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Michigan State University, Ph.D., 1975
Physical Geography

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SEASONAL CHANGE IN THE AXIS OF MAXIMUM LAKE-SNOW IN WESTERN LOWER MICHIGAN

By

Norton D. Strommen

A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Geography

1975

ABSTRACT

SEASONAL CHANGE IN THE AXIS OF MAXIMUM LAKE-SNOW IN WESTERN LOWER MICHIGAN

By

Norton D. Strommen

A shift in the area of maximum lake-effect snowfall--from inland toward Lake Michigan between November and January and a return inland by March--over western Lower Michigan was investigated for the period from November, 1965, through March, 1971. The seasonal pattern for all areas of western Lower Michigan was similar but with the displacement nearly twice as great in the northwest section.

Lake-snow days for western Lower Michigan were identified for the period from November, 1965, through March, 1971. Daily lake-snow maps were analyzed to determine the axis of maximum snow; the displacement from the lakeshore was measured along three traverses, one each in southwest, west-central, and northwest Lower Michigan. Temperature differences, lake water to 850mb ambient air, were computed for each day of lake-snow using car-ferry and radiosonde data. The geostrophic wind for the surface, 850mb, 700mb, and 500mb levels were calculated for a point over mid-Lake Michigan; the observed winds for Green Bay,

Wisconsin, and Flint, Michigan, were extracted from the records at Asheville, North Carolina, for the surface, 850mb, 700mb, and 500mb levels.

The seasonal shift in the location of the axis of maximum lake-snow was found to be related to the degree of temperature difference between the lake water and the air being advected over it at 850mbs, the observed wind flow in the lower troposphere upstream and downstream from the area of active lake-snow, and the calculated geostrophic wind near mid-Lake Michigan. Increasing temperature difference between the lake water and 850mb level resulted in a smaller displacement of the axis of maximum snow for a given wind speed. The displacement of the axis of maximum lake-snow was most positively correlated with the geostrophic wind at the 850mb level. A statistically significant difference was found between the upstream (Green Bay, Wisconsin) and downstream (Flint, Michigan) observations, with a highly significant difference noted in January for the 850mb, 700mb, and 500mb levels. Of these observations, those taken at Green Bay, Wisconsin, were more positively correlated with lake-snow displacement than were the others.

Heavy lake-snow events, of four or more inches, are increasingly likely with increases in the temperature difference between the lake water and the air advected over it. Lake-snow of eight or more inches requires an additional

meteorological parameter, usually a weak short wave in the upper-level wind flow.

The ratio of snowdepth to water content, while highly variable for individual lake-snow events, consistently showed a seasonally lower ratio near the lakeshore and gradually increased inland. The monthly ratio of snowdepth to water content was similar to the annual pattern.

ACKNOWLEDGMENTS

The author wishes to express his deep appreciation to the many individuals who assisted in the completion of this study. Special appreciation is expressed to Dr. J. Harman, for his patience, words of encouragement, and advice as the study progressed.

Among the many individuals who contributed in the various phases of the study are: Mrs. Maxine Oshel, Michigan Weather Service, whose assistance was invaluable in assembling the data base and preparing snowfall maps; Dr. F. V. Nurnberger, Michigan Weather Service; Mr. W. Hodge, National Climatic Center; Dr. R. Katz, Mrs. R. Terry, and Mrs. M. Johnson, Center for Climatic and Environmental Assessment; and Mr. J. Gerka, National Environmental Satellite Service.

The study is dedicated to my wife, Rosemary, and children, Brad and Sara, whose encouragement and understanding during the difficult transition period enabled me to complete this study.

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CHAPTER I

INTRODUCTION

The modification of various climatic elements near the Great Lakes has been recognized for many years (1,2,3, 4,5,6,7,8,9,10,11). "Lake-effect" snowfall is one of the more noticeable effects experienced near the shores of the Great Lakes. This snowfall is generally defined as that which occurs along the lee shores of the lakes within a homogeneous air mass and without evidence of surface fronts or cyclonic storm activity. The persistence of the "lake-effect" snowfall, hereafter referred to as lake-snow, during the fall and winter months is responsible for the development of areas, or "belts," that consistently experience greater seasonal snowfall totals than other areas. These snowbelts have been described by Brooks and others (12,13,14,15,16,17).

More recent efforts to understand the mechanisms responsible for lake-snow were described in a series of Cornell Aeronautical Laboratory, Inc. reports (18,19,20,21). These investigations were aimed at developing an understanding of the physical processes of lake-snow that would allow, for economic reasons, cloud seeding experiments

designed to redistribute the unusually heavy snow squalls that occur on the east end of Lake Erie. Although the orientation of Lake Michigan is different, the basic dynamic mechanisms underlying the occurrence of lake-snow in western Lower Michigan are believed to be similar to those of Lake Erie.

The basic mechanisms resulting in lake-snow emphasized in these reports include dynamic and thermodynamic considerations. The dynamic considerations emphasize the role of friction, a function of surface roughness and topography, and its influence on the wind field and relationship to the coriolis force. The thermodynamic considerations emphasize heat transfer from the warmer lake water, saturation, and destabilization of a shallow layer of the lower troposphere. It is now understood that lake-snow results from the complex interactions between the thermodynamic and dynamic properties of the lower portion of the troposphere and related underlying surfaces over which the air is advected. When these interactions are in phase, or complement each other, the probability for the occurrence of heavier snow bands, often called squalls, is increased. These snow squalls contribute to the unique weather experienced around the shores of the Great Lakes.

The thermodynamic influences are most often cited in explaining the development of lake-snow. They specifically include the advection of cold, dry Arctic air for an

extended time over the warmer water of the Great Lakes. The moisture and heat thus transferred result in saturation and destabilization of the lowest layers of the atmosphere. The unstable air rises and cools, forming clouds, the process continuing as long as the cold air remains over the lake surface. Upon reaching the lee shoreline, the destabilized air is subjected to various degrees of orographic lift. As the clouds move inland, the cold surface allows a stable lapse rate to redevelop in the lower troposphere and the snowfall, often heavier at first, gradually diminishes as the clouds move farther inland.

Less information is available about the role atmospheric dynamics plays, even though it has been recognized that changes of friction affect wind speed and the coriolis influence (22,23,24). The frictional effects are most easily understood when described with respect to the windward and leeward shorelines and related to the geostrophic wind equation. The geostrophic wind is the result of a delicate balance achieved between the pressure gradient force and the coriolis force (25,26,27,28). Introduction of the variable parameter friction upsets the balance between the pressure gradient and coriolis forces, resulting in an ageostrophic wind flow and a decrease of the wind velocity with an increase in friction, or an increase in the wind velocity with a decrease in friction.

At the windward shoreline, i.e., where the air movement is from land to water, a decrease in friction and an increase in wind speed are observed. This region of velocity divergence produces subsidence of air at the shoreline, stabilizing the lower troposphere and creating a region of clear skies with respect to "lake-effect" cloud development.

At the lee shoreline, i.e., where the air movement is from water to land, friction produces the opposite effect --reduced wind speeds and a velocity convergence zone. This condition adds to the lift of the already convectively unstable lower troposphere and enhances the further development of lake-snow. Because the frictional effects vary as a function of terrain roughness, this contribution can be highly variable in complementing the convective process established during the passage of cold air over the warmer lake water.

The length of time the air spends over water and the vertical temperature gradient between the water and air are additional factors that may influence the strength of the basic convective process and enhance the lake-snow totals. The shape of the shoreline may provide additional convergence and regions of more frequent and/or intense storms (29,30,31,32). Lake-snow may occur along extensive areas or over only a small portion of the lake shore during any one storm or at any given time. The distribution of lake-snow is related in part to the direction of wind

flow; therefore mean differences among areas may arise. For example, the lake-snow belts for each of the five Great Lakes vary widely in width and in amounts. In western Lower Michigan the higher average snowfall varies in width from about 40 miles over the southwest to 65 miles over the northwest (Figure 1-1). Furthermore, in Michigan the lake-snow distribution has been observed to vary greatly from one storm to the next and with a changing distribution with respect to distance from the shoreline as the snow season evolves. Early lake-snow often falls 20-40 miles inland, but by mid-winter (January) heaviest totals usually occur within ten miles of the lake. Lake-snow in March, however, again falls at greater distances inland. This study examines this seasonally changing distribution in western Lower Michigan with data from the period November, 1965, through March, 1971, focusing particularly on the synoptic conditions that might contribute to it. Additionally, the study examines the relationship between the water content of snowcover and increasing distance from the lake shore, in order to assess the possibility that certain forms of frozen precipitation display geographic preferences within each fall of lake-snow.

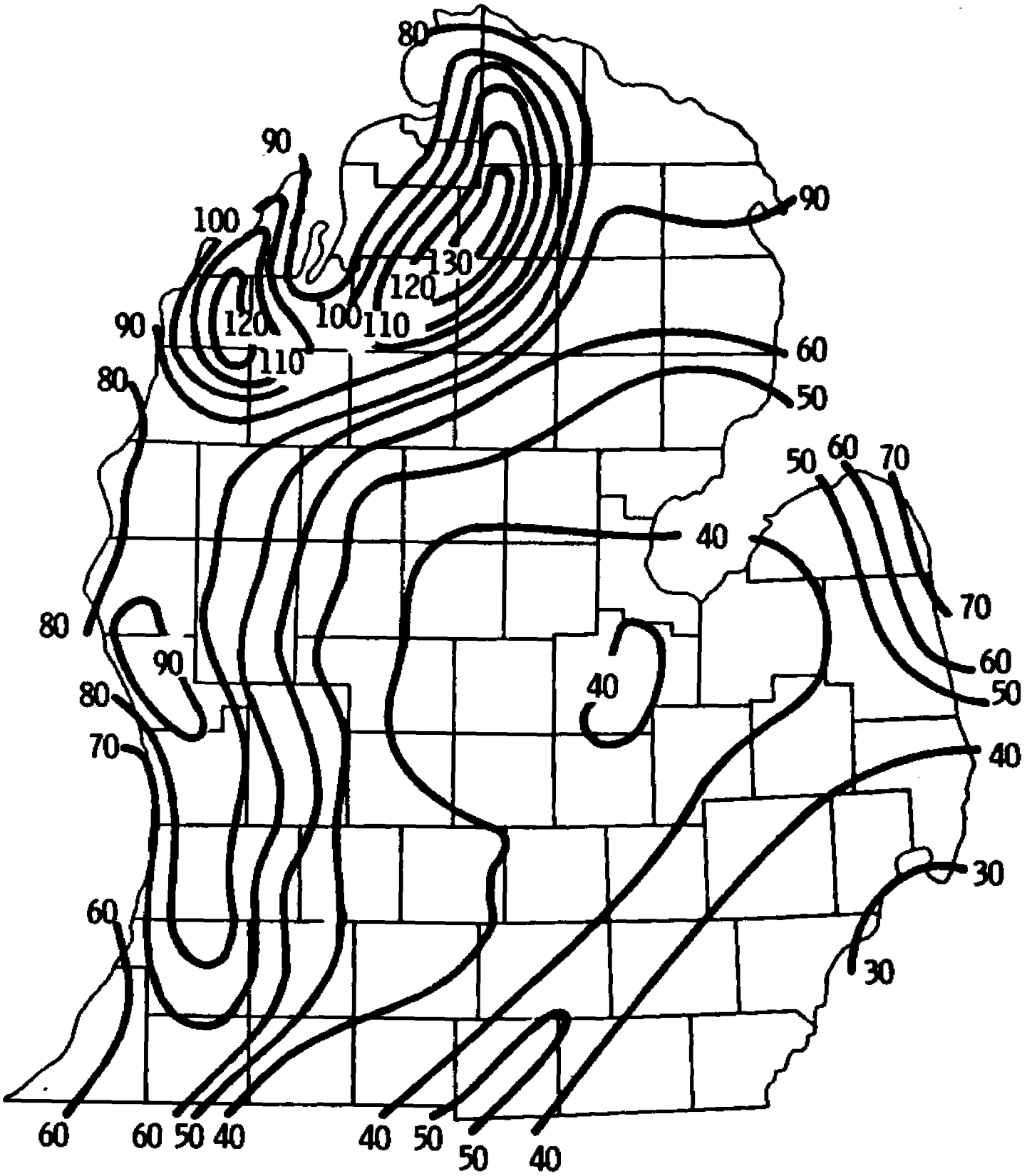

Figure 1-1.--Average annual snowfall for Lower Michigan, 1940-1969.

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CHAPTER II

REVIEW OF THE LITERATURE

Seasonal snowfall totals over the central United States generally increase from south to north, with lesser changes occurring from west to east. This pattern is the result of snowfall associated with moving cyclonic storms and their accompanying fronts. Substantial variation from this general pattern has been attributed to local influences, either large changes in terrain relief or the proximity of large bodies of water (1,2).

The snowfall pattern for each individual storm includes a core of heavier snowfall with lesser amounts observed either side of the core. This core usually lies approximately parallel to and north of the storm-center's path. These moving storms follow different paths, all originating east of the Rockies. The primary paths are the Alberta, Colorado, and Southwest, with the assigned names reflecting the geographical regions of initial cyclogenesis (3,4,5). Each produces snowfall with differing characteristics reflected in duration, snowfall depth, and water-content relationships.

One notable exception to the expected cyclonically produced snowfall pattern occurs in the Great Lakes region.

Here the lakes, with their large expanse of open water, modify the snowfall pattern with persistent localized snowfall that often begins shortly after the surface storm system passes east of the lakes and may continue for days after skies normally should have cleared. This persistent snow was referred to as flurries in the earlier literature and was first described as topographically produced by Brooks in 1915 (6).

Snow flurry activity over Lake Michigan, based on observations supplied by the car-ferry captains making runs from Ludington, Michigan, to Milwaukee and Manitowoc, Wisconsin, was explained as early as 1921 by Mitchell (7). He theorized that cold air, advected over the warmer lake water, led to the formation of the steam or fog a short distance from the west shore, a condition that continued until about mid-lake where the fog developed into a well-defined cloud deck followed shortly by the onset of flurry activity that continued to the east shore and on inland. These snow flurries were observed over the lake anywhere between 20 and 50 miles from the east shore early in the season, but were often limited to lesser distances, as little as two to three miles offshore, when the lake temperatures cooled to near freezing in January.

In 1928, Dole (8) referred to the flurries as snow squalls and described them as a hazard to aviation over western Lower Michigan. He suggested the synoptic conditions

necessary for the occurrence of these squalls included a surface trough extending southwestward from a deep low center north and east of the Great Lakes and large differences between the temperature of the air and the lake water over which it is advected. Dole also believed the sun's influence was necessary for the development of the heavier squalls, referred to as "sun showers," and that they ended when the sun set.

The influence of the lake on climatic parameters observed along the east shore versus the west shore of Lake Michigan was summarized by O'Dell in 1931 (9). He emphasized that westerly winds are stronger in winter, the precipitation total is greater, and the number of days with snowfall is much greater on the east shore than on the west.

In addition to a well-developed, stagnant low pressure system in the vicinity of the St. Lawrence Valley, Sheridan (10) suggested that winds be at least 25 miles per hour, the lake-air temperature difference be at least 20 degrees Fahrenheit, and the wind direction vary little with height in order for significant lake-snow to develop. Expanding on these concepts, Remick (11) included the frictional influence as important in producing favored areas of convergence and added the configuration of the lake shore as an important contribution. This latter factor was stressed by Thompson (12) as determining both intensity of and area affected by the snow flurries. Remick also

suggested that the thermal input by the lakes raised the low-level inversion height of the advected Arctic air from about 0.8 Km north of the lakes to between 2 and 3 Km along the south shore of the Great Lakes. For an exhaustive review of many other early studies of lake-snow climatology, the reader is referred to Eichenlaub (13).

Until the application of modern technology in the mid-1960's, little additional progress was made in understanding the roles of the various meteorological factors in producing lake-snow or in identifying any additional micro- and meso-scale features of this unique phenomenon. Perhaps the need for and economics of an adequate water supply are responsible for stimulating recent work on lake-snow development and its impact on industry, agriculture, and society. Weickman (14) expressed this need when he wrote, "It is obvious that artificial manipulation of atmospheric resources over the lakes may have a very significant influence on various human activities." The exact contribution of lake-snow to the hydrologic cycle will vary within the watershed for each lake and with change of season. Webb and Phillips (15) attempted to calculate the lake-snow contribution for the Lake Erie and Lake Huron basins by assuming a ten to one snowfall to water-equivalent ratio. They concluded that only 6 percent of the mean seasonal snowfall for the Lake Erie basin was a result of lake-effect snow. Jiusto (16) showed that the snowfall to water-equivalent

ratio average was six to one near the shore and increased to fifteen to one inland and as the season progressed. However, the snowfall to water-equivalent ratio was also described as highly variable, depending on the type of snow observed, and ranged from less than five to one to more than fifty to one.

Lake-snow occurrences observed by radar and satellite confirm two basic cloud patterns, the multi-band and single-band storms (17,18,19,20,21). The characteristics of the multi-band storms associated with shorter air trajectories include lower inversion heights, smaller air and lake water temperature differences, and roll-type convection. The single-band storms are more persistent and intense, have a better organized surface circulation, show a thermally driven circulation, and develop wider flow approximately parallel to the longer axis of the lake. Similar features have been observed in the North Atlantic and Sea of Japan during cold air outbreaks in these areas (22,23,24,25,26). Because Lakes Erie and Ontario lie parallel to the path taken by many Arctic air invasions, snow squalls to their lee often assume the latter characteristics, whereas multi-band storms are more characteristic in western Lower Michigan.

The changing frequency of lake-snow and its contribution to the hydrologic cycle may be tied to worldwide climatic trends. Earlier in this century a general warming

trend was noted, whereas during the last two decades substantial cooling has prevailed (27,28). This cooling trend was linked by Namias (29,30) to changes in oceanic temperatures over the central Pacific, and resulted in a circulation pattern over the central United States that was more frequently favorable for the development of lake-snow during the 1960's.

Using the latest in modern technology, radar, satellites, computers, instrumented aircraft, and a denser climatological network, researchers at Cornell Aeronautical Laboratories, Incorporated, State University of New York at Albany, and Penn State University have focused on detailed observation of storms in progress and development of a computerized numerical model that predicts the major features of the observed lake-snow events. Typical single-band lake-snow situations over the eastern Great Lakes were studied during this cooperative effort. The storms over Lake Erie, analyzed by McVehil (31,32), were characterized by an air trajectory into western New York from south of Lake Superior through Illinois, Indiana, and Ohio, and a confluence line over southern Lake Erie where low-level winds displayed a 20 to 60 degree difference in direction. Winds south of the confluence line, for 50 to 100 miles, were southwest to south-southwest and subjected to a strong cross-isobar flow of 60 to 90 degrees, whereas winds to the north of the confluence line, for about 25 miles, were

west to west-northwest. A storm over Lake Ontario on February 3-4, 1965, was observed by Peace (33) to have a surface confluence zone parallel to the upper-level winds; a marked surface wind shift, southwest to northwest, under the north edge of the most intense snowfall; and a confluence zone parallel to the pressure field. The pressure gradient was stronger to the south of the confluence zone.

These intense, single-band storms had many similarities in wind structure and distribution. For example, inflow from the surface continued up to about 1.5 Km and was strongest from the south; above 1.5 Km to the cloud top an outflow prevailed and was strongest to the south. Radar also confirmed that although the north edge was sharp, the south edge tended to be more diffuse. This latter feature, confirmed later by aircraft observations, was the result of snow crystals carried in the outflow from the upper portions of the cloud (34,35).

Work on numerical models for the lake-snow development included as many of the new concepts as possible, but computer limitations in resolving the many dependent variables in three dimensions necessitated compromises. However, the primary features of lake-snow were obtained by dividing the model considerations into three basic layers. The lowest, characterized by a superadiabatic lapse rate, represents a zone of upward heat flux. This layer was arbitrarily limited to the lowest 50 meters. The second layer,

characterized as a homogeneous layer, extends from the 50-meter level to about 5 Km or less and is terminated by a layer that is characterized by an isothermal or stable lapse rate. The results generated from this three-layer model generally produce a lake-snow development that agrees with the major lake-snow features observed in the earlier field work (36).

Utilizing the results of these later studies, some adjustments of earlier conclusions concerning lake-snow development are necessary. Because of the observed mobility in orientation of the snow band locations over the eastern lakes, the sea breeze, frictional convergence, and orographic effects must be ruled out as primary mechanisms controlling shape, location, and movement of these storms. Once the storm has formed by heating of the air from below, these effects may intensify the resulting precipitation, with the heavy snowfall rates primarily a function of the strong moisture concentration into a narrow convergence line (37).

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CHAPTER III

METHODS

Determination of the Study Area

The study area is located along the east shore of Lake Michigan and extends north to south the entire length of Michigan's Lower Peninsula. Three traverses, extending inland and perpendicular to the Lake Michigan shore, were selected to measure the displacement from the lake shore to the axis of maximum observed snowfall. One traverse completely crosses the southwest lower climatic division, another the west-central lower climatic division, and the third crosses the northwest lower climatic division and part of the northeast lower climatic division (Figure 3-1). These provide a sample from the climatic divisions most strongly affected by lake-snow in Lower Michigan.

