Quantitative Estimates of the Effect of Lake Michigan on Snowfall

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ABSTRACT

A climatological study of snowfall in the snowbelts of Michigan shows that decade-average amounts varied by a factor of 2 during the period from 1909/10 through 1980/81.

The effect of Lake Michigan on total winter snowfall along its shores has been estimated. A long-term average effect of ~ +10% is found for the Wisconsin shore south of Sheboygan, and an average of ~ +60% for the Michigan shore, south of Hart, with a minimum effect in the 1930s and a maximum in the 1960s.

1. Introduction

The Great Lakes of North America exert large and significant effects on weather in their vicinity. Among the more obvious of these effects are the lake-induced snow storms which occur when cold, arctic air masses move across the relatively warm lakes. These storms, loosely termed "lake-effect snow storms," are responsible for the increased snowfall observed along the downwind shores of all of the Great Lakes. Thomas (1964) has provided an excellent summary of the early literature on studies of snowfall around the Great Lakes.

The University of Chicago Cloud Physics Laboratory is currently involved in a study of lake-effect snow storms over Lake Michigan, using aircraft, Doppler radars, and surface and upper-air data. In order to view our observations from the past few winters in the context of the longer-term climatological record, we have investigated snowfall patterns around Lake Michigan and along the south shore of Lake Superior for the winters of 1909/10 through 1980/81. The basic data for this study are published snowfall amounts recorded by the climatological data network maintained by the National Oceanic and Atmospheric Administration and its predecessor organizations. Some of the results from our study are reported in this paper.

As is readily apparent to those who have attempted it, accurate measurements of depths of newly fallen snow are subject to considerable error. Avoidance of areas of drifting and/or wind scour, and separating new snow from previously fallen snow are difficult and depend solely upon the judgment of the observer. Melting of snow falling on surfaces warmer than 0°C will result in undermeasurements. This can be serious during fall and spring months.

In this analysis, snowfall measurements are averaged over many stations and over long blocks of time, which should reduce the effects of observational errors.

2. Data and data reduction

This paper is based upon monthly snowfall amounts reported by stations in Michigan and parts of Wisconsin, Illinois and Indiana. Within this study area, snow has been observed in every month of the year. However, most of the seasonal snow occurs in the period of November through March. More than trace amounts are infrequent from June through August in the northern regions of this study, and from June through October in the southern regions.

Compiled monthly snowfall data were obtained from *Monthly Weather Review* (1909–1913), U.S. Department of Agriculture *Climatological Data* (1914–1940), and U.S. Department of Commerce *Climatological Data* (1940–1981).

The basic analysis unit for this study is the monthly snowfall amount at many individual stations. An effort was made to incorporate all late reports and corrections. Trace amounts are considered to be zero amounts. In cases where monthly totals were not published because of "missing" records, we have used estimates obtained by interpolating from surrounding stations that did report. In these interpolations, subjective allowance was made for local snowfall patterns (asymmetries) as revealed by analyses of long-term snowfall patterns. The number of "missing" records varied with time, and are much more numerous since 1950, both in absolute numbers and as percentages of all possible reports. No account has been made for movement of stations and changing of observers during the period covered by this study.

After preliminary results of this study were in hand and it was clear that there had been marked changes in the amount of snow in the snowbelt of Lower Michigan, a decision was made to prepare a series of snowfall analyses based upon 10-year average data. This raised the problem of how to handle data from stations with records which either started or stopped within a given

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TABLE 1. Decade-average snowfall analyses; the number of stations, within each decade, requiring snowfall estimates for various listed number of months; and the total number of station-months for which estimates were made.

Number of months estimated	Decade						
	1910s	1920s	1930s	1940s	1950s	1960s	1970s
0	76	97	139	89	73	125	103
1–5	54	59	51	99	104	141	126
6–10	23	20	18	25	53	53	54
11–15	8	6	9	5	43	16	24
16–20	10	3	5	2	19	10	17
21–25	4	0	3	5	13	10	8
26–30	1	0	0	4	10	2	8
Total number of stations used	176	185	225	229	315	357	340
Total number of station-months estimated	698	427	528	745	2171	1402	1743

10-year period. Data sequences that were very short and/or very irregular were simply ignored. Records from stations with more than 30 "missing" months in any decade were disregarded in analyses. Station-months for which we estimated snowfall totals are shown in Table 1. This table shows that between 22 and 61% of the stations had perfect records (no missing months), and that about 74% had five or fewer months of missing records in any given 10-year period.

3. Long-term snowfall patterns

The long-term patterns of seasonal snowfall are shown in two different ways. Figures 1 through 7 present snowfall patterns within each of the seven decades covered by this study. Locations of stations whose records were used in these analyses are indicated. In these figures the placement of isolines over Lake Michigan is uncertain, as indicated by the long dashes. To the

