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Winter Climatology and Ice Characteristics: St. Marys River — Whitefish Bay Waterway

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WINTER CLIMATOLOGY AND ICE CHARACTERISTICS:

ST. MARYS RIVER-WHITEFISH BAY WATERWAY

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CONTENTS

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ABSTRACT

On a regional basis the thermal behavior of Lake Superior and its interaction with the atmosphere in late fall and early winter promote widely varying temperature and snowfall patterns around the lake periphery. Field investigations indicate that snow-ice layers make up a large portion of the total ice thickness at select sites around the lake and on the St. Marys River Waterway. On a local waterway scale for the St. Marys River, temperature controls on ice thicknesses and structures appear to be more significant at river sites where ice is more stable for a larger part of the ice season. Further, assessing the thermal control on ice behavior by only one meteorological station far removed from river sites is susceptible to misrepresentation of actual on-the-site temperature regimes.

Field observations of radiation, temperature, wind, ice thickness and structure indicate a close relation between climatic parameters and ice growth and decay. Just analyzing one isolated parameter, usually freezing degree days, is not justified in predicting ice growth and changes in ice structure.

De-icing schemes, particularly dusting with darkened materials, must account for climatic factors to be successfully implemented. There is a marginal probability of successful deicing by dusting for the St. Marys River as suggested by an analysis of solar radiation and air temperature.

INTRODUCTION

The disciplines of hydrology, geology, and climatology are important in river and lake ice studies. Climatology, the major focus of this report, is significant because the seasonal heat balance at the water and ice interface partially dictates ice thickness, structure, and distribution.

The relationship of heat flux to ice growth, ice structure, and decay has been formulated by many investigators and is illustrated in Figure 1 (Scott and Rogotzkie, 1961). The science which studies these interactions of energy at the hydro-atmosphere interface is termed micrometeorology. Microclimatology extrapolates micrometeorology over areas and long term intervals. The nature of energy exchange at the earth's surface is very complex. It is dependent on the surface configuration and the dynamics of temperature and wind relationships with height above the surface. The energy exchange is not strictly dependent on low level temperature and wind differences, but it also includes fluctuations in the circulation of the atmosphere. Transfer of heat, momentum, and water vapor occur over broad regions as well as within the shallow layer of air immediately adjacent to the ground. One of the major problems of climatology is the interrelationship of climatic factors on both the micro and macroclimate scales. These are significant for river and lake ice studies, since there can be many factors at each of these scales that are important, and they must be fully understood before any causative factors in ice formation and decay can be pinpointed. For example, the cycle of winter ice phenomena of the Lake Superior basin could be influenced dramatically by a small snow squall. At the same time the synoptic weather maps of the air mass over that region show no dramatic change. On the other hand, a large mid-winter migratory low pressure cell lasting a considerable period of time may affect locations over the entire basin, overriding any local climatic differences that normally occur along the Lake Superior shoreline. The duration of local versus regional conditions can dictate the nature of the ice cover for that particular winter. For example, ice cover thickness for two seasons may be equal, but the length of the formation and decay periods may be quite different. This can be caused by the length of time that the ice cover is influenced by either local or regional climatic conditions.

To understand the relationships between climatology, ice formation, growth, and decay in the Whitefish Bay-St. Marys River waterway, a field program was implemented in the 1968-69 winter ice season. Results of this study serve to aid in understanding the relationship of climate to ice and to increase knowledge on the feasibility of de-icing techniques in this area. Included in this report are a review of the regional air masses which affect the St. Marys waterway in the winter season; an analysis of records from selected surface weather stations along the waterway and the southern Lake Superior shoreline; a review of the freeze-up and break-up climatology along the waterway; the importance of micrometeorology and its relation to the ice sheet; the feasibility of de-icing by dusting procedures; and a discussion of the Mississippi and St. Marys River climatology and ice thicknesses.

In this waterway region only one first order weather station is located at the Sault Ste. Marie Airport. An additional network was established to gain an understanding of the temperature and precipitation variations along the waterway. The network is shown in Figure 2. All stations included hygrothermagraphs housed in standard shelters. Snow gages were maintained at the Little Lake, Pt, Iroquois, and Lake Nicolet sites. Solar radiation was recorded for the period of investigation at three stations along the waterway: Whitefish Pt., Pt. Iroquois, and Detour. St. Marys River ice sheet was investigated at a location adjacent to Pt. Iroquois. The length of record at Whitefish Pt., Goulais Bay. Pt. Iroquois, and Lime Island was from mid-January to early February, and ran through May 7.

REVIEW OF REGIONAL WINTER CLIMATOLOGY

North American Winter Air Mass Distributions and Movements

The Whitefish Bay-St. Marys River waterway, connecting Lake Superior with Lake Huron, is constantly subjected to atmospheric influences of these two lakes, and Lake Michigan. The winter climatology of the waterway is partially dependent on expanses of open lake water, fetch distances along its course, and exposure to local topography. Superimposed on these local and basin wide factors are the North American air mass movements and Migration patterns over the upper Midwest during the winter ice season.

Local climatic modification is imposed on winds, air temperatures, snowfall, cloud and fog frequencies, and water vapor transfer. Lake Superior modifies the climate of the waterway to a greater degree than any of the other lakes, because of its large surface area, depth, and location relative to the prevailing westerly winds of this latitude.

Table I gives a brief summary of the air masses that normally influence the climate of the waterway region. An air mass is defined as a widespread body of air which is homogeneous in horizontal extent. If an air mass remains stagnant long enough over a homogeneous region, radiation and vertical convection will cause the vertical temperature and moisture to reach equilibrium with the surface beneath. The atmosphere will assume properties representative of the type of underlying surface. Air masses moving from their source regions to other areas will retain many of their source properties.

The classification of air masses is genetic--that is, they are recognized by how and where they form, for example, polar masses tracking southward are termed polar. Air masses are modified as they move out of their source regions. Many types of moderating influences have been recognized. Diagram 1 illustrates the major moderating influences. The thermodynamic influences are most significant in the St. Marys waterway. The winter season polar air masses, which dominate the climate of the waterway region, are modified thermodynamically and mechanically because of the presence of Lake Superior.

During the winter lake-ice season, the waterway assumes a marginal location between the Azores high pressure formations which extends into the southeastern United States; interior Canada high and the large Icelandic low pressure center off the southeastern coast of Greenland. During the autumn months the Icelandic low moves eastward and intensifies, and a high pressure dome forms over central Canada. In November, the northern lake basin encounters frequent cyclonic activity, as storm tracks converge from frontogenesis source regions in Alberta and Colorado. In January, migratory lows from Alberta give peak frequency of occurrence east of the northern lake basins. During the month of February, westerly winds prevail (zonal flow) and centers of cyclonic activity are displaced to the south of Lake Superior. In the spring months, the Icelandic low is most intense westward toward Canada; the Azores high intensifies and is displaced westward; and meridional flow is maintained over the eastern and central United States. Westerly and southerly flow commences and imports warm, moist air into the northern lake region. The spring thaw period is initiated at this time.

The major consideration in ice formation is the nature, development, migration, and intensification of cold air domes that build in northern and central Canada. These usually penetrate the mid-section of the continental United States, often presenting frost problems to agriculture in the far south. For Sault Ste. Marie, it has been estimated that Canadian arctic and polar air masses prevail 68 percent of the time in January and 86 percent of the time in April (figures are after Niedringhaus, 1966), while for Detroit 75 percent and 64 percent respectively. Maritime polar and tropical air masses, which very rarely penetrate to the Lake Superior latitudes in winter and spring, have less than one percent probability of occurrence in January and April. Detroit figures are 3 percent and 17 percent respectively.

Air masses partially control the temperature, precipitation, and wind regimes. For example, the largest January totals of precipitation in the waterway region are mainly associated with two weather types: a frontal snowfall accompanying low pressure migration from the Alberta frontogenesis region; and a high pressure cell centered just south of the Great Lakes feeding westerly and northwesterly flow across Lake Superior. Snows caused by lake modification of air flow, steepening of lapse rates near the water surface and convective and condensational activity, predominate. In April, families of low pressure cells tracking from the southern plains states into the Great Lakes region bring the largest precipitation totals to the waterway. Two other types also bring high precipitation totals; 1) An Alberta low pressure migration, and 2) a high pressure cell positioned over Lake Superior with another high over the southeastern Atlantic States. A stationary front forms the "col" between these two air masses, and frontal cloud and precipitation marks the boundary.

The most frequent air masses affecting the waterway during the month of January are the continental Arctic and modified continental Polar. Under the influence of these air masses there is a 70 to 90 percent chance that at least a trace of snow will be recorded, and a 35 percent chance that at least a 0.5 inch of snow will fall. During April, continental Polar and modified continental Polar air masses are the influencing factors and the chances become 50 to 75 percent and 20 to 50 percent respectively.

For the less frequent air masses, the maritime polar and tropical, there is close to 100 percent chance of at least a trace of precipitation in January hardly any probability for .05 inches water equivalent. In April, these figures are 58-100 percent for a trace; 42-100 percent for .05 inches water equivalent.

Lowest temperatures on the waterway occur in January, and are normally associated with three types of weather: (1) a high pressure cell directly over the lake basin, originating in northwestern Canada; (2) a high pressure cell centered immediately south of the lake basin, originating over central Canada; and (3) a high pressure cell located just northeast of Lake Superior bringing cold, easterly winds to the waterway. For April, the lowest temperature conditions accompany the first two conditions, and also following an Alberta low cold front passage directly over the northern lake basin.

Higher temperatures in January are associated with infrequent influxes of warm air from southerly latitudes during the movement of a family of low pressure cells north of the lake basin. Slow moving or stationary lows commomly cause the familiar early-to-mid-winter thaws which last for several days. The extent of thaw is variable from year to year and dependent upon short-term movements of pressure cells. In April, the warmest weather generally accompanies stationary frontal conditions extending across the upper lake basin. This front separates a northern, cold interior high pressure cell from a southern, warm maritime high pressure cell. Warm moist air flows northward into the Lake Superior area during these conditions. The duration and stagnation of these two highs determine the extent of regional warming temperatures over a period of several days to a few weeks.

LAKE SUPERIOR MESOCLIMATOLOGY

Lake modification of air masses and the resultant alteration of climatic elements occurs during the winter ice-forming and spring ice-decay periods. A short analysis of selected Lake Superior weather stations illustrates some influences on local climatology. In January there is a mean temperature difference of 8-10°F between eastern and western portions of the basin at similar latitudes (Figure 3). The warmest zones stretch from the Keweenaw Peninsula to Grand Marais in the Upper Peninsula of Michigan. Farther east from this zone, mean January temperatures drop several degrees. During the spring period of ice decay, the coolest zones are at the eastern end of Lake Superior, since the cold lake waters tend to modify the spring warm-up period. Areas west of the lake often experience a rapid, early spring thaw. The mean April temperature of 38°F (3.5°C) at the Sault Ste. Marie airport is several degrees lower than locations at the western end of the lake.

For the November 1968, to April 1969 period, four first-order weather stations listed in Table II illustrate these principles.

TABLE II

Station	Latitude	Longitude	Elevation
Duluth, Minnesota International Airport	46° 50' N	92° 11' W	1428 feet
Marquette, Michigan U. S. Post Office	46° 34' N	87° 24' W	677 feet

Station	Latitude	Longitude	Elevation
Sault Ste. Marie City-County Airport	46° 28' N	84° 24' W	721 feet
Alpena, Michigan Phelps Collins Field	45° 04' N	83° 34' W	689 feet

Freezing and thawing degree-days indicate the above pattern for the four stations. The curves shown in Fig. 4 are superimposed and indicate the seasonal progression of below freezing temperatures; when the curve slopes downward, thawing is taking place.

Table III lists station total and thawing degree-days.

TABLE III

	Freezing Degree-Days (Freeze-up to Max)	Thawing Degree-Days (Max to April 30)
Duluth	2321	280
Sault Ste. Marie	1666	210
Marquette	1019	310
Alpena	1205	290

These results confirm previous discussions of the thermal pattern around Lake Superior (Kopec, 1965; Leighly, 1941). An analogous argument has also been given for the large Hudson Bay water body (Hare, 1949).

Duluth is prone to frequent Canadian, Polar, and Arctic air mass pulsations. For winter 1968-69, this station attained a freezing degree-day total of 2321, more than twice that of Marquette (Table III). This could be explained partially by the Duluth station elevation which is 851 feet higher than that of Marquette, but the difference mainly results from the open waters of Lake Superior locally raising the temperatures at Marquette. This phenomenon recurs yearly in the winter period. It is only diminished when the very rare event of a frozen Lake Superior occurs. It has been suggested (e.g., Rondy, 1969) that Lake Superior very rarely freezes over entirely. The process of local modification is attributable to the large temperature gradient induced when a cold air mass overrides the open waters of Lake Superior. This creates a very large instability condition, promotes the absorption of heat by the air mass from the lake, and transfers heat to the peripheries of the lake through advection processes. This phenomenon generally occurs in early to mid-winter. From mid-winter to spring, it is diminished as the lake overturn is being completed and the frequency of cold air masses is reduced. In the winter of 1968-69, from late December and mid-January to late January Duluth doubled the Marquette freezing degree day total and from February 5 to mid-April attained only one-third more freezing degree days than Marquette.

Sault Ste. Marie at the southeastern end of Lake Superior also displays a lake-effect temperature regime. However, the region along the waterway is frequently controlled by cold air from the land masses to the north and east. The cumulative freezing degree-day totals indicate that the airport station had the second most severe thermal regime of the four stations given. Alpena is listed for comparison with locations south of the waterway. During the spring thaw season, as suggested by the basinwide temperature map, the lake creates lower temperatures east of the basin. The progression of the cumulative freezing degree-day plots indicates there is a lag effect of spring warm-up in the waterway region. Sault Ste. Marie, from the first day when above freezing temperatures were recorded until April 30, attained the lowest thawing degree-day total of the four stations given.

Sunshine, snowfall, and snow on the ground are other helpful indices for the study of ice formation and decay. Records of these factors can be viewed together as indicators of weather events which partially determine the winter ice history. Figure 5 shows plots of these factors for the winter 1968-69, November through April, for all stations. Sunshine is severely diminished during the early ice season. Daily radiation reached less than 100 langleys for well over 50 percent of the days in the period November through January. The percent of possible radiation reaches a yearly low during the early winter season. This condition is most accentuated for Sault Ste. Marie. Mean November and December cloud cover statistics show that the Sault Ste. Marie area is cloudy more than 70 percent of the time. For Marquette and Sault Ste. Marie, the peak snowfall period occurs in the early ice season. This is indicated by snowfall and snow on the ground (Figure 5).

Highest snowfall in the Lake Superior basin commonly occur in the eastern portions of the Keweenaw Peninsula and in a zone from Marquette to Whitefish Point. The high totals are presumably due to lake effect snowfalls plus the snow added from mid-winter migratory low pressure systems. Other high snowfall areas have been recognized on the lee side of the other Great Lakes (Mitchell, 1921; Sheridan, 1941; Remick, 1942; Wiggin, 1950; Eichmeier, 1961; Muller, 1962;Richards, 1963; Thomas, 1964; Peace and Sykes, 1966). The mean annual snowfall is approximately 80-100 inches (200-250 cm) for the waterway. For the high snowfall areas west of the waterway, the totals on occasion may reach 200 inches (over 5 m). Locations east of Lake Superior generally experience a larger amount of snowfall in comparison to those areas to the west of the lake. This is significant for the potential of snow ice formation. Figure 6 locates ice observing points around the basin from which data on ice thickness and structure have been obtained. The map portrays the ratio of snow ice to lake ice thickness for all locations for the period March 8-14, 1968. The ratio fluctuates over the winter ice season in relation to time of snowfall and air temperatures. The map illustrates conditions at the time of maximum ice thickness. Therefore, the pattern illustrates the fully developed ice structure for the winter ice season 1967-68. The very large snow-ice totals in the southern and eastern portions of the basin correlates with the highest snowfall areas.

RELATIONSHIPS OF WATERWAY CLIMATE AND ICE

Freeze-Up Period Ice formation depends on heat balance which is a function of the intensity of anticyclonic cold waves, the extent of lake modification, and the fall overturn mechanism of the lake and river water. Snow contributes in many ways to the progression of ice growth. It acts as a cooling agent and provides nuclei for skim ice formation and contributes to many unique ice features, such as ball ice. Redistribution and reworking of initial skim ice formation occurs in the bay and lake locations affected by strong currents and waves. The 1967 ice cover freeze-up sequence for the St. Marys waterway, northern Lake Huron and southeastern Lake Superior is given by Snider (1967). The only substantative observations of the areal pattern of freeze-up along the waterway are periodic aerial observations taken by the Lake Survey Center and the Department of Transport of Canada. Charts indicate the ice coverage along the waterway and the lake environments. They show that lower river sections from Lake Nicolet to Detour Passage normally have the earliest ice sheet formation on the waterway. Channel sectors from the "Soo" locks to Pt. Iroquois, and in Whitefish Bay proper, do not normally form a consolidated ice cover as early as the lower river.

Lake Survey Center has maintained an extensive network of ice observation stations in the Lake Superior basin in past years. Other observation sites have also been established along the St. Marys waterway. Two of the sites are chosen to illustrate the local differences in the ice cover between areas near Whitefish Bay and those in the lower sections of the St. Marys waterway. The two sites are Raber Bay and Gros Cap Light (Figure 2). Ice observations during 1968-69 indicate that Raber Bay had formed a solid ice sheet in early December. However, Gros Cap Light did not have a solid ice sheet until the end of January. Figure 7 displays these relationships for both the 1967-68 and the 1968-69 ice seasons, and shows the much earlier freeze-up in Raber Bay. However, the dates of freeze-up and ice growth at both locations, are controlled by the weather.

Local climatology along the waterway suggests that air temperatures were cooler farther inland from Lake Superior, especially in the lower portions of the waterway. Figure 8 shows five stations which span the waterway from Whitefish Bay to the lower river sections. The graphs are of freezing degree days and show a comparison between Sault Ste. Marie airport station and all of the other stations. The relationship is that the first three stations (Whitefish Pt., Goulais Bay, Pt. Iroquois) show lower totals of freezing degree-days than the sites farther inland (Sault Ste. Marie and Lime Island). The reason for this pattern can be attributed to the large heat reserve of Lake Superior conveying heat to the air-water interface and to the nearshore locations. It is also suggested that this warmer-to-cooler relationship with distance from the lake would be accentuated during extreme anticyclonic flow across Lake Superior.

Explanation of the ice thickness growth curve in the early-to mid-ice season period involves more than understanding the air temperature factor. A consideration must be given to the influence of variations in snowfall and snow cover on the ice sheet. For the two years of detailed observations at these two sites, extreme variations in ice structure were observed. The structure profile through time corresponds to the periods of heavy snowfall which provides snow ice development as well as the thermal factors. Figure 7 indicates that the thickness of snow ice was only a part of the total ice thickness and varied from season to season. This is quite noticeable at Raber Bay which had a very stable ice cover. A careful inspection of Figure 9, particularly temperatures and snowfall from the beginning of November through mid-December, show that during the 1968-69 season, although the snowfall totals were not drastically higher than 1967-68 season, temperatures during this period were much lower, which tended to preserve the snow on the ice cover.

In the 1967-68 ice season the first sub-zero cold period influenced the Lake Superior basin in the first and second week of January. On the other hand, in 1968-69 sub-zero weather was recorded 2 to 3 weeks earlier and Raber Bay recorded 5, 10, 15, and 20 inch (13, 25, 38, and 51 cm) thicknesses well before it did in 1967. This was primarily due to greater development of snow and slush ice layers. The interesting feature of Figure 7 for Gros Cap Light is that these relations are reversed, i.e., thicker ice ranges occurred earlier in 1967 than in 1968. It is suggested here that these reverse relationships are a function of site factors unique to those portions of the river system. The more stable ice cover areas appear to correspond more strongly with thermal controls of climate. However, Gros Cap Light illustrates that present simple climatic models (e.g., predictions of ice growth versus freezing degree days) will not apply with great accuracy and will only partially explain the progression of ice development at sites such as Gros Cap Light--a site with large exposure to bay wave action and strong water currents. The Raber Bay site is more similar to inland lake areas where successful application of more simplistic ice growth models has been accomplished (Jones, 1969).

<u>Mid-Season Period</u> Ice growth to the seasonal maximum is a function of many factors in addition to temperature. After the initial waterway freeze-up, snowfall and snow on the ice provides the potential for snow-ice formation. This process has been described in detail by Shaw, 1965.

During the middle of the ice season, a common weather phenomenon the familiar January thaw can contribute to ice loss in some cases. The thaw period alters the bay and river ice sheet, and slows down ice growth. It may also change snow into slush which may be sandwiched between lower ice layers and subsequent snowfalls. This slush-ice layer feature is common to this region (Marshall, 1965). The January thaw of 1968 was initiated by a series of low pressure cells passing across the Lake Superior basin with temperatures rising sharply at both extremities of Lake Superior. The scale and intensity of the thaw phenomenon and its influences on Lake Superior ice distribution have not been studied in detail. Should an intense thaw occur, following a very late freeze-up of the waterway, it is entirely possible that deicing could occur, and navigation operations could be continued.

Break-Up Period Ice decay and break-up in the spring season is determined mainly by warm air advection in the waterway region; increased solar radiation intensities and subsequent changes in the ice surface albedo; and the mode of precipitation, e.g., rain providing a large latent heat input (Richards, 1964). Surface and sub-surface runoff from melting snow aids the ice deterioration both thermally and mechanically by forming shore moats and raising water levels in the bay and along the waterway. It has been shown that runoff water provides heat to the ice cover by conduction (Scott, 1961).

Once snow has melted, the land surface absorbs large quantities of heat energy due to its low albedo. Late season cool air masses from Canada, which otherwise would tend to restrict early spring ice decay, are thereby modified over the land. On the other hand Lake Superior is generally cooler than the spring air masses over the basin, causing cold lake inversions in the spring season (Strong, 1968). The degree of shading in Figure 10a and Figure 11 show that the spring thaw is retarded near Lake Superior. However, two sites farther inland show an anomalous pattern. Rocky Point and Hilton Beach are exposed to broad expanses of late season ice and cold water bodies. In comparison to the Sault Ste. Marie airport trend, these sites were the coldest inland stations. Aerial ice reconnaissance observations during this period indicate that the Raber Bay ice sheet remained longer than ice above the Soo Locks. The breakup of the ice sheet normally follows three stages; deterioration and weakening of the ice sheet with no noticeable decrease in thickness, caused by absorption of solar radiation by impurities along the crystal boundaries;formation and widening of leads; and shifting the ice floes by wind and water currents (Williams, 1967). Ice structure, snow depth, and ice sheet thickness are important considerations in determining the time of natural breakup from year to year. The thermal balance of the ice cover determines the initial stage in ice breakup that is, the internal weakening of crystal boundaries and progression of ice sheet temperatures toward the freezing threshold from sub-freezing regimes. These rapidly changing conditions cause large variations in the ice break-up from one year to the next. A late season cold spell prevented rapid ice decay in the 1969 break-up period. This did not happen in 1968, however.

