BULLETIN 52

Precipitation Climatology of Lake Michigan Basin

by STANLEY A. CHANGNON, JR.

Title: Precipitation Climatology of Lake Michigan Basin.

Abstract: Average annual precipitation over Lake Michigan (29.6 inches) is 6 percent less than that of the land portion of the basin. The results of this comprehensive study are more valid than those of previous studies, which estimated lake and land precipitation as equal, because they are based on more detailed land and lake data and greater knowledge of lake effects. The best possible measures of average seasonal and annual precipitation for the lake and the basin are determined from three detailed studies of thunderstorms, hailstorms, and snowfall combined with lake-land ratios (based on upwind land data rather than commonly used downwind data). The lake suppresses thunderstorm activity by 20 percent in summer, but in the fall increases it by 50 percent and also causes 400 percent more hail days in lower Michigan. Lake effects cause 25 to 100 percent greater snowfall along the eastern shore. Average lake precipitation is 4 percent higher in winter, 7 percent lower in spring, and 14 percent lower in summer than basin land precipitation; they are equal in fall.

Reference: Changnon, Stanley A., Jr Precipitation Climatology of Lake Michigan Basin. Illinois State Water Survey, Urbana, Bulletin 52, 1968.

Indexing Terms: climatology, Great Lakes, hail, hydrologic budget, lake effects on atmospheric phenomena, Lake Michigan, snow, snowfall precipitation, surface water resources, thunderstorm precipitation, thunderstorms, water yield.

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Precipitation Climatology of Lake Michigan Basin

by Stanley A. Changnon, Jr.

ABSTRACT

A detailed climatological study shows that the average annual precipitation over Lake Michigan is 6 percent less than that of the land portion of the basin. This is contrary to results of most previous studies which indicated that lake and land precipitation were equal. However, the results of this study are more accurate than the earlier findings because they are based on more detailed information from recent lake precipitation studies, a greater knowledge of the effect of the lake on the atmosphere, and a greater volume of weather data than existed when the previous studies were made.

The chief purpose of this study was to obtain the best possible measure of the average precipitation over the lake in order to estimate more accurately the total water resource of the Lake Michigan Basin. The 6-percent lower precipitation over the lake means that on the average the Lake Michigan Basin receives about 700 billion gallons less water from precipitation per year than would be received if the average lake precipitation were equal to that over the land.

This report presents the results of four separate investigations. The first three quantify the effect of the lake on thunderstorms, hailstorms, snowfall, and the amount of precipitation from these conditions. In the final investigation these results were combined with land and limited lake precipitation data to derive the average lake precipitation values.

The lake both suppresses and enhances precipitation activities, its effects varying seasonally and areally. Lake-effects suppress summer thunderstorm activity by 20 percent over the southern end of the lake, but increase fall thunderstorm activity by 50 percent. During fall, lake-effects cause 400 percent more hail days in lower Michigan than occur in surrounding areas The lake also causes 25 to 100 percent more snowfall and days of heavy snow along the eastern shore than occur along the western shore.

The amount of annual thunderstorm precipitation on the east side of lower Lake Michigan averages about 10 percent less than that on the west side. The west-east decrease in thunderstorm precipitation actually begins over the land area immediately west of the lake, and most of the lake-effect decrease occurs over the western half of the lake.

Average annual precipitation from snowfall on the east side of the lower lake is 33 percent greater than that on the west side. Most of the west-east increase in snowfall precipitation occurs near the eastern shore with maximization 10 to 25 miles inland in western Michigan.

Average lake precipitation in summer is 8.4 inches, which is 14 percent lower than that of the surrounding area. The average winter lake precipitation is 5.4 inches, which is 4 percent higher than that of the surrounding land area. The average spring lake value is 7.4 inches, 7 percent less than the land average, and that in the fall is 8.4 inches, which is equal to the land average.

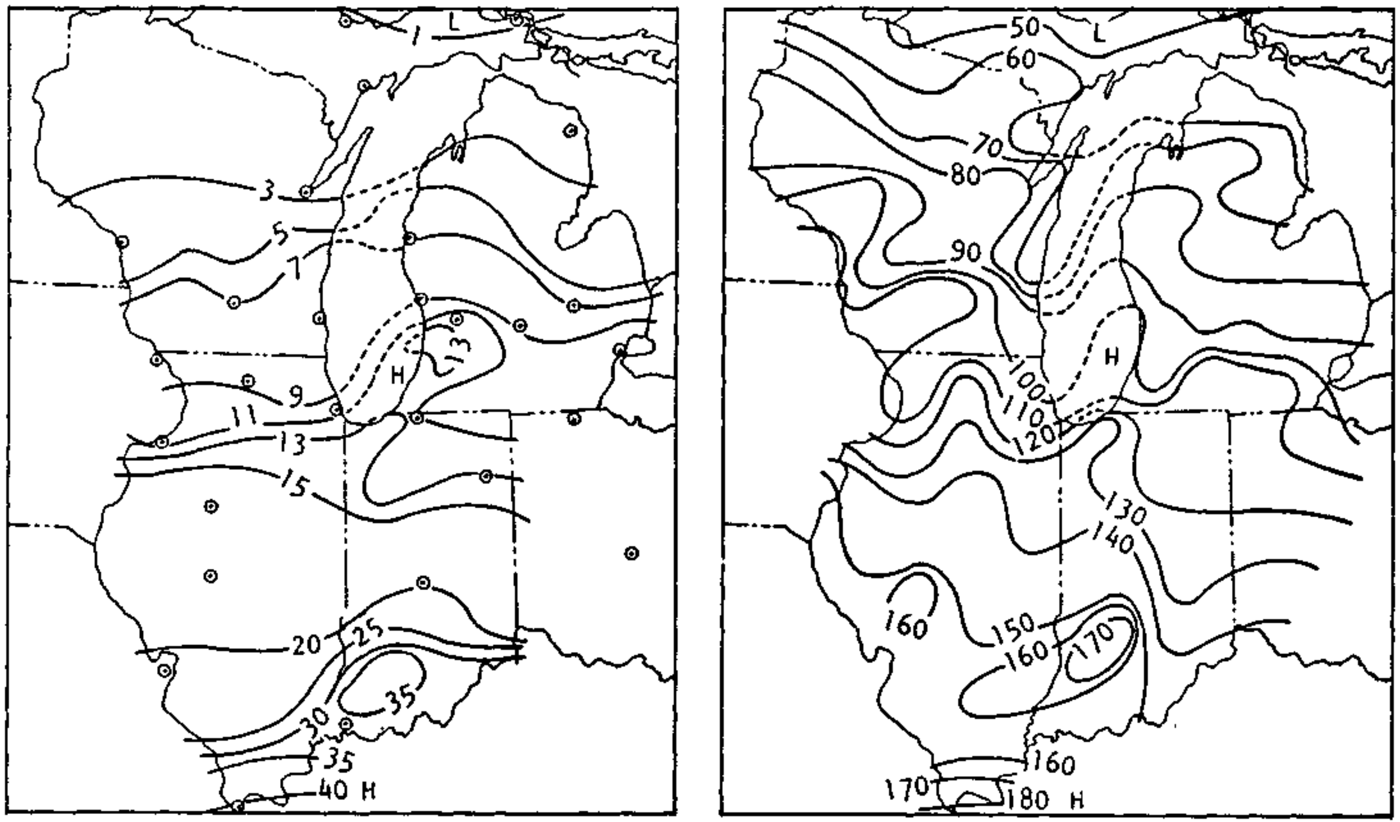
The average annual precipitation over the lake is lowest, less **than 27 inches, in the west-central portion, and highest in the extreme southeastern and northeastern portions. The lake average annual value is 29.6 inches.**

INTRODUCTION

An exhaustive climatological study of the precipitation regime of the Lake Michigan Basin has been performed to obtain the best possible estimates of the average precipitation over the lake. Increasing national concern with water resources has focused greater attention on the Great Lakes.

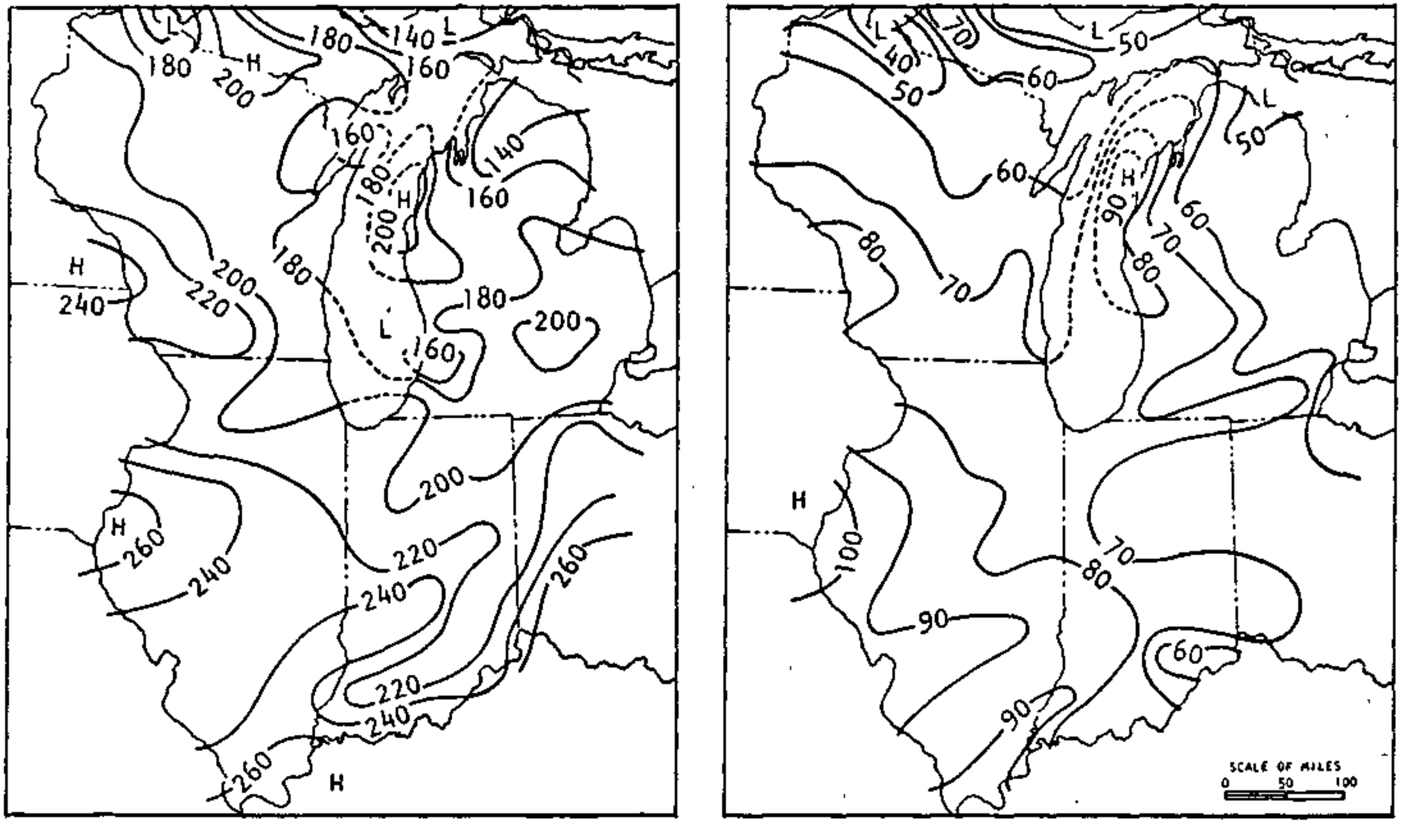
Scientific evaluation of Lake Michigan as a resource is limited because the water budget of the lake has never been properly measured. The lake surface comprises 30 percent of the basin and only a very few short-term measurements of precipitation have been made on the lake. If accurate calculations of the average annual precipitation could be derived, the lake's water budget could be estimated immeasurably better.

The lake comprises 22,400 square miles and is a major influence on the lower atmosphere. At most times of the year the lake water temperature is quite different from the temperature of air masses passing over the lake, so that the lake is constantly acting to either warm or cool the overlying air. Through evaporation the lake also serves as a moisture source for overlying air masses. This



a. Winter (December-February)

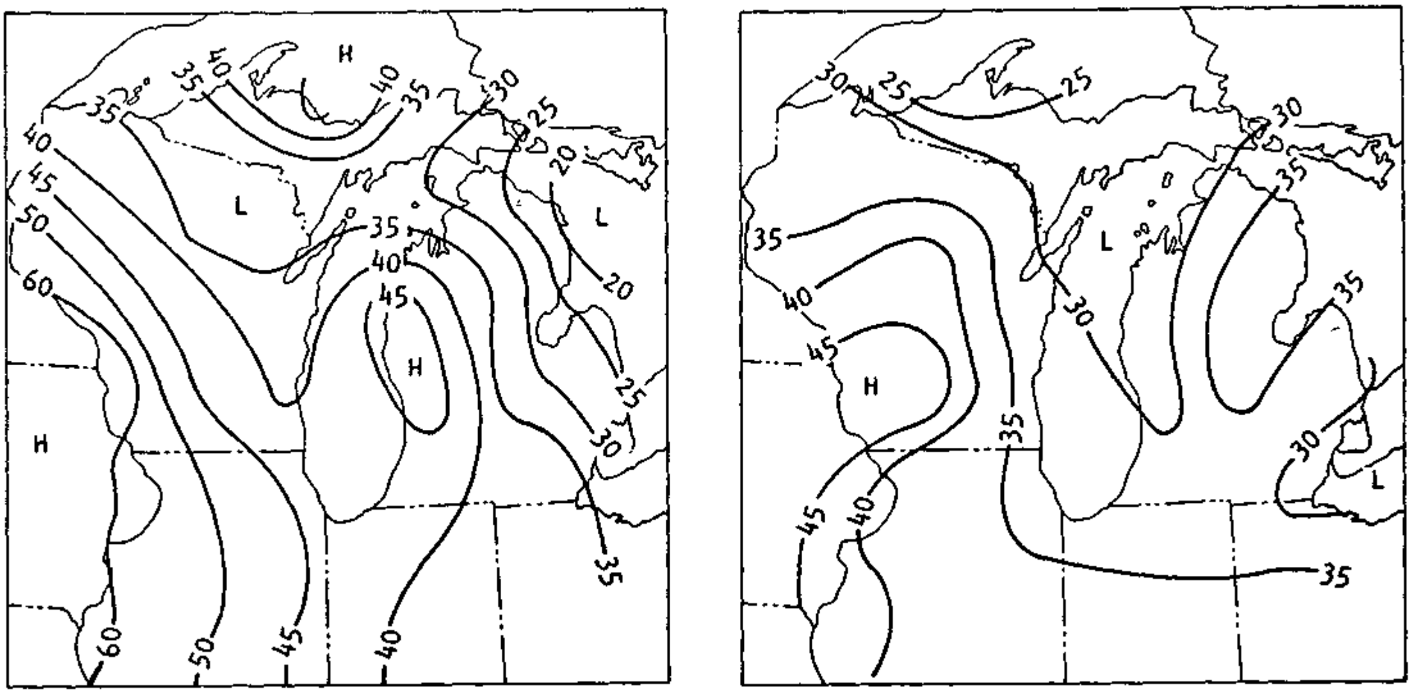
b. Spring (March-May)



c. Summer (June-August)

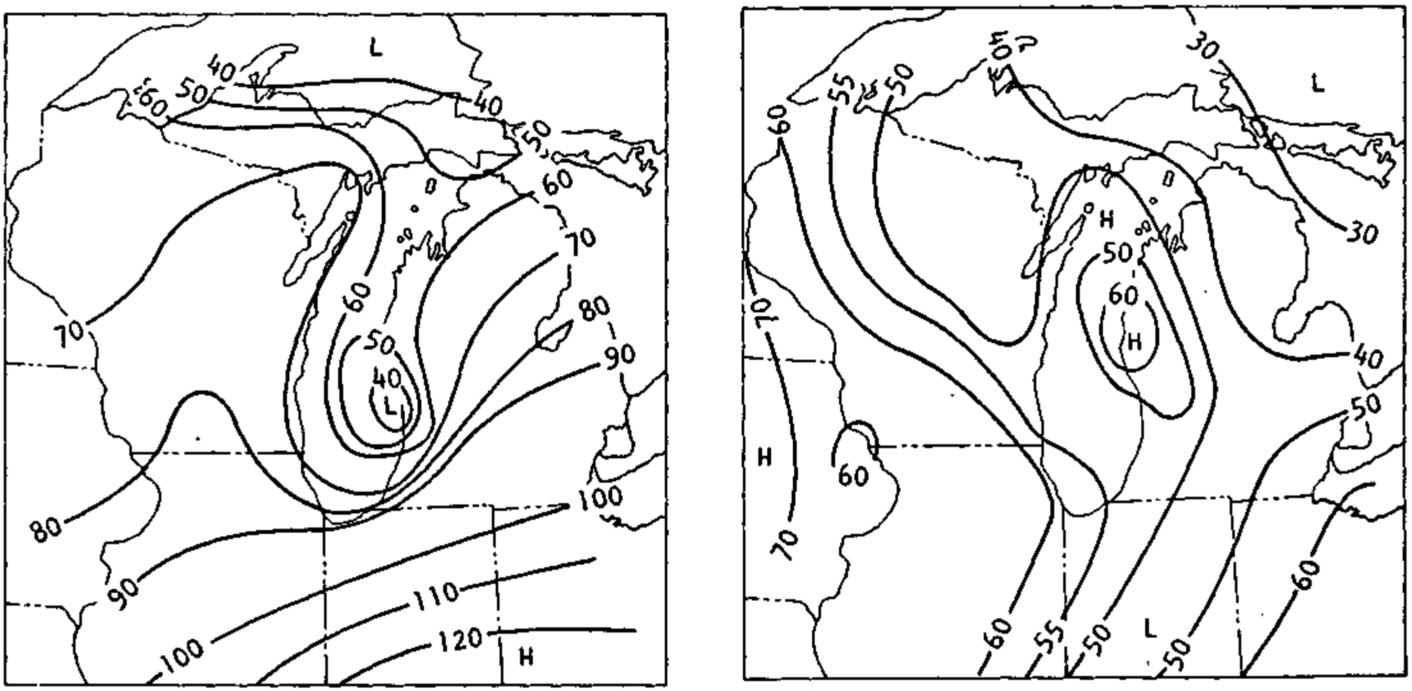
d. Fall (September-November)

Figure 3. Seasonal numbers of thunderstorm days in an average 10-year period



a. 0000-0600 CST

b. 0600-1200 CST



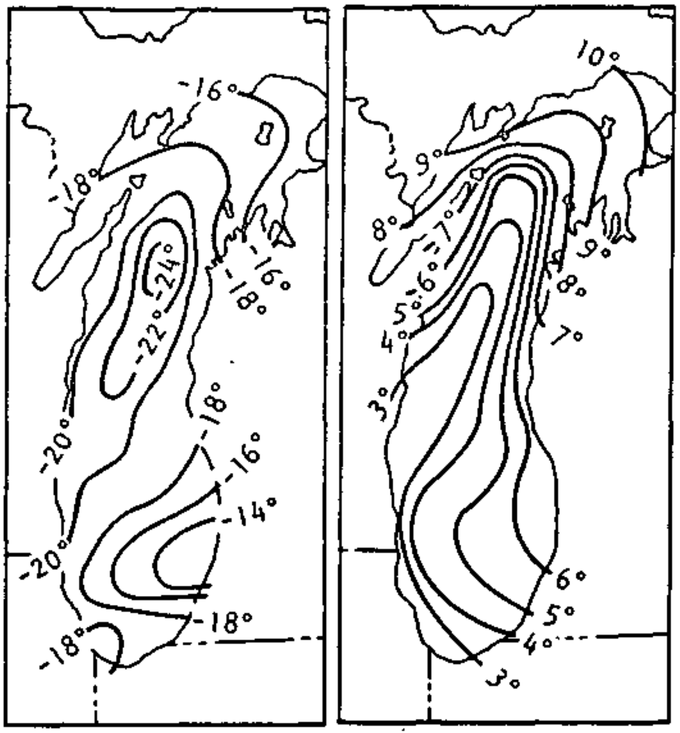
c. 1200-1800 CST

d. 1800-2400 CST

Figure 5. Number of summer thunderstorm days in 6-hour periods during an average 10-year period

The pattern on figure 6b shows the differences between the mean summer surface water temperatures and the no-lake-effect mean minimum air temperatures, which usually occur during the nocturnal period of 1800-0600. These differences indicate 1) that during portions of the night the entire lake surface is warmer than the air over the lake and 2) that the difference is greatest in the northern end of the lake. As shown in figure 3c, the lake-effect in summer is to reduce thunderstorm activity in the area around the southern half of the lake and to increase the activity in the northern half.

The four 6-hour thunderstorm-day patterns for the fall season are depicted in figure 7. The pattern for the early period of the day (figure 7a) indicates lake-induced increases throughout much of lower Michigan, although a small low appears in the Grand Haven area. A similar increase over much of the lake, northeastern Wisconsin, and lower Michigan is apparent in the 0600-1200 period.



a. For maximum air b. For minimum air

Figure 6. Differences between **mean summer water temperatures and the mean no-lake-effect surface air temperatures, ° F**

However, a minor low in incidences appears in the southwestern lake and adjacent area.

In the fall afternoon period (figure 7c) the lake-effect continues to amplify thunderstorm frequencies, especially in central lower Michigan and over the northern lake and its perimeter. The nocturnal period beginning at 1800 has a thunderstorm-day pattern which is quite similar to that shown for the nocturnal period beginning at 0000. In the 1800-2400 period the lake apparently produces increased thunderstorm activity in lower Michigan and to a lesser extent over the northern half of the lake. An apparent lake-effect is the area of lower incidences that again appears at Grand Haven.

The four 6-hour patterns for the fall season reveal that the lake-effects which act to increase thunderstorm activity persist throughout the day, although the percentage of increase in the nocturnal hours is somewhat greater than in the daylight hours. This fall increase is also widespread in each 6-hour period so that much of Michigan, the lake, and portions of extreme northeastern Wisconsin experience additional lake-induced thunderstorm activity.

Such increases are not unexpected since during much of the fall season the lake is quite warm in relation to the surface air temperatures and since the lake also serves as a source of moisture. Measures of the lake-effect in fall on air temperatures and moisture content of the lower atmosphere appear in figure 8. The mean lake water temperatures are slightly lower than the no-lake-effect mean maximum (daytime) surface air temperatures (figure 8a), particularly along the southwest side of the lake where daytime thunderstorm frequencies appear somewhat lower (figure 7b). In portions of the northern lake the water temperature is higher than the maximum surface air temperature, which also supports findings for the daytime thunderstorm patterns in that area.

