CONTENTS

SUMMARY

This report describes the research and findings of a 1-year project primarily directed towards evaluating methods of using radar to obtain accurate estimates of the presently unmeasured precipitation over Lake Michigan. As a part of this research, a detailed climatological analysis was performed to obtain generalized estimates of the mean annual and seasonal precipitation over the lake and to determine reasonable explanations for the mean precipitation patterns derived. The results of the climatological research also serve as a means of evaluating the need for a future radar-instrumented project to measure lake precipitation.

One of two radar techniques studied showed promise as a method for accurately measuring lake precipitation on a seasonal basis. This promising method is based on an interpolation of the radar-indicated precipitation using raingage data from both sides of the lake to calibrate the radar. Data from 19 rain periods on two dense raingage networks were used to evaluate the two radar techniques. If implemented, the radar-interpolation method would require several radar facilities as well as extensive raingage networks surrounding the lake. Therefore, the collection of adequate data to provide accurate measurements of mean lake precipitation would be an extremely expensive undertaking.

The climatological analysis of lake precipitation was based on (1) widespread and long-term land data, (2) island station

data, and (3) new information from recent research on how the lake affects the precipitation processes. This analysis provided estimates of the possible extremes of the mean annual and seasonal lake precipitation. Since the differences between these extremes for each season were small, it appears that rather accurate and useful estimates of the average lake precipitation are obtainable from climatological data. The maximum differences are comparable with those obtainable from the best radar technique presently available. The climatologically-derived mean annual and seasonal precipitation patterns were compared with various thunderstorm, hail, and snowfall data; and patterns from these related phenomena supported those derived for precipitation.

Many of the research findings of this project were assembled and presented in two research papers that were given at the Ninth Conference on Great Lakes Research held at the Illinois Institute of Technology, Chicago, on March 28-30, 1966. These papers (listed below) are to be published in the Conference Proceedings, and reprints will be obtained for wide distribution in late 1966. Additional details are given in another paper, "Adjustment of Radar Estimates of Storm Mean Rainfall with Raingages," and this paper will be presented at the Twelfth Conference on Radar Meteorology in Norman, Oklahoma during October 1966. Consequently, this final report contains only brief descriptions of the research and the data employed, and presents only the major findings and conclusions. The papers to be published are: "Measurement of Precipitation Over Lake Michigan," and "Effect of Lake Michigan on Severe Weather."

INTRODUCTION

An adequate evaluation of the water resources of Lake Michigan is not possible until precipitation over the lake can be measured accurately, since the lake surface constitutes over 30 percent of the basin area. An accurate measurement of the water budget of Lake Michigan is becoming increasingly important in the evaluation of regional water resources. Only gross estimates of the water budget have been possible because of the lack of quantitative measurements of precipitation and evaporation over the lake, for which past efforts have been blocked by lack of technical capability for such measurements.

The increasing need for accurate measurements of precipitation over the lake led to this study and to evaluation of radar techniques for direct measurements or accurate estimates. As pointed out by Bruce and Rodgers (1962) and many others, lake precipitation may differ from land precipitation anywhere from 1 to 20 percent. Thus, any acceptable technique for the measurement of precipitation over the water must be able to differentiate land-lake differences of these magnitudes.

During the past 40 years, several climatological estimates of lake precipitation have been made (Freeman, 1926; Day, 1926; Horton and Grunsky, 1927; Brunk, 1962). These estimates were derived from various interpretations of land-station measurements of precipitation.

Evaluation of differences of 1 to 20 percent through use of island raingage data and nearby land raingage data is difficult and argumentative because of the potential measurement differences resulting from varying gage exposures (Hunt, 1959; Kohler, 1959; Changnon, 1961; Weiss and Kresge, 1962). Furthermore, most comparisons have been based on relatively short periods of record, such as used by Williams (1964), and such observed land-lake differences may be largely due to natural variability of precipitation that occurs in 5- to 15-year periods (Huff and Changnon, 1966). As would be expected, previous studies have yielded significantly different estimates of lake precipitation. Also, these studies are limited in their application because they represent conditions over only a small portion of the lake.

