NOAA Technical Memorandum ERL GLERL-47

DEPARTMENT OF COMMERCE
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FORECASTING ICE-COVER FREEZE-UP, GROWTH, AND BREAKUP ON THE ST. MARYS RIVER

Great Lakes Environmental Research Laboratory
Ann Arbor, Michigan
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FORECASTING ICE-COVER FREEZE-UP, GROWTH, AND BREAKUP ON THE ST. MARYS RIVER*

Gordon M. Greene

A 10-year time series of meteorological variables, water temperatures, and ice observations was used to develop methods for the prediction of ice-cover formation, growth rates, and decay at five sites along the St. Marys River, the channel connecting Lake Superior and Lake Huron. A site-specific heat transfer coefficient and observed water temperatures at Sault Ste. Marie, Mich., can be used to predict ice-cover formation. Standard errors in the predictions at the five sites are 30- to 60-percent lower than the corresponding standard deviations of the observations. A simple Stefan relationship with an average standard error of 8 cm over the season can be used to simulate ice-cover growth. Unlike the ice formation prediction method, ice growth prediction is quite sensitive to the accuracy of the air temperature forecasts. No one method can be used to predict ice-cover breakup at all five sites. Breakup dates are most strongly correlated with the date at which water temperature rises above 0°C at Sault Ste. Marie. This date, however, can be less than 1 week prior to breakup at some sites or may occur after breakup. Maximum ice-cover thickness in the river and maximum ice-cover extent on Lake Superior are both poor predictors of the breakup date.

1. INTRODUCTION

The purpose of this report is to describe methods of forecasting ice events at a number of sites on the St. Marys River. These events include ice-cover formation, growth, and breakup. Because the river is used for shipping and power generation, the quality and lead-time of ice forecasts is of considerable concern. For example, the need for breakup forecasts is illustrated by table 1, which compares the official opening date of the St. Marys River with the last date in each season that icebreaker assistance was needed for ships traversing Whitefish Bay at the upstream end of the river and the river itself. Notice that there can be a need for assistance more than 3 weeks past the opening date. Some foreknowledge of the expected breakup time would simplify icebreaker operations.

The following definitions of forecasting and of the ice events to be forecast will help to clarify the purpose of this report. The terms "freeze over" and "freeze-up" are used synonymously and refer to the date upon which the river channel at a certain point has a solid ice cover roughly 5-cm thick. Although there may have been previous skim ice formation, it is

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TABLE 1.--*St. Marys River opening dates*

Season	Official opening date	Last date that icebreaker assistance was needed	
		St. Marys River	Whitefish Bay
1971-72	Apr. 1	Apr. 10	Apr. 10
1972-73	Apr. 1	Mar. 28	Mar. 28
1973-74	*	Apr. 2	Apr. 2
1974-75	*	Apr. 23	Apr. 21
1975-76	*	Apr. 12	Apr. 14
1976-77	*	Apr. 17	Apr. 17
1977-78	*	Apr. 24	Apr. 24
1978-79	Mar. 24	Apr. 14	Apr. 16
1979-80	Mar. 24	Apr. 17	Apr. 7
1980-81	Mar. 24	Apr. 1	Apr. 10

*River kept open as part of Winter Navigation Demonstration Program.

after the freeze-up date that ice grows and generally remains solid until breakup.

The term "breakup" refers to both the period from maximum ice thickness to ice-free conditions and to a single date at a site after which the river remains ice-free. The context makes clear which is being discussed. Allen (1977) discusses a more elaborate set of defining criteria, but the required data are not available for the St. Marys River sites.

Few portions of the river are monitored continuously; hence, the use of a single date is misleading. Available data were analyzed, however, to narrow the gap of uncertainty as much as possible. For example, to determine breakup it was necessary to find the last evidence of ice presence and the first evidence of ice absence. The date of breakup was then assigned as the midpoint of this period. In many cases, this period is a genuine phenomenon and not just an artifact of insufficient observations. Freeze-up and breakup are transitional processes, taking place over the course of a few days rather than in one discrete jump.

The term forecast is used here as synonymous with prediction. Based on present knowledge, one is computing the amount of elapsed time expected for a given system to achieve a given state. The degree of sophistication in forecasting techniques ranges from the integration of the set of hydrodynamic and thermodynamic equations describing the processes in the air and water to the experience of an ice fisherman who unconsciously interprets ice texture and color.

Because of the limitations of the available data, the techniques described in this report are primarily empirical, although the freeze-up and growth techniques have a theoretical base to justify their use. The freeze-up forecast technique is an adaptation of a water temperature decay method developed by Bilello (1964). This technique depends on the computation of a site-specific heat transfer coefficient. The growth forecast technique is based on the simple Stefan solution to the growth of ice as a function of the temperature gradient in an existing ice sheet (Michel, 1971). It requires the forecast of air temperature. Finally, the breakup techniques are a collection of linear regression equations relating certain ice-cover characteristics to the time of breakup. The validity of these techniques are a direct function of the quality of the data used to generate them. Thus, they are a first approximation, but their use will lead to improved data gathering and analytic techniques.

Before describing the data sets and techniques in detail, a brief summary of ice conditions along the St. Marys River can be given. Further information is provided in Brazel (1971). Figure 1 shows the St. Marys

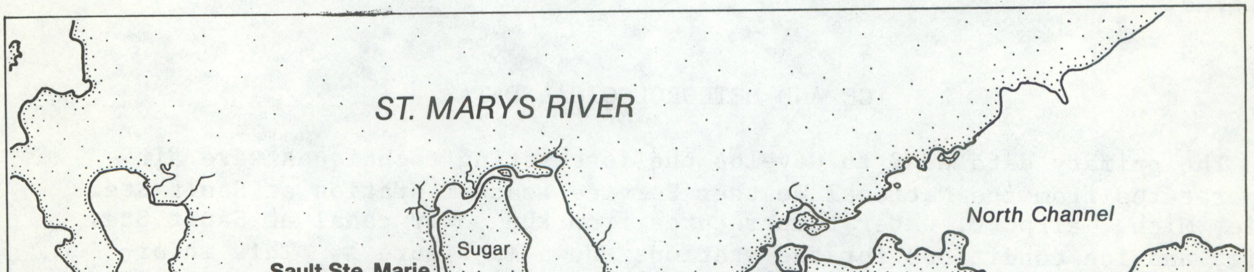


FIGURE 1.--*Study stations on St. Mary's River for data collection and the forecasting of ice-cover events.*

River, connecting Lake Superior and Lake Huron. Specific sites chosen for forecasts are identified by a station name and number that corresponds to those assigned during the U.S. Lake Survey ice thickness measurement program (Sleator, 1978). Because of differences in data availability, there is not a site-specific freeze-up, growth, and breakup technique for all eight stations.

Generally speaking, freeze over first occurs in Lake Munuscong (mean date, December 17) and Raber Bay (mean date, December 21). The next site to freeze over is Mosquito Bay (mean date, January 2). (January 2 is also the mean date of water temperature dropping to 0°C at Sault Ste. Marie, Mich.) The last sites to freeze over are in the faster reaches of the river at stations 402 and 403 (mean date, January 12) and station 401 (mean date, January 13). The mean date of maximum ice thickness ranges from February 25 at station 401 to March 16 at station 302.

The pattern of mean dates for ice-free conditions at the stations studied generally reverses the freeze over trend. Stations 401 (March 25) and 402 (March 30) are the earliest to clear. Next is 302 on April 19, then 108 on April 21, and finally 303 on April 24. It should be remembered that these are all mean dates; in any given season, the pattern of growth and decay may vary. The distance between Mosquito Bay and Raber Bay is less than 60 km, however, so the temperature effect of any one weather system will be felt almost simultaneously. The two factors that primarily distinguish one station from another are current velocity and snowfall patterns.

2. ICE AND METEOROLOGICAL DATA

The primary data used to develop the forecasting techniques were air temperatures from the National Weather Service weather station at Sault Ste. Marie, Mich., airport, water temperatures from the power canal at Sault Ste. Marie, and ice conditions for the stations shown in figure 1. This information is summarized in this section. Copies of the data are available from the author.

The temperature of the river water at Sault Ste. Marie is an indicator of the rate at which the river is cooling. As shown in the bottom portion of figures 2a-n, the water cools roughly 12° to 15°C between October 1 and January 1. The mean date at which the water cools to 0°C (and remains at 0°C) is January 2, although the date ranges from December 6 to January 20.

The upper diagram in figures 2a-n shows the relation between observed mean daily air temperatures and the 30-yr (1941-70) normal. There are two important points that need clarification in dealing with this air temperature data: the applicability of Sault Ste. Marie air temperature to the entire river, and the use of temperature normals.

Although six of the eight forecast sites are located within 15 km of Sault Ste. Marie, one could question the extension of this air temperature to stations 302 and 303. To justify such a use, mean monthly air

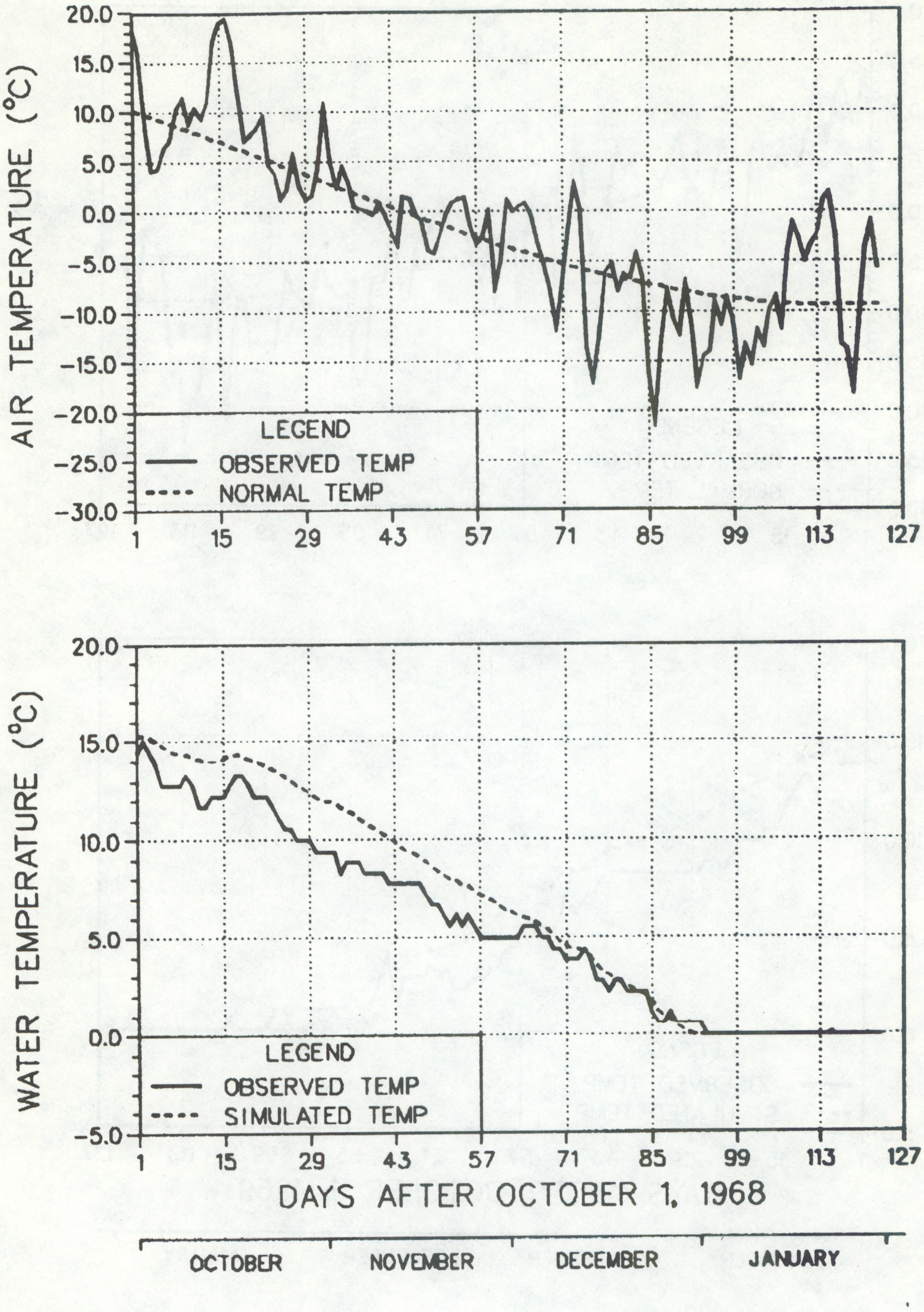


FIGURE 2a.--*Winter season air temperatures and water temperatures at Sault Ste. Marie, 1968.*