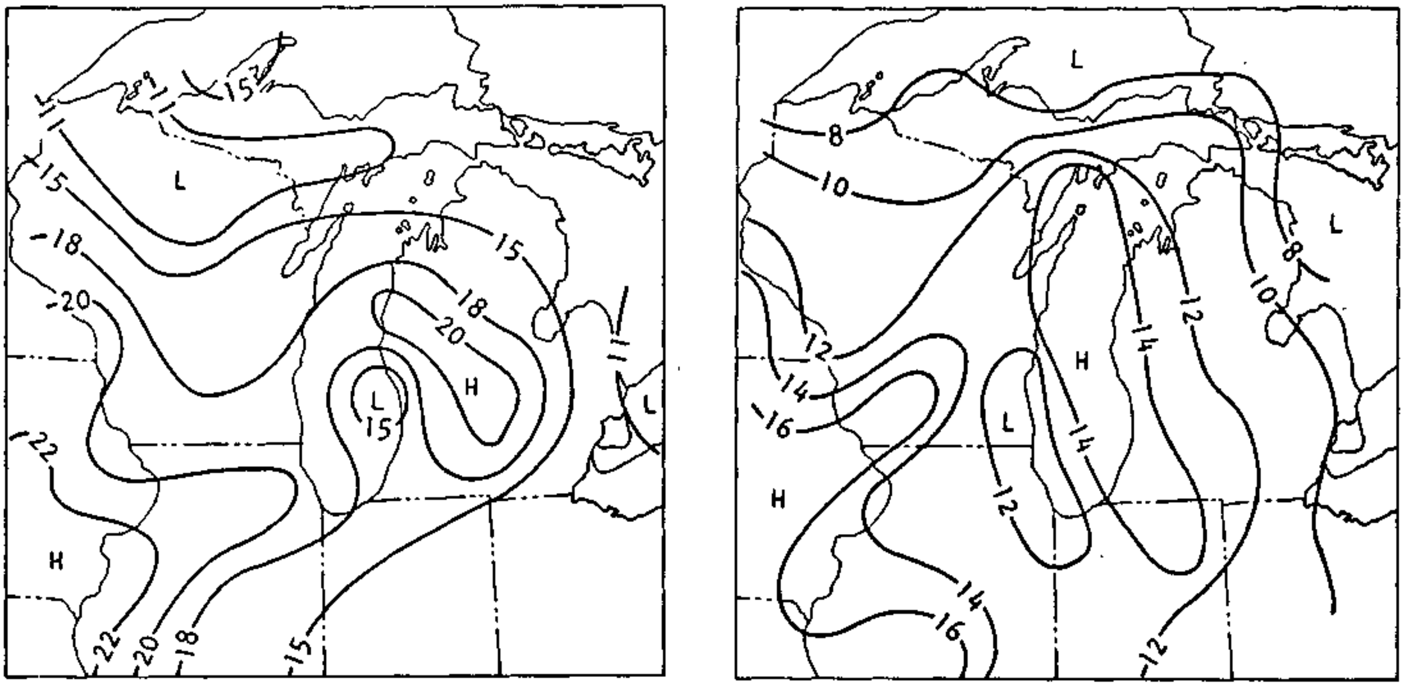
Lake water temperatures in fall are markedly higher, 12 to 19 degrees, than the no-lake-effect mean minimum (nocturnal) air temperatures (figure 8b), and this nocturnal difference is greatest along the east and northeast portions of the lake near where nocturnal thunderstorms in fall are quite frequent (figures 7a and 7d). Statistics on noon dew points and cloudy days (figures 8c and 8d) indicate that the lake adds moisture to the lower atmosphere in fall and thus frequently changes the lapse rate.

Adjusted Patterns. The thunderstorm-day data were adjusted by several techniques to define further the lake-effect on thunderstorm activity and to, obtain a better measure of the degree and areal extent of this influence.

An average no-lake-effect thunderstorm pattern developed for summer is presented in figure 9a. Comparison of this map with the actual pattern based on all the data (figure 3c) reveals the degree and areas of difference. A measure of these differences was obtained by superimposing the no-lake-effect map on the actual pattern map. The residuals, presented in figure 9b, reveal that the area along the southeastern shore of the lake has from 5 to 40 fewer thunderstorm days in a 10-year period as a result of lake-effect. Around the northern portion of the lake the lake-effect produces increases that vary from 5 to 35 thunderstorm days.

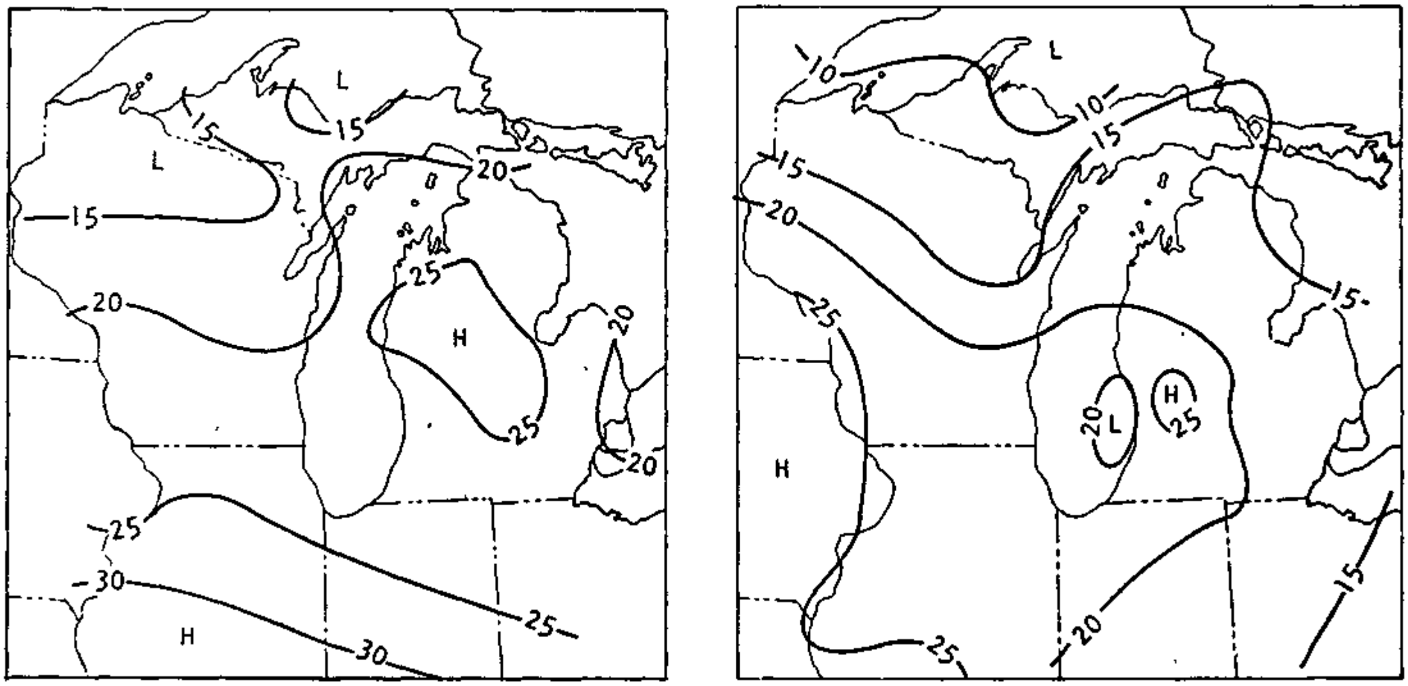
Figures 9a and 9b were compared to obtain measurements of the percentage change in thunderstorm-day frequencies produced by the lake. This pattern (figure 9c) shows that the maximum increases and decreases in the summer are both' in excess of 20 percent. The patterns of figures 9b and 9c reveal that in lower Michigan the area experiencing decreased thunderstorm activity is somewhat larger than the area experiencing increases, but the magnitude of the differences is about the same. The changes in lower Michigan during summer are largely a result of the lack of convective thunderstorms since there is very little diminishment of frontal thunderstorms." The thunderstorm area showing lake-effect in upper Michigan is largely a result of effects produced by Lake Superior.

Figure 10 is a series of similar maps for the fall season. The average fall thunderstorm-day pattern based on data from no-lake-effect stations, in figure 10a, compared with the fall pattern based on all data (figure 3d) reveals the large areal extent of the lake-effect. A map of differences between the two patterns (figure 10b) shows that the lake-effect increases thunderstorm days throughout much of Michigan. The area of maximum increase, 30 days per 10 years, is almost as large an increase as that shown in the same area in the summer season (figure 9b). Expressed as a percent of the no-lake-effect values, the lake-



a. 0000-0600 CST

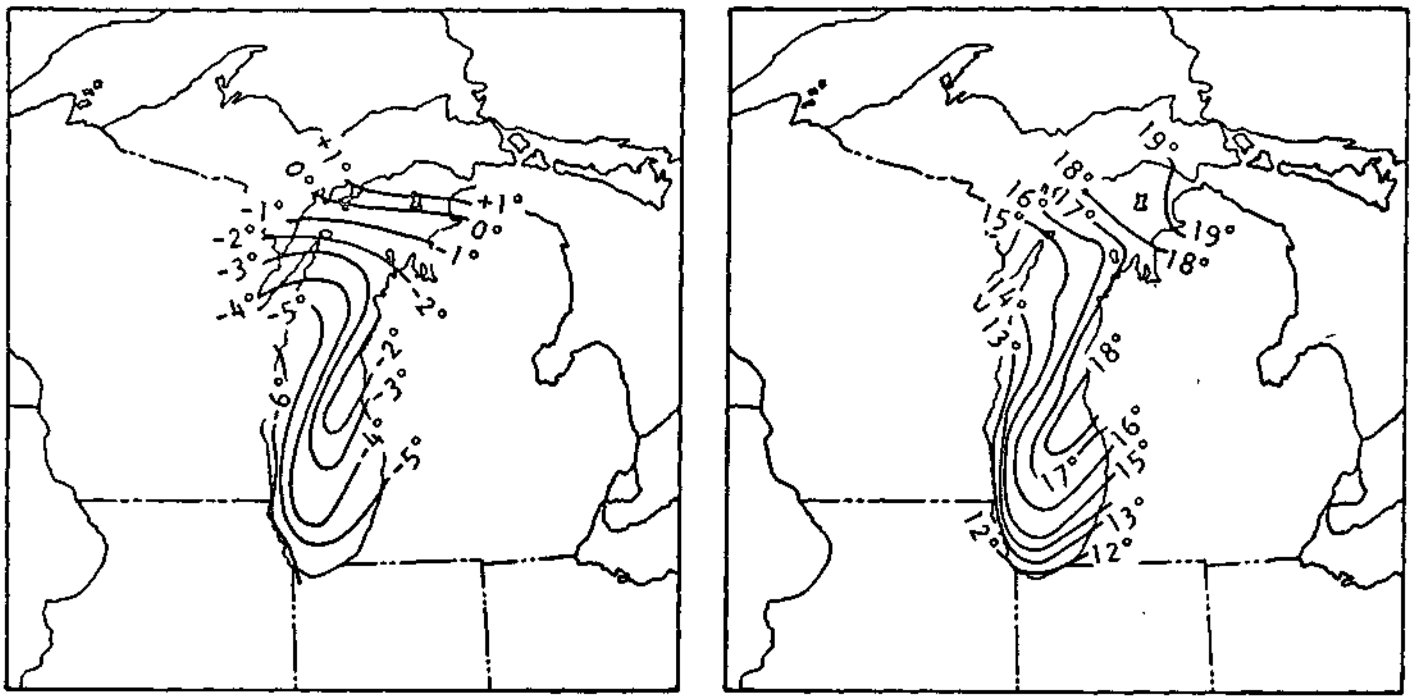
b. 0600-1200 CST



c. 1200-1800 CST

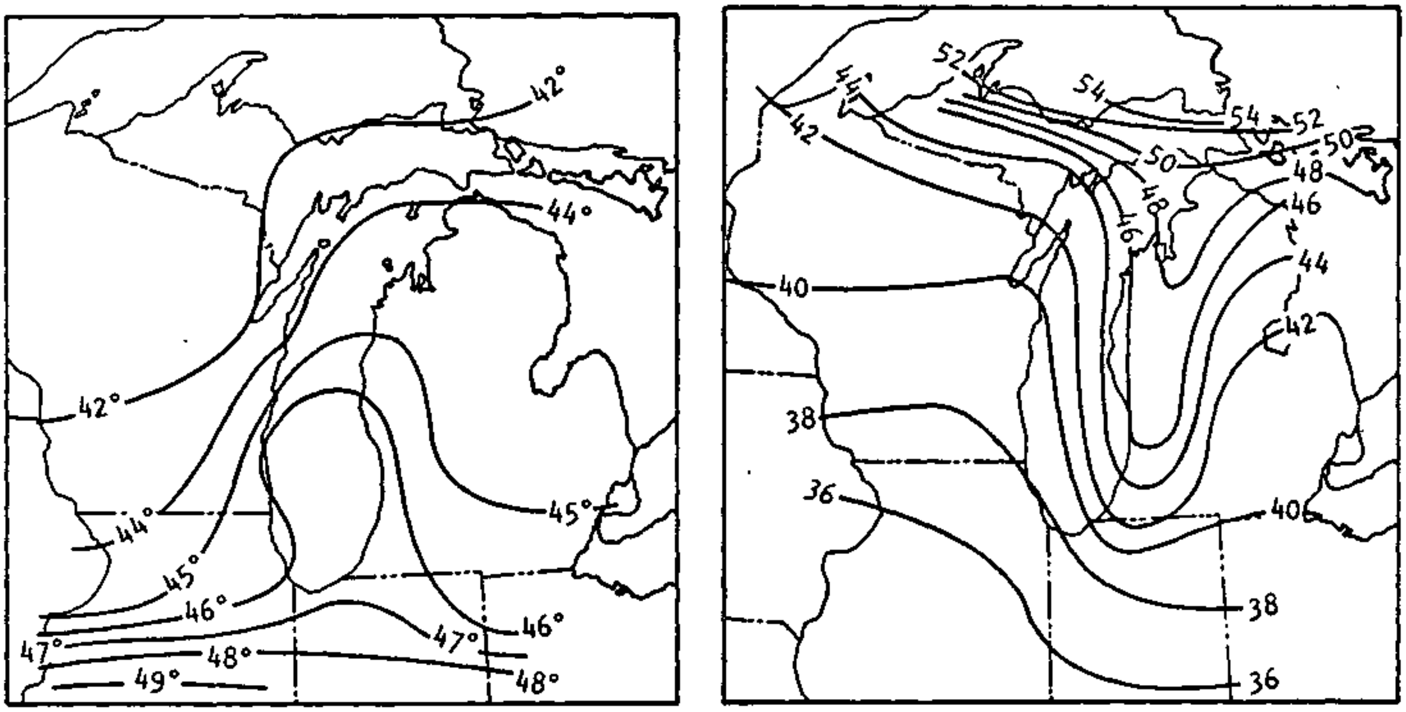
d. 1800-2400 CST

Figure 7. Number of fall thunderstorm days in 6-hour periods during an average 10-year period ,



a. Difference between mean water temperature and no-lake-effect mean maximum air temperature, °F

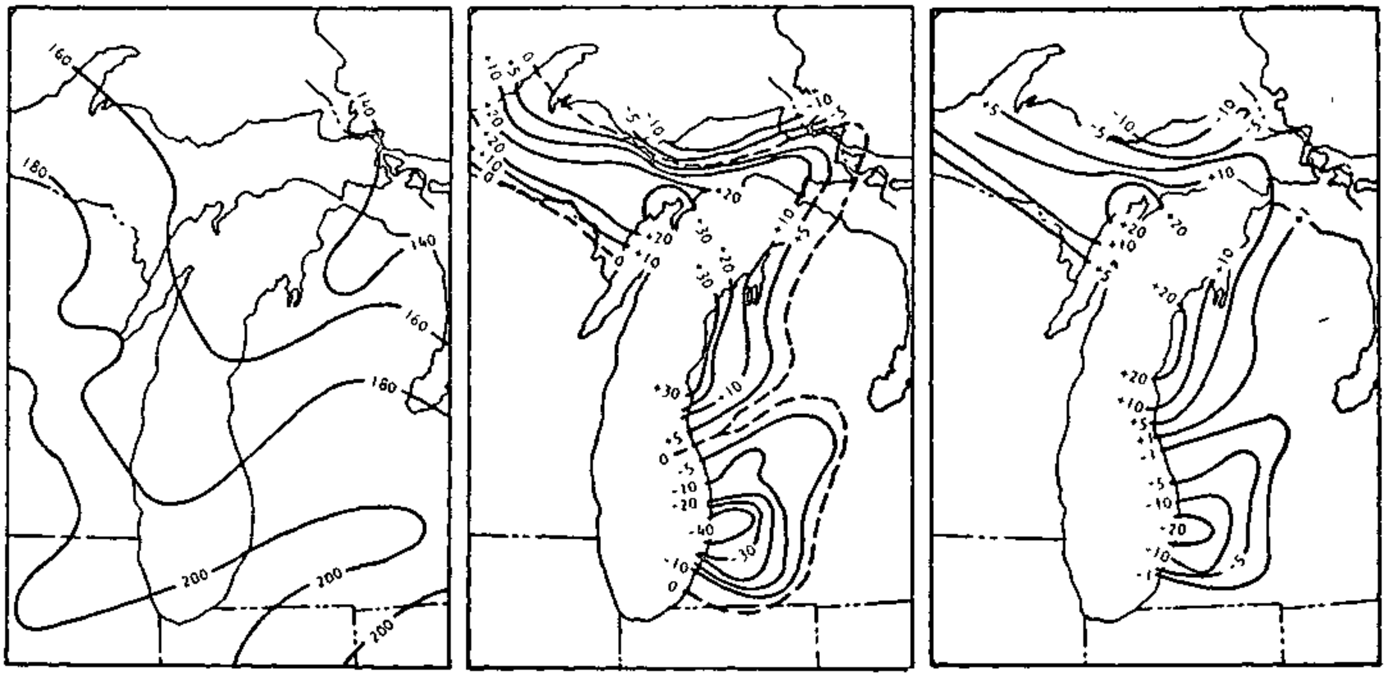
b. Difference between mean water temperature and no-lake-effect mean minimum air temperature, °F



c. Mean dew point temperatures, 1230-1300 CST

d. Mean number of cloudy days

Figure S. Patterns of fall weather conditions

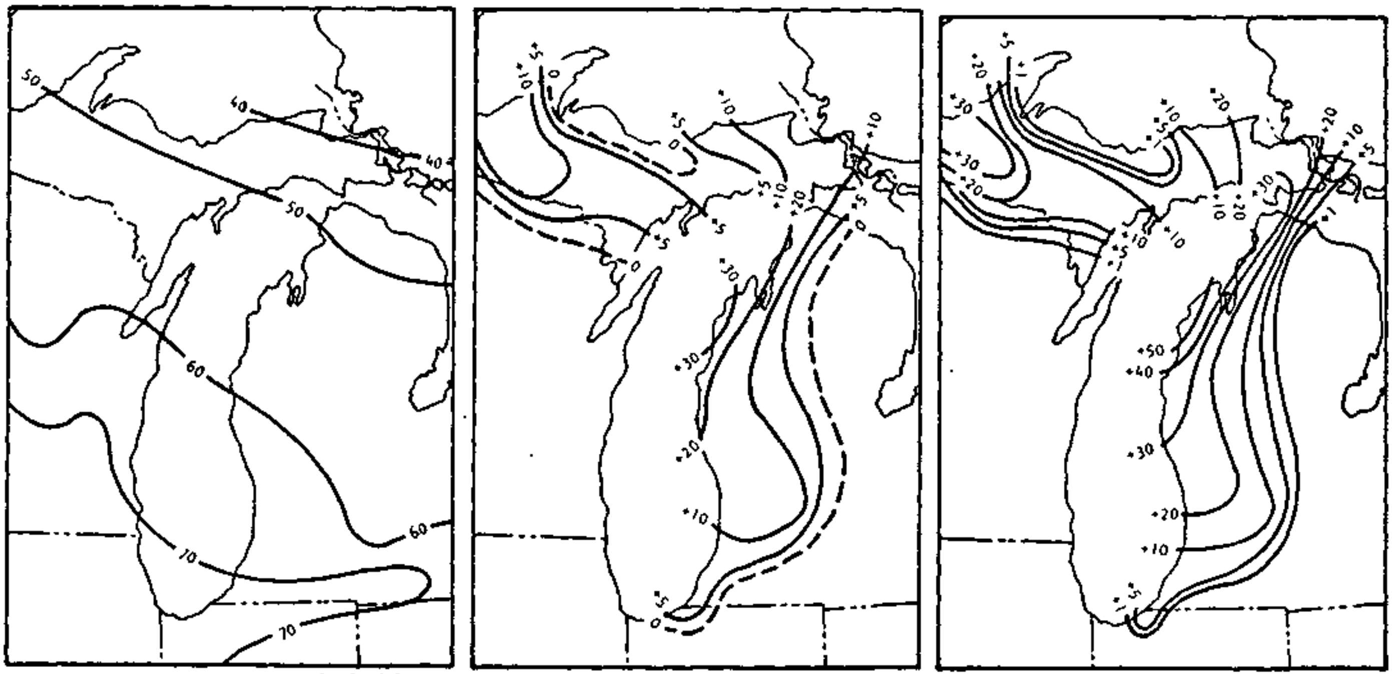


a. Average number of summer thunderstorms with no-lake-effect

b. Increases and decreases in thunderstorm days attributed to lake-effects

c. Lake produced increases and decreases in thunderstorm days expressed as a percent of the values based on no-lake-effect

Figure 9. Lake-effect on summer thunderstorm-day distribution during an average 10-year period



a. Average number of fall thunderstorms with no-lake-effect

b. Increases in thunderstorm days attributed to lake-effects

c. Lake produced increases in thunderstorm days expressed as a percent of the values based on no-lake-effect

Figure 10. Lake-effect on fall thunderstorm-day distribution during an average 10-year period

effect in fall produced 30 percent increases in thunderstorm days over sizeable portions of the area along the eastern shoreline (figure 10c).