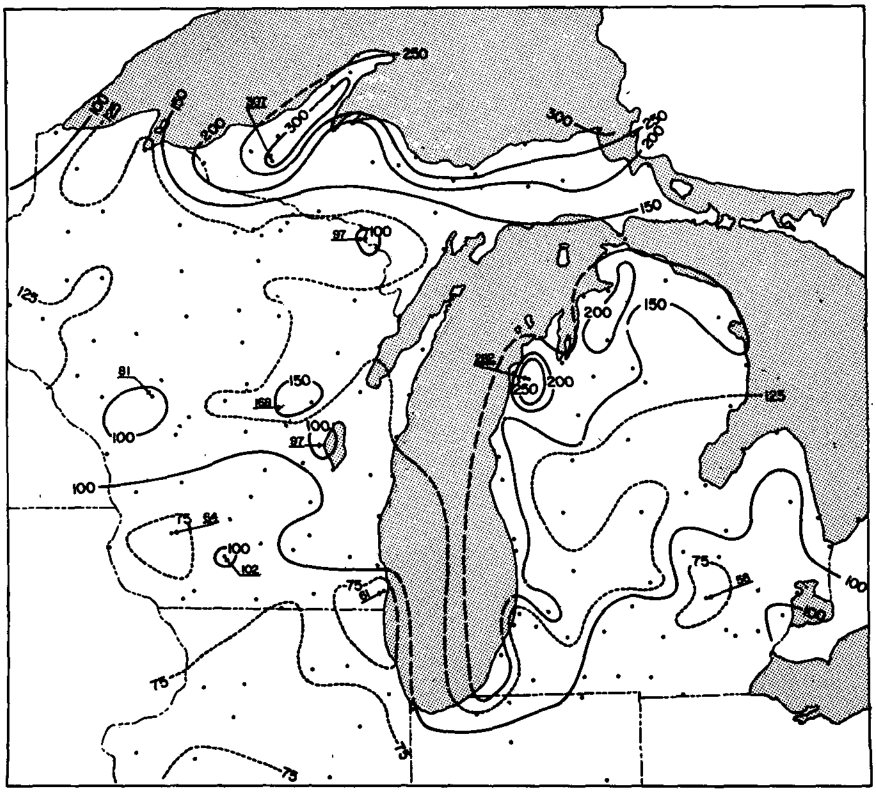

FIG. 1. Average winter total-snowfall for the 1910s (winters of 1910/11 through 1919/20).

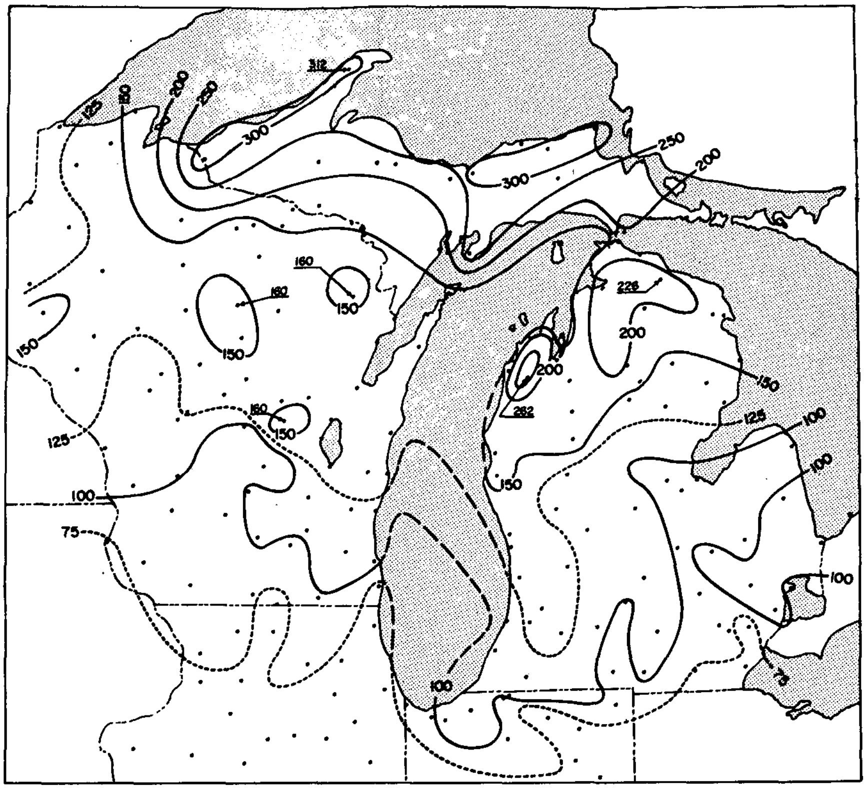

FIG. 2. As in Fig. 1 but for the 1920s (winters of 1920/21 through 1929/30).

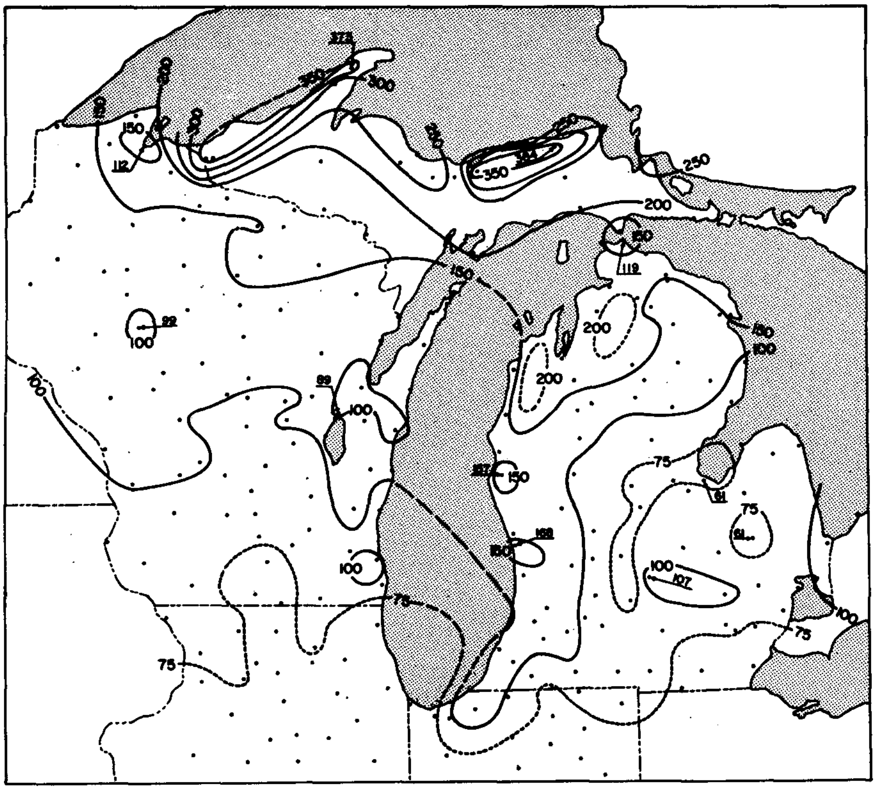

FIG. 3. As in Fig. 1 but for the 1930s (winters of 1930/31 through 1939/40).