To locate these traverses initially, I plotted on maps monthly snowfall totals for each climatological station in the Lower Peninsula to determine general snowfall patterns. The axis of maximum snowfall was then drawn on each monthly snowfall map for the period from October, 1965, through April, 1971. The axis of maximum snowfall was not always continuous from north to south across all climatic divisions, particularly for the early and late snow season

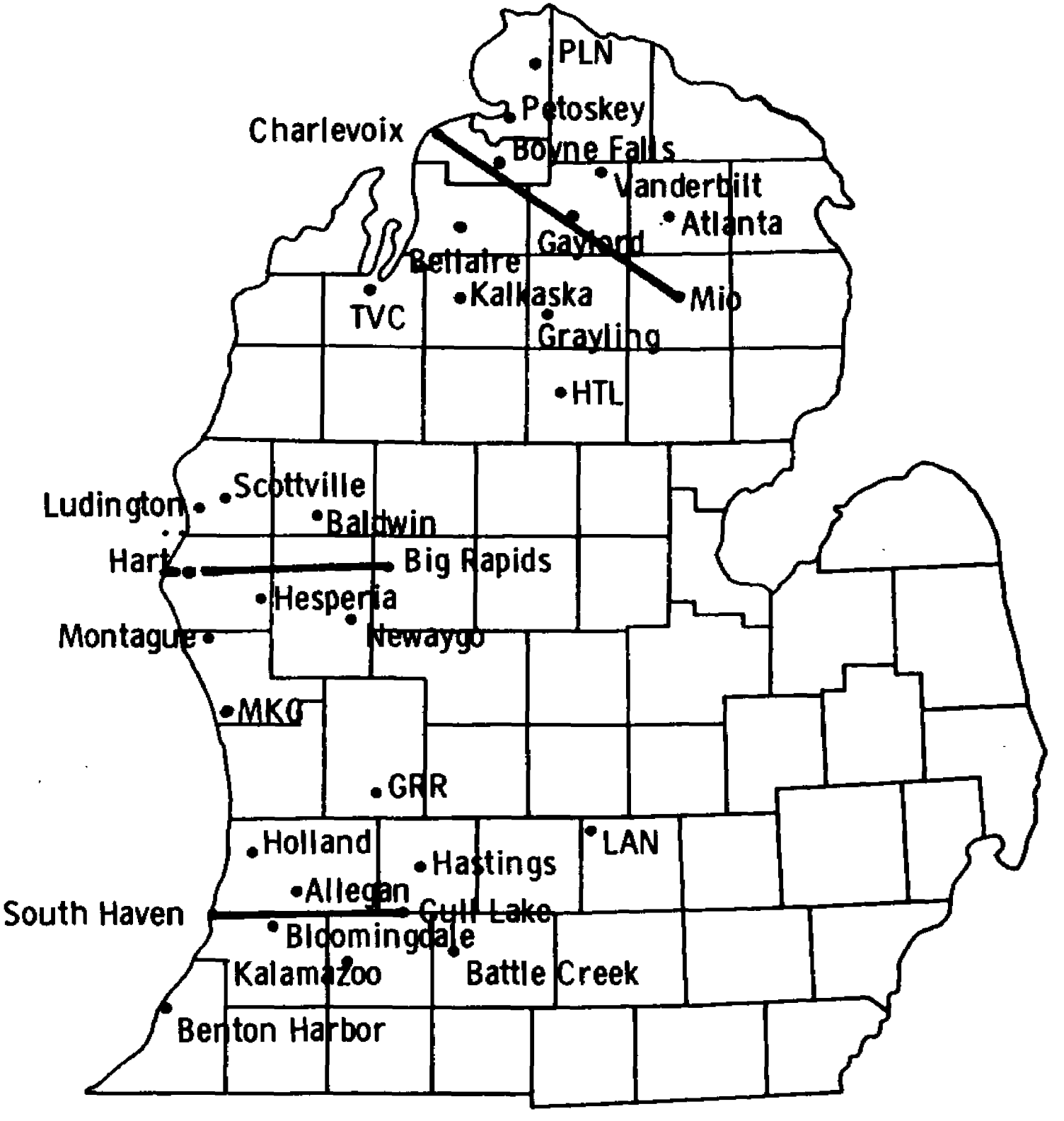

Figure 3-1.--Location of traverses used in study area.

months of October, November, March, and April. The total monthly snowfall for the areas considered generally increased from south to north in agreement with the pattern normally expected if the Lake Michigan influence were absent. The monthly snowfall totals used initially in determining the displacement inland of the axis of maximum snowfall reflect the distributions of both lake-snow and snowfall associated with traveling cyclones.

Additional considerations in selecting the traverse locations were the frequency of observed lake-snow, terrain and/or relief, and distribution of climatological stations, and the direction of the upper-level wind flow. Because the frequency of lake-snow decreases from north to south, a sample was desired for the areas of varying frequency for lake-snow development. The terrain relief, like the frequency of lake-snow, generally decreases from north to south and is known to have some influence on lake-snow amounts (1). The traverses selected are near or include climatological stations located on the lake shore and extend inland so that as many other stations as possible could be utilized to help in locating the axis of maximum snowfall. Variability in data density and quality may have some influence on the results, a problem minimized by consideration of the patterns along the traverses both north and south of the one in question. The traverses are also oriented parallel to

the prevailing, west to northwest, upper-level wind flow during periods of lake-snow.

With the three traverses selected, the displacement inland of the axis of maximum snowfall was measured for the months where the axis was clearly identifiable for the six seasons from October, 1965, through April, 1971. The axis location shifts closer to the lake shore between fall and winter but backs to an inland position as spring approaches (Table 3-1).

Table 3-1.--Displacement for axis of maximum snowfall for winter seasons 1965-66 through 1970-71.

Division	Month	Average	N	R
Southwest	November	27.0	4	17 to 36
	December	19.2	5	8 -- 34
	January	10.6	5	5 -- 16
	February	13.2	6	6 -- 23
	March	20.7	3	19 -- 23
West Central	November	19.7	3	10 -- 36
	December	12.0	6	8 -- 24
	January	10.0	6	7 -- 23
	February	9.7	6	8 -- 12
	March	12.0	2	10 -- 14
Northwest	November	34.8	6	31 -- 37
	December	34.0	6	26 -- 37
	January	19.4	5	7 -- 33
	February	28.0	6	12 -- 37
	March	38.3	4	35 -- 43

N = number of seasons

R = range of displacement in miles from the lake shore.

The favorable agreement in the shifting location of the axis for maximum snowfall along all three traverses suggests a similar control mechanism over the entire western portion of Lower Michigan. Because of this agreement, western Lower Michigan is considered a favorable area for testing the hypothesis on the shifting location of the axis of maximum observed lake-snow with the progression of the snow season.

The Physical Setting

The Lower Peninsula lies in the eastern lake section of the Central Lowland Province and the western division of the Lower Peninsula (2). This area is bounded by Wisconsin to the west of Lake Michigan; Indiana and Ohio on the south; Lake Erie, the Detroit River, Lake St. Clair, and Lake Huron on the east; and the Straits of Mackinac to the north. The Lower Peninsula was covered by glaciers during the Wisconsin glacial period, which ended approximately 12,000 to 16,000 years ago in Michigan. The present surface relief is primarily the result of glacial deposition centered over the former Michigan basin. Elevations above Lake Michigan vary from 50 to 200 feet over most of southern Lower Michigan, but increase to about 800 (1400 MSL) in north-central Lower Michigan (Figure 3-2).

The climate in the study area varies from a cool-summer, humid continental type in the north to a warm-summer, humid continental type in the extreme south (3). July

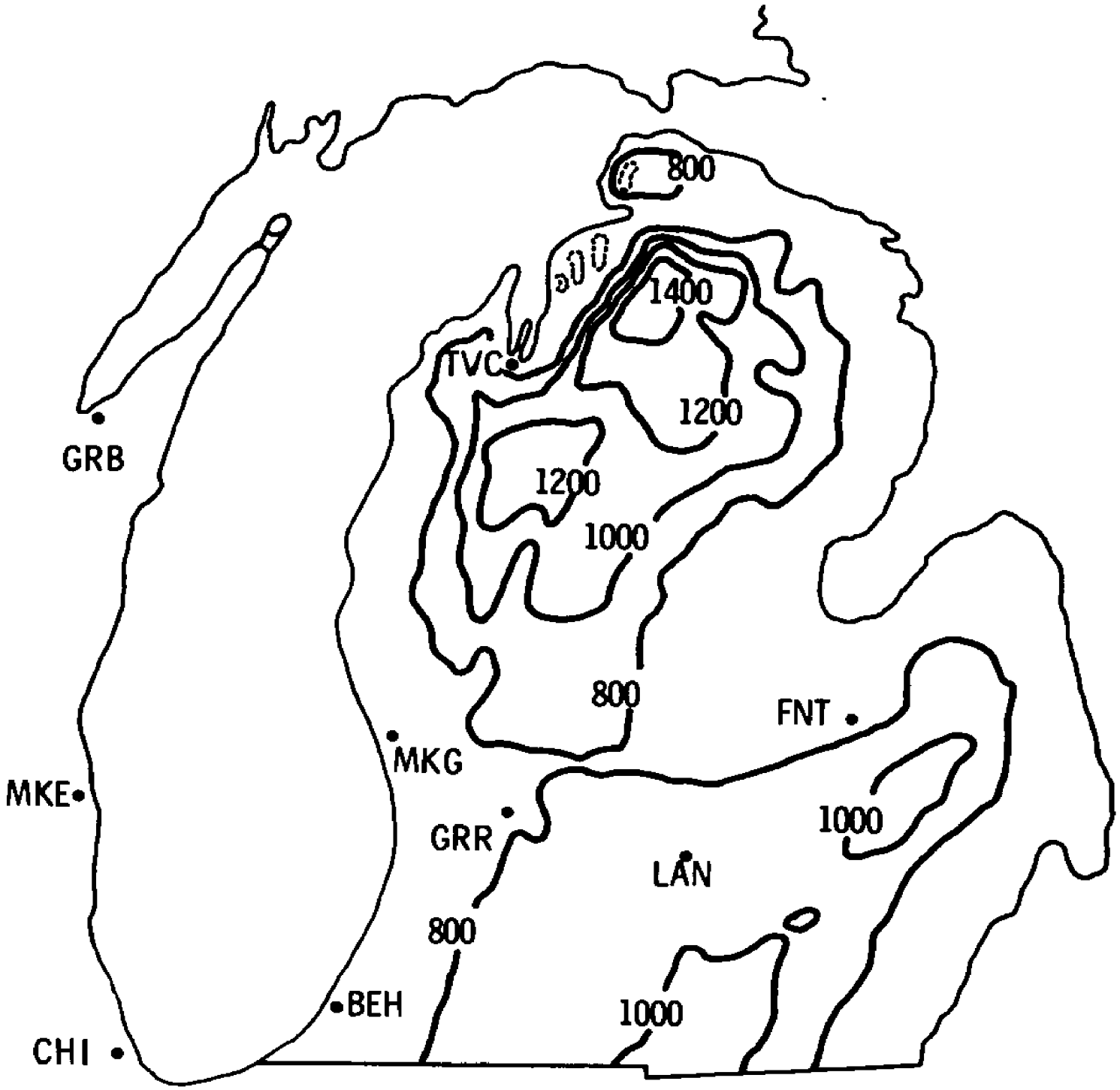

Figure 3-2.--Location of selected stations and elevation in the study area.

temperatures average about 65°F in the north and increase to over 72°F in the south. January average temperatures vary from 17°F in the north to 27°F in the south. The mean annual temperatures similarly vary from about 42°F to 49°F. Stations closer to Lake Michigan display a semi-marine rather than continental-type climate. The annual precipitation varies from over 36 inches in the southwest to less than 28 inches in the east-central section. The prevailing winds vary from southwest to northwest with the change of seasons (4). Average annual snowfall ranges from less than 30 inches in southeast Lower Michigan to 60 inches in the southwest to over 120 inches in the east-central section of the Northwest Lower Climatic Division (5).

Methods

To test the hypothesis, the writer developed the data utilized to determine a possible control of the changing displacement of the axis of maximum lake-effect snowfall. These data included determination of lake-snow days, the existence of an axis of maximum daily snowfall for lake-snow and the associated displacement, the temperature differences between the lake water and the air being advected over the lake, and the associated wind direction and speed. Data utilized for the study were located in archives of the National Climatic Center (NCC), Asheville, North Carolina; Atmospheric Sciences Library (ASL), Washington, D.C.; the

National Environmental Satellite Service (NESS), Suitland, Maryland; and the State Climatologist's Office, East Lansing, Michigan. The ASL data were on microfilm and included the machine analysis output of the National Meteorological Center (NMC), Suitland, Maryland. The data from NCC were extracted from original and quality-controlled records.

Snowfall Data

Snowfall maps were plotted for each observed occurrence with a trace or more, to identify days of lake-snow; data were obtained from the published Monthly Climatological Data (MCD) for Michigan (6) and supplemented whenever possible by a seasonally operated snowfall network (7). Each day with snowfall was then assigned to a category of lake-snow (L), lake-snow and storm (L&S), or non-lake-snow (N).

To determine if a given day had experienced lake-snow, the Daily Weather Map series (8) was examined for the location of storm systems and fronts. If no cyclonic storm centers or fronts crossed the Great Lakes and if skies were essentially clear west and north of the Great Lakes, but cloudy with snow showers from Michigan eastward, this date was accepted as a lake-snow day and identified as (L) on the map. Not all lake-snow days could be this easily identified. In some cases, the surface storm system had recently crossed Lake Michigan or was located over the eastern portion

of the Great Lakes. In this case, when the observed snowfall over the interior portion of the Lower Peninsula was a trace or zero, but heavier snow was observed along the lake shore, the day was classified as lake-snow and storm and the daily map marked (L&S). This procedure eliminated those cases when a substantial portion of the total snow was possibly cyclonic in origin. Admittedly, it does allow for the inclusion of a small contribution of cyclonic snow, but this contribution is believed to be minimal and was judged not to influence the location of the axis of maximum snowfall being studied.

The snowfall observations from Michigan's climatological stations do not correspond to the synoptic map times published in the Daily Weather Map series. Most Michigan cooperative stations take one daily observation about 6 PM EST (Figure 3-3), whereas the published synoptic maps were for 1 AM and 1 PM EST. This difference was not considered a major obstacle since the hypothesis does not require the consideration of the actual time of beginning or the duration of snowfall. The National Climatic Center, responsible for quality control for the cooperative climatological observations, as a matter of routine practice does adjust precipitation totals from stations taking readings at other times to ensure that the data are in agreement with other stations.

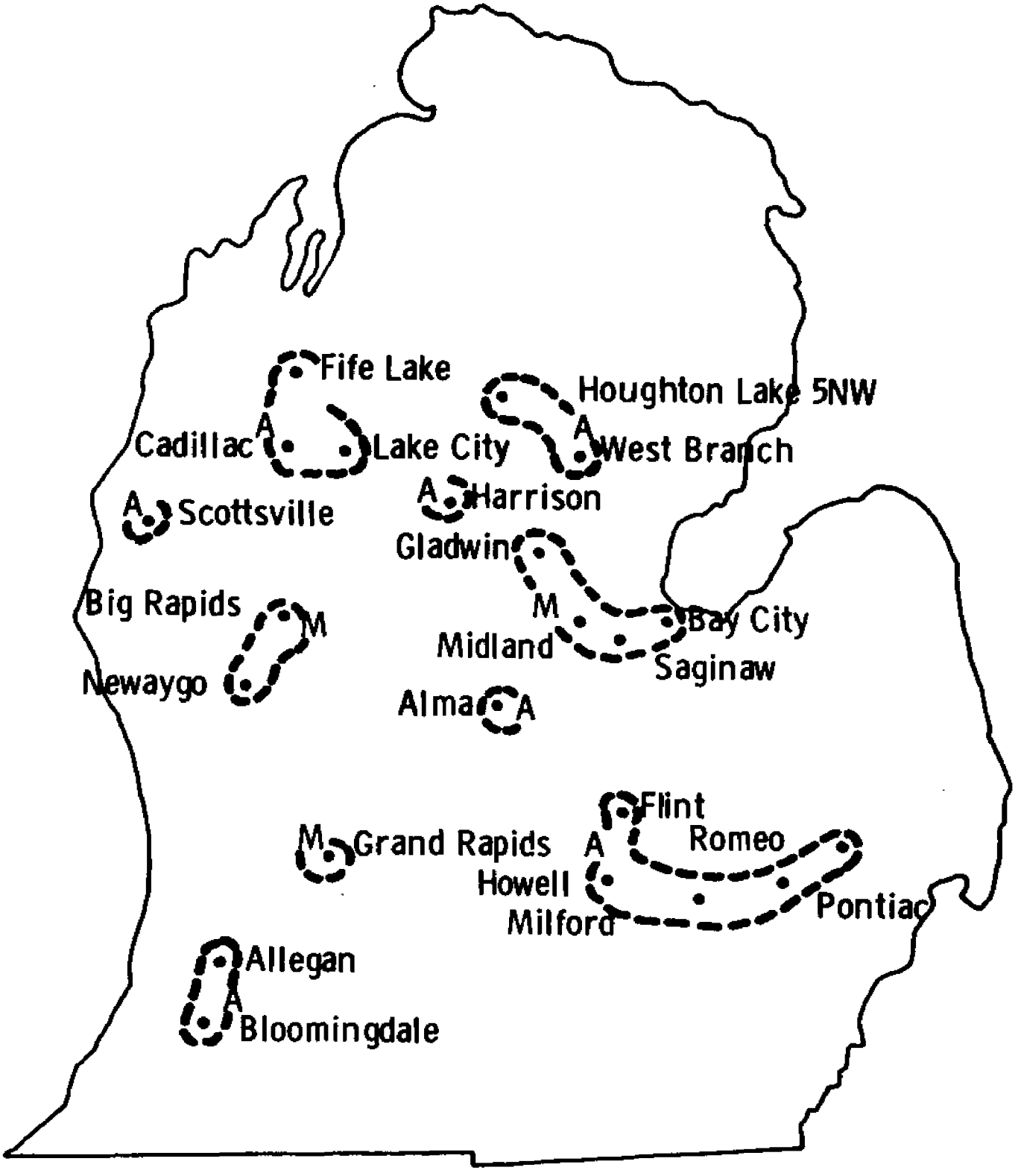

Figure 3-3.--Time of cooperative climatological observations. The cooperative climatological observations are late PM unless indicated by M (midnight) or A (AM).

The (L) and (L&S) maps were then analyzed for snowfall patterns at one- or two-inch intervals to determine the axis of maximum snowfall. The displacement (ΔD) of the maximum snowfall from the shoreline was then measured along each traverse. In cases where the indicated snowfall axis did not cross the actual location of the traverse but was observed within 25 miles to the north or south of the traverse line, this displacement distance was accepted. After the dates of (L) and (L&S) snow had been identified, they were combined as a pool for subsequent use in the remainder of this study.

The snowfall/water-equivalent ratio was measured through field surveys and determined by use of cooperative station records. The ratio is obtained by dividing the observed snowfall by the measured water content from the cooperative station records and the measured snowdepth divided by the water content of a sample snow core in the field surveys. The ratio is highly variable for individual storms in the former case, but is much less variable in the latter approach. Two field surveys, on February 14-15, 1972, and January 10, 1973, were made to sample the snow-depth to water-content ratio in Michigan's Upper Peninsula lake-snow belts where long snow accumulation occurs and rainfall during the winter months is less frequent. The samples were cut with a standard eight-inch precipitation gauge equipped with cutting edge and the water content

determined by weighing the sample with the standard spring-activated scale (9). These data provided an indication of how the snowfall to water-content ratio varied from the lake shoreline toward the interior of the peninsula.

Temperature Data

Temperature data for each lake-snow day were extracted for the 850 mb, 700 mb, and 500 mb levels from microfilm maps obtained from the Atmospheric Sciences Library (10). The data plotted on these maps were collected from the 0000 GMT and 1200 GMT radiosonde releases. Occasionally the maps contained only the raw data, and the isothermal and isoheight analysis had to be completed before the desired data could be extracted. The temperature data were extracted at a point approximately midway across Lake Michigan between Ludington, Michigan, and Manitowoc, Wisconsin.

Lake Water Temperature Data

The lake water data were obtained from the original car-ferry logs available from the National Climatic Center (11). These data were taken near mid-lake on each run made between Ludington, Michigan, and Milwaukee or Manitowoc, Wisconsin, and were sampled from the engine water intake valves at a depth of about six feet. Some of the car ferry water temperatures were recorded in Fahrenheit, but most

were in Celsius. All readings were converted to Celsius for future computations.

To minimize any bias in the lake water temperature readings from the various car ferries, readings from a single ferry (SS City of Midland) were used whenever they were available, and the temperatures from the other ferries were used as supplemental data. Comparison of temperatures on days when more than one ferry made runs showed good agreement. Lake water temperatures were estimated from adjacent days when the car ferries did not make runs. During the fall and early winter months the car ferries frequently made two to four crossings per day, providing some indication of a diurnal variation. These were averaged together to give a single daily temperature, since the variation seldom exceeded more than 2° Celsius. During mid-winter the number of days with missing data increased. Fortunately, by this time, the lake water temperatures had stabilized at about 2°C and seldom varied from this reading by more than 1°C.

It is recognized that the lake water temperatures are not uniform over the entire lake, but the variation during the fall for most portions of the lake is minimized because of the more vigorous mixing in the upper layers as a result of passing storms (12,13). Thus, the mid-lake location is quite representative of the majority of lake water readings.

The temperature differences (ΔT) between the upper levels of the atmosphere and lake water were then computed for each day that lake-snow occurred. The ΔT's used in later computations were limited to the larger of the two observed values for the day in question. The temperature differences were then divided into four groups: all ΔT's lake-water minus 850 mb, less than or equal to 19°C, 20° to 24°C, 25° to 29°C, and all equal to or greater than 30°C. This was done to see if a correlation existed between increases in the ΔT values and the observed displacement of the axis of maximum snowfall.

Wind Data

Wind data used in the study included observed winds from radiosonde sites at Green Bay, Wisconsin, and Flint, Michigan, and the calculated geostrophic winds from approximately mid-Lake Michigan. Wind data for the radiosonde sites were extracted from the quality-controlled records available from the National Climatic Center (14). Only these stations adequately represent the wind both upwind and downwind of the study area during periods of lake-snow. The data are for 0000 GMT (7 PM EST) and 1200 GMT (7 AM EST), and were compiled for each day of lake-snow. The wind data extracted included direction and speed for the surface, 850 mb, 700 mb, and 500 mb levels. No substitutions were made for missing observations, but this amounted to only

1 percent of the total number of lake-snow days, a figure considered too small to influence the results significantly. The winds were initially averaged for each observation time to uncover any apparent differences between the morning and evening ascents. Only minor differences were observed; the trends were essentially the same for the AM and PM data.

Since the trends in the wind speed data from November into January and from January through March suggest that December and February were transition months, these months were split into two periods. These included December 1 to 15 and 16 to 31, and February 1 to 14 and 15 to 28 (15 to 29 for leap year). The larger variance and limited sample size for October and April indicated that these months be eliminated from further consideration for this study. Thus only the months of November through March were utilized to evaluate the change in the axis of maximum snowfall.

The observation times for the radiosonde soundings coincide quite well with the majority of the climatological observations. This late afternoon climatological observation, approximately one hour before release time for the radiosonde, does cover essentially the same period. Thus the average observed wind speed for the two daily radiosonde ascents provides representative data upwind and downwind from the area of lake-snow.

Because the available observed winds aloft were limited to two locations, a geostrophic wind over mid-Lake

Michigan was calculated. This calculation not only provided a check on the trends in the observed winds but also allowed a comparison between the observed and theoretical winds. The data to calculate the geostrophic wind were extracted from the microfilmed machine analysis issued by the National Meteorological Center for the 850 mb, 700 mb, and 500 mb levels. Geostrophic wind was computed using the following equation (15): $V_g = \frac{g}{f} \frac{\Delta Z}{\Delta N}$ where ΔN is distance in degrees latitude, ΔZ is the change in height in meters, g is the acceleration of gravity, and f is the coriolis parameter. To simplify the calculation, ΔZ was held constant at 60 meters and ΔN was measured in degrees of latitude for each 60-meter change in height on the constant pressure surface at the point centered over Lake Michigan. In the computation g and f were considered constants with $g = 9.8$ m/sec^2 and $f = 10^{-4}$/sec. Solving for $Vg = \frac{52.5 \text{ m/sec}}{\phi} = \frac{102.120}{\phi}$ kts. Using this equation a table was prepared so that by knowing ΔN in degrees and tenths of latitude one could quickly read and record the corresponding wind speed (see table in Appendix D). To help in extracting the needed latitude data, an overlay was prepared for the different scales of the upper air charts. The lake-snow days were then classified into two groups by wind direction at 850 mb level, 250 to 290 degrees and 300 to 330 degrees inclusive respectively representing west and northwest flow cases. Only a small sample fell outside these ranges. This procedure was

followed to determine whether differences in displacement of the axis of maximum snowfall could be detected with a change in upper-level flow.