Similar comparisons were made to determine lake-effect changes in the number of thunderstorm days in winter and spring. In winter (figure 11a) a portion of southwestern lower Michigan has a lake-effect increase of between 1 and 5 thunderstorm days in a 10-year period. In the spring season (figure 11b) the lake-effect reduces thunderstorm activity along the western shore of the lake, but increases thunderstorm activity along most of the eastern shore of the lake. The winter and spring increases and decreases are relatively small in comparison with those in summer and fall.

The decreases and increases in thunderstorm days occurring during an average 10-year period are shown in figure 11c. The lake-effect produces more than 70 additional thunderstorm days in some portions of the eastern lake shore, whereas in other portions the lake-effect causes 20 fewer thunderstorm days than expected. Squall lines normally form over the lake about twice a year, and this would represent 20 more thunderstorm days on the eastern shore than on the western shore in 10 years.

Profiles. Another expression of the lake-effect on thunderstorms in summer and fall is presented in figures 12 and 13. The purpose of these west-east profile graphs was to compare the lake-effect on thunderstorm frequencies across the northern portions of the lake with that across the southern portions. The profiles were selected to display changes going east from a no-lake-effect station to lake-effect stations and on to a station with no-lake-effect.

The south profile (figure 12) shows the major reduction in summer thunderstorm days at all stations near the lake in the two daylight periods. The north profile also indicates decreases on both sides of the lake in these daylight periods. Dashed lines labeled the climatological gradient connect the two no-lake-effect station values in each graph, and these lines furnish a basis for measuring the degree of lake-effect. Increases or decreases were determined by comparing the actual profile with these climatological gradients.

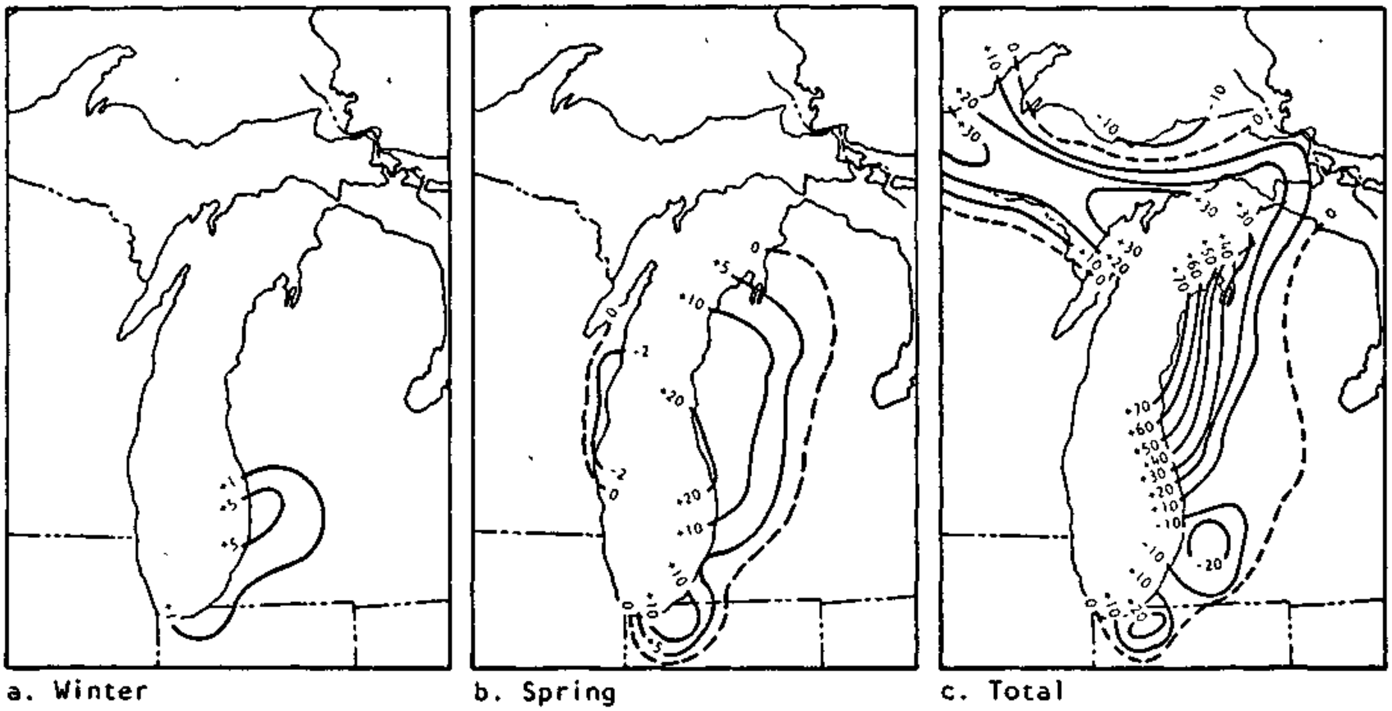
In the two summer nocturnal periods (figure 12) there is a suggestion along the south profile of a slight decrease in activity on the west side of the lake, but a definite increase in activity occurs on the east side of the lake.

The north profiles of summer thunderstorm days for the two nocturnal periods indicate increases in thunderstorm activity on both sides of the lake, and the increases on the east side are much greater than those along the south profile.

The summer total thunderstorm days for both profiles also are shown on figure 12. The southern profile reveals the great reduction in thunderstorm days that occurs on both sides of the lake, whereas across the north the lake-effect in summer results in a moderate decrease on the west and an increase on the east.

Similar profile graphs prepared for the 6-hour periods of the fall season are shown in figure 13. The easternmost station selected for the southern profile was Detroit since Lansing appeared to have fall thunderstorm activity resulting from lake-effects (figure 7).

The southern profile for the fall total days reveals that the lake-effect is minor on the west side of the lake. Increases in thunderstorm activity in the south appear east of the lake in each of the four periods, but these increases



a. Winter b. Spring c. Total

Figure 11. Lake-effect on winter, spring, and total thunderstorm-day distributions during an average 10-year period

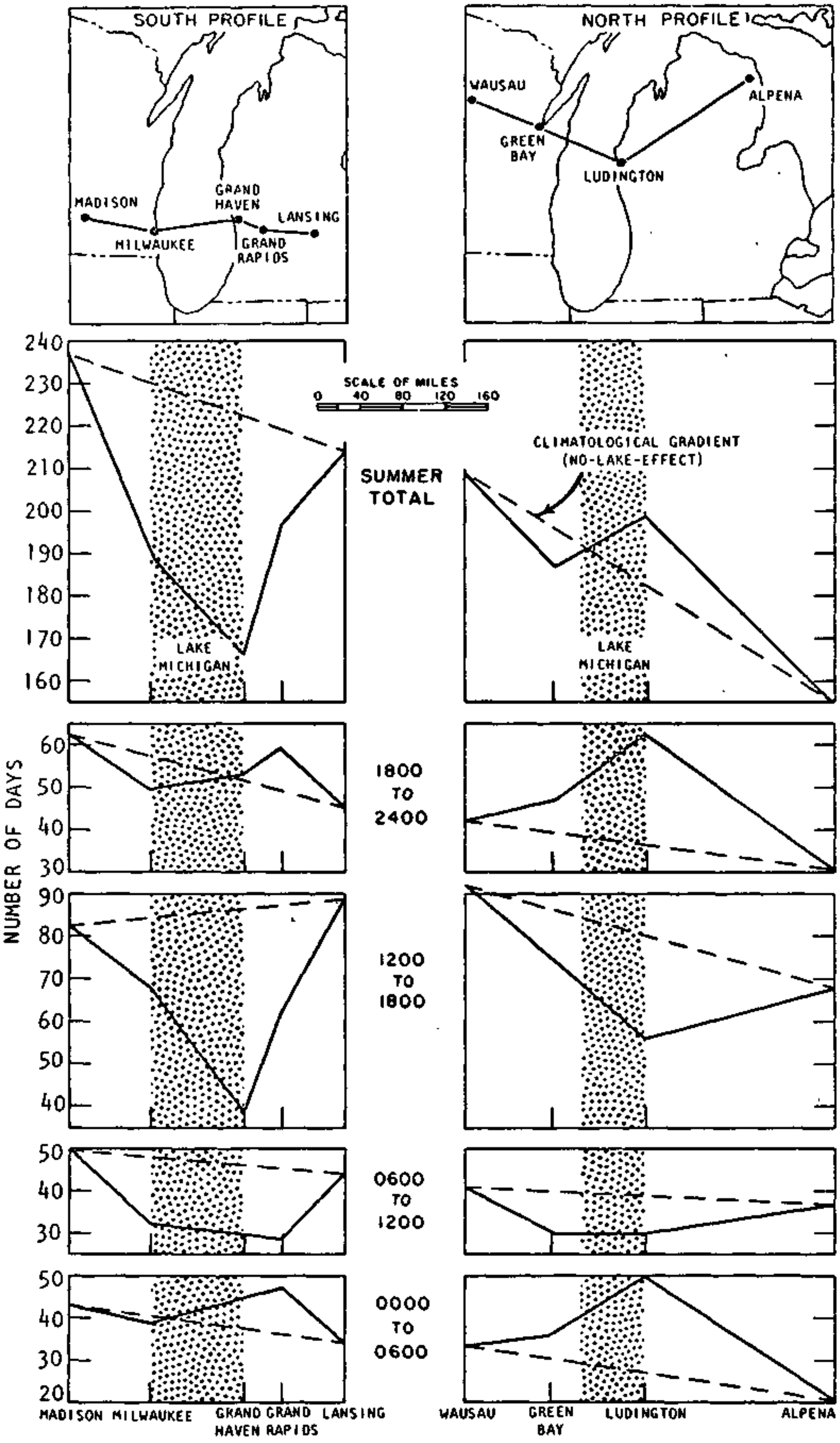


Figure 12. West-east profiles across Lake Michigan for summer thunderstorm days in an average 10-year period

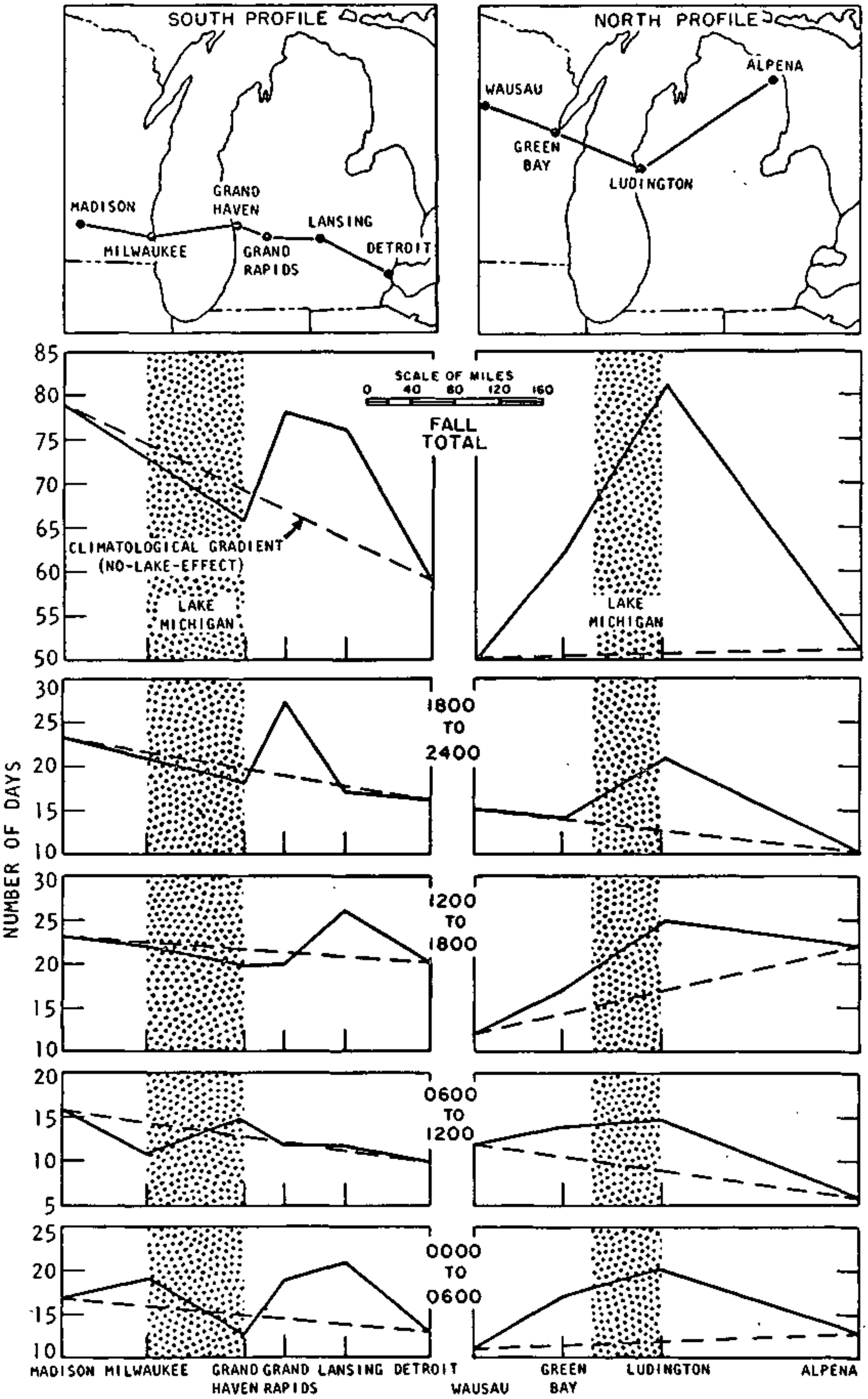


Figure 13. West-east profiles across Lake Michigan for fall thunderstorm days in an average 10-year period

maximize at different distances from the lake. In general, in the south, the lake-effect nocturnal increases in fall tend to occur farther inland (Grand Rapids and Lansing) than do those in summer. In fact, the fall total profile across the south indicates a lake-effect decrease at the eastern shoreline.

The north profiles in fall indicate that the lake-effect increases activity in all four 6-hour periods. The impact of these lake-effect increases in thunderstorm activity in the fall is further revealed by the September thunderstorm-day frequencies at Ludington, Escanaba, and Sault Ste. Marie which rank as the fourth highest monthly averages at these stations. Throughout the rest of the lake area and the upper Midwest, September thunderstorm-day averages rank as the fifth largest and May averages rank fourth.

Point Frequencies. To obtain point measurements of the seasonal amount of lake-effect by 6-hour periods, the thunderstorm data from six stations around the lake were compared with thunderstorm frequencies calculated from seasonal no-lake-effect maps for the same periods of the day.

Table 2. Changes in Summer Thunderstorm-Day Frequencies Due to Lake-Effects

	Difference in average number of days per 10 years between actual frequencies and no-lake-effect frequencies				
	6-hour time periods, CST				
Station	00· 06	06· 12	12· 18	18· 24	Season total
Milwaukee	—1	—14	—9	—8	—32
Grand Haven	+10	—15	—52	+8	—49
Grand Rapids	+13	—16	—30	+13	—20
Escanaba	+3	—4	+25	+15	+39
Ludington	+10	—10	—24	+23	—1
Chicago	0	-4	—13	+2	—15
	Difference between actual frequency and no-lake-effect frequency, as percent of no-lake-effect frequencies				
Milwaukee	—2	—30	—12	—14	—14
Grand Haven	+29	—33	—58	+18	—23
Grand Rapids	+37	—35	—33	+29	—9
Escanaba	+10	—13	+39	+43	+24
Ludington	+25	—25	—30	+57	—0.5
Chicago	0	—11	—14	+3	—6

Table 2 shows the summer differences expressed in the number of thunderstorm days and in percentages. The large negative departures in days occur in the summer afternoon periods, and these are also the largest percentage departures. Thus, lake-effects in the summer afternoon hours cause point reductions of up to 58 percent (Grand Haven) in thunderstorm activity and increases of up to 39 percent (Escanaba). Nocturnal increases in thunderstorm activity during the summer are sizeable with 43 to 57 percent increases at Escanaba and Ludington, respectively. At Ludington the increases in activity in the 0600-1800 period match the decreases in the 1800-0600 period so that the net effect in summer is less than 1 percent.

Table 3. Changes in Fall Thunderstorm-Day Frequencies Due to Lake-Effects

	Difference In average number of days per 10 years between actual frequencies and no-lake-effect frequencies				
	6-hour time periods, CST				
Station	00· 00	06· 12	12· 18	18· 24	Season total
Milwaukee	+3	—2	0	+1	+2
Grand Haven	+1	+6	+1	—1	+7
Grand Rapids	+6	+3	0	+9	+18
Escanaba	+2	+7	+7	+4	+20
Ludington	+9	+5	+7	+5	+26
Chicago	+3	—1	—2	0	0
	Difference between actual averages and no-lake-effect averages, as percent of no-lake-effect frequencies				
Milwaukee	+19	—15	0	+5	+3
Grand Haven	+8	+67	+5	—5	+11
Grand Rapids	+46	+33	0	+50	+30
Escanaba	+25	+87	+50	+33	+47
Ludington	+81	+50	+39	+31	+47
Chicago	+17	—8	—8	0	0

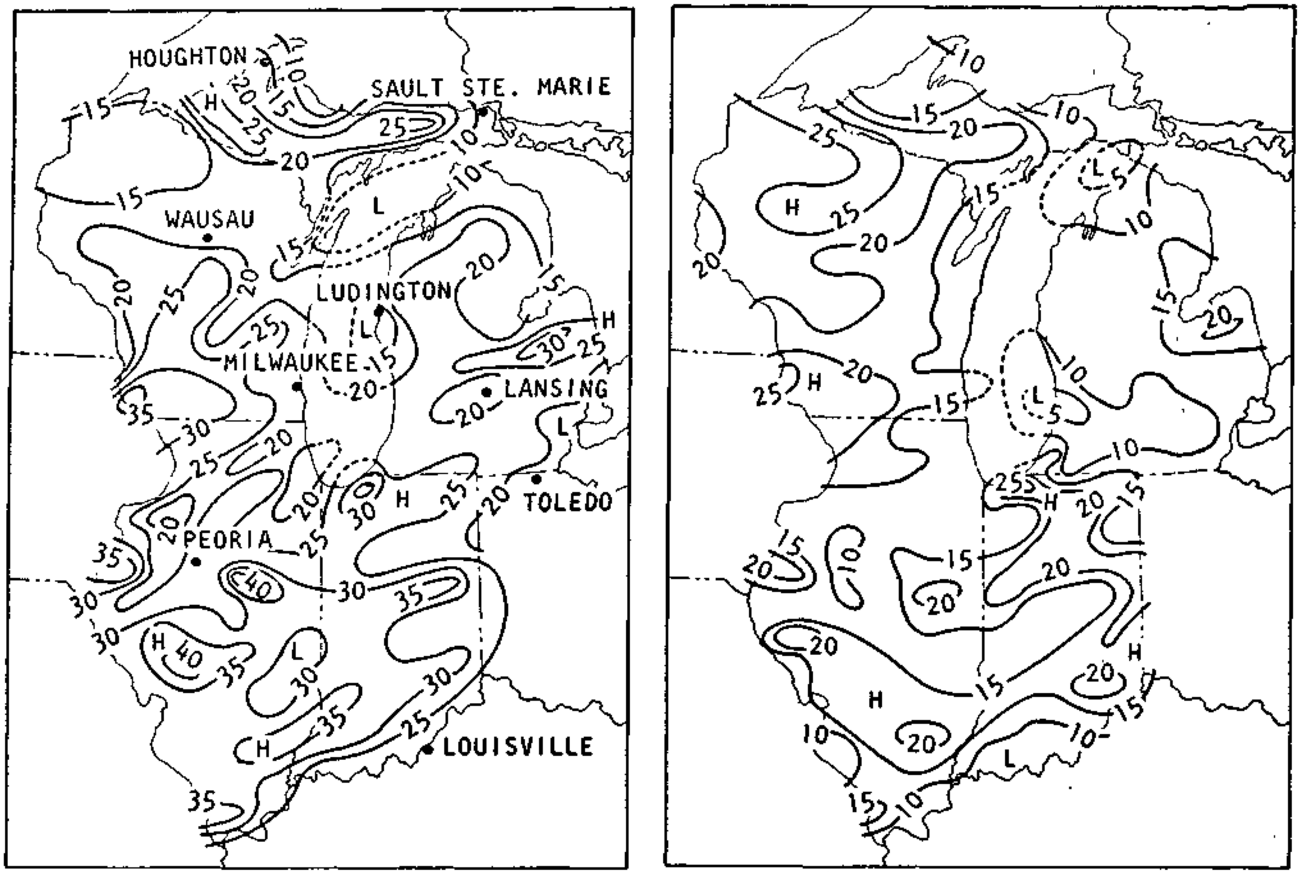
Table 3 contains similar data for the fall season. Although the fall increases in number of thunderstorm days are smaller than those in summer, the percentage increases are often larger. Escanaba and Ludington both have 6-hour periods with lake-effect increases greater than 80 percent. The daylight period data for Chicago and Milwaukee suggest that the lake serves to reduce activity along the lower west side of the lake in fall. The daytime decreases at Chicago are matched by the nocturnal increases so that the net lake-effect in fall on thunderstorm activity at Chicago is zero. In general, the lake-effect increases in the fall nocturnal periods are greater than those in the daylight periods. Convective thunderstorm activity increases at night in the fall."

Inspection of the seasonal totals (table 2) reveals that the lake-effect changes in summer range from 24 percent increases to 23 percent decreases in thunderstorm activity. In the fall totals (table 3) the lake-effects cause changes ranging from 0 to 47 percent increases.