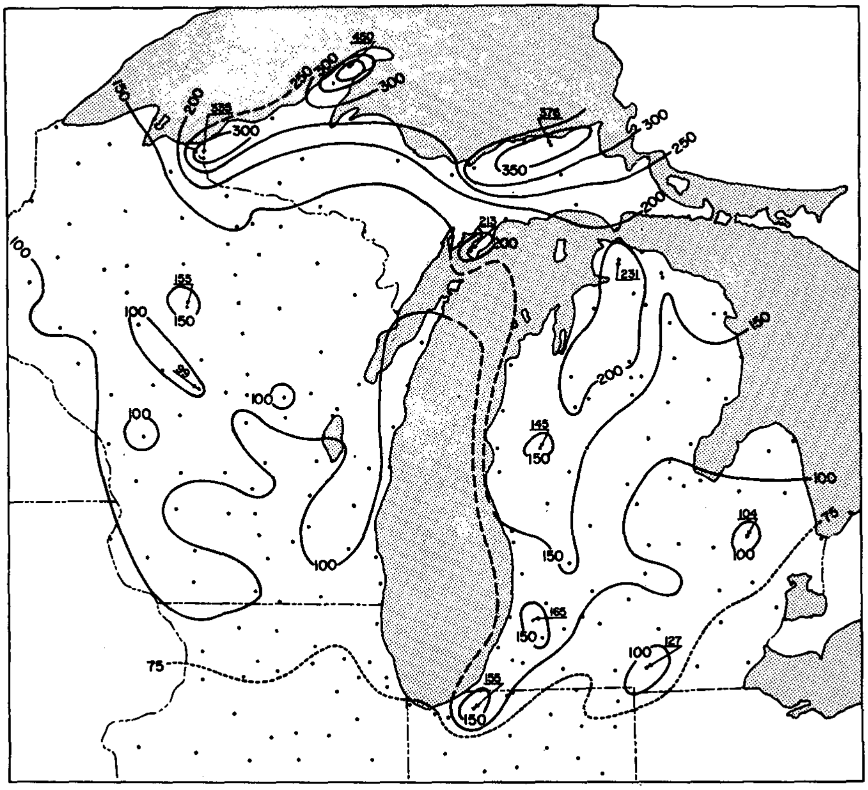

FIG. 4. As in Fig. 1 but for the 1940s (winters of 1940/41 through 1949/50).

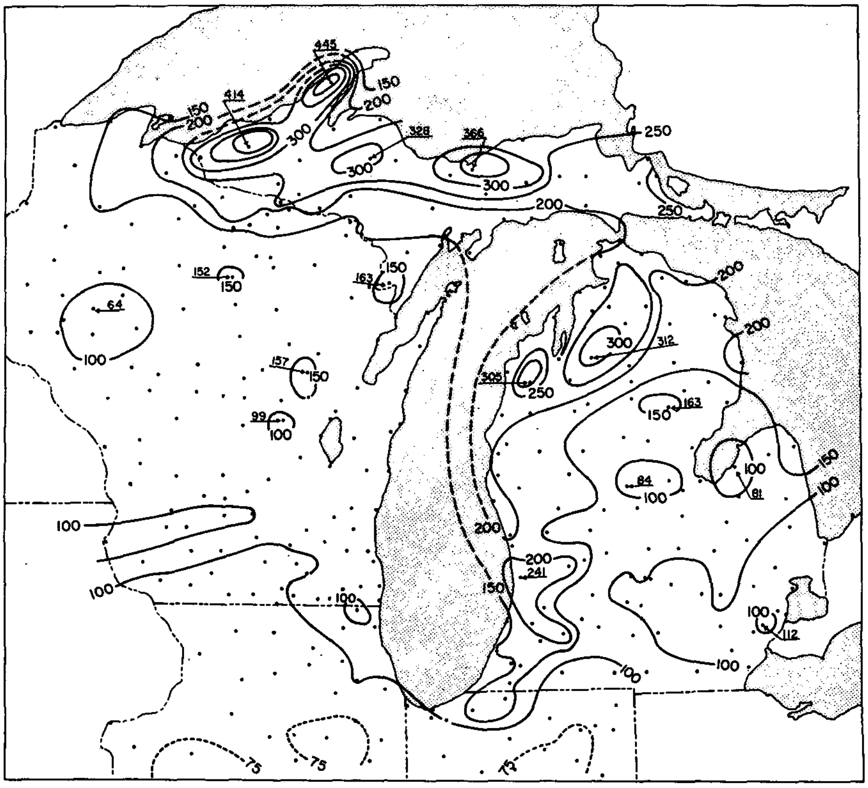

FIG. 5. As in Fig. 1 but for the 1950s (winters of 1950/51 through 1959/60).

