THE SPATIAL DISTRIBUTION OF LAKE-EFFECT SNOWFALL WITHIN THE VICINITY OF LAKE MICHIGAN

KENNETH FREDERIC DEWEY
Department of Geography,
University of Toronto, Toronto, Ontario, Canada

ABSTRACT.—The average monthly and annual snowfall patterns are analyzed for the region within 100-150 miles of Lake Michigan. From these patterns the distribution of lake-effect snowfall is determined for the study region.

During the last few years much attention has been given to Great Lakes Climatology. Among the many parameters being studied is snowfall. It has been illustrated by several authors that excessive amounts of snowfall occur along the shorelines of the Great Lakes, especially along the lee shore of the lakes (Falconer, Lansing, and Sykes, 1964; Sheridan, 1941; Pack, 1963; Namias, 1960; Bolsenga, 1967; Johnson and Mook, 1953; and Williams, 1963). Muller (1966, p. 256) developed a map for mean seasonal snowfall in the Great Lakes region and surrounding areas. The most outstanding features of this map are the snowbelts associated with the frequently recurring lake squalls coming off the Great Lakes.

These excessive amounts of snowfall along the shores of the lakes have been explained to be an overt manifestation of lake-effect snow showers. Lake-effect snowfall by definition occurs as a result of cold air being advected over the warm moist surface of a lake. The air in contact with the surface warms rapidly, gains moisture and under superadiabatic lapse rate conditions rises rapidly forming convective clouds and precipitation. During the periods of lake-effect snowfall it is assumed that the snowfall is generated specifically from the vast reservoir of heat and available moisture in the lake, and that there is no direct influence from either cyclonic or frontal systems.

PURPOSE OF THE STUDY

It is the purpose of this study to conduct an analysis of the phenomenon lake-effect snowfall for a single lake in the Great Lakes basin. Lake-effect snowfall is studied indirectly by analyzing the spatial variation of snowfall within the vicinity of Lake Michigan. Average monthly and annual snowfall amounts are determined for the study region and the patterns analyzed.

THE STUDY AREA

A boundary was chosen for this study to average between 100 and 150 miles inland from the shoreline of Lake Michigan. Lake Michigan offers several advantages which do not exist for any of the other Great Lakes. There is a dense network of reporting stations along all sides of the lake. There is topographic uniformity throughout most of the study region. And, there is little interaction between Lake Michigan and the other lakes in the Great Lakes basin.

Sources and Utilization of Data

The U. S. Department of Commerce's data records for each of the states within the region of study were examined. A list was compiled indicating all reporting stations in the study area that kept systematic monthly and annual records of snowfall. A total of 145 stations were included in the study.

Monthly and annual snowfall amounts were tabulated for the stations in the study region for 10 successive snowfall seasons beginning October 1959 and ending March 1969. Monthly snowfall amounts were tabulated for the four months November to February of each snow season. An average monthly and annual snowfall amount was computed for each of the 145 stations in the study.

These averages were compared to the long-term averages which were available in the "Climatography of The United States" series. It was noted that the 10 year averages obtained in this study were significantly higher than the long-term averages. The average increase over the study region was from 10% to 15%. In his recent study, Eichenlaub (1970) found that there has been a 100% increase in the average snowfall amounts of western Michigan. There is no definite answer to the question of what is causing this increase in snowfall and lake-effect snowfall. There are however several possible explanations for this climatic change which warrant further research. Namias (1960) suggested that an increase in snowfall can result from a shift in the position of the mean troughs and ridges over North America. It has also been suggested that a general cooling of the atmosphere has been occurring since the 1930's. Finally further research should investigate the role of atmospheric pollution in increasing the amount of snowfall (especially near the large industrial complexes like Chicago-Gary, Milwaukee, and Muskegon).