Hail Patterns

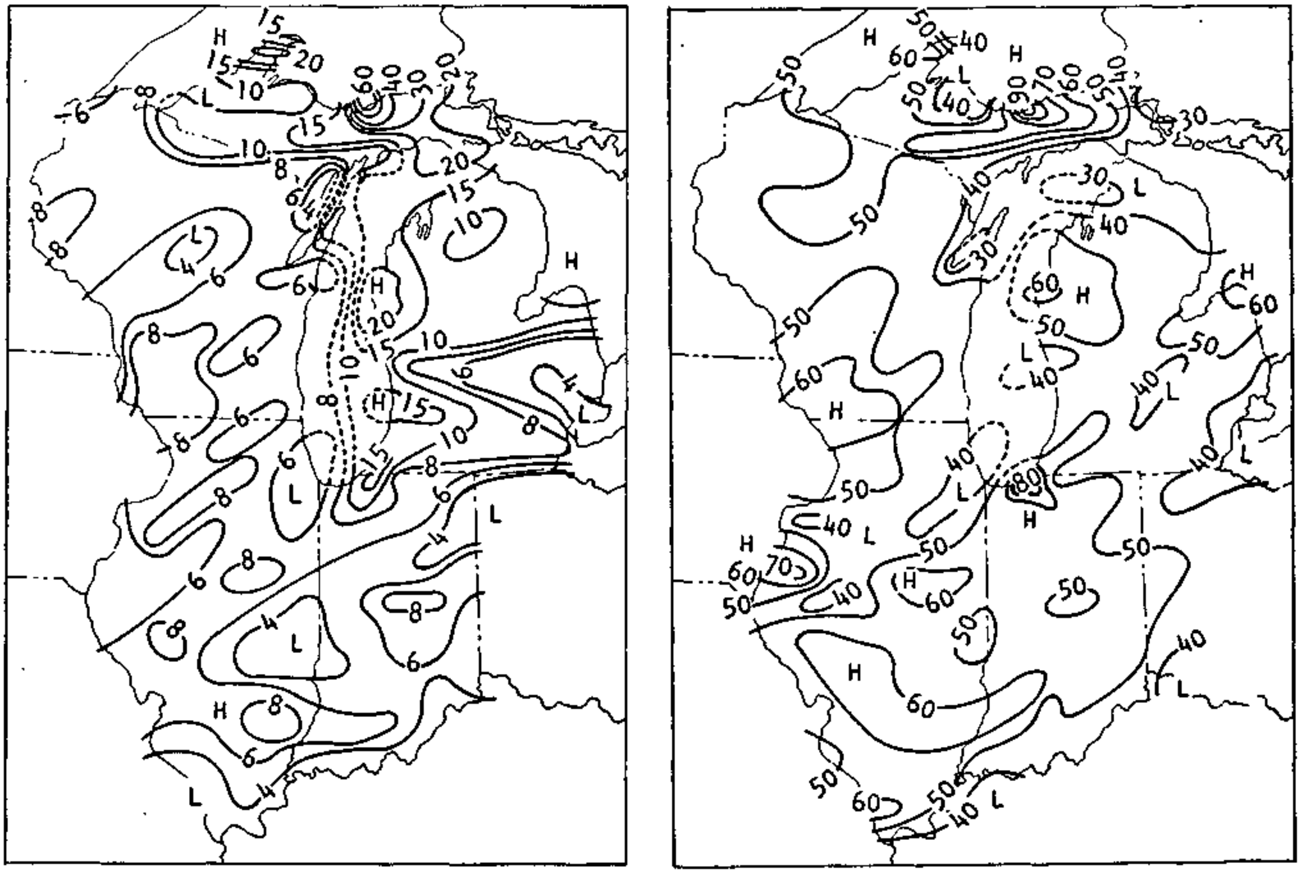
Average Patterns. The second phase of the climatological investigation of severe weather dealt with the average areal distributions of hail days, expressed as the number during an average 20-year period. Hail is a less frequent event than thunderstorms and is often considered to represent a more advanced stage in the convective process. Interestingly, the lake-effects influence hail frequencies to a greater degree than they do thunderstorm frequencies.

The average patterns for hail days in the three seasons of greatest hail occurrence are portrayed in figure 14. Hail-



a. Spring (March-May)

b. Summer (June-August)



c. Fall (September-November)

d. Total number of hail days in an average 20-year period

Figure 14. Patterns of seasonal and total number of hail days in an average 20-year period

day patterns are somewhat more difficult to assess for lake-effects than thunderstorm-day patterns because the hail-day patterns over the central United States do not always conform well with latitudinal variations. The summer hail-day pattern in western Illinois (figure 14b) is one example. Thus, the effect of Lake Michigan on hail incidence cannot be assessed in as much detail as was the lake-effect on thunderstorm activity.

The spring hail-day pattern (figure 14a) suggests a lake-effect minimum along the eastern shore of the lake which does not agree with the findings for thunderstorms. The high in central lower Michigan may also be a lake-induced feature, but there is no ready meteorological explanation. An hypothesis for this increase can be offered since most spring hailstorms in this area are associated with eastward moving cold fronts. As these fronts move across the lake their low-level unstable layer is destroyed by the cold, stable lake which in turn reduces convective activity and results in few hail occurrences on the eastern shore. However, once the cold air mass, which is now colder and more stable, moves inland over Michigan, a new unstable layer is developed which might cause new and even greater development of convection and hail over the interior of the state.

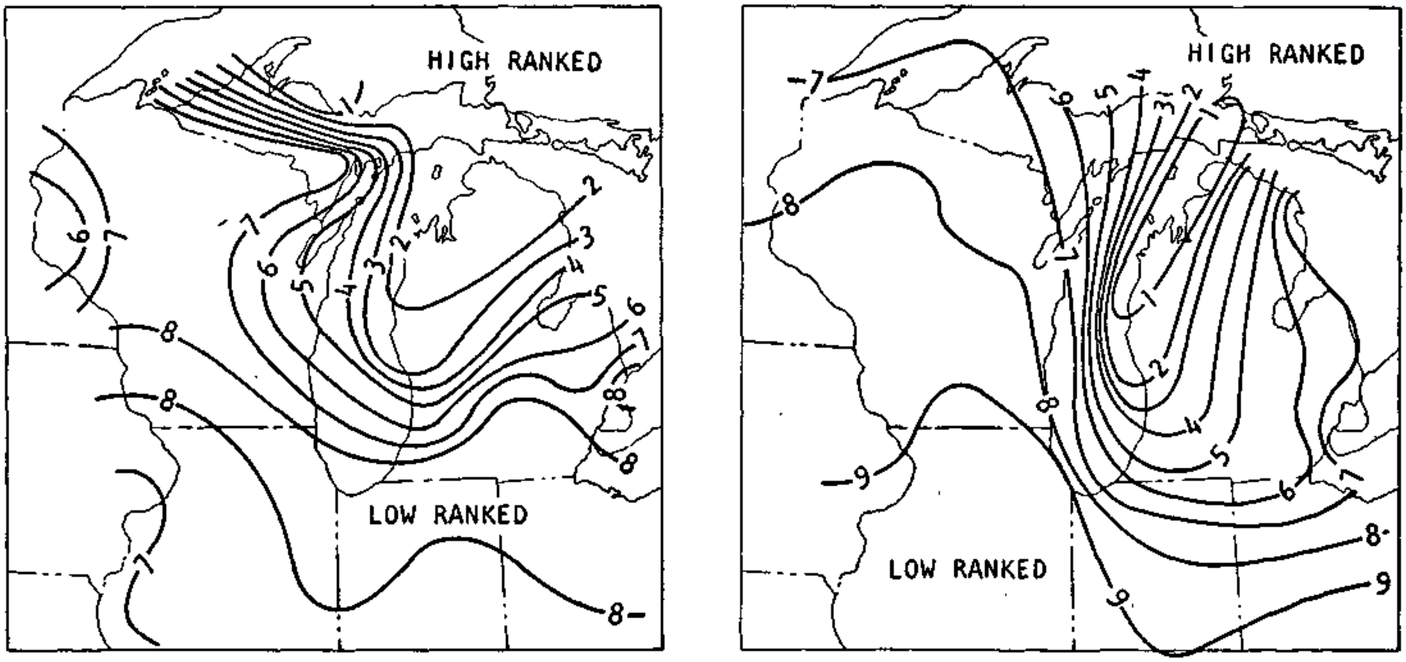
The average summer hail-day pattern (figure 14b) reveals a distinct diminishment of hail activity due to lake-effects throughout most of lower Michigan. It appears reasonable to assume that without Lake Michigan most of this area would experience between 12 and 18 days with hail in an average 20-year period. Thus, the actual values of 10 hail days or less in lower Michigan represent decreases ranging from 10 percent in the central portions to as much as 60 percent in the area south and east of Muskegon. The eastward extension of the hail isolines in the upper Michigan peninsula cannot be definitely assigned to lake-effects since the continental climatological pattern, as revealed by the 20-day isoline on figure 14b, suggests a ridge of higher incidence extending into this general area.

The fall pattern of hail days reveals more significant changes from lake-effects than does any other seasonal map of hail days or thunderstorm days. In the no-lake-effect areas of Wisconsin, Illinois, and Indiana the average hail-day values range from 4 to 8 per 20 years. Thus, the hail-day values greater than 8 shown throughout much of lower and upper Michigan (figure 14c) represent increases deriving from lake-effects. These values represent increases ranging from 50 to 400 percent above the values expected with no-lake-effect. However, the hailstone sizes in fall are frequently quite small, 0.25-inch diameter or less."

The resulting average total hail-day pattern (figure 14d) is a composite of the various increases and decreases shown in the three seasons. The large increases in the fall season produce an area of high incidences in northwestern lower Michigan and also in northwestern Indiana. The summer lake-effect decreases, particularly along the lake's southeastern shore in Michigan, create a low incidence area there in the total hail pattern.

Rank Patterns. The particular significance of the lake-effect increases in hail days during fall was further investigated using the individual monthly average hail-day values at first-order stations. Figure 15 displays a pattern based on the ranked values for September and October developed on a scaling in which the highest monthly average is assigned rank 1, the second highest value is rank 2, etc.

As shown in the Wisconsin, Illinois, and Indiana areas,



a. Rank of September average

b. Rank of October average

Figure 15. Pattern of rank values based on monthly average number of hail days

the September averages for hail days usually achieve a rank of seventh or eighth among the 12 monthly values. The many lake-effect hail incidences in upper and lower Michigan in September make the total hail days large enough to rank as the first or second largest monthly values.

Figure 15b reveals that the October hail-day averages rank first at Ludington and Sault Ste. Marie; without lake-effects October hail-day frequencies would have ranked seventh or eighth in this general area. This area of Michigan and another small one on the southeast side of Lake Erie are the only areas in the Midwest where September and October hail-day averages rank either first or second, further emphasizing the significance of lake-effects on convectivc processes in the fall season.

EFFECT OF LAKE ON SNOWFALL

Snowfall is a significant contributor of precipitation in the Lake Michigan Basin. Land-measured average snowfall amounts represent between 20 percent (south) and 30 percent (north) of the mean annual basin precipitation. The effect of Lake Michigan on snowfall production over the nearby land areas has been recognized for many years and has been rather extensively studied.'[9,17] The patterns on figures 16 and 17 reveal the pronounced effect of the lakes on the production of snow and 1-inch snowfalls in both upper and lower Michigan.

The amount of snowfall occurring over Lake Michigan is difficult to determine, but the goal of this snowfall study was to assess the lake-effect on snowfall in order to estimate the average pattern of lake snowfall and to use the results in developing the climatological estimates of the average winter precipitation pattern over the lake.

During the fall and early winter the lake water cools more slowly than the surrounding land, and thus is often relatively warmer than the air passing over it. The lake frequently acts to warm as well as to moisten the dry winter air masses moving from the southwest, west, and northwest. Lake-effect snowfalls can occur when certain synoptic conditions bring cold, dry continental air masses across long fetches of the unfrozen lake. Willett[18] calculated that the average vertical exchange of heat and moisture from the lake to overlying arctic air extended 1.5 miles and increased the low-level air temperature by 18 F and the moisture content of the air by a factor of four.

Lake-effect snowfalls generally do not occur in any areas where the lake has become frozen, which sometimes occurs in late winter in the upper lake. Since the lake temperature in late winter more closely approximates that of the air,

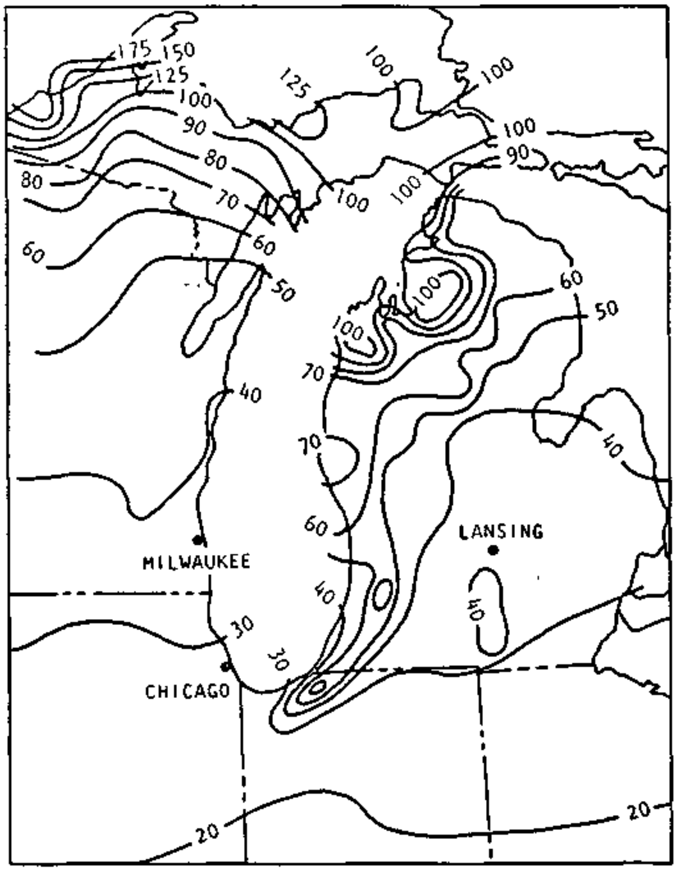


Figure 16. Average annual snowfall, inches

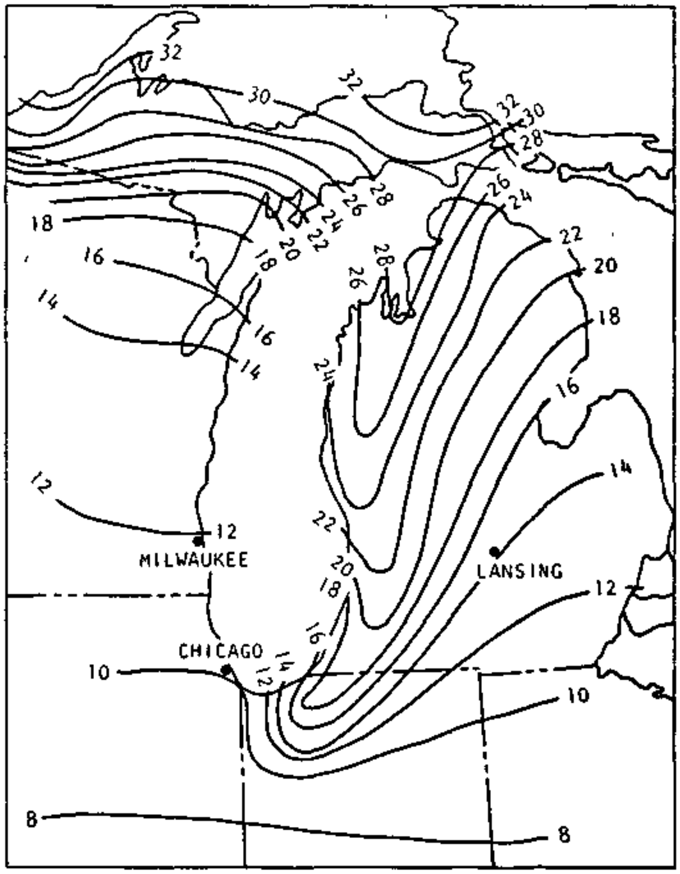
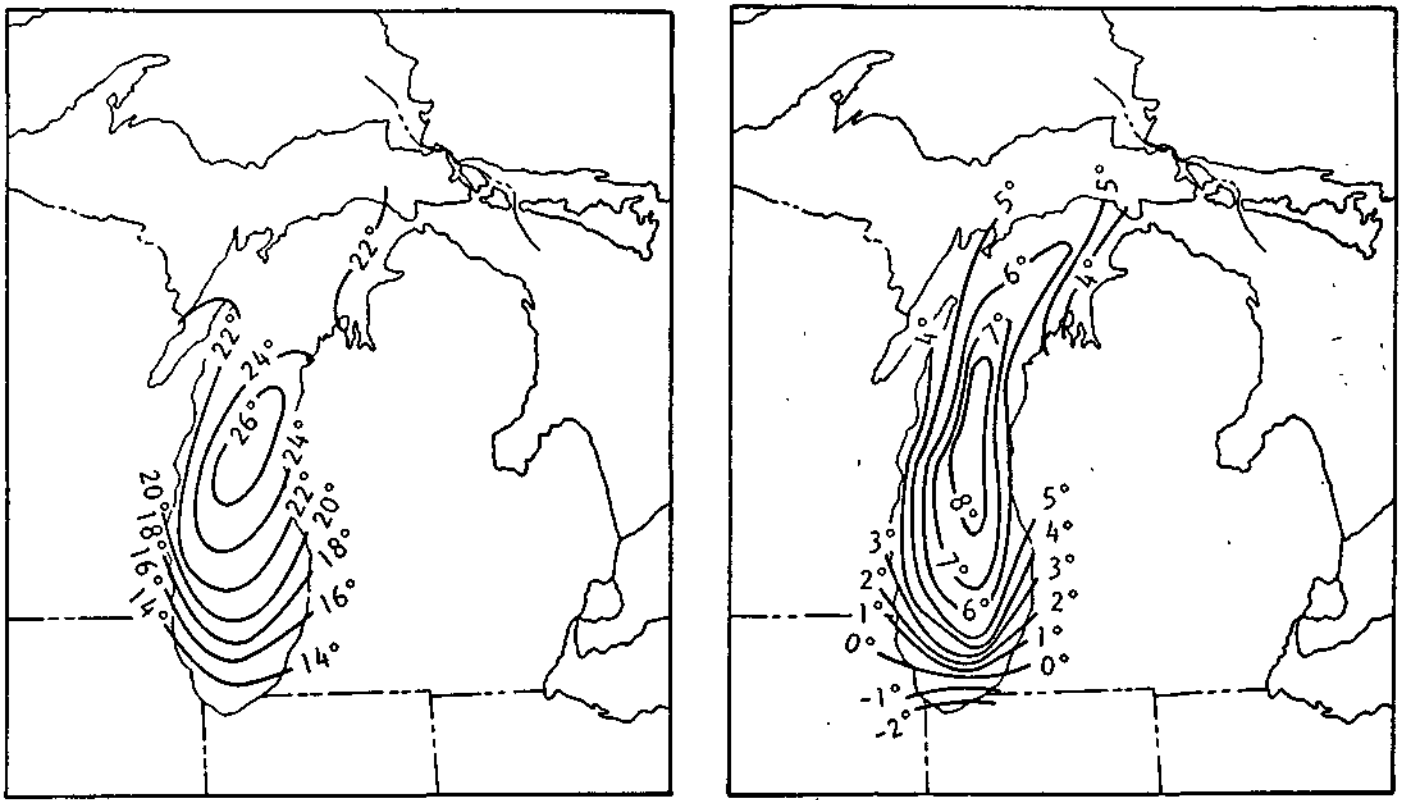
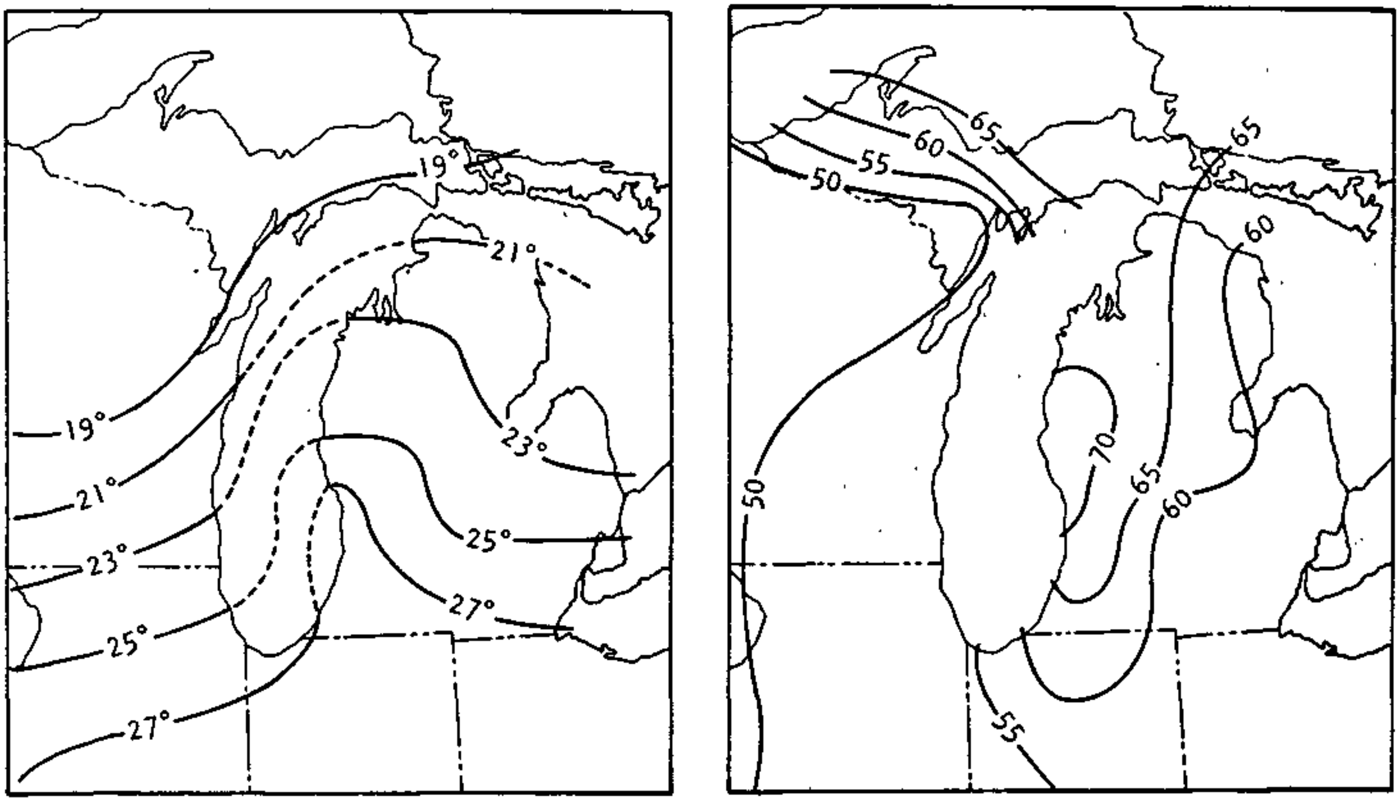


Figure **17.** **Average** annual number of **days** with snowfall of 1 **Inch** or more



a. Differences between mean water temperature and no-lake-effect mean minimum air temperature, °F