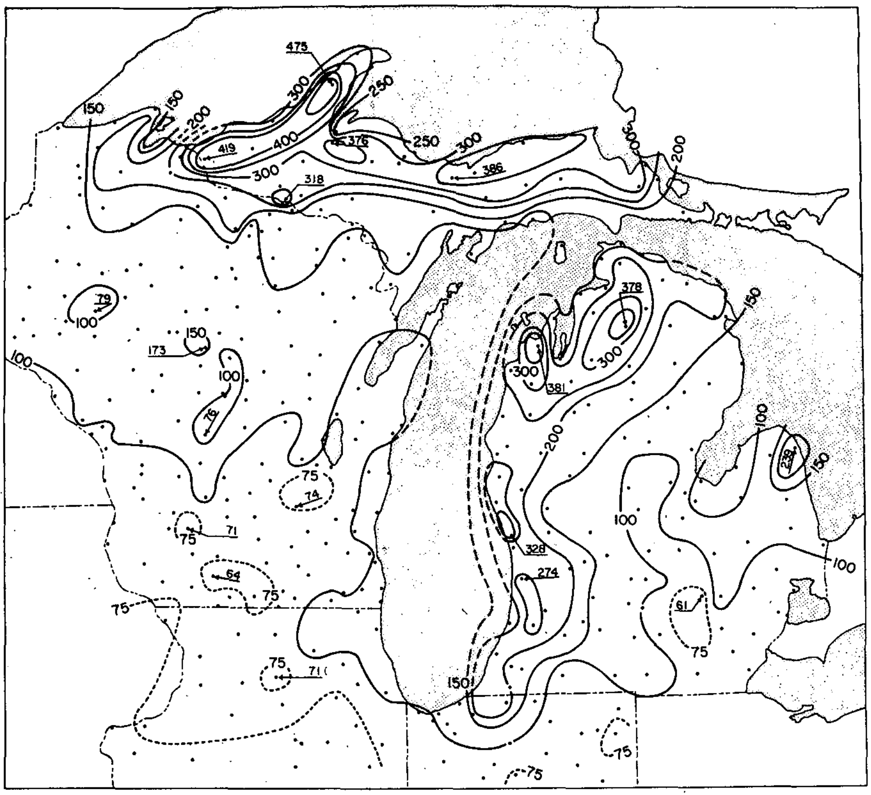

FIG. 6. As in Fig. 1 but for the 1960s (winters of 1960/61 through 1969/70).

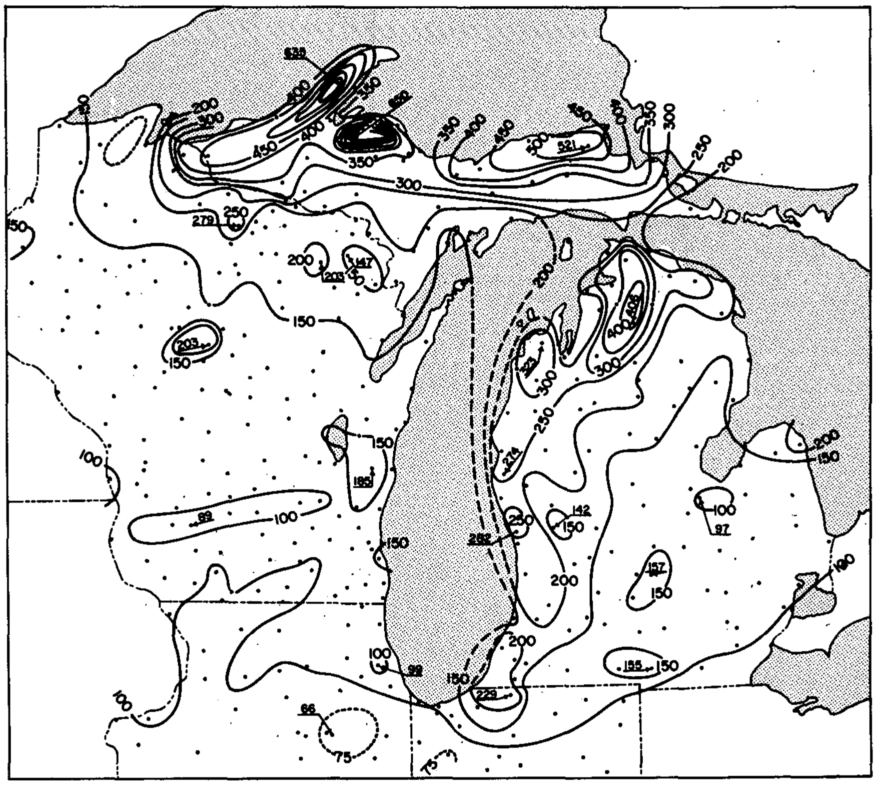

FIG. 7. As in Fig. 1 but for the 1970s (winters of 1970/71 through 1979/80).

extent that shore-station data allow, we have placed the over-lake isolines rather close to the eastern shore. This is in keeping with the conclusions of Changnon (1968) who reported ". . . 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." One of the objectives of our current research is to reexamine this question, making use of systematic aircraft measurements over the lake and nearby shore areas.

Figures 1 through 7 show several features in common; also there are several marked differences. The snowbelt regions along the south shore of Lake Superior and the east shore of Lake Michigan are clearly evident in all. The snowbelt south of Lake Superior maximizes in the Keweenaw Peninsula, where hills produce upslope lifting to augment effects of lake-induced convection. Secondary maxima also are evident along the southeast shore of Lake Superior. The snowbelt of Lower Michigan appears as a narrow band of enhanced snowfall amounts extending from the south end of Lake Michigan northward along the east shore to a point north of Muskegon where it widens and intensifies. In northern Lower Michigan higher terrain (450–500 m above lake level) provides upslope lifting to augment the effects of lake-induced convection. In addition, cold air traversing northern Lower Michigan often has been modified by passage over Lake Superior as well as over Lake Michigan.

