized areas of influence were developed for Chicago. These involved consideration of a) prevailing motion of raincells (sorted by any given direction); b) the prevailing pre-rain lower (boundary layer) level winds that tend to focus the locale of urban-forced convergence (and urban temperature and aerosol effects); and c) the integration of these two motions with the expected time delay for urban effects to be realized in clouds and before any altered rain reaches the surface. These motions are illustrated in figure 19 for two of the basically different conditions found at Chicago.

Figure 19a shows a sequence for the average conditions with northwest cell motion (typically cold frontal conditions). Pre-rain lower level winds are from the south, and this develops a northward displaced urban plume, or "urban shadow." The second phase displayed under figure 19a shows the area of urban shadow plus a delay factor, or "reaction line" which is the delay of any rain effect due to the time of cloud intercept and modification before the effect on the rainfall processes is realized at the surface, given the cell motion. For



a. The average situation with northwest cell motion and cold frontal conditions



b. The average situation with southwest cell motion and squall line conditions

Figure 19. Schematics of hypothesized interactions of urban influences with raincells, and where urban altered precipitation is apt to occur under two prevailing weather conditions.

example, cells entering the northwest corner of the urban shadow would not realize any possible change in the surface rainfall, on the average, until they had moved 5 to 10 miles further southeast. This is the defined reaction line shown in figure 19. Beyond that reaction line, one can denote a potential "rain altered area" streaming over the city and downwind. This rain altered area is shown in the third map of figure 19a having begun north of the city and streaming out over southern Lake Michigan and northwestern Indiana. The five major high rainfall areas in the 1977-79 pattern are portrayed in figure 19a. One notes that four of these fell within the postulated urban-altered rain area. Figure 19b shows a similar analysis done for southwest moving cells (typically squall line conditions), and one finds all the major high rainfall areas in the postulated rain altered area.

Such analyses although hypothetical and conceptual, help support a realistic understanding of where urban-related highs in rainfall should likely appear.

A major mystery as yet not unraveled at Chicago concerns the ability of the urban area to exert a major effect on the well-organized convection of squall line storms. Case studies at St. Louis (Changnon, et al., 1974) indicated that convergence produced by the city in advance of some squall lines had an influence by initiating pre-line convective activity which merged and helped enhance rainfall. Regardless of the mechanisms, convective intensity associated with squall line storms is greatly intensified by urban influences.

Examination of these mechanisms was further illuminated by the raincell research. Initiations of raincells in squall line conditions were increased by about 150% within the city (from a predicted 3% to an actual 8% of the total in the urban area), and increased about 30% with stationary fronts. Raincell initiations were not increased in the city area with the other synoptic weather types.

The Chicago urban area also experienced an increase in mergers of raincells, a dynamic interaction known to produce sizable rainfall increases. The number of raincell mergers over Chicago was 400% greater than predicted from control area frequencies, and these tended to occur along and just west of the lakeshore. Potential interaction of urban and lake influences is suggested and discussed in a later section of the summary under "lake influences."

Examination of the characteristics of raincells initiating or passing across the urban area revealed they were relatively more intense and longer lasting than are rural or lake raincells. In particular, the squall line and stationary frontal cells crossing the urban area were slower, longer lasting, and bigger rain producers than the cells with all other weather conditions. In contrast, the cold front raincell was typically the fastest, smallest, and least producer of rainfall over the urban area. The results on raincell initiation, their basic characteristics of motion and rainfall yield; and frequency of mergers all indicated that urban effects were being realized in squall line, and to a lesser extent, in stationary frontal conditions.

Examination of urban influences classified according to degree of organization of convection, indicated that a distinct urban maximization of rainfall occurred in all three degrees of organization; well organized lines, semi-organized squall areas, and isolated cells. However, the urban influence percentagewise was much greater with lines (+110%) and with the isolated convection (+75%) than with squall areas (+10%). These results tend to support the prior squall line findings. Potentially, the pre-storm flow conditions in squall lines (and organized lines) may focus urban effects better than in the squall area or squall zone conditions where cells are moving in a semi-organized fashion and the lower level wind fields are not strong and often disorganized by the widespread convection.