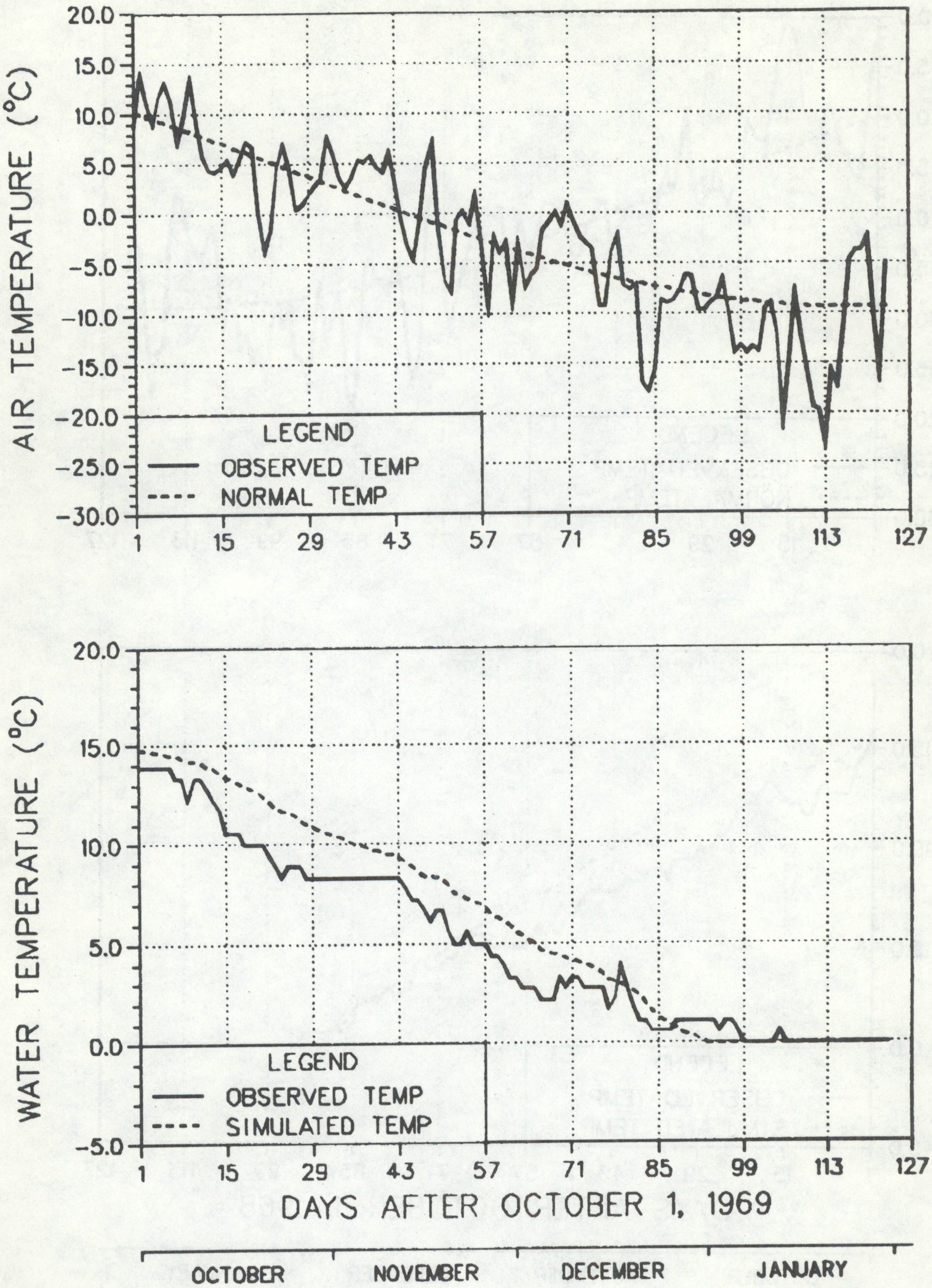


FIGURE 2b.--*Winter season air temperatures and water temperatures at Sault Ste. Marie, 1969.*

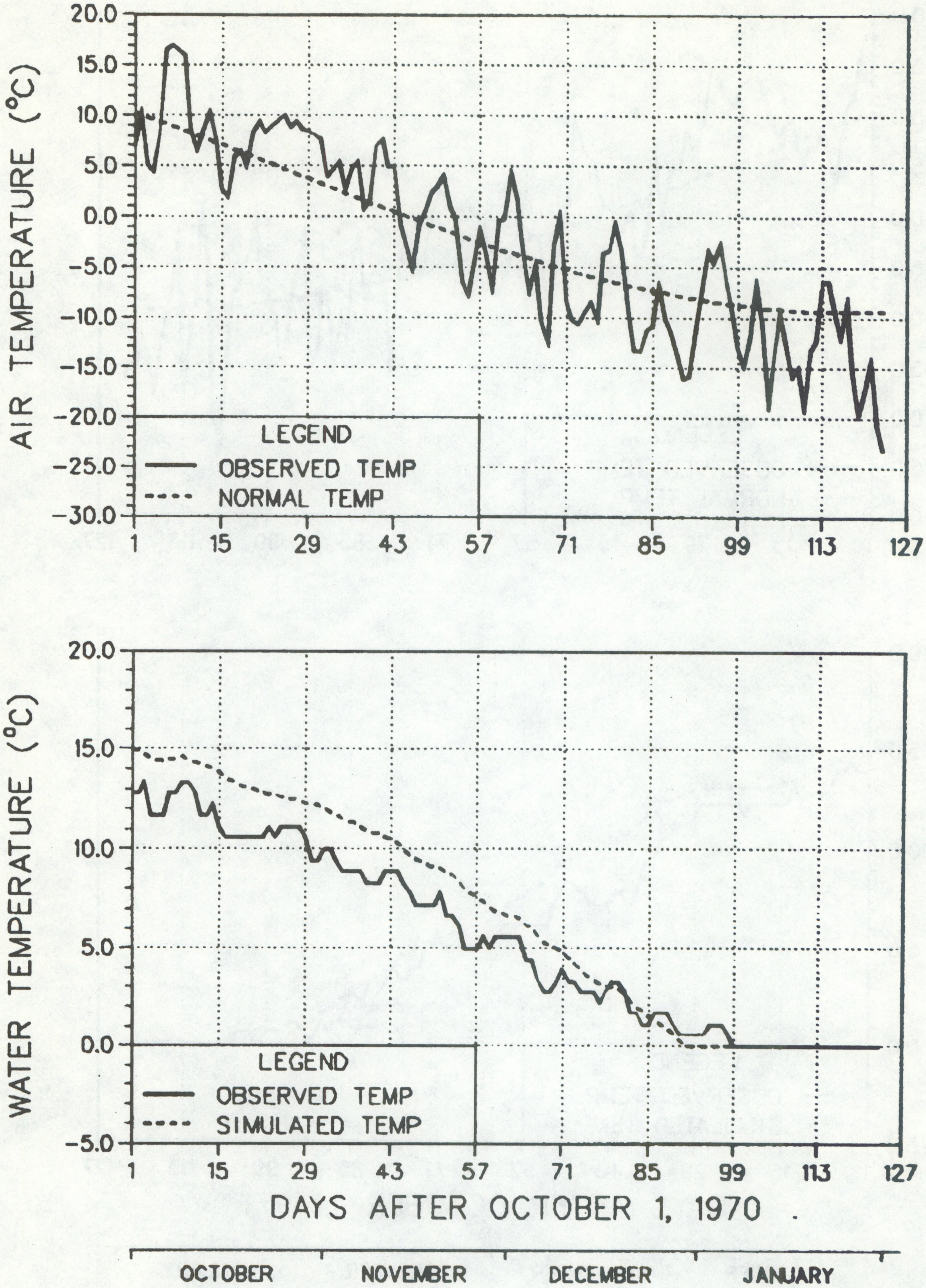


FIGURE 2c.—*Winter season air temperatures and water temperatures at Sault Ste. Marie, 1970.*

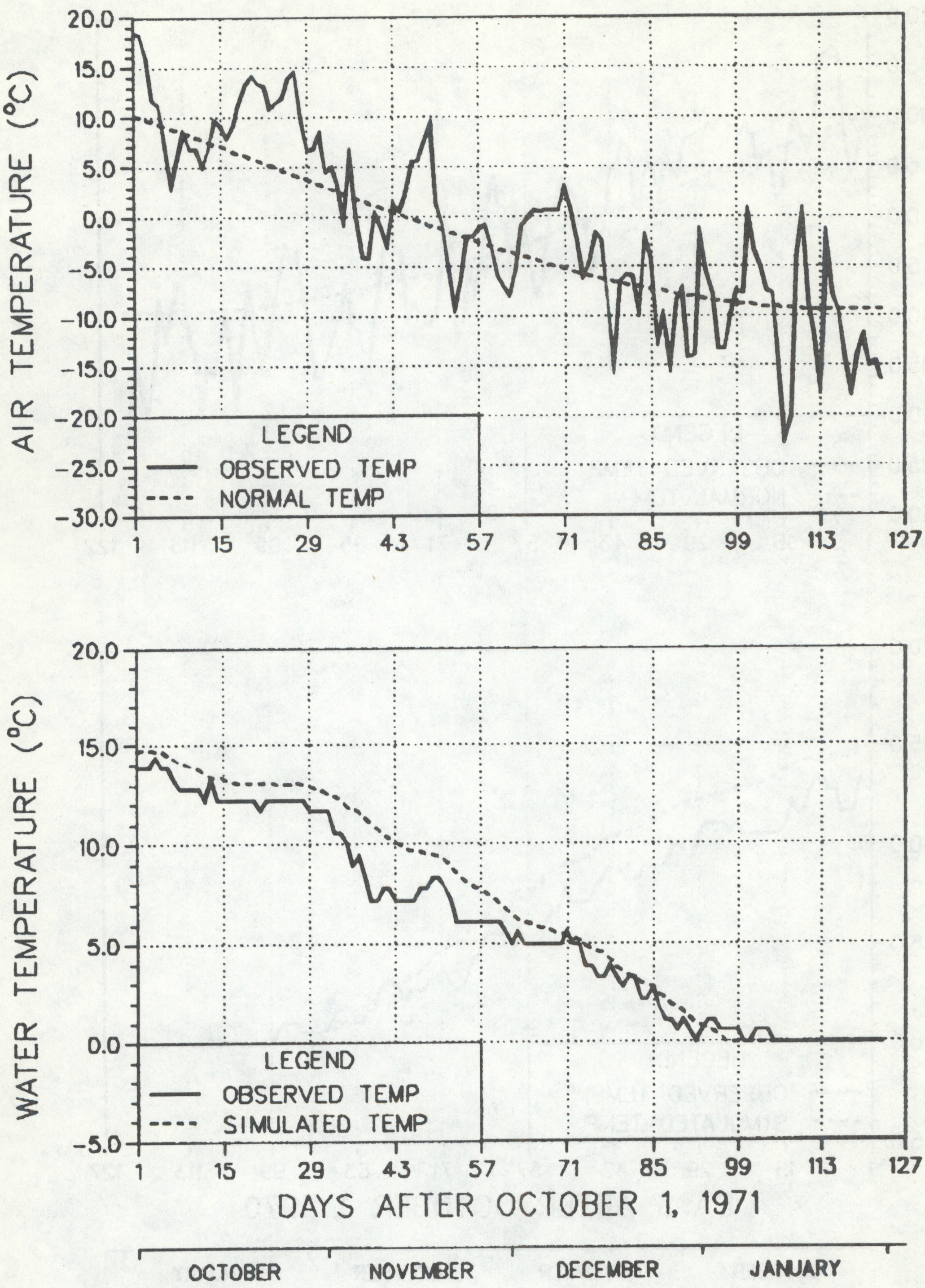


FIGURE 2d.--*Winter season air temperatures and water temperatures at Sault Ste. Marie, 1971.*

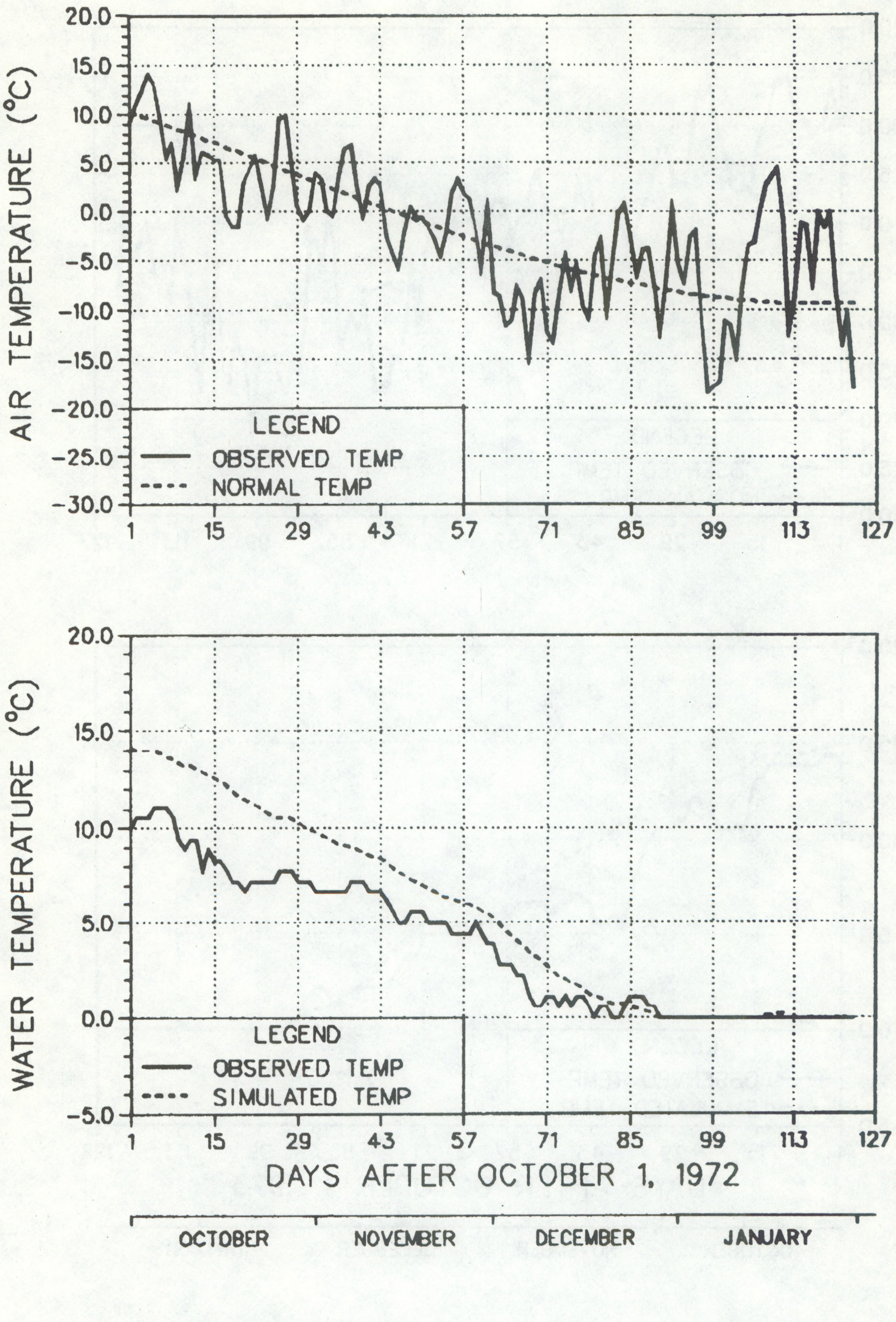


FIGURE 2e.--*Winter season air temperatures and water temperatures at Sault Ste. Marie, 1972.*

