AN INVESTIGATION OF THE LA PORTE, INDIANA, CONVECTIVE RAINFALL ANOMALY

by

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(1967)

SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
January, 1969

Signature of Author ....
Department of Meteorology, 20 January 1969

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ABSTRACT

During the period 1935-1960, La Porte, Indiana, received an abnormal amount of convective rainfall. Many explanations have been offered for this increased summer precipitation. This paper examines the four most feasible explanations. They are:

1. Instrument - observer bias. This theory argues that the extra rainfall is fictional, having resulted from systematic gage or observer error.
2. Chicago heat island. This theory proposes that the heat from the Chicago metropolitan area causes more convective activity over Chicago which in turn causes more rainfall at La Porte (35 mi. east of Chicago).
3. Chicago air pollution. This theory maintains that Chicago's air pollution increases the precipitation nuclei in the clouds over and downwind of the city thereby increasing the rainfall in the La Porte area.
4. Lake Michigan processes. This theory suggests that the lake-induced meso-scale circulation around Lake Michigan interacts with the meso-scale wind fields associated with squall lines to produce a strong convergence zone around the southern tip of Lake Michigan which is most intense in the La Porte area.

Based on a detailed examination of each alternative, the first three were rejected, while the Lake Michigan explanation was given a qualified acceptence. The evidence supporting these conclusions is too abundent to list here, but the most important single piece of evidence is a set of statistics which show conclusively that the anomalous rainfall comes from organized systems of thunderstorms (primarily squall lines) and not from isolated convective showers.

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I. INTRODUCTION

A. Statement of the problem

During the period 1935-1959, La Porte, Indiana, received an abnormal amount of convective rainfall. For these years, La Porte averaged 24.6 inches of summertime rainfall (May-September), while the composite average for the twenty-three stations within fifty miles, and including La Porte, was only 18.0 inches. Since La Porte's rainfall exceeded that of the seven nearest stations in fifteen of the twenty-five summer periods, the anomaly is too persistent to have resulted from the random spatial variation of convective rainfall. Stations so near to each other with no topographic differences (see Figures 1 and 3) should have equal probability of having the highest rainfall for any one year. Based on this, the probability of La Porte being the highest by chance for fifteen or more out of twenty-five years is approximately one in ten million using the binomial probability distribution. Therefore, there must be some systematic process which caused the extra rainfall. This paper shall attempt to identify this process and thereby explain the anomaly.

B. History of the problem

Stanley Changnon of the Illinois State Water Survey first uncovered the La Porte anomaly in 1961 while analyzing summertime rainfall patterns in Illinois and Indiana. His report (Changnon 1968) is the only extensive treatment of the subject. He describes the anomaly thoroughly and suggests that industrial pollutants and heat cause it. Stout (1961) mentions the La Porte case briefly in his report on cloud initiation due to industrial processes, Lyons (1966) suggests a possible role for Lake Michigan in explaining the anomaly, and many experts have speculated on the causes in newspapers and news magazines, but as yet there has been no complete examination of the possible causes of the anomaly.

C. Plan of attack

The first step is to describe, in as much detail as possible, the La Porte anomaly to determine which of the many explanations offered in the literature should be considered in the investigation. Next, each possible cause is examined to see how well it agrees with the pertinent data in accordance with the governing physical laws. Finally, based on these examinations, a conclusion will be reached on the cause or causes which seem to offer the most satisfactory solution to the problem.

D. Significance of the problem

The results of this study will have a significant bearing on the prospects for climate modification. If it is found that Man's activities have inadvertently caused the extra rainfall, this will lend much support to the proposition that Man, through his own directed efforts, can produce significant changes in rainfall over selected areas. If, however, it is found that natural processes have caused the anomaly, this will remind Man to be cautious in apprais-ing his ability to alter the climate significantly.

II. DETAILED DESCRIPTION OF ANOMALY CHARACTERISTICS

To intelligently select a set of possible explanations, one must be familiar with the finer details of the anomaly. These detailed anomaly characteristics will also be helpful later in the examination phase.

A. Available data

A meaningful description of the anomaly requires extensive climatological data for the meso-scale region around La Porte. The bulk of this data comes from the following U. S. Weather Bureau records:

1. Indiana, Illinois and Michigan monthly and daily rainfall for sixty stations, 1900-1967
2. South Bend and Chicago (MDW) hourly rainfall, 1955-1959
3. United States synoptic weather maps, 1955-1959
4. South Bend and Chicago (MDW) daily observations, 1955-1959
5. Chicago (MDW) hourly observations, 1956-1959
6. Chicago (MDW) radar data, 1958-1959.

In addition, some climatological data was acquired from literature and through personal communications. It would have been desirable to have many more observations in the immediate vicinity of La Porte, but such records have not been kept. Nevertheless, the available data is sufficient to insure reasonable confidence in the findings of the investigation.

B. Characteristics of the anomaly

The maps in Figures 2 and 3, which give the spatial and temporal variations of the rainfall pattern from 1920-1967, show the scale of the anomaly to be approximately thirty miles, barely enclosing Valpariso and South Bend. The maps also indicate that the La Porte anomaly first became large in the late 1930's, reached its maximum in the 1940's, decreased some in the 1950's, and became much smaller after 1960. The La Porte rainfall graph in Figure 4 demonstrates this temporal variation in respect to three nearby stations, South Bend, Valpariso, and Plymouth.

A magnitude analysis of daily rainfall shows that approximately 90 percent of the anomalous rainfall comes from daily amounts greater than one inch. Figure 5 gives the temporal variation of the number of days falling into each daily rainfall category and only the $R>1.00$ graph shows the anomaly (R=daily rainfall in inches). Figure 6 shows the spatial variation for the number of days falling into each daily rainfall size category for the 1955-1959 period and only the $R>1.00$ map shows the sharp La Porte maximum. In addition, a radar and synoptic study of the seventeen $R>1.00$ cases during 1958-1959 shows that in sixteen of the cases the rainfall came from organized frontal or squall line thunderstorms. Moreover, a hail study by the Illinois State Water Survey (Changnon 1968), discloses that La Porte had two and one half times as many hail days as surrounding stations for the period 1951-1965. All these facts indicate that the anomalous rainfall results from a local intensification of well-developed frontal and squall line thunderstorm systems and not from isolated convective showers occurring over La Porte.

Also, to get a feeling for the day to day variation, the anomaly size was calculated for each of 104 different La Porte summertime convective rainfall cases for the 1955-1959 period (all cases for which the five stations within thirty miles averaged greater than .10 inches were included). The anomaly size for each case was defined as follows:

$$\text{anomaly size} = A = \left[\frac{\text{La Porte rainfall} - \text{area average}}{\text{area average}}\right] \times 100.$$

The area average is based on the rainfall at Ogden Dunes, Valpariso, South Bend, Niles and La Porte (see Figure 1). The following table summarizes the results:

cases	$A<-20$	$-20<A<20$	$20<A<60$	$60<A<100$	$A>100$	$\bar{A}$
104	17	42	22	11	12	+30

For complete results (dates, rainfall amounts, times of occurrence, etc.) see the appendix. Not only does this study give us an idea of the variability of A from one case to the next, but it also will enable us to correlate anomaly size with the physical factors involved in the different theories under consideration.

C. Selection of possible explanations

Only those theories which can conceivable account for the salient features of the anomaly described above can be chosen as possible explanations. Therefore, from the different theories that meteorologists have suggested since the anomaly became known, the author selected the following set:

1. Instrument - observer bias
2. Chicago heat island
3. Chicago air pollution
4. Meteorological processes related to Lake Michigan.

The reasons for considering these four alternatives will become evident in the next two chapters, where they are described and examined in detail.

III. EXAMINATION OF THREE POSSIBLE CAUSES

As stated in the last chapter, there are four possible causes which we will consider. This chapter will examine the first three: instrument-observer bias, Chicago heat island, and Chicagio air pollution, while the next chapter will present the fourth: meteorological processes related to Lake Michigan.

A. Instrument-observer bias

Instrument-observer bias includes any rain gage or human error which causes a systematic inaccuracy in the rainfall recorded. This possibility must be considered because a local bias,not only would account for the small scale of the anomaly, but also would create a temporal variation if the error went unnoticed for a sufficient period of time. Acceptance of this explanation would render the anomaly a fiction and therefore close the case. Thus, this possibility must be handled carefully before proceeding to the theories involving real physical processes.

The main argument for this theory is that a new observer, Herbert J. Link, took the La Porte job in 1927, about eight years before the anomaly appeared and this same observer, using the same gage, recorded La Porte's rainfall during the entire period of the anomaly. Thus, any bias introduced by Mr. Link or his rain gage could have acted throughout the twenty-five year period. Also, since there were no rainfall stations within ten miles of La Porte during the anomaly period to corroborate Mr. Link's data, the large magnitude and small scale of the anomaly tends to cast doubt on its reality.

A closer look at this argument, however, reveals many deficiencies. In the first place, the argument is based entirely on circumstantial evidence; no specific instances of instrument or observer error have ever been proven. In addition, there is considerable evidence which directly refutes the inferences made in the supporting argument. Consider the following anomaly characteristics:

1. No anomaly exists for rainfall during the cold half of the year (Changnon 1968).
2. No anomaly exists for snowfall (Changnon 1968).
3. The anomaly size fluctuates during the twenty-five year period (see Figure 4).
4. The anomaly becomes much smaller after 1960.

Since the same person using the same rain gage[1] has been making the observations 365 days a year, measuring all kinds of precipitation, from 1927 until this very year (1968), a long-term systematic error, peculiar to the observer or the rain gage, could scarcely account for these four characteris-

[1] Mr. Link received a new rain gage in 1966.

tics. Furthermore, a Weather Bureau team inspected the La Porte rain gage in 1962 and found it satisfactory, having an exposure equivalent to that of most substations (Changnon 1968). Moreover, a radar study of the fifteen R>1.00 inch rainfall cases during 1958-1959 for which W.B.610-3 forms from Chicago (MDW) were available shows that in all fifteen cases strong echoes were reported over La Porte for at least one hour, indicating that the La Porte rainfall is not fictitious. Furthermore, the rainfall maps (see Figures 2 and 3) indicate that, although, the anomaly is sharply centered at La Porte, it does extend out to nearby stations. In other words, if La Porte is removed, the anomaly is still discernable. Finally, a new station, established in 1960 at Phillip's Air Port in Michigan City just eight miles from La Porte, substantiates Mr. Link's record. For the period 1960-1967 this station averaged 18.1 inches (May-September) while La Porte averaged 17.9 inches.

Based on these facts, we must reject the instrument-observer bias explanation and accept the anomaly as real. Changnon (1968) reaches this same conclusion in his report:

> "The facts supporting a factual increase certainly outweigh those for a fictional increase, and the answer to the questions posed in this study is that the anomaly is fact."

B. Chicago heat island

We include the Chicago heat island effect as a possibility, since it operates on the same scale as the anomaly and has shown a similar temporal increase over the period in question. A report on urban climates prepared by the Stanford Research Institute (1968) states that, for most urban areas, the core city averages about three degrees centigrade warmer than the surrounding rural areas for the early morning hours (0000-0800 LMT) during the summer. This so-called heat island effect is especially pronounced when the atmosphere is clear, calm, cool and stable. Also, Demarrais (1961) observes that the lapse rates over large cities are often super-adiabatic at night during the months of June, July and August. This temperature difference would tend to make the air over the core city rise. The local vertical acceleration is: $a = g(T-T_0)/T_0$, where:

a = vertical acceleration, m/sec^2.

g = acceleration due to gravity = $9.8\ m/sec^2$.

$T-T_0$ = city-rural temperature difference = 3 degrees.

T_0 = rural temperature = 20C = 293K.

Substituting we get:

$$a = (9.8)\ (3)\ /\ 293 = .1\ m/sec^2 = 10\ cm/sec^2.$$

Since mixing and other factors have been ignored, this, at best, is a rough upper bound for a. Nevertheless, vertical accelerations of this order of magnitude, coupled with a fairly deep unstable layer could conceivably initiate convective showers over Chicago and the prevailing westerly winds aloft would on the average tend to carry these showers in the direction of La Porte which is thirty-five miles to the east.

Mitchell (1961), based on a study of ten large cities in the eastern United States, states that the urban heat effect increases as the city grows which could explain the temporal variation of the anomaly. With this in mind, the author made a comparison between the forty year temperature records (1920-1959) for the Chicago city office in downtown Chicago and the Aurora College station in a semi-rural area thirty-five miles to the west. The difference in the August mean temperatures for each decade was taken as a measure of the heat island strength and plotted with the La Porte rainfall graph (see Figure 7). These graphs indicate a good temporal agreement between the strength of the heat island and the size of the anomaly.

Thus, on the surface, the Chicago heat island theory appears to have some merit. However, when we look beneath the surface, this theory breaks down. The first and most obvious argument against this explanation is that almost every city creates a heat island, yet no other La Porte-type anomaly has been found. Detailed studies of the rainfall patterns around Pittsburgh, Pennsylvania and Birmingham, Alabama, for the years 1925-1959, reveal no significant anomalies, although both cities are heat islands (see Figures 11 and 12). The Illinois State Water Survey, using twelve recording rain gages, conducted a thirteen year micro-scale analysis of the rainfall patterns around the twin cities of Champaign and Urbana, Illinois (Changnon 1961). This urban complex has a population of approximately 100,000 and, according to Lowry (1967), should show a significant heat island. Yet, the results of the study showed no summertime anomaly to the east of the urban area.

Another piece of evidence against this theory is that the heat island effect occurs during the early morning hours, while according to the 104 rainfall cases from the 1955-1959 period, the A values associated with rainfall cases occurring during the early morning (0000-0800 LMT) do not tend to be larger than those that occur during the rest of the day (0800-2400 LMT). The following frequency table of A values demonstrates this fact:

time	cases	$A<-20$	$-20<A<20$	$20<A<60$	$60<A<100$	$A>100$	$\bar{A}$
0000-0800	33	6	16	7	2	2	+19
0800-2400	70	11	25	15	9	10	+37

This table, in fact, suggests that the non-morning A values tend to be larger than the morning A values, but the difference is not significant at the .05 level.

In addition, Mitchell (1961) found that the heat island was weaker on Saturday and Sunday than during the rest of the week. Therefore, if the heat island were causing the anomaly, one would expect more anomalous rainfall during the week than on weekends. A frequency table for work days vs. non-work days does not show this however.

day	cases	$A<-20$	$-20<A<20$	$20<A<60$	$60<A<100$	$A>100$	$\bar{A}$
M-F	73	10	32	12	10	9	+31
S-S	31	7	10	10	1	3	+27

This table indicates that there is no significant difference between week day A values and weekend A values.

Moreover, the urban heat theory cannot explain why the anomaly was not large from 1920-1930. Chicago had well over a million population and an urban topography during this period. Certainly the heat emitted during the 1920's was not significantly different from that emitted during the 1930's. Therefore, if the urban heat were the true cause, the anomaly would not have changed so much between the 1920's and 1930's. Likewise, the anomaly's decrease in the 1950's and 1960's is inconsistent with the heat explanation, because the city has continued to grow during these periods.