Examination of rainfall rates, another way to get information about urban influences, showed that the city core had a 31% increase in rates of greater than 6 mm per hour, but none with lesser rain rates. The south lake area east of Chicago showed an enhancement in both light and in moderate-to-heavy rainfall rates. Increases ranged from 5 to 30% and extended about 25 miles east of Chicago. The rainfall rates in the moderate to heavy class (> 6 mm per hour) with squall lines exceeded the west rural values out over southern Lake Michigan, being 77% greater in the nearest 5 miles east of Chicago and 27% greater 25 miles east of Chicago. No other synoptic weather type showed an increase in rainfall rates of any intensity east of Chicago.

In summary, the urban influences over and beyond Chicago and southern Lake Michigan are largely due to the ability of the urban conditions to sizably affect convection in the squall line conditions. Cells are initiated over the city, raincells are bigger and more intense over the city and over the lake, and there are more cell-to-cell interactions or mergers over the city, leading to higher rain rates.

Lake Effects

The principal effect of Lake Michigan on summer convection and hence on rainfall has been noted (through satellite, radar, and raingage studies) as one acting to stablize atmospheric conditions and to decrease precipitation under certain situations. This study aimed at getting relatively detailed measurements of the lake-related decreases in rainfall, both over the lake and adjacent land areas (if any existed), and in attempting to better explain the lake influences on precipitation.

It was noted that the rainfall quantity and rates over the adjacent rural land areas north of Chicago (west of the lake) and southeast of the lake (in June and July) were decreased to about 17% over the upwind rural areas. This overland decrease just west of the lake appeared with all synoptic weather types. Rainfall amounts east of the north lake rural area (north of Chicago) and out over the lake in a series of five zones (each 5 miles wide) revealed that the first zone (nearest the shore) was 22% less than the upwind rural (area unaffected by lake) value, the next zone was 19% less, then 35%, then 45%, and then 55%. These decreases are illustrated in figure 20. All rainfall patterns and statistical analyses of zones defined east of the western' shore showed a decrease in rainfall north of the urban-influenced high stretching east of Chicago.

Over the lake in the "no urban effect" area, the total rainfall pattern revealed two distinct lows, a narrow (5- to 10-mile wide) low lying parallel and adjacent to the western shore line, and then a more major low beginning 20 to 25 miles east of the western lakeshore. In general, there was a west-to-east decrease in a summer total rainfall, as revealed in figure 20. This decrease occurred, in varying degrees, under all rain motion conditions and synoptic weather conditions. It was least however, in the squall line conditions. In general, the lake-related rain reductions were realized, as noted above, over adjacent land areas, extending typically 5 to 10 miles inland. Here decreases in total summer rain and in rainfall rates were about 10% in the southeast area and 17% in north lake area.

Examination of the frequency of varying rainfall rates over the lake (in the non urban effect north area) revealed a modification from the western shore line out to 15 to 20 miles. This area had more light (2 to 6 mm per hour) rainfall rates but fewer moderate to heavy rainfall rates than did the rural areas west of Chicago. However, out to this distance (20 miles east of the western shore) the number of incidences of precipitation was not different than in the rural area. In other words, a shift to less intense rainfall was occurring but with no apparent decrease in the total time of rainfall. However, beyond 20 miles, there was a reduction in the number of incidences of rain, being 25% less than rural values at 25 miles east of the western shoreline.

An important indication found in several data sets related to apparent interactions, in some circumstances, of lake and urban lake effects. Apparently, the lake effects help focus or enhance the urban rainfall, either through lake breeze circulations as triggers to convective activity, and/or as suppliers of low-level moisture. For example, the isolated convective precipitation pattern shows major rainfall highs all around the western and southern ends of Lake Michigan and located 5 to 15 miles inland from the lake. The frequency of mergers (Fig. 17) shows the maximizations in the urban area parallel to the lake shore and located from 1 to 10 miles inland. The largest rain-producing raincells were those that went from the urban-to-lake area or the rural-to-urban-to-lake areas, suggesting in both cases an urban and lake interaction. The squall area rains showed a series of isolated highs largely in the urban area located parallel to the lake shore and just inland.