Satellite Data

Satellite photographs were used to document the cloud patterns with ground-observed data. The earlier satellite photographs have poorer resolution but are still sufficient to portray in desired detail many features of lake-snow. The NOAA-2 VHRR satellite prints now becoming available have a much higher resolution and detail is much clearer. These data were obtained from the National Environmental Satellite Service (16).

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CHAPTER IV

RESULTS

Hypothesis

The hypothesis for this research is that the seasonally changing axis of maximum snowfall in western Lower Michigan is related to the strength of the westerly winds during periods favorable to the development of lake-snow. It is suggested that the displacement inland of the axis of maximum snowfall is the result of the speed of the westerly winds in the lower troposphere during the occurrence of lake-snow. Thus the average wind speed during periods of lake-snow is expected to be lower at times when the axis of maximum snow is closest to the lake shore, and higher when the axis of maximum snow is farther inland. It is further suggested that the frequency of heavy lake-snow, amounts greater than eight inches in 24 hours, increases as the ΔT (difference in the lake versus ambient air temperature at 850 mb) increases. Thus the larger the $\Delta T = {}^{T}lake - {}^{T}850mb$, the greater the likelihood of heavy lake-snow. Additionally, it is suggested that the water content of the snow is generally higher nearer Lake Michigan than at sites inland.

Displacement (ΔD) of the Axis of Maximum Snowfall

Based on six winters, from November, 1965, through March, 1971, 257 lake-snow days were identified. January, with 85 days, had the greatest number whereas March, with 23, had the least. Because December and February were treated as transitional months and divided into two periods, the sample period with the smallest number of lake-snow days was December 1-15 with 22 days (Table 4-1).

Table 4-1.--Lake-snow days by periods.

Period	Designator	Number of Days With Lake-Snow
November	N	33
December 1-15	D_1	22
December 16-31	D_2	42
January	J	85
February 1-14	F_1	28
February 15-28 or 29	F_2	24
March	M	23

The average location of the axis of greatest snowfall for the seven periods shifts from inland early in the lake-snow season toward the lake shore in mid-winter and then retreats inland as spring approaches. This trend is the same for all three traverses but the actual shift is over a greater distance in the Northwest Climatic Division (Figure 4-1). The Southwest and West-Central Climatic Divisions average location shifts from between 20 and 25

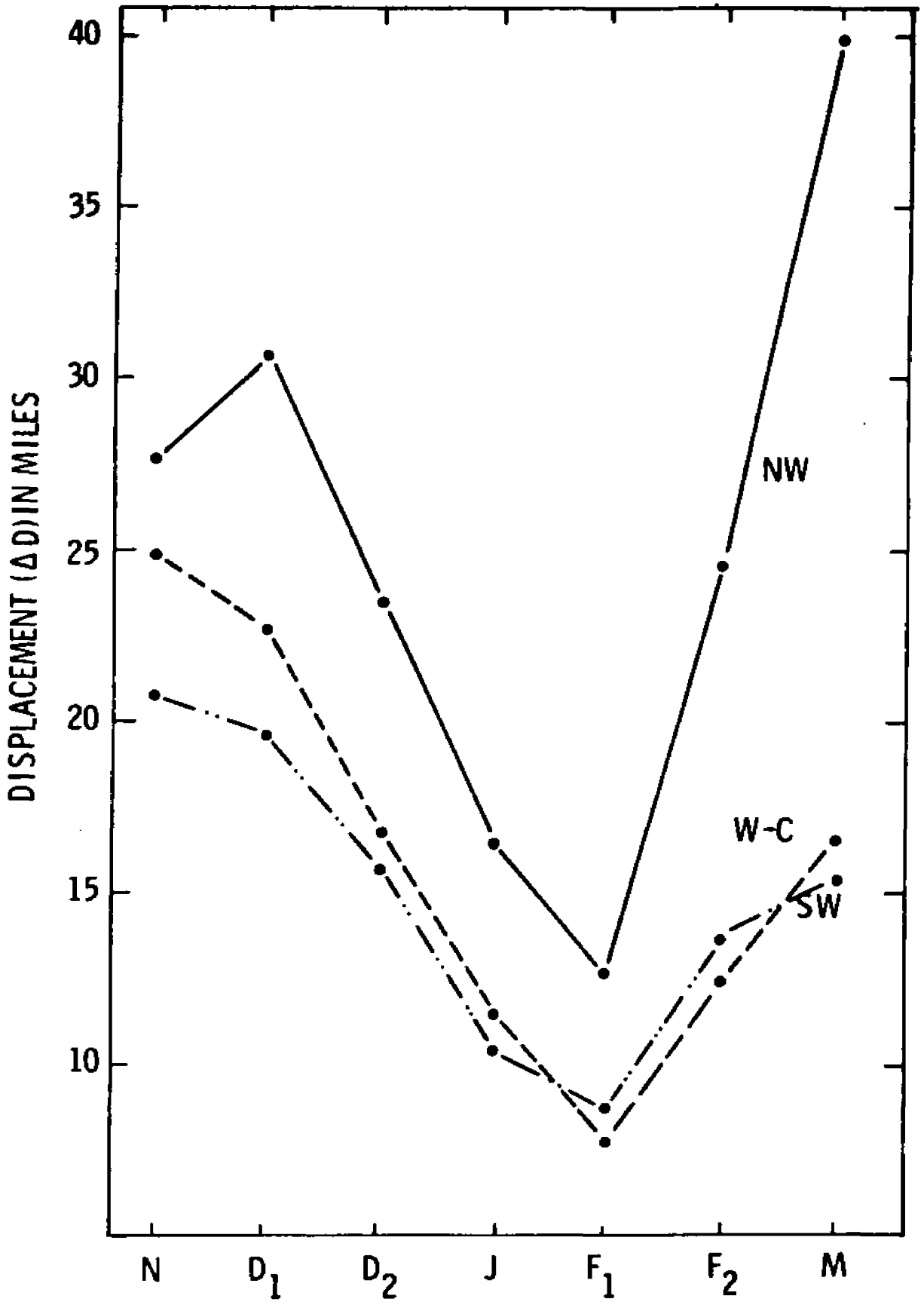

Figure 4-1.--Average displacement (ΔD), axis of maximum lake-snow, by designated periods from November, 1965, through March, 1971.

miles inland during November and early December to eight to twelve miles inland during January and early February and then retreats to fifteen to seventeen miles inland during March. The average location over the Northwest Climatic Division varies from 27 to 31 miles inland during November and early December to thirteen to sixteen miles in mid-winter and retreats to about 40 miles inland by March. In each Climatic Division the average displacement early in the lake-snow season is about double the average displacement during mid-winter (Figure 4-1).

Types of Snowfall Patterns

Three basic snowfall patterns are associated with lake-snow in western Lower Michigan. These include a basic single area of lake-snow (Figure 4-2); a band of lake-snow more or less uniformly distributed and approximately parallel to the lake shore (Figure 4-3); and a band of lake-snow more or less uniform and parallel to the lake shore but with one or more areas of much heavier snowfall (Figure 4-4). The latter two patterns, of almost equal frequency, account for 84 percent of the total observed lake-snow events during the study period.

Types of Cloud Patterns as Seen From Satellite

The Very High Resolution Radiometer (VhRR) infrared photograph for December 7, 1972, shows the basic cloud patterns expected during periods of lake-snow. Skies are

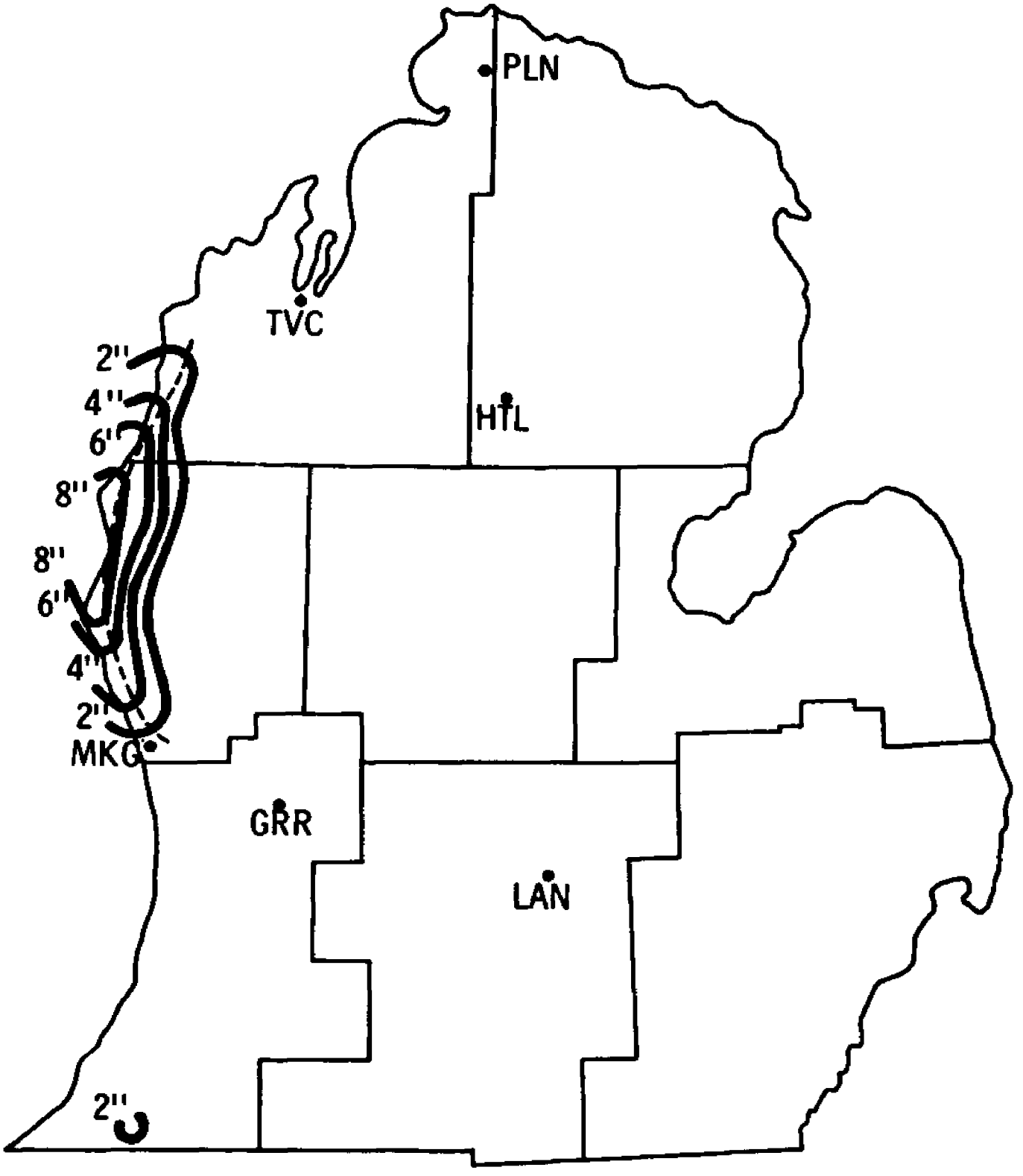

Figure 4-2.--Single area lake-snow, January 15, 1967.

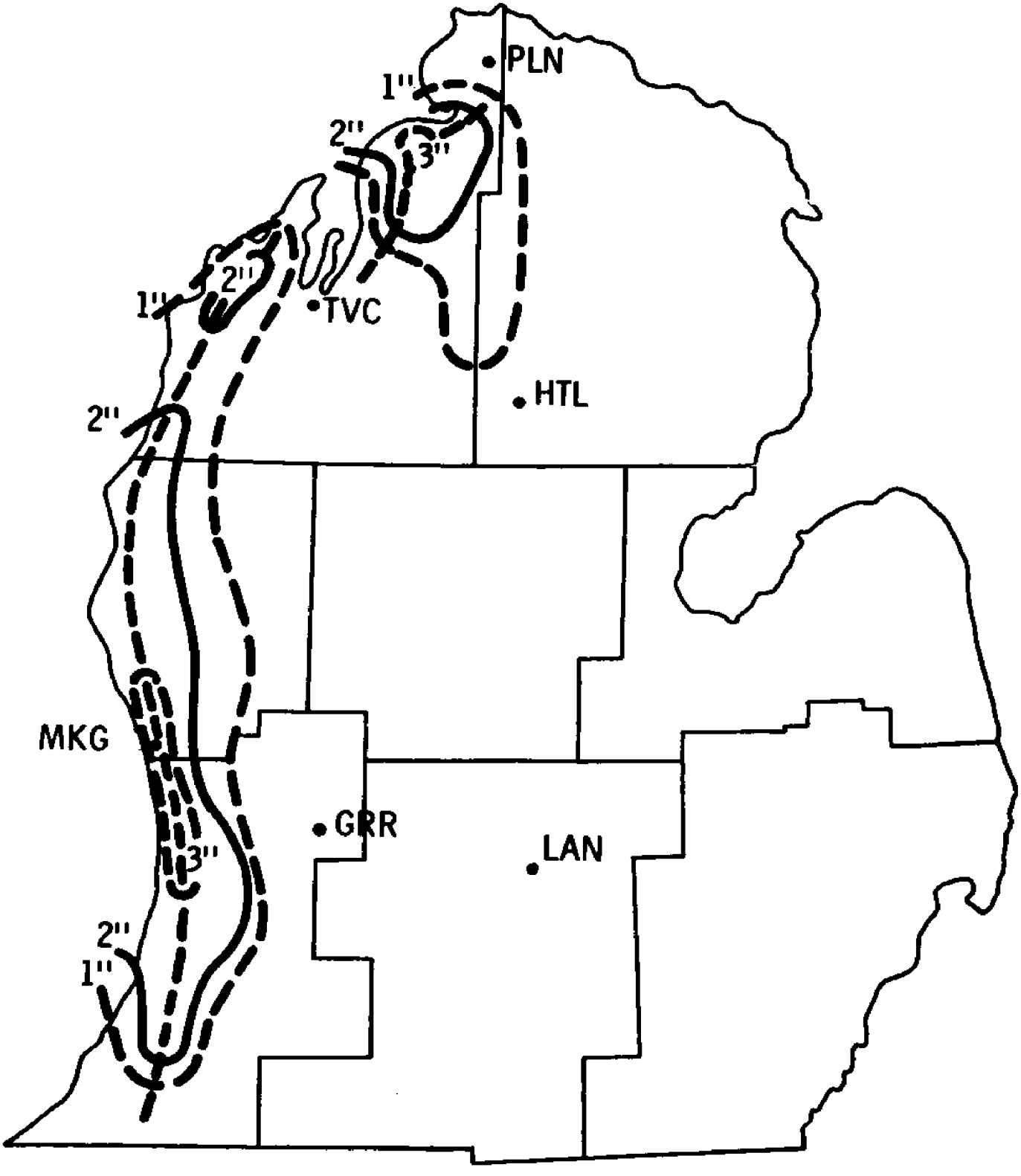

Figure 4-3.--Nearly uniform lake-snow band, January 18, 1967.

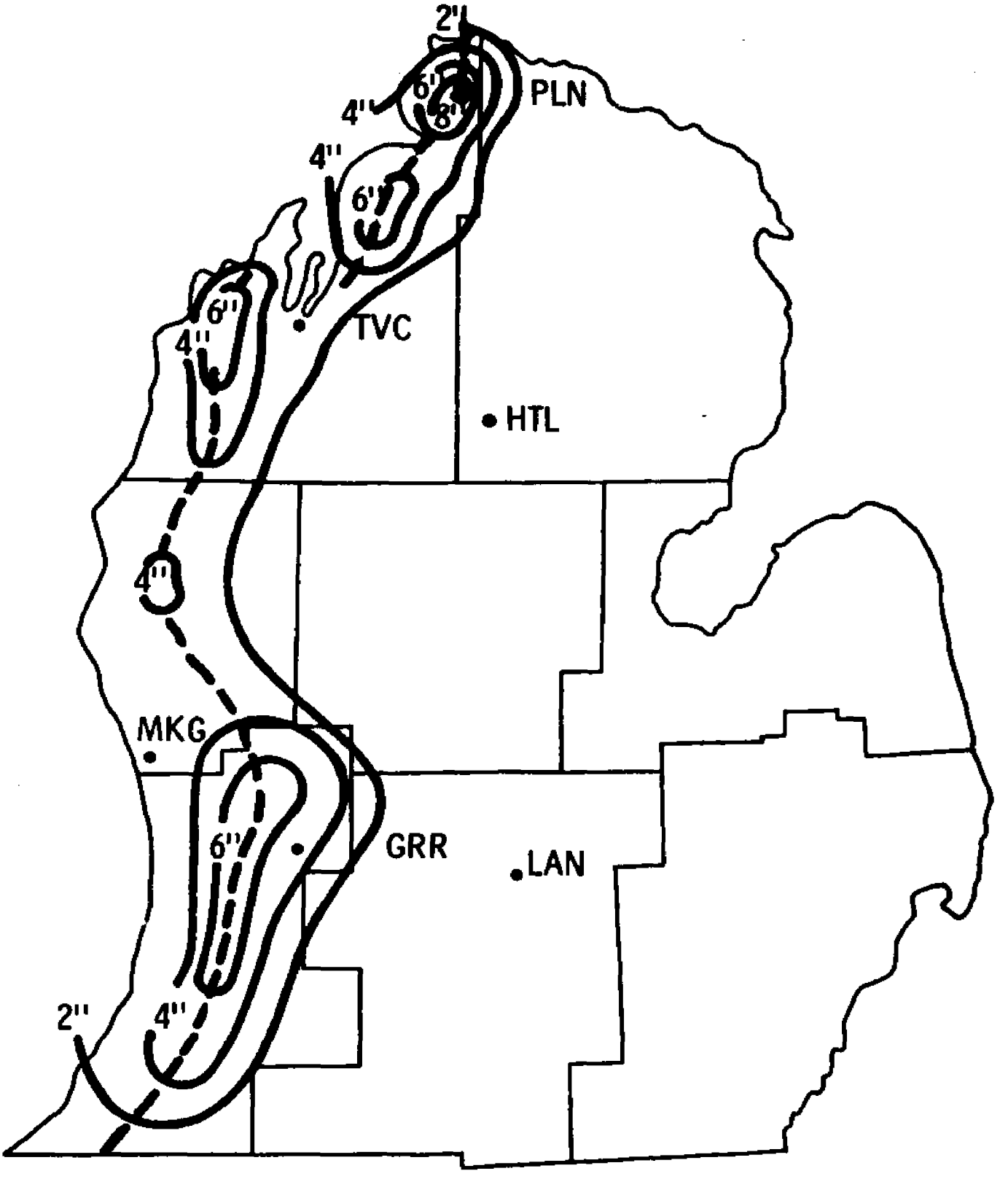

Figure 4-4.--Lake-snow with one or more areas of much heavier snow, November 15, 1969.

clear over most of the area west and north of the Great Lakes region and over northern Illinois. Narrow cloud bands develop approximately twelve to eighteen miles east of the west shore of Lakes Michigan, Huron, and Superior. These cloud bands continue across the respective lakes and extend inland approximately 40 to 65 miles before dissipating. The narrow bands converge into a single larger band or mass over northeastern Lake Huron (Figure 4-5).[1] When cold air is present and winds diminish to less than six to eight knots, a convective cloud pattern develops over Lake Michigan (Figure 4-6). In this photograph cloud-free areas exist along both the east and west shores of Lake Michigan. When surface and lower tropospheric winds over the Great Lakes are easterly, the cloud pattern shifts to the western portion of Lake Michigan (Figure 4-7). The final satellite photograph for January 27, 1971 (Figure 4-8), depicts cloud-free areas along the west shore of the lakes. The narrow single bands of clouds that cover most of Lake Superior merge into a somewhat enlarged cloud band near the south-central shore and extend south-eastward across northern Lake Michigan into the Traverse City area of northwest Lower Michigan. A second, denser cloud band appears over southeastern Lake Michigan with a break or weakening in the cloud pattern apparent over a portion of west-central Lower

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[1]Resolution is about one-half nautical mile in Figure 4-5, allowing easy identification of many natural geographic features such as lakes and streams.

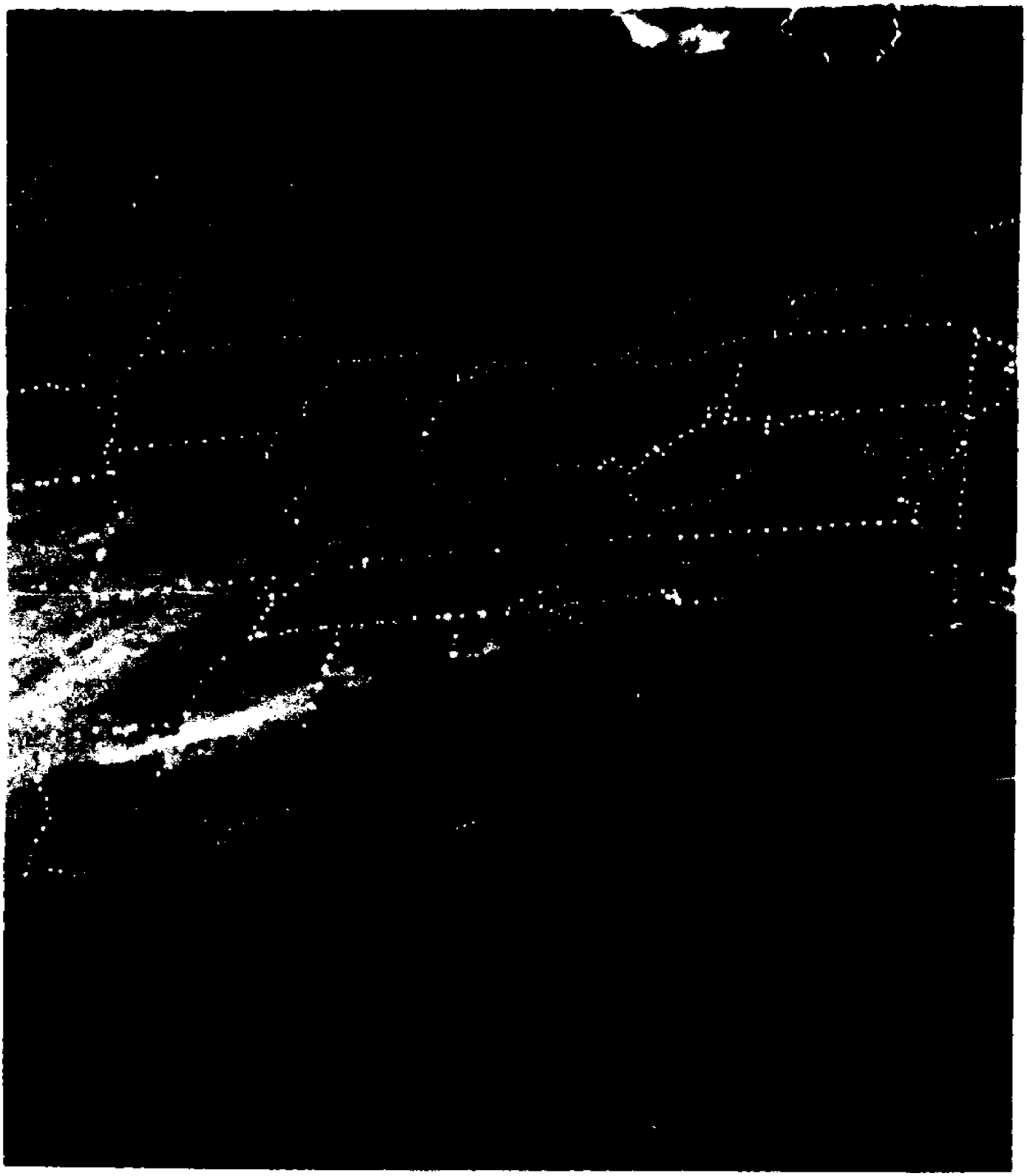

Figure 4-5.--NOAA-2 VhRR satellite photograph for December 7, 1972, about 9 PM EST.