DE-ICING BY ICE COVER DUSTING

The most important thermal influence on the ice cover from mid-winter to breakup is the quantity of heat conveyed into and out of it by propagation of radiation. Solar radiation is the major determinant of ice sheet temperature during the breakup period.

The individual fluxes of radiant energy can be broken down into four components: shortwave incoming radiation (SWI), shortwave reflected radiation (SWR), longwave incoming radiation (LWI), and longwave outgoing radiation (LWO). The sum of these components will be a net gain or loss of energy by radiation (termed net radiation). A gain in the radiation quantity will be positive and a negative.

A method of altering albedo (ratio of reflected to incoming solar radiation) is to darken the ice surface by lowering the amount of radiation reflected thus increasing absorbance of radiation. A greater amount of radiant heat energy is made available for melting snow and ice, thereby promoting breakup. Dusting with dark materials is a common method used to lower albedo values of an ice sheet (Cavan, 1969). This technique is most effective in the early spring when incoming radiation is increasing day-by-day, and the net radiation balance of the ice sheet is changing from negative to positive. Dusting before the abundant solar energy is available and net radiation balance becomes positive will be relatively ineffective.

To make the most effective use of the atmosphere as a de-icing medium, air temperatures must be near or above the freezing threshold, otherwise the upper layers of the ice sheet will remain below freezing and breakup will be retarded. The condition is particularly prevalent when the ice sheet is under the influence of Canadian arctic and polar air masses. Calm winds, clear skies and rapid drops in air temperature near the surface are common conditions for ice making. The variation of daily temperatures under Canadian air mass conditions cover a wide range. Daytime values may reach the freezing threshold, but night temperatures may dip tens of degrees lower. Ice and snow surface temperatures must be close to the freezing threshold to enable dusting to be effective and to commence positive ice sheet heat balances once dusting applications are initiated.

Ice and snow surface temperatures are a function not only of air mass temperature, but also of the amount of radiation emitted by the surface into the atmosphere. A snow cover on the ice sheet indirectly regulates this heat quantity by providing a high albedo and acting as a poor conductor of heat. It acts as an insulator and retards radiation to the atmosphere from the ice and water beneath. In mid-winter a heavy snow cover reduces ice growth by protecting the ice sheet from very cold air. In spring snow may act to preserve the ice sheet by protecting it from heat gains from the warming atmosphere.

Wind regulates snow-drift and snow-pack distribution. It greatly alters regional snow thickness on the ice sheet, depending on the wind force and direction. Fetch distances play an important role in this redistribution. Under strong, cold winds techniques, such as dusting and bubbling, will be relatively ineffective; in the first case winds may alter a predetermined application pattern thought to be most effective for surface melt; in the second case, cold winds may act to convey away to the atmosphere any heat at the water surface induced by a bubbling system. Perhaps the most important factor is that winds--their strength, direction, and turbulent structure--can quickly alter an entire ice sheet over a short period of time.

Fog is important because it restricts both de-icing techniques and navigation. In fact, producing open water by de-icing while air temperatures are considerably lower than 32°F will provide potential low level instability, evaporation-condensation, and induce fog formation.

The St. Marys waterway is prone to frequent spring fogs. On April 17, 1969, for example, 32 ships were anchored waiting for a large regional fog to dissipate (Detroit News, April 17, 1969). This fog was associated with warm moist air passing over the cold lakes in spring. Fog thus replaced ice as an early spring shipping hazard.

Dusting Potentials for St. Marys River. Solar radiation, air temperature, precipitation, wind speed and wind direction are important climatic influences on the successful employment of dusting.

Long-term data were gathered on incoming solar radiation and air temperature from the Sault Ste. Marie airport records. The radiation data represent actual recorded daily radiation totals in langleys (1 langley = 1 cal/cm^2/min). Figure 12 illustrates that dusting potentials are stronger in the Arctic than in the more temperate zones, because the melting period is in June-July in polar regions rather than in March-April. The daily radiation totals north of 60°N latitude are much greater in summer than in the spring in southerly regions. This is the main reason for the large success and more advanced dusting development program in the Soviet Union.

In Lake Superior latitude during the month of March the top of the atmosphere receives only 500 to 700 langleys of radiation per day. Only 300 to 500 langleys reach the earth's surface. Of this amount a large portion is reflected back into the atmosphere from ice and snow surfaces. Dusting could reduce albedoes to 10 to 20 percent and increase the absorption by 250 to 450 langleys per day. This represents 3 to 6 centimeters of potential ice melt per day for the month of March.

For analysis, the radiation records at Sault Ste. Marie from 1953 to 1969 were categorized into steps of 80 langleys each and frequencies of daily radiation totals were calculated at two week intervals for the period from March 1 to April 30, bracketing the break-up period. Figure 13 shows the number of days that certain threshold totals were reached during each two week period. The numerical values are presented in Table IV.

TABLE IV
RADIATION RECORD AT SAULT STE. MARIE, MICH.
1953-69 DATA

Radiation	March 1-15		March 16-30		March 31-April 14		April 15-30	
in langleys	days	%	days	%	days	%	days	%
0-80	<1	1.6	<1	2.0	<1	4.0	<1	5.4

Radiation in langleys	March 1-15 days	%	March 16-30 days	%	Mar 31-Apr 14 days	%	April 15-30 days	%
80-160	1.2	8.3	1.4	9.6	1.0	6.7	1.8	12.5
160-240	2.2	15.0	1.4	9.2	1.2	8.5	1.6	10.4
240-320	2.6	17.5	1.6	10.8	1.2	8.0	1.2	7.9
320-400	3.8	24.5	1.9	12.5	1.3	8.9	1.0	6.8
400-480	4.1	27.5	3.2	21.6	2.5	16.5	1.7	11.2
480-560	<1	6.7	3.5	23.4	2.7	18.2	1.3	8.8
560-640	--	---	1.6	10.4	3.5	23.5	2.9	19.6
640-720	--	---	---	----	<1	6.2	2.5	16.6
< 720	--	---	---	----	---	----	<1	<1

The figure shows that none of the four periods attain high percentages in any one radiation class. The highest is 27 percent and few periods attain percentages greater than 20 percent.

The reliability in expectancy of threshold values for planning time schedules for dusting is not especially high. Reliability falls off and variation of radiation regime increases from March to April.

During the period March 1-15 the ice sheet on the waterway system usually shows no signs of deterioration and may even show growth, and only an exceptionally early melt would initiate ice decay. Given proper weather conditions dusting would initiate surface snow melt and start internal metamorphism of the ice cover. It is unlikely that enough heat could be provided by dusting for rapid ice melt and break-up during this early period. The incoming radiation totals given in Figure 13 and Table IV should be lowered by 10 to 20 percent albedo with dust cover to arrive at correct absorption estimates. Inspection of daily mean air temperatures show that they are seldom above or within 10°F of freezing. Consecutive days of above freezing were not recorded in the early March period. Minimum temperatures on many occasions reached 0°F (-18°C).

Break-up of ice on the waterway system is well underway in the period March 31-April 14. The ice cover is in a state of rapid deterioration and may even be gone from portions of the waterway. The time of physical ice breakup varies considerably from year to year. With solid, stable ice conditions in portions of the waterway during this period, dusting would be most effective, given proper weather conditions. Highest chances of given radiation totals fall in the category 560 to 640 langleys per day. This represents (with 10 to 20 percent albedo) 500 to 590 langleys or 440 to 510 langleys per day. Five of the 15 years had 480 to 720 langleys per day for greater than 50 percent of the two week period. Two of the five years had seven consecutive days with 480 to 720 langleys totals.

Temperatures are usually near 32°F (0°C) during early April and provide ideal conditions for dusting. The chances of a late snowfall become lessened with above freezing temperatures. Rainfall, more frequent in this period, provides latent heat input, and is advantageous to ice deterioration, although it may restrict dusting operations considerably. Dusting experiments near Ottawa (Williams, 1967), at a latitude comparable to the St. Marys waterway, demonstrated that weather variations from year to year determined the success of dusting. The year 1963 had low March temperatures and snowfall and was a poor year for dusting. In 1965 melting was initiated by an early March dust application, but a later March cold spell and accompanying snowfall reduced the effectiveness of the operation. In early April dusting produced effective results.

The expected radiation and temperature trends for the St. Marys waterway indicate that of the four two-week periods analyzed the late March to early April period is the most effective for dusting. Operations must be geared to the late March period. Chances of early dusting success is highly dependent on local weather forecasting, the geology of the ice sheet on the waterway, ice sheet thermal regimes, and preparation-application decisions. For 1969 the upper and lower river ice sheets on the St. Marys waterway showed ice growth initiated by a late March cold spell and snowfall in the breakup period. The late season snowfall would have restricted dusting or necessitated a re-application. Plans would have had to include storage of extra dusting materials.

Albedo measurements of natural ice at a point on the upper waterway substantiate previous findings. They indicate that clear lake ice has a very low albedo, 10-20 percent, approximately one-fourth of albedo measured for snow snow and slush ice (Bolsenga, 1968). Dusting, therefore, would not be required to initate melt where lake ice is exposed, because of a natural low albedo. Though snow covers the St. Marys River ice sheet, it can be removed so that abundant radiation will be absorbed by the ice cover. However, clear lake ice is a very high transmitter of radiant energy. Laboratory results show that clear ice 10 cm thick absorbed only 2 percent of transmitted radiation in the visible wavelengths, while bubbly ice absorbed 26 percent in the same wavelength region (Lyons and Stoiber, 1959).

Dusting will absorb incoming radiation and convey heat into the ice sheet. Dust grains may even penetrate the ice sheet along crystal boundaries. A dusting medium will reduce transmission of shortwave radiation through the ice cover to the water beneath, and instead provide heat by conduction to the upper zone of the ice sheet. Internal metamorphism and phase change from solid to liquid will be speeded.

The thickness of the dust layer determines the amount of energy transferred from the atmosphere to the ice sheet. Ostrem (1959) has found that unique features over glaciers are preserved by thick mantles of wind-blown or waterborne debris. On the other hand a very thin application of dust may not provide a sufficiently rapid heat transfer over short periods to compensate for heat losses which may occur with unexpected below freezing temperatures. Williams (1967) found that removing the snow cover and applying dust was more effective than only removing the snow cover. This indicates that removing the snow cover and dusting may be necessary for most effective results.

Lake Survey Center field parties collected data on channel ice thickness and structure along the St. Marys River in 1969. The field work was performed in late February and early March, covering the river from Gros Cap Light to Detour Passage. The data indicate ice sheets ranging from 11 to 28 inches (28 to 71 cm) in thickness were located on the southern part of the river--Raber Bay, Lime Island, and Lake Munuscong channel segments. Snow ice layers ranging from 2 to 22 inches (5 to 56 cm) were also found in these segments. Snow cover thicknesses ranged from 5 to 11 inches (13 to 28 cm) on these stretches, and were greater than snow covers on the river portions above the locks to Gros Cap Light.

The greater total thicknesses, greater snow ice and slush layer thickness, and greater stability of the ice sheet in the Lake Munuscong to Lime Island section in early spring argues for the feasibility of a de-icing program in that portion of the river. Greater wind fetches over Whitefish Bay and the upper river, thinner ice sheets, and a more dynamic break-up, restrict programming of dusting for these areas. The scale of the dynamic processes during break-up tend to restrict programs other than normal ice breaking procedures.

Short-term forecasts can determine the exact time for dusting distributions and if needed reapplications. Considerations such as ice sheet structure, thickness, and stability can be forecast with a degree of accuracy before dusting is to be employed.

For St. Marys waterway, it is suggested that dusting will be marginally successful and highly dependent on peculiarities of day-to-day weather conditions at the time of break-up. For this reason, only the most stable ice areas would benefit from dusting. These areas correspond to St. Marys River shallow zones in the lower waterway stretches previously mentioned.

MICROCLIMATOLOGY FIELD PROGRAM 1968-69

The microclimatology of a portion of the upper St. Marys River ice sheet was monitored from mid-winter to the break-up period in 1969. Two instrument towers were placed on the ice sheet. One measured total spectrum radiation, the other contained aspirated thermocouple air temperature sensors at three levels above the ice sheet. Water temperatures were measured by an array of thermocouples at several water depths. Wind speed and direction sensors were placed onshore immediately adjacent to the shoreline.

This was necessitated by power requirements for those instruments.

Operations commenced February 20 and terminated April 6, 2 days prior to ice drifting away from this portion of the river. The following measurements were made:

1 - Air temperature at 0.5, 1, and 3 meters,
2 - Wind speed at 0.5, 1, and 3 meters,
3 - Wind direction at 3 meters,
4 - Net all-wave spectrum radiation,
5 - Incoming shortwave spectrum radiation,
6 - Surface reflection of shortwave radiation,
7 - Total spectrum incoming radiation,
8 - Water temperature at 0.12, 0.25, 0.5, 1, 2, 3, 4, and 5 meters below the bottom of the ice sheet.

Observations of ice thickness and structure were made adjacent to the micrometeorology site every other day, when possible. Instrumentation, logistical support, and maintenence were provided by the Meteorological Support Activity, U. S. Army Electronics Command, Fort Huachuca, Arizona. Daily calibrations of instruments were carried out in the field.

Air temperature, humidity, and precipitation data were recorded from an onshore site at Pt. Iroquois. The instrument complex was set on the ice sheet several thousand feet offshore over a point where the water depth was comparable to channel depth, 25 to 30 feet (7.6 to 9.1 m). The site consisted of a solid, snow cover lake-ice sheet. The site represented a refrozen lead area in the upper St. Marys River. To the north of the site, toward Whitefish Bay, a large pressure ridge trending NE to SW effectively sealed the bay from the upper river, providing a stable ice sheet once this ridge had developed. Channel-ward from the measuring site was a very large zone of rafted lake ice and snow--imposing difficult conditions under which to initiate a field micrometeorology program. The smoother ice zone was thus chosen for analysis. This site, however, is not to be considered fully representative of the upper St. Marys River ice sheet, which is generally composed of complex ice layers. Though the micrometeorologic data gathered in 1969 is valuable, future studies should be conducted on other ice types typical of the waterway, particularly lower river sections having complex snow, slush, and lake ice layers, and where the ice remains longest and is most stable. The site must be relatively stable to insure a long measurement period, the safety of personnel, and the recovery of the instrumentation.

The 1969 measurement program was an attempt to further understand the relationships between ice sheet thicknesses and the role of some climatic factors. Ideally, observations of this nature need to be conducted for the entire ice season at a series of sites along the waterway. Eventually such reports could be put to use for enhancing normal forecasting procedures and gaining knowledge of the thermal characteristics of different ice types.

In the previous section, the importance of various climatic processes was summarized. The significance of microclimatic factors on changing ice sheet thicknesses and overlying snow covers is now pointed out to give an example of the previous points for the Pt. Iroquois site on the upper river.

Figure 14 displays daily summaries of the microclimatic parameters over the measurement period. The figure shows four radiation curves and the mean daily albedo from February through April. The four radiation curves are: (1) solar incoming radiation, (2) solar reflected radiation, (3) absorbed solar incoming radiation, and (4) net radiation. A fifth curve shows the amount of daily radiation received at the top of the atmosphere at 47°N latitude. Recorded values at the earth's surface are always less because of absorption of part of the available solar radiation by the atmosphere. Other climatic data are given in Figure 14 for the measurement period. Figure 15 gives examples of normal ice and snow albedoes under different weather conditions. The albedo varies with the sun angle and over several days according to weather changes and surface conditions. The last set of figures include the changes in ice, snow, and slush layer thicknesses over this same period, plus snow-on-ground measures at a site onshore from the Pt. Iroquois ice sheet. Table V provides summary field season weather conditions.

TABLE V

Date	Air	Pressure	Sky	Precipitation
1. 20-25 Feb.	Warm	High	Cloudy	Little Snow
2. 26 Feb.-13 March	Cold	High Low	Clear	None
3. 14-25 March	Warm	Low	Cloudy	Snow/Rain
4. 26-31 March	Cold	Low High	Ptly Cldy	Some Snow
5. 1 April-6 April	Warm	High Low	Cloudy	Snow/Rain

The radiative fluxes and albedoes (Figure 14) show distinct changes due to the weather fluctuations and changing ice and snow surface conditions. There is a wide range in daily totals of radiation for the measurement period, particularly after March 20. Both the lowest and highest radiation totals came during this period. A large low pressure system in mid-March with associated snow, rain, and cloudiness accounts for these variations. The importance of this low pressure system was many-fold on the consequent heat balance of the ice sheet at the measurement site: (1) solar radiation values were variable and fluctuated greatly. (2) absorbed radiation showed the highest totals of the recording period. (3) net radiation shifted to positive values. (4) surface albedo dropped as low as 16 percent mean daily value. Prior to March 20 solar radiation was as high as 400 langleys per day. However, absorbed amounts and net radiation totals were low, because of the very high surface albedo of the snow-covered ice, reaching from 60 to 99 percent.

A significant period occurred just after the increases in solar radiation during mid to late March. A late season cold snap and snowfall altered radiation regimes back to totals similar to early March values. This period covered several days and retarded ice decay. Mean daily albedo rose sharply to over 80 percent because of snowfall on the ice sheet (Figure 15). Lake ice, which had decreased in thickness in late March, increased in thickness. Snow cover on the ice sheet reached 6 inches (15 cm) (Figure 14). Immediately after the early April influx of cold air into the waterway region, temperatures rose rapidly to above freezing, and melted the snow cover on the ice. Albedoes once again were lowered and net radiation rose to 250 langleys per day--enough potential energy to melt 1.5 inches (3.8 cm) of ice and initiate internal thermal metamorphism of the ice sheet. A large heat input resulted from latent heat exchange from rainfall, because liquid precipitation striking the ice sheet loses heat in the phase change from liquid to solid. This results in a net heat gain by the ice sheet. The process of ice melt is important in the spring when warm, moist maritime polar, and tropical air masses influence the Great Lakes basin. Snow cover during the warm period in early April was immediately reduced to slush, and lake ice again began melting.

The thermal balance of the ice sheet and variations of microclimatic elements, such as radiation, were essentially determined by the predominant air mass and synoptic weather conditions over the five periods mentioned. This is perhaps a more typical result expected for lake ice cover areas. The stratigraphy of a complex ice sheet would not show as strong a relationship with climatic heat fluxes. For example, snow ice diffuses solar energy and also reflects more energy away from the surface than lake ice. Absorptivities are much lower in complex snow and lake ice layers. Experimental estimates show that bubbly ice has half the absorptivity of clear ice (Lyons and Stoiber, 1959).

Albedoes and surface temperatures were dependent on general weather and surface conditions. Figure 15 shows natural albedoes for 3 four-day periods. Two cloudy, one clear. In Figure 15-A temperatures changing the wetness of the snow cover influenced albedoes on March 21 and 22. March 23 and 24 were days of cold and snowy weather, resulting in higher albedoes. These two periods illustrate the process of rising temperatures on lowering albedoes and fresh snowfall on raising albedoes.

The clear period (Figure 15-B) demonstrates that sun angle prescribes a diurnal trend to albedo when there are no major changes in snow cover and when stable, clear weather predominates. Albedoes may range over 50 percent within the same day. The sun's altitude influences local albedoes (Hubley, 1955). Figure 15-C shows the effect of rainfall, which had melted the snow cover on the ice and thus reduced the albedo. On March 23 recorded albedoes reached 80 percent. During the next three days, however, albedoes never reached 40 percent and averaged 10 percent. These findings correlate with the sequence of events described, for example, by Langleben, (1968) and Bolsenga (1968).

Surface temperature, which must be close to freezing for effective dusting operations, is shown in Figure 14. It was determined from the following relationships since it was not measured directly:

longwave outgoing radiation = $\varepsilon\sigma T^4$

where ε = coefficient of emissivity (= 1 for snow)

$\sigma = 8.14\times10^{-11}$ langley/min/°K^4 (constant)

T = surface temperature (°Kelvin)

Surface temperature shows a very distinct warming trend associated with the increase in absorbed solar radiation and high air temperatures in mid-March. However, from previous studies it is expected that below surface ice temperatures do not correspond directly with air and surface temperatures over time, but lag considerably in response to fluctuations in air and surface temperature (Schwerdtfeger, 1966). A large decrease in surface temperature would generally occur in the late March to early April cold period.

Air temperatures during the measurement period at standard Stevenson screen height very rarely rose above the freezing threshold. The trend of the mean daily temperature illustrates the sharp influence of two cold periods--one in early March and one in early April. The total ice growth trend corresponds quite closely to the air temperature trend (Figure 14).

It is significant, however, that the magnitude of ice thickness increments over time may be better estimated by either the net radiation trend or the surface temperature trend. It is questionable whether an accurate estimate of near-surface air temperatures and the magnitudes of temperature extremes can be fully assessed by normal National Weather Service screen height thermometers. For example, at the micrometeorologic temperature profile mast, of 867 total hourly mean temperature observations from March 1 to April 6 at o.5, 1, and 3 meters, 62 percent of the observations were thermal inversions in this 3 meter air layer--20 percent of the inversions were greater than 1°F between the 0.5 m and 3 m levels. Many observations showed extremes of 6-8°F inversions. Figure 16 illustrates six sample inversions during the coldest period of the recordings, early March. Generally, the lower the temperature, the stronger the magnitude of the inversion and the more inaccurate the empirical estimate of ice growth by a simple predictive model using temperature at screen height.

For the waterway region, the two most common wind directions are northwest and east. Figure 17 shows winds for the month of March at the Soo airport station. The 1969 recordings for the period February 6 to May 7 indicate that the majority winds came from the northwest and the southeast. Forty-six percent of the time winds were from the northwest or across the Whitefish Bay toward the St. Marys River. The winds were due mostly to the influence of Canadian air masses with highs migrating into the Lake Superior area. Southeasterly and easterly winds occurred 31 percent of the time and were mostly associated with passage of low pressure cells to the south of the waterway.

Mean daily wind speeds (Figure 17) are highly variable due to low level convection and regional air flow associated with local and large scale pressure gradients over the lake basin. High wind speeds, averaging over 10 mph (4.5 m/s) were recorded from mid-March to the first of April.

The pattern of dusting and the type of material used should be closely geared to expected wind directions and forces. The type and nature of the surface of the ice sheet determines aerodynamic roughness and turbulent structure of the wind next to the surface. The smoother the surface, the less frictional force will be imposed on material applied for dusting, and the less risk of distortions in a given application pattern. If the surface is too smooth, or dust material too dry or light, applications may be severely altered from predetermined designs.

MISSISSIPPI AND ST. MARYS RIVER CLIMATOLOGY AND ICE COVERS

The climatology for the winter ice season of the upper Mississippi and Great Lakes Basin is variable from year to year and over areas within each respective basin. The upper Mississippi Basin covers approximately the same area as the entire Great Lakes Basin and is a "land-locked" area in the mid-continental United States. This contrasts with the Whitefish Bay-St. Marys River Waterway which is central to the Great Lakes system. The surrounding lakes influence local climatology as previously mentioned.