Bruce and Rodgers (1962) concluded that the best potential method for obtaining a true measure of lake precipitation would be the use of radar. Radar has been employed to study the lake effects on a few convective storm systems (Pearson, 1958; Stout and Wilk, 1962), and has shown promise as a tool for analyzing lake effects on such systems.

RADAR MEASUREMENT OF PRECIPITATION OVER LAKE MICHIGAN

An evaluation was made of the present capability of radar to provide accurate over-water measurements of precipitation. As indicated earlier, some limited research has been carried out in this direction by several investigators, but a reliable definition of radar's capability to achieve the required measurement accuracy has not been accomplished. In the radar study, two techniques were evaluated through use of radar and recording raingage data collected simultaneously in 15 storms during 1964-1965 on the East Central Illinois Raingage Network of the Illinois Water Survey. This network consists of 49 raingages in an area of 400 square miles (Figure 1). Radar observations were made at a site about 20 miles east of the network with an M-33, 10-cm set equipped with a gain step device for defining storm rainfall intensity and a camera for recording the scope data presentation. The 10-cm radar is used for rainfall measurements because the precipitation attenuation problem is minor compared with that of shorter wavelengths. These radar and raingage data were available from other studies and therefore, were obtained at no cost to this research grant.

In addition to the Illinois storms, data from four Oklahoma storms obtained from the Severe Local Storms Laboratory of the U. S. Weather Bureau were used in the study. These storms passed over a concentrated raingage network encompassing an area of approximately 1200 square miles operated by the Agricultural Research Service. This network was under surveillance by a WSR-57, 10-cm radar of the U. S. Weather Bureau.

Method of Analysis

In the first phase of the radar study, the reliability of radar measurements of percentage increases or decreases in rainfall from one region to another in the same storm was evaluated. If these percentage changes could be measured with acceptable accuracy by radar, the effect of the lake in increasing or decreasing the surface precipitation with respect to the adjacent land could be evaluated simply by a sufficient number of radar observations