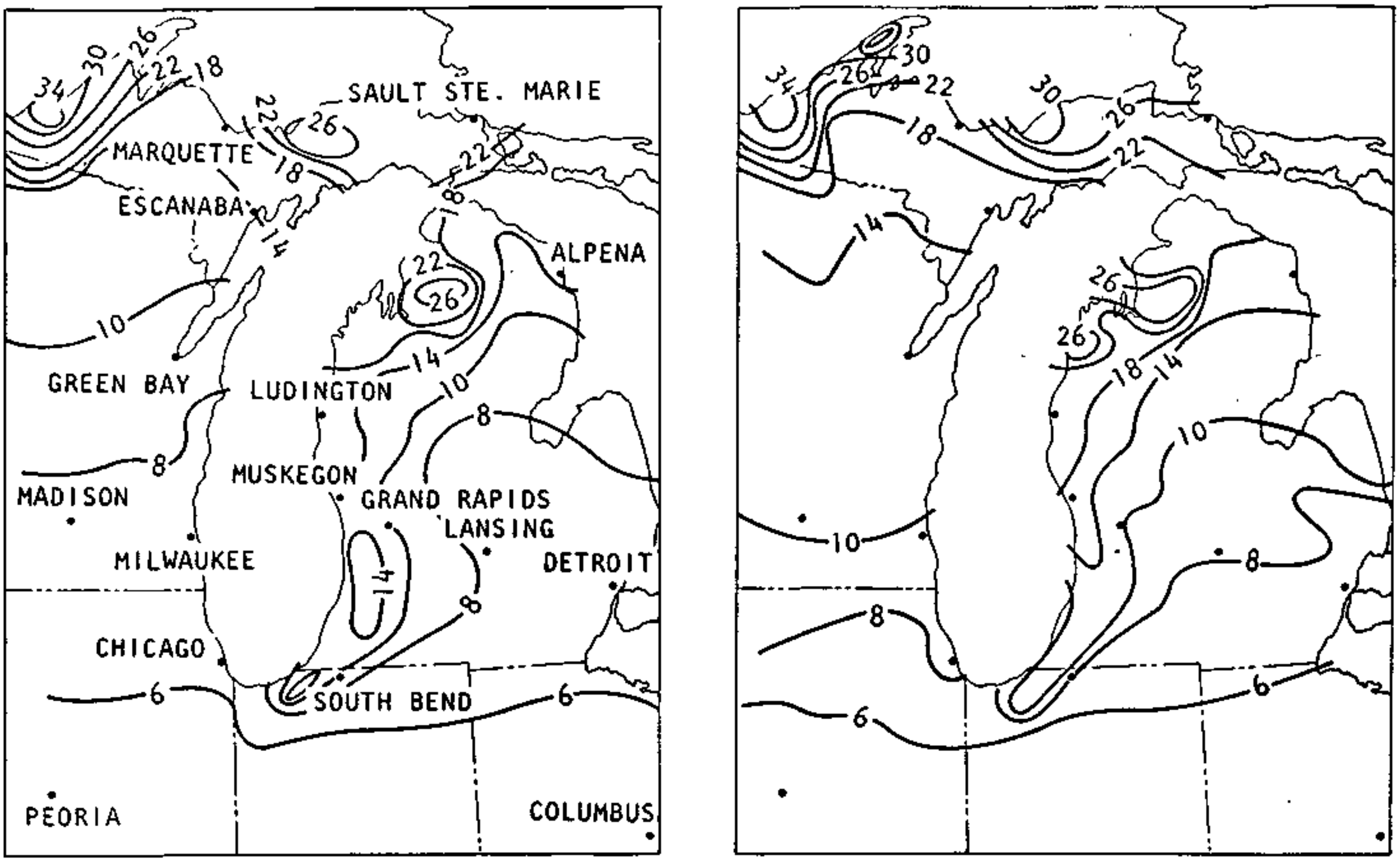
b. Differences between mean water temperature and no-lake-effect mean maximum air temperature, °F



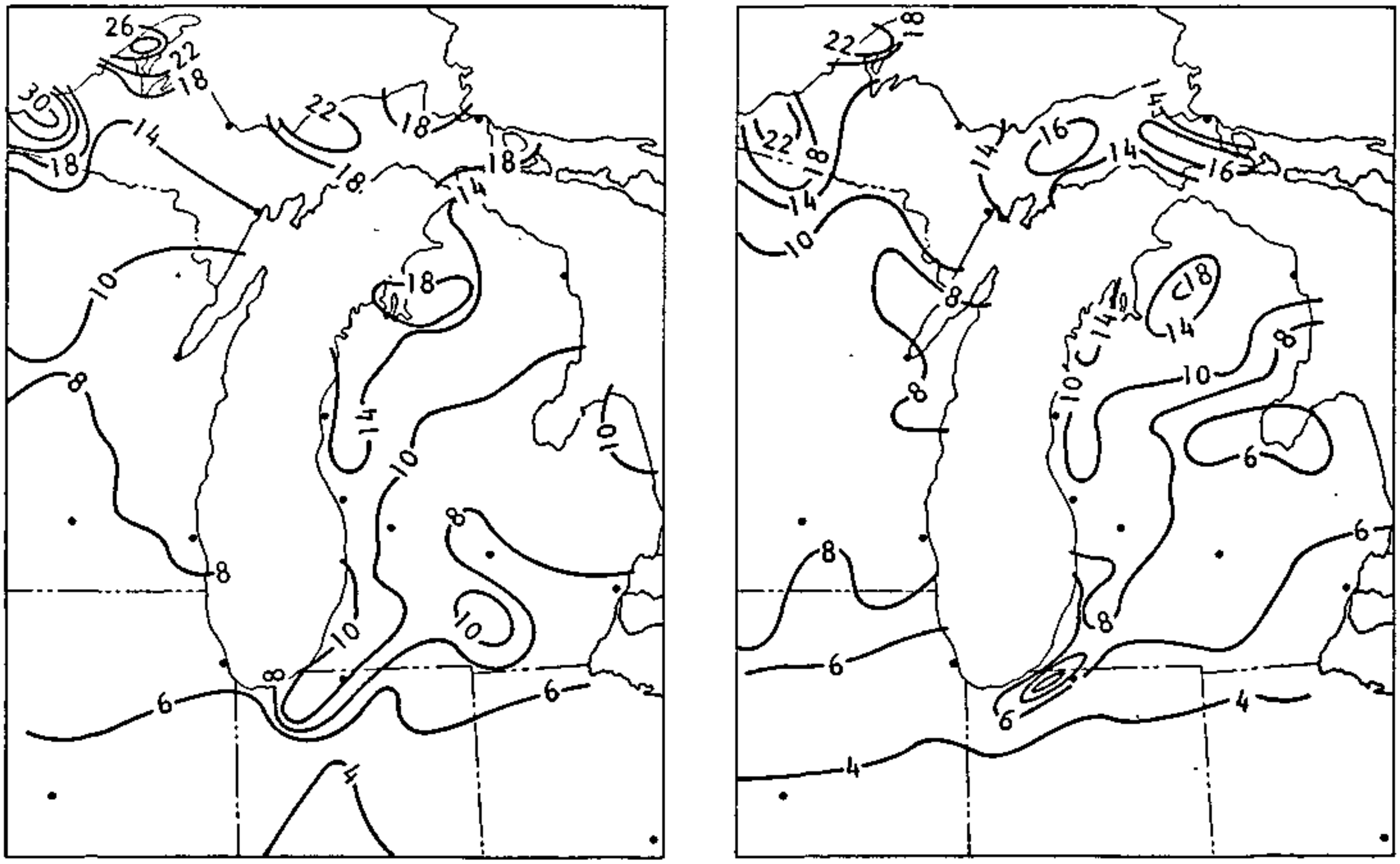
c. Mean dew point temperatures, 1230-1300 CST

d. Mean number of cloudy days

Figure 18. Patterns of winter weather conditions



a. December b. January



c. February d. March

Figure 19. Avarage monthly snowfall, inches

cluded that most lakc-effect snowfall was derived from a few relatively heavy snowstorms in the average season. The 1-inch snowfall data certainly support this conclusion and strongly reveal the lake-effect.

Table 4. Average Number of Days with I-inch or More Snowfall on the West and East Sides **of** Lake Michigan at Two Locations

	Mid-lower lake		Extreme tower lake	
	Green Bay and Milwaukee (west)	Muskegon and Grand Rapids (cast)	Chicago (west)	South Bend (east)
November	1	3	1	3
December	3	6	3	4
January	3	6	2	4
February	3	4	2	4
March	2	3	2	2
Season total	12	22	10	17

Values in table 4 provide a measure of the west-east differences across Lake Michigan at two general latitudinal locations. The lake-effect is apparent with 100 to 200 percent greater numbers of days on the east side in November, December, and January, and 50 to 100 percent larger numbers on the east in February and March. The time change in these precentages is another illustration of how lake-effects on snow production decrease during the cold season.

Lake Snowfall Pattern

The average annual pattern of snowfall on the land areas around Lake Michigan (figure 16) closely approximates the average winter precipitation pattern (see figure 31) since snowfall is the major contributor of precipitation in that season.

A specific goal of this lake-effect snowfall study was to develop an estimated pattern of the average annual snowfall on Lake Michigan. Thus, this study was concerned with the placement of the average snowfall isopleths on the lake, and this pattern was largely determined from deductive findings and knowledge concerning the occurrence of lake-effect snows.

Eichenlaub[8] has shown 1) that lake-effect snowfalls represent 40 percent of the total snowfall along the immediate eastern shore of Lake Michigan, and 2) that most of this lake-effect snowfall occurs with synoptic weather types featuring strong westerly flow in the lower levels and nonfrontal conditions. These findings suggest that the isopleths over the lake resulting from lake-effect snows have generally north-south orientations. Wiggin[27] indicated that the most favorable conditions for lake-effect snows would usually produce north-south oriented cells of snowfall along the shore and inland.

The climatological profiles of average annual snowfall indicated that when lake-effect snowfall develops over the lake it begins somewhere within 20 miles of the eastern shoreline. Ship masters of lake ferries have reported that development of lake snowfall occurs within 10 to 20 miles of the eastern lake shore.[8] Marks[16] has reported that with the westerly flow conditions favorable for lake-effect snows, the snowfalls, as depicted by radar and visual observations, developed as lines or bands paralleling the shore at distances ranging from 1 to 10 miles west of the eastern shoreline. These observations and findings indicate that most lake-effect snows that develop over the lake occur as areas parallel (nearly north-south) and relatively close (1 to 20 miles) to the eastern shore.

These findings were used to prepare an average pattern of annual snowfall on Lake Michigan (figure 21). The orientation of the isopleths extending eastward from Illinois and Wisconsin was considered to be latitudinal until they came within 20 miles of the eastern shore. Their orientations were then made generally parallel to the shoreline at locations determined from the profile analysis. Where necessary they were curved inland to meet the intersection with their matching isopleth (value) on the eastern shore.

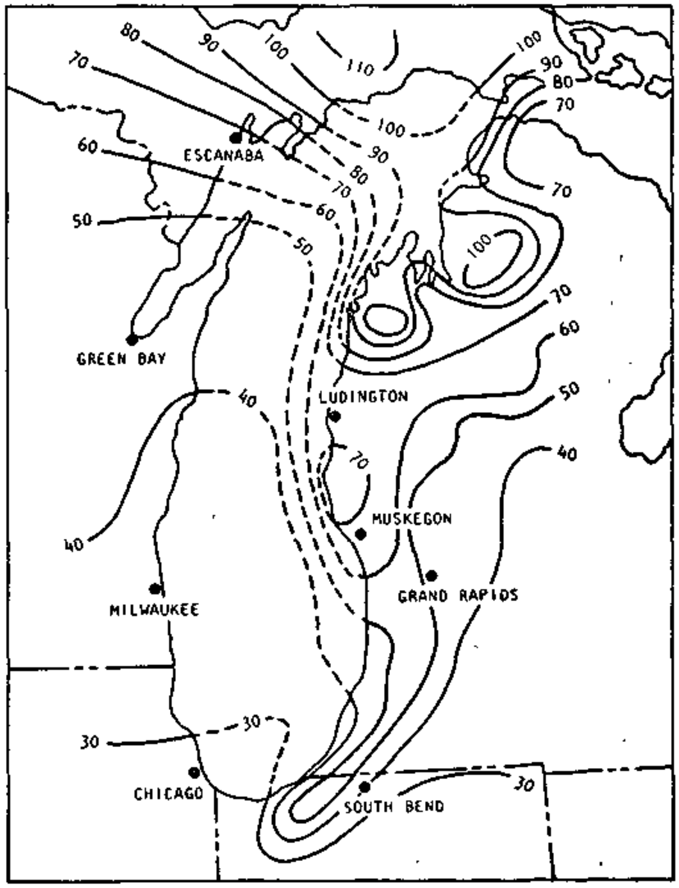


Figure 21. Average annual snowfall pattern (inches) aver Lake Michigan and environs

A more detailed measure of the effect of Lake Michigan on thunderstorms and snowfall is provided by the precipitation values associated with these two phenomena. However, the determination of the liquid precipitation produced by snowfall and by rainfall from thunderstorms is a very difficult, time-consuming, and a somewhat subjective task. As a compromise, 14 years of daily data from 41 stations located around the southern half of the lake (figure 22) were carefully analyzed to provide monthly, seasonal, and annual statistics on the amount of precipitation on: 1) days when thunderstorms occurred on only the west side of the lower lake, 2) days with measurable snowfall (≥ 0.1 inch) on only the west side, 3) days with thunderstorms on only the cast side, 4) days with measurable snowfall on only the east side, 5) days with thunderstorms on both sides of the lower lake, and 6) days with measurable snowfall on both sides of the lake.

This comprehensive study of precipitation around the southern half of Lake Michigan was pursued 1) to obtain more precise, detailed measures of the lake-effect on thunderstorms and snowfall, as revealed in their precipitation values, and 2) to obtain average seasonal and annual patterns of thunderstorm precipitation that would be helpful in the computation of the over-lake patterns of total average seasonal precipitation.

It can be reasonably assumed that there are days in each season when the lake does not affect thunderstorm activity or snowfall production, that there are times when it acts to suppress either activity, and that there are other days when the lake can act to induce or enhance thunderstorms or snowfall.

Precipitation data from days with thunderstorms or measurable snowfall on both sides of the lower lake were considered to represent no-lake-effect conditions, and the resulting patterns provide a measure of areal changes due to broad-scale synoptic features which would exist without the lake.

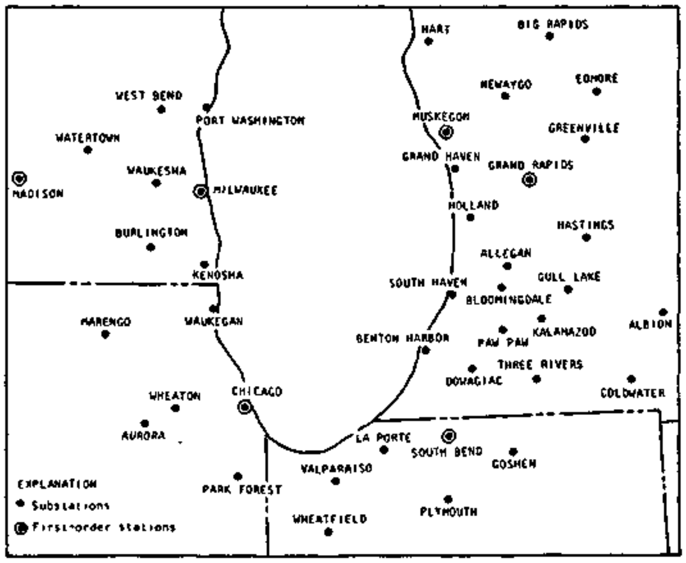


Figure 22. Stations used in the analysis of precipitation from thunderstorms and snowfall

Results from precipitation data associated with thunderstorms or snowfall on only the west side of the lower lake (west-side-only) were assumed to be measures of negative or suppressive lake-effects. Results derived from precipitation data associated with thunderstorms or snowfall occurring on only the cast side of the lake (east-side-only) were assumed to be a measure of positive or enhansive lake-effects.

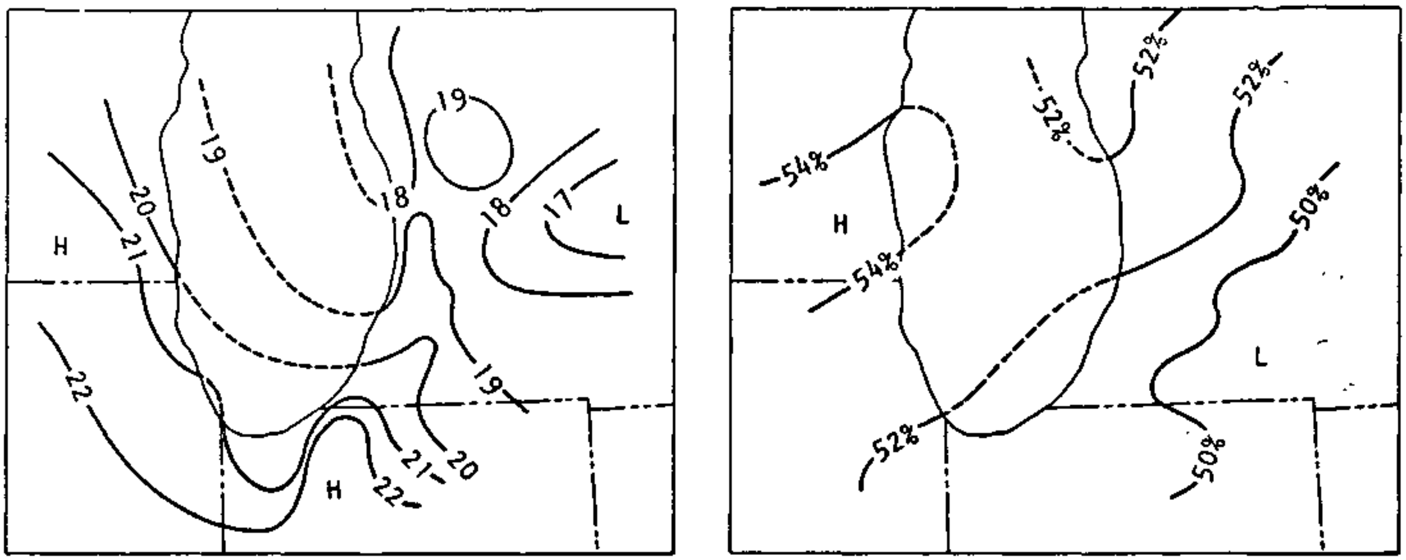
Comparison of the precipitation amounts of the east-side-only conditions with those of the west-side-only provides a measure of the net effect of the lake on precipitation production by thunderstorms and by snowfall.

Figure 23 presents maps showing the average annual precipitation from days with thunderstorms and days with measurable snowfall. Also shown are maps illustrating the percent of the total average annual precipitation derived from that on days with thunderstorms and that on days with snowfall. The expression of amounts as percentages provides a measure of the relevance of the precipitation from these two conditions.

The thunderstorm-day precipitation pattern (figure 23a) reveals a general decrease eastward across the lake and lower Michigan, although a ridge of higher amounts located inland and parallel to the eastern lake shore extends from northwestern Indiana into Michigan. Using long-term records at Chicago, Changnon[28] showed that the actual average annual thunderstorm precipitation at Chicago was 17.3 inches which is about 4 inches less than that based on thunderstorm-day values obtained from the 1951-1964 period (figure 23a). This illustrates that a portion of the precipitation on thunderstorm days was not produced by thunderstorms. The percentage pattern for thunderstorm-day precipitation in figure 23b is less variable than the pattern in figure 23a, since all station values are in the range from 49 to 55 percent of the average annual precipitation.

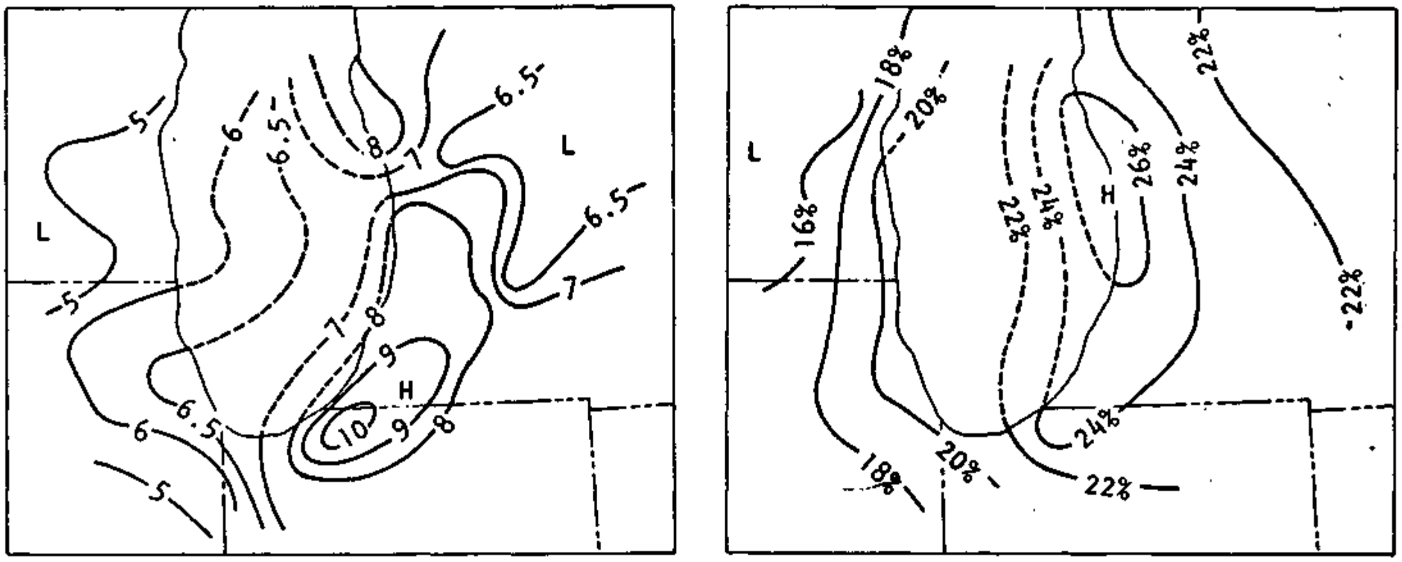
The average annual precipitation from days with measurable snowfall (figure 23c) is greatest along the eastern shore of the lake and is least in the Wisconsin-Illinois area. The percentage of the total average annual precipitation occurring on snowfall days (figure 23d) has a similar pattern, with 24 to 27 percent contributions along the eastern shore and less than 18 percent on the west.