Although Sault Ste. Marie is farther north than most Mississippi locations along the major navigational channels, it enjoys a somewhat milder climate than expected for its latitude. The contrast between Duluth, Minnesota (cold), and Sault St. Marie, Michigan (warm), has been shown. As a result the magnitude and duration of below freezing temperatures critical to the freeze-up and subsequent ice development stages, is quite similar to locations farther south in latitude. Although the Mississippi and St. Marys are within different local climatic regions, many similarities in climatic extreme and mean values are evident.

To determine which Mississippi River area is most similar in some ways to the St. Marys River several temperature and precipitation parameters and indices were extracted from long term (1931-68) climatological data. Graphical correlations were developed to show the areas of similarity on the Mississippi River.

A qualitative comparison was made of monthly temperature and precipitation characteristics of seven first order National Weather Service Mississippi River stations plus Sault Ste. Marie, Michigan (which is assumed to represent waterway conditions). The Mississippi River stations are listed in Appendix II. The following climatic parameters were investigated:

1. mean monthly temperatures,
2. mean monthly maximum temperatures,
3. mean monthly minimum temperatures,
4. number of days temperature less than 0°F,

5. number of days temperature less than 32°F,
6. number of days maximum temperature greater than 32°F,
7. monthly snowfall totals,
8. monthly rainfall totals.

Mean values for the eight variables are given for the months November through April. Figure 18 illustrates the similarity of Sault Ste. Marie values to areas along the Mississippi.

Mean Temperature. Figure 19 indicates that the freeze-up months of November through January show similarities between the St. Marys waterway and locations on the Mississippi to the north of La Crosse, Wisconsin, and south of Minneapolis, Minnesota. During February and through April the similarities lie further north. This displays the continentality of Mississippi locations against the lake controls experienced the St. Marys waterway. March and April are months of rapid thaw on the Mississippi due to interior land mass heating. The St. Marys waterway is controlled to a large extent by the cold lakes in these months. This tends to cause temperature similarities to lie further north of Minneapolis in this later break-up period. Every temperature-related statistic in Figure 18 shows this relationship. A general shift of temperature similarities from locations just south of Minneapolis in the freeze-up period to north of Minneapolis in mid-winter to break-up periods is evident (on the mean).

Snowfall. Snowfall totals along the St. Marys River and at Mississippi River stations investigated are higher than normally encountered at that latitude. This is due both to mean storm track frequencies and to localized snow storms on the Great Lakes. The mean yearly snowfall along the Mississippi south of St. Cloud, Minnesota, does not approach that of the St. Marys River.

Peak snowfall months are different for the two rivers. Early season snowfall at Sault Ste. Marie is three to four times the Mississippi River section totals at this time of year. A March snow fall peak occurs on the upper portions of the Mississippi. The mean values are only 1 to 2 inches (2.5 to 5 cm) less than March totals for the St. Marys River.

Rainfall. In the transitional months of November and April, the similarities in total rainfall exist south of La Crosse, while during the months of December through March the St. Marys rainfall regime coincides with locations north of Minneapolis along the river.

Ice Cover. Data on Mississippi River mean ice thickness were plotted for the years 1959 to 1968 (Figure 20). The horizontal axis represents distance from Minneapolis to St. Louis. Locks and dams, sites of ice observations, are identified by number. The vertical axis represents the time November to April. Monthly ice thickness data were plotted for each station and contoured to illustrate the following:

1. times of different ice thicknesses at a particular location,

2. ice thickness values at locations along the river at a particular time,
3. ice thicknesses along pool sections at a certain time, which are similar to thicknesses along other sections at another time.

The result is the time-distance pattern of the Mississippi ice cover. This plot relates directly to the time-distance factors in the climate of this area. Figures 21-29 express the yearly variations in ice thickness along the upper river. Data for Lake Pepin (between Locks and Dams 3 and 4) were estimated from the composite diagram (Figure 20). The diagrams are contoured at 5 inches (12.6 cm) intervals, with one auxillary contour at 2.5 inches (6.3 cm).

The general pattern follows expected and observed climatic gradients of colder, more severe winter conditions from south to north along the river section. Ice thickness generally decreases from Minneapolis to St. Louis in response to more-to less severe winter climate. In each year there are many southern locations along the section which attain ice thickness values greater than northern locations. For example, in the year 1964-65. Locks and Dams 11 to 17 showed much thicker ice sheets than from 8 to 10, well to the north. Water currents, channel morphology, pool size, and fluctuations in discharge can distort the expected ice thickness pattern shown in Figure 20. Choice of ice observation sites and inaccuracies in measurement from one site to another can also distort the analysis in comparing sites.

The years 1961-62, 1962-63, and 1966-67 were heavy ice years along the entire section. Light ice years were 1959-60 and 1963-64. The other years are difficult to classify for the whole section, since certain zones were heavy and others light. Heavy and light ice years coincide with extremes in monthly temperatures for those years, as indicated by Table I and Figure 30. The months of January and February show mean temperature values for heavy ice years well below those of the light ice years. The relation to climate is only made clear when extreme seasonal conditions (severe and mild weather) occur.

During moderate years more complex factors than those mentioned here appear to be at play. The variation in ice thickness is controlled more by short term weather conditions and hydrologic factors of each pool area. The process of ice formation and decay along the river during these years can only be well understood by on-site hydrologic and climatic investigations.

A long term record of St. Marys River ice thickness comparable to Mississippi data network is not available for analysis because the St. Marys ice survey program has only been maintained since 1968. For several locations within the St. Marys River system, ice attains maximum thickness greater than 20 inches (51 cm) which is comparable to northern areas of the Mississippi basin, at the latitude of Minneapolis.

CONCLUSION

A climatic comparison has been given between portions of the Mississippi and St. Marys waterways. Areas just south of Minneapolis appear to be most similar to St. Marys River conditions, both in terms of some climate and ice cover characteristics.

The ice cover thicknesses appear on the average to be similar between the lower St. Marys and Lake Pepin. Lake Pepin ice structure resembles that of the lower St. Marys River both having complex snow, snow-ice, and lake-ice layer developments. Lake Pepin represents a very large pool which remains relatively stable over several months. It is much the same size and depth, attains similar maximum ice thickness, and is influenced by much the same climatic extremes as the St. Marys River sections from Lake Nicolet to Detour Passage.

Micrometeorological investigations were initiated by the Lake Survey Center on a lake-ice portion of the upper St. Marys River. They can provide a clearer picture of the causes behind ice development and structure in a particular year, and from year to year. This is particularly important in association with a hydrological investigation of river segments above and below areas of examination. Channel morphology, discharge rates, water turbulence and man-made controls are significant factors which can dictate ice distribution and thickness.

A permanent micrometeorological installation over a representative portion of Lake Pepin, a study of the heat, momentum, and vapor exchange among water, ice, and air will aid in understanding and eventually forecasting ice development and deterioration. The choice of the site on the ice sheet is important so that ice conditions typical of the lake as a whole are sampled. St. Marys ice data has shown how varible ice structure can be over a waterway system.

The St. Marys project employed numerous weather stations along the St. Marys waterway, since this area lies in a transitional climatic zone. Lake Pepin does not represent a zone of wide variation in climatic variation. The number of stations needed would have to be assessed by expected regional climatic differences. It is important that stations employed be set up immediately adjacent to or on pool sections so that local exposures will be properly represented. Airport sites, as demonstrated by 11 stations transects near Sault Ste. Marie, may bias local temperature extremes normally prevalent over river locations during the winter season.

The Lake Survey Center employed a network of temperature and humidity sensors housed in a standard National Weather Service type shelters. This method samples the air layer adjacent to the ice surface (4 feet - 1.2 m - above it). Infrared photography taken from airborne platforms cannot, at present, accurately estimate the atmospheric variables in the boundary layer of air, but can, in association with a ground network, provide a picture of extremes in ice, water, and land surface temperatures which, in association with ground stations, can be used to estimate the heat exchange between water and ice surfaces. The advantages are that the area of investigation is areally sampled instantaneously; no interpolation of temperature is needed.

REFERENCES

Bolsenga, S. J. "Total Albedo of Great Lakes Ice", U. S. Lake Survey Bulletin B 68-1, Nov. 1968, pp. 16-36.

Byers, H. R. Synoptic and Aeronautical Meteororology, McGraw-Hill Co., N. Y. 1937.

Cavan, B. P. "A Literature Review of Dusting Technology in De-Icing", U. S. Lake Survey, Research Report 5-7, Dec. 1969. 23 pp.

Eichmeier, A. H. "Snowfall, Paul Bunyon Style", Weatherwise, Vol. 4, No. 6, 1961, pp. 124-127.

Hare, F. K., and Montgomery, M. R. "Ice, Open Water, and Winter Climate in the Eastern Arctic of North America: Part I", Arctic, Vol. 2, No. 2, 1949, pp. 79-89, 149-164.

Hubley, R. C. "Measurements of Diurnal Variations in Snow Albedo on Lemon Creek Glacier, Alaska", Journal of Glaciology, Vol. II, Oct. 1955, pp. 560-563.

Jones, J. A. A. "The Growth and Significance of White Ice at Knob Lake, Quebec", The Canadian Geographer, Vol. XIII, No. 4, Winter 1969, pp. 354-372.

Kopec, R. J. "Areal Extent of the Great Lake's Significant Influence on Vicinal Temperature Regimes". PhD dissertation, Clark University, University Microfilms, Inc. Ann Arbor, Michigan, 1965, 122 pp.

Langleben, M. P. "Albedo Measurements on an Arctic Ice Cover from High Towers", Journal of Glaciology, Vol. 7, No. 50, June 1968, pp. 289-297.

Leighly, J. B. "Effects of the Great Lakes on the Annual March of Air Temperature in their Vicinity", Papers of the Michigan Academy of Science, Arts, and Letters, Vol. 27, 1941.

List, R. J. (ed) Smithsonian Meteorological Tables. Smithsonian Institution, Washington, D. C., 1958.

Lyons, J. B. and Stoiber, R. E., "The Absorptivity of Ice: A Critical Review". Scientific Report No. 3, Geophysics Research Directorate, Air Force Cambridge Research Center, Air Research and Development Command, U. S. Air Force, Bedford, Mass., 1959.

Marshall, E. W. "Structure of Lake Ice in the Keweenaw Peninsula, Michigan", Pub. No. 13, Great Lakes Research Division, The University of Michigan, 1965, pp. 326-333.

Mitchell, C. L. "Snowflurries Along the Eastern Shore of Lake Michigan", Monthly Weather Review, Vol. 49, No. 9, 1921, pp. 502-503.

Muller, R. A. "Snowfall Patterns in the Eastern Lake Erie and Eastern Lake Ontario Snow Belts and Their Relation to Snowfall in New York", Proc. Conf. on Lake Effect Storms, Fredonia, N. Y., April 1962, pp. 18-26.

Niedringhaus, T. E. "A Climatography of Michigan". PhD dissertation Michigan State University, University Microfilms, Inc., Ann Arbor, Michigan, 1966, 230 pp.

Ostrem, G. "Ice Melting Under a Thin Layer of Moraine, and the Existence of Ice Coves in Moraine Ridges", Geografiska Annaler, Vol. 41, 1959, pp. 228-230.

Peace, R. L., and Sykes, R. B., "Mesoscale Study of a Lake Effect Snow Storm", Monthly Weather Review, Vol. 94, No. 8, August 1966, pp. 495-507.

Remick, J. T. "The Effect of Lake Erie on the Local Distribution of Precipitation in Winter". Bull. Amer. Met. Soc., 1942, Vol. 23, No. 1. pp. 1-4, Vol. 23, No. 3, pp. 111-117.

Richards, T. L. and Devco, V. S. "The role of 'Lake Effect Storms' in the Distribution of Snowfall in Southern Ontario", Proc. East. Snow. Conf., 1963, Quebec City, Feb. 14-15, 1963, pp. 61-85.

Richards, T. L. "The Meteorological Aspects of Ice Cover on the Great Lakes", Monthly Weather Review, Vol. 92, No. 6, June 1964, pp. 297-302.

Rondy, D. R. "Great Lakes Ice Atlas". U. S. Lake Survey, Research Report 5-6, April 1969.

Schwerdtfeger, O. "The Effect of Finite Heat Content and Thermal Diffusion on the Growth of a Sea Ice Cover", Journal of Glaciology, Vol. 5, No. 39, October 1964, pp. 315-324.

________________ "On the Response of a Sea Ice Cover to Changes in Surface Temperature", Journal of Glaciology, Vol. 6, No. 45, October 1966, pp. 439-442.

Scott, J. T., and Rogotzkie, R. A. "Heat Budget of an Ice Covered Inland Lake", Technical Report No. 6, University of Wisconsin, 1961.

Shaw, J. B. "Growth and Decay of Lake Ice in the Vicinity of Schefferville (Knob Lake), Quebec", Arctic, Vol. 18, No. 2, June 1965, pp. 123-132.

Sheridan, L. W. "The Influence of Lake Erie on Local Snows in Western New York", Bull. Amer. Mete. Soc., Vol. 22, No. 10, 1941, pp. 393-395

Snider, C. R. "Great Lakes Ice Season of 1967", Monthly Weather Review, Vol. 95, No. 10, Oct. 1967, pp. 685-696.

Strong, A. E. "The Spring Lake Anticyclone-Its Inducement on the Atmospheric and Water Circulations", Special Report No. 34, Great Lakes Research Division. The University of Michigan, Ann Arbor, Michigan, 1968.

Thomas, M. K. "A Survey of Great Lakes Snowfall", Pub. No. 11, Great Lakes Research Division, The University of Michigan, 1964.

Wiggin, B. L. "Great Snows of the Great Lakes", Weatherwise, Vol. 3, No. 6, 1950, pp. 123-126.

Williams, G. P. "Ice-Dusting Experiments to Increase the Rate of Melting of Ice", Tech. Paper No. 239, Division of Building Research, National Research Council, Ottawa, Canada, 1967.

APPENDIX I - LOCATIONS OF WEATHER

STATIONS ESTABLISHED BY LAKE SURVEY CENTER

Station	Latitude	Longitude	Elevation in Feet (MSL)	Period of Record
Goulais Bay	46°42'N	84°29'W	600'	20 Dec-30 April
Whitefish Point	46°46'N	84°58'W	600'	19 Dec-7 May
Point Iroquois	46°29'N	84°38'W	600'	20 Dec-6 May
Brimley	46°25'N	84°33'W		20 Jan-4 May
Soo Airport*	46°28'N	84°22'W	721'	Continuous
Hay Point	46°28'N	84°09'W	600'	24 Jan-4 May
Homestead	46°24'N	84°09'W	600'	23 Jan-3 May
Lake Nicolet	46°24'N	84°16'W	600'	16 Jan-7 May
West Neebish	46°16'N	84°11'W	600'	1 Feb-3 May
Rocky Pt.	46°11'N	84°07'W	600'	25 Jan-6 May
Hilton Beach	46°15'N	93°50'W	600'	3 Feb-1 May
Lime Island	46°05'N	84°00'N	600'	20 Dec-2 May

*First order National Weather Service station.

APPENDIX II

MISSISSIPPI RIVER WEATHER STATIONS

Station	Latitude	Longitude	Elevation (MSL) in Feet
St. Cloud, Minnesota Whitney Memorial Airport	45°35'N	94°11'W	1034
Minneapolis-St. Paul Minnesota International Airport	44°53'N	93°13'W	834
La Crosse, Wisconsin Municipal Airport	43°52'N	91°15'W	651
Dubuque, Iowa Municipal Airport	42°24'N	90°42'W	1056
Moline, Iowa Quad City Airport	41°27'N	90°31'W	582
Burlington, Iowa Municipal Airport	40°49'N	91°10'W	703
St. Louis, Missouri Lambert Field	38°45'N	90°23'W	535

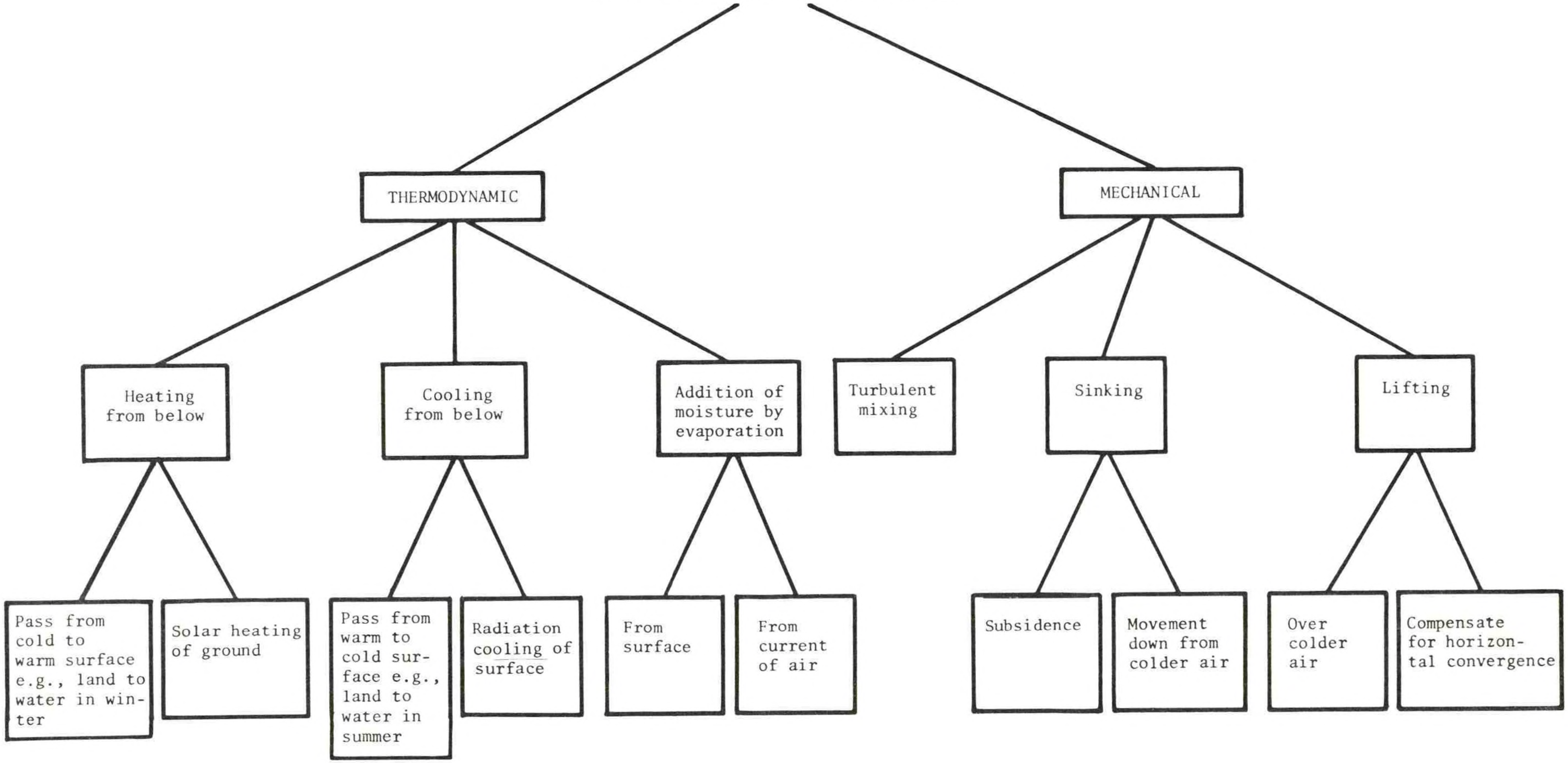
TABLE I
WINTER AIR MASSES
AFFECTING WATERWAY

TYPE	SOURCE REGION	FREQUENT TRAJECTORY	CHARACTERISTICS
Continental Arctic	Arctic Ice Cap and Northern Canada	Southern Canada and Northern U. S.	Extremely cold, dry, stable
Continental Polar	Central Canada, Northern Great Plains, Great Basin	Southward along Mississippi R. Valley into Southern Great Plains	Cold, dry, stable
Maritime Polar	A) Northern Pacific B) Northwest Atlantic	A) Along Pacific coast, interior of Pacific Northwest B) South westward through St. Lawrence Valley	A) Cool, moist, unstable B) Cool to cold, moist, unstable
Maritime Tropical	Gulf of Mexico Caribbean Sea	Northward through Mississippi Valley and N.E. U.S.	Warm, moist, unstable, becoming more stable over land because of surface chilling lowering lapse rate
Modified Continental Polar	Same as Continental Polar	Into S.E. U. S. , returning to N.E. U.S. along western flank of anticyclone	Warmer, more moist, and more unstable than unmodified CP.