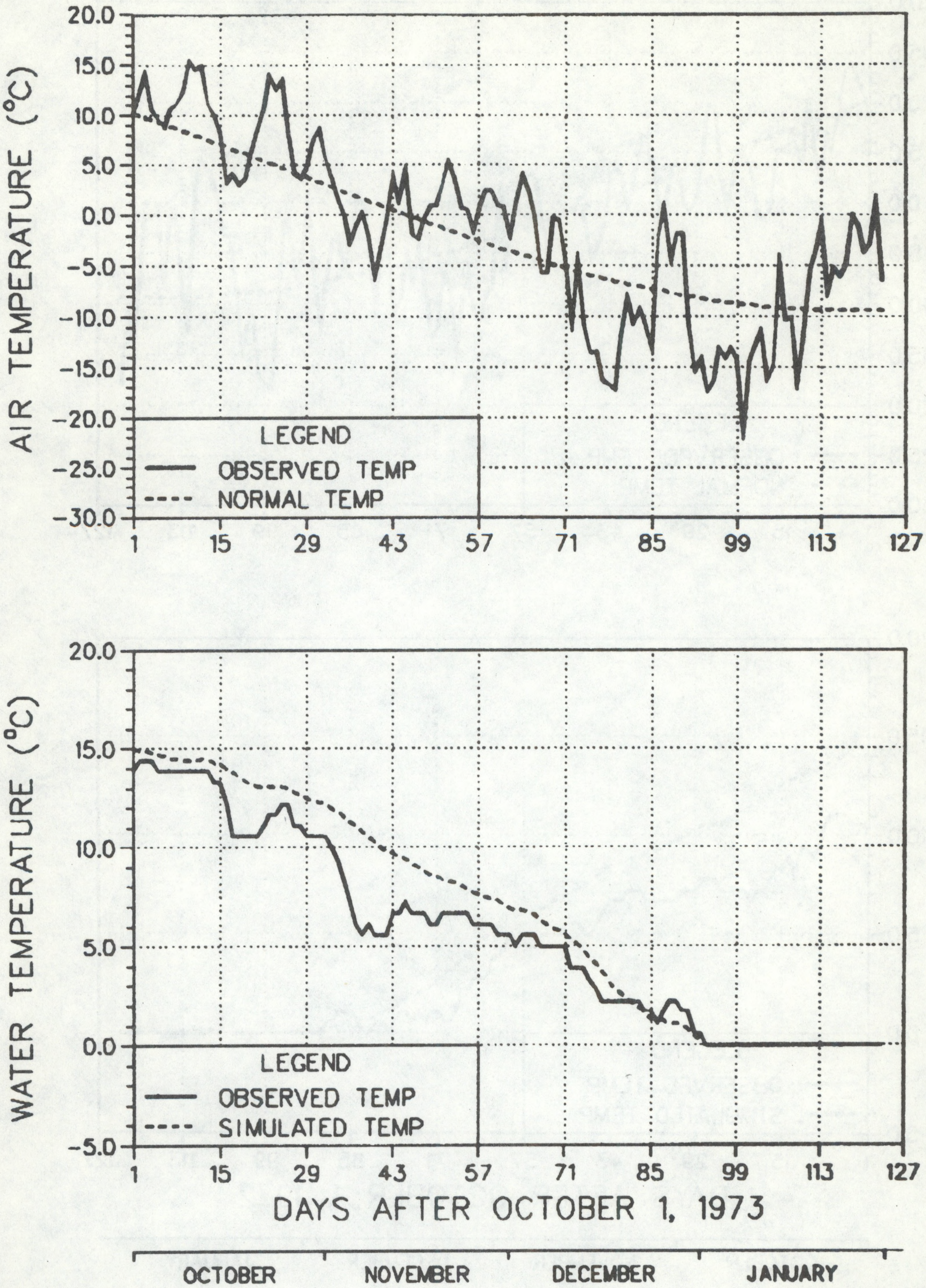


FIGURE 2f.--*Winter season air temperatures and water temperatures at Sault Ste. Marie, 1973.*

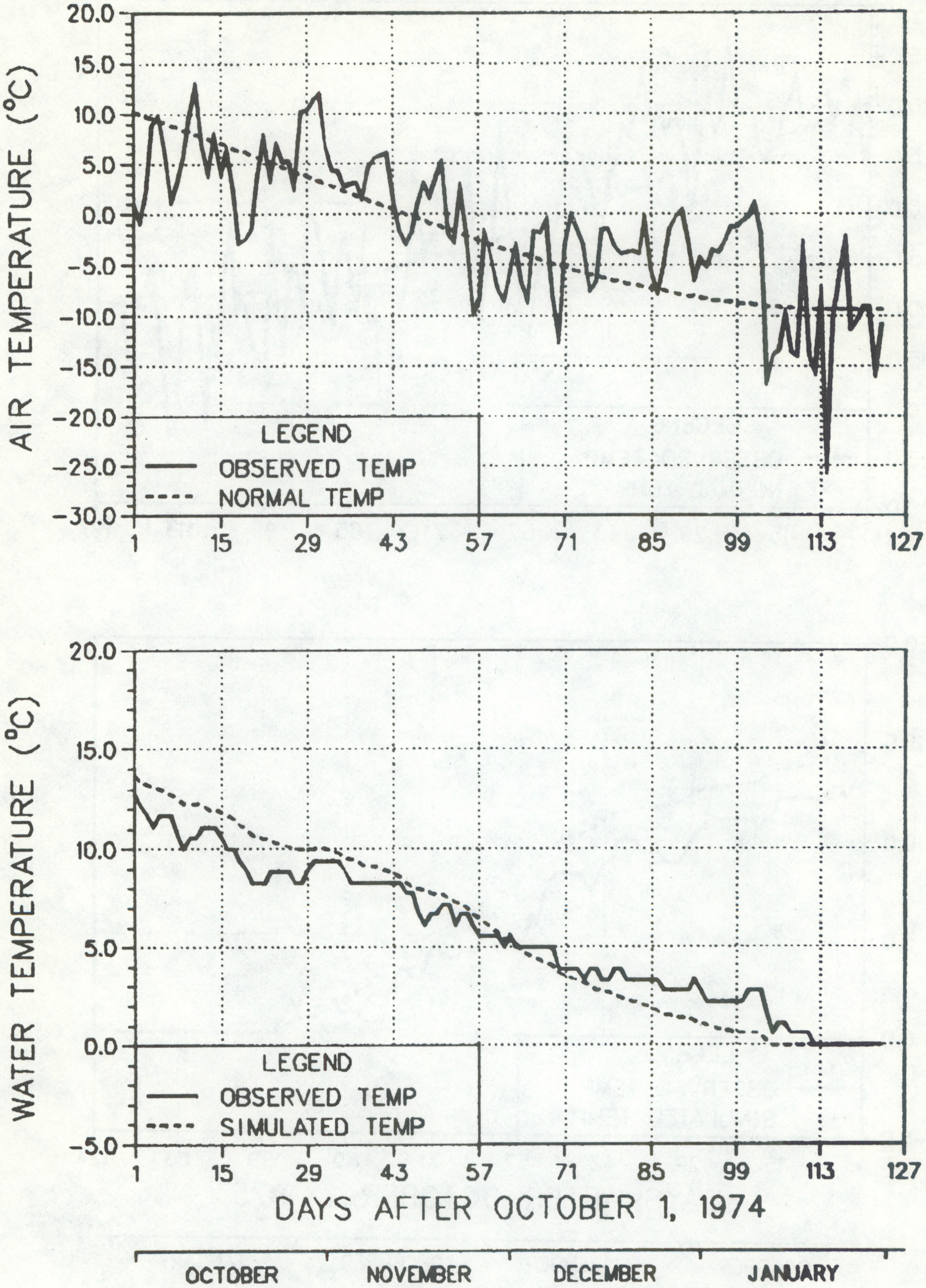


FIGURE 2g.--*Winter season air temperatures and water temperatures at Sault Ste. Marie, 1974.*

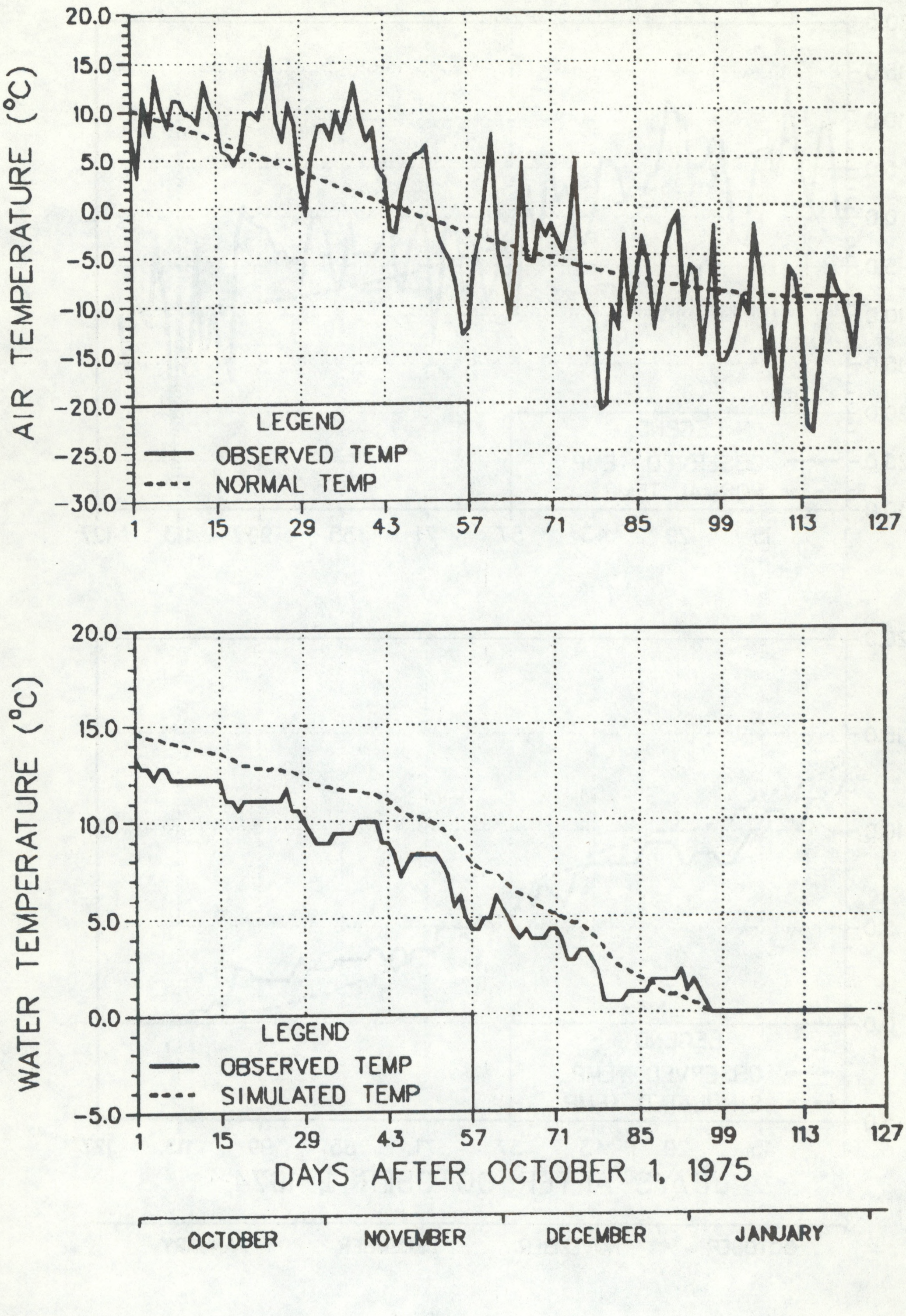


FIGURE 2h.--*Winter season air temperatures and water temperatures at Sault Ste. Marie, 1975.*