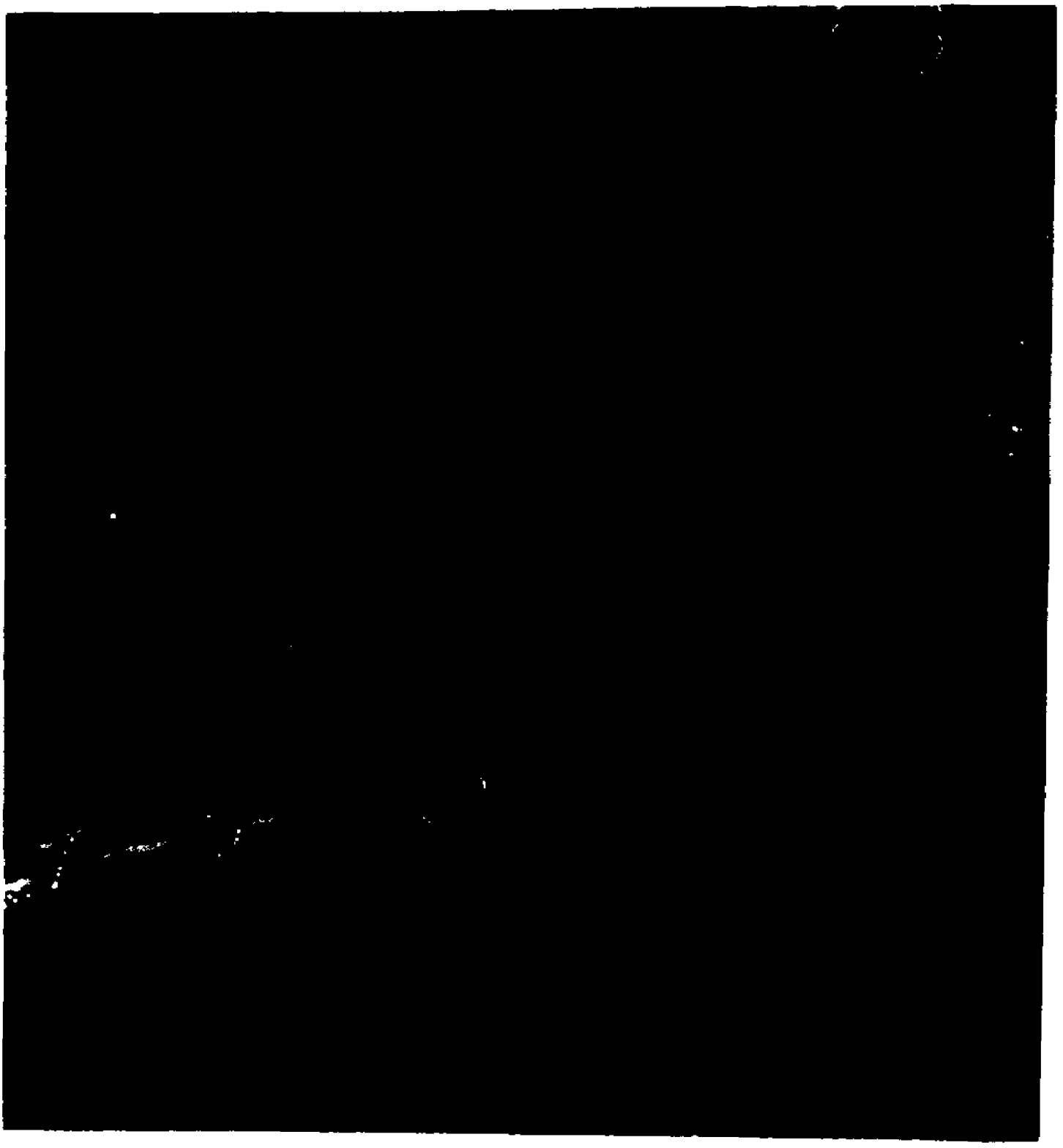

Figure 4-6.--ATS satellite photograph for January 9, 1974, at 1817Z (1:17 PM EST).

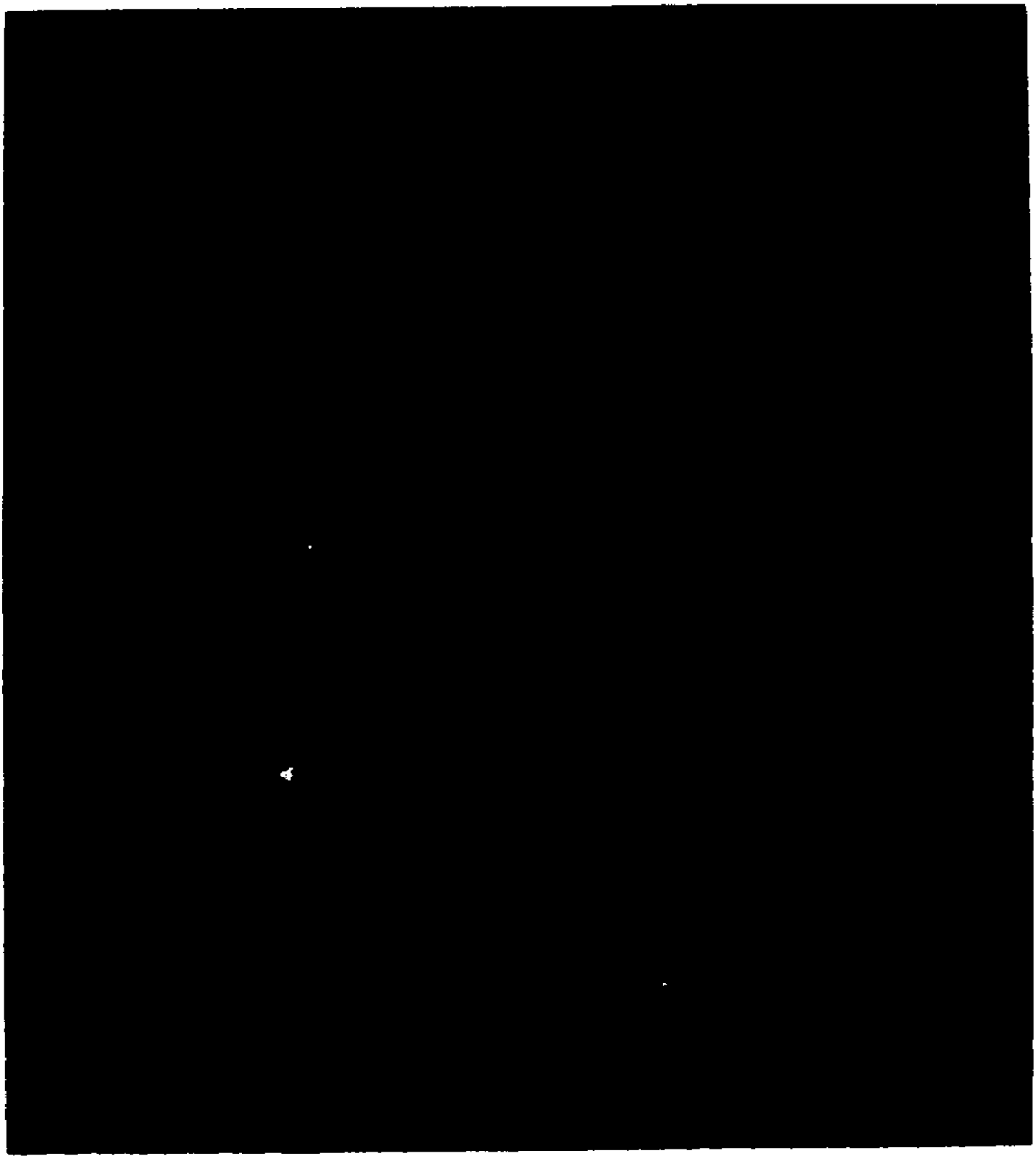

Figure 4-8.--ATS satellite photograph for January 27, 1974.

Michigan. The pattern of lake-snow for January 27, 1971 (Figure 4-9), corresponds to the satellite photograph in Figure 4-8. The observed pattern of broken areas of concentrated snowfall agrees well with the overall pattern of cloud density.

Displacement ΔD Versus Lake-Air Temperature Difference

The initial theory suggests that displacement, ΔD, of the axis of maximum snowfall will decrease as the temperature difference, ΔT, between the lake and the ambient air at 850 mb level increases. Displacement as a plot against temperature difference confirms that this relationship is weak. The south traverse for November actually assumes a positive slope to the regression equation of best fit with a significant Student t value, t = 2.45 (Figure 4-10). Displacement versus temperature difference for the west-central traverse in March has a slight negative slope but a much lower Student t value, t = .086 (Figure 4-11). This suggests that the relationship between ΔD and ΔT is somewhat random and changes as the lake-snow season progresses. This pattern is typical of all three traverses. Additional data are in Appendices A and B.

Geostrophic Wind Versus Displacement by Temperature Differences and Wind Direction Groups

The lake-snow days were put into four groups based on temperature differences ($\Delta T = T_{lake} - T_{850mb}$) and

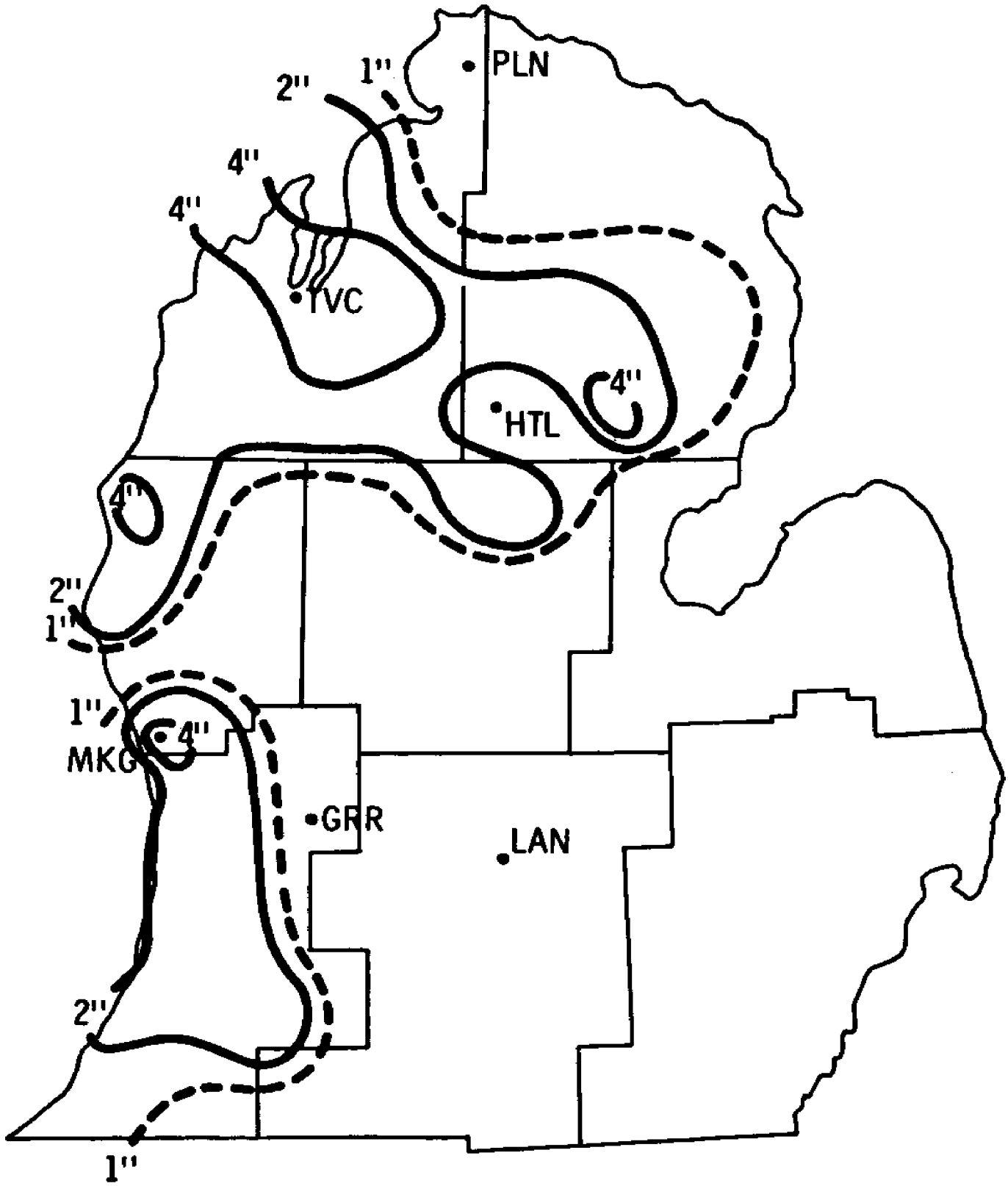

Figure 4-9.--Lake-snow for January 27, 1971.

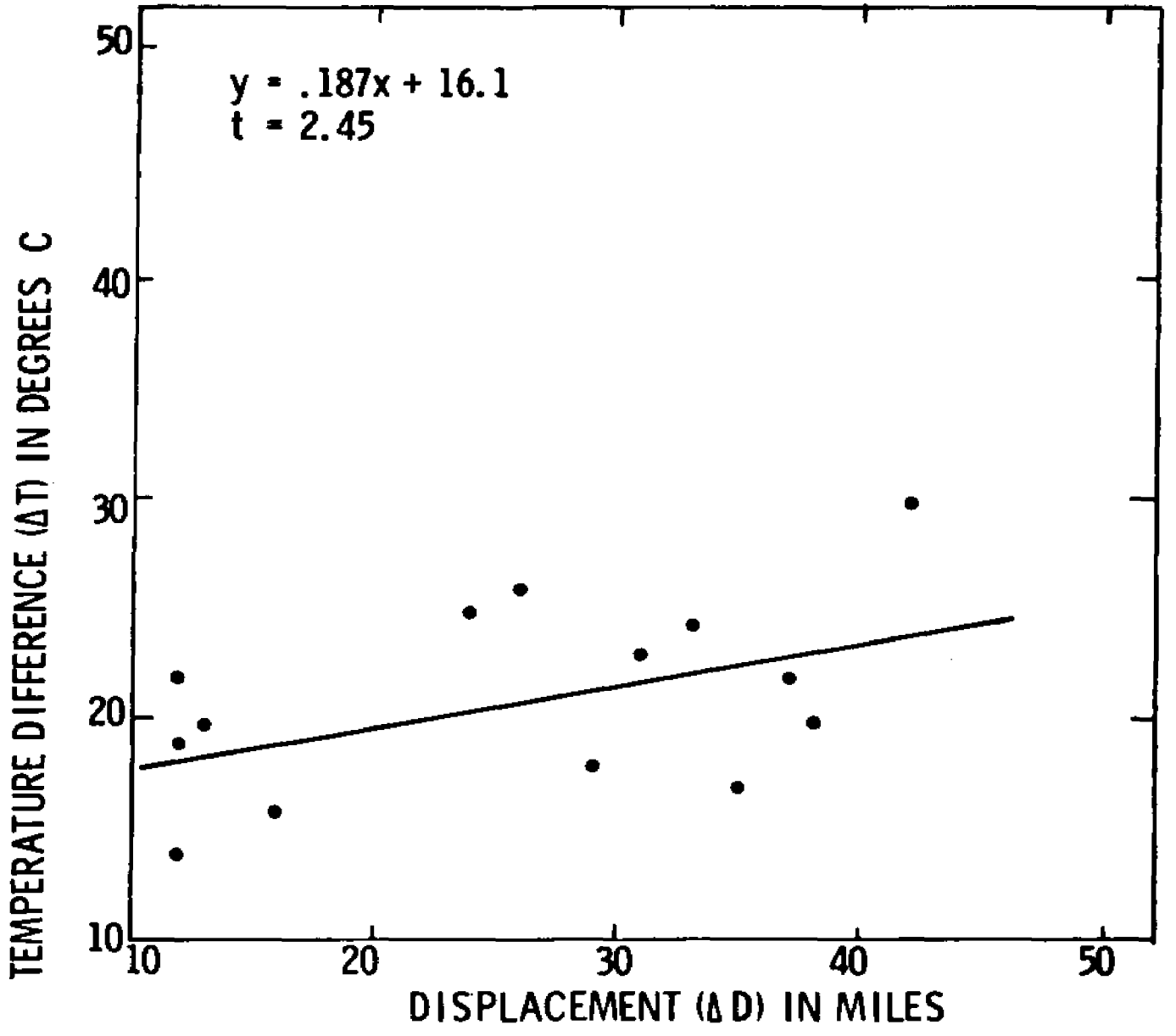

Figure 4-10.--Displacement of axis of maximum snowfall for lake-snow versus temperature difference, surface to 850 mb, for November along south traverse.

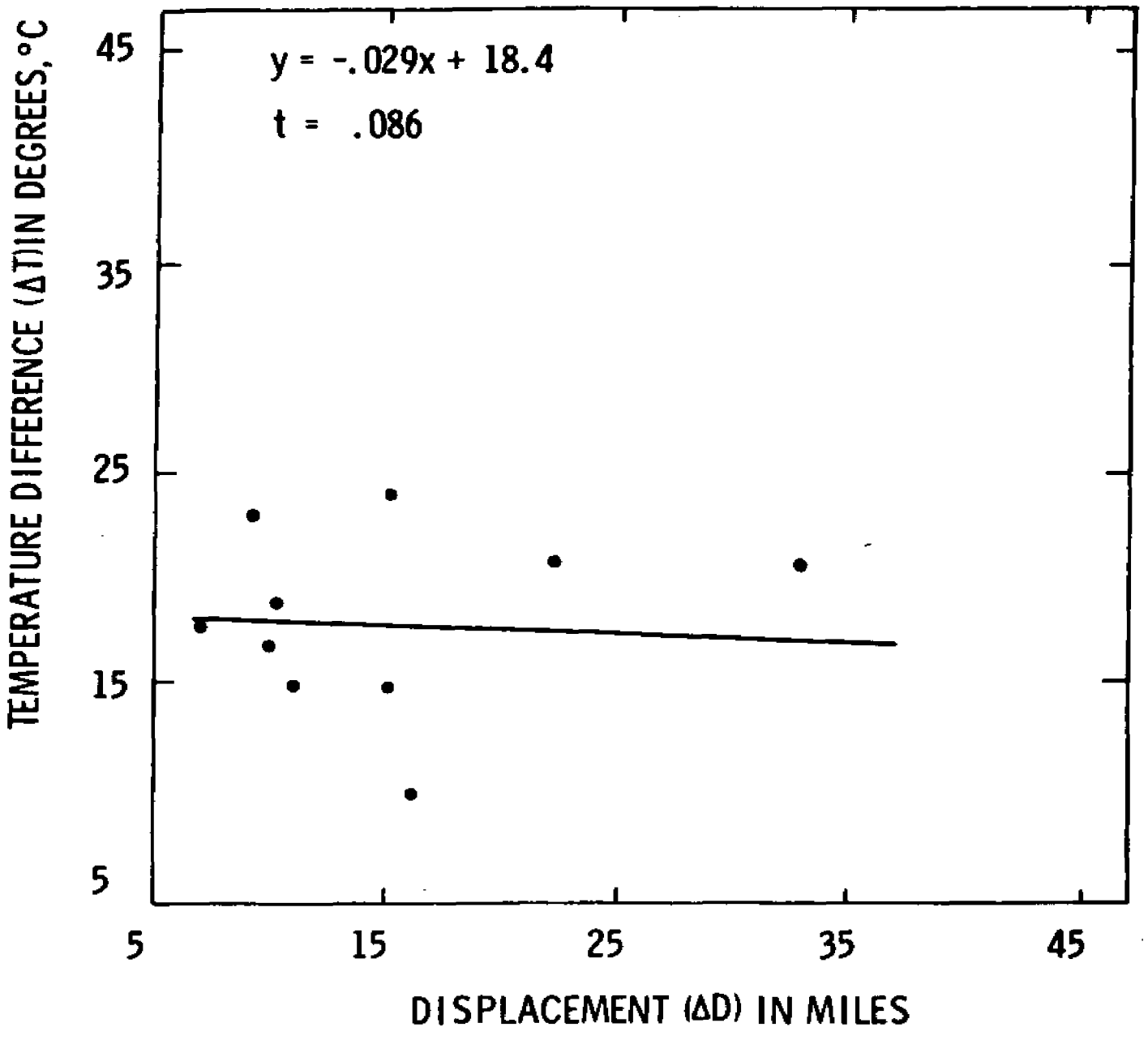

Figure 4-11.--Displacement of axis of maximum snowfall for lake-snow versus temperature difference, surface to 850 mb, for March along W-C traverse.

two groups based on wind direction as follows:

Temperature difference

Group I	less than or equal to 19°C
Group II	20°C to 24°C
Group III	25°C to 29°C
Group IV	equal to or greater than 30°C

Wind direction

Group A	250° through 290° (west wind)
Group B	300° through 330° (northwest wind)

In grouping the lake-snow events by temperature difference and wind direction, it was necessary to use the Northwest Lower Climatic Division data to obtain the best possible sample size. The larger number of lake-snow events was still not adequate to evaluate some groups. The geostrophic wind speed as a plot against the displacement of the axis of maximum snowfall by temperature and wind direction groups suggests three features. First, a significant correlation exists between the geostrophic wind and displacement; second, increasing temperature difference exerts a somewhat selective influence; and third, a relationship exists between the direction of the wind at the 850 mb level and the observed displacement of the axis of maximum snowfall. For the northwest wind, Group B, a strong positive correlation exists between the calculated geostrophic wind speeds at 850 mbs and the displacement of the axis of maximum snowfall for temperature groups of 20°-24°C and 25°-29°C (Figure 4-12). The sample size was inadequate for temperatures greater than or equal to 30°C. For west winds,

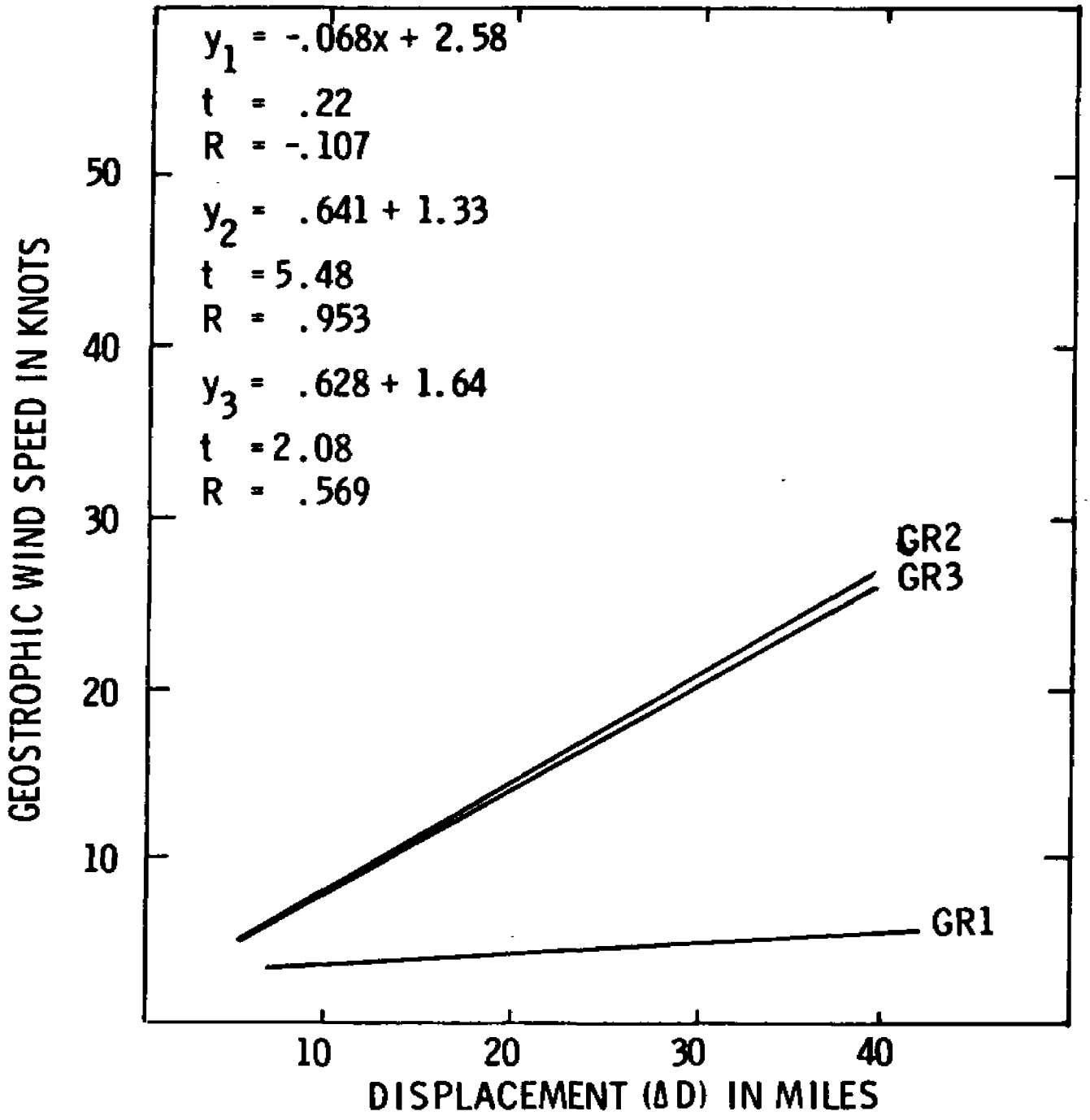

Figure 4-12.--Geostrophic wind speed in knots versus displacement of axis of maximum snowfall for winds from the northwest by ΔT Group 1, Group 2, and Group 3 for January in northwest Lower Michigan.