After Niedringhaus, 1966

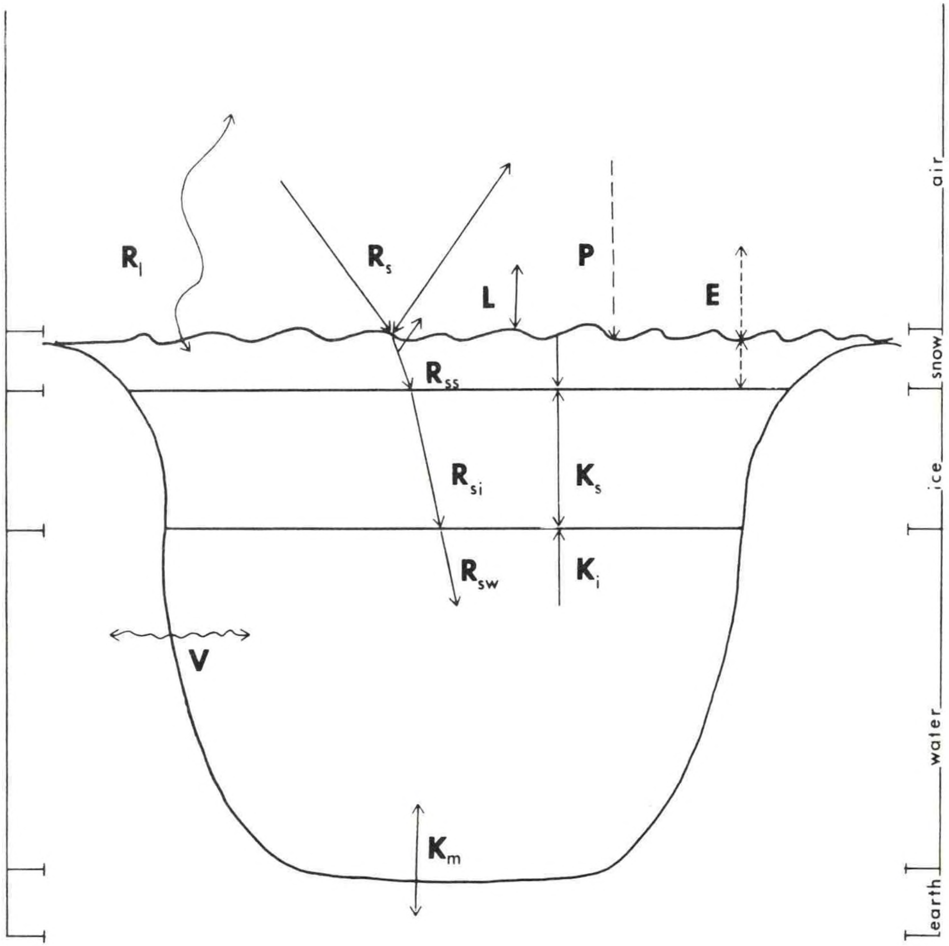
DIAGRAM I

MODIFICATION OF HOMOGENEOUS AIR MASSES



After Byers, 1937

CROSS SECTION REPRESENTATION OF THE HEAT FLUXES OF A RIVER WITH A WINTER COVER OF ICE AND SNOW*



Heat fluxes of a River ice sheet

R_s - net incoming solar radiation

R_{ss} - incoming solar radiation absorbed by snow

R_{si} - incoming solar radiation absorbed by ice

R_{sw} - incoming solar radiation transmitted to water

R_l - net long wave radiation

L - sensible (turbulent) heat exchange with the air

E - latent heat exchange with the air

K_s - sensible heat conducted between ice and snow

K_i - sensible (turbulent or molecular) heat exchange through the water to the ice

K_m - sensible (turbulent or molecular) heat exchange between the water and bottom sediments

V - advection of heat in and out of lake in water

P - sensible or latent heat added in rain, snow, etc. (above or below a reference 0° C so that latent heat of snow is negative in sign)

Modified from Scott and Ragotzkie, 1961

Figure 1

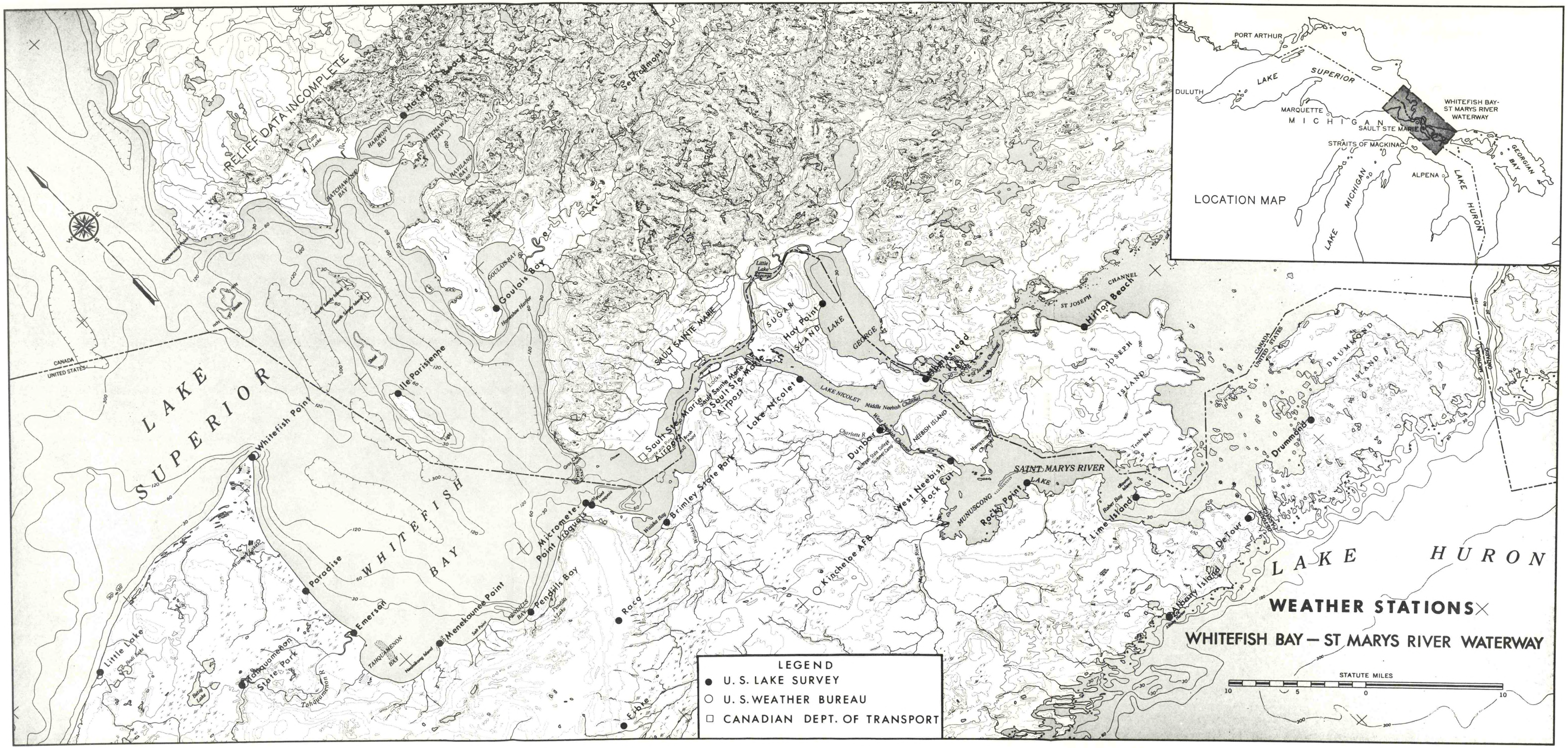
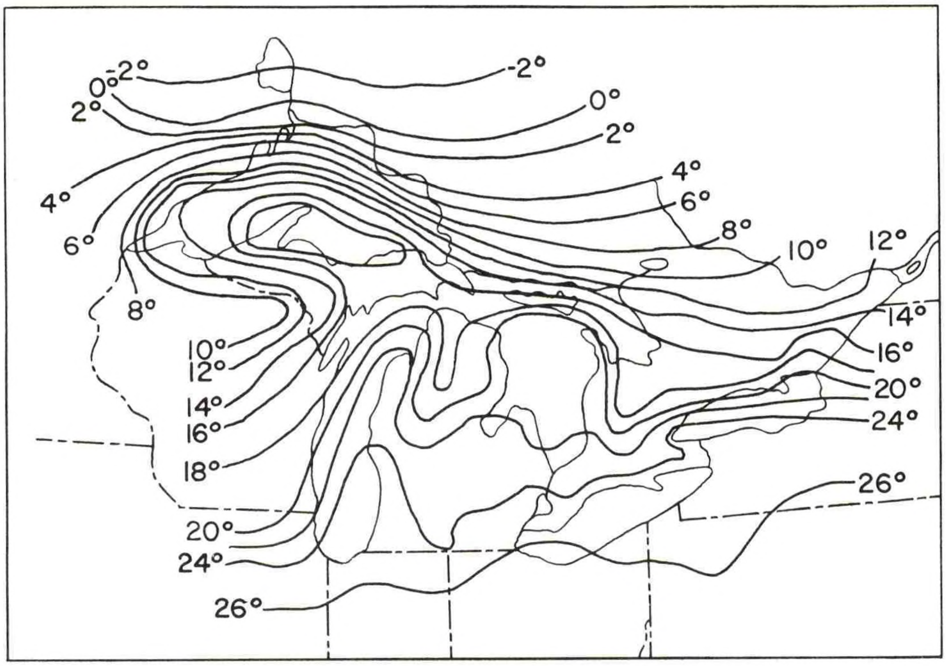
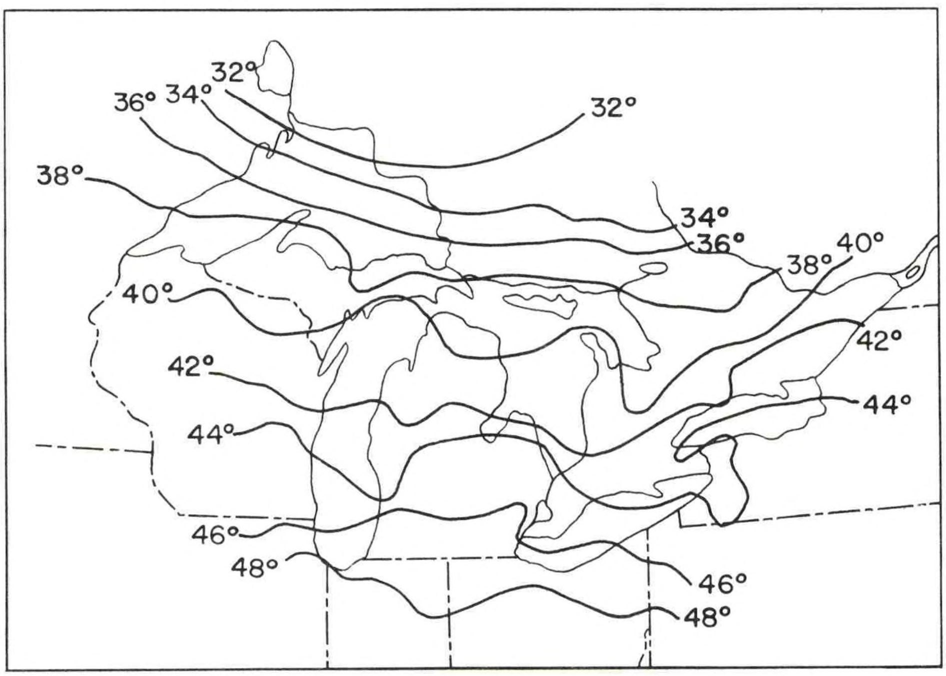

WEATHER STATIONS
WHITEFISH BAY — ST MARYS RIVER WATERWAY
LEGEND
● U. S. LAKE SURVEY
○ U. S. WEATHER BUREAU
□ CANADIAN DEPT. OF TRANSPORT
STATUTE MILES
10 5 0 10
LOCATION MAP
PORT ARTHUR
DULUTH
LAKE SUPERIOR
MARQUETTE
MICHIGAN
SAULT STE MARIE
WHITEFISH BAY-ST MARYS RIVER WATERWAY
STRAITS OF MACKINAC
ALPENA
LAKE MICHIGAN
LAKE HURON
GEORGIAN BAY
RELIEF DATA INCOMPLETE
LAKE SUPERIOR
WHITEFISH BAY
LAKE HURON
Harmony Beach
Goulais Bay
Ile Parisienne
Whitefish Point
Paradise
Emerson
Menekaunee Point
Pendills Bay
Point Iroquois
Micrometer
Little Lake
Tahquamenon State Park
Raco
Eckerman
Brimley State Park
Sault Ste Marie
Sault Ste Marie Airport
SAULT SAINTE MARIE
Lake Nicolet
Hay Point
SUGAR ISLAND
LAKE GEORGE
Little Lake George
Kincheloe AFB
Dunbar
West Neebish Rock Cut
NEEBISH ISLAND
LAKE NICOLET
Middle Neebish Channel
ST JOSEPH CHANNEL
Hilton Beach
ST JOSEPH ISLAND
SAINT MARYS RIVER
MUNUSCONG LAKE
Rocky Point
Lime Island
DeTour
Albany Island
DRUMMOND ISLAND
Drummond
CANADA
UNITED STATES
HARMONY BAY
BATCHAWANA BAY
GOULAIS BAY
TAHQUAMENON BAY
PENDILLS BAY

Figure 2

MEAN MONTHLY AIR TEMPERATURE*



January Mean Air Temperatures



April Mean Air Temperatures

After Kopec, 1965

Figure 3

CUMULATIVE FREEZING DEGREE DAYS 1968-69

Figure 4

WEATHER ELEMENTS NOVEMBER - APRIL 1968 - 69

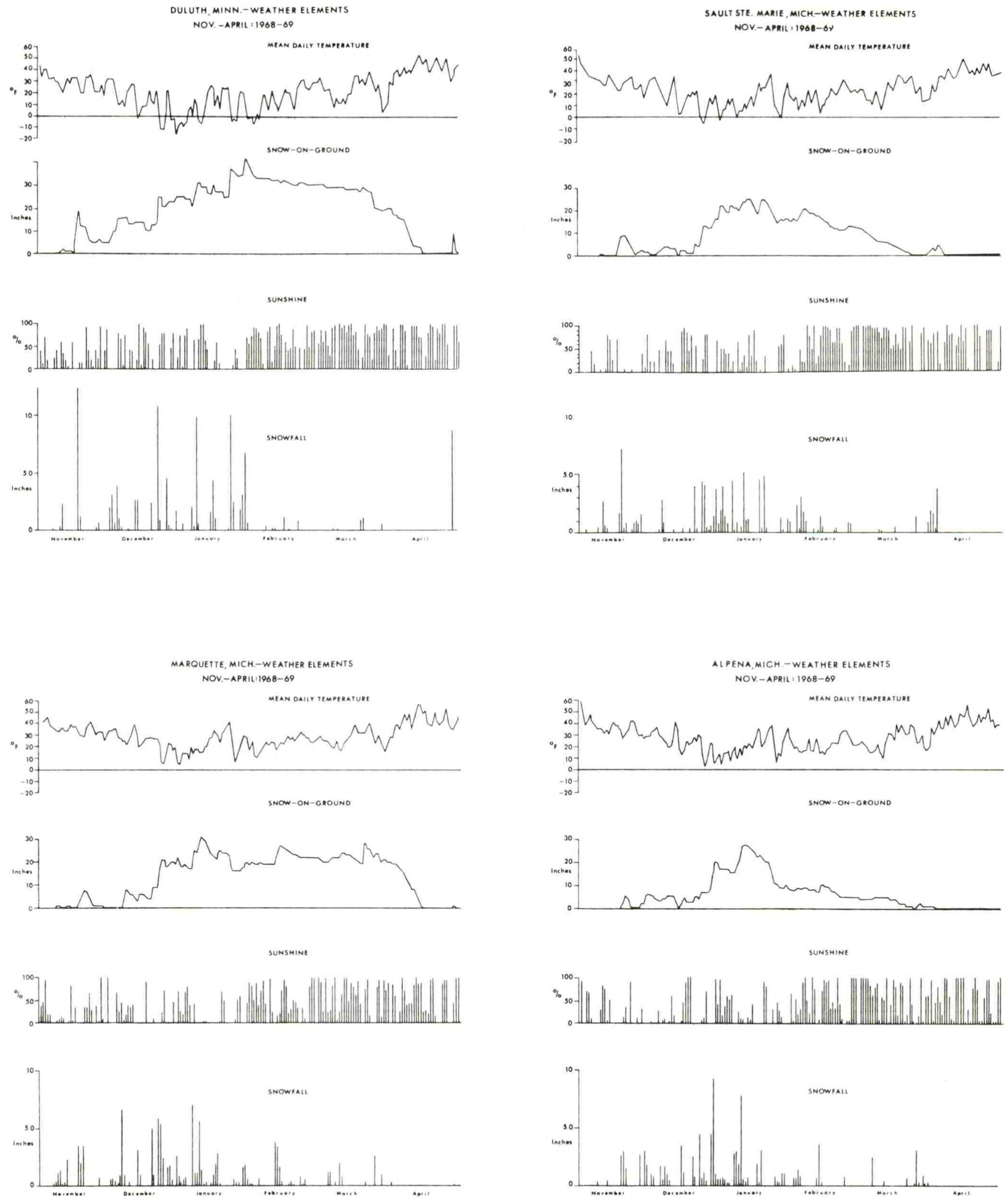


Figure 5

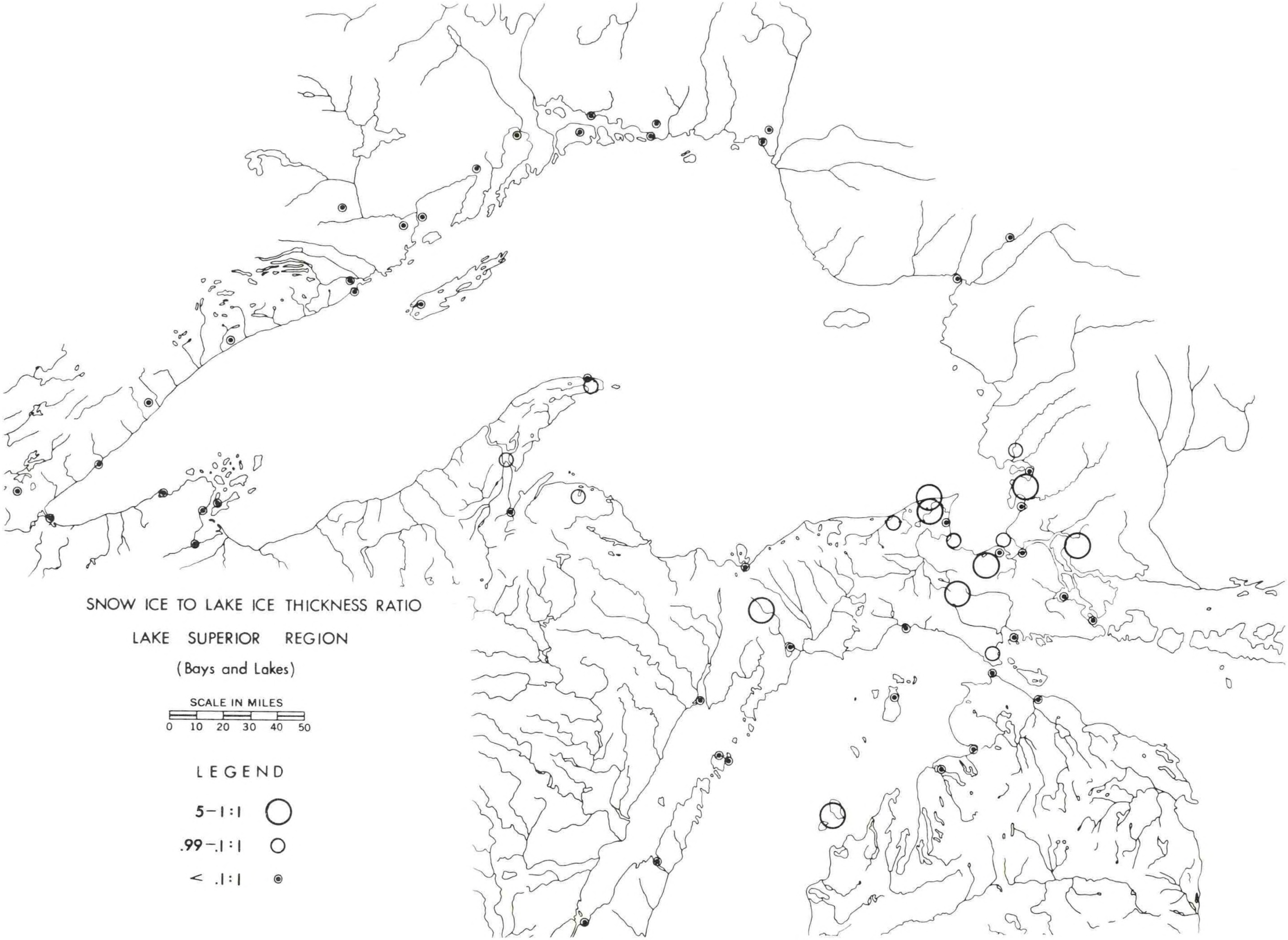
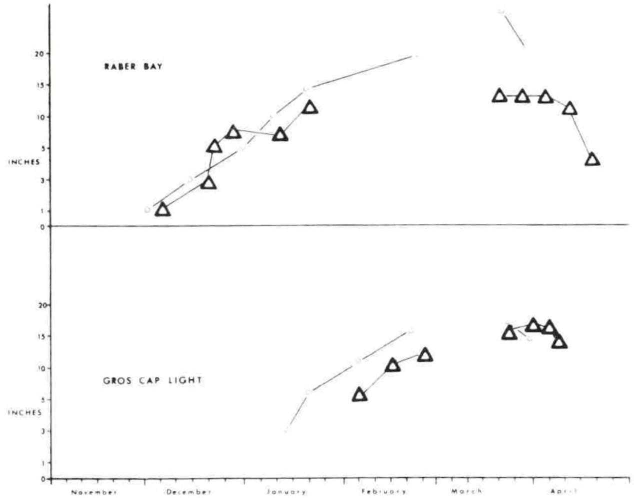
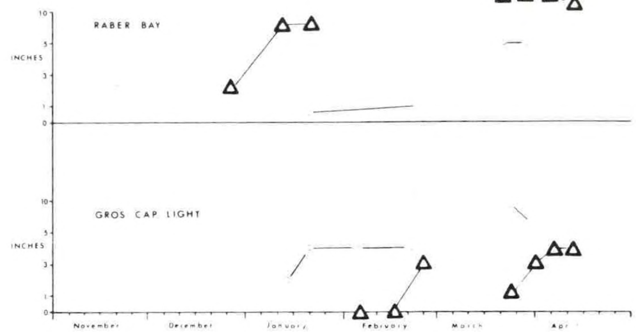

SNOW ICE TO LAKE ICE THICKNESS RATIO
LAKE SUPERIOR REGION
(Bays and Lakes)
SCALE IN MILES
0 10 20 30 40 50
LEGEND
5–1:1
.99–.1:1
< .1:1

Figure 6



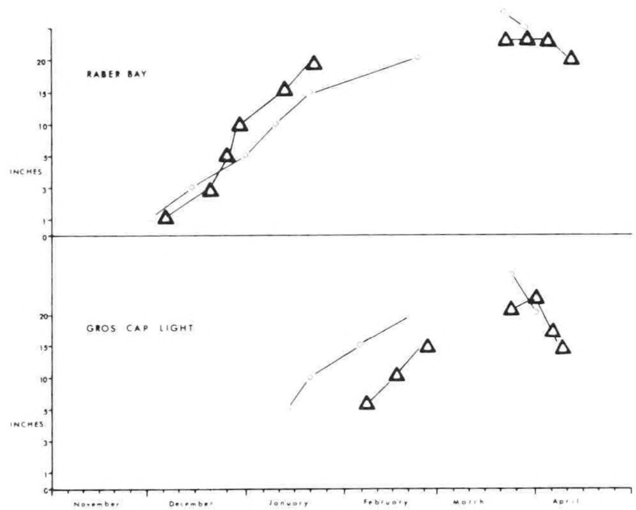
ICE THICKNESS AND STRUCTURE
AT RABER BAY AND GROS CAP LIGHT
(Lake Ice)

1967-68
1968-69



ICE THICKNESS AND STRUCTURE
AT RABER BAY AND GROS CAP LIGHT
(Snow Ice)

1967-68
1968-69



ICE THICKNESS AND STRUCTURE
AT RABER BAY AND GROS CAP LIGHT
(Lake and Snow Ice)

1967 68
1968-69

ICE THICKNESS THRESHOLDS

RABER BAY, MICHIGAN
(Lower River)

Year	Date	Snow & Lake Ice	Snow & Slush Ice	Thickness Thresholds Lake Ice	Thickness Thresholds Total
1967	Dec 1	1	---	--	--
	Dec 14	3	---	3	1
	Dec 31	5	---	5	5
1968	Jan 9	10	---	10	10
	Jan 20	15	0.5	14.5	15
	Feb 23	20	1.0	19.0	20.0
1968	Dec 4	1	---	1	1
	Dec 19	3	---	3	3
	Dec 21	5	---	5	5
	Dec 27	10	2.0	8	10
1969	Jan 11	15	8.0	7	15
	Jan 20	20	8.0	12	20

GROS CAP LIGHT, MICHIGAN
(Upper River)