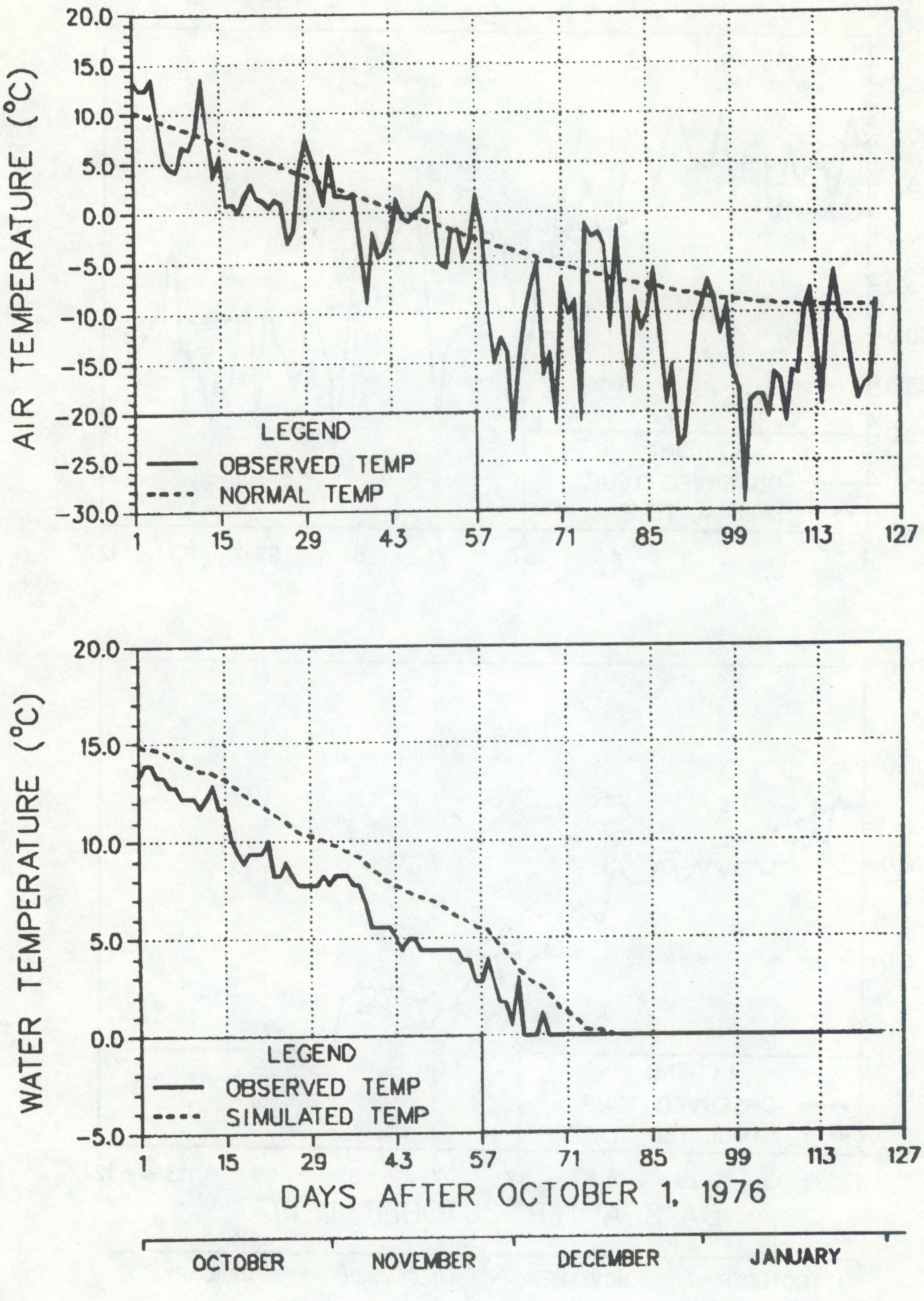


FIGURE 2i.--*Winter season air temperatures and water temperatures at Sault Ste. Marie, 1976.*

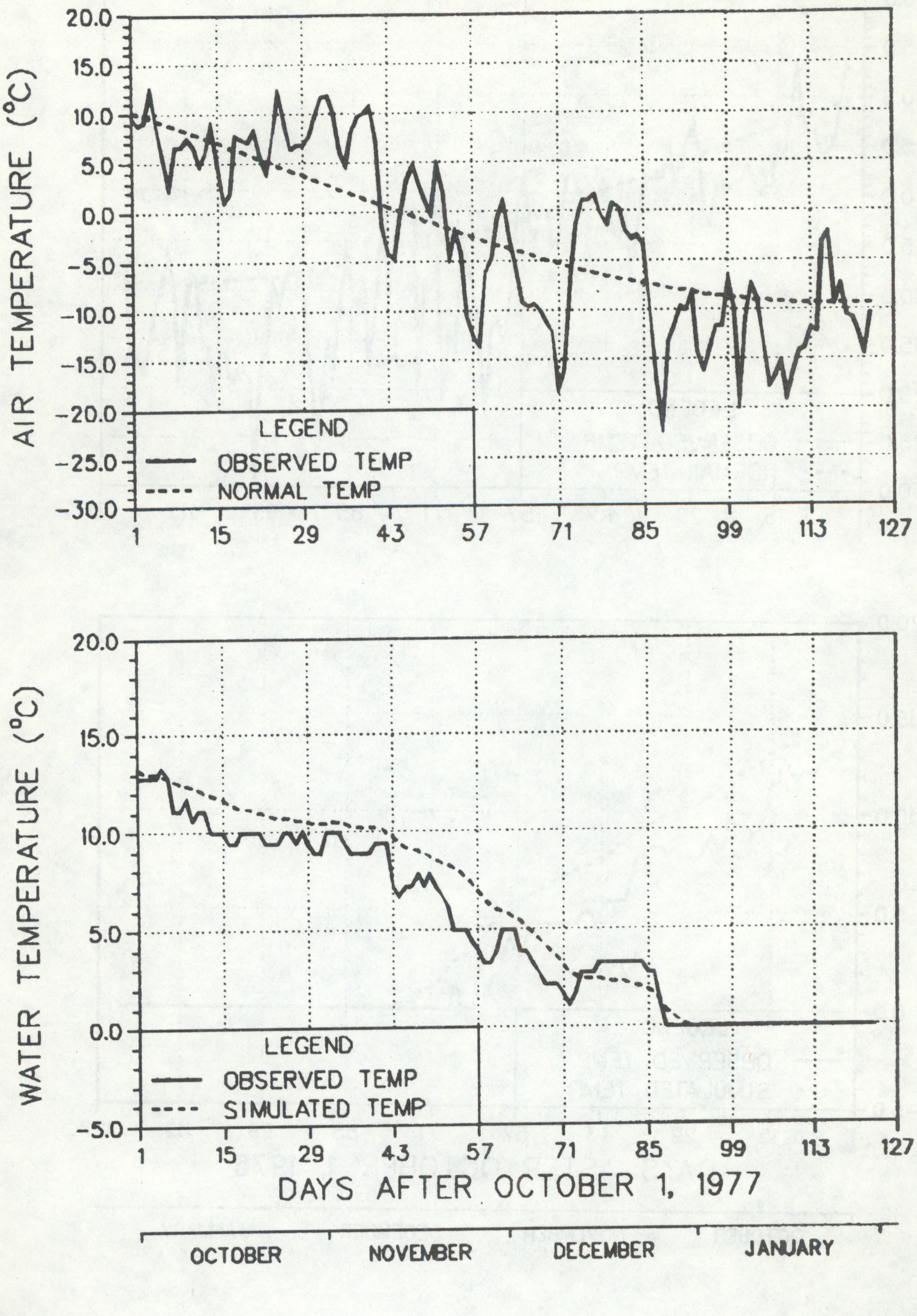


FIGURE 2j.--*Winter season air temperatures and water temperatures at Sault Ste. Marie, 1977.*

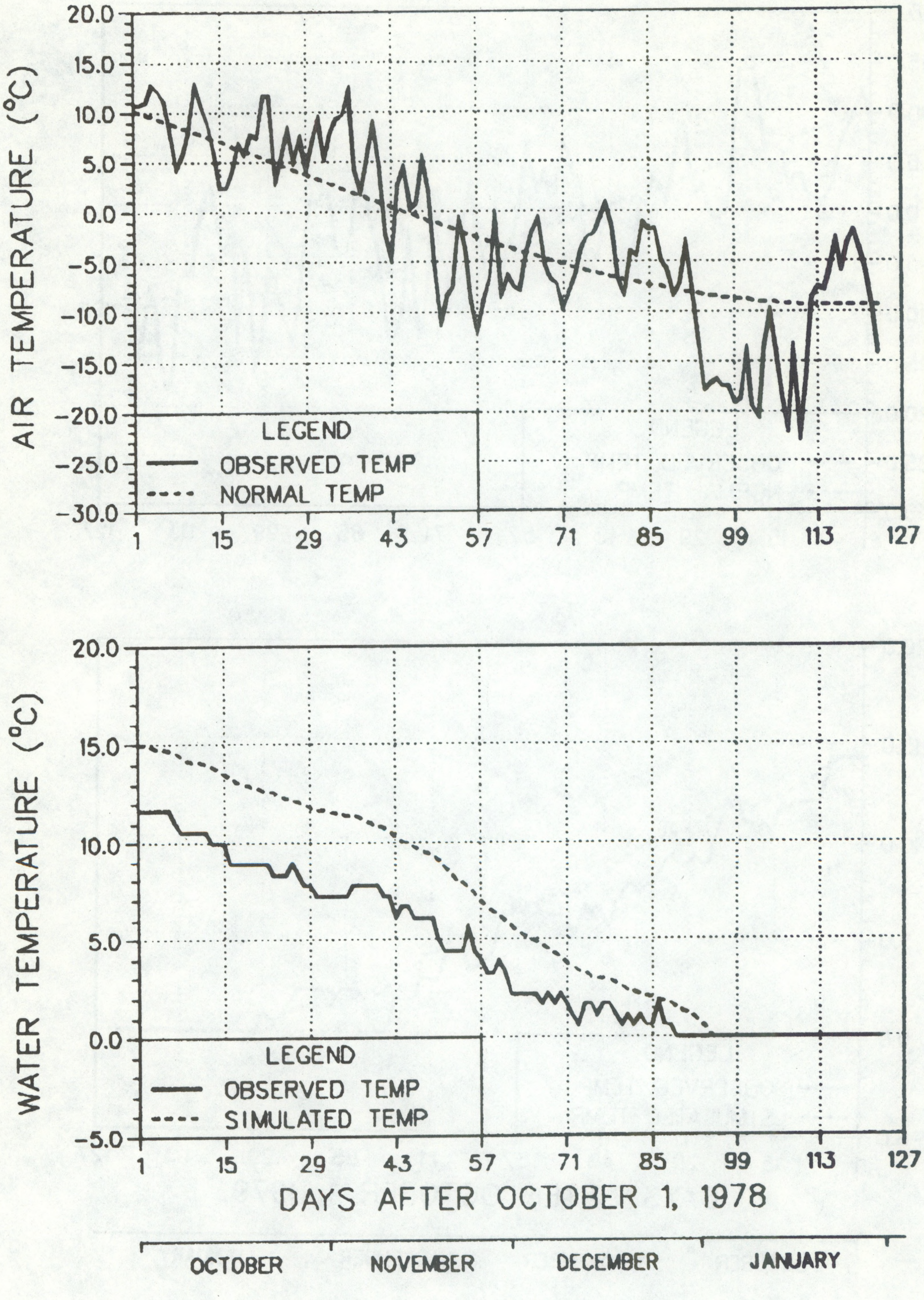


FIGURE 2k.--*Winter season air temperatures and water temperatures at Sault Ste. Marie, 1978.*