Finally, the Chicago heat island theory is not consistent with the more detailed characteristics of the anomaly. The extra rainfall comes primarily from squall lines and organized frontal thunderstorms and not from isolated showers of local origin (see pp. 11-12). Therefore, the only way the heat island could cause the extra rainfall would be for it to somehow intensify the thunderstorm systems as they moved over the city. This is highly unlikely since strong heat islands develop under clear, calm, cool and stable conditions, whereas squall lines and frontal thunderstorms develop under exactly opposite conditions. Thus, when a system of thunderstorms passes over Chicago, the heat island effect is probably too weak to affect it significantly.

Without further supporting evidence to refute the above inconsistencies, we must reject the Chicago heat island explanation.

C. Chicago air pollution

This theory must be examined not only because it is of the same scale of the anomaly and has experienced a similar temporal variation, but also because it is accepted by most meteorologists as the most probable cause of the anomaly. Since scientists interested in weather modification have believed for many years that they could make rain by seeding clouds with precipitation nuclei and since the air pollution from Chicago does most likely increase the nuclei concentrations in the clouds passing over La Porte, it stands to reason that the rain makers would accept this explanation. But, in addition to popular support, such individuals can offer abundant physical evidence in support of their views.

In the first place, air pollution does seem to influence the rainfall near industrial areas. Ashworth (1929), in one of the earliest studies on this subject, concluded that smoke from the manufacturing area of Rochdale, England had caused a small, but steady increase in rainfall over the thirty year period from 1897-1927. Believing that soot particles caused the increase, he plotted the average rainfall rates against the average soot fall for each day of the week (see Figure 8). These curves show that the average rainfall rates on week days exceed the average rate on Sunday and that there is good daily agreement between the rainfall rate and the soot fall. In a similar rainfall study for Louisville, Pittsburgh, and Buffalo, Landsberg (1961) discovered that there were more frequent and larger rainfalls on week days than on Sundays. Kratzer (1956), in an extensive study of European cities, found that large industrial centers receive five to ten percent more rainfall than surrounding areas.

Further supporting the air pollution explanation are studies which show that Chicago's air pollution does indeed contain vast quantities of potential precipitation nuclei. The annual report of the Chicago Air Pollution Control Department (1968) states that Chicago's industries emit about 700 tons of particulate matter per day during the summer, maintaining an average airborne particulate concentration of about 120 $\mu g/m^3$. Based on an average particle weight of about 10^{-11} grams, this, approximately, is 10^{7} particles per cubic meter. Robinson, Chambers, and Bates (1967) identified the major substances normally found in such particulate matter as:

Silicates	Tars	Nitrates
Carbon	Resins	Sulfates
Metallic dust	Solid oxides	Organic compounds.

At the same time, Fletcher (1962) reports that, in the laboratory, silicates are excellent freezing nuclei and that certain sulfates act as condensation nuclei. Moreover, Kumai (1966) studied over 1,000 snow crystals under the electron microscope and found that over 800 of them contained silicates. Thus, Chicago's air pollution does contain large numbers of freezing nuclei and some condensation nuclei.

Another supporting argument for this theory is that the temporal variation of air pollution intensity, as represented by five year totals of Chicago smoke-haze days, agrees very well with the temporal variation of the anomaly (see Figure 9). Not only do the curves agree while the anomaly is increasing, 1935-1950, but the smoke-haze curve also decreases with the anomaly after 1950. Greater air pollution control may explain the smallness of the anomaly after 1960.

Looking at the distribution of pollution sources within the Chicago metropolitan area, one finds even more evidence to support the pollution explanation, because the most concentrated area of industrial activity lies along the southern tip of Lake Michigan thirty miles due west of La Porte (see Figure 1). The United States Steel plant at Gary, Indiana, occupies a large portion of this area (10 sq. mi.). Because of its position and size, this steel complex probably accounts for over half of the pollution that affects the La Porte area and many supporters of the air pollution theory feel that the particulates coming from these steel mills are the primary cause of the added rainfall.

> "The large concentrations of steel mills around Gary could very well support the high incidence of rainfall at the La Porte station... Either the exposure of the gage or the pollution from the steel mills has contributed to the anomaly." (Stout 1961).

The steel production graph certainly supports this contention, since it matches the temporal variation of the anomaly almost exactly (see Figure 10). Moreover, in 1959 the open hearth process was partially replaced by the basic oxygen process and this change in the steelmaking process may explain the anomaly decrease after 1960 (Changnon 1968). In addition, many studies show that steel mills emit more freezing nuclei than any other industrial process. Telford (1960) measured ice crystal concentrations downwind from industrial areas along the southeast coast of Australia and found that steel mills were by far the most prolific source of ice nuclei. Stout (1961) reports that new cumulonimbus clouds often developed downwind from the steelworks at Chester, England, and Soulage (1958) states that the exhaust gases from electric steel furnaces emit as many as 3×10^{15} freezing nuclei per day. Langer (1968) made actual flights through the smoke plumes over the Gary steel mills and found that each large smokestack emits approximately 10^{13} nuclei per minute which is comparable to a Skyfire AgI smoke generator. Thus, the Gary steel mills do increase the average freezing nuclei concentration over the La Porte area.

So in summary, Chicago's air pollution does increase the precipitation nuclei, primarily freezing nuclei, over the La Porte area, not only when we consider the city as a whole, but also when we consider the single source most responsible for air pollution in the La Porte area. This fact, together with the reported cases of increased rainfall around industrial areas and the good temporal agreement between Chicago air pollution and the anomaly, presents a convincing case for the Chicago air pollution explanation.

Now consider the evidence against this theory. First, there are no La Porte-type anomalies downwind from other high pollution areas. Yes, as mentioned above, there are many cases of rainfall increases of five to ten percent around industrial sites, but upon closer examination, it is found that these increases are confined to the city proper and that most of these increases have resulted from cold season stratiform precipitation. Landsberg (1956), after studying the seasonal variation of the rainfall at Tulsa, Oklahoma, concluded that most of the eight percent excess over rural areas was due to wintertime precipitation.

> "The winter values are relatively higher; this is also favorable to the hypothesis... because shower conditions in summer are not likely to be much affected."

Kratzer (1956) likewise found that most of the precipitation increase in manufacturing areas of Europe occurred during winter. He reports that many times light snow fell from stratified cloud decks over industrial communities while no snow fell on the countryside. Moreover, Changnon (1961) in his micro-scale study of precipitation patterns around Champaign-Urbana concluded that urban nuclei effects on precipitation are most pronounced in the winter and have little effect during the summer.

To further test this argument, the author made a detailed study of the summertime rainfall patterns around Pittsburgh, Pennsylvania and Birmingham, Alabama, both of which are famous as steel manufacturing centers. The Allegheny County Health Department in Pittsburgh and the Jefferson County Department of Health in Birmingham report that Pittsburgh and Birmingham are comparable to Chicago in particulate emissions. Chicago's industry emits approximately 700 tons per day in the summer, while Pittsburgh and Birmingham emit 350 and 600 tons respectively. Moreover, the three cities have similar varieties of particulates since the steel industry is the leading source in each city, accounting for 70 percent of the particulates in Chicago and for 75 and 85 percent respectively in Pittsburgh and Birmingham. Considering ninety stations within sixty miles of Pittsburgh and fifty stations within sixty miles of Birmingham, the five year average rainfall patterns were mapped for the period 1925-1959 (see Figures 11 and 12). These maps reveal that the rainfall patterns remain relatively constant around Pittsburgh and Birmingham over the thirty-five year period and that no La Porte-type anomalies appear. (The constant rainfall peak forty miles southeast of Pittsburgh is caused by a 3,000 ft. high ridgeline as shown by the Pittsburgh terrain map.) The lack of any rainfall anomalies downwind from these two highly polluted cities certainly casts doubt on the Chicago air pollution theory.

Another fact to consider is that La Porte has no rainfall anomaly during the cold season when the pollution effects, if acting, would be a maximum. In fact a graph of the monthly variation of the anomaly size, based on the 1955-1959 case studies and Changnon's report (Changnon 1968), demonstrates that the anomaly is largest in mid-summer when the particulate concentration is at its lowest point (see Figure 13).

Furthermore, the 1955-1959 study shows that there is a poor correlation between high anomaly values and conditions conducive to high pollution concentrations at La Porte. In the first place, there is no correlation between high A values and low visibilities. The following frequency table shows that there is no significant difference between the A values associated with low visibilities and the A values associated with high visibilities. The visibilities were taken six hours prior to the rain according to the hourly reports at Chicago Midway Airport. (V=visibility in miles.)

V	cases	$A<-20$	$-20<A<20$	$20<A<60$	$60<A<100$	$A>100$	$\bar{A}$
$V\geq12$	21	3	6	6	3	3	+47
$8\leq V<12$	22	4	9	2	4	3	+33
$4\leq V<8$	12	1	3	5	1	2	+54
$0\leq V<4$	10	1	2	3	2	2	+49

In addition, there is no significant difference between the A values on week days and on weekends as shown on page 19in the section on the Chicago heat island. Finally, the A values associated with westerly winds are no higher than the A values associated with non-westerly winds. Using the average wind for the six hour period prior to the rain for each of the 104 cases, we get:

wind	cases	A<-20	-20<A<20	20<A<60	60<A<100	A>100	$\bar{A}$
W	16	3	9	0	2	2	+29
Non-W	88	14	33	22	9	10	+31

This table shows in fact that higher A values tend to occur with non-westerly winds, although the difference is not significant at the .05 level. Moreover, it indicates that westerly surface winds are uncommon prior to convective rain storms.

It is not so easy to account for the excellent agreement between the temporal variation of the anomaly and that of the air pollution and steel production. But, the smallness of the anomaly after 1960, while the air pollution remains very high, controls or no controls, suggests that this agreement is merely a coincidence.

On top of all this evidence, there is another argument which is perhaps even more convincing. This argument challenges the basic tenet of the air pollution theory which says that you can increase the rainfall over La Porte if you can get more precipitation nuclei into the clouds over La Porte. It has never been proven conclusively that seeding of cumulus clouds, with precipitation nuclei of any sort, significantly alters the amount of rainfall that will fall from them. Of course, there have been many cases of rain falling from selected clouds after being seeded, but in most of these cases the rainfall was scarcely measurable at the ground (Johnson 1963). Moreover and more important, the air pollution nuclei are primarily freezing nuclei, while studies indicate that seeding of warm based convective clouds with ice nuclei has little effect on the rainfall coming from them. Houghton (1968) states that the dominant precipitation mechanism in convective cells is the accretion process and not the Bergeron-Findeisen ice crystal process and that the only way to increase the rainfall from such cells is to increase the efficiency of the sweeping action by which the accretion process removes the condensate. Since this efficiency depends on the number of precipitation particles initiated at the cloud base, additional ice nuclei will not increase the rainfall, if the cloud base is above freezing. Thus, it is very unlikely that the extra freezing nuclei from the Gary steel mills and other Chicago industries have any effect on the anomaly-causing thunderstorms which have base temperatures well above freezing.

Thus, even though the supporters of the air pollution explanation have proven that air pollution increases the precipitation nuclei, particularly the freezing nuclei, in the skies over Chicago, their argument that these extra nuclei cause the extra rainfall at La Porte does not stand up in the light of the data and theory involved and so the Chicago air pollution theory must be rejected.

IV. EXAMINATION OF THE LAKE MICHIGAN EXPLANATION

Having examined and rejected the first three alternatives, let us now proceed to the Lake Michigan explanation.

A. Description of the Lake Michigan explanation

Many have speculated on the role of the lake in the La Porte anomaly, but no one has formulated a complete explanation based on the lake-induced processes. Changnon (1968) suggests that the shape of the shoreline tends to cause a convergence zone at the southern tip of the lake. Lyons (1966) reports that the cool dome of air over the lake has a definite effect on the distribution of rainfall from summertime squall lines. Moroz and Hewson (1966) show how lake breezes from Lake Michigan can intensify thunderstorms along the lake breeze front. And Estoque (1962), using a numerical sea breeze model, found that the orientation of the shoreline with respect to the geostrophic wind determines the strength of the lake breeze circulation.

Based on the work done by these investigators and the general characteristics of the anomaly, the author proposes the following explanation based on lake effects. This theory asserts that the spatial variation of the anomaly results from a combination of the following two lake-induced processes:

1. During squall line passages, interaction between the lake breeze front and the squall line outflow, coupled with the dissipative effect of the cold water surface, produces a horseshoe-shaped heavy rainfall zone around the southern tip of Lake Michigan.
2. The southwest-northeast orientation of the shoreline adjacent to La Porte intensifies the lake breeze circulation and focuses the heaviest rainfall within the horseshoe zone on the La Porte area.

In addition, this theory proposes that a temporal variation in the number of squall lines passing over Lake Michigan causes the temporal variation in the anomaly. This explanation obviously agrees with the salient characteristics of the anomaly described on pp. 11-12, since the author is aware of these features, but we must examine this theory in more detail to see if the physical processes involved account for the finer details of the anomaly.

Leaving the temporal variation until later, let us examine the two processes which seem to explain the spatial variation. For convenience during the discussion the first process will be referred to as the "horseshoe process" and the second process will be referred to as the "Estoque focusing process". First consider the horseshoe process.

B. Horseshoe process

Lyons (1966) states that when a squall line approaches Lake Michigan from the west on lake-breeze days an intense convergence zone is produced by the coming together of three meso-scale air masses. As the squall line approaches the lake the cold downwash of air from the squall line meso-high, the lake breezes from the Lake Michigan meso-high, and the hot southwest winds from the tropical maritime air mass to the south all come together in a small area about ten miles in diameter and the squall line intensifies rapidly because of the increased convergence and the additional water vapor from the lake (see Figure 14). As the squall line continues to the east, the convergence region moves southward along the lake breeze front and then around the tip of the lake generating cells along its path and thereby creating the horseshoe shaped heavy rainfall area. The portion of the squall line to the north and west of the convergence region begins to decay after this region passes by, because the source of hot, unstable, tropical maritime air is cut off and is replaced by the cool stable air coming off Lake Michigan (again see Figure 14). The convergence area moves along the sea breeze front and therefore the displacement of the horseshoe rainfall pattern from the shore depends on how far the lake breeze front had penetrated inland prior to the arrival of the squall line.

Or, more precisely, the trajectory of the convergence region is along the boundary between the cool dome of air over the lake and the hot tropical maritime air over the land. So if the lake-breeze front does not penetrate inland at all, the horseshoe process would dump the heavy rainfall right along the shoreline and if the tropical maritime air should displace the cool lake air completely, the horseshoe process would not occur at all. However, on most summer days the cool dome of lake air does exist and therefore for most summertime squall lines the horseshoe process does occur to some degree. Lyons' description of the squall line passage of 7 June 1963 provides an excellent example of the horseshoe process. This squall line developed over the Great Plains on 6 June, maintained itself through the night, and by 1400 LMT on 7 June was bearing down on Lake Michigan at 30 m.p.h. (see Figure 15A). At this time, the squall line meso-scale cold front had not yet intersected the lake breeze front. Figure 15B shows the squall line at 1600 as the two meso-scale fronts have just intersected to form the convergence region 60 mi. north-northwest of Chicago (MDW). Just after 1600, according to Chicago radar, there was a sudden development of strong cells with tops above 30,000 ft. at this point. During the next two hours, the convergence area moved south-southeast generating new cells along its path. At 1800 it was over the western suburbs of Chicago where the radar showed the strongest echoes yet with tops near 50,000 ft. and surface winds in excess of 70 m.p.h. (see Figure 15C). Also, by 1800 the northern portion of the squall line had decayed rapidly with no echoes moving more than 20 mi. out over the lake. Finally, Figure 15D shows a close-up of the squall line as it rounds the tip of Lake Michigan and depicts the axis of heavy rainfall as it heads into Indiana moving parallel to the shoreline and about 20 mi. inland. The rainfall reports from this squall line later revealed the heaviest rainfall to be along the line of maximum penetration of the sea breeze front which also, of course, was the trajectory of the convergence region, thereby confirming that the strongest cells developed along this trajectory.