Group A, a significant correlation exists between the calculated geostrophic wind speed and snowfall displacement for temperature Groups I and II (Figure 4-13). The sample size was too small for the remaining temperature groups.

A plot of the regression equations for west and northwest wind directions suggests two features of the lake-snow. First, the increasing temperature difference results in a smaller displacement for the same geostrophic wind speed, and second, winds of equal velocity will result in a larger displacement in the axis of maximum snowfall when the wind direction is perpendicular to the lake shoreline (Figure 4-14).

Observed Wind Velocities Upstream and Downstream From Lake-Snow Activity

The wind velocity observed upstream and downstream from the area of lake-snow was compared using the radiosonde data taken at Green Bay, Wisconsin, and Flint, Michigan, respectively. The average wind speed for the 257 lake-snow days is summarized for the surface, 850 mb, 700 mb, and 500 mb levels in Figures 4-15, 4-16, 4-17, and 4-18, respectively. The observed wind speeds are nearly equal early and late in the snow season, with significantly lighter winds at Green Bay (stronger at Flint) during the mid-winter periods of late December, January, and early February. The average calculated geostrophic wind velocity was compared with the observed 850 mb average values at Green Bay and

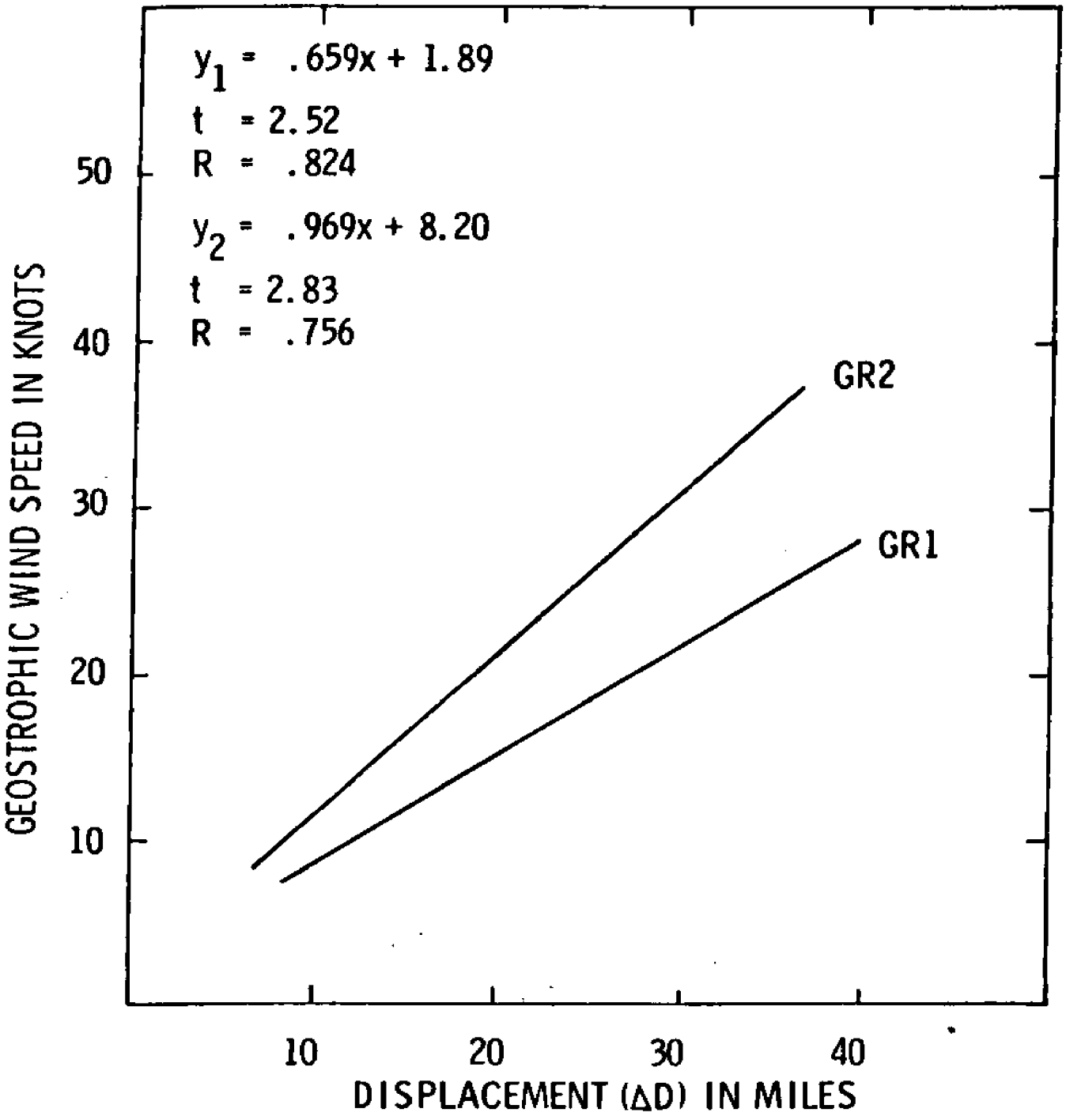

Figure 4-13.--Geostrophic wind speed in knots versus displacement of axis of maximum snowfall for winds from the west by ΔT Group 1 and Group 2 for January in northwest Lower Michigan.

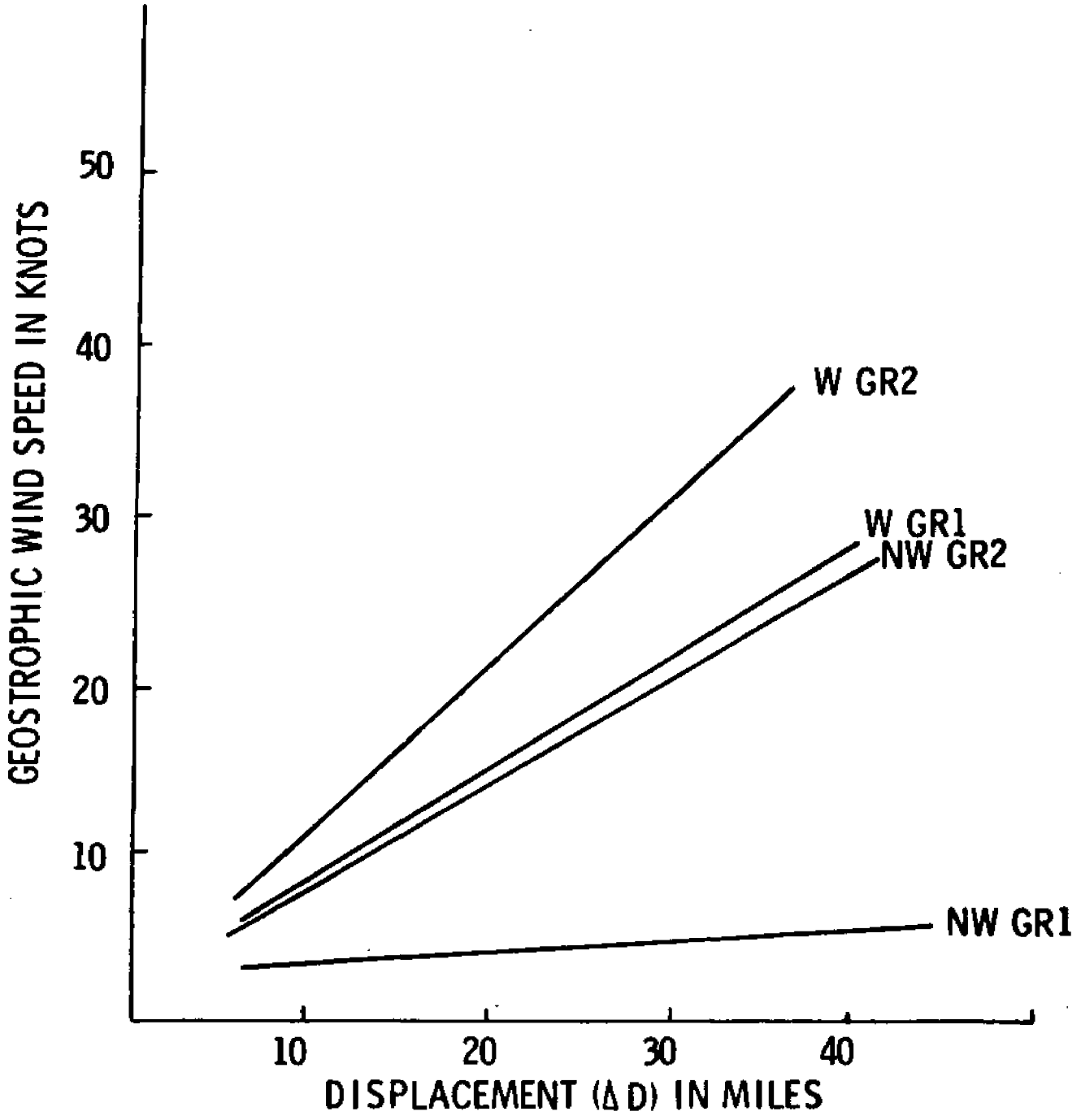

Figure 4-14.--Geostrophic wind by direction versus displacement of axis of maximum snowfall by ΔT groups in January for northwest Lower Michigan.

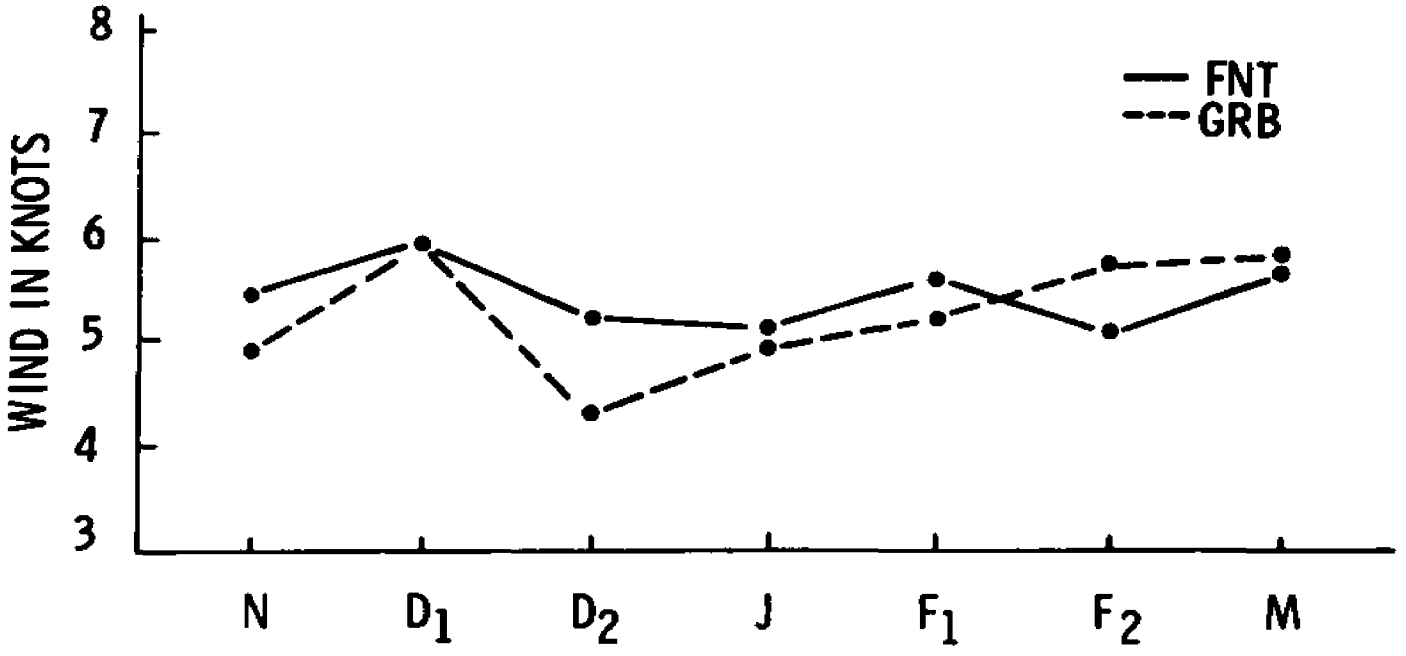

Figure 4-15.--Average observed surface wind during periods of lake-snow by periods from November, 1965, through March, 1971, for Green Bay, Wisconsin (GRB), and Flint, Michigan (FNT).

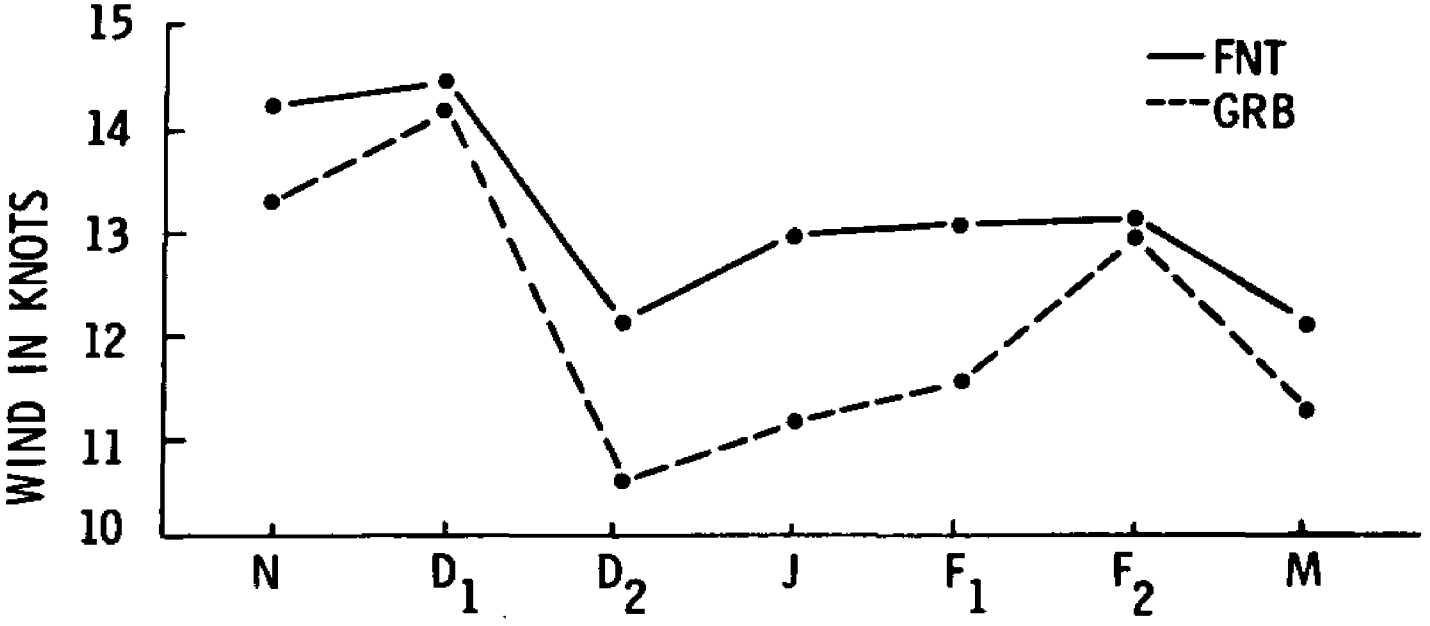

Figure 4-16.--Average observed 850 mb wind during periods of lake-snow by periods from November, 1965, through March, 1971, for GRB and FNT.

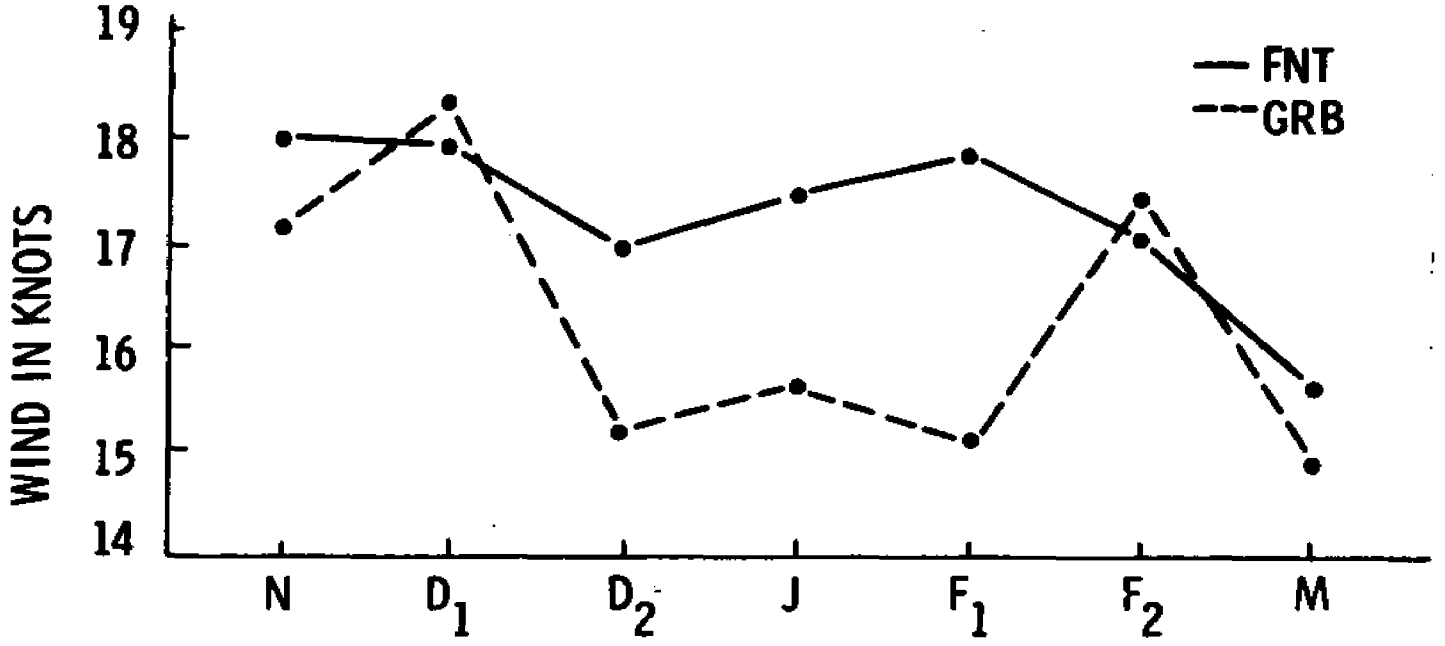

Figure 4-17.--Average observed 700 mb wind during periods of lake-snow from November, 1965, through March, 1971, at GRB and FNT.