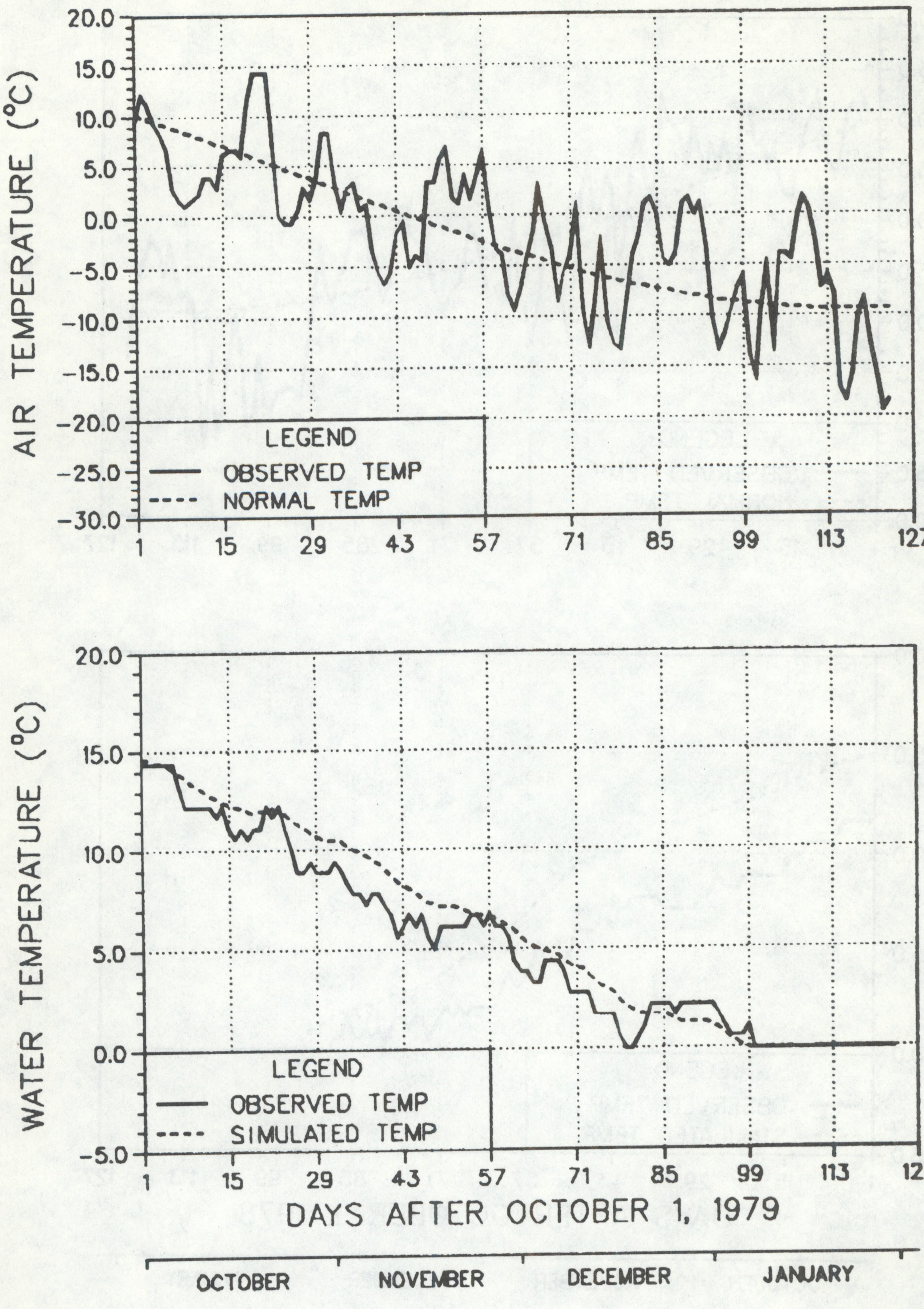
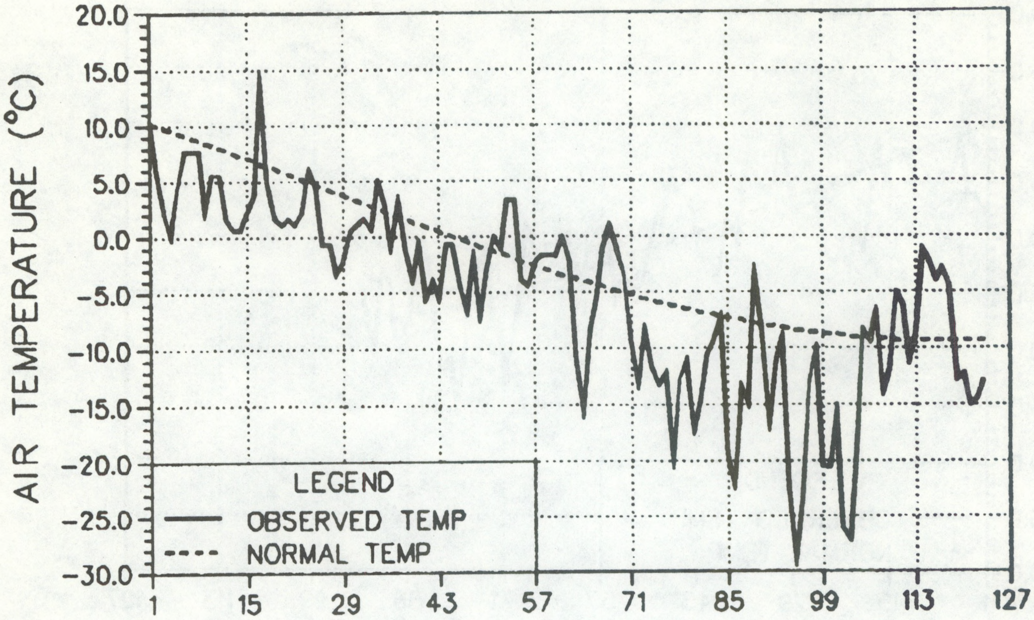


FIGURE 21.--*Winter season air temperatures and water temperatures at Sault Ste. Marie, 1979.*



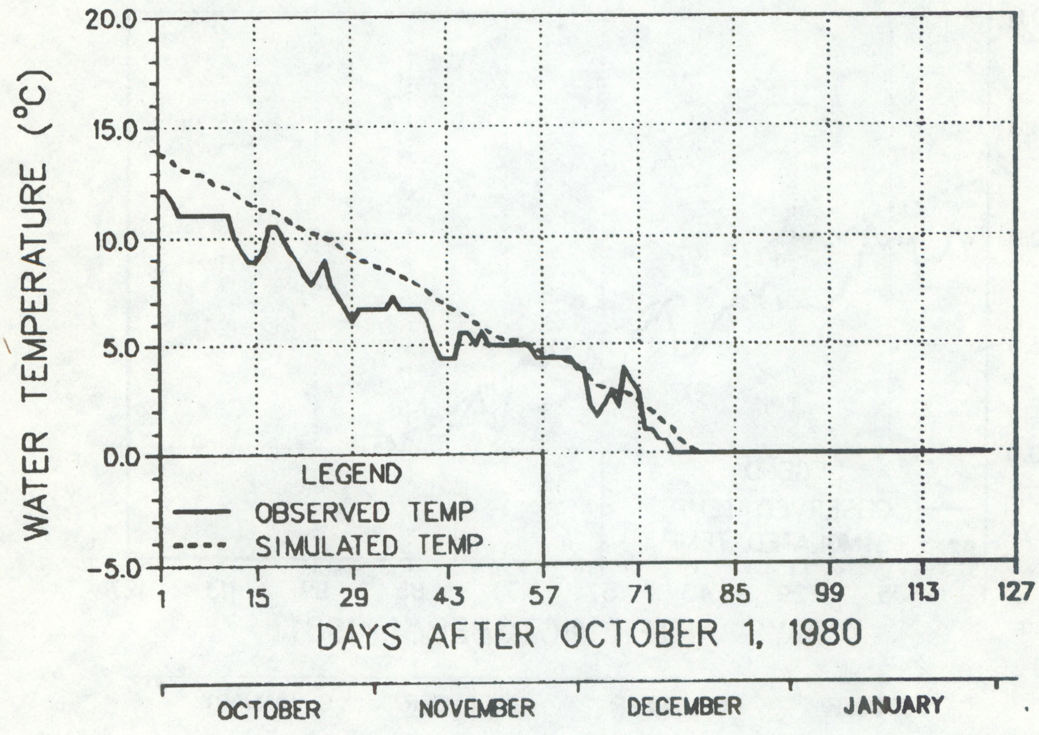


FIGURE 2m.--*Winter season air temperatures and water temperatures at Sault Ste. Marie, 1980.*

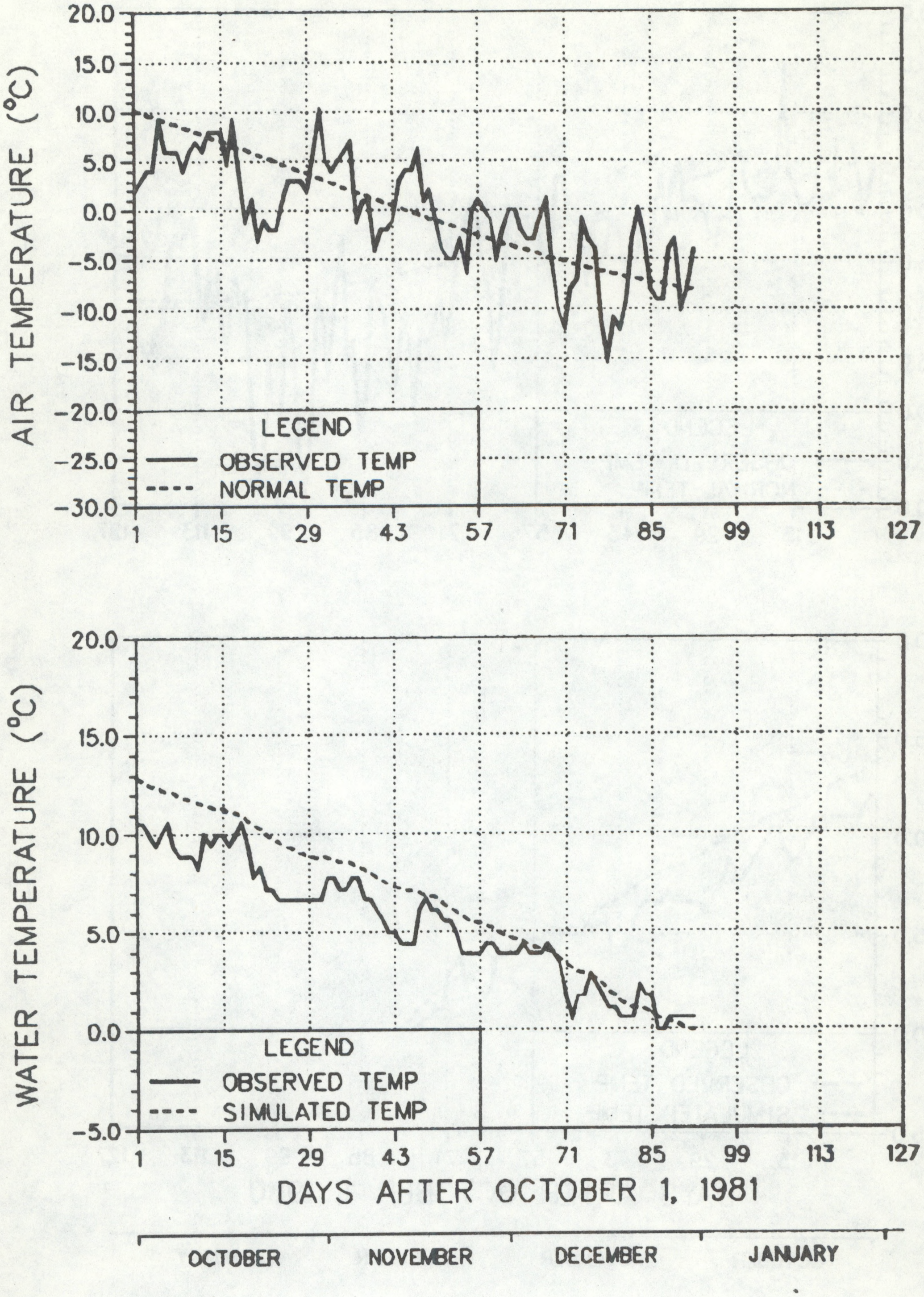


FIGURE 2n.--*Winter season air temperatures and water temperatures at Sault Ste. Marie, 1981.*

temperatures from November 1971 to April 1977 for Sault Ste. Marie, Dunbar, Mich., and De Tour Village, Mich., were compared. The stations are highly correlated: $r^2 = 0.98$ for Sault Ste. Marie and Dunbar and $r^2 = 0.95$ for Sault Ste. Marie and De Tour Village. A paired-t test of the station means shows that Sault Ste. Marie and Dunbar temperatures are not significantly different at the 95-percent confidence level. Station means for De Tour Village are significantly warmer than those at Sault Ste. Marie, but only by 1°-2°C. For the purposes of this study, such a difference was not judged significant in light of uncertainties concerning the rest of the data.

Part of the forecasting technique is to project expected departures from "normal" air temperatures. There are a number of "normals" available, however. Table 2 lists the mean monthly temperatures from two different data sets. The first set is derived from the mean daily air temperatures for the period 1897-1977 (Assel, 1980). The second set is the standard 30-yr normal used by the National Climatic Center.

For the purposes of this study, the standard 30-yr mean was chosen. This normal can be represented by extracting the first harmonic from the data (Davis, 1973). The formula for simulating the normal daily temperature (°C) at Sault Ste. Marie for Julian date "D" takes the form:

$$T_a = 4.45 + [-12.6 \ \mathrm{COS}(2\pi D/365) - 5.8 \ \mathrm{SIN}(2\pi D/365)] \qquad (1)$$

TABLE 2.--*Sault Ste. Marie monthly mean air temperatures*

Month	Mean monthly temperature computed from mean daily temperatures 1897-1977 (°C)	Mean monthly temperature computed from mean daily temperatures 1941-70 (°C)	Average daily standard error of 30-yr harmonic vs. 80-yr daily (°C)
Oct.	7.6	7.9	1.0
Nov.	0.4	0.4	1.0
Dec.	-6.5	-6.6	0.7
Jan.	-9.9	-9.6	1.5
Feb.	-10.2	-9.3	1.9
Mar.	-4.7	-4.4	1.0
Apr.	3.1	3.4	1.4

The first harmonic accounts for 99.6 percent of the variance found in the original data. It is this equation that was used to compute the normal air temperature curves shown in the upper portion of figures 2a-n.