Analysis of The Average Annual Snowfall Pattern

The average annual snowfall was portrayed on the map of the study region using an isopleth interval of 10 inches (Figure 1). In an analysis of the annual as well as the monthly snowfall patterns it should be emphasized that the positioning of the isopleths across the lake is based upon estimation. Although there are values of snowfall at the shoreline of each side of the lake it is difficult to determine the correct gradient of isopleths across the water. According to Changnon (1968, p. 23) "When lake-effect snowfall develops over the lake it begins somewhere within 20 miles of the eastern shoreline." On the annual snowfall map and all maps of monthly average snowfall, it was found in this study that the isopleths generally tended to parallel both the eastern and western shorelines, so it seemed most likely that the isopleths over the lake would also tend to follow a north-

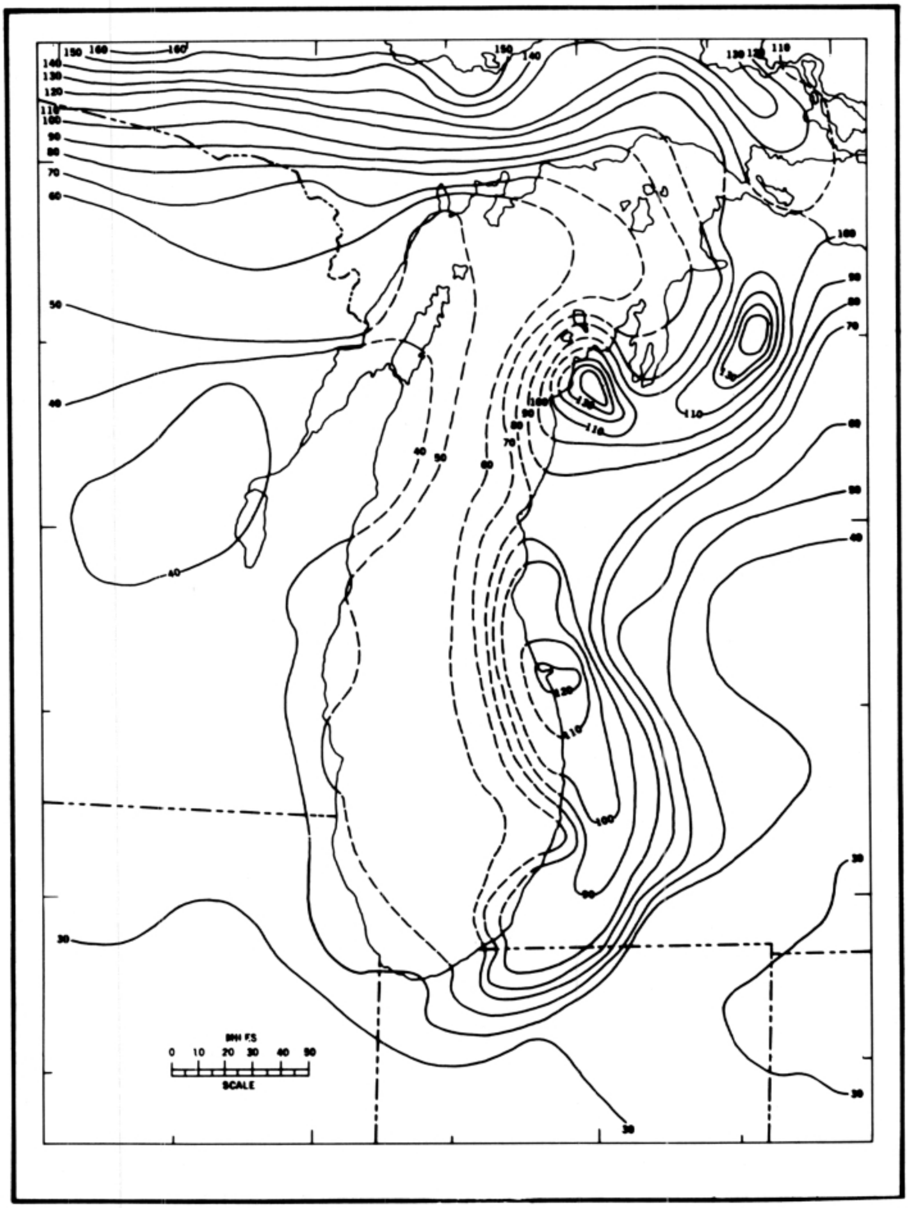

FIGURE 1. Average Annual Snowfall In Inches.

south direction. However, it was also assumed that the isopleths of snowfall are more tightly spaced along the eastern shore than the western shore.

Were there no Lake Michigan one would expect the isopleths to be oriented in an East-West direction across the study region, with snowfall increasing to the north. However, this latitudinal positioning of isopleths occurs only within 75 miles of the western edge of the study region, within 50 miles of the southern boundary of the study region, and at a maximum, within 50 miles of the eastern edge of the study region. The remainder of the study region has a snowfall pattern which could not exist without the presence of Lake Michigan.