There are several separate maxima in the snow pattern along the eastern shore of Lake Michigan. In the north, separate maxima are noted southwest of Grand Traverse Bay, and to the east of Grand Traverse Bay south of the Straits of Mackinac. These correspond to regions of significant hilliness. Farther south, local maxima in snow amounts are found near Muskegon and along the southeast corner of the lake, near South Bend, Indiana, and Benton Harbor, Michigan.

The major difference to be found in Figs. 1 through 7 is the average amount of snow reported. Through the 1910s and 1920s the Keweenaw Peninsula maximum was slightly more than 300 cm, whereas by the 1970s it had increased to over 600 cm. Along the southeast coast of Lake Michigan the average seasonal snowfall totals changed from 125–150 cm in the 1910s to over 200 cm in the 1970s. Similar changes can be noted in other snowbelt areas. This observation brings to mind the statement by Eichenlaub (1970) that ". . . in recent decades [prior to 1960] the lake effect mechanisms have been hyperactive. . . ." Our studies show that this effect continued, and even increased, throughout the 1960s and 1970s.

One must ask to what extent this increase may be attributed to the greater number of reporting stations in the later years, especially after 1950. Considering the relatively small extent of the snowbelts, we note that the greater the density of observing points the more likely a small area of maximum snow will be sampled. However, there are many snowbelt stations with long continuous records of snowfall. These stations showed substantial increases in snowfall during the period from ~1930 through 1980. The records from several such stations around Lake Michigan are shown in Fig. 8. The inset curve for each station shows the amount of snow received each winter from 1909/10 through 1980/81. The applicable scales are shown in the lower left corner. Map locations for the individual stations are indicated by closed circles connected to their corresponding snowfall curves.

All stations show a marked year-to-year variation in snowfall amounts. Stations that are usually upwind of Lake Michigan (e.g., Madison and Green Bay, Wisconsin) show at most a very slight upward trend, presumably due to long-term climatic variations. In contrast, curves for stations within the snowbelt of Lower Michigan (extending from Traverse City, Michigan, south to South Bend, Indiana) show a distinct pattern with a minimum of snowfall during the 1930s or early 1940s and sharp increases thereafter. At Muskegon, the average seasonal snowfall increased almost threefold from 1930 to 1980. A similar, though less pronounced, pattern is seen in the records from Grand Rapids and Allegan, Michigan, which are near the inland edge of the snowbelt.

Since the pattern of marked increases in snowfall from the 1930s through the 1970s is found at all snowbelt stations, but not at stations well-removed from the lake, both upwind and downwind, it is reasonable to conclude that this increase is attributable to an enhancement of the lake effects on winter storms. Obviously, the magnitude of the effect of Lake Michigan on snowfall has changed substantially over the 72 years covered in this study. We will discuss briefly a possible cause for this increase in a later paragraph.

4. Quantitative estimates of lake-induced snowfall

In an effort to obtain quantitative estimates of the effect of Lake Michigan on snowfall, we developed a simple interpolation model based upon the geographical areas outlined in Fig. 9. Area 3 covers most of the snowbelt along the eastern shore of Lake Michigan, south of Hart, Michigan (see Fig. 8). Area 2 is of similar size along the western shore. Areas 1 and 4 were chosen as comparison areas, similar in size and latitudinal extent to Areas 2 and 3 and sufficiently removed from the lake as to minimize the lake's effect on their snowfall. Note by comparing Fig. 9 with Fig. 7, that Areas 1 and 4 are essentially free of any obvious lake effect. These comparison areas are separated from Areas 2 and 3 by about the same distance as that between Areas 2 and 3.

Our interpolation model assumes that snowfall in Areas 1 and 4 is caused mainly by large scale synoptic systems with little direct influence from the lake, whereas snow in Areas 2 and 3 represents a combination of synoptic and lake influences. We now pos-