We can test the validity and significance of the horseshoe process by looking at the squall line rainfall pattern around Lake Michigan over the five year period 1955-1959. During this period twenty-nine summertime (May-September) squall lines passed over Lake Michigan according to synoptic maps, Chicago and South Bend hourly reports, and Chicago radar data. To make this an objective test of the horseshoe process, six of the twenty-nine squall lines were discarded because they were preceeded by prevailing surface winds of greater than 15 m.p.h. and strong surface winds would displace the cool dome of air over the lake and prevent the horseshoe process from happening. For the other twenty-three squall lines the total rainfall was plotted using daily and hourly rainfall reports. The resulting map, not only presents a definite horseshoe pattern of heavy rainfall, but also, when subtracted from the total summer rainfall map for 1955-1959, practically eliminates the anomaly (see Figure 16). This finding strongly suggests that the horseshoe process is real and significant. At least for the 1955-1959 period it seems to explain why La Porte has more summer rainfall than those stations which lie outside the horseshoe zone.

C. The Estoque focusing process

The horseshoe process alone, however, does not explain why La Porte has more rainfall than other stations within the zone. Figure 16 shows that La Porte received more squall line rainfall than any other station within the heavy rainfall ring. Thus, there must be some other process which causes the horseshoe process to be most intense in the La Porte area. The author proposes that this other process is the Estoque focusing effect spoken of previously.

Estoque (1962) in a numerical study of sea breeze circulations under varying synoptic conditions found that when the geostrophic wind was parallel to the shoreline with lower pressure over the water, the sea breeze circulation was intensified. For instance, for a 10 m.p.h. geostrophic wind along the shore, he found that the sea breeze circulation produced on-shore winds of up to 15 m.p.h. and vertical velocities of up to 25 cm/sec, with the maximum convergence occurring about ten miles inland during the late afternoon. He explains that this occurs when isobars are parallel to the shore, because the cross isobar flow continually pushes the warm land air against the cool dome of air over the water and prevents the sea breeze front from pushing the warm air far inland. In this manner, a strong horizontal temperature gradient is maintained within a thick layer of the atmosphere (3,000-5,000 ft.) and thus a corresponding strong water to land pressure gradient is maintained at the surface and this keeps a vigorous sea breeze going. In other words, by keeping the sea breeze circulation from over extending itself and becoming too shallow, this synoptic pressure pattern causes the circulation to be deeper and closer to the shore and therefore stronger. Of course if the geostrophic wind were very strong, the cross-isobar flow would suppress the sea breeze entirely, but in summer, pressure gradients are generally too weak to do this. If this process is acting, it would certainly intensify the horseshoe process because it would increase the convergence and the available water vapor in the convergence region as it moves through the

La Porte area. Let us go to the data now and see if this Estoque focusing process is really occurring.

La Porte's geographic position supports the reality of the Estoque process, since the shoreline adjacent to La Porte runs from southwest to northeast and seventeen of the twenty-three squall lines considered above had southwest geostrophic winds. Moreover, La Porte is thirteen miles inland which puts it near the area of maximum lake breeze convergence according to Estoque's model.

Furthermore, on 26 July 1966 the Illinois State Water Survey conducted a study of the lake-breeze circulation along the shoreline about twenty-five miles northeast of La Porte. On this day, the geostrophic wind was approximately parallel to the shoreline and they found a definite intensification of the sea breeze in this area:

> "Mean shoreline and inland winds indicate that there was about a 40 degree confluence of the streamlines in this zone. Using a smooth isotach-streamline field, divergence was calculated, yielding values as high as -45×10^{-5} sec^{-1}. These values are comparable to those found along windshift zones in squall line meso-systems." (Lyons 1968)

Before drawing any conclusions, however, we must test this Estoque process to see if the anomaly is larger when the process should be acting. To remain objective, we cannot confine our attention merely to the twenty-three squall lines which have accounted for the anomalous rainfall, but we must consider all convective rainfall occurrences during

1955-1959. With this in mind, the 104 convective rainfall cases will be used to see if there is a correlation between high A values and those meteorological conditions associated with the focusing process. Remember the A value for each case is based on how La Porte's rainfall compares with the rainfall at Valpariso, Ogden Dunes, South Bend, and Niles, all of which lie in the horseshoe zone of heavy rainfall (see p. 11).

According to Estoque, the primary meteorological condition necessary for lake breeze intensification is that the geostrophic wind be parallel to the shore line with low pressure over the water. Therefore, if this focusing process is acting in the La Porte area, those cases out of the 104 which occur with southwest geostrophic winds should have higher A values than the other cases. The following data display shows this to be true.

geos. wind	cases	$A<-20$	$-20<A<20$	$20<A<60$	$60<A<100$	$A>100$	$\bar{A}$
SW	65	9	22	15	9	10	+43
Non-SW	39	8	20	7	2	2	+08

Not only does this table show that the $\bar{A}$ for SW cases exceed the $\bar{A}$ for non-SW cases by 35 which is a significant difference at the .05 level, but it also shows that nineteen of the twenty-three cases for which A is greater than +60 and ten of the twelve cases for which A is greater than +100, occur with southwest geostrophic winds. In fact only four of the thirty-nine non-SW cases have A's greater than +60 whereas nineteen of the sixty-five SW cases have A's this high. This evidence alone implies that the Estoque focusing process does intensify the convective rainfall at La Porte, but to be more certain we should consider some other correlations.

Estoque's model also showed that the maximum lake breeze intensification occurs in the early evening. Therefore, those convective rainfall cases that occur in the evening (1600-2400 LMT) should have higher A values than those cases which occur at other times of the day. Classification of the A values according to size and time of occurrence yields the following results:

time	cases	$A<-20$	$-20<A<20$	$20<A<60$	$60<A<100$	$A>100$	$\bar{A}$
1600-2400	38	3	11	10	7	7	+56
0000-1600	66	14	31	12	4	5	+19

This table shows that the evening cases have an $\bar{A}$ which is significantly larger than the $\bar{A}$ for the non-evening cases. Moreover, 63 percent of the evening cases (24 of 38) have A values greater than +20 while only 32 percent of the non-evening cases (21 of 66) have A values this high.

Another feature in the Estoque intensification process is that it increases the available water vapor. Now for a lake breeze to increase the available water vapor over the land the mixing ratio over the lake must be higher than that over the land. Thus, when the mixing ratio over Lake Michigan exceeds that over the land and a southwest geostrophic wind generates a strong lake breeze circulation in the La Porte area, the available water vapor should be substantially increased. So, if the focusing process is real, those cases that have both a southwest geostrophic wind and a higher mixing ratio over the lake should have even higher A values than those cases with southwest geostrophic winds alone. To test this, the author calculated the lake-land mixing ratio difference, Δr, for 84 of the 104 cases. The mixing ratio over the land was calculated for each case from the average humidity and temperature at South Bend for the six hour period prior to the beginning of the rain and the mixing ratio over the lake was assumed to be the saturation mixing ratio at the lake water temperature. Tabulating the A values we get:

(SW, $+\Delta r$)	cases	$A<-20$	$-20<A<20$	$20<A<60$	$60<A<100$	$A>100$	$\bar{A}$
Yes	23	1	8	6	5	3	+57
No	62	12	24	13	5	8	+27

The $\bar{A}$ for the twenty-three (SW, $+\Delta r$) cases exceeds the $\bar{A}$ for the other sixty-two cases by 30, but this is not a significant difference at the .05 level because of the small sample size. However, this $\bar{A}$ of +57 is somewhat larger than the $\bar{A}$ of +43 for those cases having only a southwest geostrophic wind and this is encouraging.

Going one step further, consider those evening cases with SW geostrophic wind and positive Δr. All three of these conditions are conducive to Estoque intensification and therefore, when occurring simultaneously, should produce the highest A values of all. Classifying the A values and calculating the averages we get:

(SW,+Δr, even.)	cases	A<-20	-20<A<20	20<A<60	60<A<100	A>100	$\bar{A}$
Yes	13	0	3	3	4	3	+84
No	71	13	28	15	7	8	+27

The thirteen yes cases have an $\bar{A}$ of +84 which exceeds the $\bar{A}$ of the seventy-one no cases by 57. The probability of a difference this large occurring by chance is only.07 in spite of the small sample size. In addition, 54 percent of the yes cases (7 of 13) have A values greater than +60 whereas only 21 percent of the no cases (15 of 71) have A values greater than +60. Furthermore, and most important, the $\bar{A}$ of +84 for the thirteen (SW,+Δr, even.) cases is higher than the $\bar{A}$ of +56 for the twenty-three (SW,+Δr) cases and the $\bar{A}$ of +43 for the sixty-five SW cases. In other words, $\bar{A}$ seems to become higher as one adds more conditions favorable to Estoque focusing.

These statistics demonstrate with marginal significance that higher A values accompany those meteorological conditions that favor the Estoque process. This association is not very conclusive by itself, but coupled with the evidence presented above, it certainly suggests that the Estoque focusing process does cause the higher A values and does intensify the horseshoe process in the La Porte area.

D. Temporal variation

Although the horseshoe process, coupled with the Estoque focusing process, seems to explain the spatial character of the anomaly, these two processes, of themselves, cannot account for the temporal variation of the anomaly, since Lake Michigan has not changed significantly in thousands of years. The author agrees with this reasoning and, as mentioned earlier, proposes that the time variation results, not from temporal changes in the two lake-induced processes, but rather from temporal changes in the number of squall lines upon which these two processes may act. In other words, the size of the anomaly for any time period depends on how many squall lines passed by during that period.

To test this idea, one should go through the climatological records and count the squall lines for each year to see if the squall line variation matches the anomaly variation. This, unfortunately, is not possible because over the years the definition of a squall line has varied and as the number of reporting stations has increased, it has become easier to distinguish squall lines from scattered thunderstorms. Thus, one must instead examine the changes in the large scale weather patterns and see if they would cause the squall line frequency to vary as the anomaly does. Fortunately, there is usable evidence in this area.

Stout (1961), for example, states that there was a greater frequency of summertime cold fronts moving through the upper Mississippi Valley during the 1940's and 1950's than there were prior to 1940 and after 1960. Since squall lines are often associated with cold fronts, there were also probably more squall lines during this period. Much more convincing evidence is offered by Willett(1968), who in his studies on the relationship between the large scale circulation patterns and sunspot cycles, found that during the period 1935-1960 there was a greater frequency of 500 mb troughs moving through the central United States in winter and in summer because of a persistent blocking pattern in the Atlantic. On the other hand, prior to and after this period, the circulation over the United States tended to be more zonal and therefore there were fewer 500 mb troughs moving through during the 1920's, early 1930's, and during the 1960's. Now a greater frequency of summertime 500 mb troughs would certainly cause more squall lines and therefore there were probably more squall lines passing over Lake Michigan from 1935-1959 than before or after this period. Thus, based on the findings by Stout and Willett, the temporal variation of squall line frequency appears to match the temporal variation of the anomaly rather well.

Of course, one may ask why the anomaly does not exist to a lesser degree prior to 1935 and after 1960, since the number of squall lines does not go to zero for these periods and also why, during the past hundred years, there has been no previous rainfall anomaly at La Porte when most certainly the squall line frequency must have peaked at some other time during this long period. A careful scrutiny of the rainfall maps (see Figures 2 and 3) answers the first question, for these maps show that during the 1920's, early 1930's and 1960's, there still is a recognizable anomaly in northwest Indiana, very much smaller, but nevertheless, discernable. Answering the second question, there have been no previous reports of sharp rainfall anomalies at La Porte during the past hundred years because, prior to 1920, there were scarcely enough reporting stations to draw meaningful rainfall contours and, prior to 1897, there was no rainfall record at La Porte. So, large anomalies may very well have occurred before, but have gone unnoticed.

E. Weak points

In spite of the abundent evidence in support of the Lake Michigan theory, there are some weak points which must be considered. First, the evidence, supporting the horseshoe and Estoque processes, is based on data from the five year period 1955-1959, and to take the conclusions based on this non-random sample of data and to apply them to the entire anomaly period is somewhat questionable. Second, the argument supporting the Estoque process is based to a large degree on marginally significant statistics which, of course, leaves room for doubt. Finally, the argument supporting the explanation of the time variation is indirect and weak since it is based purely on the good agreement between the temporal variation in 500 mb trough frequency and the temporal variation of the anomaly. These three weaknesses, although simple and obvious, cannot be ignored.

F. Conclusion

Based on all the evidence presented, the Lake Michigan theory seems to explain the La Porte anomaly, at least for 1955-1959. However, since it is much easier to reject an explanation than to accept one, we cannot in the light of the above weaknesses give unqualified acceptance to this theory. But since this explanation surpasses the other explanations examined, we can declare the Lake Michigan explanation to be the most tenable theory for the La Porte anomaly offered so far.

V. CLOSING

A. Summary of results

We have rejected the instrument-observer bias, Chicago heat island, and Chicago air pollution explanations and have accepted the Lake Michigan explanation with reservations. The facts supporting these conclusions are too numerous to restate at this time, but we should re-emphasize the fact that the anomalous rainfall comes from organized systems of heavy thunderstorms (mostly squall lines) and not from isolated convective showers. This evidence is particularly important not only because it casts much doubt on the heat island and air pollution theories and supports the Lake Michigan explanation, but also because it is based entirely on observed statistics and therefore is indisputable.

B. Confidence in findings

We are particularly confident in the rejection of the heat island and air pollution theories because this rejection is based primarily on the fact that the physical processes involved in these theories most likely could not intensify squall line thunderstorms. Whereas, the statistics show that the anomalous rainfall comes from these type thunderstorms. The conclusion concerning the instrument-observer bias explanation is not quite so certain. Although the facts presented in the examination certainly suggest that the anomalous rainfall is real, there will always be some doubt here because there were no nearby rainfall stations during the anomalous period to corroborate Mr. Link's data. As for the Lake Michigan theory, we have a high degree of confidence in the reality of the horseshoe process, but there is sufficient doubt surrounding the Estoque focusing process and the temporal variation of squall line frequency to limit our acceptance of this explanation.

C. Recommendations

To settle the La Porte question with a greater degree of certainty, the author recommends that a similar examination be conducted using the data from the 1935-1955 period to see if the results are the same as those for the 1955-1959 period. In addition, a detailed radar study of squall line passages over Lake Michigan should be made to determine the reality of the horseshoe process. A meso-scale reporting network in the La Porte area would certainly shed more light on the fine details of the rainfall patterns and the lake breeze circulations. Finally, careful attention should be directed to the La Porte area during the last part of this century to see if the anomaly grows large again.