Along the western side of the lake, the gradient of snowfall is small. For example, the distance between the 30 inch and 40 inch isopleth is 200 miles. The gradient becomes steeper near the northern margin of the study region, but this is a result of the additive influence of lake-effect snowfall from Lake Superior. The extent of lake-effect snowfall averages 10-15 miles inland along the western shore and the magnitude averages 10-15 inches annually. Lake-effect snowfall therefore increases the annual snowfall along this side of the lake by 30-40%.

The additive factor of lake-effect snowfall is dramatically illustrated along the lee side of the lake. Here the isopleths are packed quite closely together, their high gradient indicating a region of copious snowfall. The penetration inland of lake-effect snowfall averages 50-75 miles in Michigan. Some areas receive more than 60 inches of lake-effect snowfall annually, which is 200% more snowfall than at the same latitude in the interior of the state.

There are three significant features in the pattern of isopleths along the eastern shoreline of Lake Michigan. First, there are three cores of extremely heavy snowfall each averaging over 130 inches. The first two cores, centered on Gaylord-Vanderbilt and Maple City in northern Lower Michigan are a function of elevated topography, as well as a peninsular effect. The land area of this region is surrounded on three sides by the close proximity of water bodies therefore increasing the magnitude of lake-effect snowfall. Elevations above sea level for these two cores respectively are approximately 1435 feet and 850 feet, or 853 feet and 268 feet respectively above the mean level of Lake Michigan (582 feet).

The effect of these hills is twofold, one effect is to provide lifting, and the other is to provide increased surface friction for the bands of snow as they move inland from the lake. In an article by R. L. Peace and R. B. Sykes (1966) which examined the conditions attendant upon lake-effect storms at the eastern end of Lake Ontario, it was made evident that the lake-effect snow bands are characteristically shallow systems with radar-detectable tops usually lying below 10,000 feet. Extreme instability is also attendant with these bands. While the relief of these two areas in northern Lower Michigan may be insignificant for orographic snowfall during cyclonic and frontal situations, it is significant for orographic snowfall during lake-effect snowfall situations.

The third core centered on Muskegon could be related to topography but not with as much confidence. Instead, the primary factors causing excessive snowfall over the Muskegon area are hypothesized to be pollution and urban influence. Several recent studies have indicated that there has been a considerable increase in the amount of air pollution downwind from Great Lakes metropolitan centers. The presence of high concentrations of ice nuclei and crystals in the Great Lakes area and the availability of moist air from off the lake is favorable for the occurrence of increased lake-effect snowfall. No significant evidence is available at the present time to confirm such a link. Therefore, with pollution becoming a more urgent problem there is the need for further research into the role of pollution in lake-effect snowfall. The urban effect results from heat being added to the bands of snowfall as they move inland from the shoreline. The heat added to the bands of snowfall increases the instability of the air masses and subsequently the fall of snow for the area surrounding Muskegon.

The hills of western Michigan increase the surface friction greatly as these bands of snowfall move across the region and this creates the second significant feature of the pattern of isopleths. This increased surface friction for areas of hills, and conversely, the relative lack of surface friction for areas of little local relief, creates a phenomenon which can be termed "avenue of penetration". It is hypothesized that where there are hills close to the shore of the lake, large amounts of snowfall result from the fact that the increased surface friction slows the storm bands down so that much of the energy is released near the shoreline and little residual energy or moisture remains by the time the band has crossed the hilly region. Conversely, where there are no topographic barriers along the shore, the bands of snowfall can progress inland with only a gradual loss of moisture and most likely extend further inland creating avenues of penetration.

The third significant feature in the pattern of isopleths as illustrated on Figure 1 is the occurrence of the maximum amounts of snowfall inland away from the shoreline. The maximum amount of lake-effect snowfall is felt at the shoreline of the western side of the lake with decreasing amounts of snowfall occurring inland. However, in Michigan (not including the Upper Peninsula) the maximum amounts of snowfall occur approximately 25 miles inland. This is in agreement with the findings in Changnon's (1968a) study of annual snowfall in the Lake Michigan basin. In his study, Changnon found that the maximization of lake-effect snowfall occurs anywhere from 10 to 25 miles inland, with 10 to 40 more inches of snow there annually than at the immediate eastern shoreline of Lake Michigan.