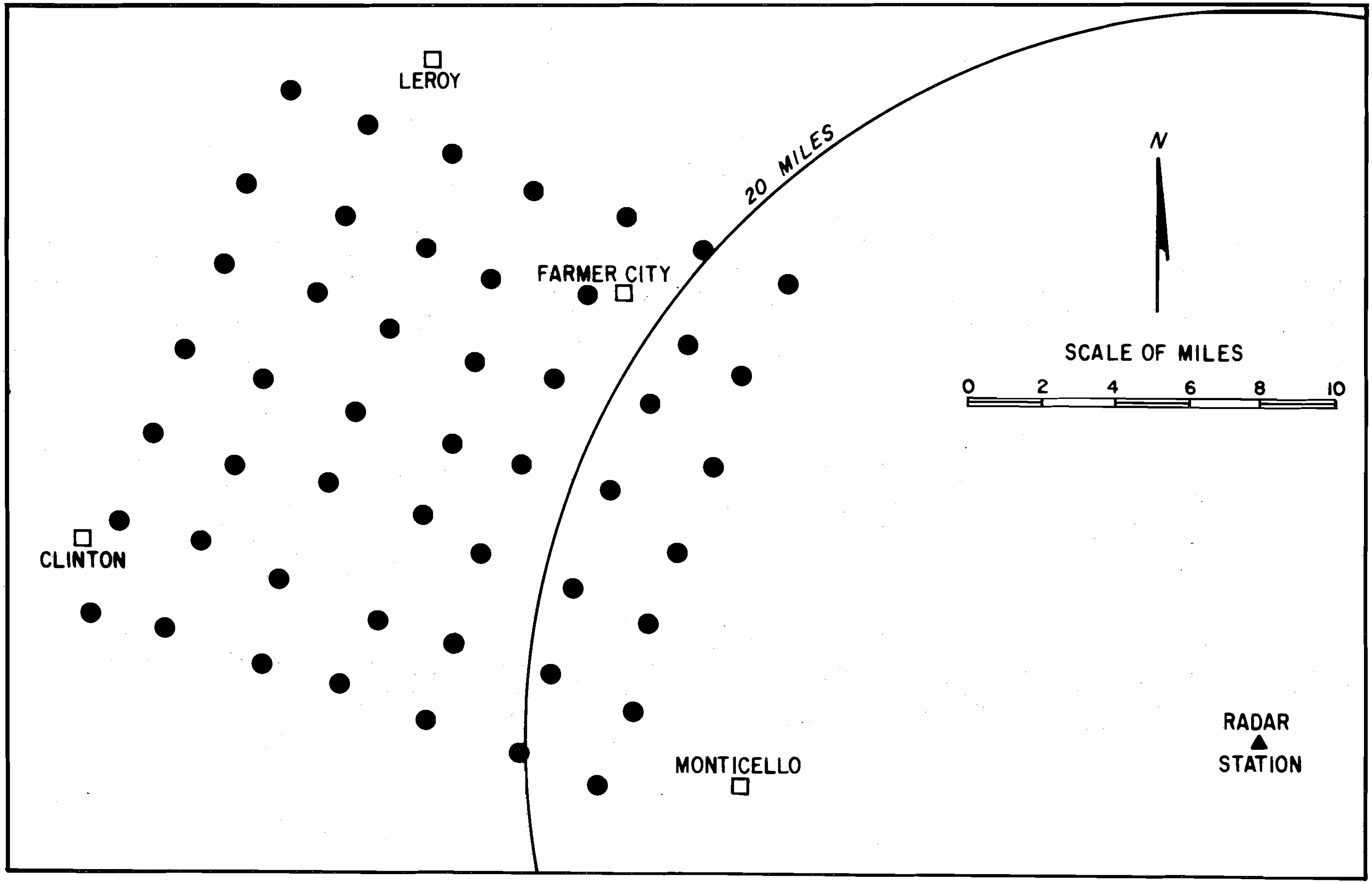


Fig. I ILLINOIS RAINGAGE NETWORK AND RADAR LOCATIONS to define the average monthly or seasonal percentage differences. Then by reference to long-term climatological data for shore stations, the climatology of the lake precipitation could be calculated through the average lake-land relation derived from the radar observations.

In the second phase of the study, the accuracy of radar-measured rainfall amounts over a given area in a given storm were evaluated, when raingages were available in the region adjacent to the given sampling area to establish more accurately the specific relationship between radar reflectivity and surface rainfall intensity in the given storm. This method would provide a highly accurate measurement of areal mean rainfall on the sampling area, provided that the raindrop size distribution in the atmosphere and, consequently, the radar-reflectivity relation remained stable throughout any given storm. The method would be applicable to quantitative precipitation measurements over Lake Michigan through use of groups of raingages on the adjacent shores to adjust the basic radar-rainfall relationship for conditions in a particular storm. More detailed information on the data and analysis are provided in another paper (Changnon and Huff, 1966).

Results of Analyses

The percentage measurement technique, the first method investigated, was found to produce unacceptable errors of estimate. For example, in the 15 Illinois storms, the radar measurement errors ranged from 0 to 67 percent with a median of 35 percent.

The second method investigated, in which raingage data were used to adjust the relationship of radar reflectivity to rainfall intensity in each storm, shows potential for relatively accurate measurements of monthly and seasonal rainfall amounts, but not for individual storm measurements. With sufficient raingages to define accurately the rainfall-reflectivity relationship on each side of the lake, indications are that monthly or seasonal rainfall could be measured with an average accuracy of approximately 2 percent on a long-term operational basis. However, individual storm estimates, while excellent for most purposes, were found to be relatively large with respect to average land-lake climatic differences in precipitation.