Combination of the two percentage patterns on figure 23 shows that precipitation on snowfall days and thunderstorm days accounts for between 70 percent (western shore) and 80 percent (eastern shore) of the total average annual precipitation. These percentages reveal the significance of these two precipitation producing conditions, and more exact knowledge of their precipitation amounts is quite



a. Average annual precipitation, inches, on days with thunderstorms

b. Percent of total average annual precipitation occurring on days with thunderstorms



c. Average annual precipitation, inches, on days with measurable snowfall

d. Percent of total average annual precipitation occurring on days with measurable snowfall

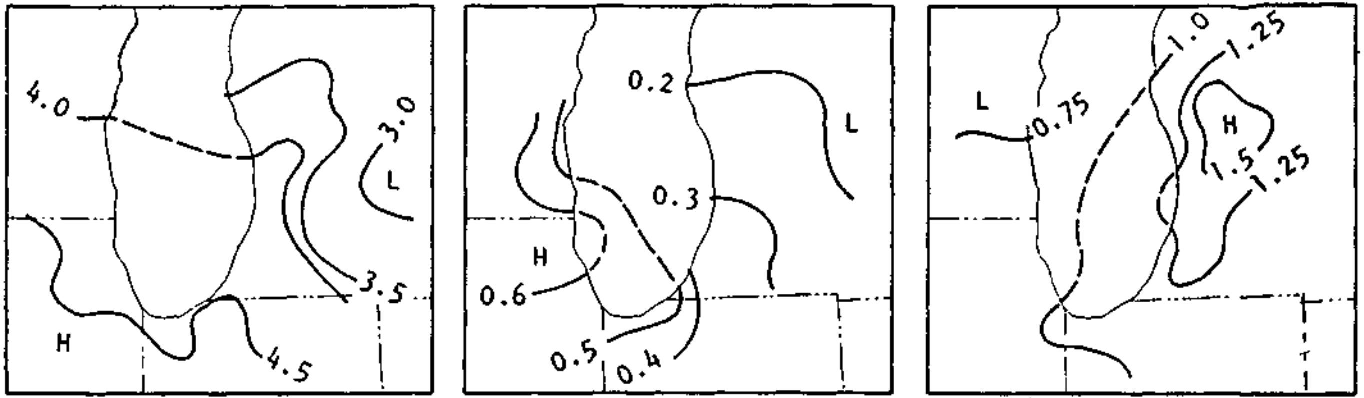
Figure 23. Average annual patterns of precipitation from thunderstorms and snowfall

meaningful since the previous two sections proved how strongly the lake affects these two conditions.

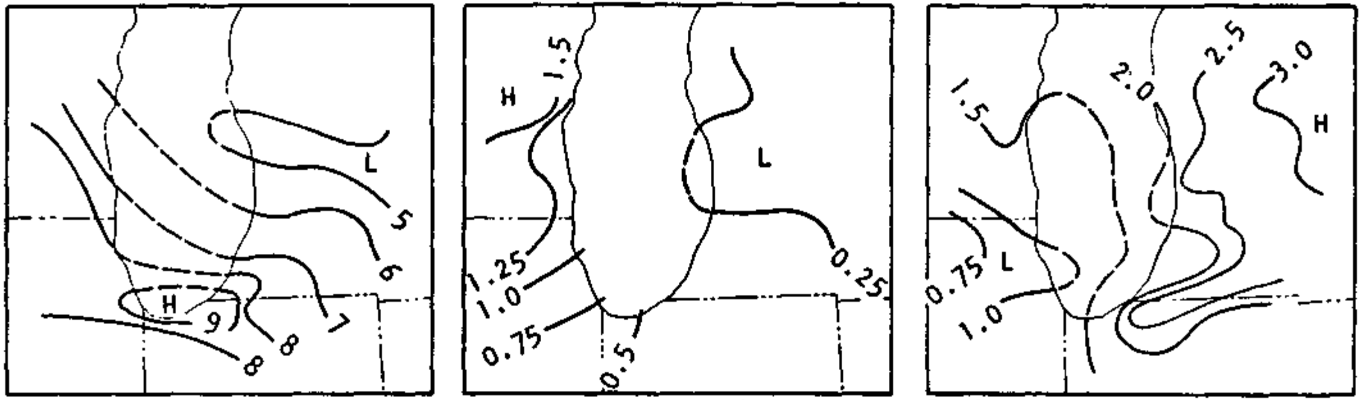
Data and Analytical Procedures

Data for the 1951-1964 period from 6 first-order stations (figure 22) were used to identify all days with thunderstorms and measurable snowfall. These data on thunderstorms, snowfall, and precipitation were obtained from monthly publications.[29-34]

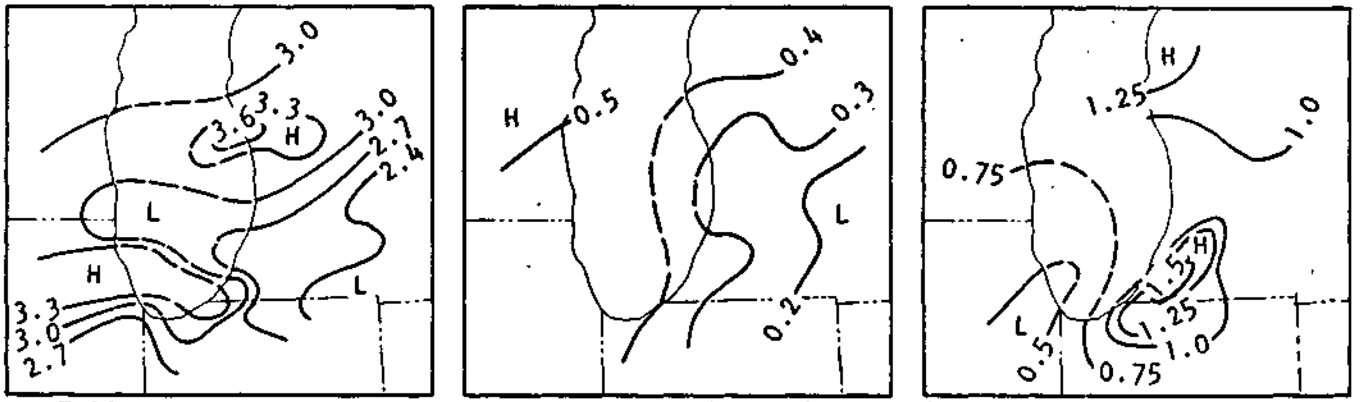
If one or more of the three first-order stations on the west side of the lake (Madison, Milwaukee, and Chicago) reported thunderstorms or measurable snowfall, a west-side-only occurrence of the event was recorded, and similarly if one or more of the three stations on the east side (Grand Rapids, Muskegon, and South Bend) reported an occurrence, an east-side-only occurrence was recorded. If the day had a west side and an east side record for either event, the day was classed appropriately as a thunderstorm day on both-sides or a snowfall day on both-sides. On a day with thunderstorms on the west-side-only all precipitation at stations on the west side was listed as thunderstorm precipitation and any on the east side was listed as non-thunderstorm precipitation. On a day with thunderstorms on both sides, all precipitation was listed as thunderstorm precipitation. In similar fashion precipitation was listed for



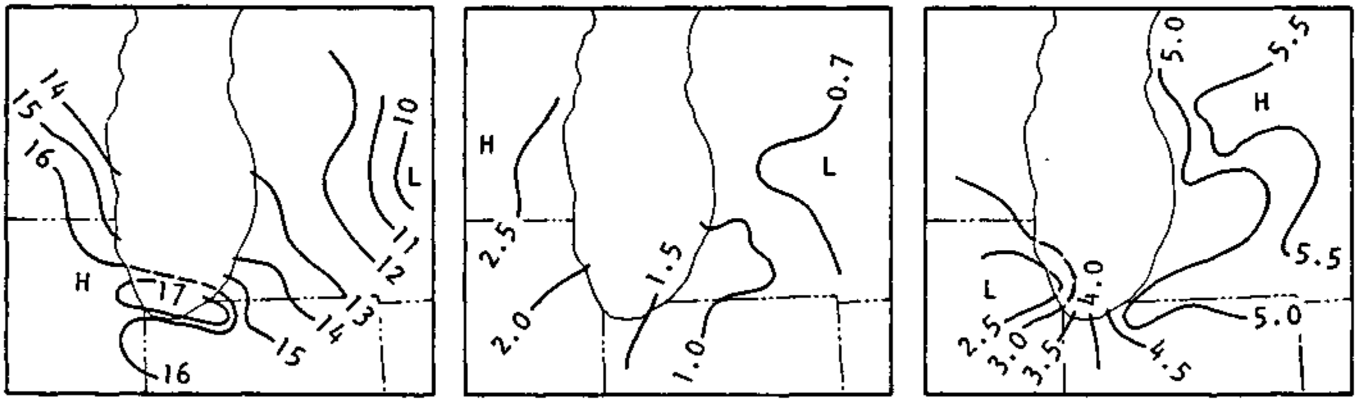
a. Spring, both-sides b. Spring, west-side-only c. Spring, east-side-only



d. Summer, both-sides e. Summer, west-side-only f. Summer, east-side-only



g. Fall, both-sides h. Fall, west-side-only i. Fall, east-side-only



j. Annual, both-sides k. Annual, west-side-only l. Annual, east-side-only

Figure 24. Patterns of average teatonal and annual thunderstorm precipitation (inches), based on thunderstorm-day **occurrences** on both-sides of lake, west-side-only, and east-side-only, 1951-1964

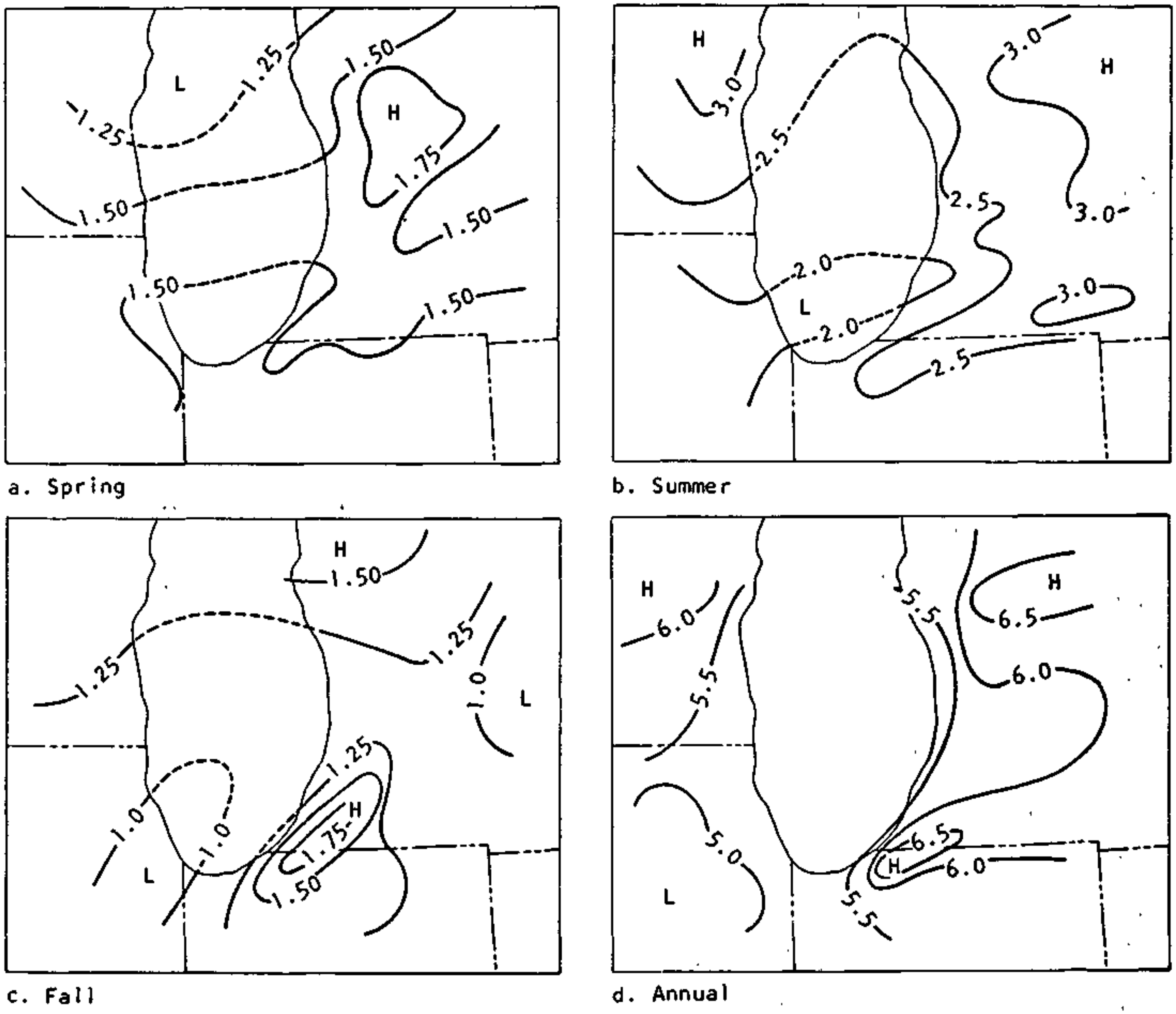
times greater than the average values on the west side during these conditions.

Estimates of the average point precipitation produced on days with thunderstorms were obtained by dividing the average seasonal precipitation values (as determined from the data for all 41 stations and for the three thunderstorm location classes) by the average number of thunderstorm days for each season and class. These point values (table 7) reveal that the average daily precipitation produced when thunderstorms occurred on both-sides was greater than that when thunderstorms occurred on only one side. This finding indicates, as expected, that convective systems producing storms on both-sides of the lake during one day were generally stronger than the convective systems when thunderstorms occurred on only one side. The notably lower point values when thunderstorms occurred on the west-side-only suggest that, on the average, these thunderstorms were beyond the mature stage, being in weaker convective systems than those associated with thunderstorms on both-sides or on the east-side-only.

Table 7. Average Daily Point Precipitation on Days with Thunderstorms around Lower Lake Michigan

Location	Precipitation, inches Spring	Summer	Fall	Annual
West-side-only	0.10	0.12	0.16	0.13
East-side-only	0.25	0.26	0.24	0.25
Both-sides	0.35	0.35	0.37	0.35

Combination of the average thunderstorm precipitation values derived for east-side-only conditions with those **for** west-side-only provides a value that measures most **of the**



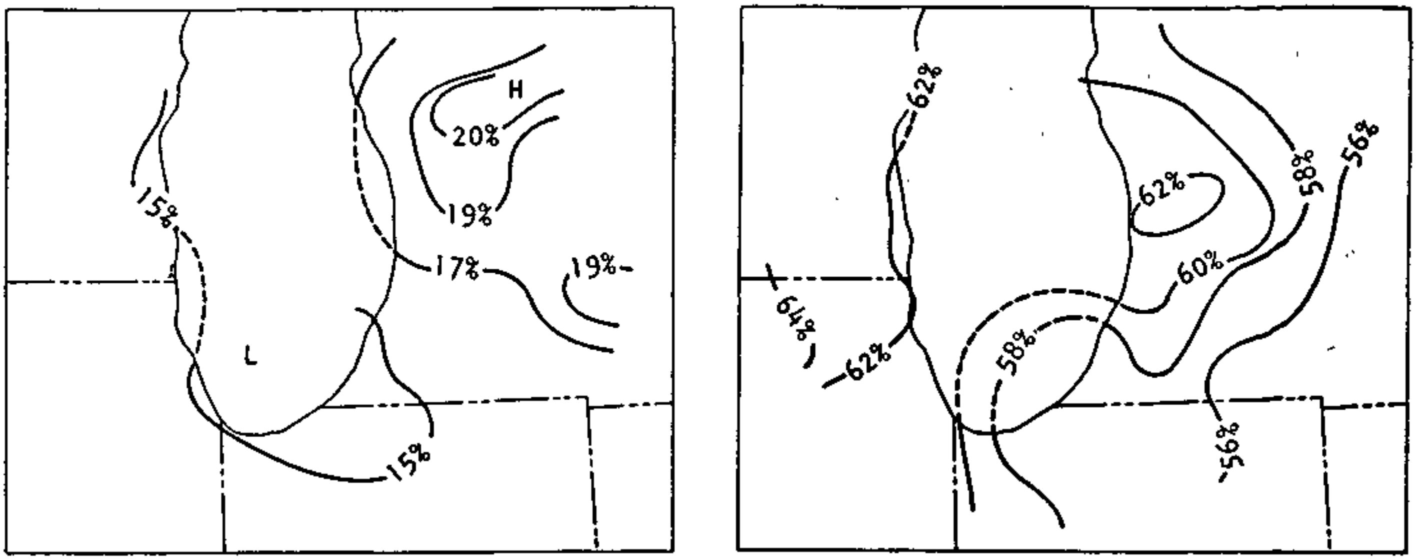
a. Spring

b. Summer

c. Fall

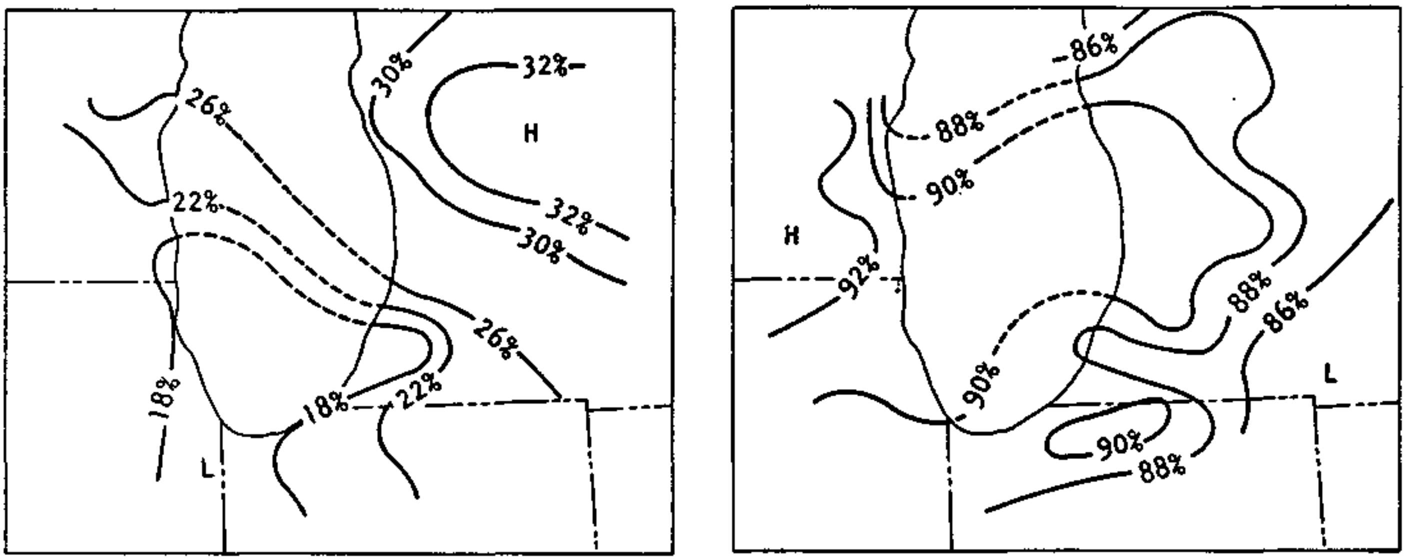
d. Annual

Figure 25. Average seasonal and annual precipitation amounts (inches), based on days with lake-effects on thunderstorm activity