It is hypothesized that this phenomenon exists as a result of the increased surface friction as the air passes from the lake onto the land surface of Michigan and Indiana, causing the air masses to slow down and begin to pile up inland some distance from the shoreline. The increased friction resulting from rough topography can enhance this process of convergence of air masses as the bands of lake-effect snowfall move inland.

Comparison of The Average Monthly Snowfall Patterns with The Annual Pattern

The average monthly snowfall patterns for each of the four months under investigation were portrayed on Figures 2-5 using an isopleth interval of 5 inches. As in the case of the annual average snowfall, the positioning of the isopleths across the lake was based upon estimation.

The three cores of extremely heavy snowfall which appeared on the map of annual snowfall appear only from December through February. During November the second core of heavy snowfall around the vicinity of Maple City has only begun to develop. The third core of heavy snowfall centered over Muskegon is well developed by this time. There is the development of a fourth core of snowfall south of Muskegon for all of the months under study except January. The significant feature of this core of snowfall is that the diameter is considerably larger, averaging three times the size of the largest of the other three cores. During January the isopleths of snowfall around the core of snowfall centered on Musekgon curve southward and are elongated to such a degree that the area represented by the fourth core might be considered to be a part of the Muskegon core.

The distributions of the average monthly snowfall also dramatically display the avenues of penetration. For all months under investigation, the tendency for fingers of heavier snowfall to extend inland is quite definite. The eastward extent of the avenues of penetration remains almost identical throughout the remainder of the snow season. The only variance from month to month is in the intensity of snowfall or amount of snowfall represented by the avenues of penetration.

As in the distribution of the average annual snowfall, there is the tendency for the heaviest amounts of snowfall to occur inland some 20 to 30 miles from the eastern shoreline for each of the months under investigation. It is significant to note that whether the month under investigation averages little snowfall or copious amounts of snowfall, the heaviest snowfall area remains identical.

Conclusions

An analysis of the annual and monthly snowfall patterns within the vicinity of Lake Michigan revealed an uneven spatial distribution of snowfall. This uneven distribution of snowfall results from the additive influence of lake-effect snowfall. The average distribution and magnitude of lake-effect snowfall was determined from these patterns. There were three significant patterns of lake-effect snowfall which appeared on all the maps of snowfall: Cores of excessive snowfall; avenues of penetration; and, a tendency for the heaviest amounts of snowfall to occur inland 20-30 miles from the shoreline.