Because the forecasting techniques are semiempirical, it is important to recall that the values of any coefficients derived from the data are a function of the climate during the period of observation. Table 3 can be used to judge the severity of winters from 1968-69 to 1977-78 by examining a number of severity indexes. As one would expect, the extremes tend to

TABLE 3.—*St. Marys River winter severity*

Season	Maximum FDD (°C)	Mean date of freeze*	Mean date of breakup*	Season duration (days)	Mean maximum thickness (cm)	Maximum extent of ice cover on Lake Superior (%)
1968-69	939	-	Apr. 7	-	44	40
1969-70	1209	-	Apr. 3	-	49	80
1970-71	1192	Jan. 6	Apr. 21	105	59	48
1971-72	1149	Jan. 9	-	-	62	95
1972-73	749	Dec. 23	Mar. 25	92	49	55
1973-74	1075	Dec. 28	Apr. 17	110	53	70
1974-75	931	Jan. 19	Apr. 18	89	42	30
1975-76	1014	Jan. 3	Apr. 5	92	43	40
1976-77	1291	Dec. 7	Apr. 7	121	56	83
1977-78	1143	Jan. 3	-	-	49	82
1978-79	1228	-	-	-	-	100
1979-80	914	-	-	-	-	75
1980-81	1102	-	-	-	-	92
1981-82	1231	-	-	-	-	97

*Based on stations 108, 302, 303, 401, and 402 and the date that Sault Ste. Marie water temperature becomes 0°C.

cluster in certain seasons, but notice that there is a temporal character as well. For example, the 1972-73 season had the lowest accumulated degree-days and the earliest mean date of breakup. The mean date of freeze over, however, was nearly 1 month earlier than freeze over for the mild 1974-75 season. The 1972-73 season could be characterized as mild because the ice cover formed early and ended early, with warmer-than-normal air temperatures. The 1974-75 season, on the other hand, could be characterized as mild because it started late and ended late, with air temperatures only slightly cooler than those in the 1972-73 season.

This next section summarizes the freeze over, breakup, and ice thickness data described later in the report. Table 4 lists the dates of freeze over for stations 108, 302, and 303; the date at which an "unsafe cover" was observed at stations 401, 402, and 403; and the date when water temperature at Sault Ste. Marie dropped to (and remained at) 0°C. The data for stations 108, 302, and 303 were taken from Sleator (1978), a report listing the U.S. Lake Survey ice thickness and stratigraphy measurements for 30 nearshore stations around the Great Lakes. Freeze over dates were determined by computing that date halfway between the last observation of no ice and the first observation of a solid ice cover that would remain for the season. A date was not identified in those cases where the interval between those two observations was greater than 2 weeks. Additionally, during some years ice observations were not made at all until a solid cover had formed. In these cases it was not possible to determine a starting date.

Freeze over data for stations 401, 402, and 403 were taken from a Corps of Engineers report (U.S. Army Engineers, Detroit District, 1980). Freeze over dates were identified as the midpoint between an open water observation and an observation of an unsafe cover (or a measured thickness). These observations were taken at weekly intervals.

The same Corps of Engineers report presents ice observations for three additional sites, East Center Pier, Pittsburg Dock, and Head of Little Rapids. These sites were not included in this study because they had fewer than six winters with identifiable freeze over and breakup dates. Presumably, the winters when open water or unsafe cover existed throughout were those during which the Winter Navigation Demonstration Program was in operation.

Table 5 presents breakup dates at the same stations as in table 4 (with one exception) and the date upon which water temperatures at Sault Ste. Marie rise (and remain) above 0°C. Breakup dates were not computed for station 403 because observations of open water were not noted in the Corps of Engineers report giving data for that station.

Table 6 summarizes the ice thickness data for stations 108, 302, and 303 (Sleator, 1978); for stations 401, 402, 403 (U.S. Army Corps of Engineers, 1980); and for stations 501 and 502 at the downstream and upstream sides of the Canadian locks at Sault Ste. Marie. Data for stations 501 and 502 are published annually by Environment Canada; however, they do not contain information on freeze over and breakup.

TABLE 4.--*St. Marys River freeze over dates*

Season	108 Freeze-over	Date SSM T_w* becomes 0°C	401 "unsafe"	402 "unsafe"	403 "unsafe"	302 Freeze-over	303 Freeze-over
1967-68	-	Dec. 27	-	-	-	Nov. 19	Dec. 23
1968-69	-	Jan. 2	-	-	-	-	Dec. 21
1969-70	-	Jan. 7	Jan. 15	Jan. 15	-	-	Dec. 16
1970-71	Jan. 15	Jan. 7	Jan. 22	-	-	-	Dec. 25
1971-72	-	Jan. 13	Jan. 21	Jan. 21	-	Dec. 26	Dec. 27
1972-73	Jan. 9	Dec. 29	Jan. 9	-	-	Dec. 2	Dec. 1
1973-74	Dec. 30	Jan. 2	Jan. 3	Jan. 3	Jan. 3	Dec. 21	Dec. 17
1974-75	-	Jan. 20	Jan. 23	Jan. 23	Jan. 23	Jan. 13	Jan. 14
1975-76	Jan. 4	Jan. 5	-	Jan. 15	Jan. 15	Dec. 17	Dec. 26
1976-77	Dec. 11	Dec. 6	Dec. 13	Dec. 13	-	Dec. 1	Nov. 26
1977-78	Jan. 2	Dec. 27	Jan. 16	Jan. 11	Jan. 3	Dec. 30	Dec. 26
1978-79	-	Dec. 28	-	-	-	Dec. 29	Dec. 29
1979-80	-	Jan. 8	Jan. 25	Jan. 25	Jan. 18	-	-
Mean date	Jan. 2	Jan. 2	Jan. 13	Jan. 12	Jan. 12	Dec. 17	Dec. 21
Stand. dev.	12.1	10.5	13.3	13.7	9.0	17.1	12.8

*Water temperature.

TABLE 5.--*St. Marys River breakup dates*

Season	108 Ice free	Date SSM T_w > 0°C	401 Ice free	402 Ice free	302 Ice free	303 Ice free
1967-68	-	Apr. 8	-	-	-	Apr. 12
1968-69	Apr. 15	Apr. 9	Mar. 24	Mar. 24	-	Apr. 25
1969-70	Apr. 19	Apr. 20	Mar. 5	-	-	Apr. 26
1970-71	-	-	Apr. 9	Apr. 9*	-	Apr. 24
1971-72	May. 13	May. 1	-	-	Apr. 29	May. 6
1972-73	-	Mar. 23	Mar. 14	Mar. 14*	Apr. 4	Apr. 9
1973-74	Apr. 26	Apr. 21	Mar. 21	Apr. 4*	May. 1	Apr. 28
1974-75	Apr. 20	Apr. 14	Apr. 10	-	Apr. 25	May. 1
1975-76	Apr. 3	Mar. 30	Mar. 26	Apr. 2*	Apr. 19	-
1976-77	-	Apr. 11	Mar. 22	Mar. 29	Apr. 15	Apr. 21
1977-78	-	Apr. 24	Mar. 28	-	-	-
1978-79	-	Apr. 12	-	Apr. 3	Apr. 6	-
1979-80	-	Mar. 28	-	-	-	-
1980-81	-	Mar. 28	-	-	-	-
Mean Date	Apr. 21	Apr. 11	Mar. 25	Mar. 30	Apr. 19	Apr. 24
Stand. Dev.	13.0	11.7	11.4	8.7	10.7	9.0

*Unsafe cover.

TABLE 6.--*St. Marys River ice-cover thickness*

		Feb. ice thickness (cm)		Max ice thickness (cm)		Date of max	Feb. snow thickness (cm)
Station	n	Mean	SD	Mean	SD	Mean	Mean
108	10	31.0	8.1	42.7	6.9	Mar. 10	7.7
302	11	47.9	11.1	60.1	8.5	Mar. 16	11.8
303	12	49.7	11.3	64.8	9.4	Mar. 13	17.6
401	12	33.7	14.5	43.6	13.8	Feb. 25	NA
402	12	37.2	10.8	49.6	11.2	Mar. 3	NA
403	12	40.0	7.9	50.7	8.5	Mar. 10	NA
501	14	32.3	11.0	44.2	15.8	Mar. 2	7.4
502	16	38.3	12.9	48.4	19.6	Mar. 1	7.7

Two features of the data in table 6 should be noted. The mean maximum ice thickness and mean February snow-cover thickness on the ice tend to increase as one moves downstream. Of additional interest is the high variability of ice thickness at Sault Ste. Marie (stations 501 and 502).

3. FORECASTING FREEZE-UP

Forecasting the formation of ice is equivalent to forecasting the cooling rate of a body of water. In its simplest form, this cooling rate can be expressed as:

$$dT_w/dt = (h/Z_wC)(T_w - T_a), \qquad (2)$$

where T_w is water temperature (°C), t is time (s), h is a heat transfer coefficient (W m^{-2} $°C^{-1}$), Z_w is the depth of convective mixing of the water body (m), C is the volumetric specific heat (J m^{-3} $°C^{-1}$), and T_a is air temperature (°C). The value of "h" is related to the particular microclimate of the forecast site and is thus a function of wind speed, atmospheric moisture content, net radiation, water turbulence, and snowfall prior to freeze-up.

For each site where freeze-up is to be forecast, one needs a value for "h" and the ability to forecast "T_w" and "T_a." The following discussion first concentrates on methods of deriving "h" and then distinguishes between forecasting at Sault Ste. Marie and forecasting at other sites along the river.

The heat transfer coefficient can be computed if one knows the total energy flux (Q_t) leaving the water surface

$$h = Q_t/(T_w - T_a). \tag{3}$$

"Q_t" can be determined either from the individual surface energy fluxes (Paily *et al.*, 1974) or by using a finite difference form of the equation governing observed water temperature decay if "Δt" is sufficiently small:

$$Q_t = (\Delta T_w/\Delta t)(Z_w C). \tag{4}$$

The daily surface energy balance fluxes were computed for the fall seasons 1967-74 at Sault Ste. Marie using "Z_w" equal to 10 m. The mean daily value for the heat transfer coefficient, "h," computed by equation (3) was 1980 kJ m^{-2} day^{-1} (47.3 cal cm^{-2} day^{-1}) with a standard deviation of 645 kJ m^{-2} day^{-1}. Similarly, daily water temperature at Sault Ste. Marie over the same time period was used to compute "Q_t" from equation (4). The corresponding value for "h" was 839 kJ m^{-2} (20.0 cal cm^{-2} day^{-1}) with a standard deviation of 472 kJ m^{-2} day^{-1}.

The disparity between the two values for "h" is large and is not reconciled by using formulations for surface energy fluxes other than those suggested by Paily *et al.* (1974). One reason for the difference must be that water temperatures at Sault Ste. Marie are altered not only by the immediate microclimate but also by the Lake Superior thermal regime.

Both methods of determining "h" were dependent on time series of "T_w" and thus are not directly applicable at sites other than Sault Ste. Marie. One way around this problem has been described in detail by Bilello (1964). Equation (2) is simplified so that the current water temperature can be expressed as a function of the previous day's water temperature and the current air temperature as follows:

$$T_w{}^t = T_w{}^{t-1} + N(T_a{}^t - T_w{}^{t-1}), \tag{5}$$

where

$$N = [1 - \exp(-k\Delta t)], \tag{6}$$

t-1 refers to the previous time interval, and k is a site-specific rate constant.

The value of "N" in equation (6) was derived for a given site for a given year by program GGMAPP3, listed in the appendix. [In the appendix, "N" in equation (6) is labeled "XN."] In this program, an initial estimate for "N" is made, the mean June air temperature is assigned to "T_w^{t-1}" on July 1, and the subsequent values of "T_w^t" are computed as shown in equation (5) for each successive day. If the day upon which the computed "T_w" reaches 0°C is later than that observed, "N" is increased and the process is repeated. Likewise, if "T_w" reaches 0°C too early, "N" is decreased. Note that "T_w" reaching 0°C at all stations other than Sault Ste. Marie is merely a surrogate measure for the formation of an ice cover.

In deriving the "N" value for Sault Ste. Marie, unlike the other sites, it would have been possible to correct computed "T_w" with observed values of "T_w" so that the simulated water temperature curve would match the observed curves in figures 2a-n more closely. Such correction would have been of little value in this study because we do not have ice formation dates at Sault Ste. Marie to actually project ice formation dates there. The fall of water temperatures there is merely a method of tracking the transfer of heat out of the river.

Values of "N" for Sault Ste. Marie, stations 108, 302, 303, and 401, are listed in table 7. The mean Sault Ste. Marie "N" value of 0.0198 is equivalent to a heat transfer coefficient of 840 kJ m^{-2} day^{-1} (20.0 cal cm^{-2} day^{-1}) and the standard deviation over those 13 yr is 127 kJ m^{-2} day^{-1}. Variability in "N" increases in the downstream stations and is most likely related to the difficulty in assigning freeze over dates at these sites because of multiple skim ice events.

Forecasting ice-cover formation at a given site proceeds as follows: Assume that one is starting to issue forecasts as of October 1. Start with the mean June air temperature at Sault Ste. Marie as the July 1 simulated "T_w." Use daily average air temperatures and the mean value for "N" for that station to step through equation (5) on a daily basis until the last date for which you have air temperatures. From this day forward, you need to project air temperatures. Look at the *Monthly and Seasonal Weather Outlook* to find the 30-day forecast for air temperature in the Lake Superior Region. A forecast of below- or above-normal temperatures means that the normal temperature generated by equation (1) needs to be increased or decreased by the class limit published in the *Monthly and Seasonal Weather Outlook*. Continue to use equation (5) to simulate "T_w" until you reach the end of forecast air temperatures. Past this date, use "T_a" computed from equation (1) and continue until "T_w" reaches 0°C. This is the forecast date of ice-cover formation. (See GGMAPP4 in the appendix.)