Another aspect of the urban-lake interaction is that the urban effects to enhance precipitation clearly overwhelm the lake effects which stablize and decrease precipitation, at least where they directly interact. The urban area has maximum rainfall increases of 15 up to 51% (depending on how it is defined). A major urban-related high extends eastward from the city out 40 miles and it had even greater percentage increases in rainfall than in Chicago with more hours of rain then elsewhere in the lake, more higher rainfall rates than over the rural or other lake areas, and more total rainfall. Thus, the urban influences to enhance and intensify convection overcome lake effects which stablize convection.

The study of lake influences on varying rain conditions under varying convective organization (lines, squall areas, and isolated cells) revealed that the lake acts to decrease raincell initiations with 20% fewer than over the land. Also, depending on location, 5 to 10% fewer raincell mergers occur over the lake than over the land. The organized lines had no apprecible lake lows north and east of Chicago, but with the less organized conditions (squall areas and isolated cells), the major overlake minima appeared. In similar fashion, the studies of raincells indicated that those developing and existing over' the lake were shorter lived, slower moving, and produced much less rain than the rural cells. However, the lake cells did have a greater instantaneous size. The cells over the lake that moved over the land did rank as the most vigorous of all rain cells, apparently reflecting dynamic lake-land influences.

Since the lake surface represents 35% of the Lake Michigan basin, uncertainties related to estimating the precipitation have been of major concern to climatologists and hydrologists. Most estimations", including those of Bolsenga (1977) and Changnon .(1968b), have concluded that the lake rainfall in the warm season was less than the surrounding land rainfall. Bolsenga's (1977) lake-land ratios for summer (June-August), based on data from northern Lake Michigan, was 0.85 (15% less) which was the greatest land-lake difference in any season. In his studies of Lake Ontario rainfall using radar and raingages, Wilson (1977) concluded that warm season rain over the central lake portion was 16% less than surrounding land with an overlake lake-land difference of 5%.

These various lake rainfall studies have been consistent in pointing out that the Great Lakes act to suppress warm season rainfall and that the lake-land differences in summer were likely the greatest of all seasons. Wilson (1977) showed that the influence of Lake Ontario was greatest when rain was falling over less than 70% of the land basin, an indicator that when scattered shower conditions existed (those more dependent on local heating), the relatively cool lake was a very stabilizing influence. A few case studies based on the behavior of radar echoes over Lake Michigan have also revealed diminishment of rain over the lake in summer (Lyons, 1966; Lyons and Wilson, 1968).

We used our data to measure the "average" lake influence on summer precipitation (at least as defined by the 3-summer sample). The overlake values for 5-mile wide zones were determined and expressed as a percent of the northwest rural average of 652 mm for the 3 summers. This profile and indices developed from the related zonal values over the lake could be considered as a means to predict lake rainfall amounts over a period of years, given one wisely utilized shoreline values. The profile of figure 20 depicts the minor trough parallel and closely adjacent to the western shore. It also shows the 17% decrease in the 8-mile wide land area adjacent to the lake and presumed to be related to the stabilizing effects of Lake Michigan. Although the radar study did not extend to the eastern shore of Lake Michigan across the north lake area, we utilized NWS raingage values for the 87 rain periods to determine the