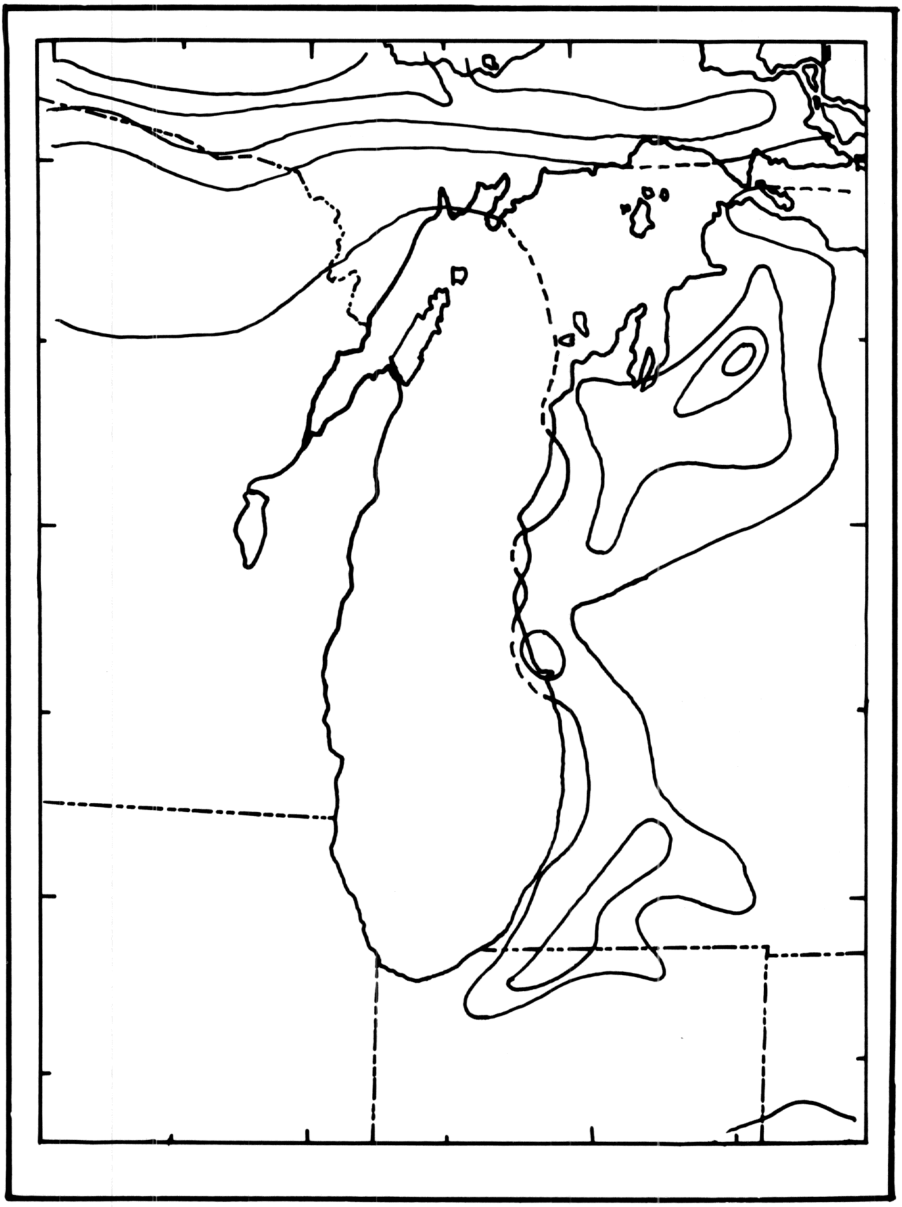

FIGURE 2. Average November Snowfall Pattern (5 inch interval).