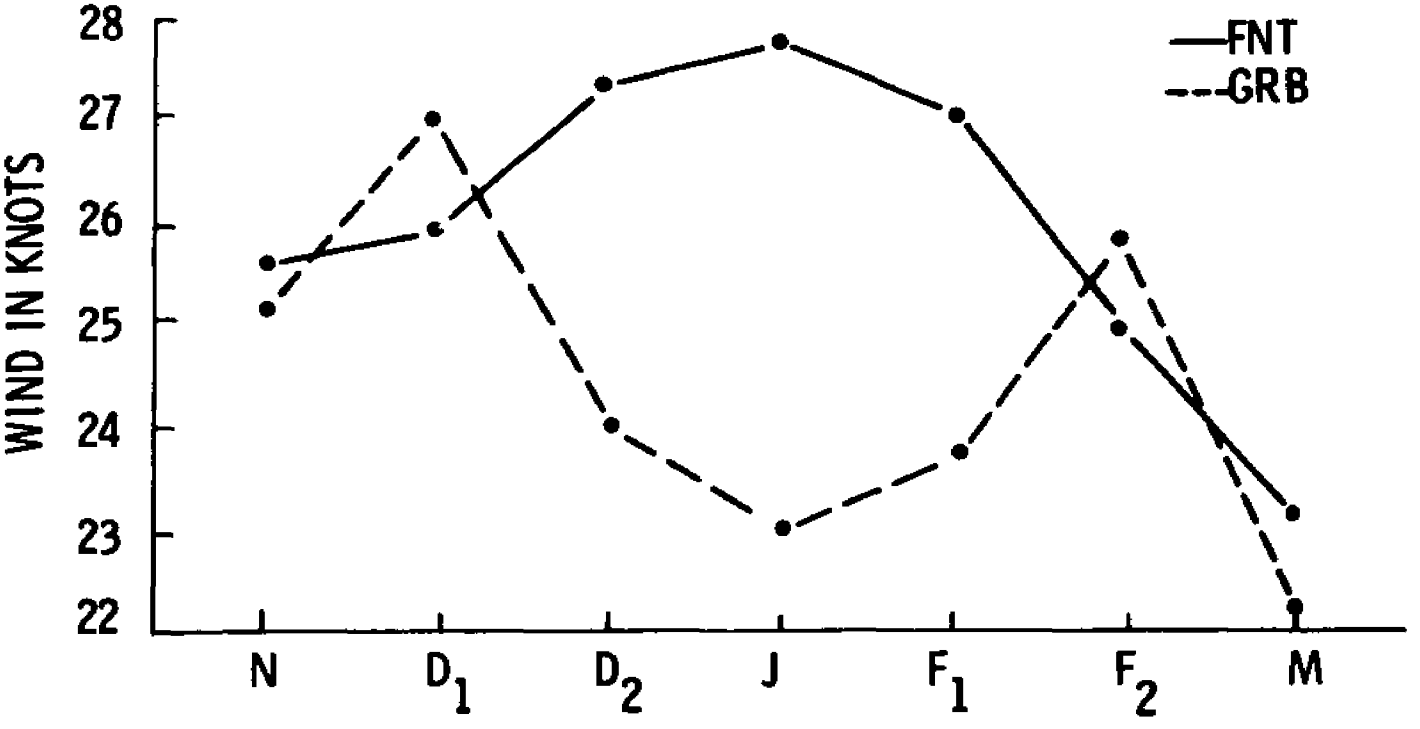

Figure 4-18.--Average observed 500 mb wind during periods of lake-snow from November, 1965, through March, 1971, at GRB and FNT.

Flint. The calculated velocities are in better agreement with the observed wind speeds at Green Bay, whereas the observed Flint wind speeds are generally higher. An exception occurs late in the lake-snow season when the calculated geostrophic values at 850 mbs are the highest (Figure 4-19). The differences between the observed wind speeds at Flint and Green Bay were tested for significance; the results are presented in Table 4-2.

Table 4-2.--Student t values, converted to percentage, as test of significance of difference between Green Bay and Flint winds during periods of lake-snow.

Level	Nov.	Dec. 1-15	Dec. 16-31	Jan.	Feb. 1-14	Feb. 15-28	March
Surface	72%	50%	96%	71%	82%	55%	56%
850 mb	61%	61%	92%	97%	87%	56%	66%
700 mb	66%	54%	88%	94%	68%	52%	64%
500 mb	56%	59%	89%	99%	88%	63%	60%

Relationship of Heavy Snow to Season and $\Delta T = T_{lake} - T_{850\ mb}$

The frequency of observed heavy lake-snow equal to or greater than four inches (Figure 4-20) and lake-snow equal to or greater than eight inches (Figure 4-21) generally increases by month from November into January and then decreases into March. The percentage of lake-snow occurrences is highest for the temperature differences of 15°-19°C and 20°-24°C, with about 33 percent each. The

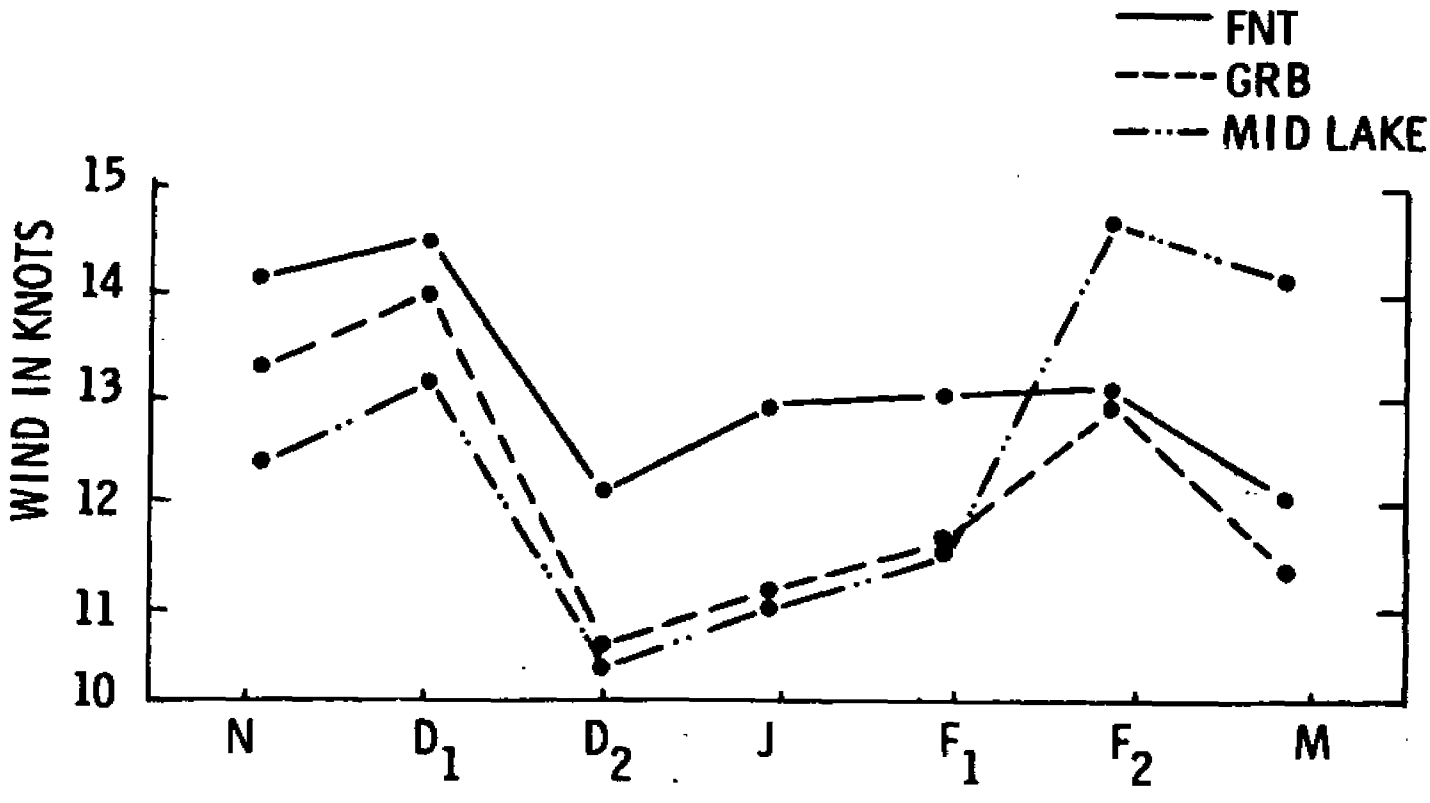

Figure 4-19.--Comparison between the observed 850 mb wind at GRB and FNT and the calculated geostrophic wind at mid-Lake Michigan.

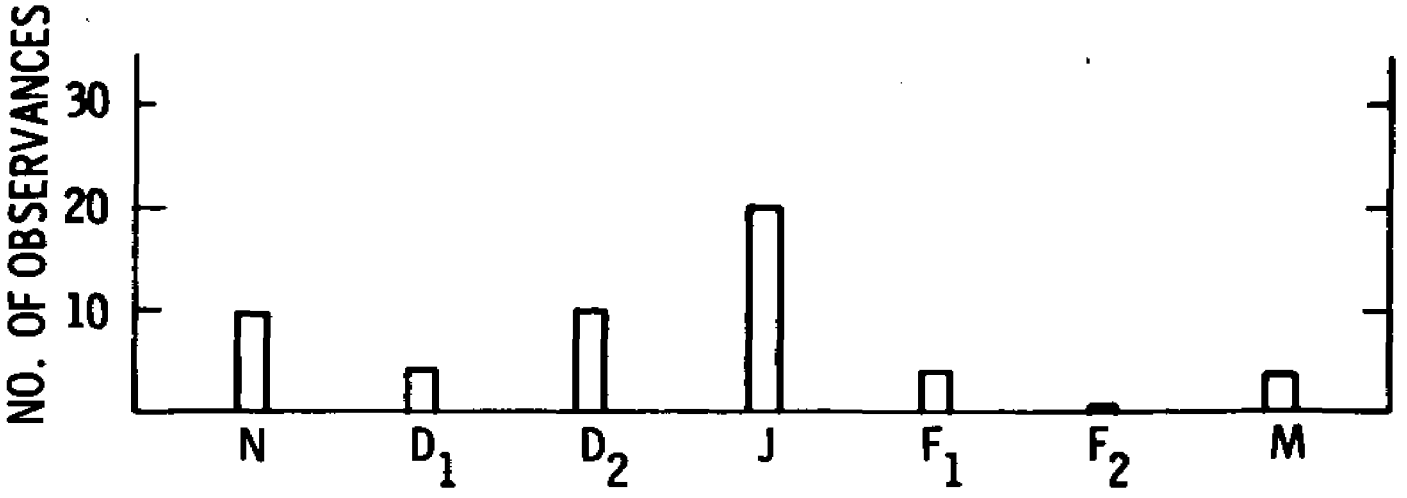

Figure 4-20.--Number of lake-snow occurrences with snowfall greater than or equal to four inches by periods.

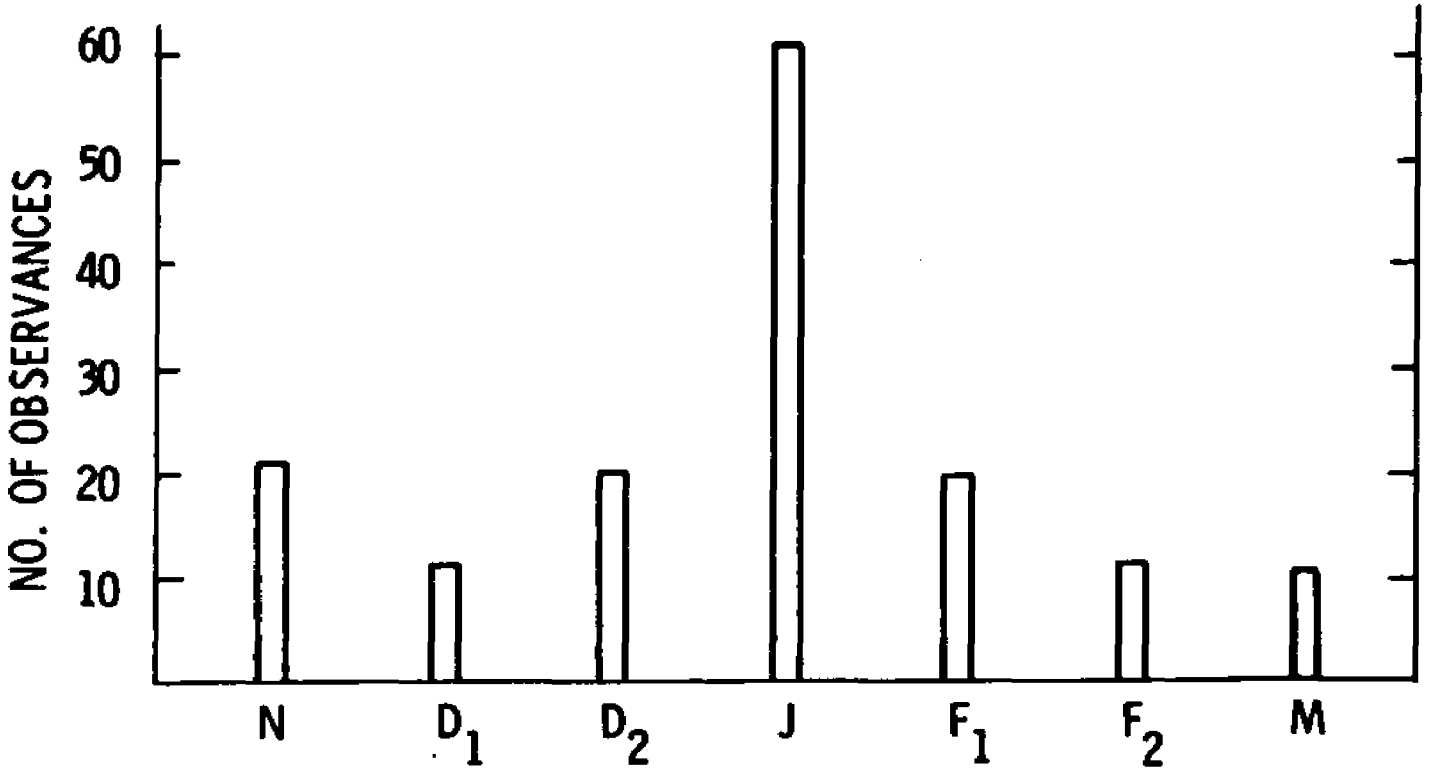

Figure 4-21.--Number of lake-snow occurrences with snowfall greater than or equal to eight inches by periods.

percentage drops systematically for the 25°-29°C, 30°-34°C, and equal to or greater than 34°C groups (Figure 4-22).

The percentage of lake-snow occurrences that produced snowfall equal to or greater than four inches progressively increases to 100 percent as the ΔT group values increase (Figure 4-23). In other words, the probability of receiving a heavy lake-snow at one or more locations appears to be related to the temperature difference between the lake and ambient air temperature at 850 mb. This trend did not continue when snowfall equal to or greater than eight inches was considered (Figure 2-24). The percentage again increases through ΔT group 25°-29°C, but falls to zero for the larger temperature differences greater than 34°C. This finding suggests that the temperature difference alone is not capable of producing lake-snow equal to or greater than eight inches in a 24-hour period over western Lower Michigan.

Snowfall Versus Water Content

The water-equivalent ratio for the northwest Lower Climatic Division (Figure 4-25) shows the monthly lake-snow versus water-content values and the annual ratios for Cross Village, Petoskey, Boyne Falls, and Gaylord, Michigan, respectively. In the annual values the lowest ratio is at the lake shore locations with the ratio, i.e., lower water content for a given snowdepth, increasing at the inland sites. For example, at Gaylord the ratio is 21 to 1 and

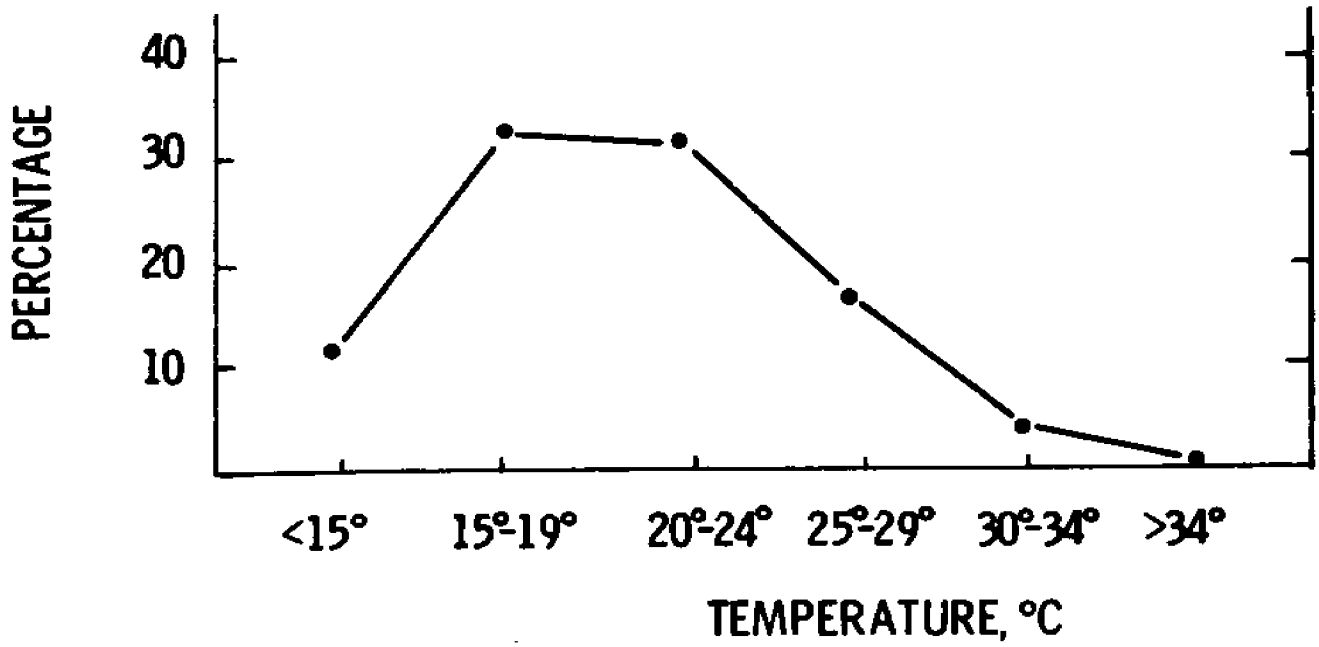

Figure 4-22.--Percentage of lake-snow occurrences by ΔT groups from November, 1965, through March, 1971.

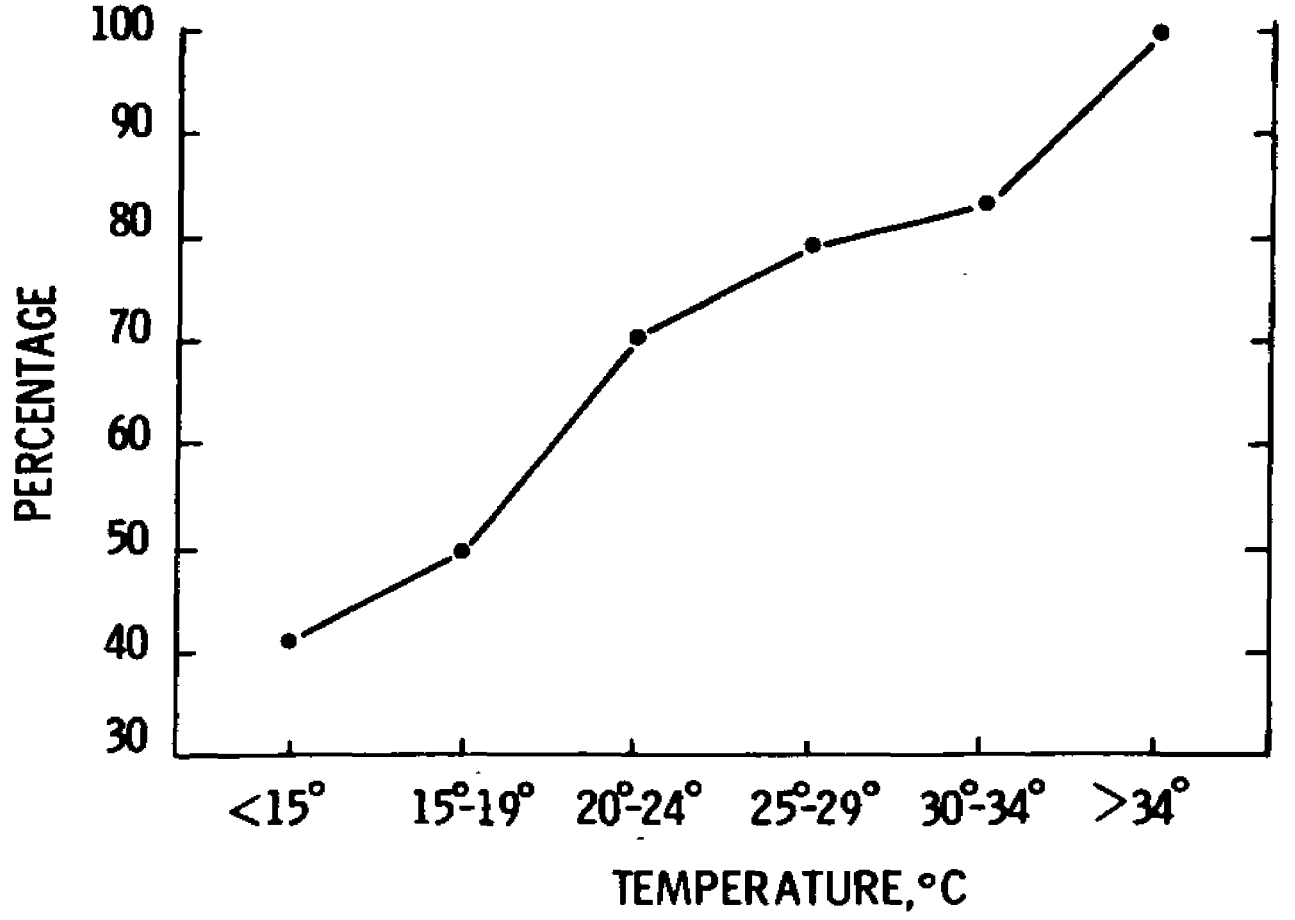

Figure 4-23.--Percentage of ΔT groups by ranges in degrees C that resulted in lake-snow greater than or equal to four inches at one or more locations in western Lower Michigan.

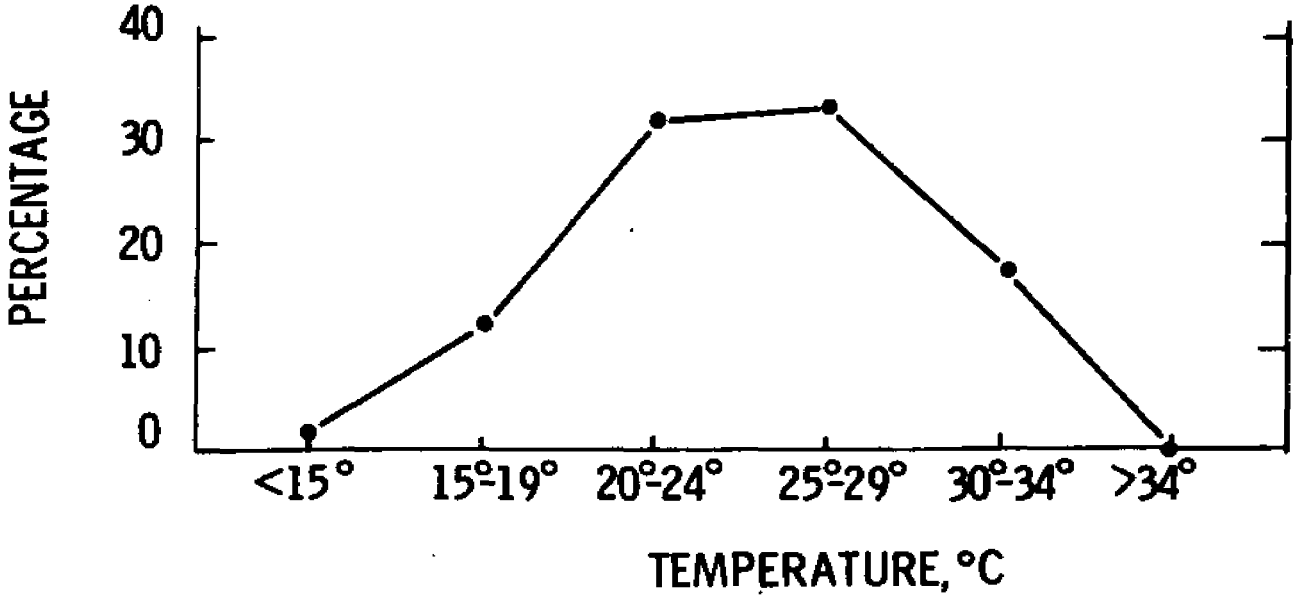

Figure 4-24.--Percentage of ΔT groups by ranges in degrees C that resulted in lake-snow greater than or equal to eight inches at one or more locations in western Lower Michigan.