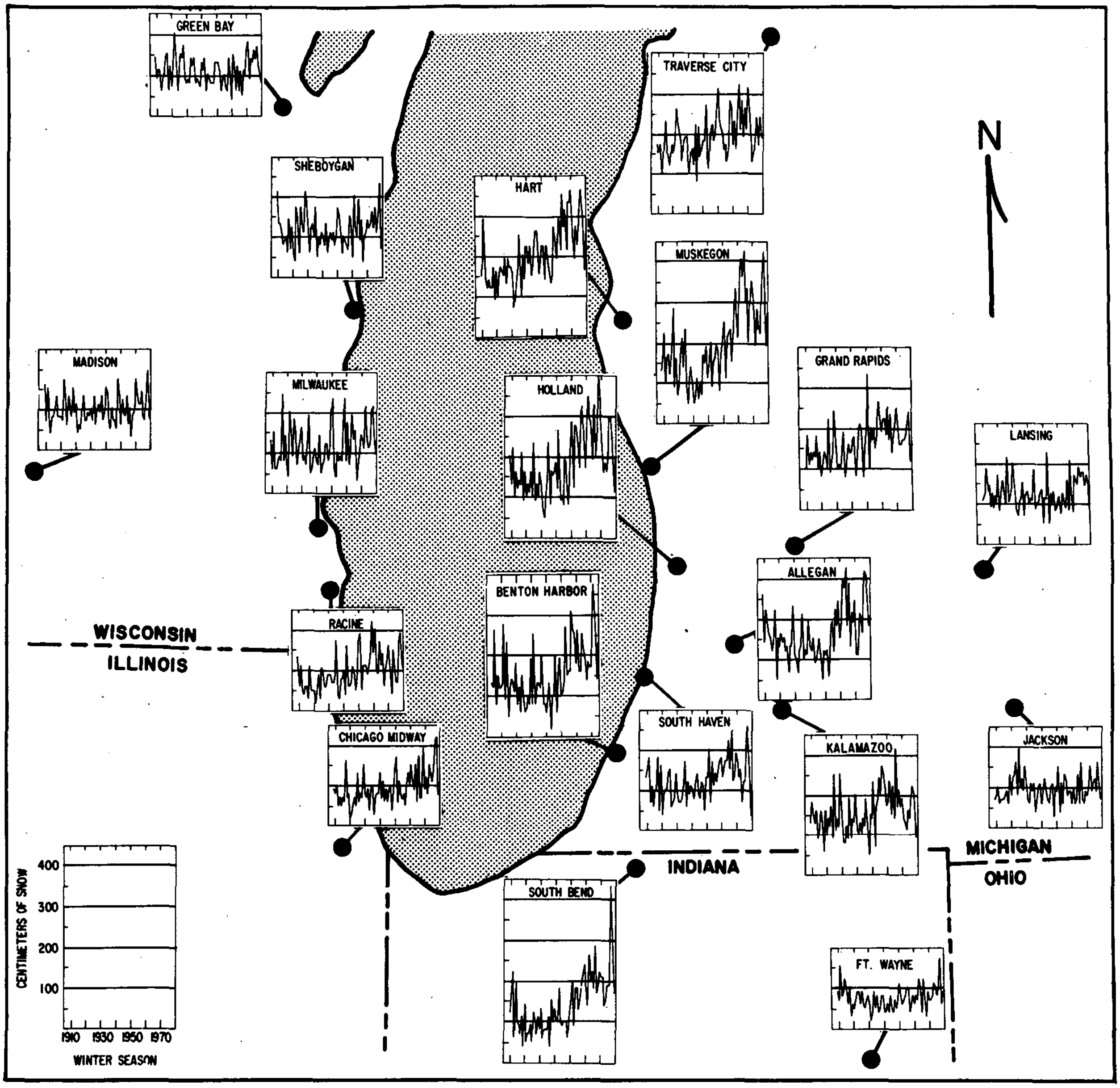

FIG. 8. Graphs of total winter snowfall, from the winter of 1909/10 through the winter of 1980/81, at 19 stations around Lake Michigan.

tulate that in the absence of lake effects the expected snowfall in Areas 2 and 3 can be estimated by interpolation between the snow amounts observed in Areas 1 and 4. We know of no easy way to test this postulate. In principle it could be tested by using periods when Lake Michigan was completely frozen over. Nevertheless, such periods are very infrequent and poorly documented. Moreover, they probably represent a set of meteorological conditions nonrepresentative of average winter conditions.

The results of our analyses are shown in Figs. 10 and 11. For convenience, we have connected the dots corresponding to observed snow amounts by straight lines, although we do not propose that the actual snowfall follows this pattern. In every decade the average winter snowfall in Area 4 exceeded that in Area 1. In all but one decade, the snowfall in Areas 2 and 3 was clearly above the linear interpolation between Areas 1 and 4. A quantitative estimate of the lake-effect is obtained by taking the ratios of observed to predicted snow amounts in Areas 2 and 3. Results are plotted near the points representing observed snow amounts. This analysis finds a decade-average lake-effect increase in snow along the lower Wisconsin and Illinois shore between zero and 21%, averaging about 10%. In the snowbelt of Lower Michigan, the effect ranged from about +31% to +120% with a 70-year average of 64%. Interestingly the lake-effect reached a minimum in the

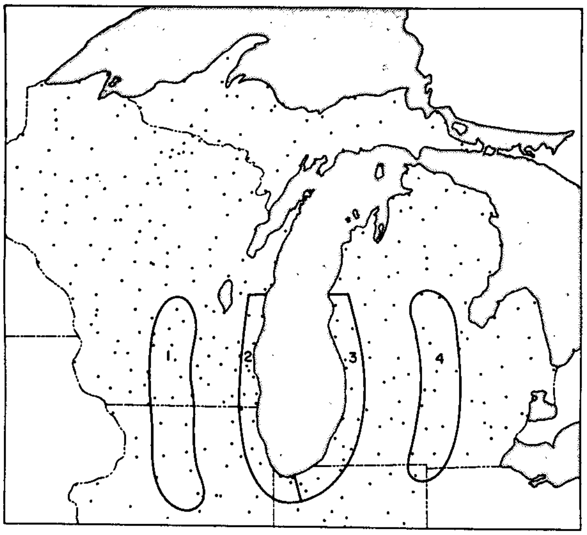

FIG. 9. Areas used in estimating effects of Lake Michigan on total winter snowfall.

1920s and maximum in 1960s. Our estimate of lake-effects on snowfall for individual winters within the 1970s is shown in Fig. 11. Only in one winter was there more snow in Area 1 than in Area 4. For three of the ten years the snow in Area 2 was less than that predicted by linear interpolation. Since "negative" lake-effects on snow seem unlikely, this result is attributed to sampling variability since one or two major storms could unduly influence any single winter's total. In all ten individual years, Area 3 snow exceeded that predicted by linear interpolation.