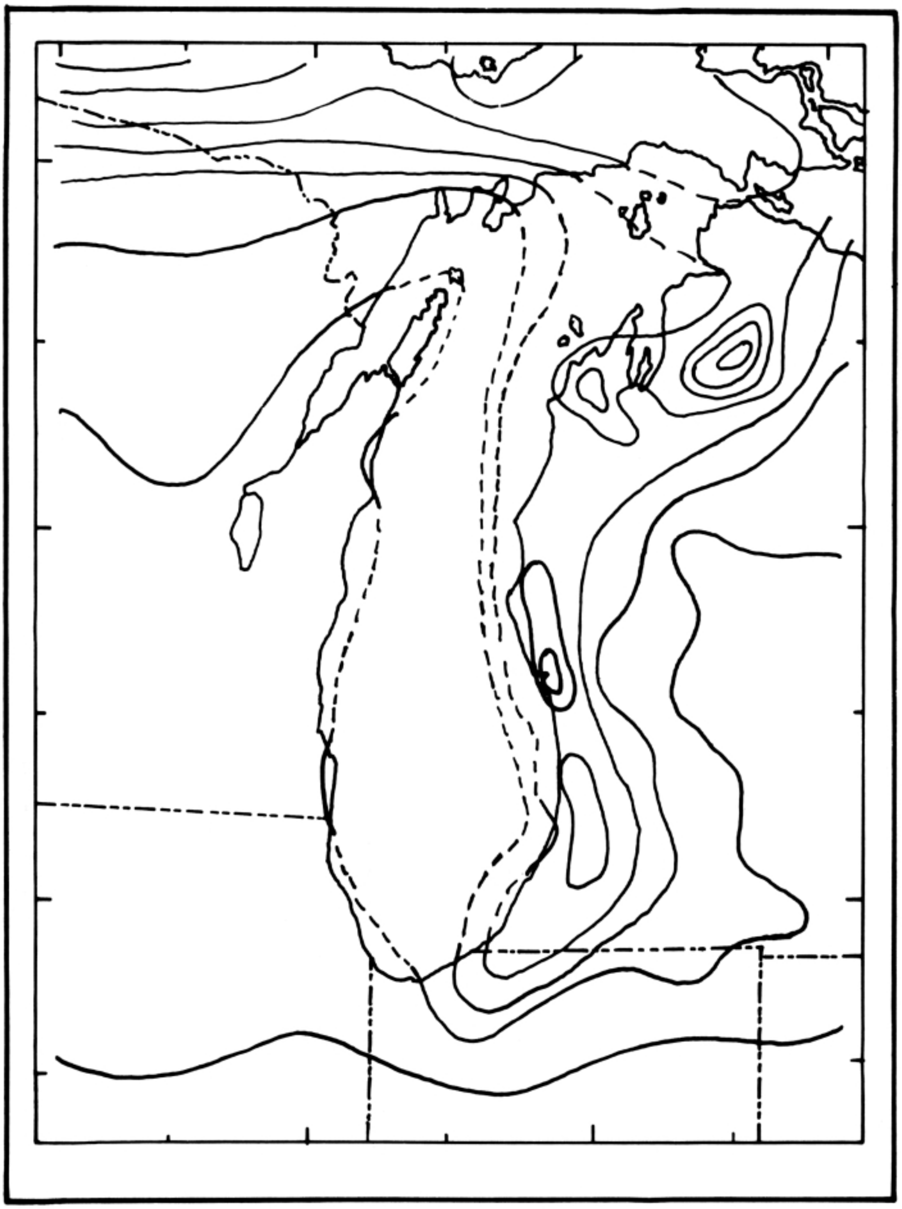

FIGURE 3. Average December Snowfall Pattern (5 inch interval).

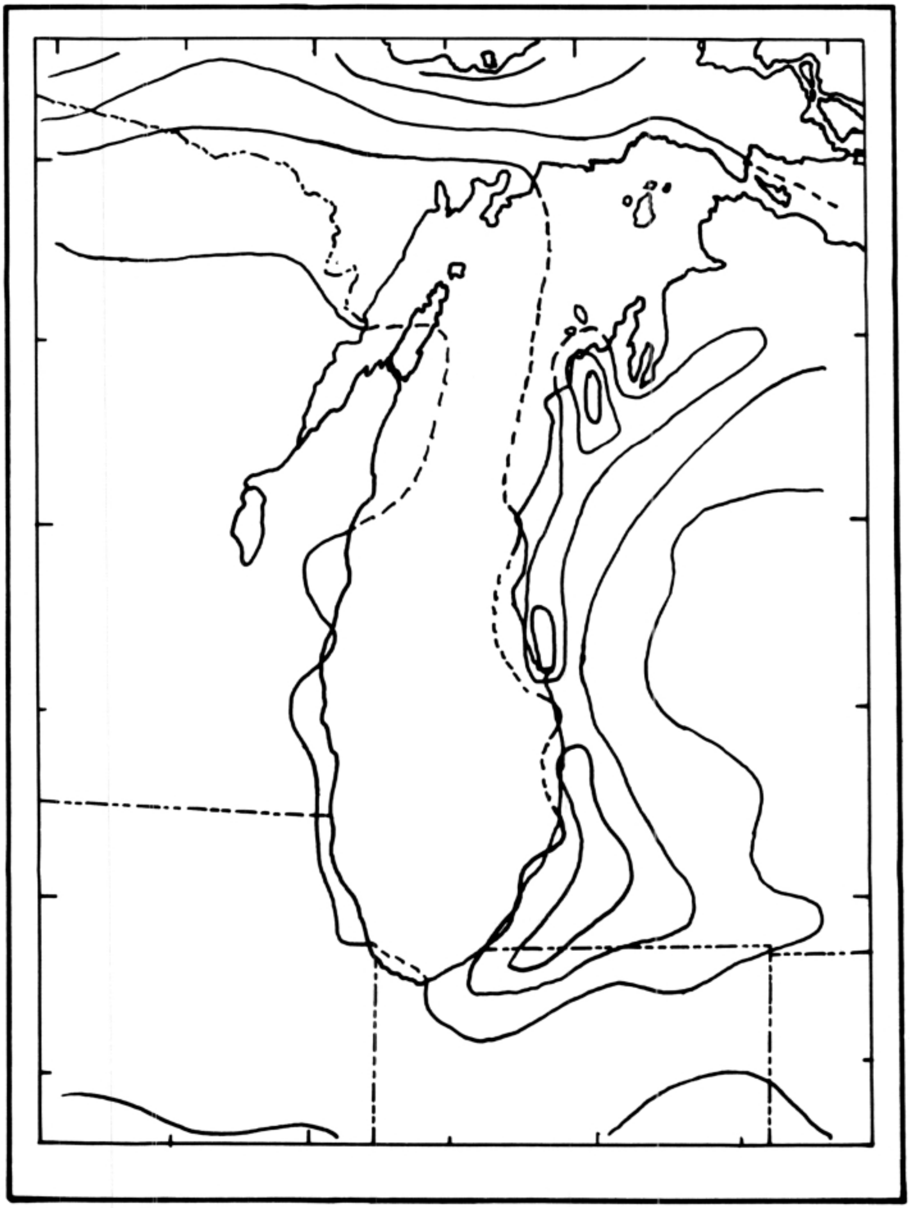

FIGURE 4. Average January Snowfall Pattern (5 inch interval).