Year	Date	Snow & Lake Ice	Snow & Slush Ice	Lake Ice	Total
1968	Jan 13	5	2	3	5
	Jan 20	10	4	6	10
	Feb 4	15	4	11	15
	Feb 21	20	4	16	20
1969	Feb 5	5	0	5	5
	Feb 15	10	0	10	10
	Feb 24	15	3	12	15

Figure 7

REGIONAL DAILY FREEZING DEGREE DAYS
(20 DEC., 1968-10 JAN., 1969)

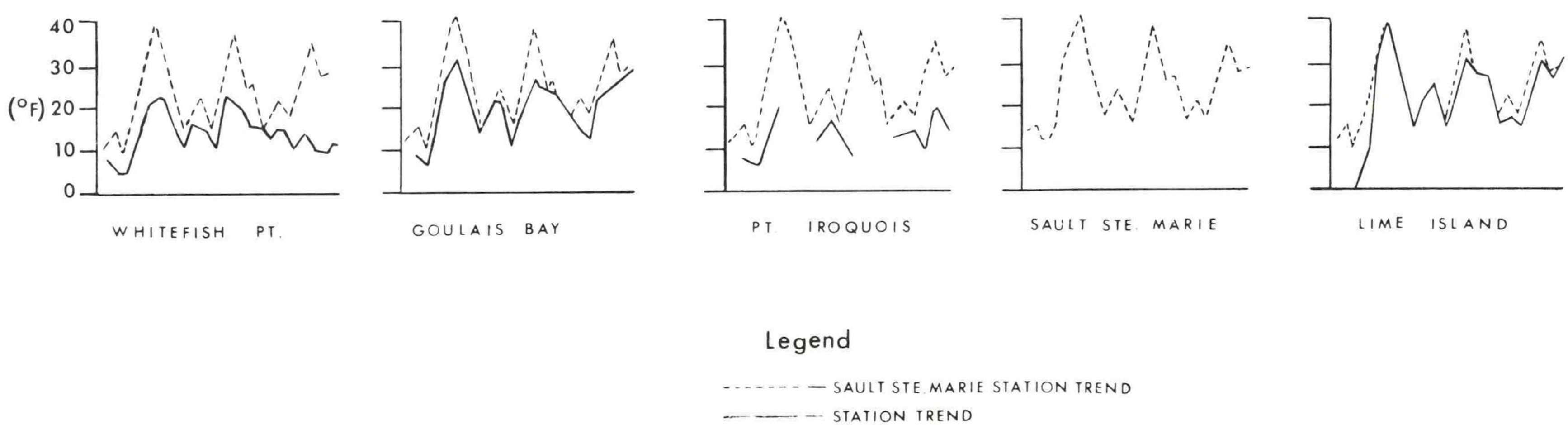


Figure 8

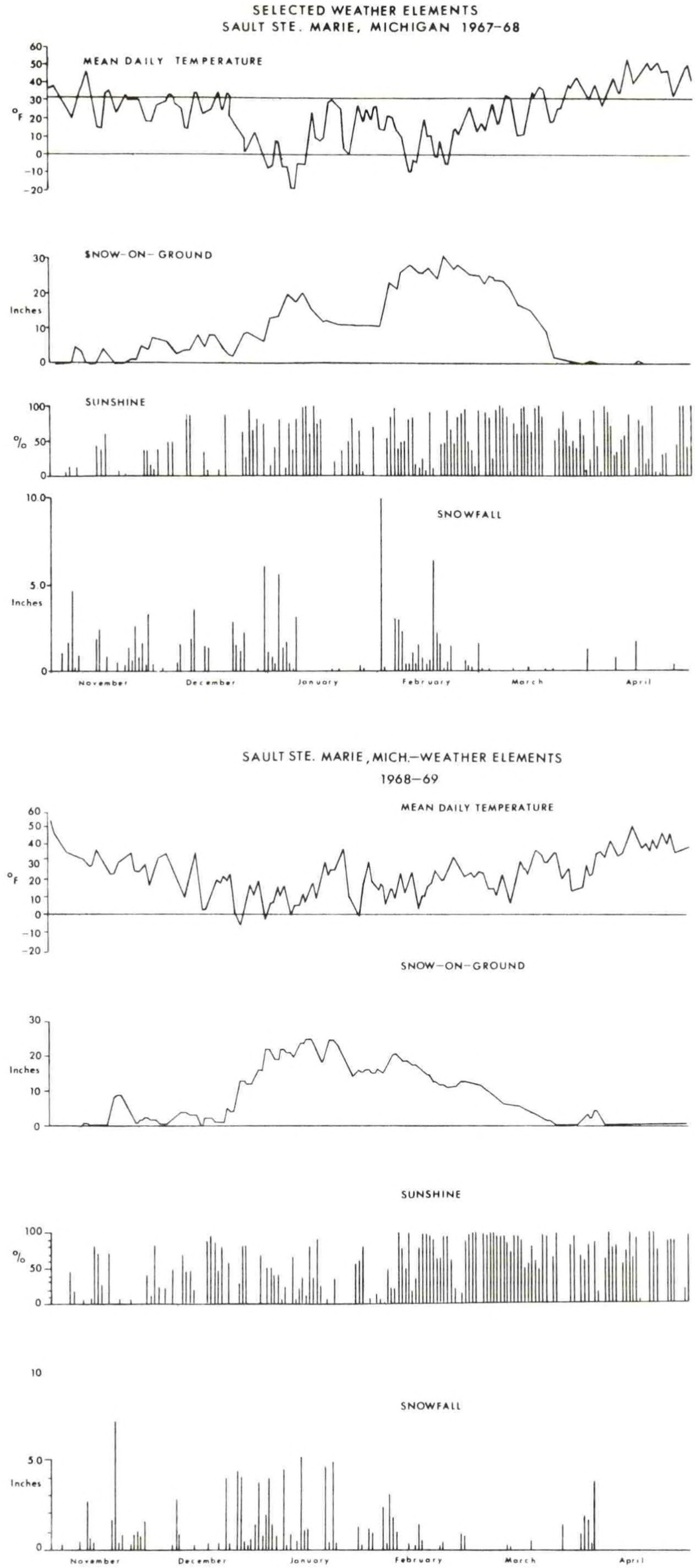

SELECTED WEATHER ELEMENTS
SAULT STE. MARIE, MICHIGAN 1967-68
MEAN DAILY TEMPERATURE
°F
SNOW-ON-GROUND
Inches
SUNSHINE
%
SNOWFALL
Inches
November
December
January
February
March
April
SAULT STE. MARIE, MICH.—WEATHER ELEMENTS
1968—69
MEAN DAILY TEMPERATURE
°F
SNOW—ON—GROUND
Inches
SUNSHINE
%
SNOWFALL
Inches
November
December
January
February
March
April

Figure 9

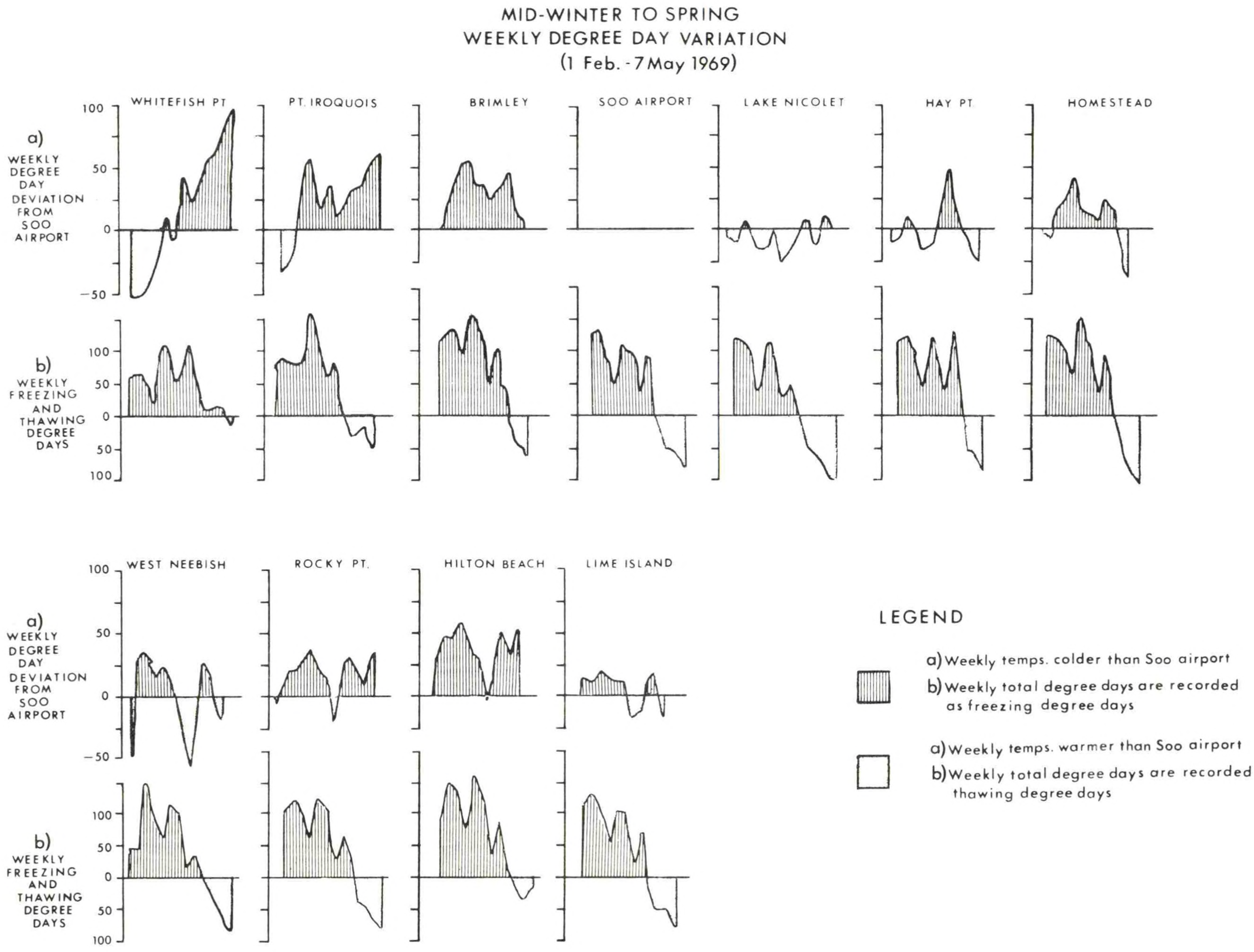

MID-WINTER TO SPRING
WEEKLY DEGREE DAY VARIATION
(1 Feb. - 7 May 1969)
WHITEFISH PT
PT. IROQUOIS
BRIMLEY
SOO AIRPORT
LAKE NICOLET
HAY PT
HOMESTEAD
WEST NEEBISH
ROCKY PT.
HILTON BEACH
LIME ISLAND
a) WEEKLY DEGREE DAY DEVIATION FROM SOO AIRPORT
b) WEEKLY FREEZING AND THAWING DEGREE DAYS
100
50
0
-50
LEGEND
a) Weekly temps. colder than Soo airport
b) Weekly total degree days are recorded as freezing degree days
a) Weekly temps. warmer than Soo airport
b) Weekly total degree days are recorded thawing degree days

Figure 10

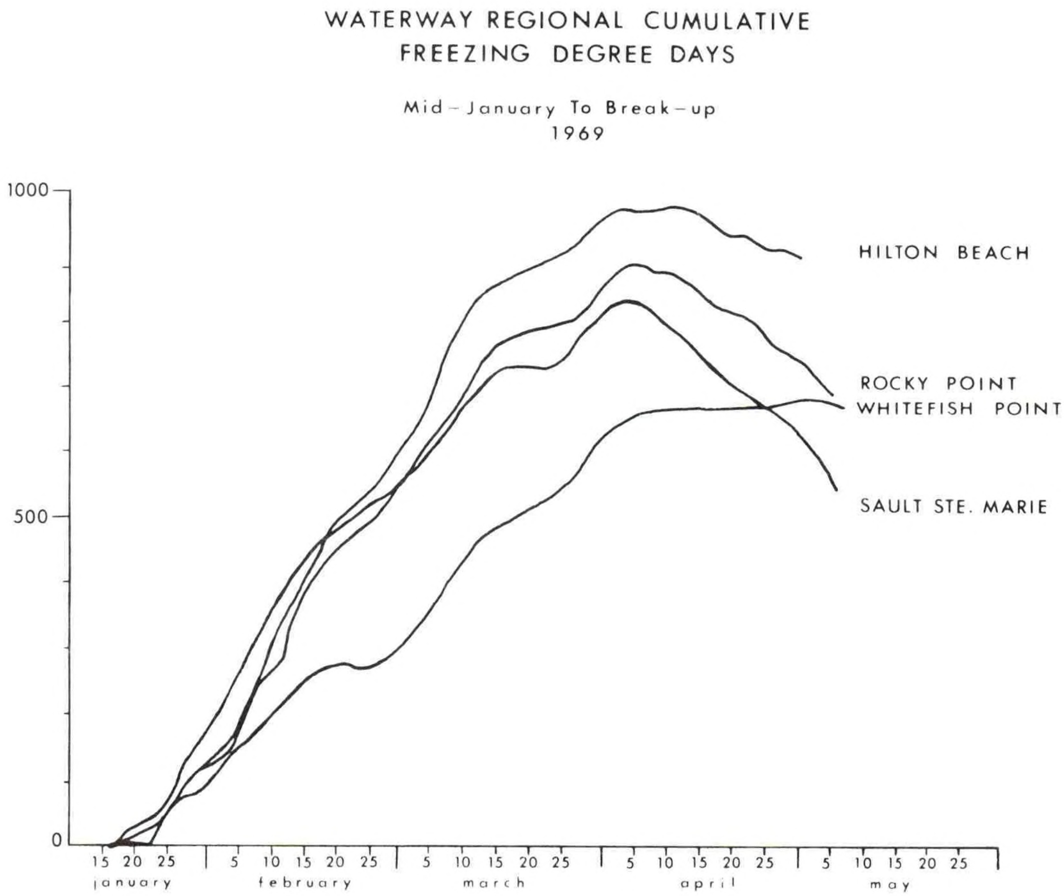

WATERWAY REGIONAL CUMULATIVE
FREEZING DEGREE DAYS
Mid-January To Break-up
1969
1000
500
0
HILTON BEACH
ROCKY POINT
WHITEFISH POINT
SAULT STE. MARIE
15 20 25
january
5 10 15 20 25
february
5 10 15 20 25
march
5 10 15 20 25
april
5 10 15 20 25
may

Figure 11

The daily varation of the solar radiation at the top of the atmosphere as a function of latitude. The units are langleys per day. Modified from List (1958).