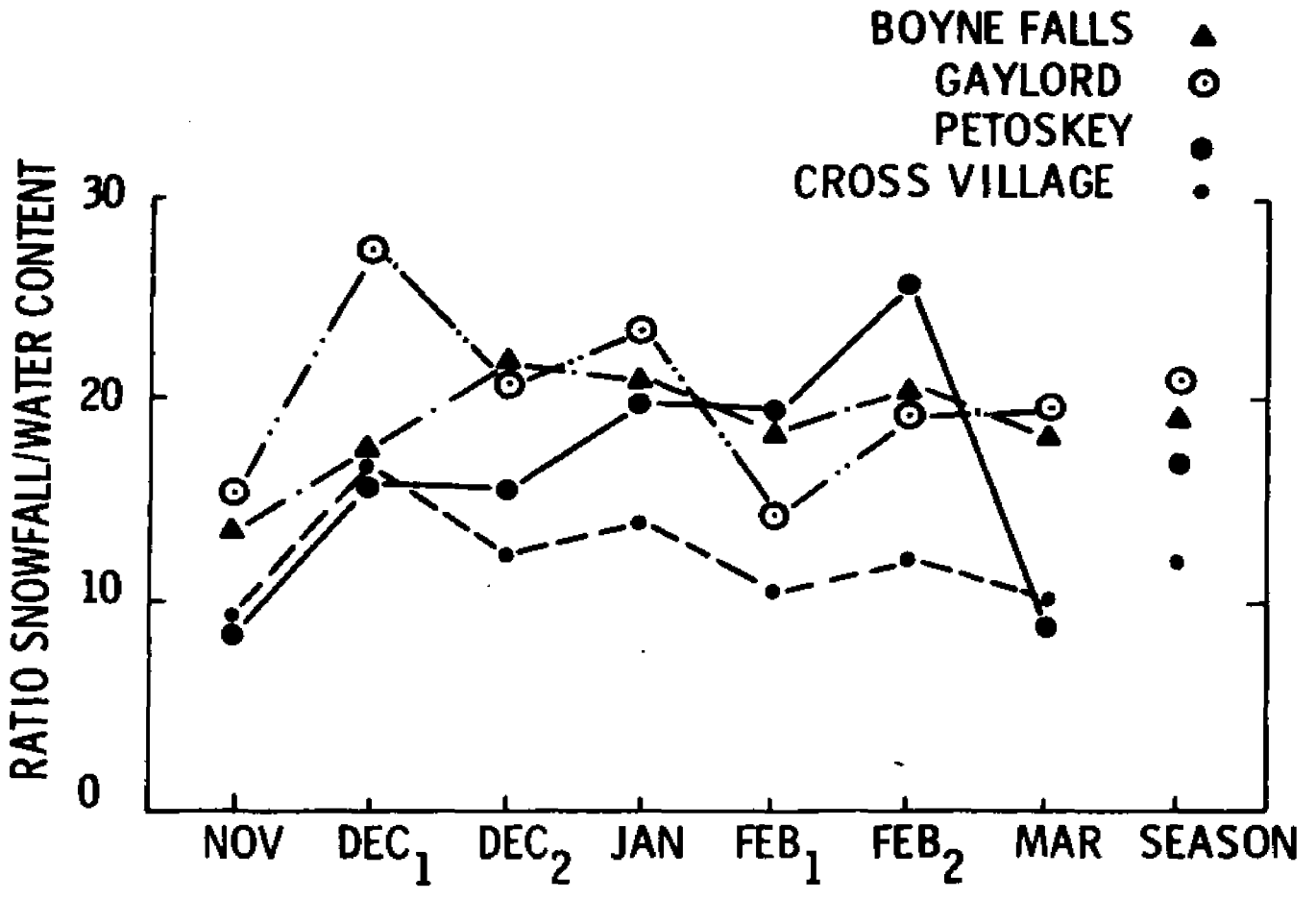

Figure 4-25.--Snowfall/water-content ratios by period and season from November, 1965, through March, 1971, for Cross Village, Petoskey, Boyne Falls, and Gaylord, Michigan.

at Cross Village the ratio is eleven to one. Thus an inch of lake-snow at Gaylord contained on an average approximately one-half the water content observed in an inch of lake-snow at Cross Village. The general trend of lower ratios close to the lake was also found in the field surveys conducted in the lake-snow belts of the Upper Peninsula (Figures 4-26 and 4-27).

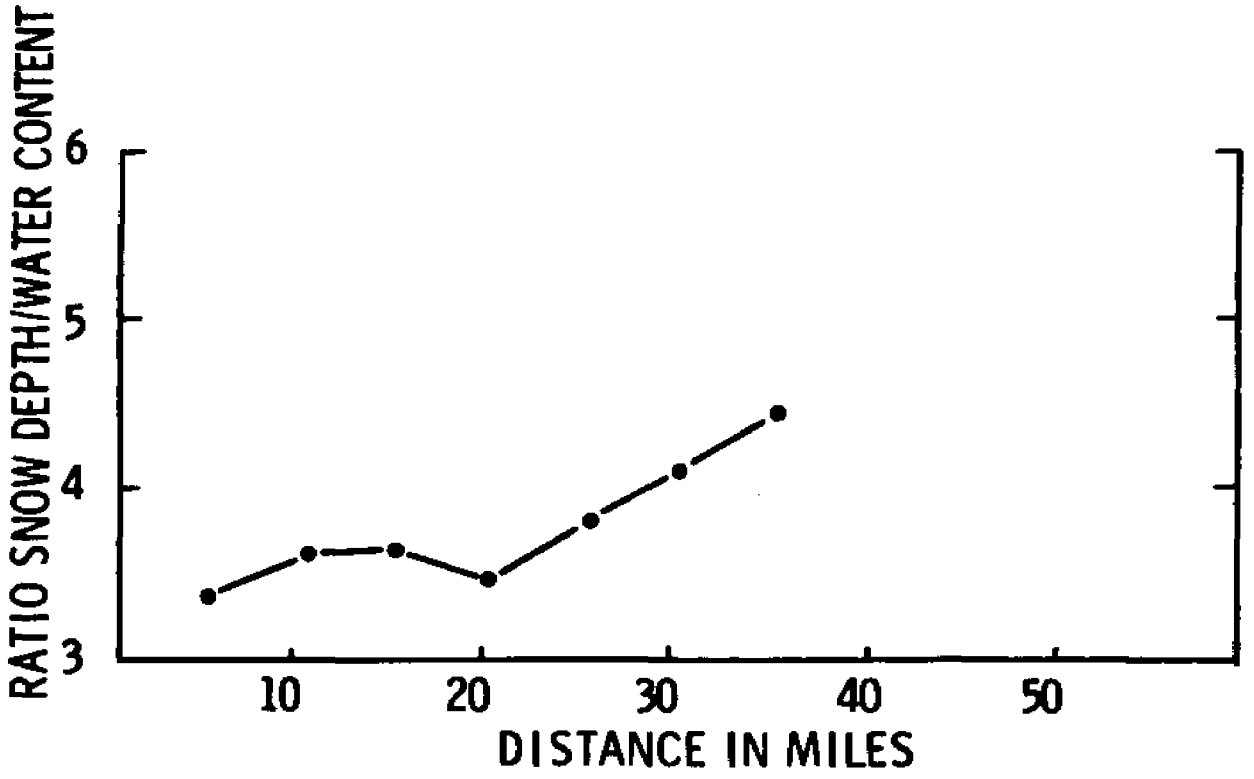

Figure 4-26.--Field survey February 15, 1972, of snowdepth/water-content ratio from Lake Superior eastward along county 210 and U.S. 2.

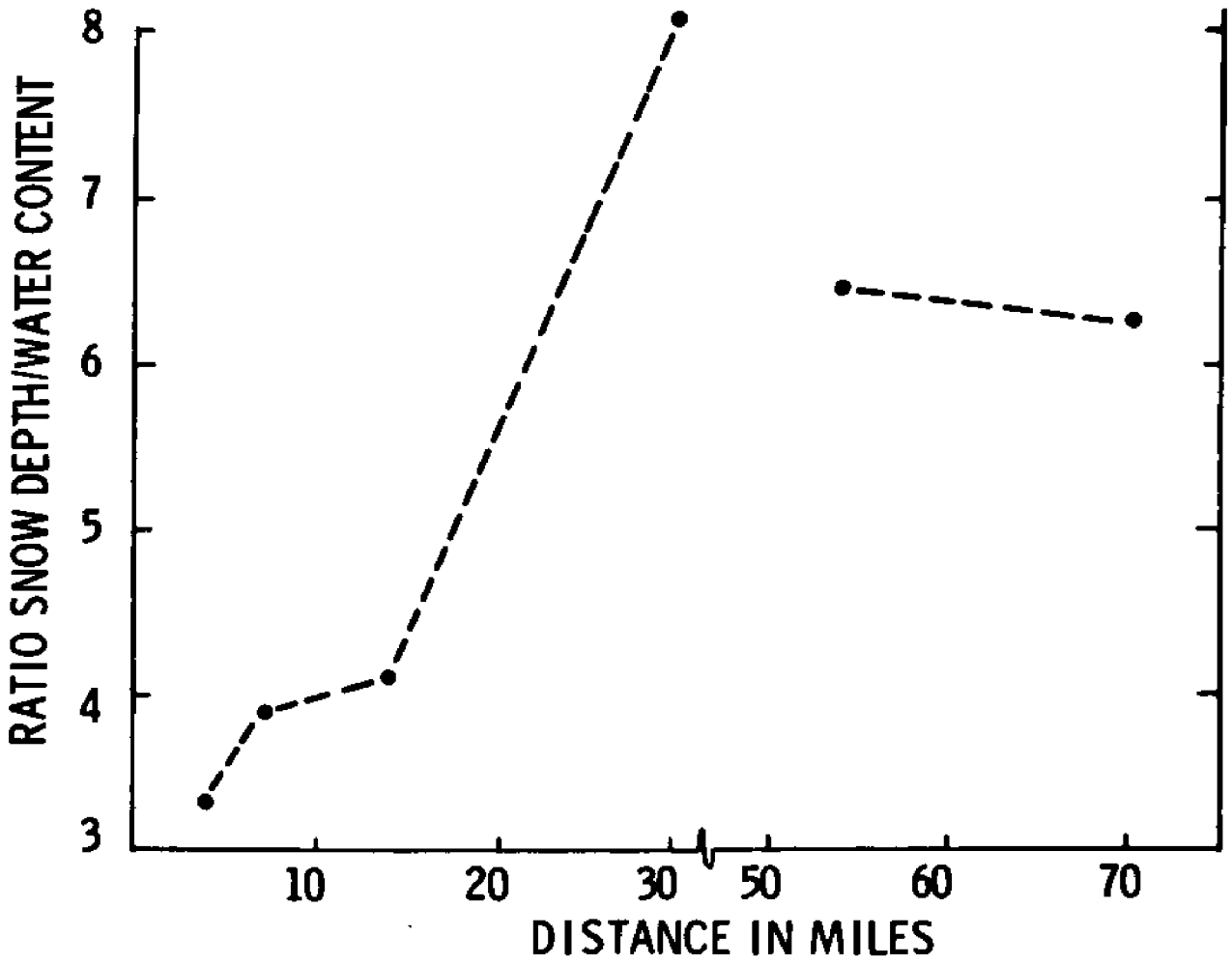

Figure 4-27.--Field survey January 10, 1973, of snowdepth/water-content ratio from Lake Superior south along M77.

CHAPTER V

DISCUSSION OF RESULTS

Seasonally Shifting Axis of Maximum Lake-Snow

The seasonal shift in the axis of maximum snowfall is a feature of the lake-snow "belt" in western Lower Michigan. Changes in the meteorological factors with the progression of the lake-snow season are believed to be related to the shift in the axis of maximum snowfall.

The shift in the axis of maximum snowfall is not uniform in all areas of western Lower Michigan. In the southwest and west-central sections, the seasonal change in the distance of maximum snow from the lake shore is similar. The terrain features are also quite similar in these two areas. However, in northwest Lower Michigan, the distance of the seasonal shift is almost double that recorded in the southwest and west-central sections. Two factors that contribute to the larger displacement observed in northwest Lower Michigan are related to the terrain in that area. First, in early fall, the probability is higher, at higher elevations, that any precipitation received will be in the form of snow (1); these snowfall totals would normally be highest over the highest terrain. Second, orographic uplift

(Figure 3-2) will normally enhance the precipitation amounts observed at the higher elevations, but during mid-winter, when winds are lightest and snow normally falls nearer the shoreline, the orographic effects are minimized. Thus I believe the greater displacement during the fall and spring periods is related to the higher elevation of parts of interior northwest Lower Michigan.

Displacement Versus Temperature Difference $\Delta T = T_{lake} - T_{850mb}$

The displacement inland of greatest lake-effect snowfall, when evaluated with respect to the vertical temperature difference, ΔT, does not show any statistically significant pattern. It varies from a weak positive slope to a weak negative slope, for the regression line of best fit, as the season progresses. This finding suggests that the possible influence of the temperature difference is overshadowed by some other meterological parameter. The lapse rate of about 13°C between the lake-water surface and the 850 mb level corresponds to neutral stability, and the present study has shown that cloud development with resulting precipitation will begin when this lapse rate is reached or exceeded. When the data are grouped by ΔTs and wind direction, it becomes evident that displacement is reduced as ΔT increases for a given wind velocity with both west and northwest flow (Figures 4-12 and 4-13). In other words, the greater the temperature difference, the smaller

the displacement if other factors remain constant. It appears that the larger ΔTs are indicative of a greater instability in the lower troposphere and result in a more rapid transfer of moisture (water vapor) to the developing lake-snow system. This moisture and released latent heat of condensation combine to produce a more favorable environment for the nuclei accretion and aggregation within the clouds, which produces an earlier fallout of the snow at a location nearer the lake shore. Earlier in the fall an increase in the frequency of hail (small ice pellets) has been noted over western Lower Michigan (2). I believe the higher frequency of hail is the result of nuclei accretion when large temperature differences exist between the lake water and air advected over it but when cloud temperatures are too warm for crystalline snow to occur. However, the wind clearly plays the more dominant role in determining the displacement of the axis of maximum lake-snow. During late February and March, the increasing displacement inland of the heaviest lake-snow may be related to increasing wind speeds and their ability to advect snow that is predominantly crystalline in form because ΔTs are relatively small, the lake temperatures are colder, and partial ice cover limits the available moisture supply.

Wind Velocities and Displacement

The observed wind speed values from Green Bay, Wisconsin, and Flint, Michigan, represent the lower

troposphere flow upstream and downstream from the lake-snow area of western Lower Michigan. In earlier studies of lake-snow, the convective cell movement over Lake Erie was observed to be closely related to the wind speed and direction at about 1.5 Km (3). Thus, the 850 mb wind is assumed to be the most representative of the lake-snow cloud movement over Lake Michigan.

The calculated geostrophic wind for the mid-point over Lake Michigan was compared with the observed values at both Green Bay and Flint, with the calculated values more closely approaching the observed values for Green Bay. This finding suggests the upstream winds are more representative of the lower troposphere in the area of lake-snow than the downstream wind flow. Since a positive correlation exists between the calculated wind speed and observed displacement (Figures 4-12 and 4-13), I conclude that the Green Bay wind values, collected closer to the area of active lake-snow, are a more reliable predictor of the displacement of the axis of maximum snowfall.

A larger discrepancy between the calculated geostrophic wind and the observed winds at Green Bay was noted during late February and March (Figure 4-19). One possible explanation for this discrepancy is that late spring Arctic air outbreaks are vigorous and short in duration. The calculated winds are based on the degrees and tenths of latitude required to observe a 60 m change in the height of the

850 mb contour. The pressure gradient after a vigorous cold air outbreak may be slightly slower in weakening. If this is true, then the calculated wind velocity would be biased toward higher average speeds. Perhaps this finding indicates geostrophic wind to be the better indicator of displacement during late season lake-snow periods.

The difference between upstream and downstream winds represents a velocity convergence or divergence that occurs over western Lower Michigan during periods of lake-snow. Although a weak, possibly nonsignificant, velocity convergence (decreasing speed downstream) is noted in early December and late February, a velocity divergence (increasing speed downstream) dominates the mid-winter windflow at all levels, surface to 500 mb (4).[1] The difference between these observed average wind values is greatest during the mid-winter period of late December, January, and early February. The level of significance (as determined by a Student t test for the difference between the observed winds at Green Bay and Flint) decreased rapidly for periods removed from mid-winter, including either November or March. The greater difference between the observed wind speeds at Green Bay and Flint, during mid-winter, may play a role in the seasonal shift of the axis of maximum lake-snow.

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[1]This pattern is noted up through the 500 mb level, even though work by Davis suggests there is no active transfer of properties of the atmosphere above the isothermal layer that in theory is considered the top of the lake-snow development and seldom reaches this high.

The results of this study indicate that wind speeds are lighter upwind than downwind during periods when lake-snow displacement is small. This tendency becomes more accentuated upward through the lower troposphere to the 500 mb level in January, and suggests that the total vertical wind profile may seasonally have some impact on the displacement of the axis of maximum lake-snow. If the total vertical wind profile contributes to determining the displacement of lake-snow, then the shape of the profile should be considered. For example, if, during two lake-snow events, the wind profiles are similar from the surface up to 700 mbs but one then displays more rapidly decreasing wind speeds above this level, the displacements would be different and the smaller displacement would be related to the vertical profile of lighter overall wind. The exact importance of the discrepancy between the wind velocities from Green Bay and Flint with respect to the shift in the axis of maximum snow is not clearly understood. I have observed that during periods of velocity divergence, lake-snow is often more restricted to the western portion of Michigan. A satellite photograph (Figure 4-5) shows that cloud dissipation may be rapid to the east of the lake-snow area. Therefore, subsidence may be occurring over central lower Michigan, which may restrict the movement of lake-snow activity toward the east and confine it to the lake shore area (Figures 4-15 through 4-18).

Heavy Snow as Related to Increasing ΔTs

Initially, it was believed that the frequency of heavy snowfall would increase as ΔT increased. This assumption is based on the premise that the larger the ΔT, the more rapid will be the vertical flux of moisture transferred from the lake and the stronger the convective development in the lower troposphere. Figure 4-23 confirms that as ΔT increases, the frequency of heavy snow at one or more locations in western Lower Michigan increases to 100 percent for amounts equal to or greater than four inches. This pattern, however, does not hold true for snowfalls or eight or more inches, which occur with greatest frequency when the ΔT is between 24° and 29°C. A survey of the upper air charts indicated that nine out of ten cases of heavy snow were associated with a weak shortwave impulse passing through the Lake Michigan area during the observation periods in question. This finding indicates that although the large ΔT values may be sufficient to produce heavy snow (four inches or more), some form of weak convergence aloft is needed to give snowfall of eight or more inches in 24 hours.

Snowfall Versus Water-Content Ratio

It was theorized that the snowfall closest to the lake would contain the highest water content per unit depth of snowfall. This assumption is based on the relationship between the various types of precipitation observed with

lake-snow. Graupel, snow pellets, and/or small hail were frequently observed close to the lake shore but less frequently inland. These types of snow, related to convective activity, are generally denser or heavier than the crystal-type flakes, and a proportionally stronger wind is necessary to achieve a predetermined displacement. Thus, on an average, these denser snow particles fall closer to the lake shore, resulting in a higher water content per unit depth of snowfall. This trend was confirmed by both the average snowfall and water content from each lake-snow event and the field surveys conducted in the Upper Peninsula lake-snow belts. The actual ratios were much lower in the Upper Peninsula because of the compaction or settling of the lake-show as the winter season progressed. During the 1972 survey, there were two layers of ice in the core samples, indicating that rain or freezing rain had fallen earlier over that area.

For stations close to the lake, the average annual ratio of snowdepth to water content from individual storms was more than double that from the field surveys. These averaged from twelve to seventeen to one for stations near the shore, whereas the inland stations for the season averaged twenty-two to one. The variability was much greater for individual months. There was no apparent systematic variation in the ratios during the progresssion of the lake-snow season.

CHAPTER V--REFERENCES

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CHAPTER VI

SUMMARY AND CONCLUSIONS

This study was designed to evaluate the hypothesis that the seasonal shift in the axis of maximum lake-snow is related to seasonally changing wind velocities and the temperature difference between the lake-water and air advected over the lakes. Additionally, the study explored a possible relationship between the heavy lake-snow occurrence and increasing temperature difference between the lake-water and air advected over the lake, with a lesser emphasis on the changing distribution of the snowdepth/water-content ratio with increasing distance from the lake shore. Several results emerged from the study.

Location of Axis of Maximum Lake-Snow With Progression of Winter

The shift in the location of the axis of maximum lake-effect snowfall is a feature of the entire lake-snow belt in western Lower Michigan. Between November and January, the heaviest snowfall tends to occur progressively nearer the lake shoreline, but through February and March the area of heaviest lake-snow gradually progresses inland again. The seasonal shift covers a greater distance in the

northwest section, possibly because of the greater elevations in this area. The terrain reaches an elevation of over 1400'MSL, and relief is over 800' above Lake Michigan. Most of this change, about 600', occurs between ten and twenty miles inland along the northwest traverse for measuring the displacement of the axis of maximum snowfall. The sharp rise results in an orographic enhancement for lake-snow, whereas the higher elevations farther inland increase the probability that a precipitation occurrence will be in the form of snow. Decreasing elevation farther inland along the traverse, with subsidence of air flowing eastward from the higher interior elevation, additionally contributes to cloud dissipation.

Meteorological Factors Influencing the Shift in the Axis of Maximum Lake-Snow

A strong positive correlation was shown to exist between the geostrophic wind speed at 850 mbs and the displacement inland of the axis of maximum snow for lake-snow events. The average calculated geostrophic wind speed was in close agreement with the average observed wind speed for Green Bay, Wisconsin, for all periods of the study except late February and March. The pattern of average observed wind speed for Green Bay, Wisconsin, which was highest during November and early December, decreased to lower values during mid-winter (late December through early February), and increased again by late February, was positively

correlated with the inland displacement of heaviest lake-snow. The large discrepancy between the upstream (Green Bay, Wisconsin) and the downstream (Flint, Michigan) average observed wind speeds implies a divergent flow pattern during mid-winter. This divergent flow may produce sufficient subsidence over central Lower Michigan to dissipate the lake-effect cloud development east of the active lake-snow area and restrict the eastward movement of the lake-snow.

The temperature difference between the lake surface and the ambient air passing over the lake is generally greatest during mid-winter. With increasing lake-air temperature difference, the displacement of the axis of maximum lake-snow was reduced for a given wind speed. These results are not conclusive because of the limited sample size available for certain groupings of temperature difference and wind direction. To explore this relationship further, a larger sample size would be necessary.