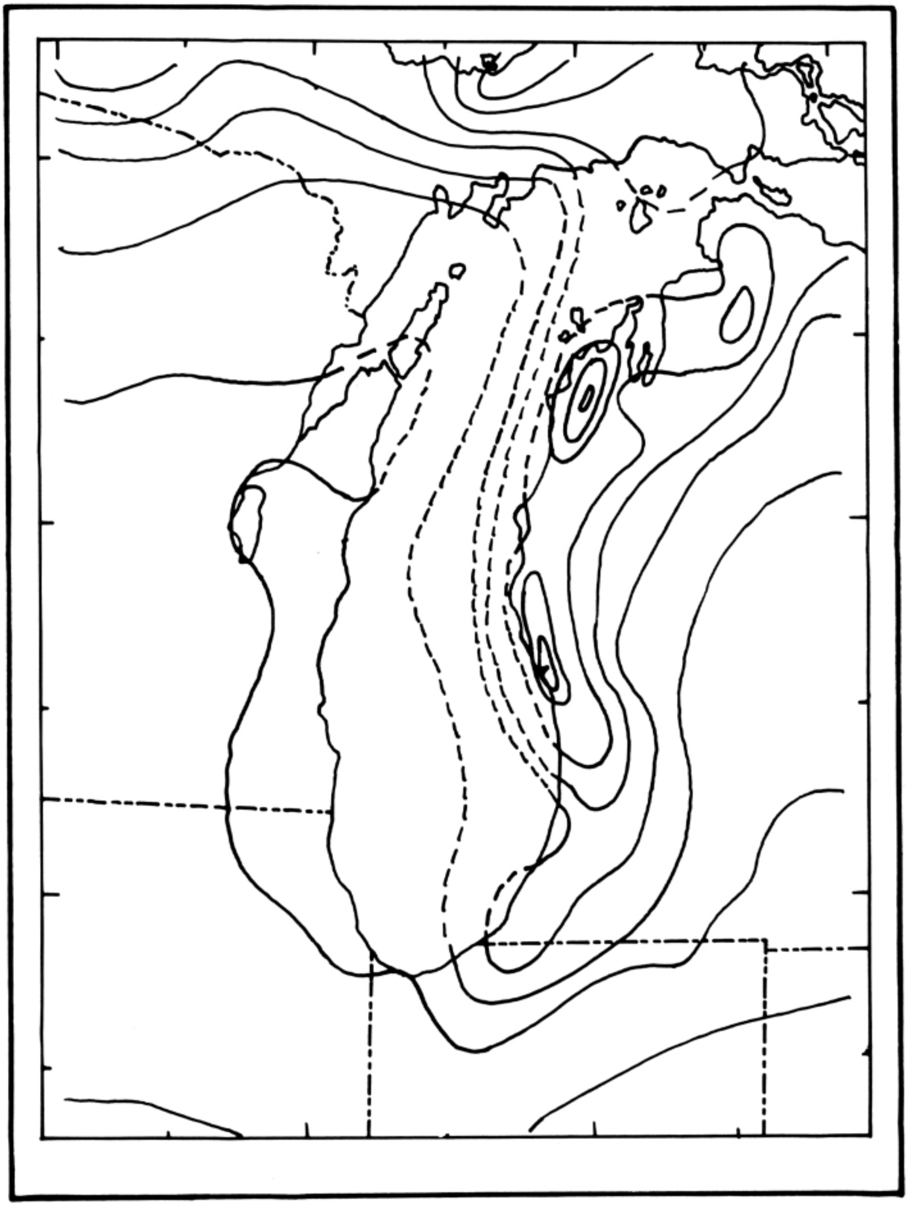

FIGURE 5. Average February Snowfall Pattern (5 inch interval).

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