D. Significance of findings

The evidence presented in this paper indicates that natural processes and not Man's inadvertent activities have caused the La Porte rainfall anomaly. This result casts doubt on the proposition that Man, through his own directed efforts, can significantly alter the rainfall in selected areas, and reminds Man to be cautious in appraising his ability to alter the climate.

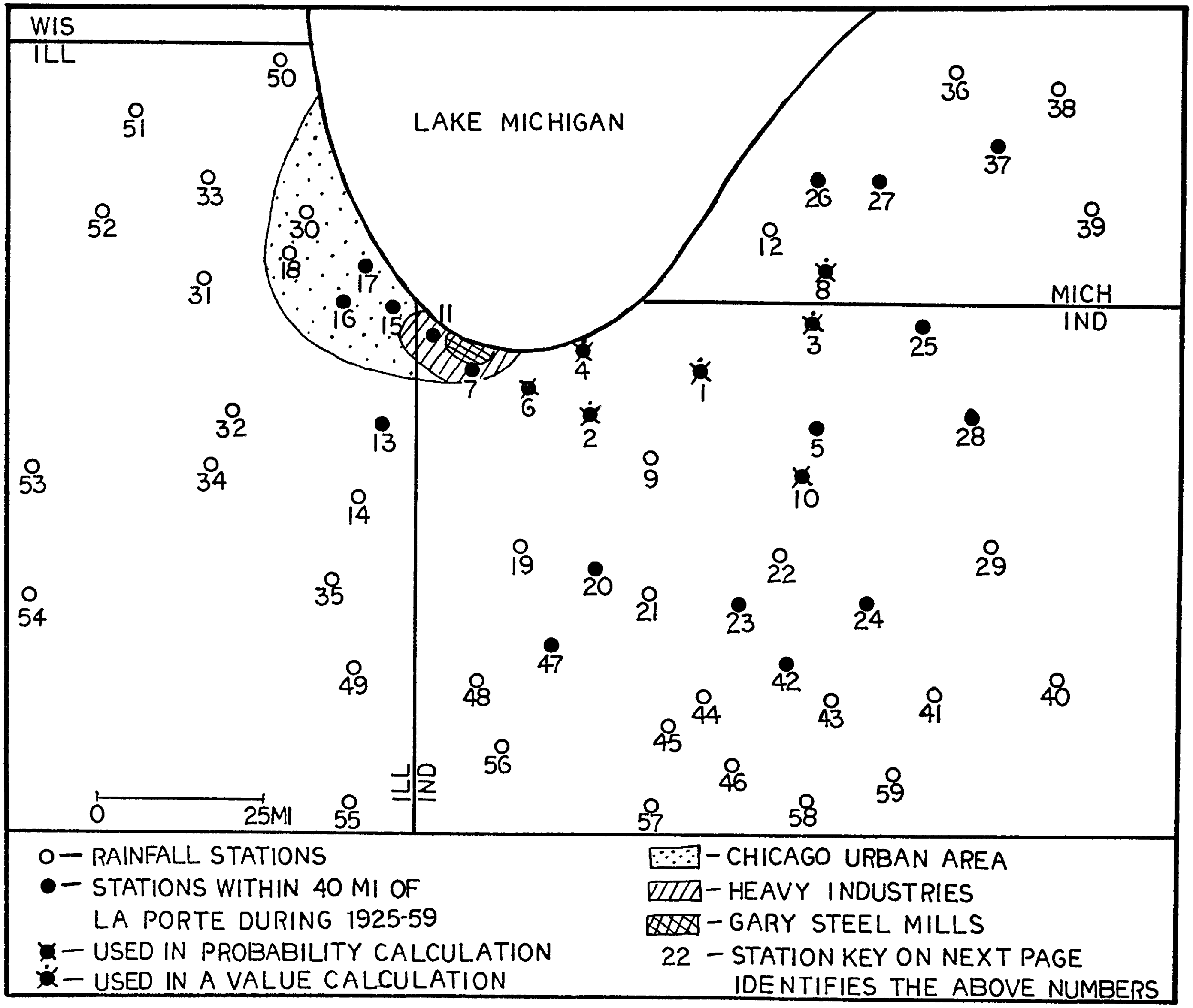

Figure 1. Rainfall stations and Chicago urban area.

Station Key For Figure 1

1	La Porte	31	Aurora
2	Valpariso	32	Joliet
3	South Bend	33	Elgin
4	Ogden Dunes	34	Morris
5	Lakeville	35	Kankakee
6	Hobart	36	Bloomington
7	Gary	37	Paw Paw
8	Niles	38	Kalamazoo
9	Wanatah	39	Three Rivers
10	Plymouth	40	Huntington
11	Whiting	41	Peru
12	Berrien Springs	42	Royal Center
13	Park Forest	43	Logansport
14	Peotone	44	Monticello
15	University of Chicago	45	Chalmers
16	Midway Airport	46	Delphi
17	Chicago City Office	47	Collegeville
18	Wheaton	48	Kentland
19	Shelby	49	Watseka
20	Wheatfield	50	Antioch
21	Medaryville	51	Marango
22	Culver Exp. Farm	52	Sycamore
23	Winamac	53	Ottawa
24	Rochester	54	Streator
25	Elkart	55	Hoopston
26	Eau Claire	56	Fowler
27	Dowagiac	57	Lafayette
28	Goshen	58	Burlington
29	Warsaw	59	Kokomo
30	O'Hare Airport		

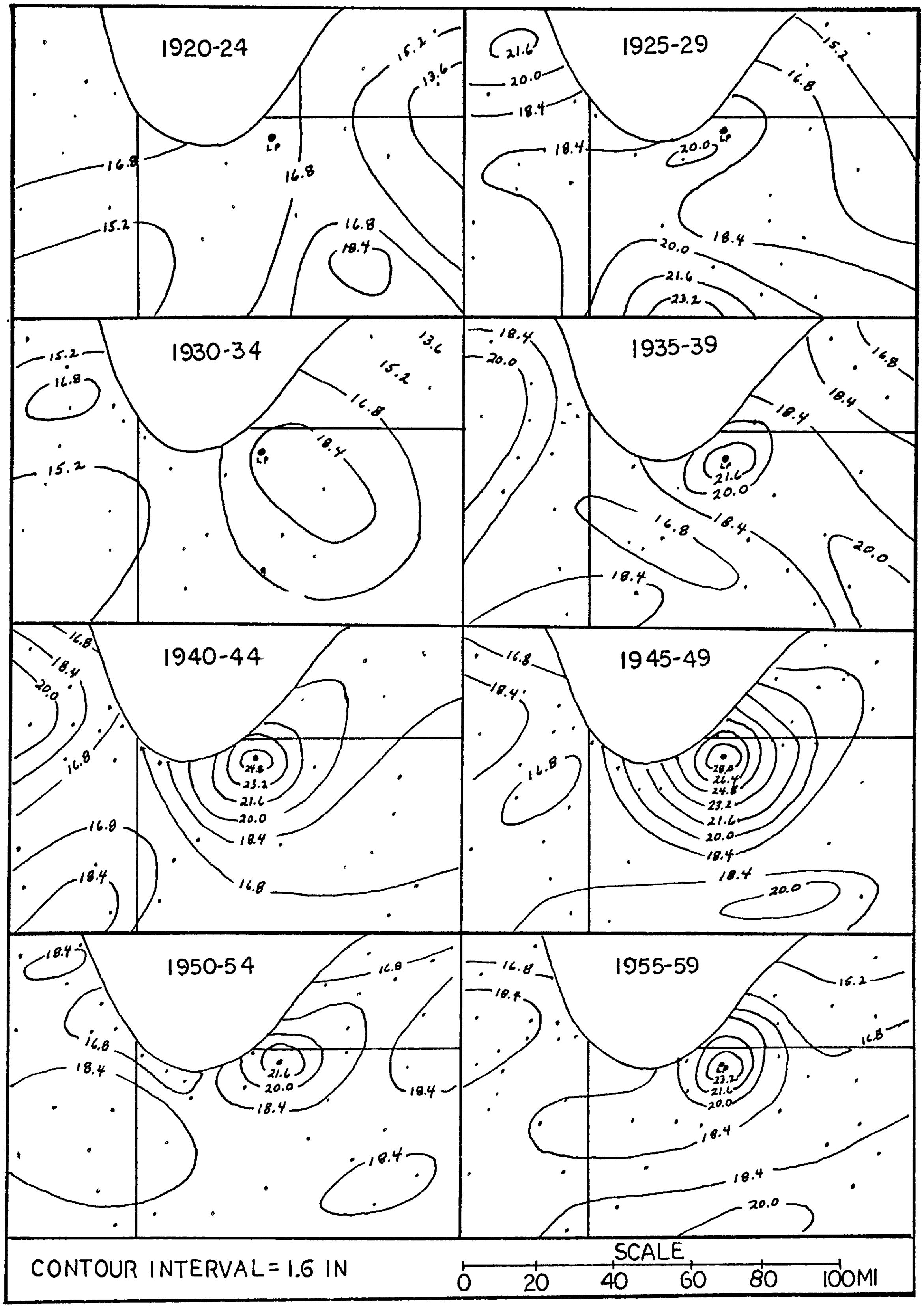

Figure 2. La Porte summer rainfall patterns (1920-1959).

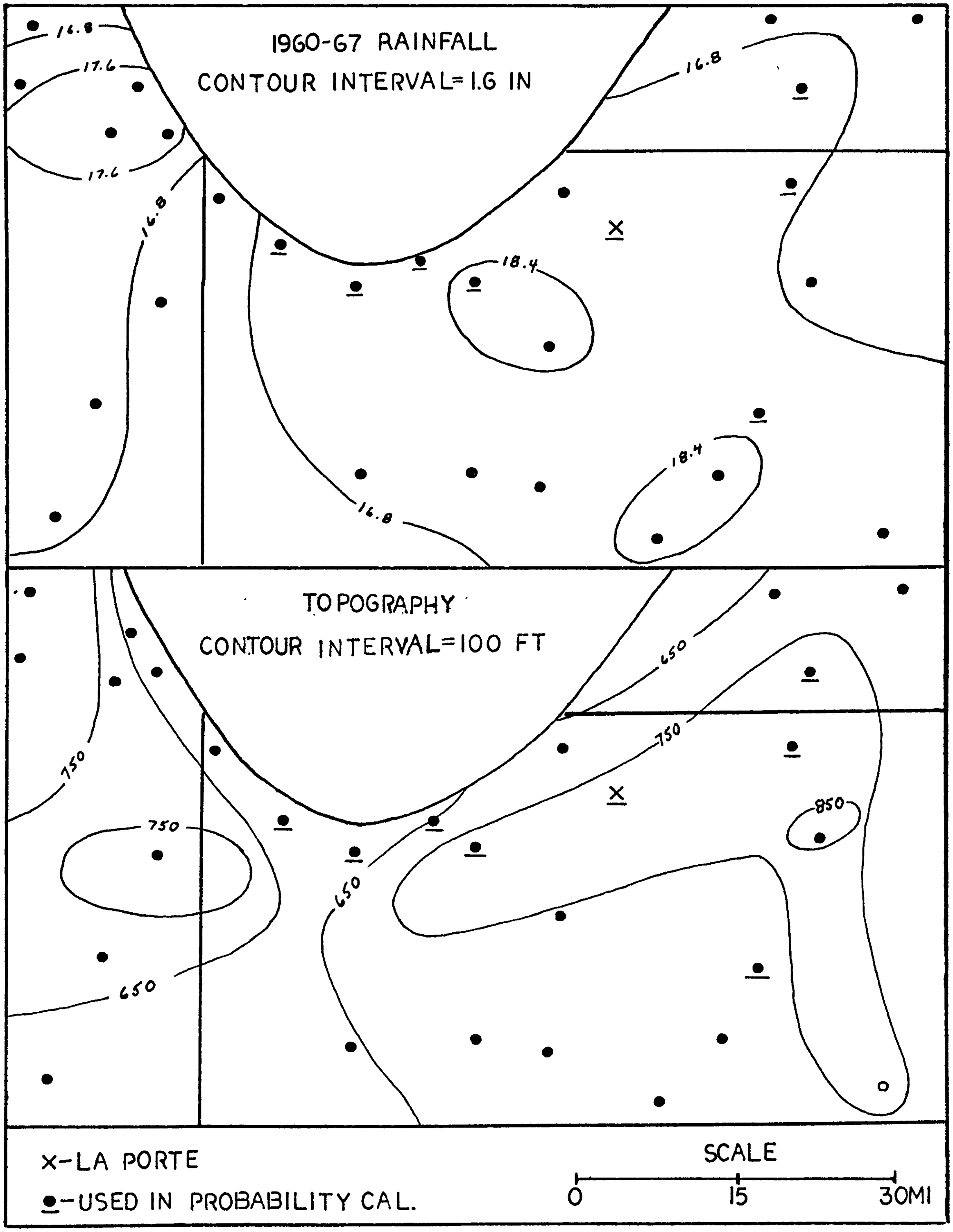

Figure 3. La Porte summer rainfall (1960-1967)

and topography.

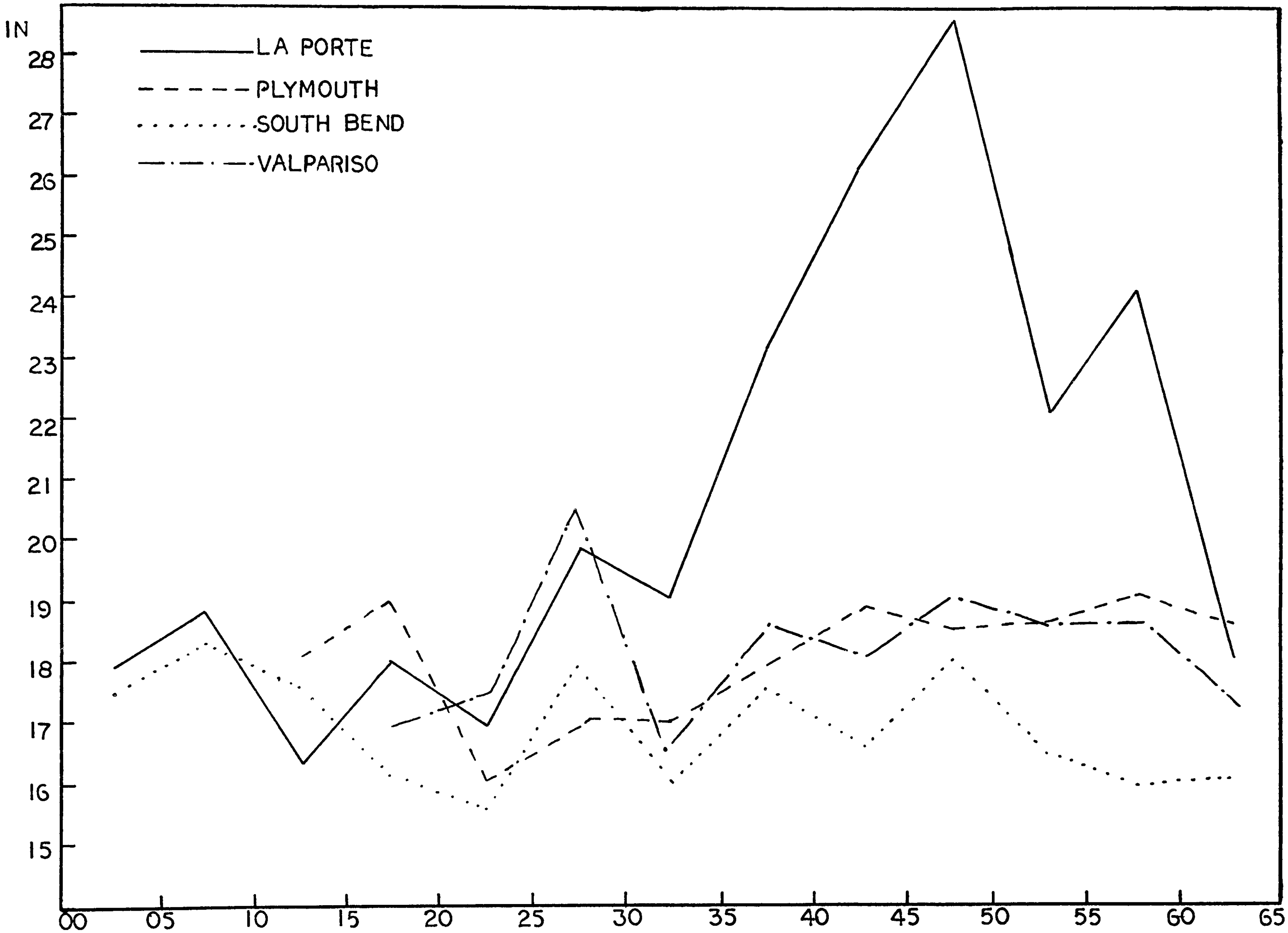

Figure 4. La Porte summer rainfall (1900-1965) compared to three nearby stations - 5 yr. averages.