An example of this process is shown in figures 3 and 4. Figure 3 shows the normal and observed air temperatures during the second half of 1981. Figure 4 shows the forecast date of freeze over (NDAY) as a function of the date the forecast was issued. Comparing the two figures, notice that air temperatures were close to normal through day 241, with the result that NDAY

TABLE 7.--*Bilello coefficients*

Season	SSM $T_w = 0°C$	108	401	302	303
1968-69	0.0182	-	-	-	0.0276
1969-70	0.0168	-	0.0137	-	0.0339
1970-71	0.0173	0.0144	0.0126	-	0.0236
1971-72	0.0177	-	0.0145	0.0275	0.0258
1972-73	0.0196	0.0154	0.0154	-	-
1973-74	0.0194	0.0220	0.0187	0.0259	0.0312
1974-75	0.0158	-	0.0144	0.0197	0.0188
1975-76	0.0195	0.0201	-	0.0352	0.0241
1976-77	0.0256	0.0221	0.0206	0.0347	0.0561
1977-78	0.0225	0.0185	0.0129	0.0202	0.0244
1978-79	0.0249	-	-	0.0242	0.0242
1979-80	0.0177	-	-	-	-
1980-81	0.0220	-	-	-	-
X	0.0198	0.0188	0.0154	0.0268	0.0290
S.D.	0.0031	0.0033	0.0029	0.0063	0.0104

continued to be 367 or January 2, the mean date for freeze over at station 108. Between days 241 and 302, air temperature generally remained below normal, with the result that "T_w" simulated by equation (5) decreased more quickly than normal. As a consequence, the forecast date of freeze over moved from January 2 to December 28. Notice that, as the date of freeze over came closer, NDAY became more variable, responding to short-term fluctuations in air temperature. It is important to note in this specific example that no forecasting of air temperatures was included; all temperatures projected past each forecast day were normal.

The general question of how well the method works should now be addressed. The program used to generate the NDAY's in figure 4 was applied

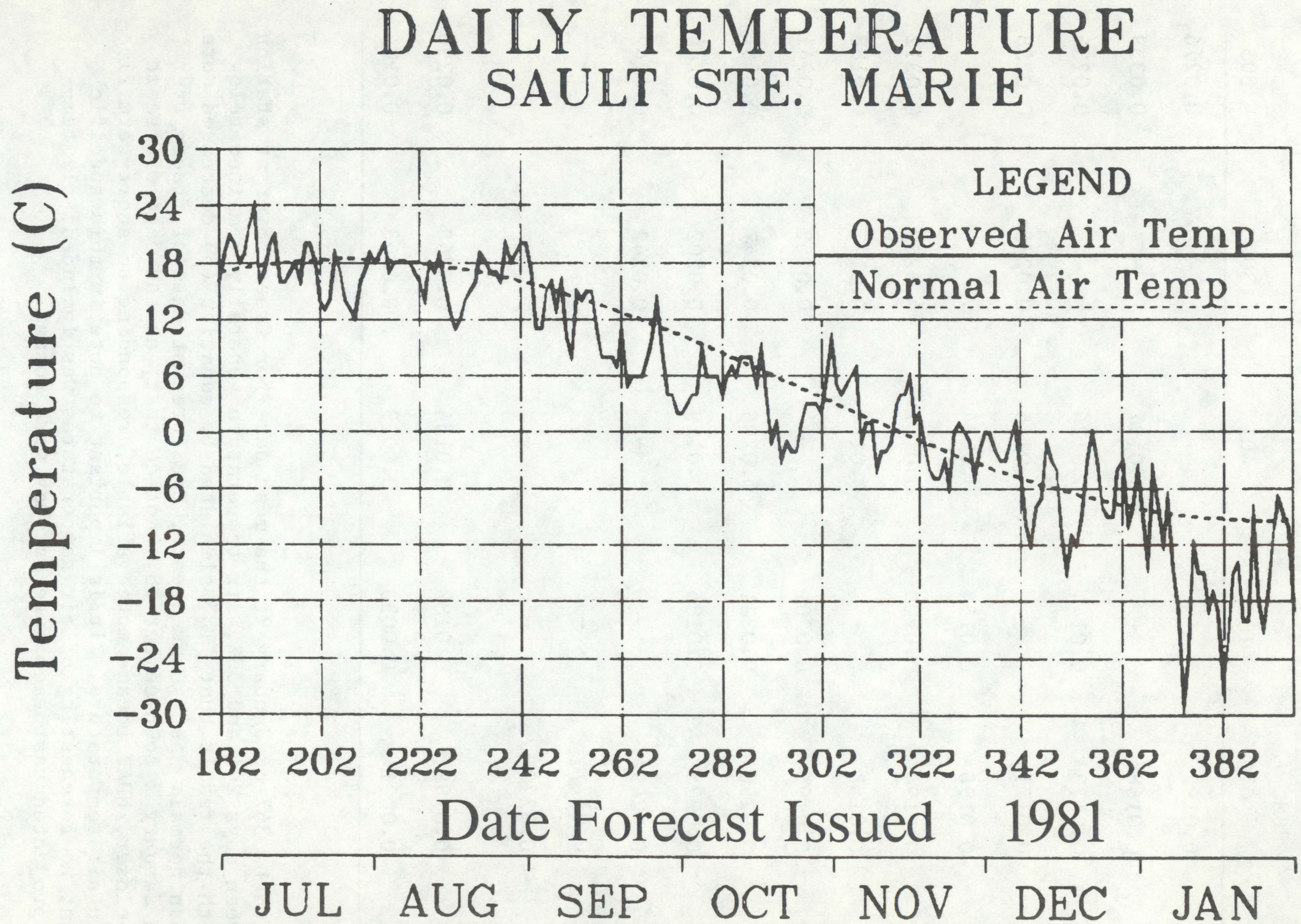


FIGURE 3.--*Air temperatures at Sault Ste. Marie used for 1981-82 sample ice-cover formation forecast.*

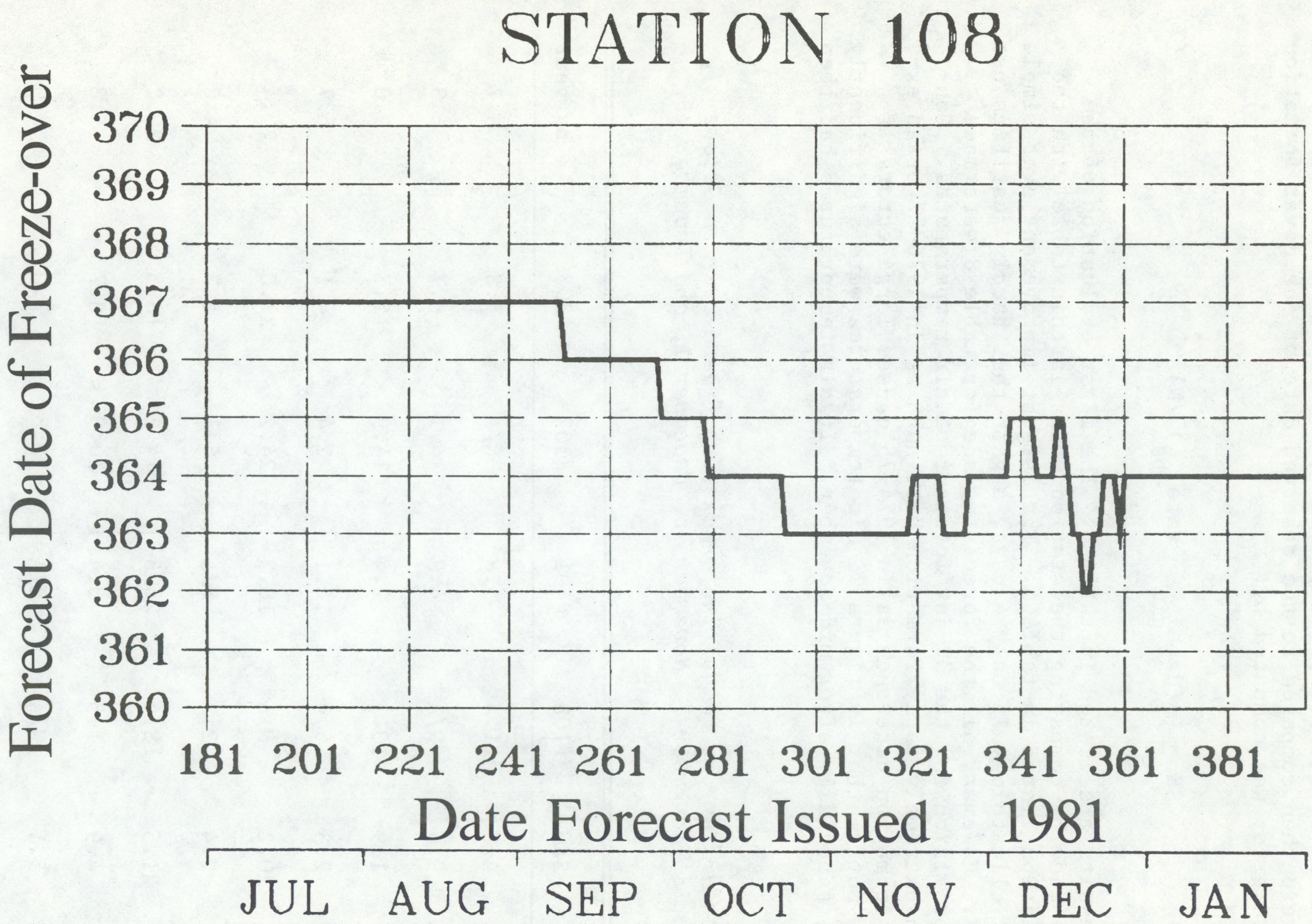


FIGURE 4.--*Predicted date of ice-cover formation at station 108, winter of 1981-82, as a function of the date of forecast.*

to every year that data were available for stations 108, 302, 303, and 401 and for water temperatures reaching 0°C at Sault Ste. Marie. The dates forecast as of October 1, October 15, November 1, November 15, December 1, and December 15 were then compared to the observed date of ice-cover formation and a standard error was computed by:

$$SE = (\sum(date_{sim} - date_{obs})^2/N)^{1/2} \qquad (7)$$

These results are listed in table 8. The first evaluation of the method can be made by comparing the station means in this table with the standard deviation listed in table 4. The largest improvement over simple observational climatology is only 4 days, a gain that hardly justifies use of the method. However, all the forecasts made for table 8 were made without any provision for the 30-day forecast of air temperatures. Consequently, an extremely early formation date such as in 1976-77 or an extremely late formation date such as in 1974-75 causes large errors if uncorrected. Notice that in figure 2i air temperatures were significantly below normal, especially after mid-November. If air temperatures had been

TABLE 8.--*Standard errors (days) in forecasting freeze over on October 1, October 15, November 1, November 15, December 1, and December 15*

Season	SSM	#108	#401	#302	#303	$\overline{X}$ by year
1970-71	4.2	11.4	5.8	N/A	5.8	6.7
1971-72	9.6	N/A	4.9	4.1	6.7	6.3
1972-73	1.9	10.3	2.4	14.9	15.7	9.0
1973-74	2.3	5.4	14.1	2.4	4.1	5.7
1974-75	20.2	N/A	10.2	24.2	27.0	20.4
1975-76	2.4	2.3	N/A	6.1	5.3	4.0
1976-77	21.5	18.4	28.6	14.2	18.3	20.2
1977-78	4.9	1.5	3.4	10.5	8.7	5.8
1978-79	5.1	N/A	N/A	5.8	7.0	6.0
$\overline{X}$ by station	8.0	8.2	9.9	10.3	10.9	

projected to be 2°C below normal after October 1 and 5°C below normal after November 15, the average standard error for 1976-77 in table 8 would have been 13.0 days rather than 20.2 days and the overall station average standard errors would be roughly 50 percent of the standard deviation listed in table 4.

To summarize, consider station 303 as an example. Based purely on past observations, there is a 68-percent chance that this station will freeze over between December 8 and January 3. If one uses a derived heat transfer coefficient and strictly normal air temperature projection, there is a 68-percent chance that a forecast date of formation will fall within 11 days of the actual date. Finally, if air temperatures can be accurately projected to be above, below, or close to normal for 30-day periods past the dates forecasts are issued, there is a 68-percent chance that a forecast date of formation will fall within roughly 5 days of the actual date.

Before discussing forecasting methods for growth and decay, it is of value to briefly consider an alternative method of predicting ice-cover formation. Examination of table 4 shows that dates of ice-cover formation are somewhat correlated with the date that the water temperature at Sault Ste. Marie drops to 0°C. For forecasting purposes, the only meaningful correlations are between Sault Ste. Marie and station 401 and Sault Ste. Marie and station 402. Ice-cover freeze over dates at these stations occur roughly 10 days after the dates upon which "T_w" becomes 0°C.

A linear regression can be made for each of the pairs with the following results:

$$\text{date}_{401} = 32.5 + 0.939(\text{date}_{SSM}) \tag{8}$$

$$\text{date}_{402} = 24.7 + 0.956(\text{date}_{SSM}) \tag{9}$$

The "r^2" values are 0.77 and 0.84, respectively, meaning that 77 percent of the variance in the date of freeze over at 401 can be explained by the variance in the date at which "T_w" becomes 0°C and that 84 percent of the variance at 402 can be explained in the same manner. These results suggest that freeze over at these two sites can be predicted much more accurately by equations (8) and (9) than by the heat transfer coefficient method, once "T_w" is 0°C at Sault Ste. Marie.

4. ICE GROWTH FORECAST

The general equation governing the growth of ice in a river channel relates the growth rate to the relative balance of heat flux from the river water to the underside of the ice sheet and the heat flux through the ice cover to the atmosphere.

$$Q_i - Q_w = \rho_i \lambda (dZ_i/dt), \tag{10}$$

where t is the time, Q_i and Q_w are the heat fluxes through the ice and from the water, respectively, ρ_i is the ice density, λ is the latent heat of fusion, and Z_i is the ice sheet thickness.