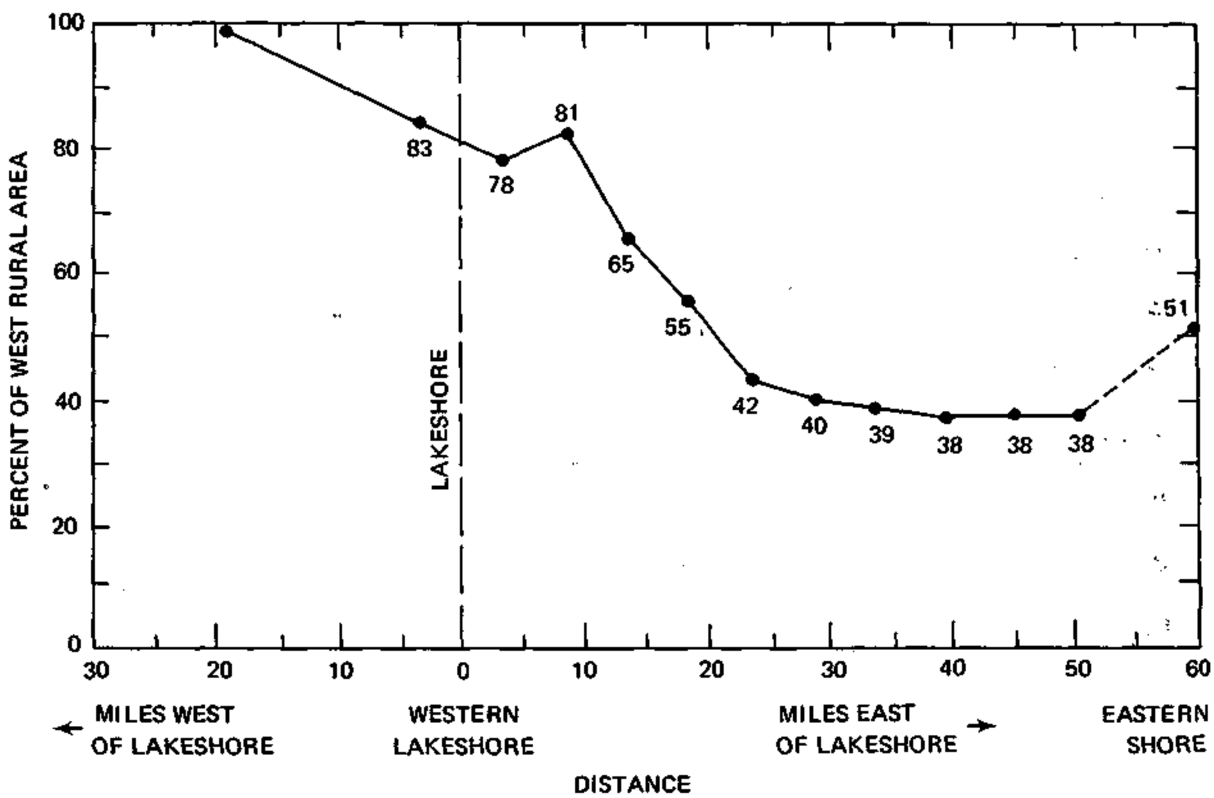


Figure 20. The average west-east profile of total summer rainfall (1977-79) across the lake area uneffected by urban influences, expressed as a percent of the northwest rural total precipitation.

values along the eastern shoreline (which was 52% of that of the upwind rural area west of the lake). This graph shows the rapid decrease in summer rainfall out to 25 miles, followed by a flat pattern with a slight increase along the eastern shore. This is similar to the profile estimated by Gatz and Changnon (1976).

If one averages the 12 over-lake values in figure 20, one realizes a sizable departure from the western rural area, averaging 50% of that value. If one utilizes only the near west shore value of 83% as a base of comparison, the departure from that value (assuming one used western shore line rain data to estimate over-lake mean rainfall) would be 68% less than the western shore line average. Another estimation would involve utilizing the immediate raingage data along the western and eastern shorelines, represented in figure 20 as values of 83 and 52, an average of 67%. Comparison of the 12 lake values with these two values would indicate that the lake average precipitation is 14% lower if estimated or determined by using raingages along the immediate shoreline on both sides of the lake. This compares favorably with earlier climatic studies done in this fashion which showed the summer decrease of 10% to 15% over Lake Michigan in summer (Changnon, 1968b).

In general, results show that the stabilizing influence of southern Lake Michigan on summer convection is considerable, but it is largely realized in the less organized and generally weaker convective conditions as reflected by squall areas, squall zones, and isolated air mass showers. The well-organized mature squall lines (which are considerably enhanced by urban influence) do not appear to experience any great diminishment by lake influences.

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