5. Discussion and conclusions

The snowfall patterns derived in this study differ from those previously published (Strommen, 1974; Dewey, 1970; Gatz and Changnon, 1976; Eichenlaub, 1970; Changnon, 1968) mainly in that they are based upon 10-season data periods which bring out more clearly the increase in lake-effect snowfall that has occurred after about 1930. This study attempts to quantify the effect of Lake Michigan on seasonal snow totals along both shores. The long-term (70-year) average effect along the west shore (south of Sheboygan, Wisconsin) was about 10% compared with roughly 60% along the east shore (south of Hart, Michigan).

Although many authors have called attention to the role of Lake Michigan in increasing snowfall along one or both shores, few have attempted *quantitative* estimates of it. In most cases estimates of lake-effects on snowfall have been based upon comparisons of snowfall amounts along the eastern shore with amounts along the western shore. Such analyses overlook the possibility for lake-effects along the western shore.

Changnon (1968) estimated lake-effects on total winter precipitation for the period 1921–51. He began by constructing a map of total winter precipitation that would occur in the absence of the lake. Comparing this with actual observations, he obtained a map of precipitation increases, attributable to the lake. This map shows values up to 5% along the Wisconsin–Illinois shore and up to 30% in the snowbelt of southwestern Lower Michigan. In the same study Changnon found that the December average snowfall in the snowbelt of southwestern Michigan ranged up to 100% greater than that at locations of comparable latitude in Wisconsin and Illinois. The comparative figure for January–February was 33%. Dewey (1970) concluded that lake-effect snowfall increases the annual snowfall along the Wisconsin shore of the lake by 30–40%, whereas some areas in western Lower Michigan receive about "200% more snow than stations at the same

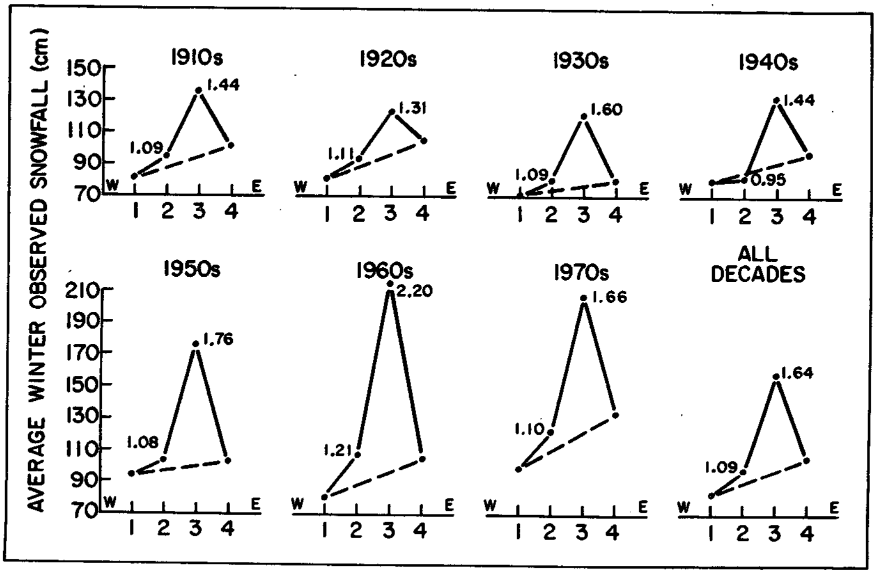

FIG. 10. Results of interpolation model used for estimating lake-effects on average winter snow during various decades. See text.

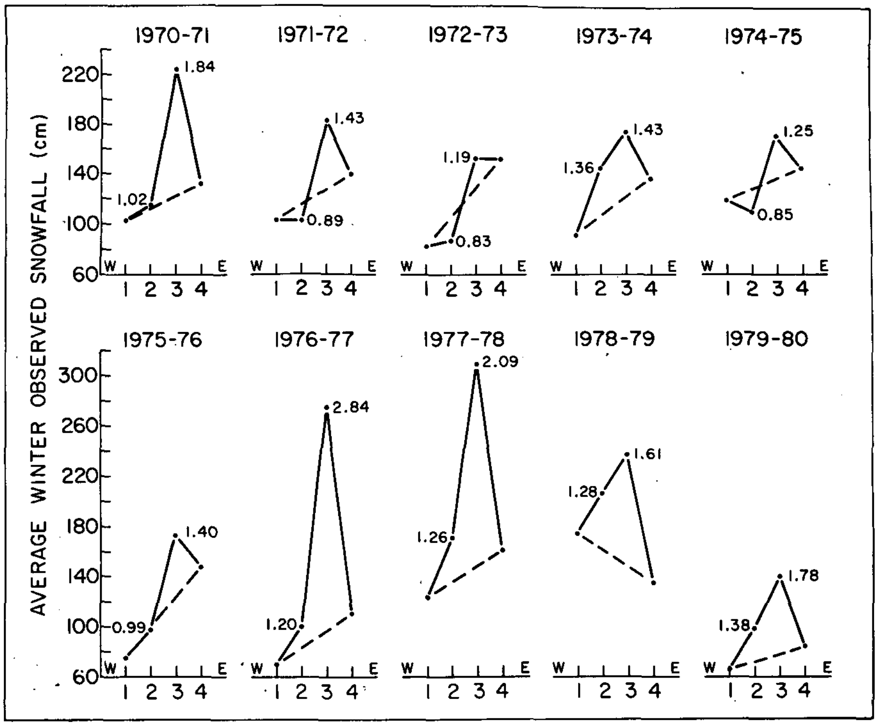

FIG. 11. Results of interpolation model applied to individual winters during the 1970s.

latitude in the interior of the state." Dewey's study covered the period of 1931 through 1969. Eichenlaub (1970) found that ". . . at least 30% of the seasonal snowfall in lee areas [from Lake Michigan] was derived from lake-atmosphere interactions." Gatz and Changnon (1976) display cross sections of average annual snowfall extending across Lake Michigan at three different latitudes. These diagrams suggest about 100% more snow along the Michigan shore than along the Wisconsin shore. Referring to lake effects along the eastern shore of Lake Michigan, Strommen (1974) called attention to its magnitude by "comparing the annual seasonal snow totals at Minneapolis and St. Cloud, Minnesota, about 40 inches [102 cm] with the annual averages in western Lower Michigan, 60–120 inches [152–305 cm]." From these one would conclude a lake-effect of between 50 and 300%.