Heavy Lake-Snow Occurrence as Related to the Increasing Lake-Air Temperature Difference

Heavy lake-snow occurrence is related to the temperature difference between the lake water and the ambient air passing over the lakes. Heavy snow amounts of four or more inches systematically increased in frequency of occurrence as the temperature difference increased. This pattern did not continue when heavy snow amounts of eight or more inches

were considered. For these amounts, the highest frequency occurred in the temperature difference group of 25°C to 29°C, and then decreased to zero occurrence for the greater temperature difference groupings. This finding suggests the influence of an additional meteorological factor unrelated to temperature, which becomes important when heavy lake-snow amounts of eight or more inches are observed.

Lake Superior moisture may contribute to the lake-snow totals in northern Lower Michigan, as indicated by satellite cloud photographs, but this contribution does not substantially influence the results of the study.

Snowdepth/Water-Content Pattern

The pattern of the snowdepth/water-content ratio was the same for both the field surveys in the Upper Peninsula and the station data from the Lower Peninsula stations. The highest water content was observed near the lake shore, decreasing at the interior locations. The ratio was much higher for the individual lake-snow events, a finding in agreement with those from the recent studies over the eastern Great Lakes (1).

Conclusions

The results of this study tend to support the hypothesis that the shift in the axis of maximum lake-snow, a feature of the lake-snow belt in western Michigan, is primarily a function of seasonally increasing or decreasing

wind velocities. A divergent wind flow over interior Lower Michigan during mid-winter, late December through early February, may help restrict the inland displacement of lake-snow. Increasing temperature differences play a secondary role in reducing the displacement of the axis of maximum lake-snow. Limited data did not allow an exhaustive analysis of all the groupings by wind direction and lake-air temperature differences. Because of the results of this study, I accept the hypothesis that the primary factor responsible for this shift is the seasonal increase or decrease of wind velocity during periods of lake-snow.

The seasonal shift in the axis of lake-snow as observed over western Lower Michigan should not be unique to this area. A similar feature, although modified by local topography, should exist along the eastern shores of Lake Huron and perhaps Lake Superior. The orientation of the remaining Great Lakes does not appear to be as favorable for observing this feature. Supplemental insight about the control mechanism of the displacement of the axis of maximum snow might be gained from the following research modification:

- acquisition of more data to provide a larger sample size for evaluation of all groupings by wind direction and temperature differences,
- determination of the vertical extent of the lower troposphere modified by each lake-snow event,

- use of data from only the vertical wind profile affected by convection associated with each lake-snow, instead of a standard profile depth,
- evaluation of the influence of vorticity advection during lake-snow events.

CHAPTER VI--REFERENCES

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APPENDICES

APPENDIX A

LAKE WATER TEMPERATURES

November Through March

1965 to 1971

APPENDIX A

Lake water temperatures from the car ferry SS City of Midland in degrees Celsius. Observations taken at 43.5°N 87.2°S ± .2°. Supplemental data were used from the SS Madison and SS City of Green Bay.

Winter of 1965-66

Day	November	December	January	February	March
1	9	6	4	3	3
2	9	5	4	3	3
3	8	5	4	3	3
4	8	5	4	3	2
5	8	5	4	3	2
6	8	5	4	3	1
7	8	5	4	3	2
8	9	5	4	3	3
9	7	5	4	3	3
10	8	4	4	3	3
11	8	5	4	3	3
12	8	5	4	3	4
13	8	6	4	3	4
14	7	6	4	3	2
15	7	5	4	3	3
16	8	5	4	3	3
17	7	6	4	3	3
18	7	6	4	3	3
19	6	5	3	3	3
20	6	5	4	3	4
21	6	6	4	3	4
22	6	6	4	3	4
23	6	5	4	3	4
24	5	5	4	3	4
25	5	5	4	3	4
26	5	5	4	3	-
27	-	5	4	3	-
28	6	6	3	2	-
29	5	6	3		-
30	6	5	3		-
31	-	4	3		-

Lake water temperatures from the car ferry SS City of Midland in degrees Celsius. Observations taken at 43.5°N 97.2°S ±.2°. Supplemental data were used from the SS Madison and SS City of Green Bay.

Winter of 1966-67

Day	November	December	January	February	March
1	6	-	5	4	4
2	5	6	5	5	4
3	-	5	4	4	4
4	5	-	4	5	4
5	7	6	4	5	4
6	7	6	5	4	4
7	7	5	4	4	3
8	7	6	4	4	-
9	6	5	4	5	-
10	6	5	4	4	-
11	6	6	4	4	-
12	-	6	4	5	-
13	-	6	4	5	-
14	5	5	4	5	-
15	5	5	4	5	-
16	5	5	3	-	-
17	6	5	-	-	-
18	6	5	3	-	-
19	5	5	3	4	-
20	6	5	3	5	-
21	6	-	5	4	-
22	6	4	5	4	-
23	6	5	5	4	-
24	6	5	5	4	-
25	6	4	6	4	-
26	6	4	6	3	-
27	-	4	-	3	-
28	-	4	4	4	-
29	-	4	3		-
30	-	4	4		-
31		4	4		-

Lake water temperatures from the car ferry SS City of Midland in degrees Celsius. Observations taken at 43.5°N 87.2°S ± .2°. Supplemental data were used from the SS Madison and SS City of Green Bay.

Winter of 1967-68

Day	November	December	January	February	March
1	9	6	-	-	3
2	9	6	-	-	2
3	8	6	-	-	4
4	8	6	-	4	4
5	8	6	-	-	3
6	8	6	-	4	-
7	8	6	-	4	-
8	7	6	6	5	-
9	8	6	6	5	-
10	7	6	7	4	-
11	7	6	7	4	-
12	7	6	6	4	-
13	7	6	7	4	-
14	7	5	6	4	-
15	7	5	6	5	-
16	7	5	2	5	-
17	7	5	3	3	-
18	7	6	4	3	-
19	7	6	5	-	-
20	7	5	6	3	-
21	7	5	-	3	-
22	7	5	-	2	-
23	6	4	-	2	-
24	7	4	-	-	-
25	7	4	-	4	-
26	7	5	-	4	-
27	6	5	-	2	-
28	6	4	-	7	-
29	6	3	-	6	-
30	6	4	-		-
31		4	-		-

Lake water temperatures from the car ferry SS City of Midland in degrees Celsius. Observations taken at 43.5°N 87.2°S ± .2°. Supplemental data were used from the SS Madison and SS City of Green Bay.

Winter of 1968-69

Day	November	December	January	February	March
1	8	7	8	-	-
2	9	8	5	-	-
3	9	9	7	-	-
4	9	9	6	-	-
5	9	7	6	4	-
6	8	-	4	4	-
7	8	7	6	4	-
8	8	7	5	3	-
9	7	7	5	4	-
10	8	7	4	4	-
11	7	7	4	4	-
12	9	7	4	4	-
13	9	8	5	4	-
14	9	8	5	4	-
15	7	8	5	4	-
16	8	7	5	4	-
17	8	6	5	4	-
18	7	7	4	-	-
19	-	7	5	-	-
20	-	7	-	-	-
21	-	7	-	-	-
22	-	7	-	-	-
23	-	6	4	-	-
24	-	7	4	-	-
25	-	6	-	-	-
26	-	6	4	-	-
27	-	6	4	-	-
28	-	7	4	-	-
29	-	-	4	-	-
30	-	7	4		-
31		8	4		-

Lake water temperatures from the car ferry SS City of Midland in degrees Celsius. Observations taken at 43.5°N 87.2°S ± .2°. Supplemental data were used from the SS Madison and SS City of Green Bay.

Winter of 1969-70

Day	November	December	January	February	March
1	8	6	6	5	-
2	8	6	6	6	-
3	8	6	5	-	-
4	8	5	5	-	-
5	8	6	5	5	-
6	8	-	5	5	-
7	8	-	4	-	-
8	8	-	4	6	-
9	8	-	4	5	-
10	8	-	6	4	-
11	8	-	5	4	-
12	7	-	6	-	-
13	7	-	6	-	-
14	6	3	4	-	-
15	6	2	5	-	-
16	7	0	6	-	-
17	7	1	6	-	-
18	7	2	5	-	-
19	7	-	4	-	-
20	7	2	-	-	-
21	6	-	4	4	-
22	7	6	-	4	-
23	7	6	6	3	-
24	6	6	5	4	-
25	6	6	5	-	-
26	6	6	4	3	-
27	6	6	6	3	-
28	6	6	6	3	-
29	6	6	5		-
30	6	6	6		-
31		5	5		-

Lake water temperatures from the car ferry SS City of Midland in degrees Celsius. Observations taken at 43.5°N 87.2°S ± .2°. Supplemental data were used from the SS Madison and SS City of Green Bay.

Winter of 1970-71

Day	November	December	January	February	March
1	11	7	6	5	-
2	10	-	5	4	-
3	11	7	6	4	-
4	11	7	6	4	-
5	9	6	-	4	-
6	9	7	-	4	-
7	7	7	-	3	-
8	7	7	-	3	-
9	9	7	-	3	-
10	-	-	-	3	-
11	7	7	-	3	-
12	7	7	-	3	-
13	8	7	4	3	-
14	8	6	-	3	-
15	10	7	4	3	-
16	9	7	4	-	-
17	8	6	4	-	-
18	8	7	4	-	-
19	9	7	5	-	-
20	9	6	6	-	-
21	8	6	5	-	-
22	9	6	4	-	-
23	9	6	5	-	-
24	8	6	5	-	-
25	8	7	5	-	-
26	7	6	-	-	-
27	7	6	4	-	-
28	8	6	4	-	-
29	7	6	5		-
30	7	6	-		-
31		6	5		-

APPENDIX B

DISPLACEMENT OF AXIS OF MAXIMUM SNOWFALL

November through March

1965 to 1971

APPENDIX B

Displacement (in miles) of axis of maximum snowfall, November through March, 1965 to 1971, by traverse, northwest (NW)/ west-central (WC)/southwest (SW), for days of lake-snow.

Winter 1965-66

Day	November	December	January	February	March
	NW/WC/SW	NW/WC/SW	NW/WC/SW	NW/WC/SW	NW/WC/SW
1					
2					
3			37/-/-		
4		40/-/-		-/ 6/ -	
5				-/23/18	
6		42/-/10			
7			38/11/14		-/ 7/18
8			-/ 5/ 4		
9					
10	22/ -/ -				
11			34/ -/18		
12					
13					
14					
15	35/ -/ -				
16		-/31/ -	31/ 5/ -		
17		-/14/14	20/ 9/ 9	35/20/21	
18		32/24/ -	4/ 8/ 4		
19			21/ 4/ 6		-/38/ -
20					
21				-/ 9/ -	
22				-/ 6/ -	
23					
24			-/ 8/17		-/10/18
25				-/31/ -	-/22/22
26				-/18/ -	
27			38/28/17		
28	-/33/42		10/ 8/16		
29			10/ 6/ 2		
30	25/15/12		9/ 7/ 2		
31			9/ 9/12		

Displacement (in miles) of axis of maximum snowfall, November through March, 1965 to 1971, by traverse, northwest (NW)/ west-central (WC)/southwest (SW), for days of lake-snow.

Winter 1966-67

Day	November	December	January	February	March
	NW/WC/SW	NW/WC/SW	NW/WC/SW	NW/WC/SW	NW/WC/SW
1		36/27/43			
2		30/27/28			
3		31/ -/19			
4	40/20/35				
5					
6					
7					
8			21/10/ -	5/18/ -	
9					
10			20/22/28		
11			-/ -/20	-/ 9/ -	
12			-/24/ -	-/ 6/ -	
13					
14					
15			-/ 2/ -		
16			14/ 7/ -	-/ 9/25	41/11/16
17			-/10/ -		39/15/12
18			12/ 6/ 7		
19			-/22/ -		
20	-/ -/12			-/16/ -	
21				28/24/15	
22		42/ -/ -		-/14/ -	
23		19/ 8/ 2		-/13/24	28/ -/ -
24		22/18/19		-/ 6/ 2	
25		34/ 5/ 2		-/ 6/ 7	
26					
27					
28					
29					
30					
31					

Displacement (in miles) of axis of maximum snowfall, November through March, 1965 to 1971, by traverse, northwest (NW)/ west-central (WC)/southwest (SW), for days of lake-snow.

Winter 1967-68

Day	November	December	January	February	March
1			16/18/ -		
2			11/ 5/ 6	16/15/ 7	
3			14/ 4/ 4	14/ -/ -	
4			12/10/11		
5	33/24/22		7/ 7/ -		
6	23/ -/24		2/ 6/ 6		
7			14/ 6/ 5		
8			4/14/16		
9					
10			6/10/ -	-/ 8/12	
11				22/ 5/ 5	
12				-/ 9/ 6	
13				-/ 6/ -	
14					
15					
16					
17				28/11/ -	
18					
19					
20				-/ 7/ 5	
21				-/ 6/ 5	
22		19/14/20			
23		30/ 7/18			
24					
25					
26		12/ 9/14			
27	21/28/31	22/ -/15			
28	19/28/ -	4/12/12			
29		-/25/ -			
30					
31		20/ 8/ 2			

Displacement (in miles) of axis of maximum snowfall, November through March, 1965 to 1971, by traverse, northwest (NW)/ west-central (WC)/southwest (SW), for days of lake-snow.

Winter 1968-69

Day	November	December	January	February	March
	NW/WC/SW	NW/WC/SW	NW/WC/SW	NW/WC/SW	NW/WC/SW
1			32/14/24		
2			28/ 9/15		
3			4/ 7/12		
4			12/10/12	15/ -/ -	
5		31/35/50	20/ 8/ 4		
6		14/22/42			
7		16/14/ 7	30/ 8/ -		
8	4/ -/ -	-/ 8/17			
9	-/ -/16				
10			-/24/29		-/15/16
11			-/ 9/ -		-/ 9/ 5
12			11/ 9/ -	7/ 7/10	
13				-/ 7/ 7	
14		-/21/20			
15		-/ -/ 6			
16					
17					
18					
19	37/10/32				
20	29/ -/29	36/20/20			
21					
22					
23		27/35/32			
24		36/ -/32	-/ 9/ -		
25		35/26/19	3/19/14		
26			8/15/ 5		
27					
28		33/12/12			
29		3/14/16			
30					
31		9/ 9/14			

Displacement (in miles) of axis of maximum snowfall, November through March, 1965 to 1971, by traverse, northwest (NW)/ west-central (WC)/southwest (SW), for days of lake-snow.

Winter 1969-70

Day	November	December	January	February	March
	NW/WC/SW	NW/WC/SW	NW/WC/SW	NW/WC/SW	NW/WC/SW
1					
2			-/17/ 6		
3		33/20/15	-/ 7/ 7	11/ 7/ 4	
4		-/10/14	2/18/11	6/ 6/ 2	
5			26/18/ -		
6			14/ 6/ 5		
7			-/ 6/ 5	-/16/ -	
8			-/ 4/ 2		
9			12/ 6/14		
10			-/10/ -		
11		33/ -/42	22/ 9/ -		
12	36/21/ -		-/15/ -	17/12/12	
13	14/14/13				-/10/ 8
14	12/18/18	-/ -/16		12/ -/ -	
15					
16					
17			-/ -/13		
18		32/29/ -	15/ 8/ -		
19		-/21/ -	11/ 6/ 5	-/16/16	
20	34/35/37	-/ -/16	10/ 7/ 2	16/16/16	
21			11/ 6/ 2		
22			-/ 6/ -		
23			22/15/32		
24		-/21/21			
25		-/19/40			
26					
27				-/16/ -	
28					
29					
30					
31					

Displacement (in miles) of axis of maximum snowfall, November through March, 1965 to 1971, by traverse, northwest (NW)/ west-central (WC)/ southwest (SW), for days of lake-snow.

Winter 1970-71

Day	November	December	January	February	March
	NW/WC/SW	NW/WC/SW	NW/WC/SW	NW/WC/SW	NW/WC/SW
1				11/ 7/ 4	
2			4/ 6/ -	7/ 5/ 4	
3					
4					
5			-/32/23		
6		32/12/15	15/ 7/13	21/ -/ -	
7			21/ 6/18		
8			-/ 5/ 6		
9				-/ 7/ 5	
10					
11					
12					
13					
14					
15			-/ 5/ -		
16			14/10/12		
17					
18			-/ 6/ 3		
19			-/ 6/ 4		
20		21/ -/ -			52/ -/ -
21					
22					
23	40/24/26				
24	36/11/24				-/14/23
25	36/10/38	4/ 6/ 8			
26		-/ 9/17	28/36/34		
27		-/ 8/25	-/11/14		
28		24/ 6/ 4	26/10/ 9	28/ -/ -	
29					
30			-/ 9/34		
31			-/ 8/ 4		

APPENDIX C

TEMPERATURE DIFFERENCE (ΔT) BETWEEN THE LAKE WATER AND 850 MB LEVEL

APPENDIX C

Temperature differences between the lake water and 850 mb level for days of lake-snow, °C. $\Delta T = T_{\text{lake water}} - T_{850\ \text{mb}}$.

Winter 1965-66

Day	November	December	January	February	March
1				14	
2					
3			15	16	
4		22		19	
5				18	
6		22			
7			16		18
8			25		
9	13				
10	13				
11			24		
12					
13					
14	14				
15			15		
16		19	19		
17	23	22	17	25	
18		24	20		
19		24	17	13	
20				28	
21				18	
22				13	
23				13	
24			19		19
25				14	21
26			20	15	
27			29		
28	30		32		
29	25		25		
30	22		24		
31			18		

Temperature differences between the lake water and 850 mb level for days of lake-snow, °C. $\Delta T = T_{\text{lake water}} - T_{850\ \text{mb}}$.

Winter 1966-67

Day	November	December	January	February	March
1		26			
2		31			
3		23			
4	17	13			
5					
6					
7					
8			18	23	
9			18		
10			16		
11			19	25	
12			13	30	
13					
14					
15			20		
16			15	20	15
17			21		24
18			28		
19	14		21		
20				15	
21				22	
22		17		13	
23		21		23	13
24		17		30	
25		17		27	
26		20			
27					
28					
29					
30	13	15			
31		13			

Temperature differences between the lake water and 850 mb level for days of lake-snow, °C. $\Delta T = T_{\text{lake water}} - T_{850\ \text{mb}}$.

Winter 1967-68

Day	November	December	January	February	March
1			30		
2				13	
3			23	13	
4					
5	20		28		
6	22		21		
7			30		
8			28		
9					
10			22	29	
11				28	
12				26	
13	15			22	
14		14			
15					
16					
17				31	
18					
19	17				
20	17			24	
21				29	
22		17			
23		19			
24					
25					
26		27			
27	23	25			
28	24	22			
29	18				
30					
31		26			

Temperature differences between the lake water and 850 mb level for days of lake-snow, °C. $\Delta T = T_{\text{lake water}} - T_{850\ \text{mb}}$.

Winter 1968-69

Day	November	December	January	February	March
1			35		
2			20		
3			26		
4			25	21	
5		22	20	16	
6		19			
7		22	21		
8	13	23			
9	16		21		
10			20		15
11			20		23
12			17	22	
13				21	
14		24			
15		22			
16					
17					
18					
19	19				
20	18	16			22
21					
22					
23		16			
24		25	13		
25	13	28	34		
26			28		
27					
28		16			
29		21			
30					22
31		25			

Temperature differences between the lake water and 850 mb level for days of lake-snow, °C. $\Delta T = T_{\text{lake water}} - T_{850\ \text{mb}}$.

Winter 1969-70

Day	November	December	January	February	March
1			17		
2			18		
3		18	18	36	
4		21	20	33	
5			19		
6			21		
7			24		13
8			24		
9			25		
10			18		
11			15	14	
12		18	16	19	
13	15		21	27	
14	20				17
15	19	15		19	18
16		16			17
17			18		
18		13	26		
19		16	24	19	
20	22	16	28	24	
21	22		29	16	
22		21	23		
23			21		
24					
25		17		25	
26		17			
27				19	
28					
29			13		
30	16		20		
31					

Temperature differences between the lake water and 850 mb level for days of lake-snow, °C. $\Delta T = T_{\text{lake water}} - T_{850\ \text{mb}}$.

Winter 1970-71

Day	November	December	January	February	March
1				35	
2			13	32	16
3		13			
4		14			
5		13	20	12	
6		22	23	18	
7		21	25	18	
8			22	23	19
9				25	
10			12		
11			14		
12			20		
13					
14					
15			15		
16			18		18
17					
18			22		
19			26		
20		17			14
21		18			
22		14			
23	26	13			17
24	25	16			18
25	20	20			18
26		24	24		
27		20	26		
28		22	26	14	
29		22			13
30			28		
31			34		

APPENDIX D

GEOSTROPHIC WIND CONVERSION FROM DEGREES LATITUDE TO METERS PER SECOND AND KNOTS

APPENDIX D

Sample computation for geostrophic wind given the following:

Z = 60 meters as a constant
N = 5.2° latitude
g = 9.8 meters/second^2 as a constant
f = 10^{-4}/second as a constant

$$V_g = \frac{9.8 \text{ m/sec}^2}{10^{-4}/\text{sec}} \frac{60 \text{ m}}{5.2° \text{lat.}} = \frac{588 \text{ m/sec}}{58.162} = 10.1 \text{ m/sec} = 19.6 \text{ knots}$$

V_g = (52.5704/lat.)m/sec and V_g = (102.1201/lat.) knots.

Conversion table computed to convert degrees and tenths of latitude to meters per second and knots.

Degrees Latitude	Meters/ Second	Knots	Degrees Latitude	Meters/ Second	Knots
.2	263	511	2.5	21	41
.3	175	340	2.6	21	39
.4	131	255	2.7	19	38
.5	105	204	2.8	19	36
.6	88	170	2.9	18	35
.7	75	146	3.0	18	34
.8	66	128	3.1	17	33
.9	58	113	3.2	16	32
1.0	53	102	3.3	16	31
1.1	48	93	3.4	15	30
1.2	44	85	3.5	15	29
1.3	40	79	3.6	15	28
1.4	38	73	3.7	14	28
1.5	35	68	3.8	14	27
1.6	33	64	3.9	13	26
1.7	31	60	4.0	13	26
1.8	29	57	4.1	13	25
1.9	28	54	4.2	13	24
2.0	26	51	4.3	12	24
2.1	25	49	4.4	12	23
2.2	24	46	4.5	12	23
2.3	23	44	4.6	11	22
2.4	22	43	4.7	11	22

Degrees Latitude	Meters/ Second	Knots
4.8	11	21
4.9	11	21
5.0	11	20
5.1	10	20
5.2	10	20
5.3	10	19
5.4	10	19
5.5	10	19
5.6	9	18
5.7	9	18
5.8	9	18
5.9	9	17
6.0	9	17
6.1	9	17
6.2	8	16
6.3	8	16
6.4	8	16
6.5	8	16
6.6	8	15
6.7	8	15
6.8	8	15
6.9	8	15
7.0	8	15
7.1	7	14
7.2	7	14
7.3	7	14
7.4	7	14
7.5	7	14
7.6	7	13
7.7	7	13
7.8	7	13
7.9	7	13
8.0	7	13
8.1	6	13
8.2	6	12
8.3	6	12
8.4	6	12
8.5	6	12