TABLE 1

ERRORS IN RADAR-INDICATED MEAN RAINFALL IN CENTRAL PART OF NETWORK USING SOUTH AND NORTH PARTS TO CALIBRATE RADAR

Storm Date	Mean Rainfall (inches)	Radar Error (percent)
	Illinois Network Data	
4/18/64	0.08	12
4/19/64	1.25	6
7/7/64	0.15	13
7/8/64	0.23	52
9/22/64	0.20	10
4/8/65	0.18	22
4/15/65	0.15	60
5/18/65	0.57	24
5/25/65(1)	0.35	29
5/25/65(2)	0.06	0
5/26/65(1)	0.23	9
5/26/65(2)	0.30	3
5/26/65(3)	0.02	50
6/1/65	0.17	12
6/8/65	0.13	8
Median	0.18	12
	Oklahoma Network Data	
4/3/64	0.21	43
4/23/64	0.10	17
5/9/64	0.89	36
5/10/64	1.14	34

The results of the storm analysis are illustrated in Table 1; individual and median radar errors are shown when the northern and southern one-thirds of the network were used to calibrate the radar for estimates over the central one-third. In the 15 Illinois storms, the median radar error was 12 percent, and the range was 0 to 60 percent.

The above findings are not applicable to snowfall measurements, for which percentage errors may be appreciably greater. Unfortunately, adequate data were not available for evaluation of radar's capability for measuring snowfall.

Conclusions

The results of the radar evaluation study indicate a strong possibility that radar observations made in conjunction with networks of recording raingages along the lake shoreline could be used to measure monthly, seasonal, and annual precipitation on Lake Michigan with sufficient accuracy to evaluate the lake-land differences. At the present level of operational technology, radar is not capable of providing consistently accurate measurements of storm rainfall over the lake, and its capability with respect to snowfall measurements is unknown.

Initiation of a large-scale program of radar measurement of precipitation over Lake Michigan is not recommended at this time, in view of existing uncertainties in its use. Both 3-cm and 10-cm wavelength radars would be needed at several radar observational points to carry out the program. The highly sensitive 3-cm radar is needed for snowfall measurements, whereas it is unsatisfactory for moderate to heavy rainfall measurements for which the 10-cm wavelength is needed. Unless the project was restricted to only a small portion of the lake area, several sets of the radars would be needed. Also, the radar observations would need to be taken in conjunction with observations from a dense network of recording gages located about the shoreline of the lake. The cost of the observational program would appear to be prohibitive in view of the uncertainties of success with the present state of knowledge and operational capability. As shown later, the climatological estimates of the mean annual and seasonal values appear to provide almost the accuracy that could be obtained from the radar program.

CLIMATOLOGICAL ANALYSES OF LAKE PRECIPITATION

The product desired from the climatological analyses was a series of mean annual and seasonal precipitation patterns for Lake Michigan. Other climatological analyses of lake precipitation have been made in prior years, but the one performed in this project is believed to be more comprehensive and meaningful than those preceding it.

This was possible for several reasons. First, there is currently long-term weather data available from many more land stations than existed when several other studies were performed in the 1925-1927 period. Secondly, there is now limited, but useful, precipitation data available for certain island and crib stations in the lake. Thirdly, research in the past ten years has furnished considerably more information on how the lake affects precipitation processes and to some extent the degree of these effects. For instance, research on thunderstorms and hailstorms (Changnon, 1966) has shown the strong effect of the lake on these conditions. Radar case studies of summer precipitation have also shown various lake effects on convective processes (Pearson, 1958; Stout and Wilk, 1962; and Lyons, 1966).

Data and Analytical Techniques

Much of the precipitation, snowfall, and temperature data employed in the climatological study were from 22-year records (1931-1952) of U. S. Weather Bureau stations. Other data on dew point temperatures, hailstorms, thunderstorms, and sky cover were obtained from long-term records at Weather Bureau first order stations scattered throughout the lake area. Precipitation data from three stations located on islands in the northern lake and from a water-intake station in southern Lake Michigan were also used.