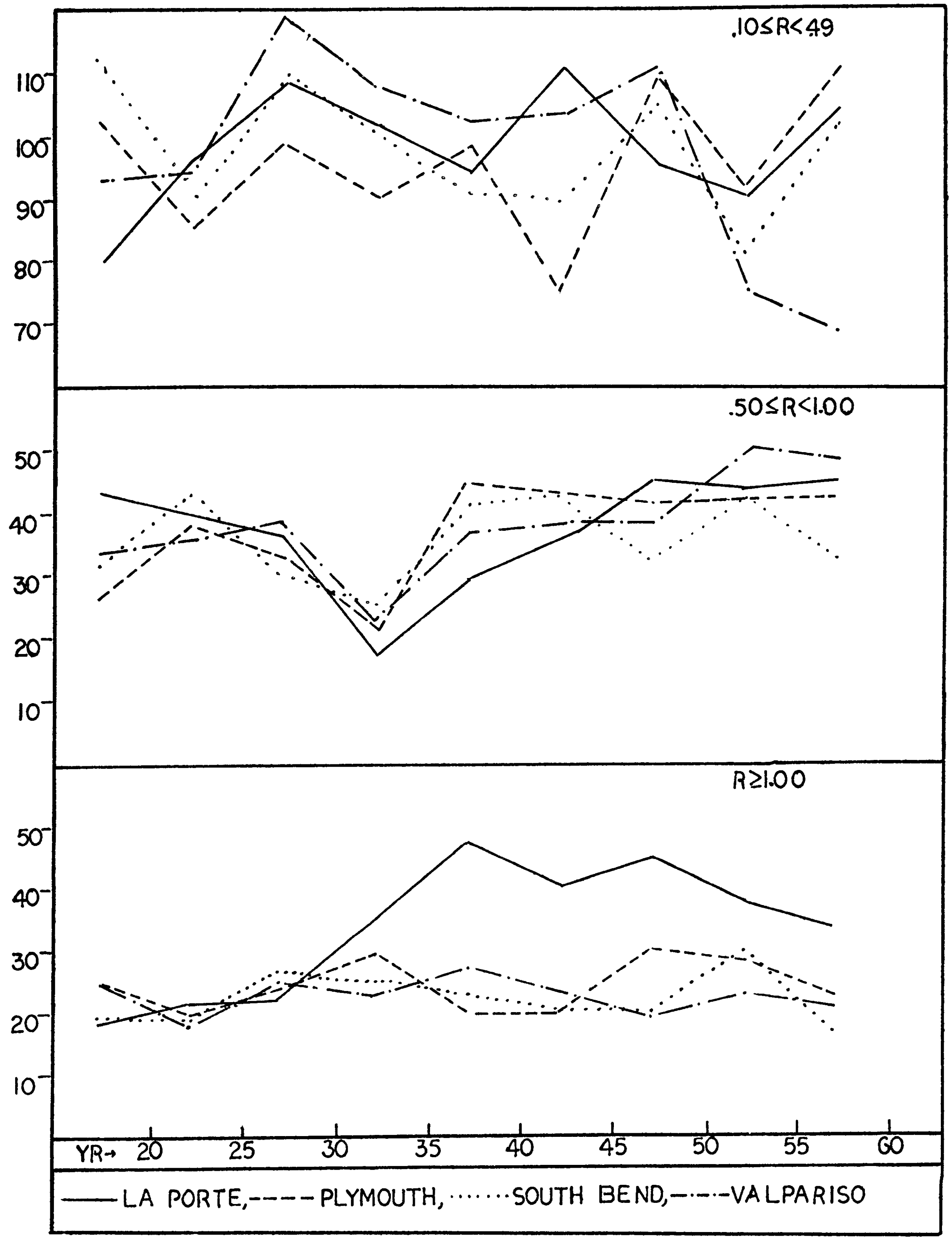

Figure 5. Number of days within each daily rainfall size category for 1915-1960 (5 yr. totals).

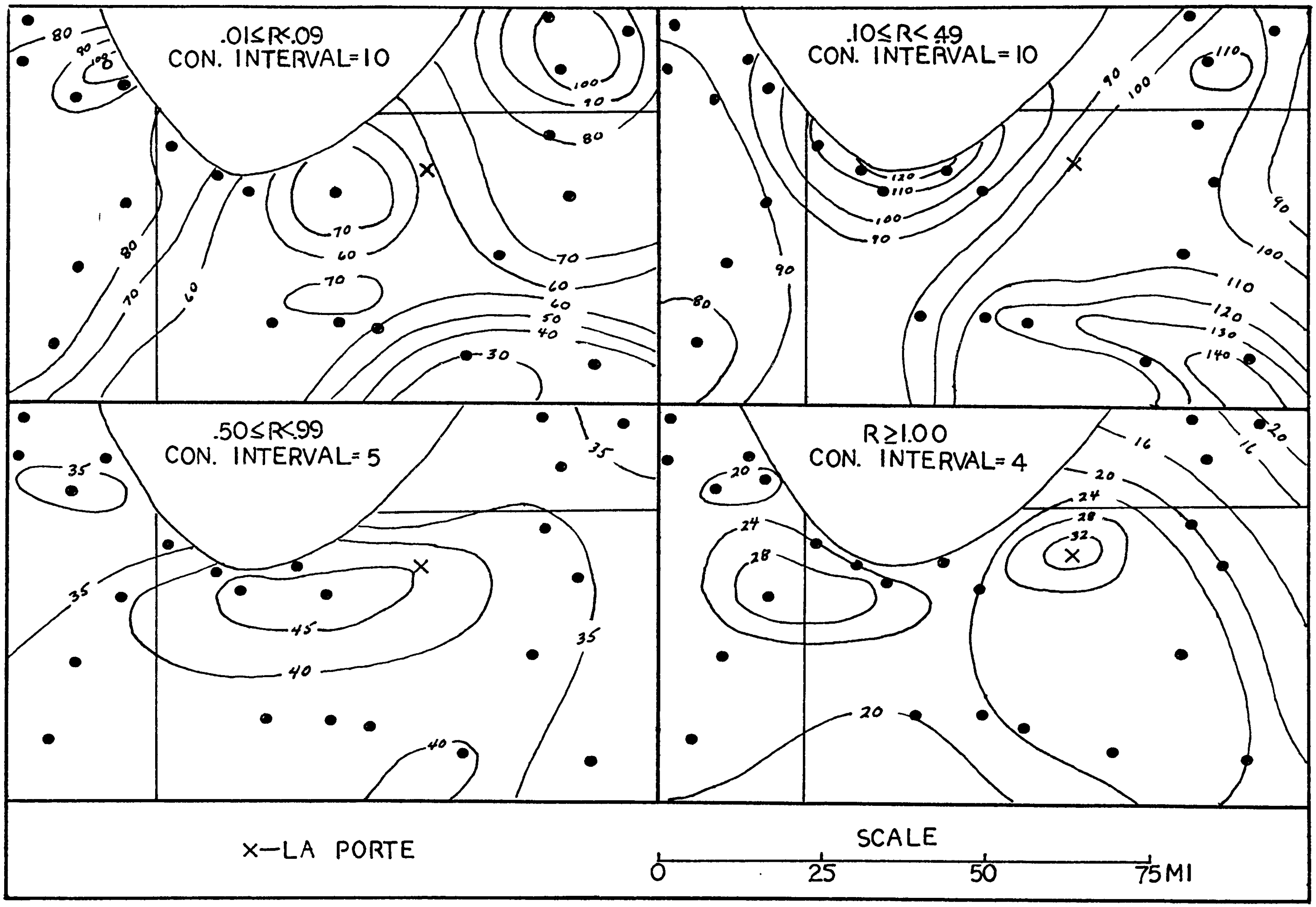

Figure 6. Number of days falling into each rainfall size category during 1955-1959.

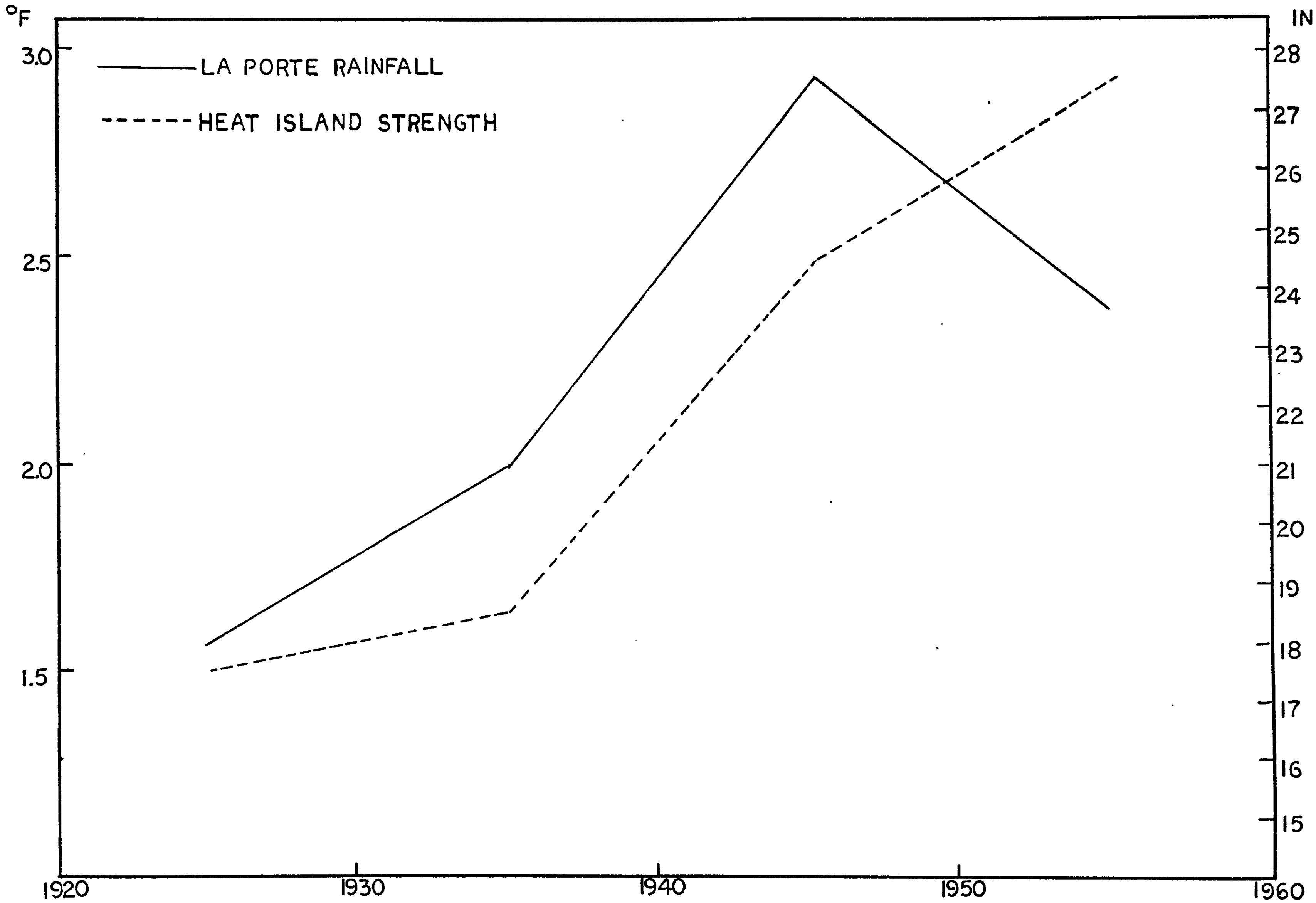

Figure 7. Variation of heat island strength vs. La Porte summer rainfall (1920-1960).