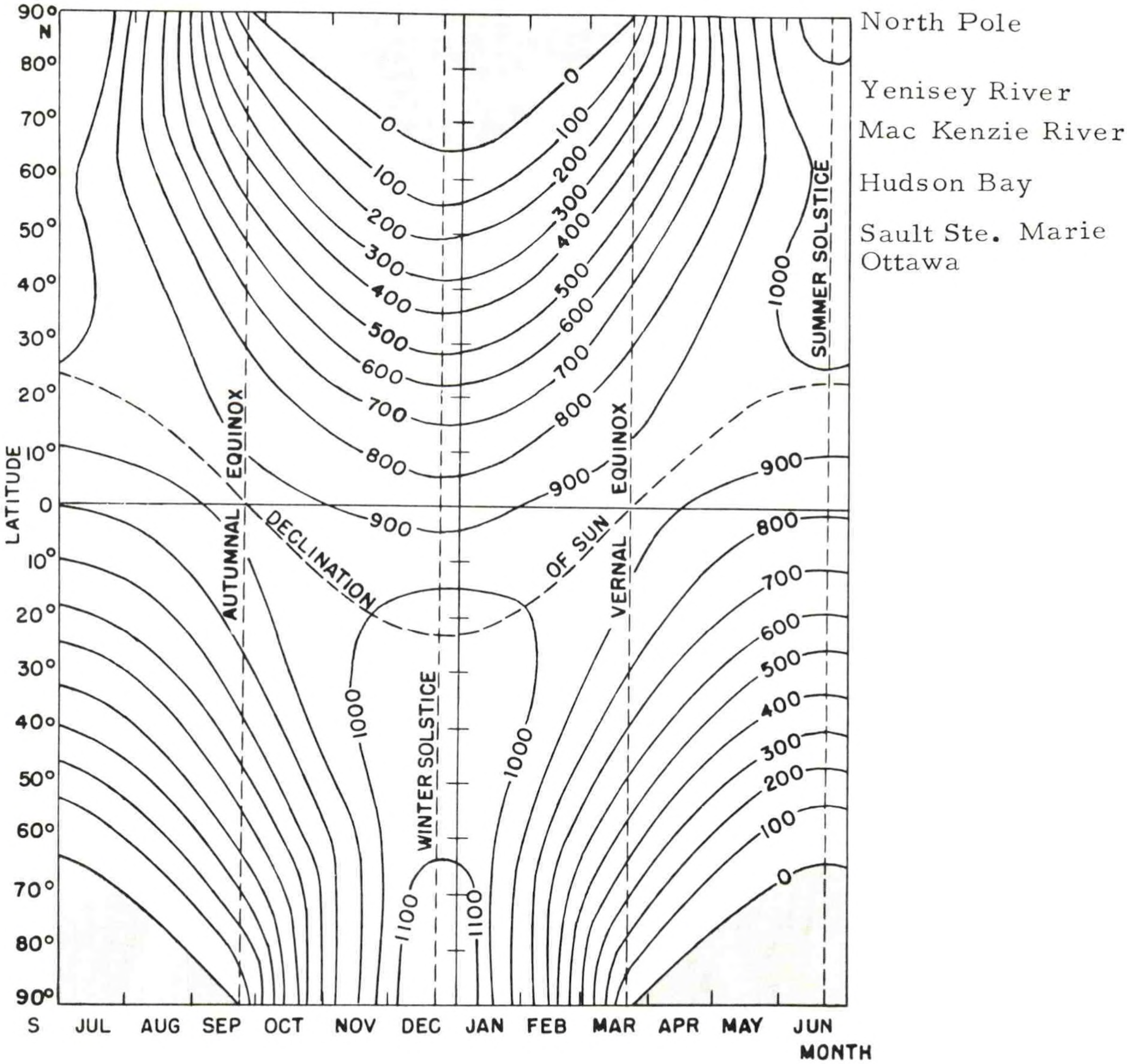


Figure 12

SOLAR RADIATION CURVES FOR BREAK-UP PERIOD

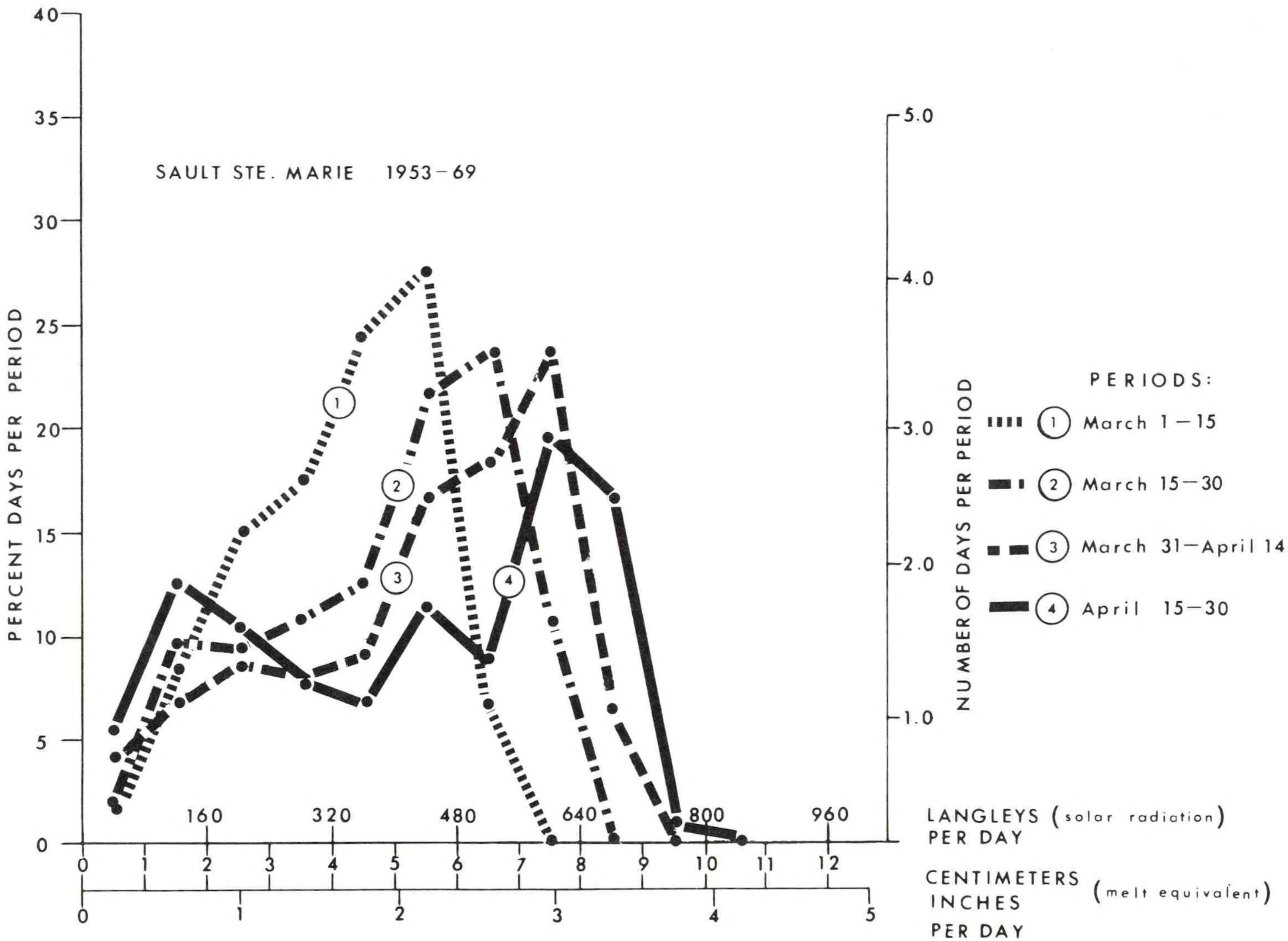


Figure 13

MICROCLIMATIC PARAMETERS AT PT. IROQUOIS

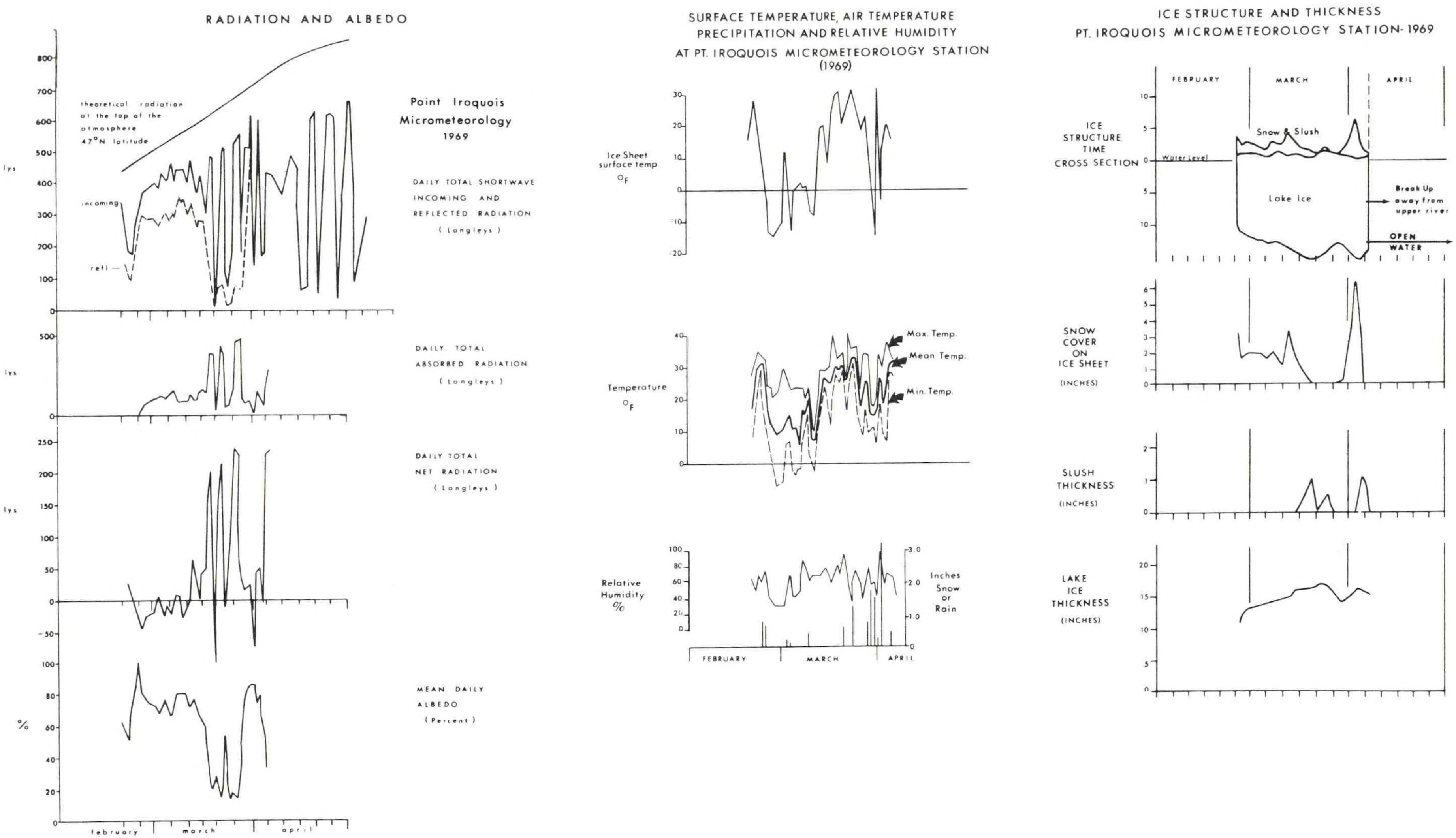


Figure 14

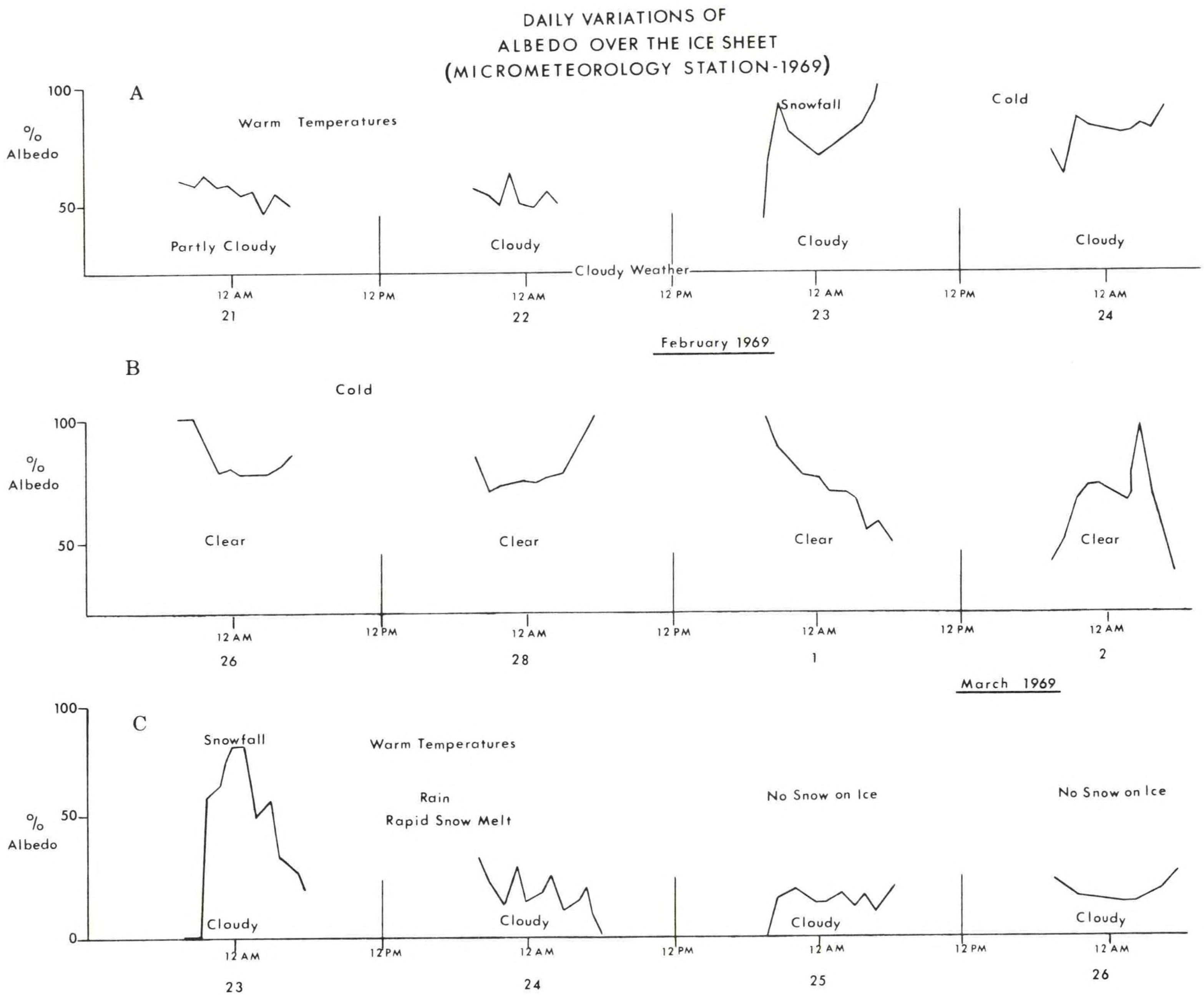

DAILY VARIATIONS OF
ALBEDO OVER THE ICE SHEET
(MICROMETEOROLOGY STATION-1969)
A
100
50
% Albedo
Warm Temperatures
Snowfall
Cold
Partly Cloudy
Cloudy
Cloudy
Cloudy
Cloudy Weather
12 AM
12 PM
21
22
23
24
February 1969
B
Cold
100
50
% Albedo
Clear
Clear
Clear
Clear
12 AM
12 PM
26
28
1
2
March 1969
C
100
50
0
% Albedo
Snowfall
Warm Temperatures
Rain
Rapid Snow Melt
No Snow on Ice
No Snow on Ice
Cloudy
Cloudy
Cloudy
Cloudy
12 AM
12 PM
23
24
25
26

Figure 15

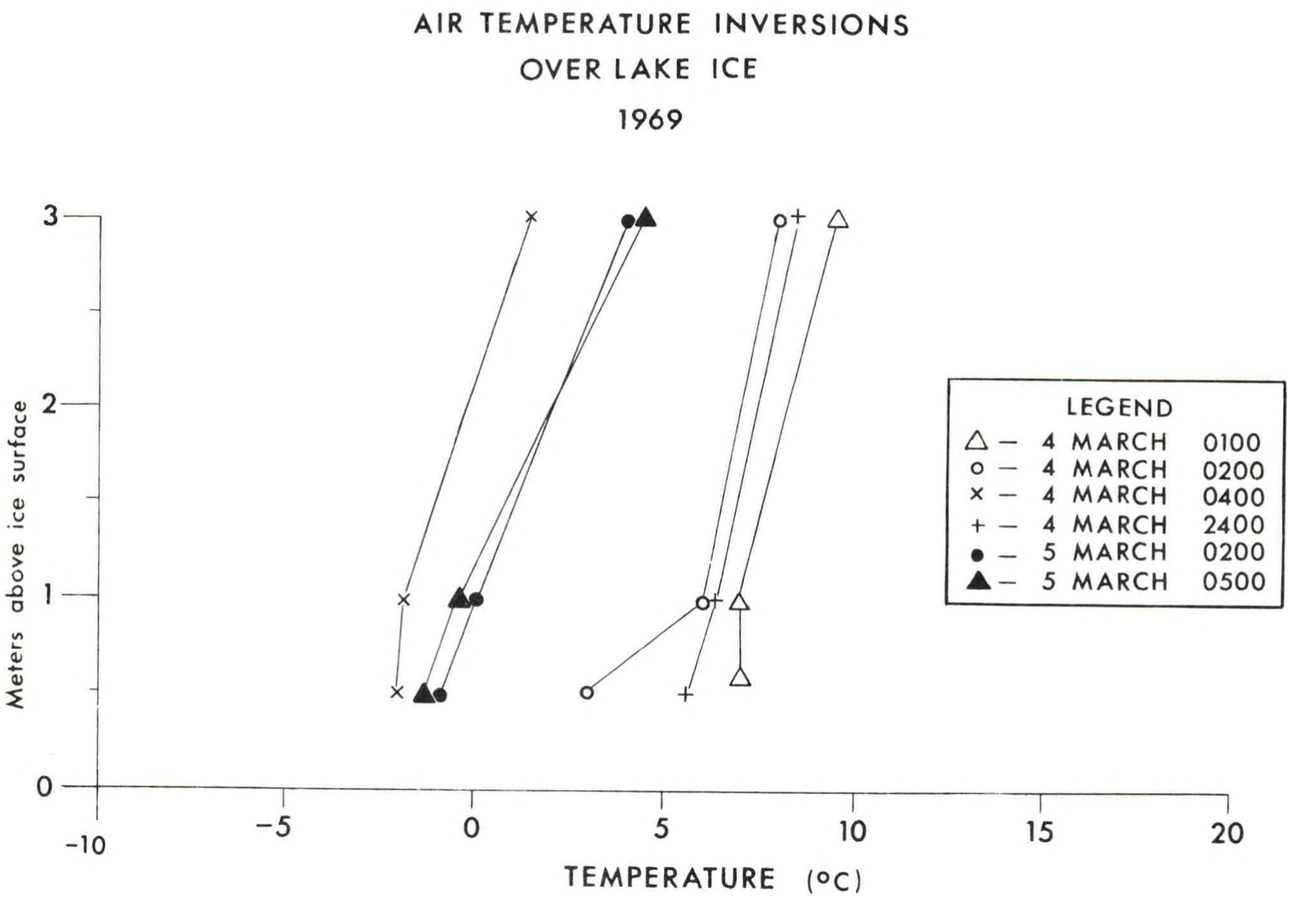

AIR TEMPERATURE INVERSIONS
OVER LAKE ICE
1969
Meters above ice surface
0
1
2
3
-10
-5
0
5
10
15
20
TEMPERATURE (°C)
LEGEND
△ — 4 MARCH 0100
○ — 4 MARCH 0200
× — 4 MARCH 0400
+ — 4 MARCH 2400
● — 5 MARCH 0200
▲ — 5 MARCH 0500

Figure 16

WIND CHARACTERISTICS

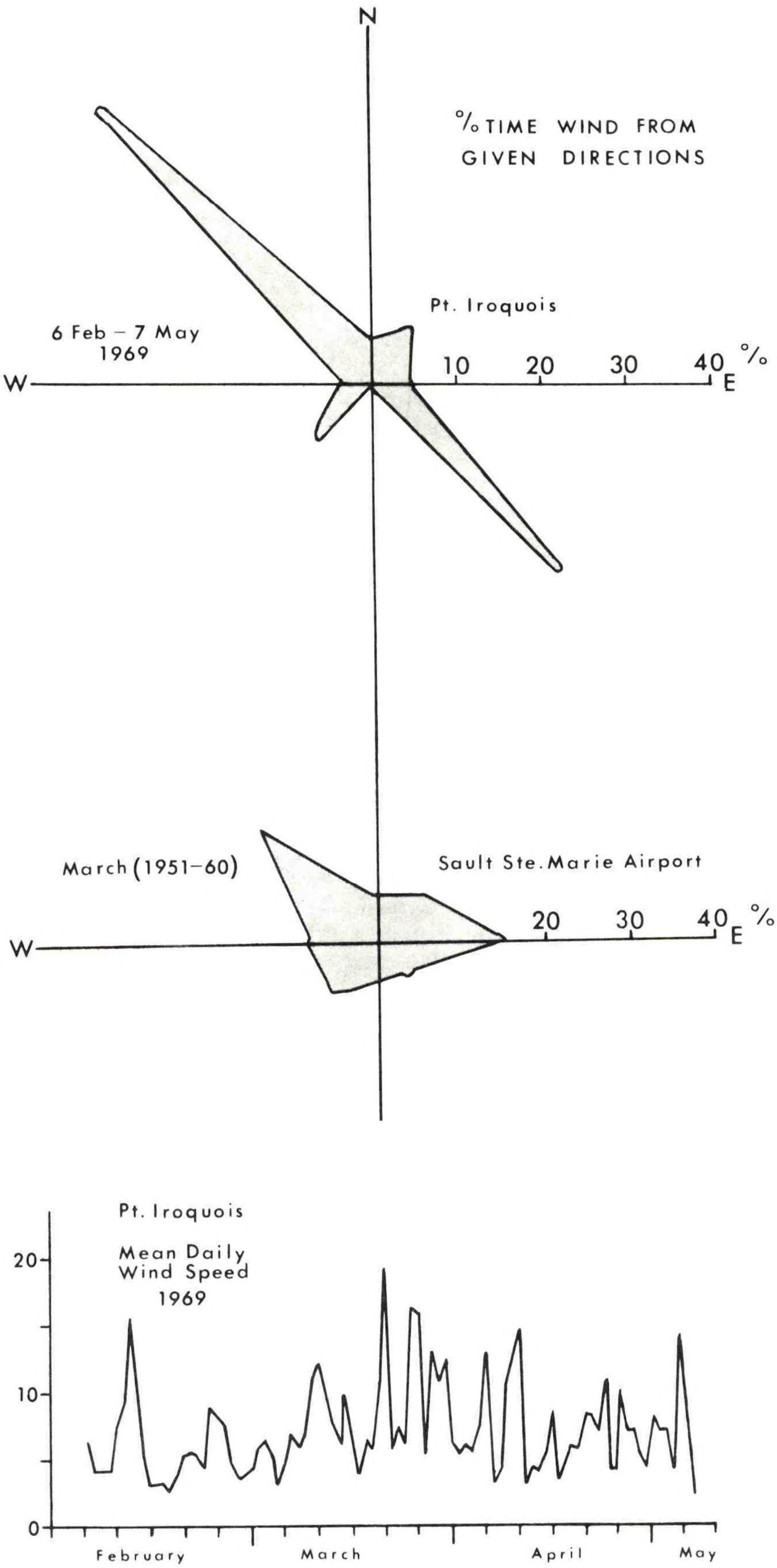


Figure 17

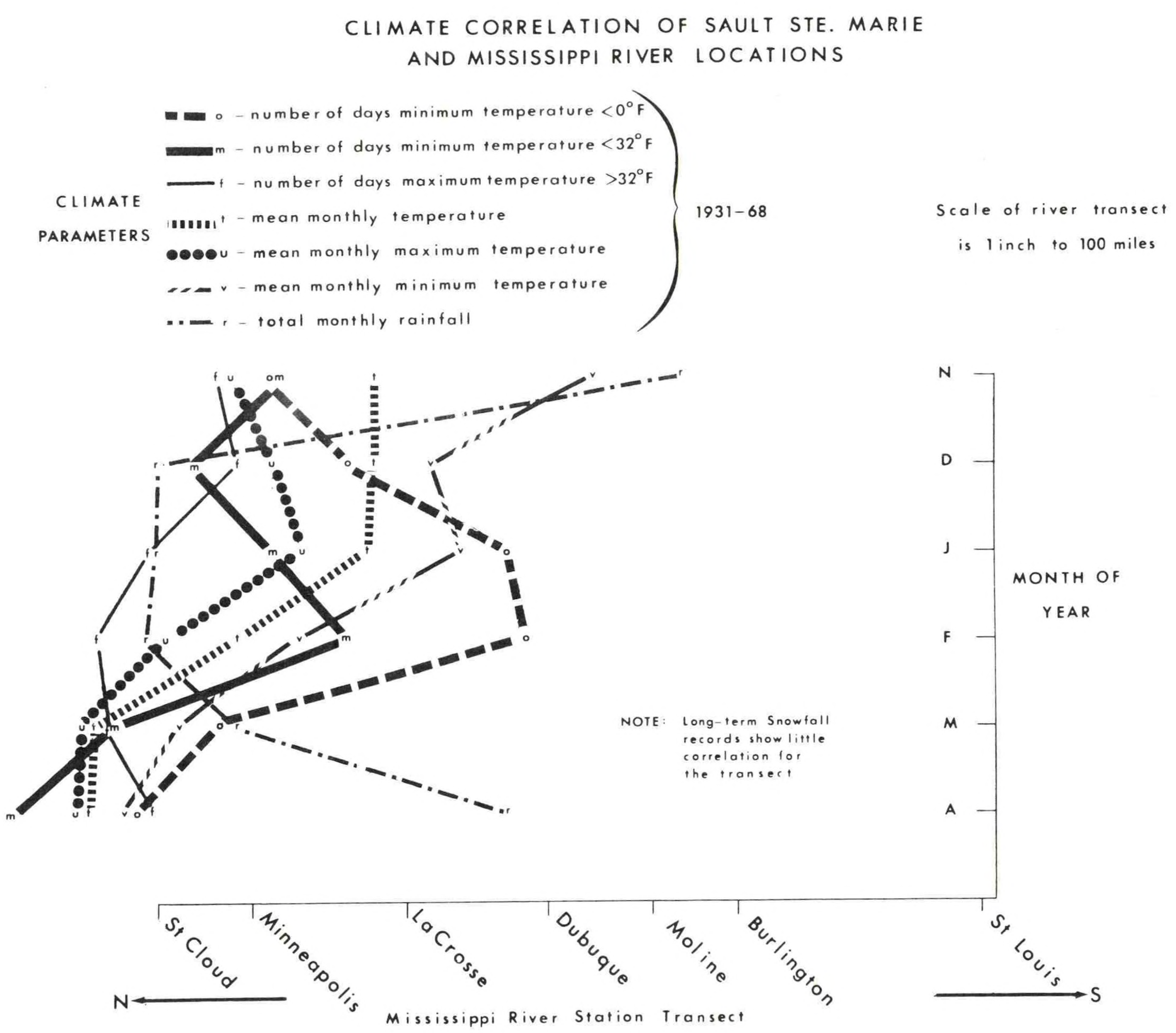

CLIMATE CORRELATION OF SAULT STE. MARIE
AND MISSISSIPPI RIVER LOCATIONS
CLIMATE PARAMETERS
o - number of days minimum temperature <0°F
m - number of days minimum temperature <32°F
f - number of days maximum temperature >32°F
t - mean monthly temperature
u - mean monthly maximum temperature
v - mean monthly minimum temperature
r - total monthly rainfall
1931-68
Scale of river transect is 1 inch to 100 miles
N
D
J
F
M
A
MONTH OF YEAR
NOTE: Long-term Snowfall records show little correlation for the transect
St Cloud
Minneapolis
LaCrosse
Dubuque
Moline
Burlington
St Louis
N
S
Mississippi River Station Transect

Figure 18

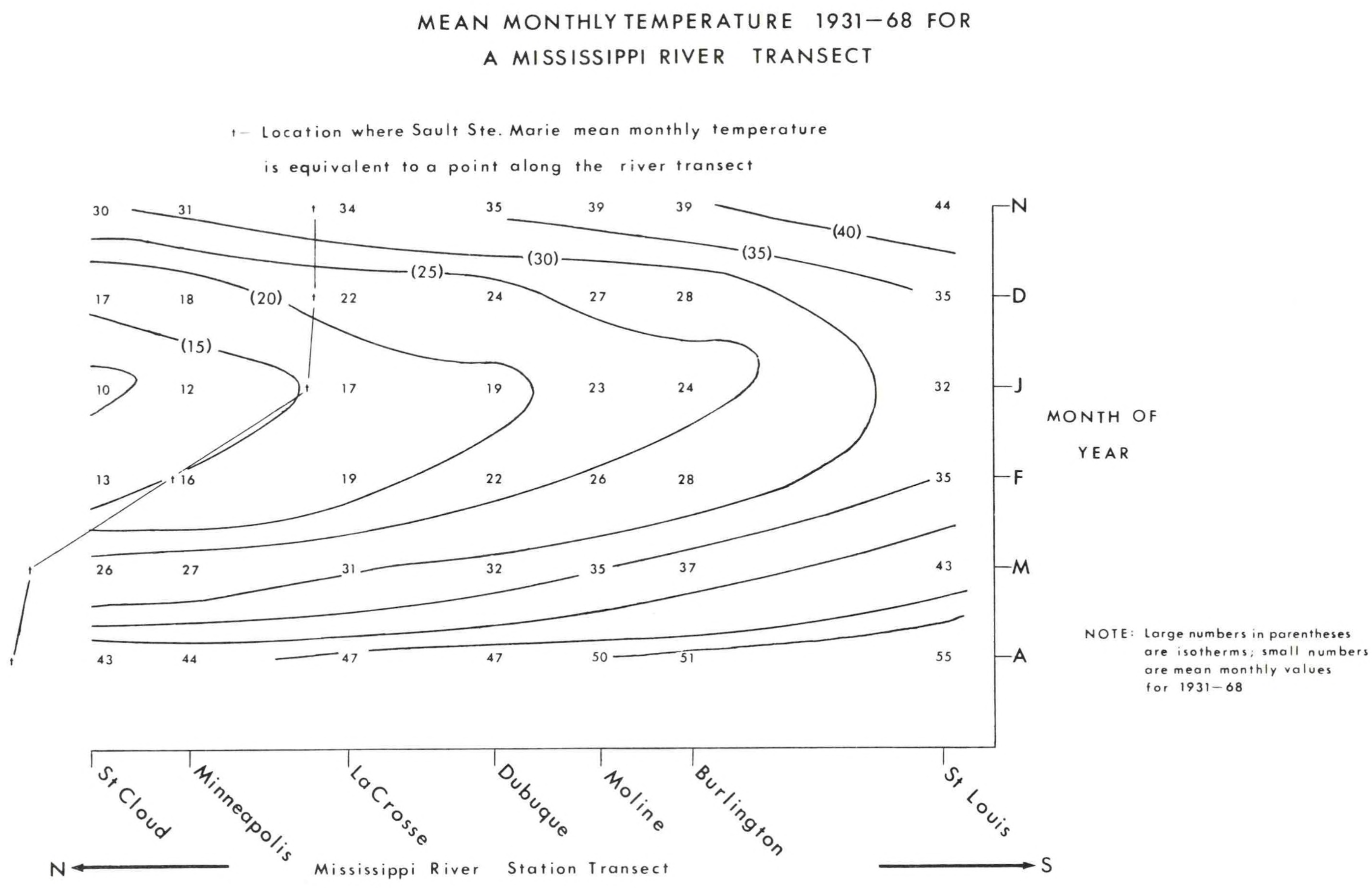

MEAN MONTHLY TEMPERATURE 1931—68 FOR
A MISSISSIPPI RIVER TRANSECT
ᵗ— Location where Sault Ste. Marie mean monthly temperature
is equivalent to a point along the river transect
(40)
(35)
(30)
(25)
(20)
(15)
30 31 34 35 39 39 44
17 18 22 24 27 28 35
10 12 17 19 23 24 32
13 16 19 22 26 28 35
26 27 31 32 35 37 43
43 44 47 47 50 51 55
N
D
J
F
M
A
MONTH OF
YEAR
NOTE: Large numbers in parentheses are isotherms; small numbers are mean monthly values for 1931—68
St Cloud
Minneapolis
LaCrosse
Dubuque
Moline
Burlington
St Louis
N
Mississippi River Station Transect
S