In each season, the mean precipitation at all land and island stations was calculated, plotted, and analyzed. Mean seasonal patterns of snowfall and thunderstorms were examined and compared with the land-based precipitation pattern. Using these comparative results and other knowledge available on lake effects, three patterns of mean precipitation were prepared for each season. One pattern was drawn allowing for the maximum possible differences in lake precipitation due to lake effects. Another pattern was drawn allowing for only the minimum possible differences in precipitation over the lake. A third pattern, representing values somewhere between these two extremes, was prepared as the 'most likely' over-lake precipitation pattern.

Another new technique was employed to obtain a measure of the lake effect on precipitation. Examination of the mean seasonal precipitation patterns over land and those for snowfall and thunderstorms clearly indicated the areal extent of lake effects on precipitation. Data from stations unaffected by lake influences in the Great Lakes region were used to compile mean precipitation patterns that would be expected if the lakes did not exist. Differences between existing mean precipitation patterns and the calculated patterns with no lake effect provided a measure of the amount of lake effect on precipitation.

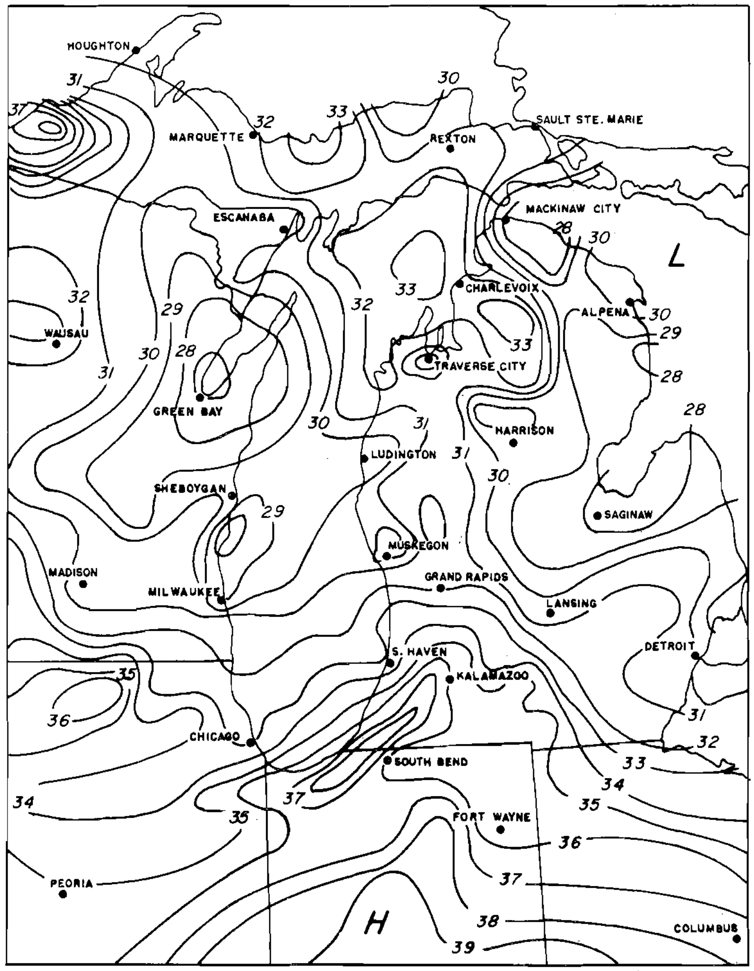
To obtain information which through comparison could support or refute the estimated mean lake precipitation patterns, detailed climatological analyses of snowfall, thunderstorms, and hailstorms were pursued. Mean patterns of snowfall were prepared along with patterns based on the daily frequencies of snowfall. The frequency of thunderstorm days and days of hail were also determined and their patterns established (Changnon, 1966).