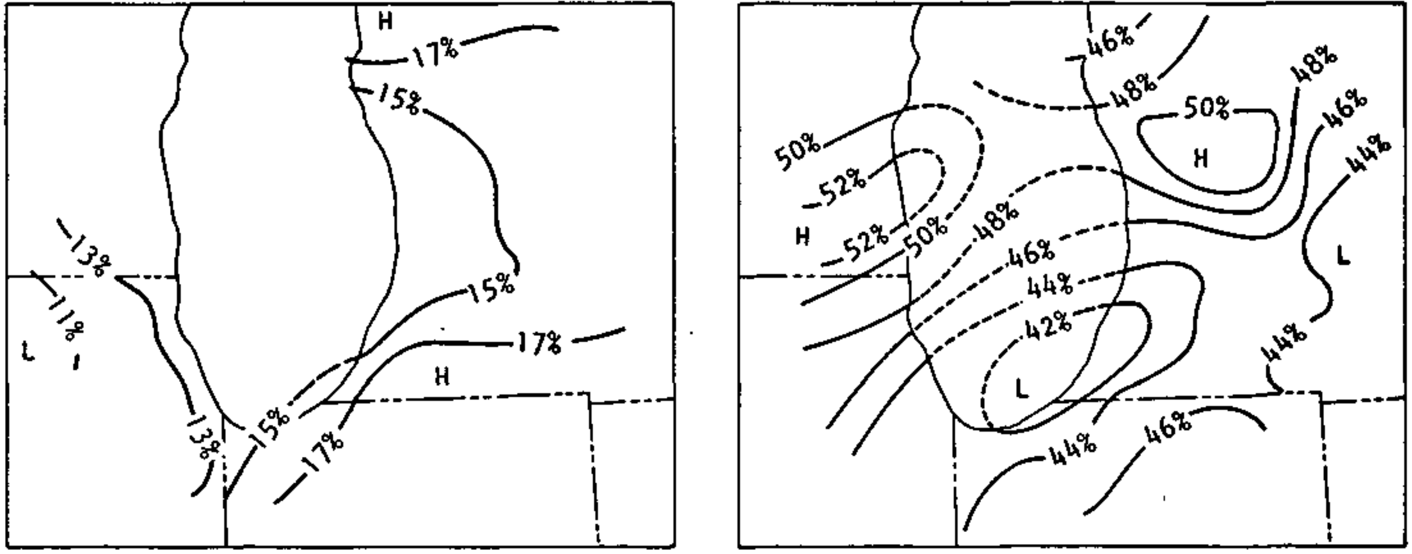
a. Spring, lake-effect thunderstorm days

b. Spring, all thunderstorm days



c. Summer, lake-effect thunderstorm days

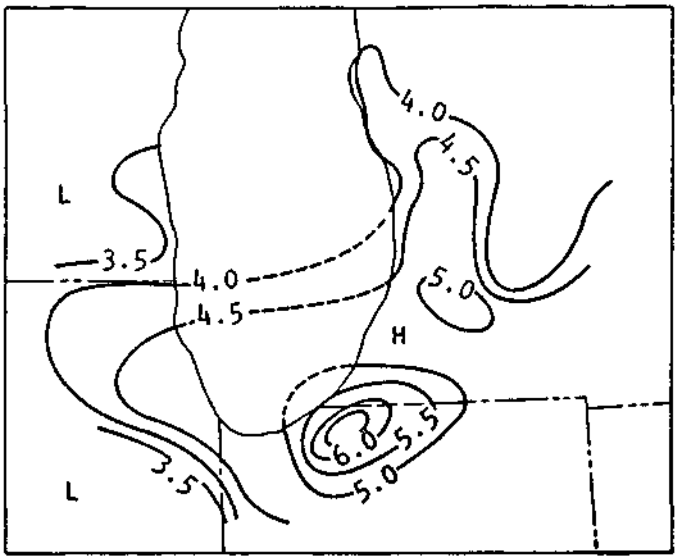
d. Summer, all thunderstorm days



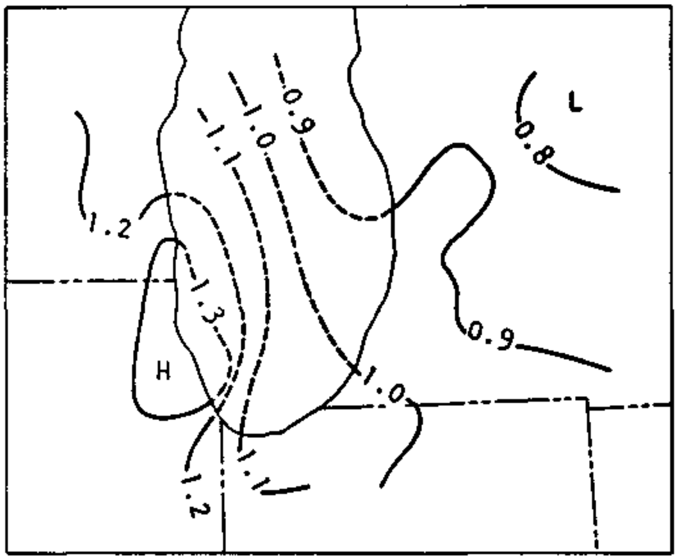
e. Fall, lake-effect thunderstorm days

f. Fall, all thunderstorm days

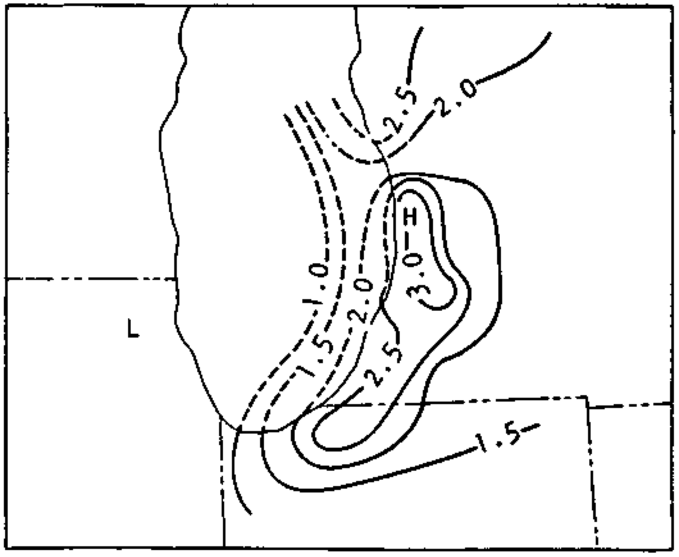
Figure 26. Percent of average seasonal precipitation produced by lake-effect thunderstorms (east-side-only and **west-side-only) and** by all thunderstorms (east-side-only and west-side-only and both-sides)



a. Measurable snowfall on both-sides



b. Measurable snowfall on west-side-only



c. Measurable snowfall on east-side-only

Figure *27.* Average annual precipitation **patterns based on different** snowfall conditions

This could result from generally heavier snows on the eastern shore and from the occurrence of snowfalls with higher moisture content inland from the eastern shore.

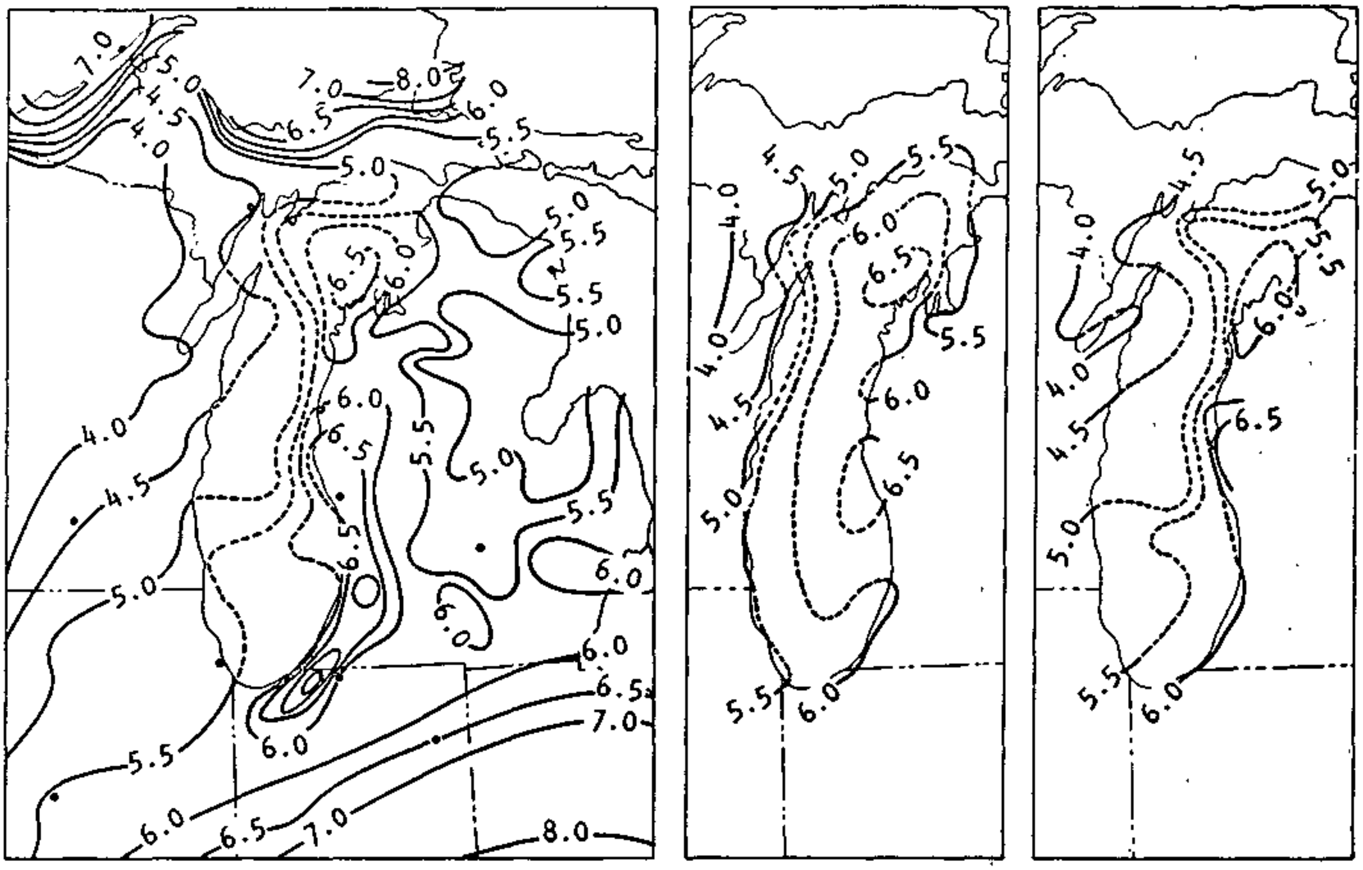
The average annual precipitation pattern based on days with measurable snowfall on the west-side-only appears in figure 27b. Although this condition is defined as one of negative lake-effects in regard to snowfall production on the eastern shore, it also represents some positive lake-effects on the production of snowfall on the southwestern shore. The 1.3-inch high along the southwestern shore suggests localized increases from occasional lake-effect snows that have been noted in this area.[17] The area average precipitation on the east side of the lake is 27 percent less than that on the west, whereas in the both-sides condition (figure 26a) the area average value for the eastern side was 20 percent greater than that for the western side.

The average annual precipitation pattern based on days when measurable snowfall occurred on the east-side-only is considered to be a measure of positive lake-effects (figure 27c). The area average amount on the east side is 2.2 inches as compared with 0.7 inch on the west-side, and the east-side value represents a 213 percent increase over the west-side average. The positive lake-effect pattern (figure 27c) has a definite ridge inland and parallel to the lake shore not unlike that depicted on figure 27a.

When positive lake-effects exist, the average point precipitation per snowfall day on the east side is only 0.06 inch (2.2 inches divided by 39 days, table 8). When negative lake-effect conditions exist (snow on west-side-only) the average west-side point amount is 0.09 inch (1.10 inches divided by 12 days).

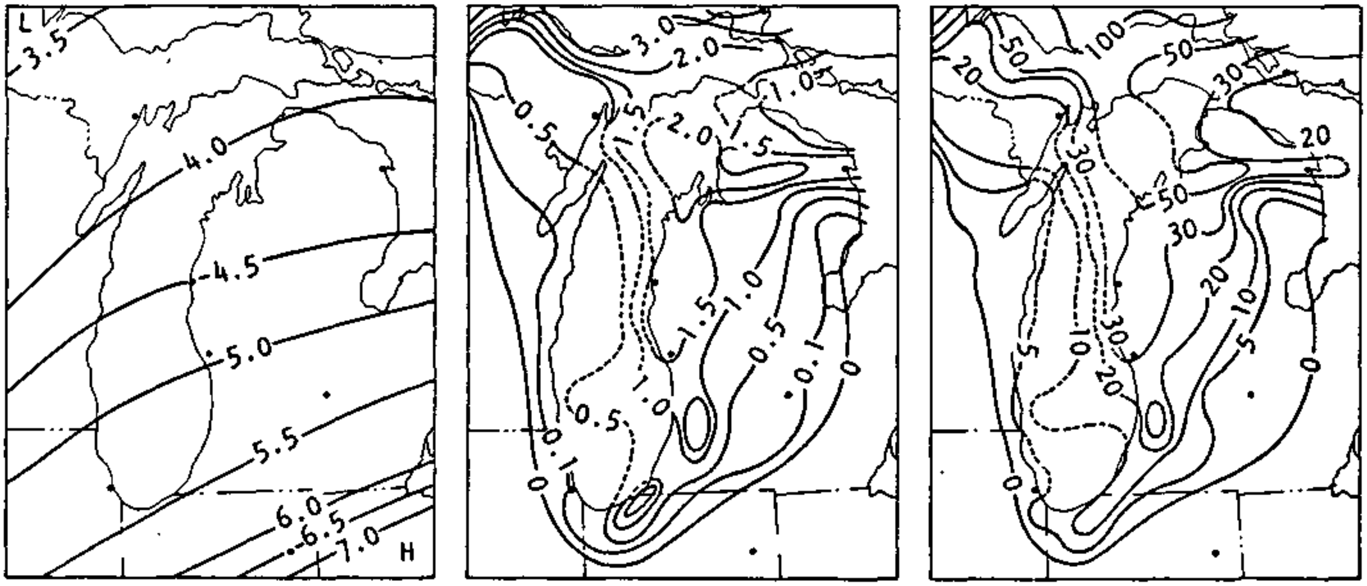
Since the precipitation data for both-sides (no-lake-effect) snowfall conditions did indicate some positive lake-effects (figure 27a), the measure of the total lake-effect on precipitation from snowfall is considered to be the sum of all three patterns shown on figure 27. Thus, the pattern in figure 23c integrates the total lake-effect along with all other snow-producing conditions.

Precipitation from snowfall increases eastward from less than 5 inches in Wisconsin and Illinois to more than 9 inches along the southeastern shore: The area average precipitation in the east, as based on the 25 easternmost stations, is 7.7 inches as compared with the area average of 5.8 inches for the west. The difference, 1.9 inches, is 33 percent of the west-side average indicating a 33 percent increase in precipitation due to lake-effects. The lake-effect increase in number of measurable snowfall days on the east was 60 percent, that for heavy snowfall days was 70 percent (table 4), and that for total snowfall was 55 percent. The precipitation increase (33 percent) is lower than that for total snowfall (55 percent) because east-side-only snowfalls of 2 inches or more are occasionally very dry and produce little or no measurable precipitation.[16]



a. Most-likely winter pattern b. Absolute-maximum c. Absolute-minimum

Figure 31. Patterns of average winter precipitation, inches

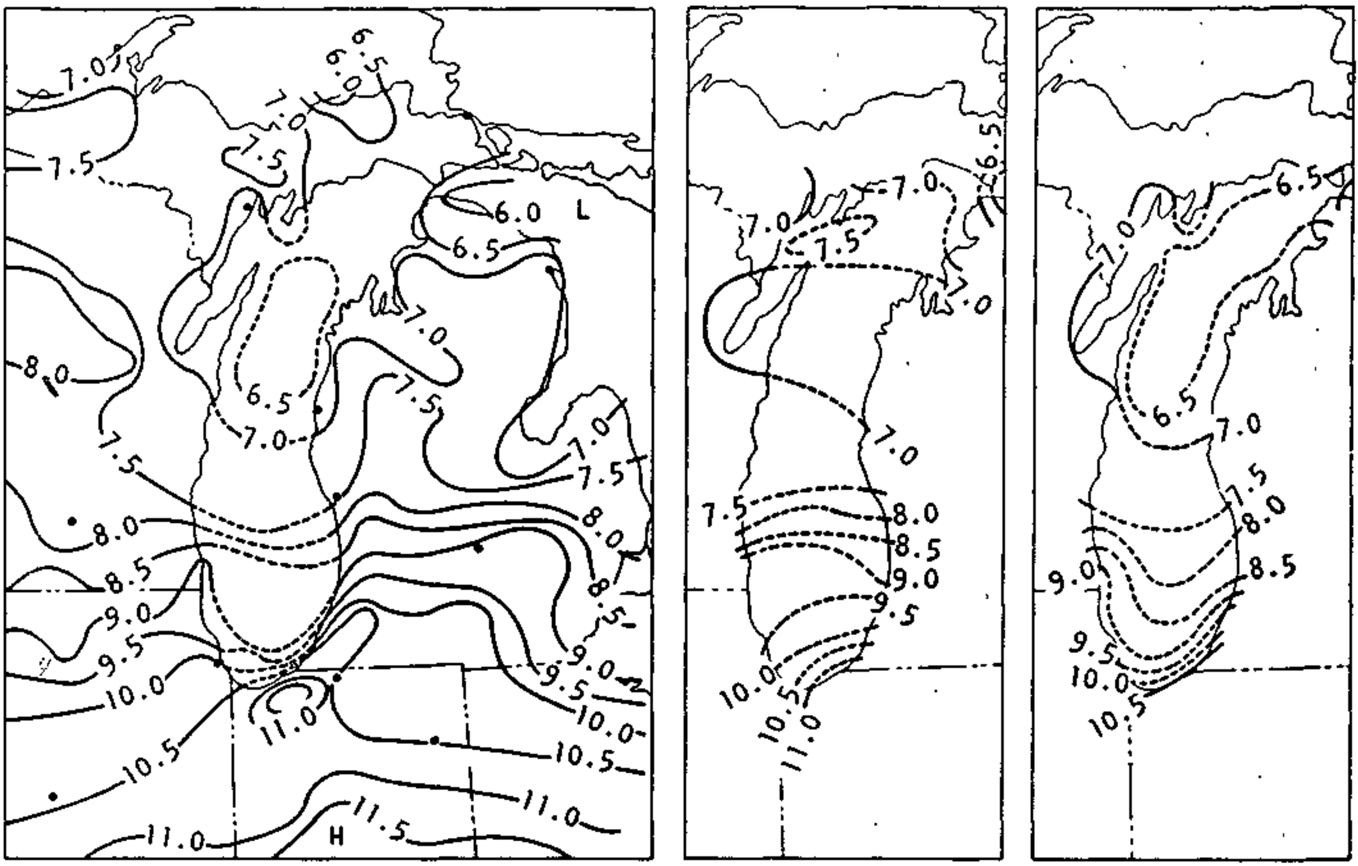


a. No-lake-effect winter precipitation pattern, inches

b. Increases, inches

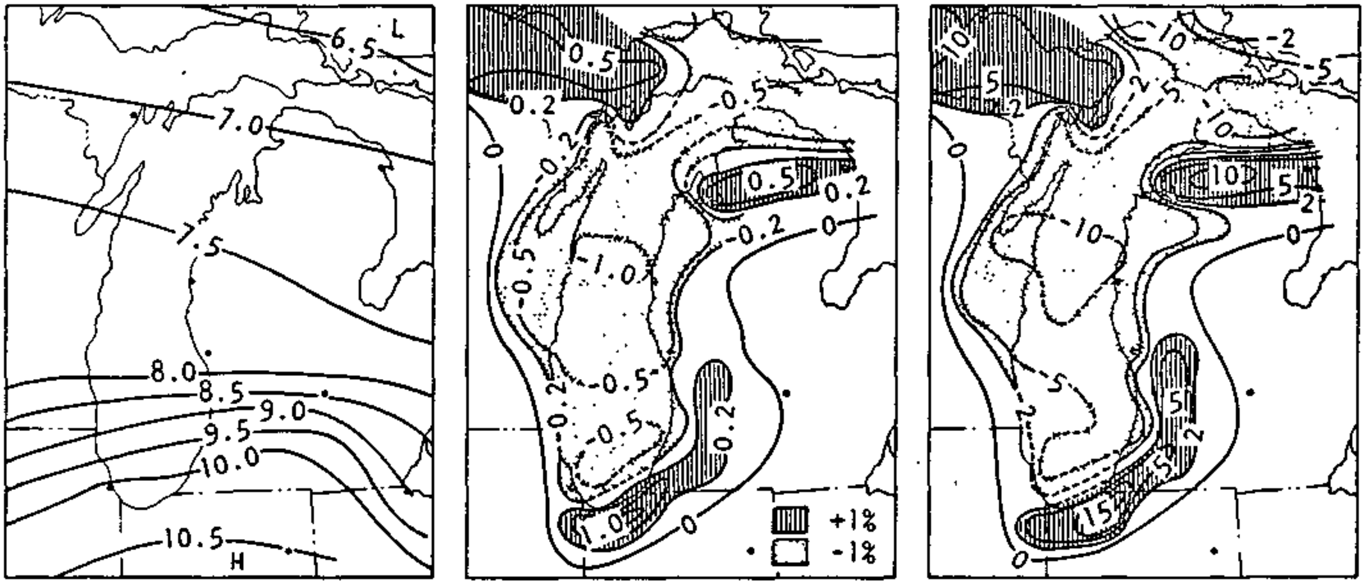
c. Increases as a percent of no-lake-effect precipitation