Figure 19

ISOPACH DIAGRAM OF
MISSISSIPPI RIVER ICE COVER
1959—68

(data for figures 21-29 Obtained from Rock Island District U. S. Army Corps of Engineers)

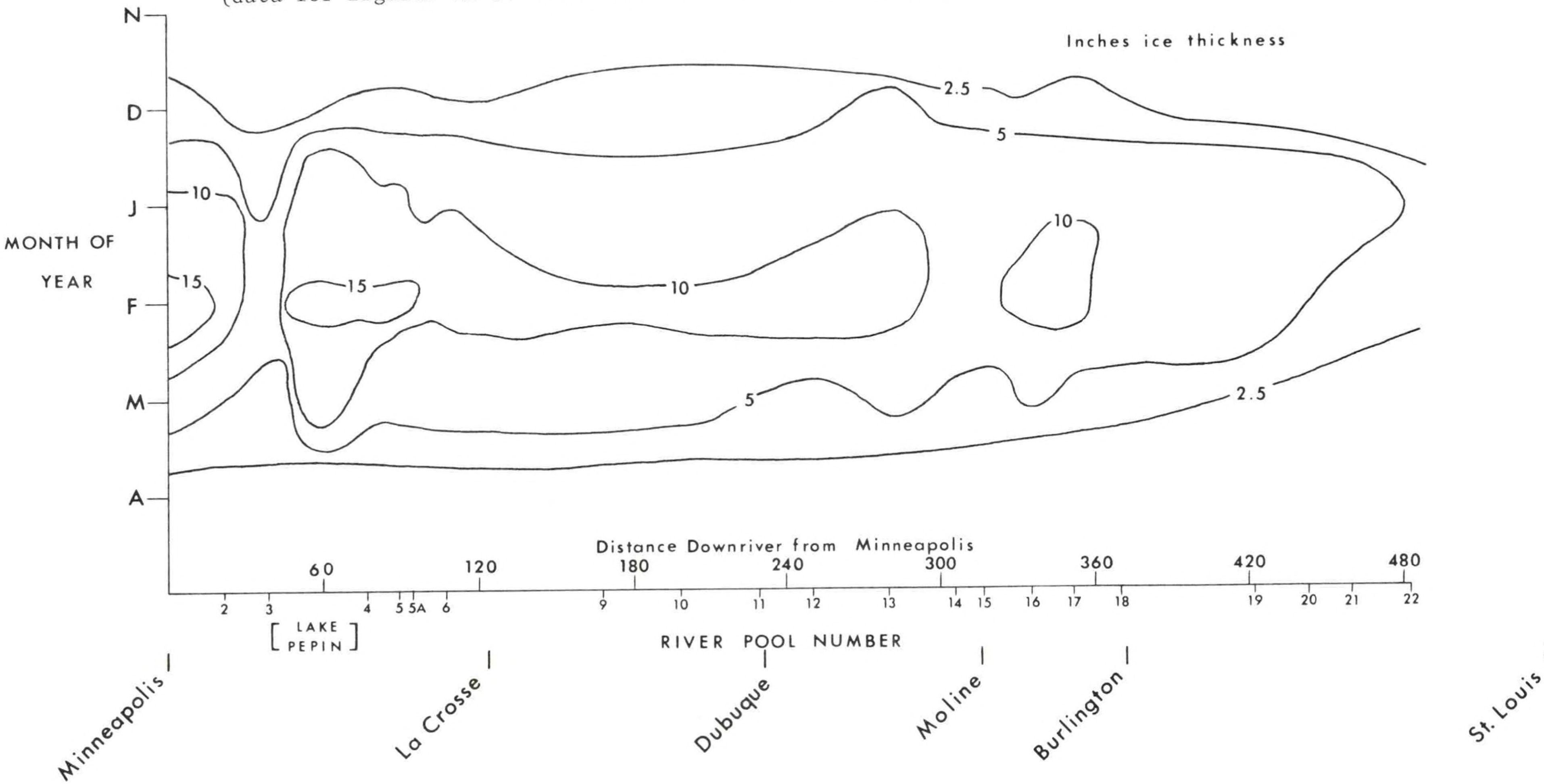


Figure 20

YEARLY ISOPACH DIAGRAM OF MISSISSIPPI RIVER ICE COVER 1959—60

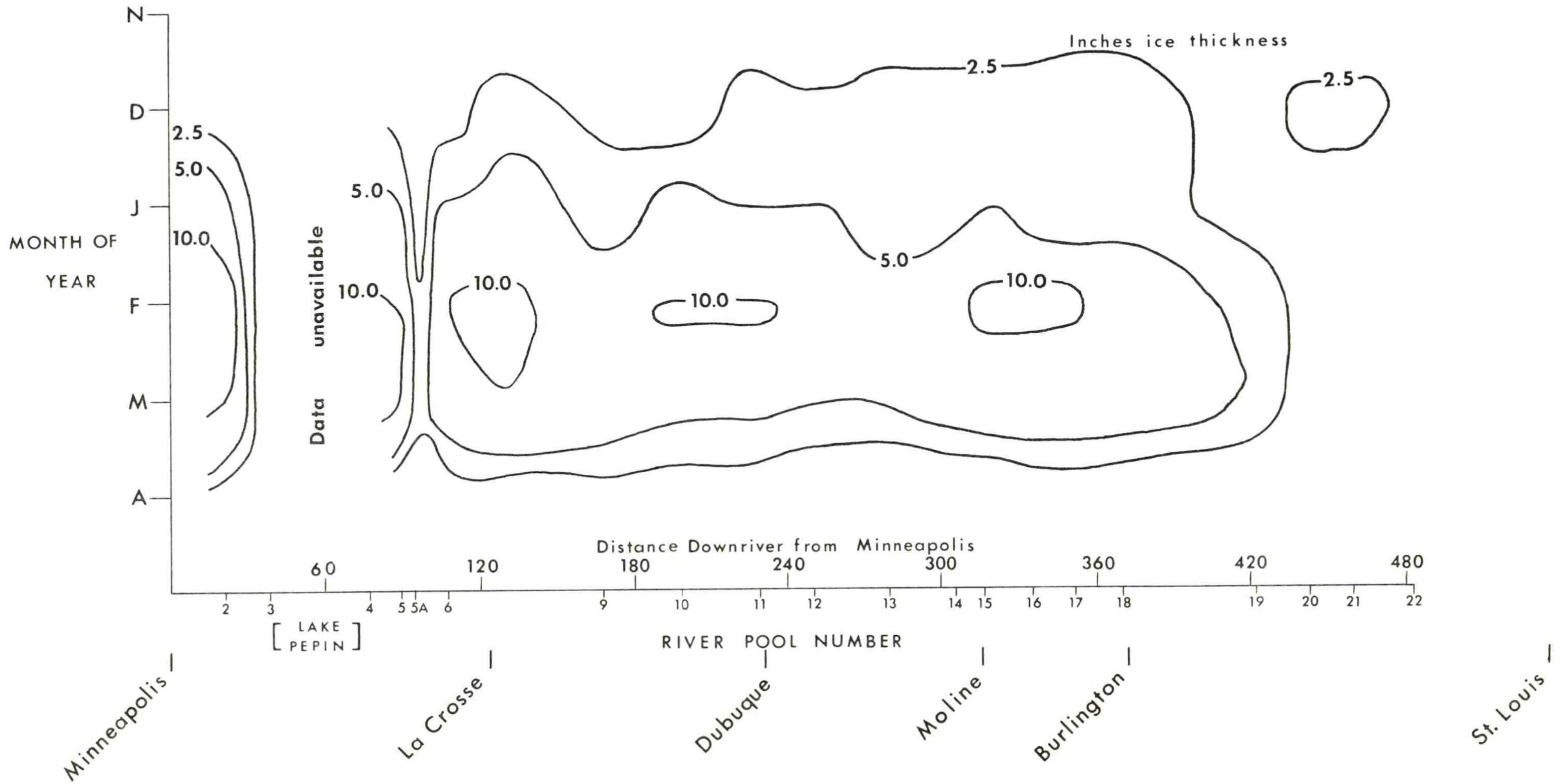


Figure 21

YEARLY ISOPACH DIAGRAM OF MISSISSIPPI RIVER ICE COVER 1960—61

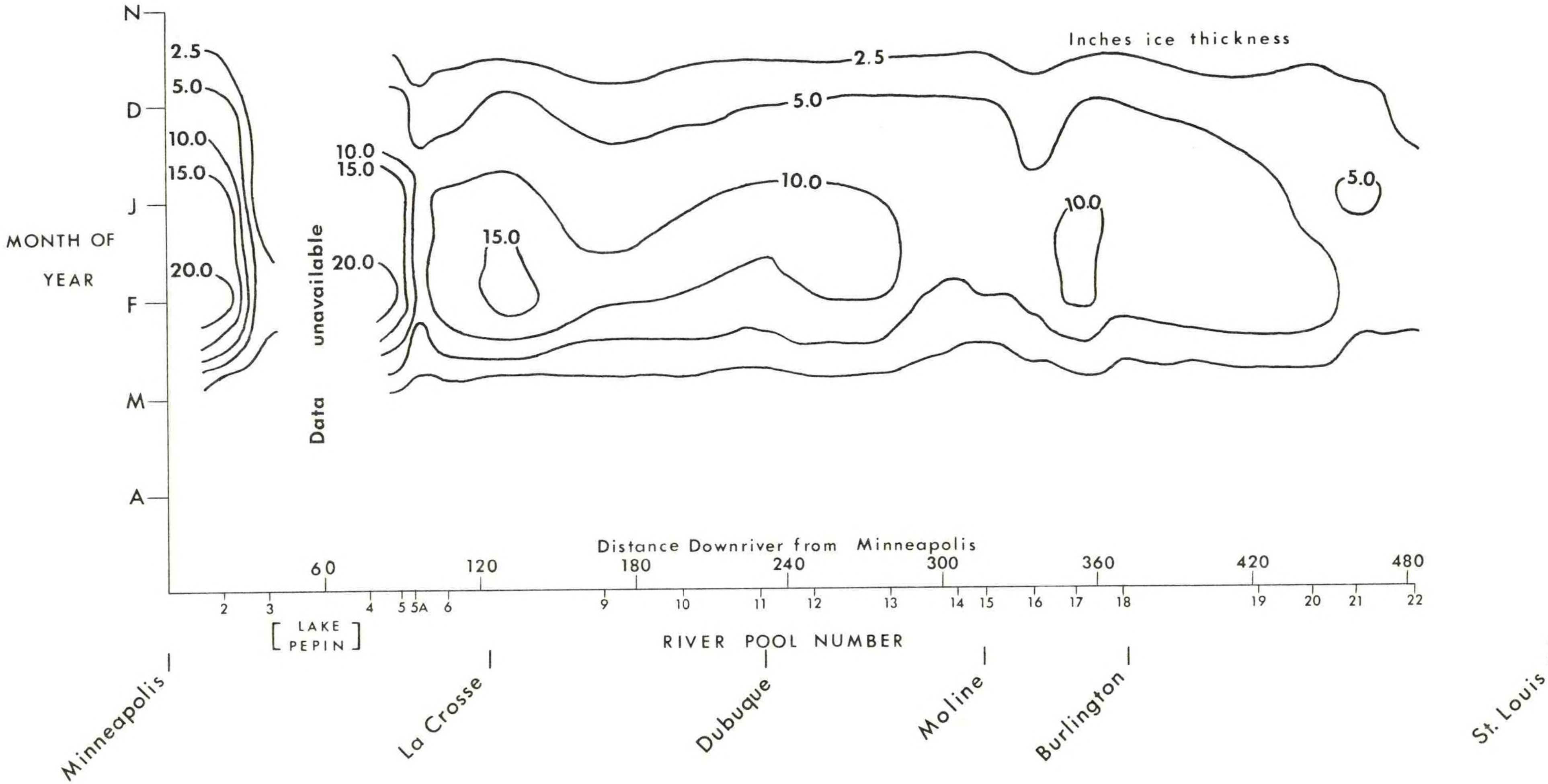


Figure 22

YEARLY ISOPACH DIAGRAM OF MISSISSIPPI RIVER ICE COVER 1961—62

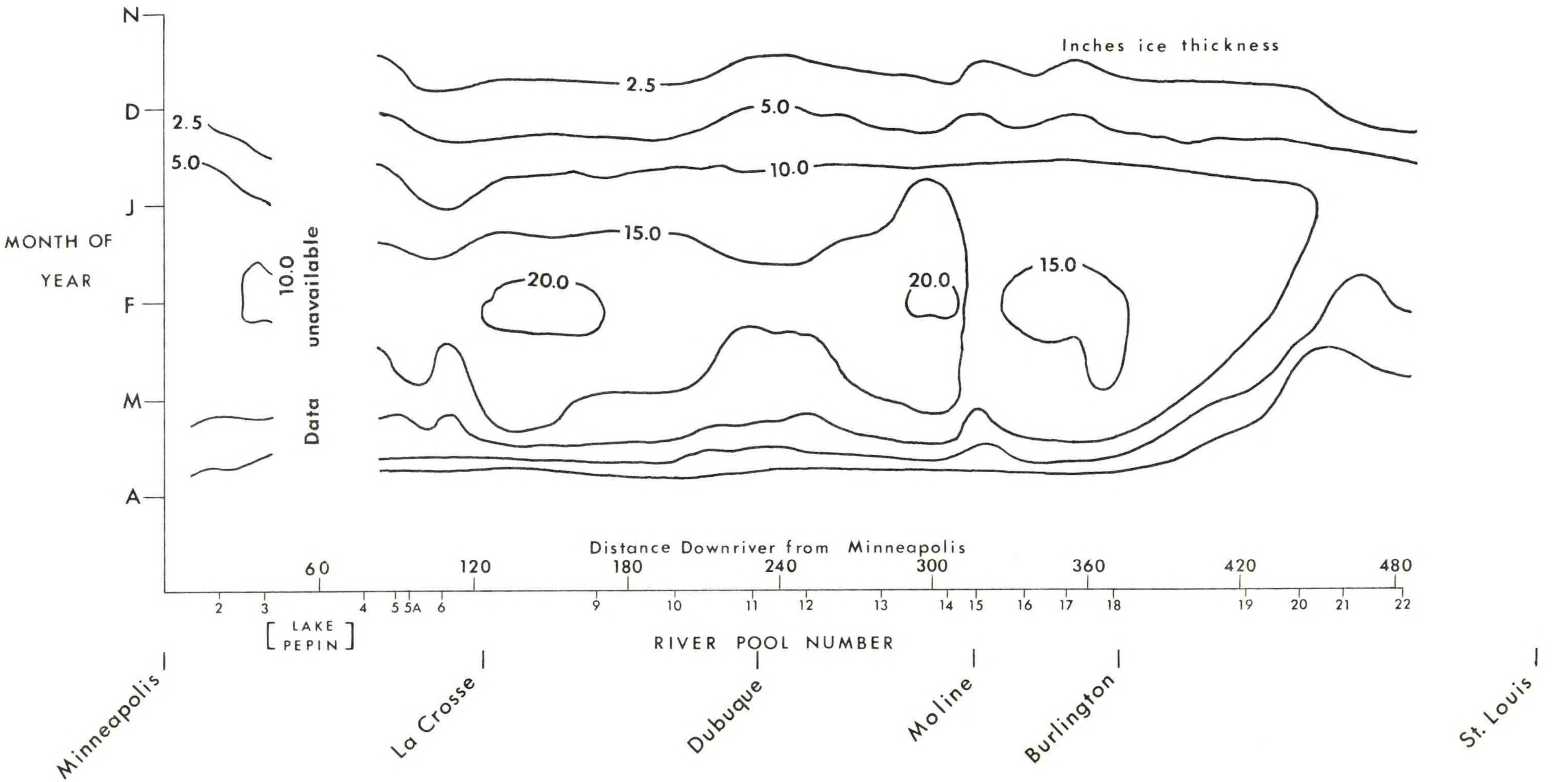


Figure 23

YEARLY ISOPACH DIAGRAM OF MISSISSIPPI RIVER ICE COVER 1962—63

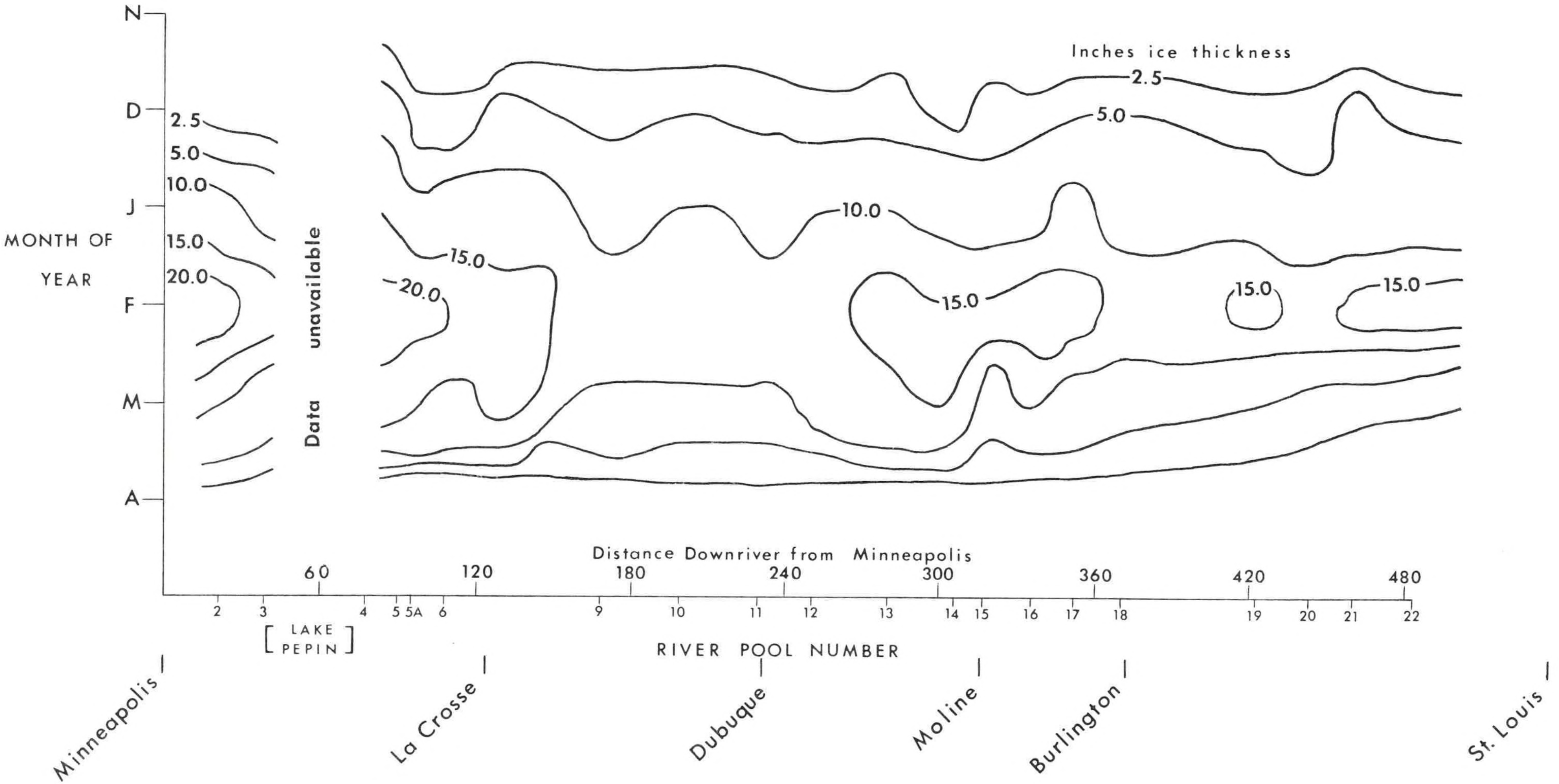


Figure 24

YEARLY ISOPACH DIAGRAM OF MISSISSIPPI RIVER ICE COVER 1963—64

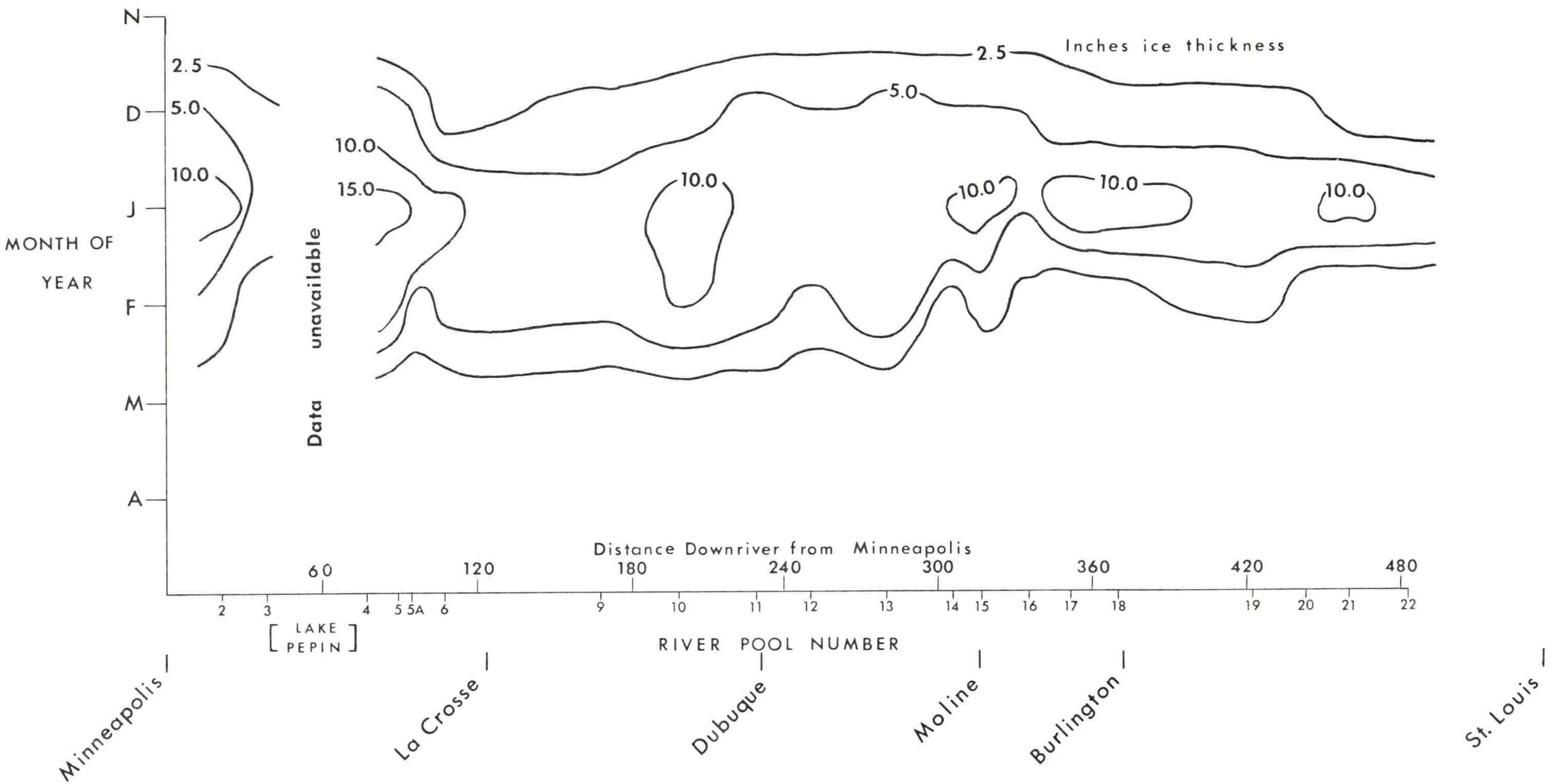


Figure 25

YEARLY ISOPACH DIAGRAM OF
MISSISSIPPI RIVER ICE COVER
1964—65

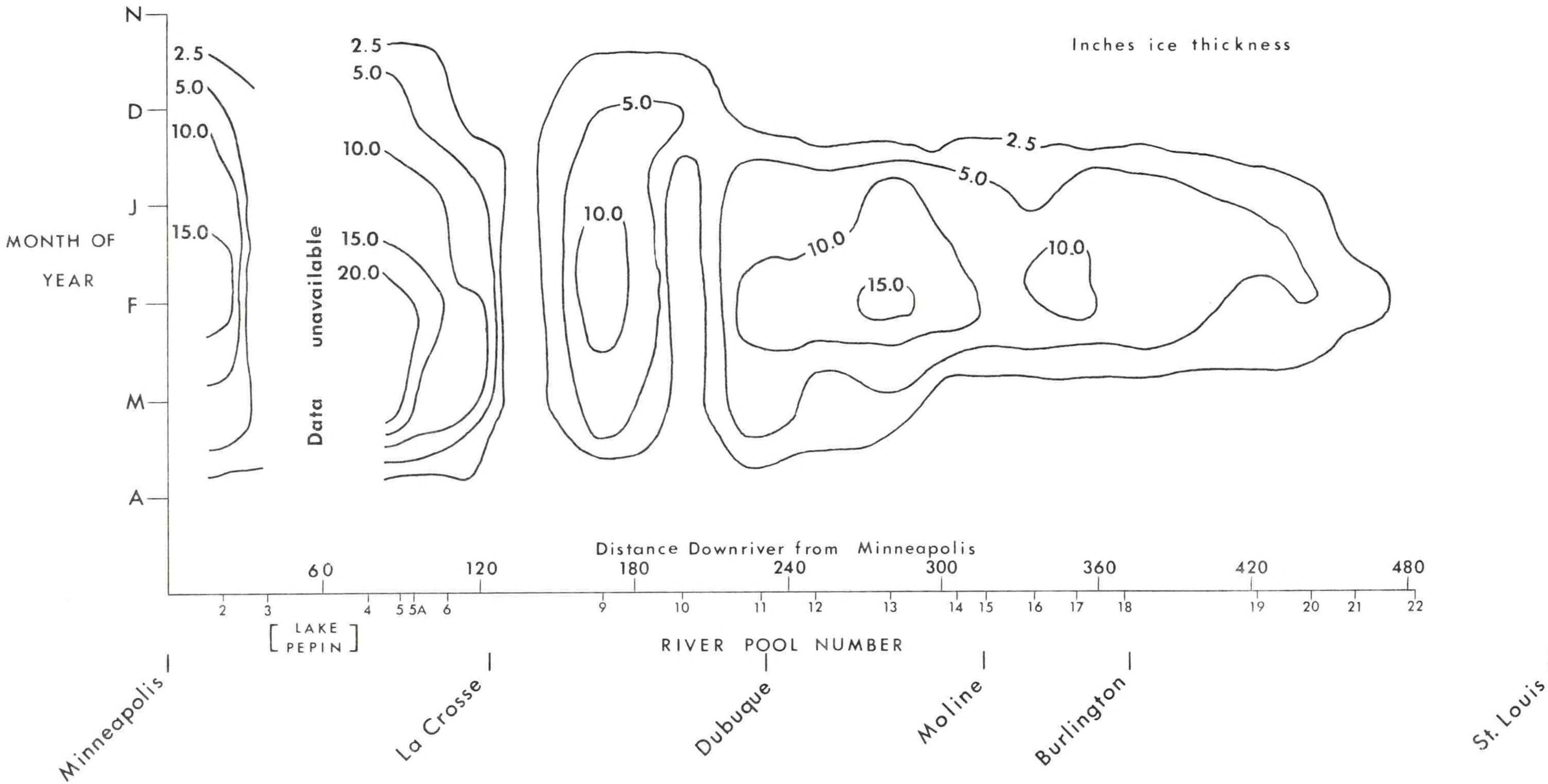


Figure 26

YEARLY ISOPACH DIAGRAM OF
MISSISSIPPI RIVER ICE COVER
1965—66

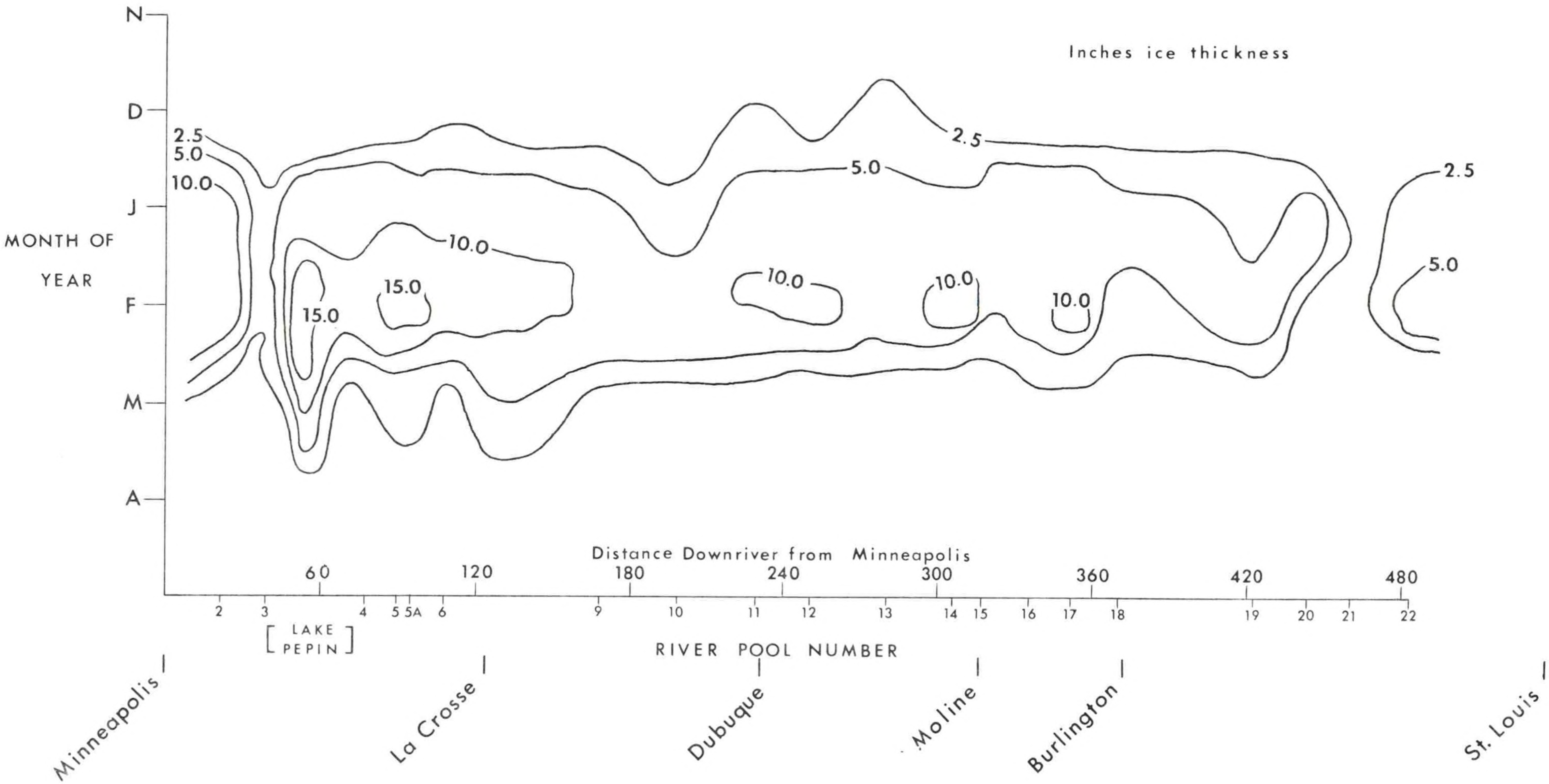