All dates in the 1951-1964 period with thunderstorms on the lake's west side, east side, or both sides were identified. Precipitation amounts at all stations surrounding the lake for this 14-year period were tabulated and sorted according to the three thunderstorm-day classes, and mean precipitation patterns were calculated for each class. Thus, the mean seasonal patterns of precipitation derived from days with different thunderstorm distributions were available and used in comparisons with the total mean precipitation for each season. A similar analysis was performed for snowfall days using first order station data to delineate all dates in the 1951-1964 period as having snowfall on the west, east, or both sides of the lake. Further information on the data and the analytical techniques employed are furnished in another paper (Changnon and Huff, 1966).

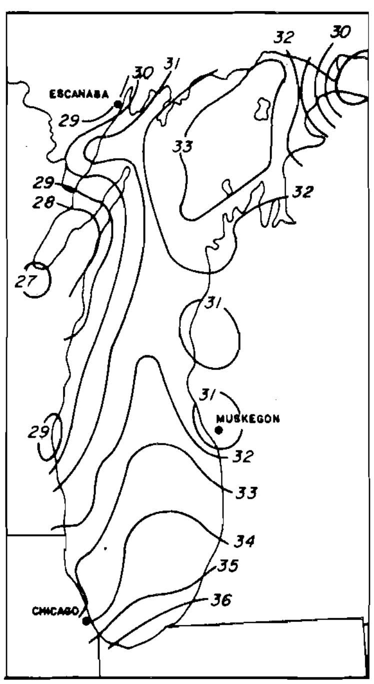
Selected Results for Annual Precipitation

Among the more important results derived from the climatological study are those for mean annual precipitation. The three mean precipitation patterns over Lake Michigan are portrayed in Figure 2. These were developed by combining the carefully constructed seasonal maps developed for all three patterns. Figure 2a (most likely pattern) indicates low precipitation along the Wisconsin shoreline with heavier precipitation in the northeastern and extreme southeastern portions of the lake. The pattern based on the maximum possible increases in precipitation due to lake effects (Fig. 2b) also indicates a west-shore low, but it is considerably more restricted in size than it is in the most-likely pattern. The precipitation pattern resulting when lake effects on precipitation are minimal is shown in Figure 2c. A comparison of the position of the 30-inch isohyet on the three patterns of Figure 2 furnishes an excellent indication of the pattern differences.

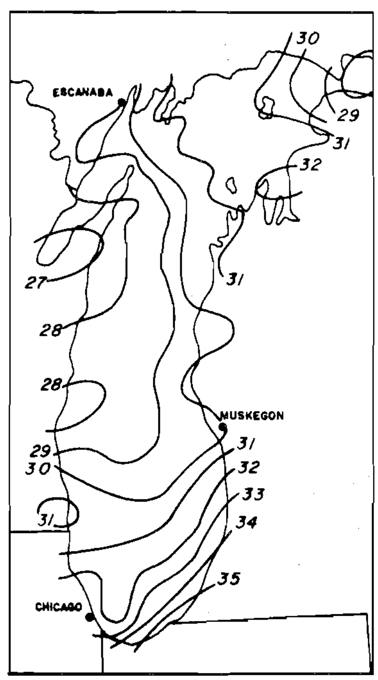
Maps portraying the degree of the effect of Lake Michigan on annual precipitation are shown in Figure 3. Figure 3a is the mean annual precipitation pattern constructed using data from stations without the effects of the Great Lakes. In other words,



a. MEAN ANNUAL PRECIPITATION, INCHES (OVER-LAKE PATTERN CONSIDERED MOST LIKELY)