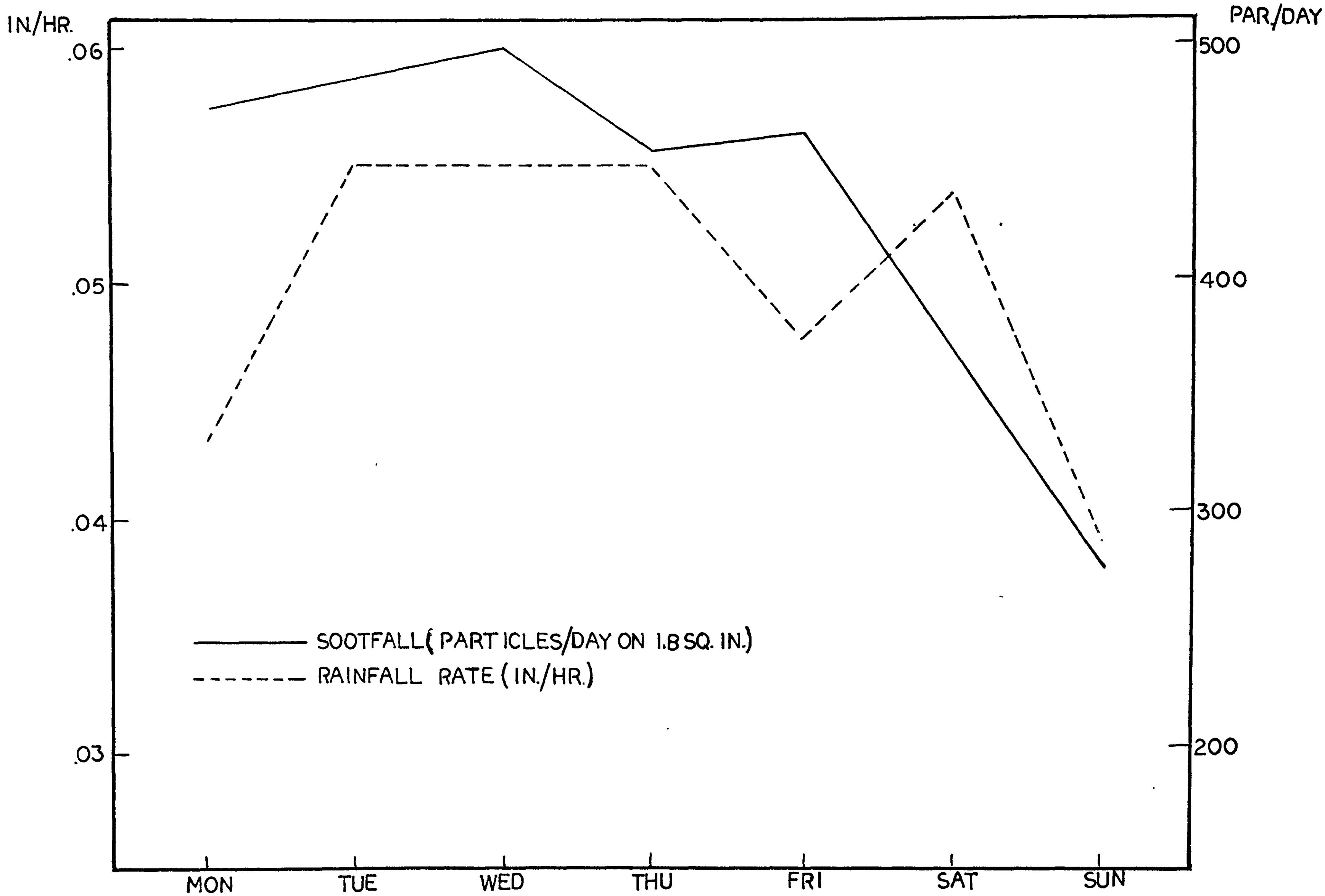

Figure 8. Average daily rainfall rate and sootfall for each day of week at Rochdale, England (1897-1927).

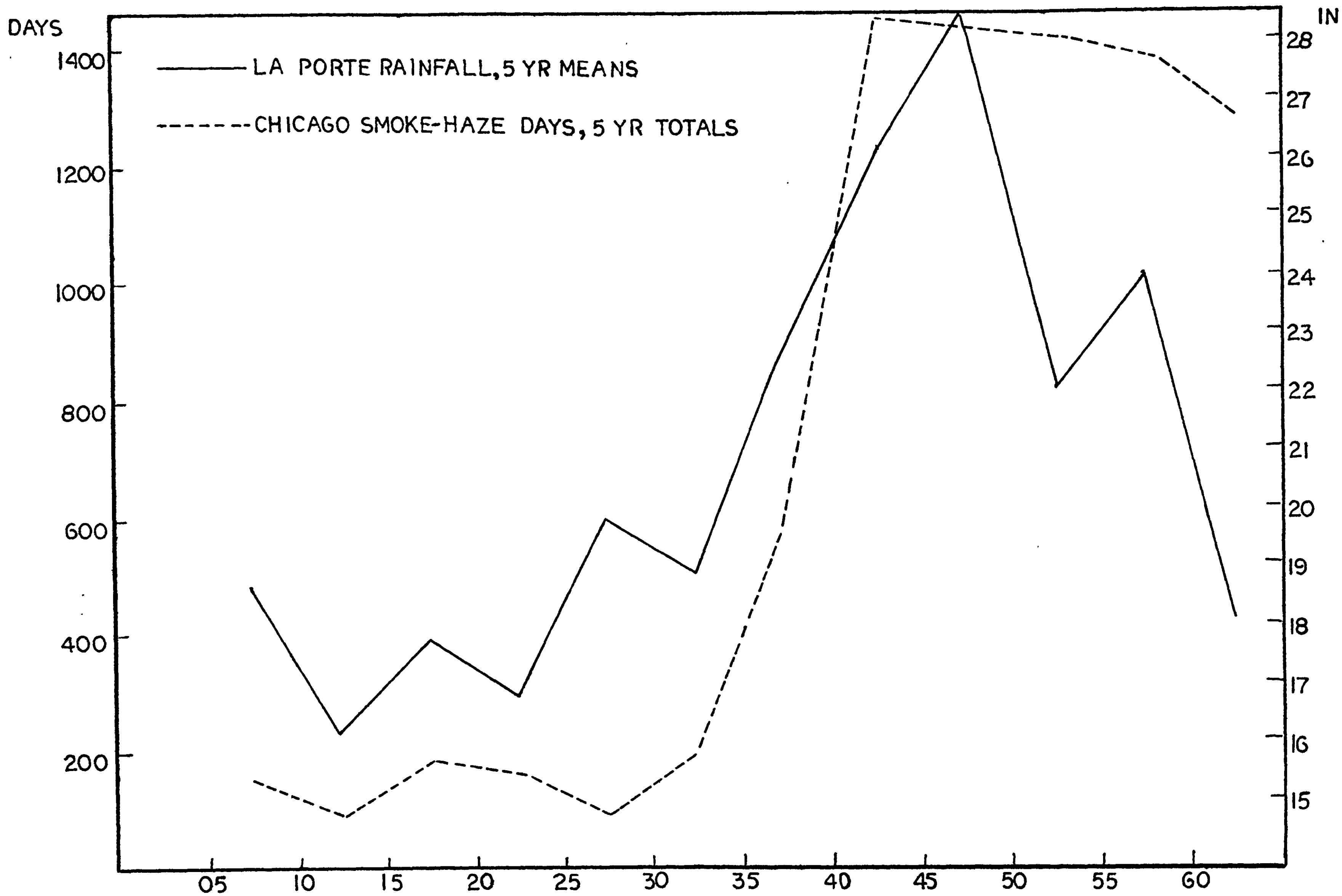

Figure 9. Chicago smoke-haze days vs. La Porte summer rainfall (1905-1965).

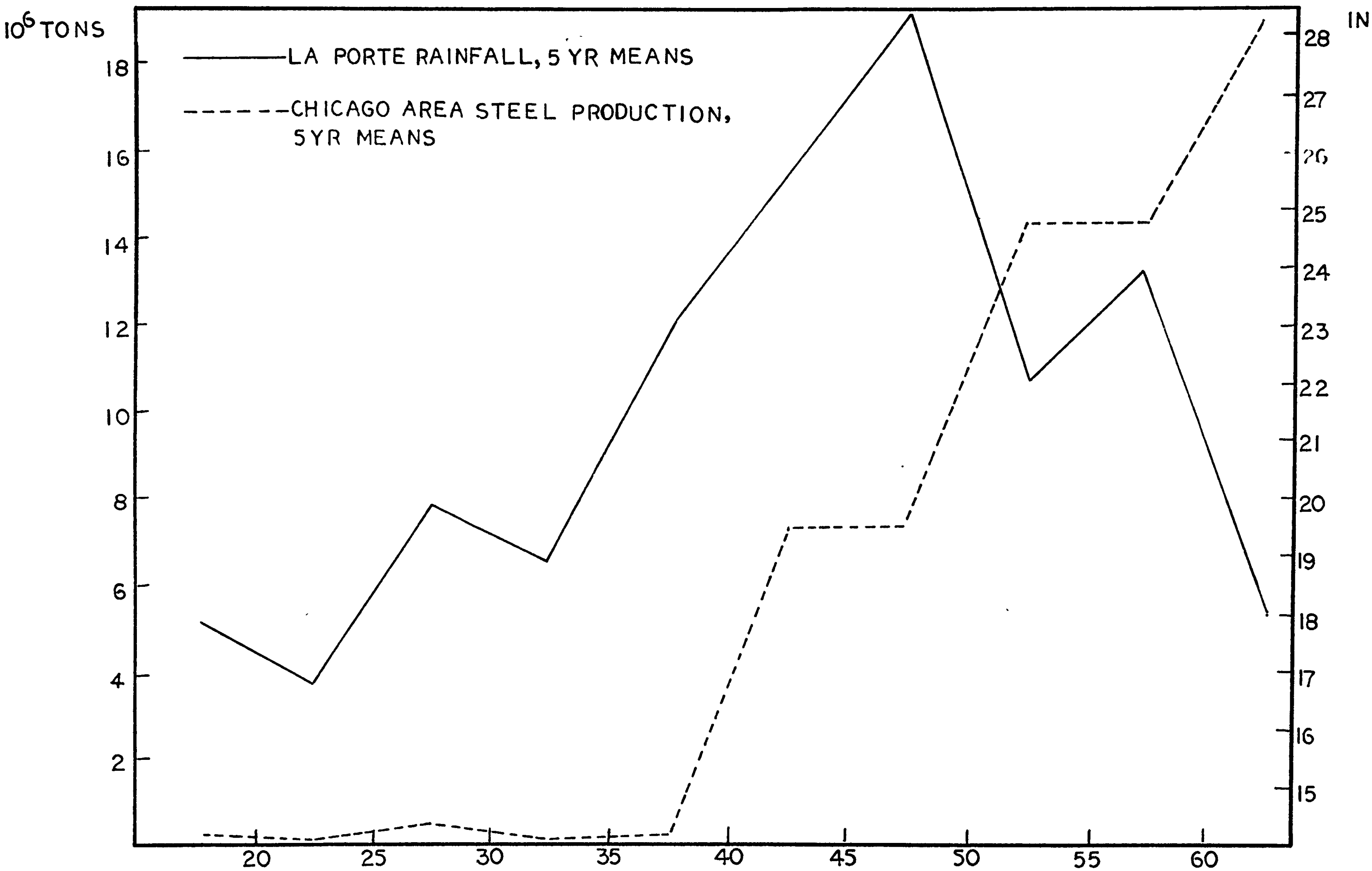

Figure 10. Variation of Chicago steel production vs. La Porte summer rainfall (1915-1965).

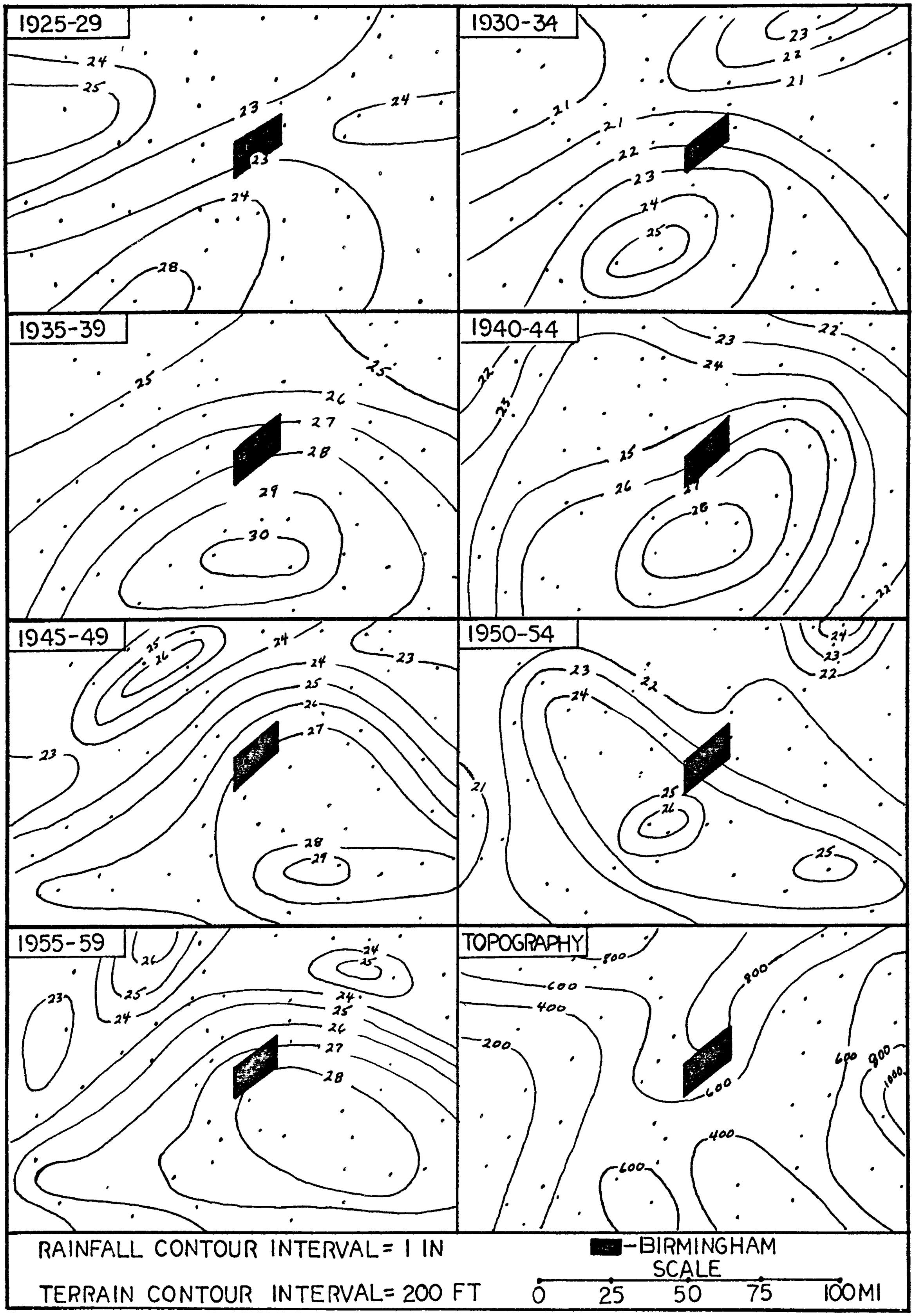

Figure 11. Birmingham summer rainfall (1925-1959) and topography.