Figure 27

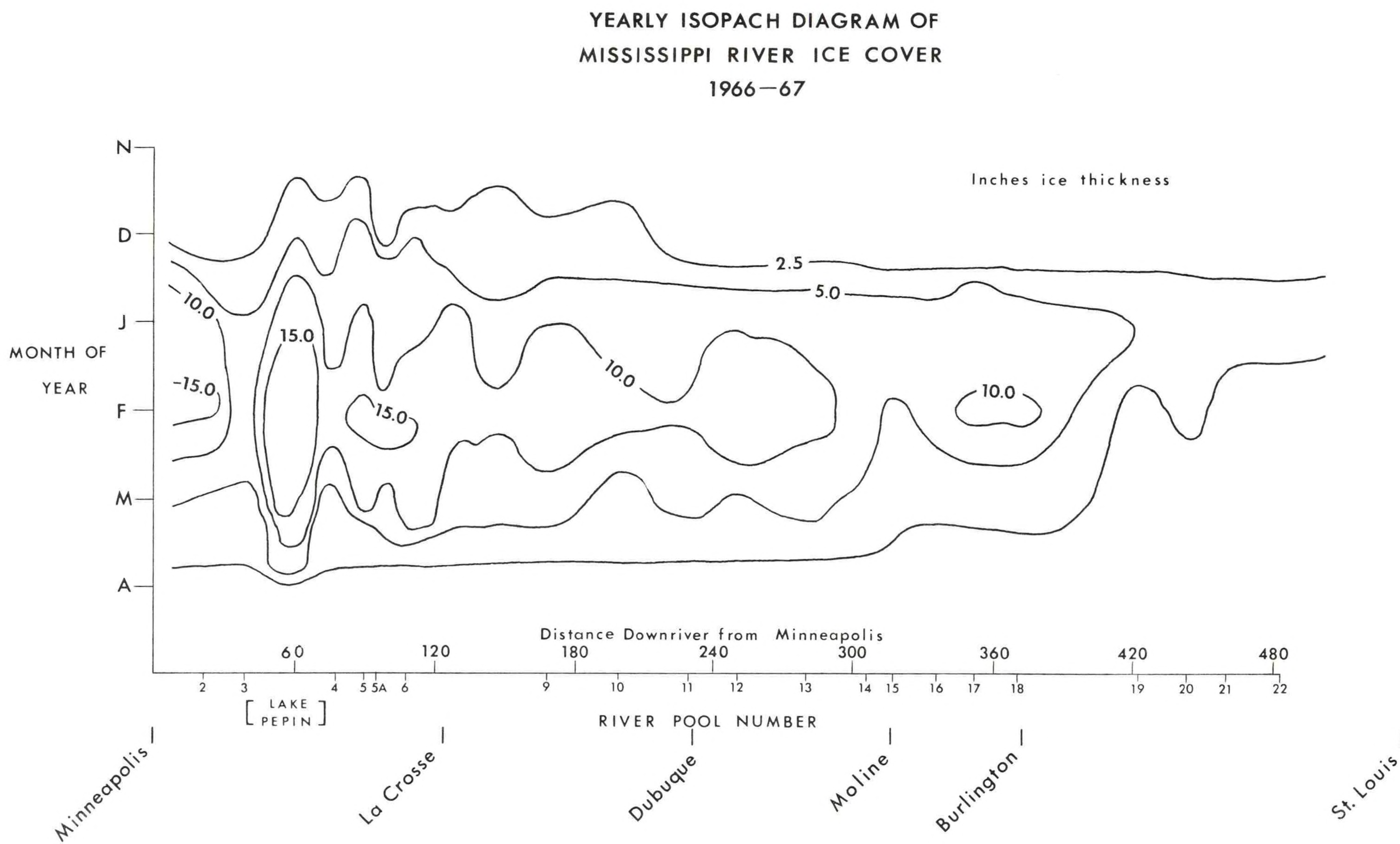

YEARLY ISOPACH DIAGRAM OF
MISSISSIPPI RIVER ICE COVER
1966—67
Inches ice thickness
N
D
J
F
M
A
MONTH OF
YEAR
2.5
5.0
10.0
15.0
-15.0
10.0
15.0
10.0
Distance Downriver from Minneapolis
60
120
180
240
300
360
420
480
2
3
4
5
5A
6
9
10
11
12
13
14
15
16
17
18
19
20
21
22
LAKE PEPIN
RIVER POOL NUMBER
Minneapolis
La Crosse
Dubuque
Moline
Burlington
St. Louis

Figure 28

YEARLY ISOPACH DIAGRAM OF MISSISSIPPI RIVER ICE COVER 1967—68

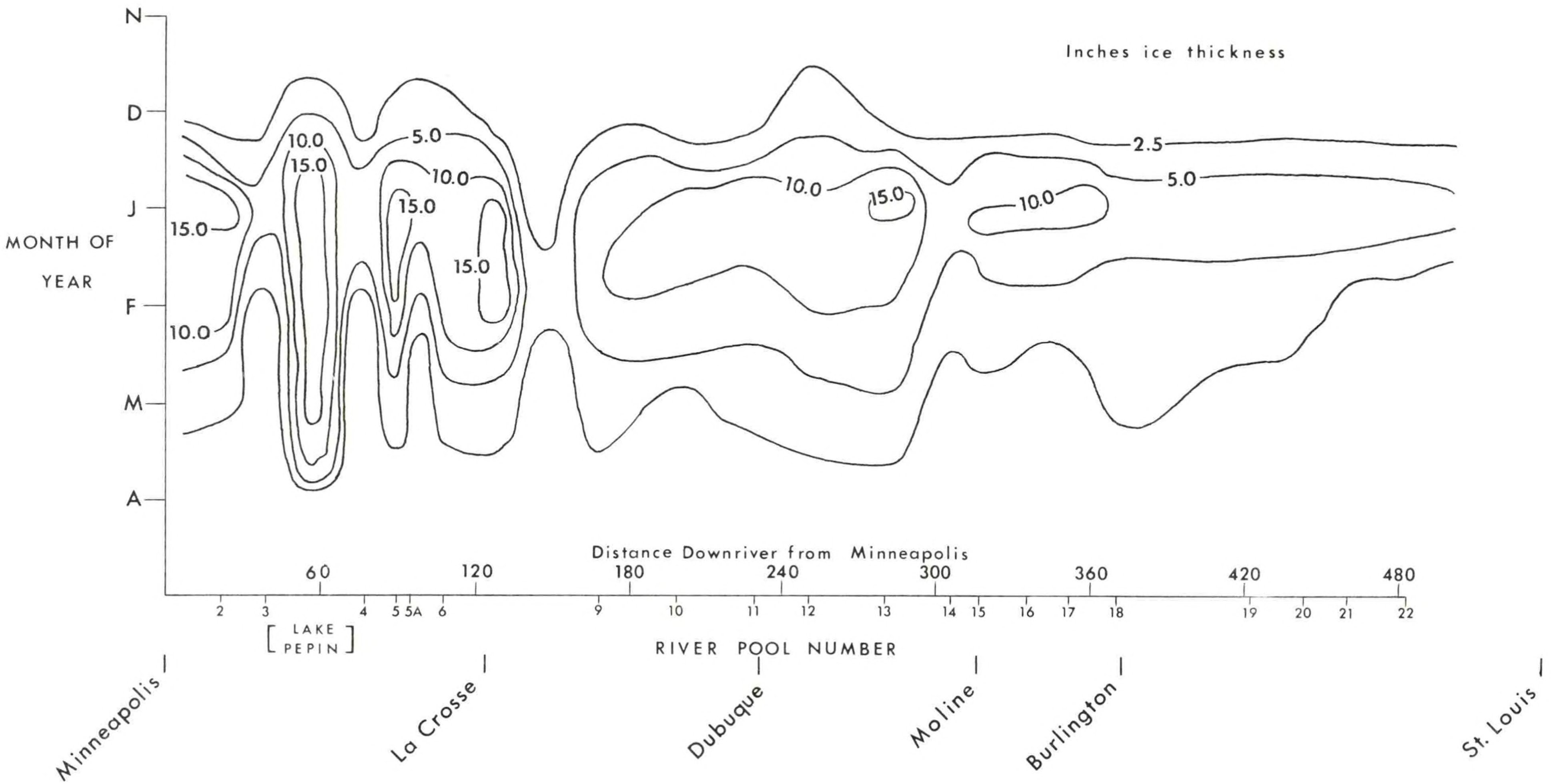
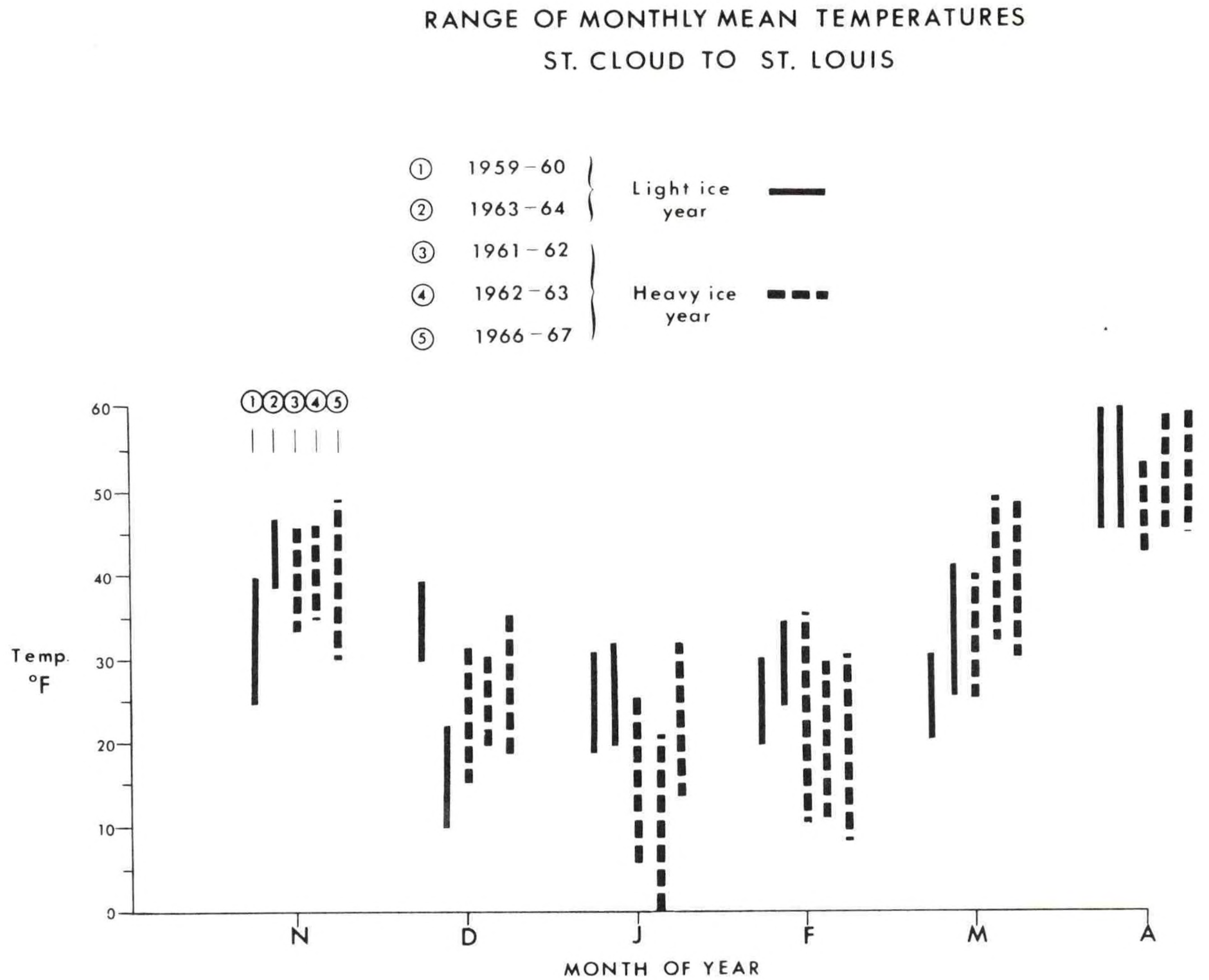


Figure 29



Monthly Temperature Ranges Along The Mississippi River Transect (°F)

Year	Nov.	Dec.	Jan.	Feb.	March	April	
1959-60	25-39	30-39	18-31	20-30	20-30	46-59	
63-64	38-47	10-23	20-33	24-34	26-42	47-59	
Mean	31-43	20-31	19-33	21-32	23-36	46-59	Light Ice
1961-62	33-46	16-32	7-26	12-37	25-40	42-53	
62-63	35-47	19-31	0-21	12-29	34-49	47-58	
66-67	30-49	18-36	14-33	8-31	30-48	45-59	
Mean	32-47	17-33	7-26	10-32	26-45	45-56	Heavy Ice

Figure 30