b. OVER-LAKE MEAN ANNUAL PRECIPITATION WITH MAXIMUM INCREASES IN PRECIPITATION DUE TO LAKE EFFECTS, INCHES



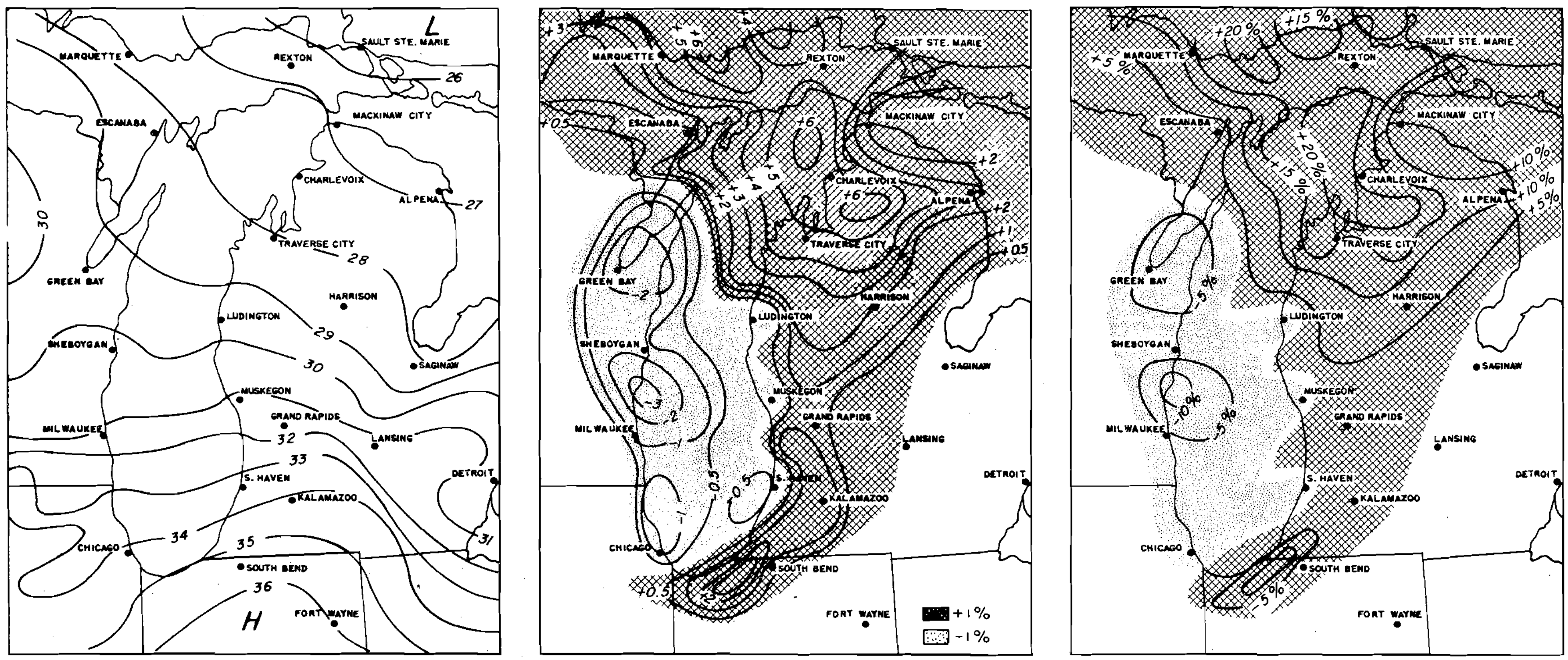
c. OVER-LAKE MEAN ANNUAL PRECIPITATION WITH MINIMUM INCREASES IN PRECIPITATION DUE TO LAKE EFFECTS, INCHES

Fig. 2 THREE PATTERNS OF MEAN ANNUAL PRECIPITATION OVER LAKE MICHIGAN

this is considered to be the pattern that would exist if the Great Lakes were not present. This map was compared with the actual pattern (Fig. 2a) on the assumption that the most-likely precipitation pattern over the lake was the best estimate of mean lake precipitation.