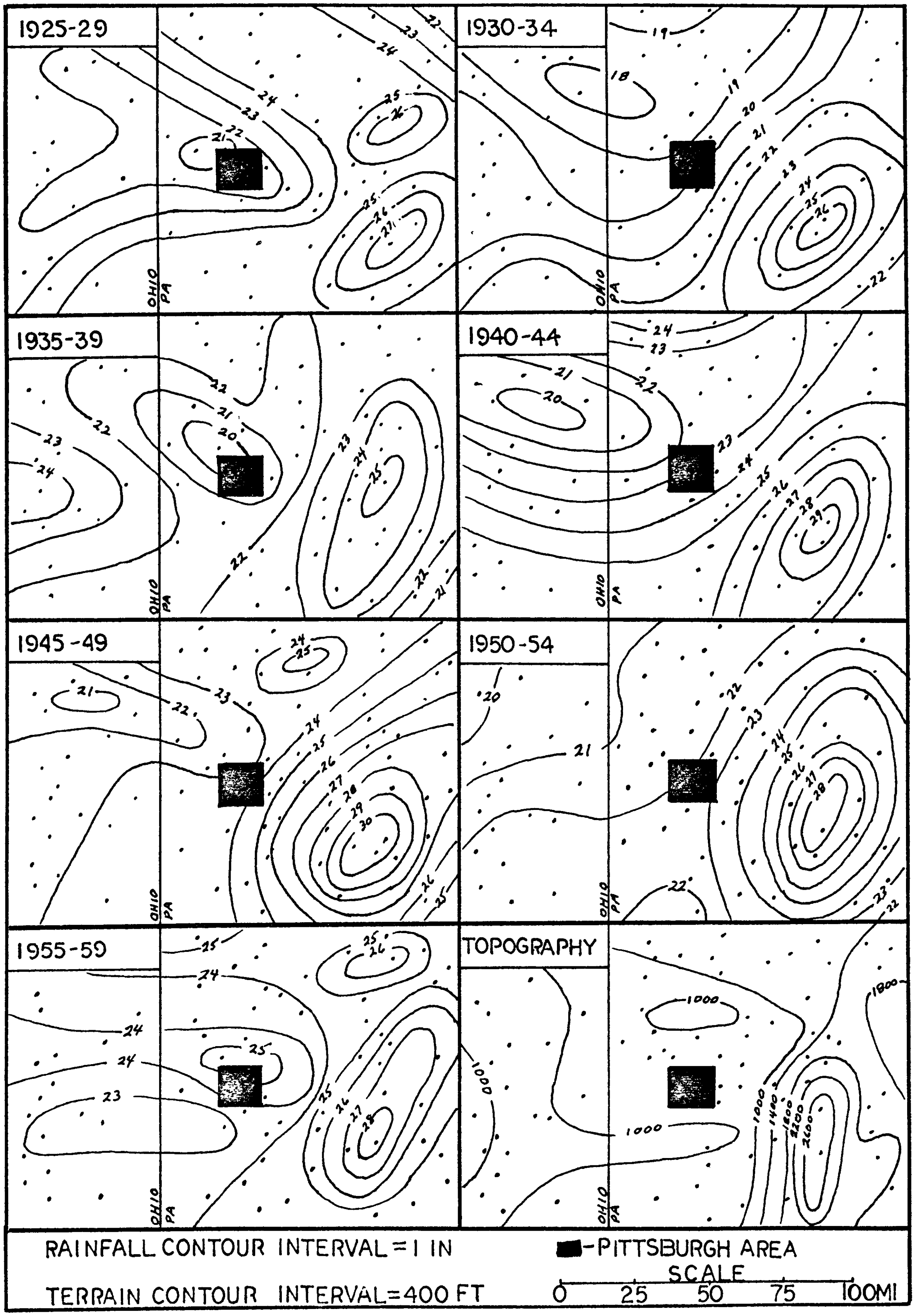

Figure 12. Pittsburgh summer rainfall (1925-1959) and topography.

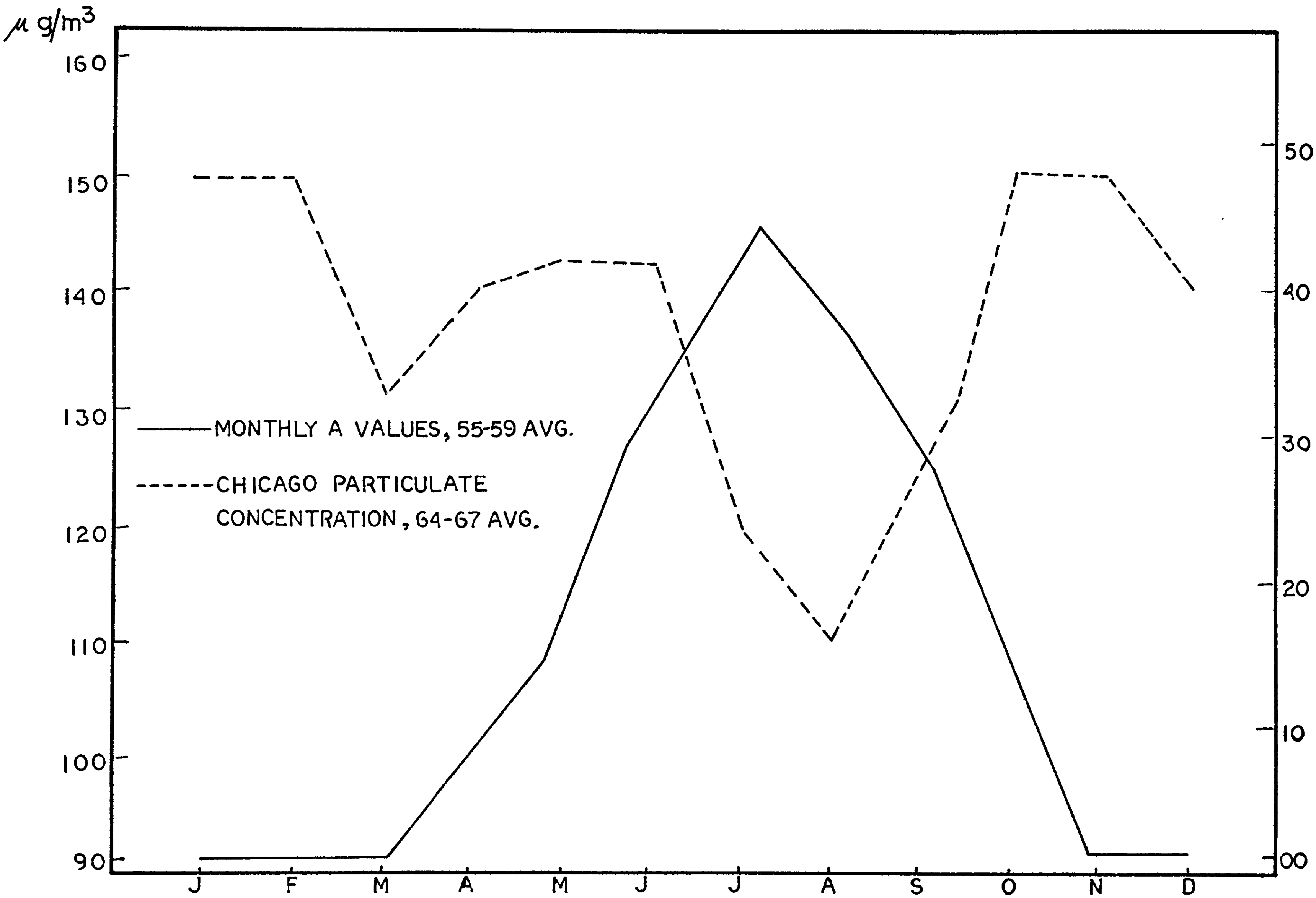

Figure 13. Monthly variation of Chicago particulate concentration vs. anomaly size.

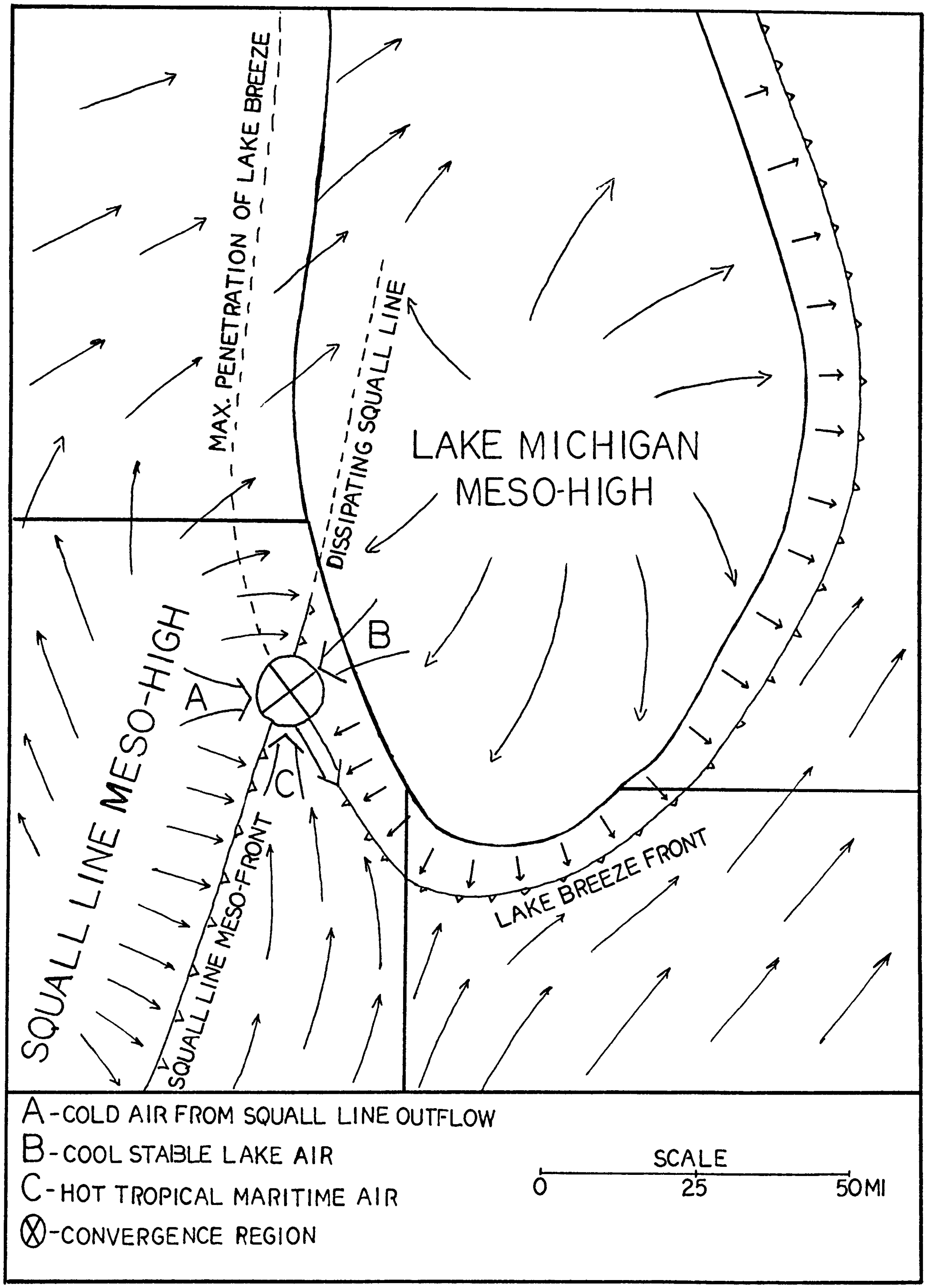

Figure 14. Hypothetical example of horseshoe process.

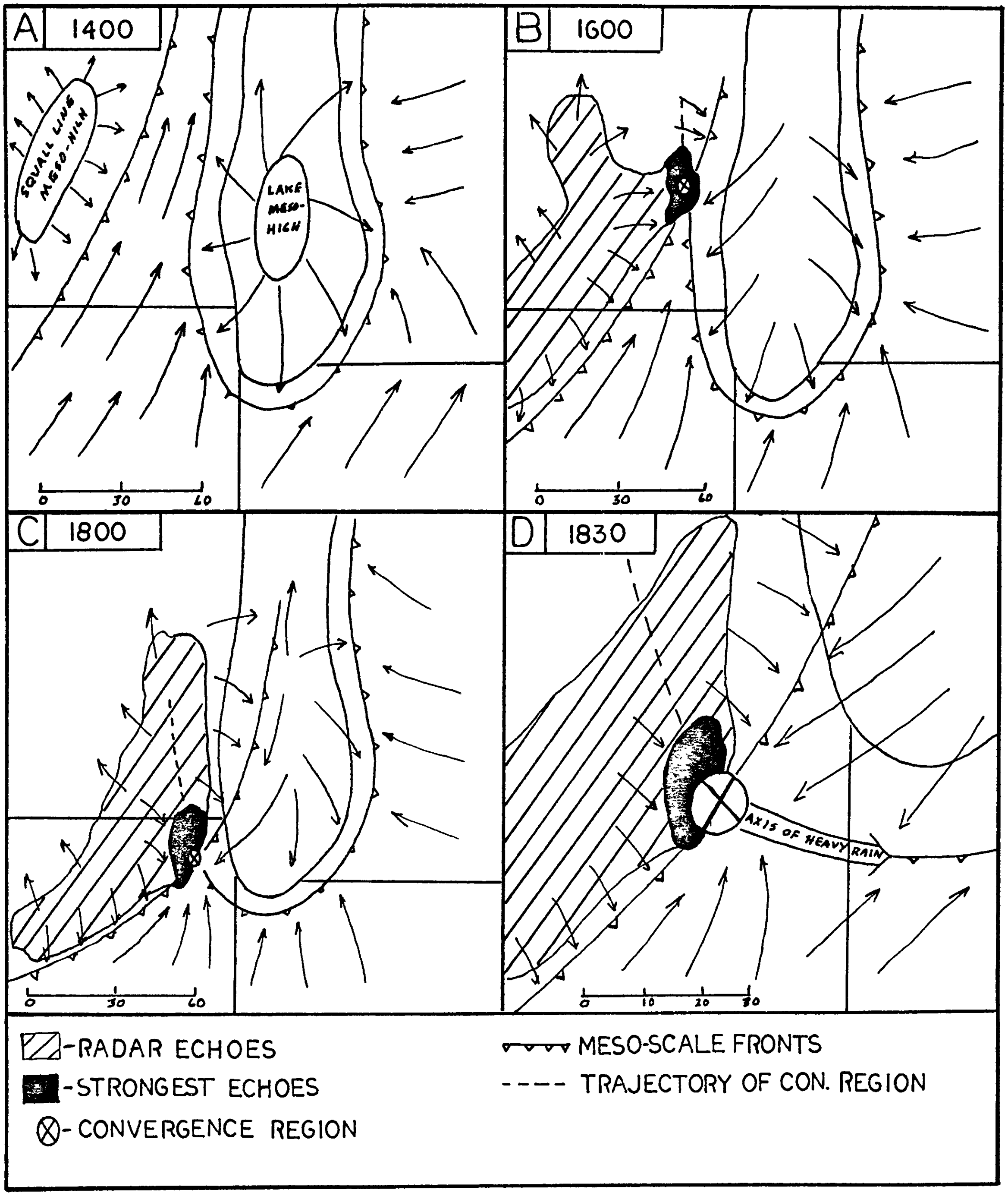

Figure 15. Squall line passage of 7 June 1963. (Lyons 1966)