Figure 32. Changes in average winter precipitation related to lake-effects



a. Most-likely spring pattern b. Absolute-maximum c. Absolute-minimum

Figure 33. Patterns of average spring precipitation, inches

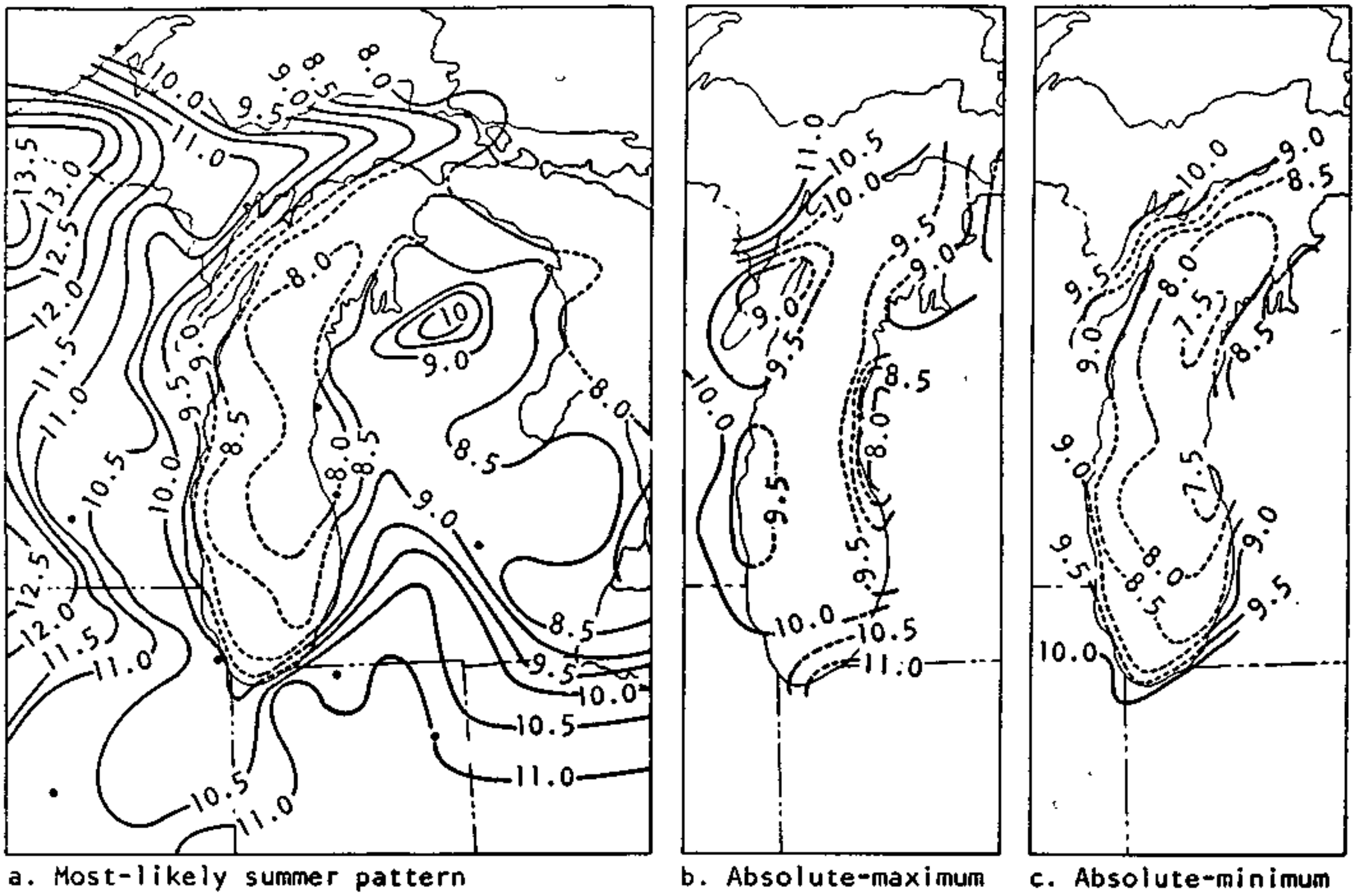


a. No-lake-effect spring precipitation pattern, inches

b. Changes, inches

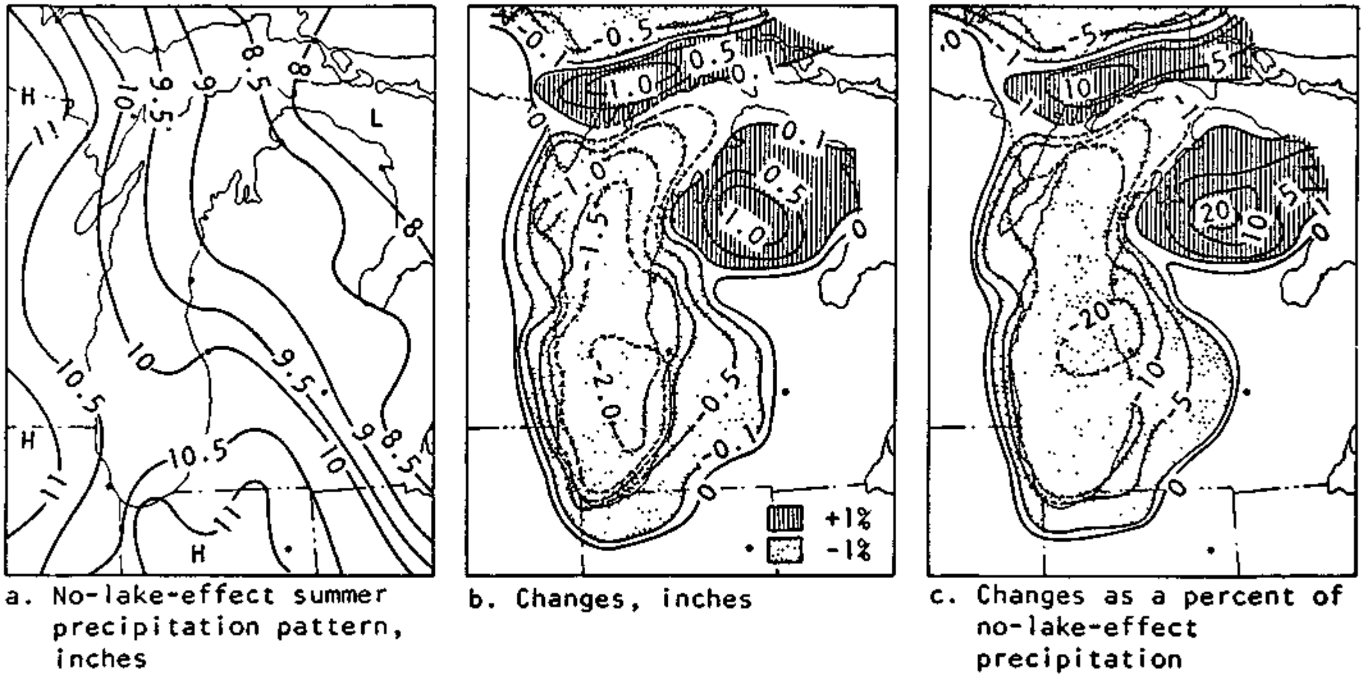
c. Changes as a percent of no-lake-effect precipitation

Figure 34. Changes in average spring precipitation related to lake-effects



a. Most-likely summer pattern b. Absolute-maximum c. Absolute-minimum

Figure 35. Patterns of average summer precipitation, inches

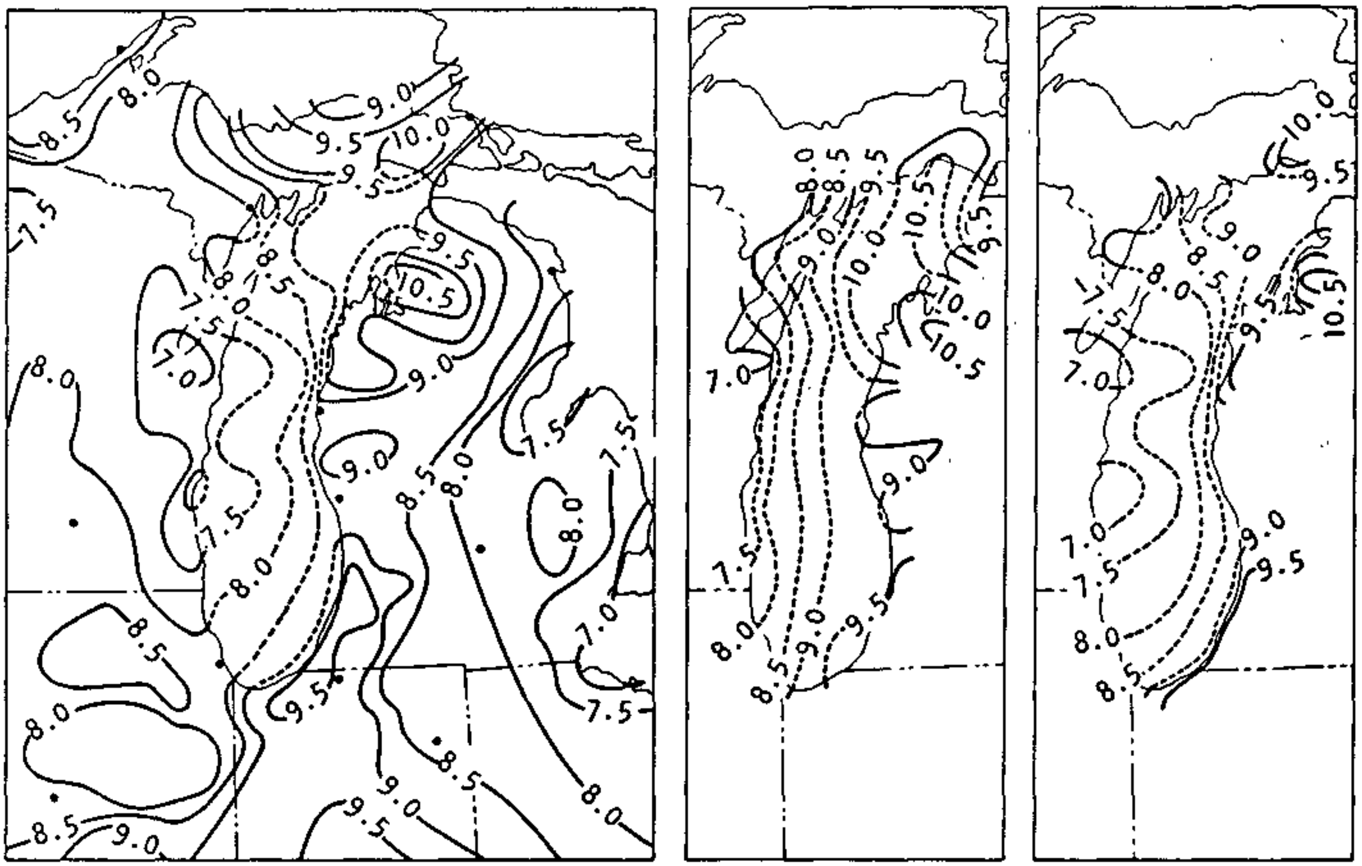


a. No-lake-effect summer precipitation pattern, inches

b. Changes, inches

c. Changes as a percent of no-lake-effect precipitation

Figure 36. Changes in average summer precipitation related to lake-effects

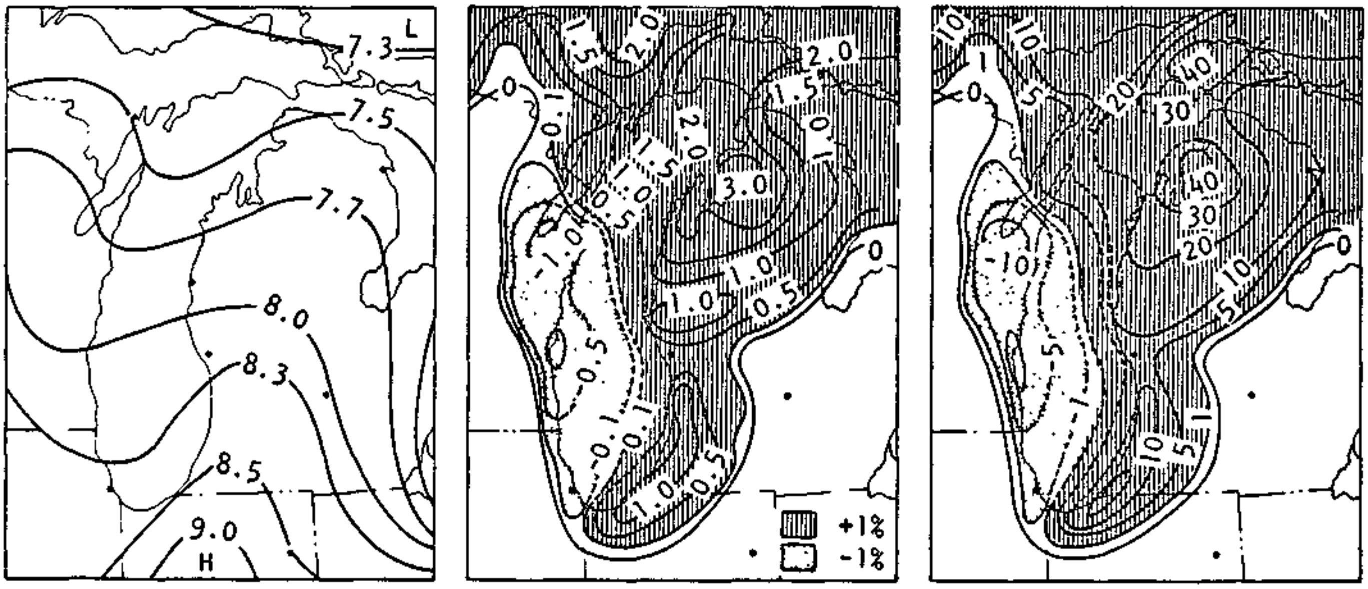


a. Most-likely fall pattern

b. Absolute-maximum

c. Absolute-minimum

Figure 37. Patterns of average fall precipitation, inches

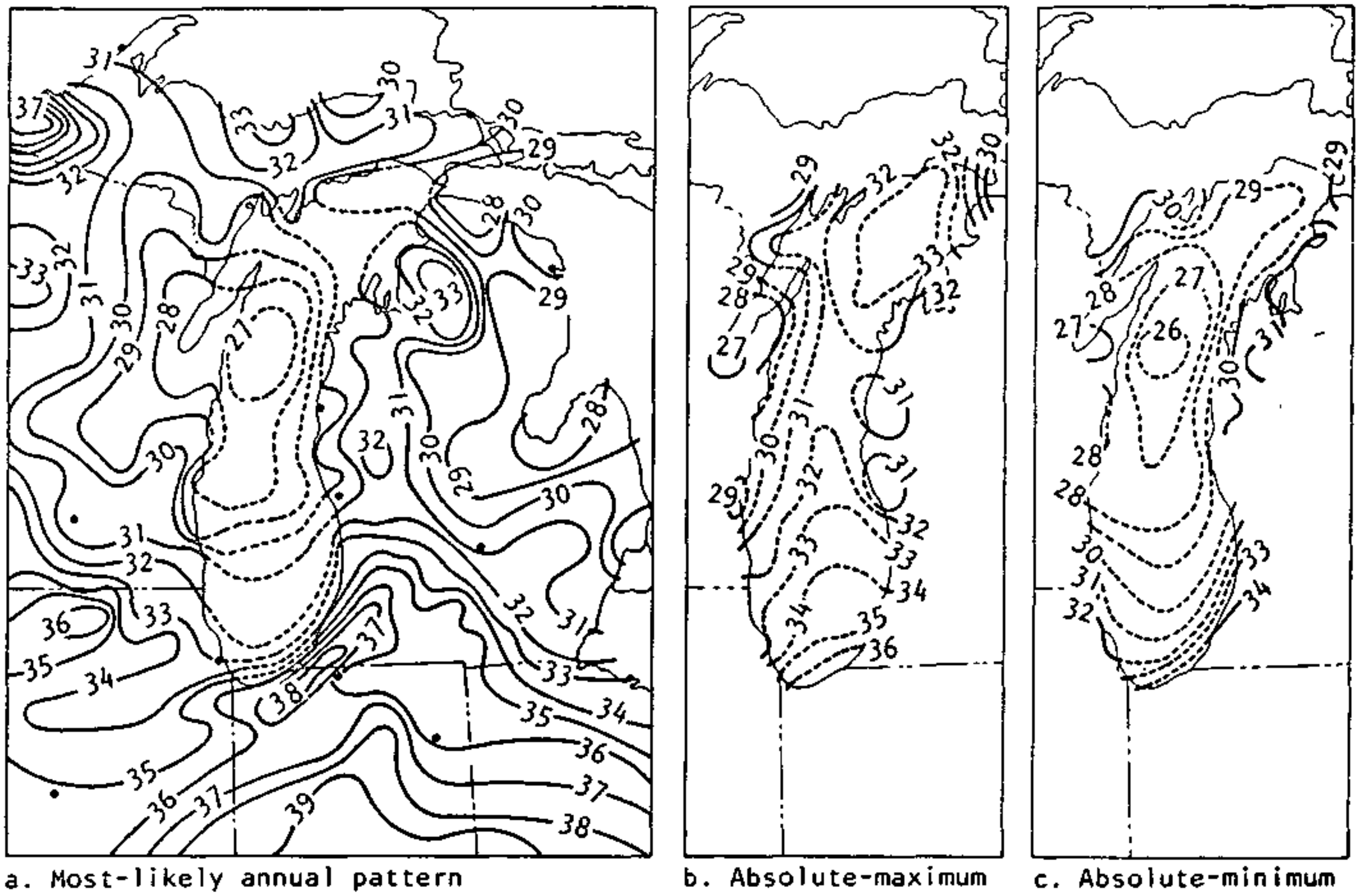


a. No-lake-effect fall precipitation pattern, inches

b. Changes, inches

c. Changes as a percent of no-lake-effect precipitation

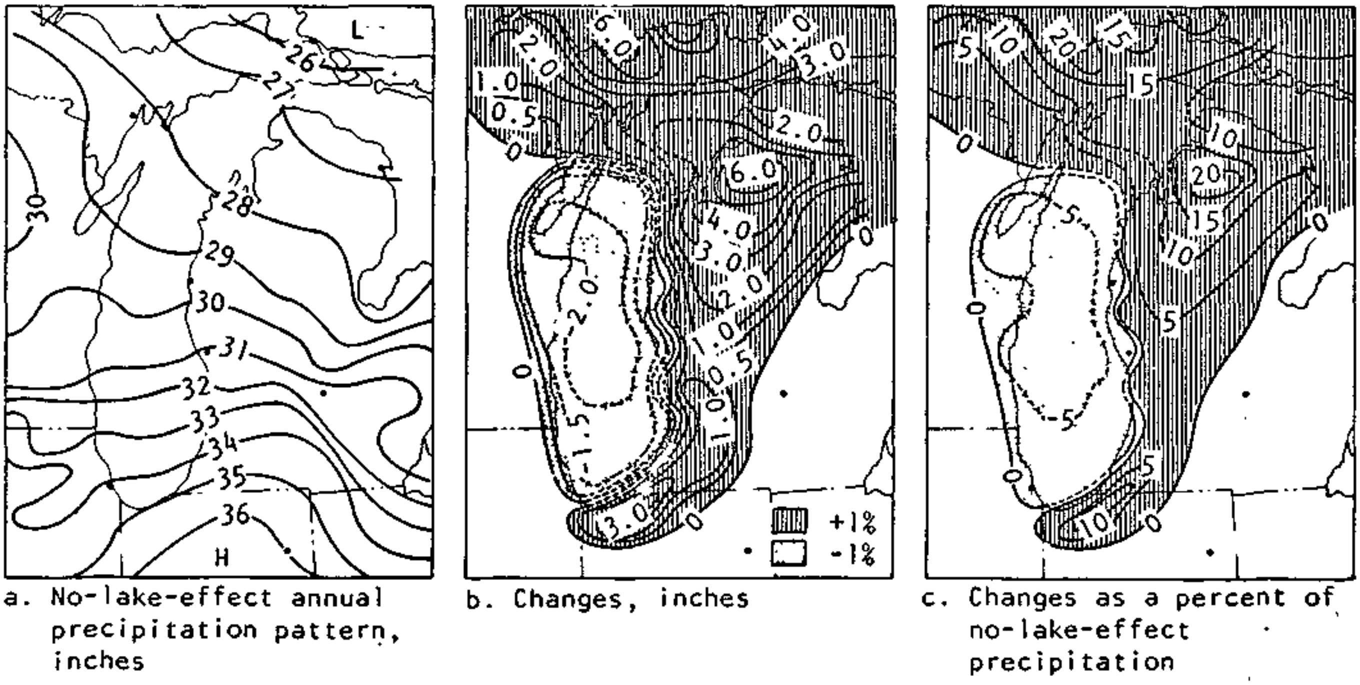
Figure 38. Changes in average fall precipitation related to lake-effects


a. Most-likely annual pattern

b. Absolute-maximum

c. Absolute-minimum

Figure 39. Patterns of average annual precipitation, inches


a. No-lake-effect annual precipitation pattern, inches

b. Changes, inches

c. Changes as a percent of no-lake-effect precipitation

Figure 40. Changes in average annual precipitation related to lake-effects

comes 8 percent lower than the land value, but is 3 percent higher under absolute-maximum lake-effects.

Differences between the three lake values for each season and the year arc shown in table 15. The differences between the most-likely values and the absolute-minimum values are relatively small, 0.22 inch or less in all seasons. The most-likely seasonal and annual values (table 12) are only 2 to 4 percent higher than those based on the absolute-minimum increases, which arc considered to be the lowest possible lake values. These small differences indicate that if the most-likely lake values are in error by being too high, the true lake values could not be much lower and the errors for overestimating are quite small.

Differences between the most-likely lake values and the absolute-maximum values (table 15) are relatively low in the winter, spring, and fall, but the summer difference is large. The most-likely value is 5 percent lower than the absolute-maximum value in spring, 7 percent lower in fall, 9 percent lower in winter, and 12 percent lower in summer. These differences measure the possible error if the most-likely values are incorrect because of underestimation. Although the most-likely average annual value was 2 percent greater than the absolute-minimum value, it is 9 percent lower than the absolute-maximum value.

The average annual precipitation values also were expressed in water quantities to illustrate the water yield of lake precipitation. As shown in table 16, the average annual volume of water derived from the most-likely precipitation pattern is 11,490.9 billion gallons. The absolute-maximum average annual lake precipitation would produce a volume of 12,565.2 billion gallons. If the average annual lake precipitation is based on the absolute-minimum pattern, the error, or difference in water yield between it and the most-likely value, would be 1191 cubic feet per second (cfs). If the average lake precipitation were at the absolute-maximum level, the water yield would be 4554 cfs more than from the most-likely value.

Table 16. Quantities of Water Produced by Precipitation on Lake Michigan Based on Average Annual Precipitation Values

Lake precipitation patterns	Water quantity (bil gal)	Water yield (cfs)
Absolute-maximum	12,565.2	53,267
Most-likely	11,490.9	48,713
Absolute-minimum	11,210.6	47,522

Comparison of Results with Other Estimates

The results obtained for the most-likely average annual lake precipitation and for the entire basin were compared with estimates of lake, land, and total basin precipitation that have been derived in earlier studies. The values from these studies and the current one are shown in table 17.

Many investigators have assumed that the precipitation measured over the land portion of the Lake Michigan Basin was representative of the average precipitation over the lake. Day[2] in 1926 employed 10 years of precipitation data around Lake Michigan and concluded that the lake precipitation was not measurably less than the land values. He noted that values at two island raingage stations were lower than the land values, but he attributed these differences to exposure differences. Others in recent years have made the same statement.[29, 43, 44, 46] Day supported his conclusion of no lake-land difference by claiming that the influence of Lake Michigan on thunderstorms and snowfall was quite small, which has been shown to be an incorrect assessment of conditions.[1]'"' Day's estimated average annual precipitation of 32.57 inches for the basin was based on data from 23 land stations with records covering the 1875-1924 period. His value is the second highest shown in table 17.

Table 17. Comparison of Average Annual Lake, Land, and Basin Precipitation Estimates for Lake Michigan

Source and year issued	Precipitation, inches Lake	Land	Total basin	Difference, lake-land. as percent of land average
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 (1966)	31.12	31.12	31.12	0
Changnon (1968)	29 56	31.37	30.76	—6

** based on Michigan-Huron combined*

Horton[3] in 1927 was the first to conclude that the precipitation over Lake Michigan was less than that on nearby land areas. He attributed the lower amounts to diminished thunderstorm frequencies and intensities over the lake. Horton believed that the lake precipitation should be considered to be as low as the lowest value from any lake island station, and that exposure differences did not account for lake-land precipitation differences since most shore raingages had exposures equivalent to those at island stations. To this end, he compared 20 years of precipitation data taken at Beaver Island with that at five land stations, and he calculated that lake precipitation was 94 percent of the land values in the warm months and 93 percent in winter. After adjusting for snowfall-catch deficiencies, he used these ratios in conjunction with data at stations surrounding the lake to calculate a lake average of 31.32 inches. His land value of 34.48 inches was based on records of 20 stations for the 1871-1924 period. These values were weighted 2:1 (land:lake) to calculate the total basin value of 33.43 inches shown in table 17.

Brunk[47] stated that there was little difference between the annual amounts of precipitation over the water and land area of the Lake Michigan-Huron Basin. His estimated average annual precipitation value for the basin, and thus for the land and lake areas, is 32.03 inches,[48] based on data for the 1875-1961 period. The Great Lakes Commis-