This comparison yielded the maps on Figure 3b and 3c. The difference in inches (Fig. 3b) indicates that, along the Wisconsin-Illinois shoreline, lake effects decrease the mean annual precipitation by as much as 3 inches. The stippled area (area of decrease) covers most of the southern two-thirds of the lake, but the decreases over the lake are small, generally 0.5 inch or less. Lake effects produce increases amounting to more than 6 inches annually in the northern lake area and over portions of Michigan.

The lake-induced changes in the mean annual precipitation were expressed as a percent of the adjusted pattern (Fig. 3a), and the percentages are shown in Figure 3c. The lake-induced decreases range from 1 to 10 percent, whereas the increases amount to more than 20 percent in the upper lake area. As shown in Table 2, the total mean lake precipitation closely approximates that over the surrounding land basin. This occurs because the large area of small decrease in precipitation over the southern two-thirds of the lake tends to balance the effect of the small area with greater precipitation increases in the northern lake area. The values for over-lake precipitation (Table 2) were derived by planimetering the patterns on Figure 2.



a. ADJUSTED (NO-LAKE EFFECT) MEAN ANNUAL PRECIPITATION, INCHES

b. CHANGES IN MEAN ANNUAL PRECIPITATION DUE TO LAKE EFFECTS, INCHES

c. CHANGES IN MEAN ANNUAL PRECIPITATION DUE TO LAKE EFFECT EXPRESSED AS PERCENT OF ADJUSTED PRECIPITATION

Fig. 3 EFFECTS OF LAKE MICHIGAN ON ANNUAL PRECIPITATION

TABLE 2

MEAN ANNUAL PRECIPITATION VALUES FOR LAKE MICHIGAN

Lake Precipitation	Mean annual precipitation (inches)	Difference between mean lake values and basin (land) value (inches)	(percent)
Maximum increases	32.28	+0.91	+3
Most likely	30.94	-0.43	-1
Minimum increases	30.01	-1.36	-4
Basin (land only)	31.37	0	0

Also shown in Table 2 is the mean precipitation determined for the land area of the Lake Michigan Basin. The three over-lake mean values were compared with the mean for the land portion of the basin, since this is a useful and common method of evaluating lake precipitation.

There are two important findings revealed by the data in this table. First, the maximum possible difference in the estimated mean lake precipitation values (maximum increase-minimum increase) is 2.27 inches per year. This amounts to 3700 cfs discharge as a measure of the maximum possible error in using the climatological estimate of the mean annual precipitation. Since the true mean is considered to be the 'most-likely' pattern, it could be in error by approximately ± 1800 cfs.

The second important fact shown in Table 2 concerns the percentage differences. These indicate that the most likely land-lake difference is only 1 percent, and the possible extremes indicate a difference of about ± 3.5 percent.

The climatological results concerning annual precipitation were compared with other previous climatological estimates of lake, basin (land), and total basin (land plus lake) precipitation, and the results are shown in Table 3.

TABLE 3

COMPARISON OF MEAN ANNUAL OVER-LAKE, LAND, AND TOTAL BASIN PRECIPITATION ESTIMATES FOR LAKE MICHIGAN

	Mean (inches)			Lake-land (basin) difference expressed as a percent of land (basin) mean
	Lake	Land (basin)	Total basin	
Day (1926)	32.57	32.57	32.57	0
Horton (1927)	31.32	34.48	33.43	-9
Brunk (1962)	32.03	32.03	32.03	0
Great Lakes Commission (1965)	31.12	31.12	31.12	0
Changnon (1966)	30.94	31.37	31.23	-1

Many investigators have assumed that precipitation measured over the land portion of the basin was representative of the lake mean precipitation. Horton and Grunsky (1927) using land-lake precipitation differences derived from one island gaging station, concluded that the lake precipitation was 9 percent lower than the land precipitation. Findings from this current research, which estimated over-lake precipitation with much more detailed data and with information not available to most prior investigators, supports the assumptions that the lake mean is not significantly different from the land-basin mean. The conclusions of Horton and Grunsky are considered erroneous largely because the single island station had data that was areally unrepresentative and temporally insufficient.