In a study covering 1970–74, Albrecht (1980) concluded that during fall and winter months the precipitation at west-shore stations averaged about 6% more than that at stations more than 30 km inland. However, when cold anticyclones were centered over the upper Midwest and winds over the lake were northerly to northeasterly, the shoreline stations received up to 25% more precipitation than did the inland stations.

The substantial differences in estimates of the magnitude of lake effects on total seasonal snow, around Lake Michigan, may be attributed both to different analysis techniques and to the different periods of time used in the studies.

Our analysis clearly shows that the contribution of lake-effect snow to total snowfall along the lee shore of Lake Michigan increased substantially during the period from about 1930 through the 1970s. The most probable cause for this is the decrease in average winter

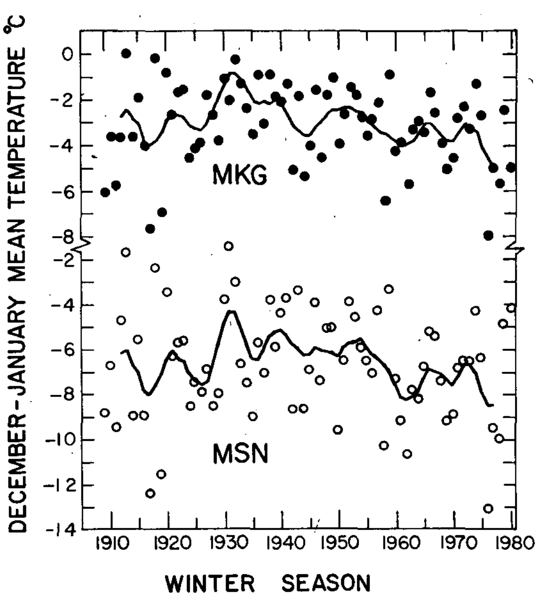

FIG. 12. December–January mean temperatures at Muskegon, Michigan (MKG) and Madison, Wisconsin (MSN) for winter seasons from 1909/10 through 1980/81.

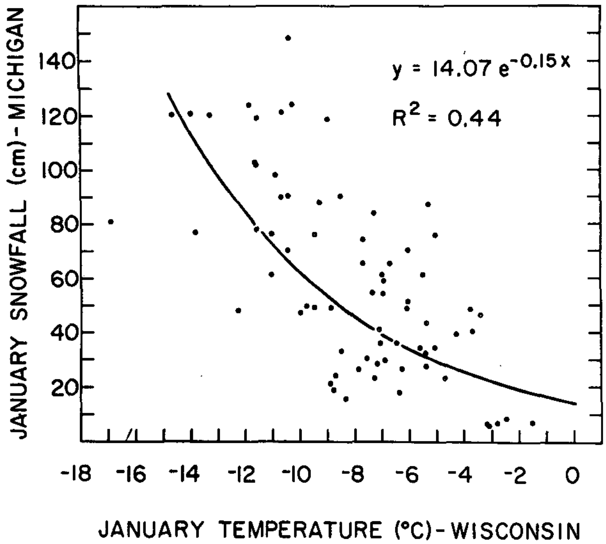

FIG. 13. Observed relationship between January monthly mean temperatures at three stations in Wisconsin (Madison, Green Bay and Sheboygan) and the January average total snowfall at three stations in Michigan (Hart, Muskegon and Grand Rapids) for winter seasons from 1909/10 through 1980/81.

temperatures that occurred during this same time interval.

Since December and January are the months of greatest lake-effect snow, we have plotted the average December–January temperatures at Muskegon, Michigan, and Madison, Wisconsin (see Fig. 12). (A roughly similar curve of winter temperature in Illinois was published by Diaz, 1980.) Superimposed on the values of temperatures for individual winters is a seven-season Gaussian-smoothed curve which suppresses some of the year-to-year variability. The very high correlation coefficient between unsmoothed two-month temperature means at the two stations ($r = 0.90$) shows that, on average, larger-scale atmospheric conditions are virtually identical at these two stations during winter months. However, the average December–January temperature at Muskegon is 3–4°C warmer than that at Madison. Most of this difference can be attributed to the presence of Lake Michigan. From the 1930s to the present, both Madison and Muskegon have experienced a drop in December–January temperatures between 3 and 4°C. In an effort to relate the amount of snowfall downwind of the lake to the temperatures of air before it crossed the lake, we compared January air temperatures at three stations in Wisconsin with January snowfall at three snowbelt stations in Lower Michigan. The results are shown in Fig. 13. Obviously, there is a strong inverse relation between monthly mean temperatures in the air upwind of Lake Michigan and monthly mean snowfall along the downwind shore. Januaries with colder mean temperatures in Wisconsin are Januaries with heavier snowfall in the Lower Michigan snowbelt.

Monthly mean temperatures represent a mixture of warm days, unlikely to produce lake-effect snow, and cold days which are most likely to produce lake-effect snows. Obviously, the type of analysis shown in Fig. 13 should be carried out on a daily rather than monthly basis. It should also involve lake–air temperature differences. Such a study has been started but no results are available as yet.

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