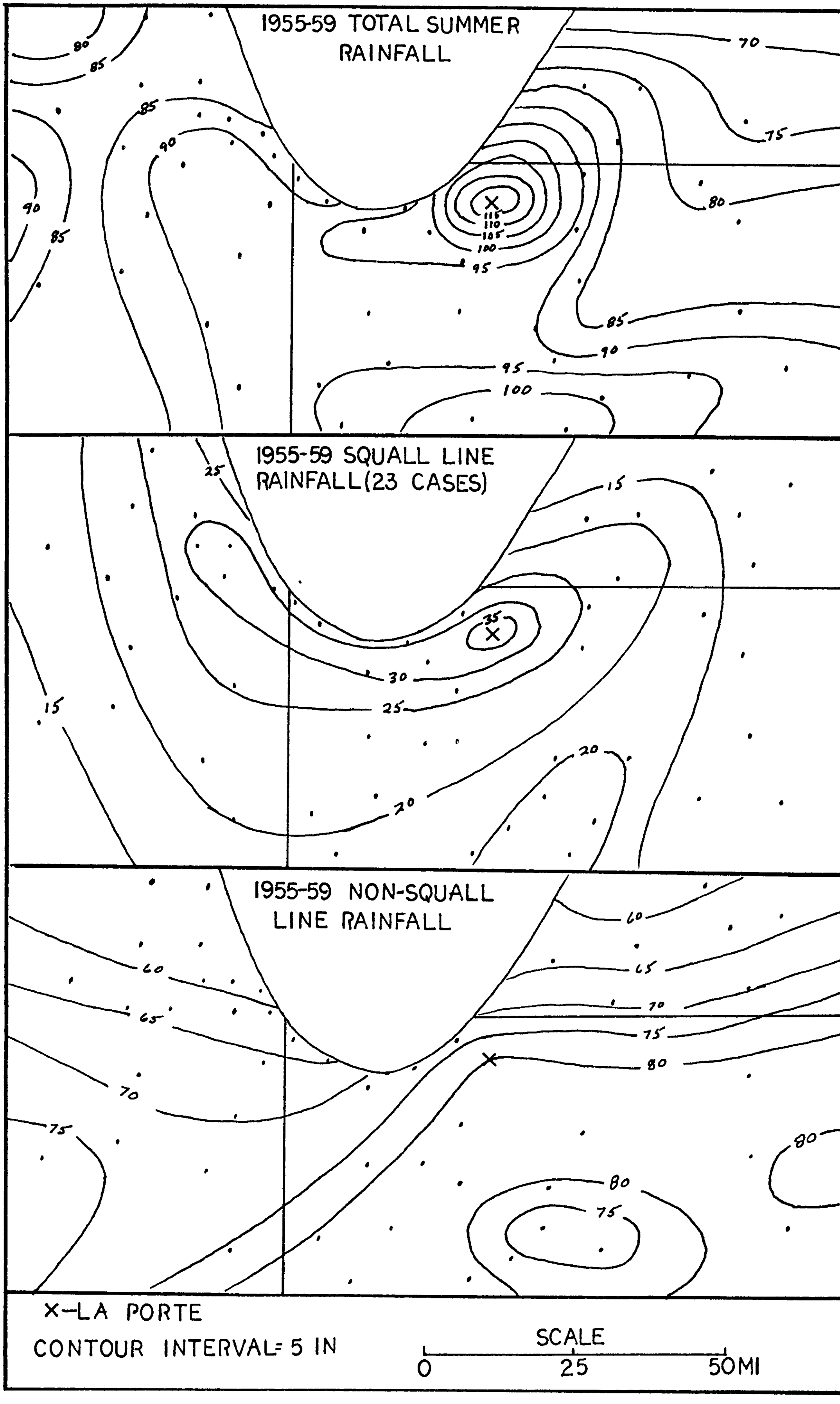

Figure 16. 1955-1959 total summer rainfall patterns.

APPENDIX

Data Used In A Value Correlations

Symbols:

n - case number

VL - rainfall at Valpariso (in.)

OD - rainfall at Ogden Dunes

SB - rainfall at South Bend

NI - rainfall at Niles

LP - rainfall at La Porte

$\overline{R}$ - area average = average of five stations

A - anomaly size = 100 X (LP - $\overline{R}$) / $\overline{R}$

CT - rainfall commencement time, LMT, according to hourly rainfall at South Bend

GW - geostrophic wind direction

D - day of week (MF = Mon.-Fri., SS = Sat. or Sun.)

V - average visibility six hours prior to CT (mi.)

Δr - mixing ratio difference between lake air and land air, $\Delta r = r_{lake} - r_{land}$

n	Date	VL	OD	SB	NI	LP	$\bar{R}$	A	CT	GW	D	V	Δr
1	5-24-55	.44	.40	.52	1.08	.62	.61	+02	0500	SW	MF		
2	5-28-55	.90	.53	1.08	1.80	.85	1.03	-18	0600	SW	MF		
3	6-6-55	.63	.48	.46	.45	.38	.44	-14	1400	SW	MF		
4	6-9,10-55	.51	.53	.72	.48	.55	.56	-18	1700	SE	MF		
5	7-6-55	.01	.21	1.34	.11	.32	.40	-20	1300	SW	MF		
6	7-14,15-55	.07	.62	.96	.42	.77	.57	+35	2300	SW	MF		
7	8-6-55	2.38	2.02	2.50	2.31	1.45	2.14	-32	0300	SW	MF		
8	8-22-55	1.22	.76	.84	.40	1.20	.84	+43	0100	SW	SS		
9	8-29,30-55	3.66	3.87	2.24	1.85	3.53	3.03	+17	1800	SW	MF		
10	9-10-55	.41	.37	.87	.58	1.01	.65	+55	1400	SW	SS		
11	9-29-55	.74	.78	1.03	.63	1.29	.89	+45	1100	SW	MF		
12	5-5-56	.78	.73	.37	.67	.61	.63	-32	1200	SW	SS		
13	5-9-56	.65	.64	1.01	.60	.88	.76	+16	1000	SW	MF		
14	5-10-56	1.48	.74	.30	.48	.71	.75	-05	0900	SE	MF		
15	5-11,12-56	.13	.10	1.34	1.63	.44	.73	-40	1500	SW	MF		
16	5-15,16-56	.53	.26	.58	.52	.45	.47	-43	0900	SE	MF		
17	5-26-56	.21	.08	.05	.09	.55	.20	+175	0900	SW	SS		
18	6-17-56	.59	.27	.65	.24	.52	.45	+16	0900	SW	SS		
19	6-26-56	.37	.49	.38	.40	.45	.42	+07	1400	SW	MF		
20	7-4,5-56	1.53	.06	.04	.01	.44	.47	+05	1600	E	SS		+
21	7-8-56	.90	1.01	.16	.18	.33	.52	-37	0400	SW	SS		-
22	7-13-56	.52	.17	.01	.01	.18	.18	00	0300	SW	MF		-
23	7-19,20-56	1.11	1.22	.90	3.52	1.24	1.60	-23	1800	SW	MF		+
24	8-12,13-56	.70	.53	2.09	1.83	1.48	1.32	+12	2000	SW	SS		+
25	8-18-56	.88	.50	.11	1.15	.45	.62	-27	0200	NE	MF		+
26	8-29,30-56	.29	.94	.31	.33	.40	.45	-11	2200	SW	MF		+
27	9-1-56	.36	.23	.38	.17	.34	.30	+13	0300	SW	MF		+
28	5-9,10-57	.18	.41	.43	.58	.36	.39	-08	1500	SW	MF		0
29	5-11-57	.66	.13	.23	.37	.51	.38	+34	0500	E	MF		+
30	5-13-57	1.00	.39	.27	.21	.37	.45	-18	0100	NE	SS		-
31	5-17-57	.23	.18	.21	.10	.25	.19	+32	0600	SE	MF		+
32	5-19-57	.20	.78	.83	.85	.75	.68	+10	0300	E	SS		+
33	5-31,6-1-57	.50	.18	.17	.07	.83	.35	+137	2300	SW	MF		-
34	6-5,6-57	.50	.20	.17	.17	.27	.26	+04	2000	SE	MF		+
35	6-7-57	.40	.45	.19	.03	.28	.29	-04	0900	SE	MF		+
36	6-11-57	.50	.27	.34	.75	1.00	.57	+75	0400	SW	MF		-
37	6-12,13-57	1.09	1.08	.48	.53	.72	.78	-08	2100	SE	MF		+
38	6-22,23-57	.52	1.14	.66	.11	.40	.57	-30	1800	SW	SS		-
39	6-28-57	.83	.03	.64	.87	.78	.79	-01	0300	SE	MF		-
40	7-12,13-57	2.98	1.97	.31	1.28	.78	2.06	-62	1400	NW	MF	10	-
41	7-17-57	.19	.07	.25	.12	.18	.16	+13	0100	SE	MF	3	-
42	7-20-57	.10	.09	.39	.20	.30	.22	+36	1200	SW	SS	3	-
43	7-22,23-57	.81	.72	.64	.42	.84	.69	+22	1300	W	MF	5	-
44	8-3-57	.86	.52	1.81	.46	.88	.91	-03	1300	SW	SS	12	-
45	8-9,10-57	2.50	1.99	.34	.42	1.88	1.42	+32	2200	NE	MF	2	+
46	8-23,24-57	.97	.39	.54	.78	.62	.66	-06	1800	SW	MF	12	+
47	8-28-57	.35	.27	.78	.75	.50	.53	-06	0800	SW	MF	7	+
48	8-28,29-57	1.42	.25	.69	.66	2.99	1.20	+149	2200	SE	MF	8	+
49	9-12-57	.27	.48	.18	.22	.13	.24	-46	1200	SW	MF	2	+
50	5-3-58	.25	.08	.19	.19	.19	.16	+19	0200	SE	MF	6	-
51	5-3,4-58	.26	.48	.13	.30	.38	.31	+23	1800	W	SS	10	+
52	5-17,18-58	.26	.20	.14	.38	.28	.25	+12	2200	SW	SS	15	-

n	Date	VL	OD	SB	NI	LP	$\bar{R}$	A	CT	GW	D	V	Δr
53	5-22-58	.28	.14	.22	.20	.13	.19	-32	0300	W	MF	8	+
54	5-31-58	1.30	.72	.27	.94	.40	.52	-23	0000	SW	SS	15	-
55	6-1-58	1.29	1.36	.96	.82	1.42	1.17	+21	1800	SW	SS	15	-
56	6-8-58	1.23	.76	.42	.68	.40	.64	-38	0800	SW	SS	12	-
57	6-9,10-58	.36	.04	.31	.42	.65	.36	+81	1800	SW	MF	1	-
58	6-13-58	1.46	1.61	.95	.65	1.62	1.25	+38	0300	SW	MF	2	-
59	6-17-58	.64	.21	.07	.14	.22	.24	-08	1200	NE	MF	10	+
60	6-19-58	00	.02	.12	.31	.48	.21	+129	0000	SW	MF	12	+
61	6-24-58	.28	.35	.33	.56	.28	.36	-22	0900	S	MF	8	+
62	6-24,25-58	.42	.28	.23	.42	.65	.40	+63	2300	SW	MF	15	+
63	7-5-58	.06	.01	1.20	.01	4.73	1.04	+294	1000	SW	SS	8	-
64	7-10-58	.66	.31	.49	.15	.76	.47	+62	1300	SW	MF	5	-
65	7-11-58	.27	.04	.09	.05	.18	.13	+38	1400	NE	MF	6	+
66	7-11,12-58	.33	.24	.01	00	.25	.17	+47	2300	NE	MF	7	+
67	7-14-58	.54	.17	.31	.10	.28	.28	00	0900	SW	SS	10	-
68	7-25-58	.11	.10	.53	.35	.32	.28	+14	0200	SW	MF	3	+
69	7-29-58	1.42	1.07	1.70	1.45	1.32	1.49	-11	1300	NW	MF	8	+
70	7-31-58	1.71	.80	.72	.44	2.08	1.15	+81	0500	NW	MF	3	+
71	8-7-58	.28	1.30	.24	.07	4.27	1.23	+248	1600	SW	MF	4	+
72	8-10,11-58	.85	.55	.18	.21	1.06	.57	+86	2300	SW	SS	12	+
73	8-15-58	.84	.56	.45	.59	.75	.64	+17	0500	W	MF	10	+
74	8-20,21-58	.52	.66	.77	.23	1.02	.64	+59	1900	SW	MF	15	+
75	8-23,24-58	.41	.41	.55	.34	.78	.50	+56	2200	SW	SS	15	+
76	8-31-58	.25	.21	.13	.18	.33	.22	+50	0100	SW	SS	12	+
77	9-3-58	.14	.08	.42	.43	.25	.26	-04	0500	S	MF	12	+
78	9-15-58	.56	.36	.09	.15	.28	.29	-03	1400	SW	MF	10	+
79	9-16,17-58	1.26	.74	1.07	.85	1.05	.99	+06	2300	NE	MF	6	+
80	9-30-58	.26	.31	.30	.40	.38	.33	+15	0800	SW	MF	8	+
81	5-9,10-59	.23	.14	.20	.13	.19	.18	+06	2300	S	SS	8	+
82	5-10,11-59	.31	.59	.30	.23	.55	.40	+38	2100	SW	SS	15	-
83	5-12,13-59	.12	.22	.15	.08	.33	.18	+83	2200	SW	MF	12	+
84	5-18,19-59	.76	.75	.37	.26	1.15	.66	+74	2300	SW	MF	10	-
85	5-20-59	.76	.27	.36	.43	.10	.38	-74	1200	S	MF	12	-
86	5-22-59	.76	.57	.48	.31	.52	.40	+30	0400	SW	MF	12	-
87	5-22,23-59	.53	.05	.18	.03	.38	.23	+65	1900	SE	MF	8	+
88	5-25,26-59	.20	.17	.29	.38	.49	.31	+58	2200	SW	MF	6	-
89	6-11-59	.24	.40	.38	.27	1.03	.46	+124	1400	SW	MF	7	-
90	6-25,26-59	1.06	.95	.66	.94	2.57	1.24	+107	2300	SW	MF	10	-
91	6-29,30-59	.33	.70	.20	.14	.15	.30	-50	2000	NE	MF	8	+
92	7-1-59	.66	.49	.46	.46	1.72	.76	+126	0200	SE	MF	3	+
93	7-10,11-59	.46	.48	.41	.17	.37	.32	+16	2100	W	MF	15	+
94	7-18-59	.59	.29	.51	.27	.27	.39	-31	0900	SW	MF	5	-
95	7-19-59	.18	.15	.11	.05	.31	.14	+121	1100	SW	SS	2	+
96	7-22,23-59	.06	3.38	1.54	3.55	5.21	2.75	+89	1800	SW	MF	10	+
97	7-29,30-59	.29	.83	.30	.03	2.01	.65	+209	2100	SW	MF	12	-
98	8-3-59	.62	.76	.18	.33	.35	.43	-19	0900	SE	SS	8	+
99	8-16-59	.23	.12	.48	.25	.51	.32	+59	0200	SW	SS	6	+
100	9-21-59	.86	.29	.52	.95	.60	.64	-06	1400	SW	MF	10	+
101	9-24-59	.61	1.03	.55	.47	.79	.69	+15	0400	SE	MF	12	+
102	9-26-59	.76	1.01	.26	1.17	1.51	.94	+61	0100	SW	MF	10	+
103	9-26,27-59	1.68	.62	1.04	.21	1.22	.95	+28	2000	SW	SS	10	+
104	9-28,29-59	.66	.01	.36	.01	.84	.24	+250	1900	SW	MF	12	+

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ACKNOWLEDGEMENTS

First of all, I would like to express my gratitude to the United States Army for making it possible for me to come to MIT for these past eighteen months. Secondly, I thank Professor H. G. Houghton for advising me on my thesis research. His suggestions, guidance and encouragement certainly contributed to the successful completion of this work. I also received assistance from Professors J. M. Austin, E. N. Lorenz, and H. C. Willett and I certainly appreciate their help. In addition, I want to thank my wife, Joyce, not only for typing all my correspondence and the final manuscript, but also for providing moral support throughout my graduate studies. Finally, and most of all, I thank God for providing me with the physical stamina and mental capacity necessary to complete this paper.