A number of assumptions and simplifications allow the use of equation (10) to simulate ice growth as a function of air temperature (Greene, 1981; Ashton, 1978). If we assume that "Q_w" is negligible during growth, that there is a linear temperature gradient through the ice, and that the surface temperature equals the air temperature, equation (10) becomes:

$$K_i(T_m - T_a)/Z_i = \rho_i \lambda (dZ_i/dt), \tag{11}$$

when only an ice layer is present, and

$$(T_m - T_a)/(Z_i/K_i + Z_s/K_s) = \rho_i \lambda (dZ_i/dt), \tag{12}$$

when a snow layer is present. In both equations, K_i is the thermal conductivity of ice, T_m is the temperature at the ice/water boundary (0°C), T_a is the air temperature, Z_s is the thickness of the snow layer and K_s is the thermal conductivity of snow. Integration of equation (11) over time leads to

$$Z_i = (2K_i/\rho_i \lambda)^{1/2} \left(\int_0^t (T_m - T_a)dt \right)^{1/2}. \tag{13}$$

Equation (12) can also be integrated in stepwise fashion as:

$$Z_i^{t+1} = \left[\left(Z_i^{t} + (K_i/K_s)Z_s \right)^2 + (2K_i/\rho_i \lambda) \sum FDD \right]^{1/2} - (K_i/K_s)Z_s \tag{14}$$

where t and t+1 define the time interval and $\sum$FDD is the freezing degree-days accumulated during the time interval.

Because it could include a snow layer, equation (14) was initially tested to determine its ability to simulate ice growth at a number of stations over years during which ice and snow thickness measurements were available. The method did not accurately simulate ice growth; seasonal standard errors of computed ice-cover thickness compared to observed values were on the order of 18-24 cm. Reasons for the failure of this equation are related to the formation of snow-ice and are discussed more fully in the recommendation section.

Although equation (13) ignores the effects of snow or ice growth, it has a long history as a thickness estimator. For application on a river, Michel (1971) suggests that (13) be used as

$$Z_i = F(2K_i/\rho_i\lambda)^{1/2} \; (\sum FDD)^{1/2}, \qquad (15)$$

where F is the site-specific empirically-determined percentage reduction in the computed ice thickness whose magnitude is a function of snow thickness, current beneath the ice, and degree to which snow-ice formation occurs and $\sum$FDD is the value for the freezing degree-days (°C) accumulated since the time of ice-cover formation. Using a value of 2.18 W m^{-1} $°C^{-1}$ for K_i, 917 kg m^{-3} for ρ_i, and 3.4 × 10^5 J kg^{-1} for λ, equation (15) takes on the final form of

$$Z_i(cm) = F(3.48 \text{ cm day}^{-1/2} \; °C^{-1/2}) \; (\sum FDD)^{1/2}, \qquad (16)$$

where F has a value between 0.00 and 1.00.

"F" values were determined for stations 108, 302, 303, 401, 402, and 403 by testing the effect of different "F's" on the overall error in estimating "Z_i." For simplicity, an effort was made to find one "F" value that could be applied consistently at all stations. An "F" value of 0.60 works best at all of the above sites except 108, where an "F" of 0.50 is best.

Table 9 lists the standard errors in thickness (in centimeters) for each season and each site. There are gaps in the table where no date of ice formation was known. Standard errors for stations range from 6 to 9 cm, with the error distributed evenly between early and late growth seasons. Given an average standard error of 8 cm, one can state that the thickness estimated by equation (16) will be within 8 cm (above or below) of the observed thickness roughly 68 percent of the time.

Figures 5a–g illustrate the use of equation (16) for station 402. The figures evoke two points of caution about the method. One should first note that equation (16) cannot tell you when decay will start. For example, figure 5a shows that, in 1970, simulated ice thickness continued to increase long past day 48, when maximum ice thickness was found, because air temperatures were below 0°C. The second caution is that there are years when the equation will consistently over- or under-predict ice-cover thickness (as shown in figures 5f and g). These figures suggest that, during each season, some mechanical or thermodynamic processes are at work that are not accounted for by equation (11) and are not consistent with processes operating during other years. One example of such a process would be snow-ice formation, the mechanics of which can significantly alter ice-cover thickness (Hinkel, 1983). (Snow-cover data are not available for station

TABLE 9.--*Standard error in simulated ice-cover thicknesses (cm)*

Season	108	302	303	401	402	403	Average yearly standard error (cm)
1967-68	-	3.6	5.8	-	-	-	4.7
1968-69	-	-	8.8	-	-	-	-
1969-70	-	-	3.2	6.9	5.3	-	5.1
1970-71	7.3	-	11.2	13.5	-	-	10.7
1971-72	-	8.2	13.1	7.4	6.1	-	8.7
1972-73	15.6	10.7	9.9	2.1	-	-	9.6
1973-74	5.0	9.9	14.7	10.1	3.8	3.0	7.8
1974-75	-	10.0	10.0	4.8	3.6	8.1	7.3
1975-76	4.5	10.8	-	-	5.8	9.0	7.5
1976-77	9.7	12.1	11.4	6.2	10.5	-	10.0
1977-78	6.4	7.8	6.4	19.0	18.7	3.6	10.3
1978-79	-	7.0	6.5	-	-	-	6.8
Average station standard error (cm)	8.1	8.9	9.2	8.8	7.7	5.9	-
F value (eq. 16)	0.50	0.60	0.60	0.60	0.60	0.60	

402.) Another possible explanation is that there was a change made in the observation site, either closer to or farther from shore. Ice-cover thickness is not uniform across the channel width because it can vary as a function of water depth, current velocity, or snow-cover depth.

To use equation (16) for forecasting rather then simulating ice-cover growth, it is necessary to know the date of ice-cover formation at a site, mean daily air temperature since freeze over, and a projection of air temperatures. This projection can be done in the same manner used for the

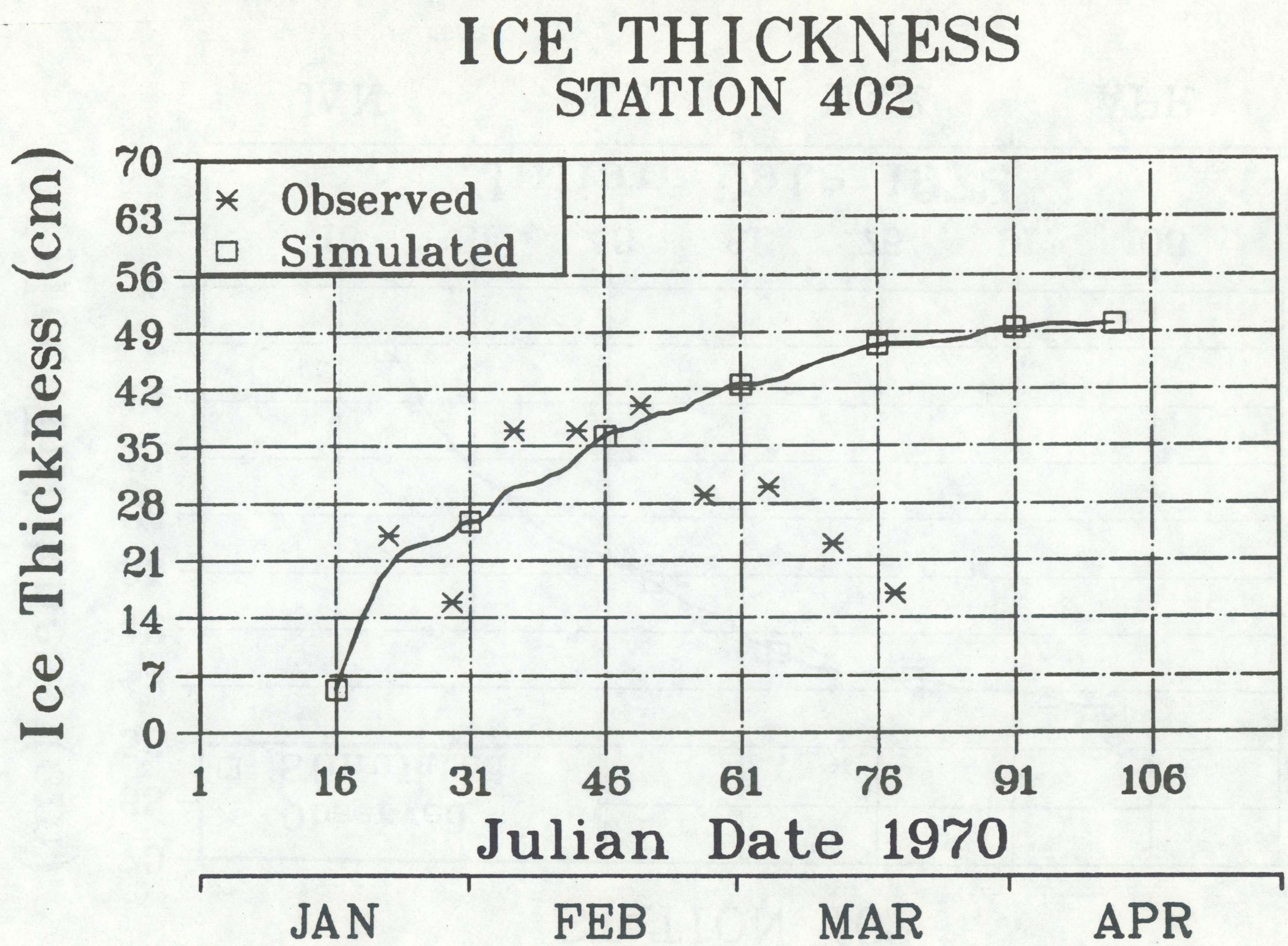


FIGURE 5a.--*Simulated ice-cover thickness at station 402 compared to observed thickness, 1970.*

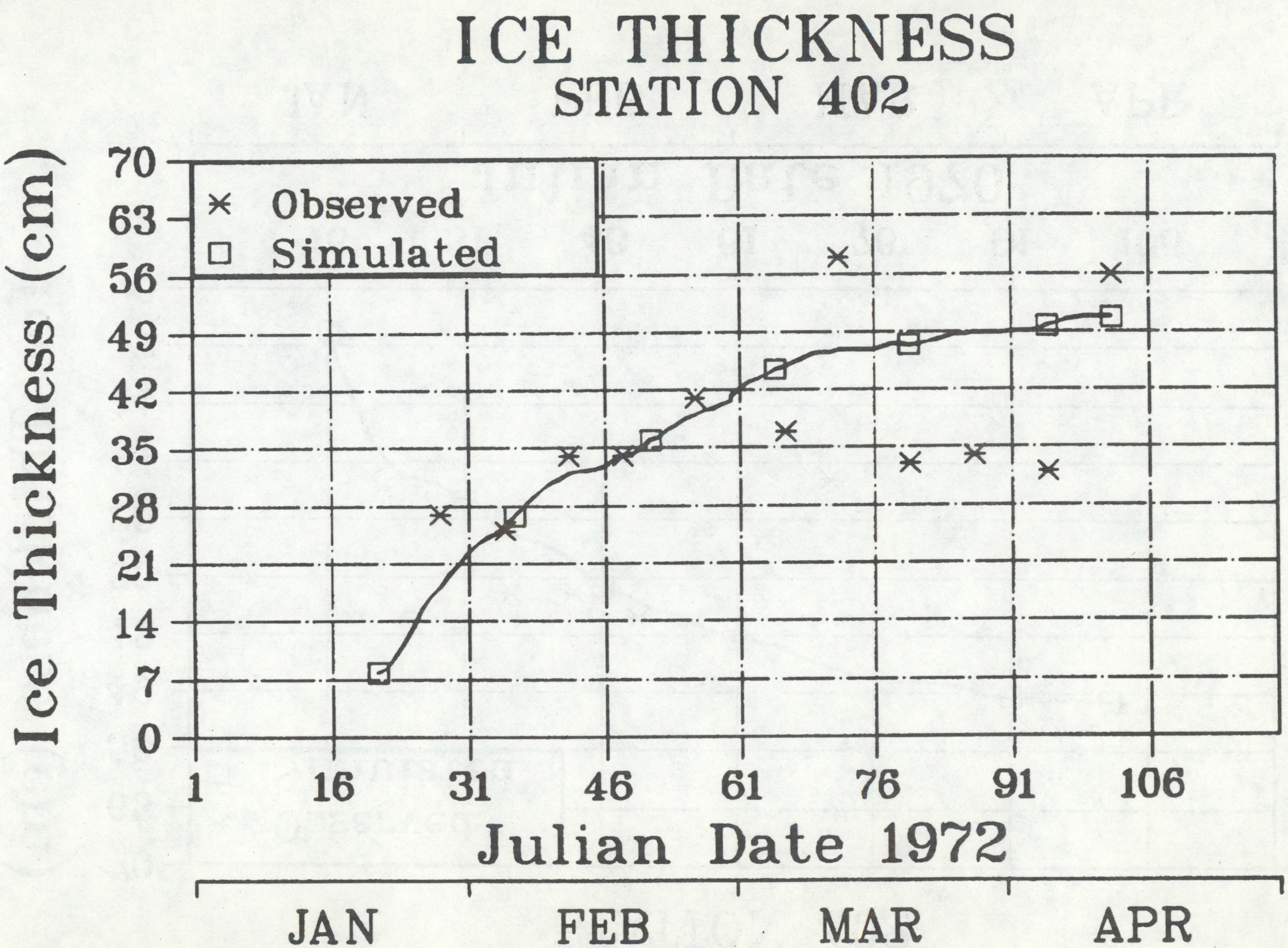


FIGURE 5b.--*Simulated ice-cover thickness at station 402 compared to observed thickness, 1972.*

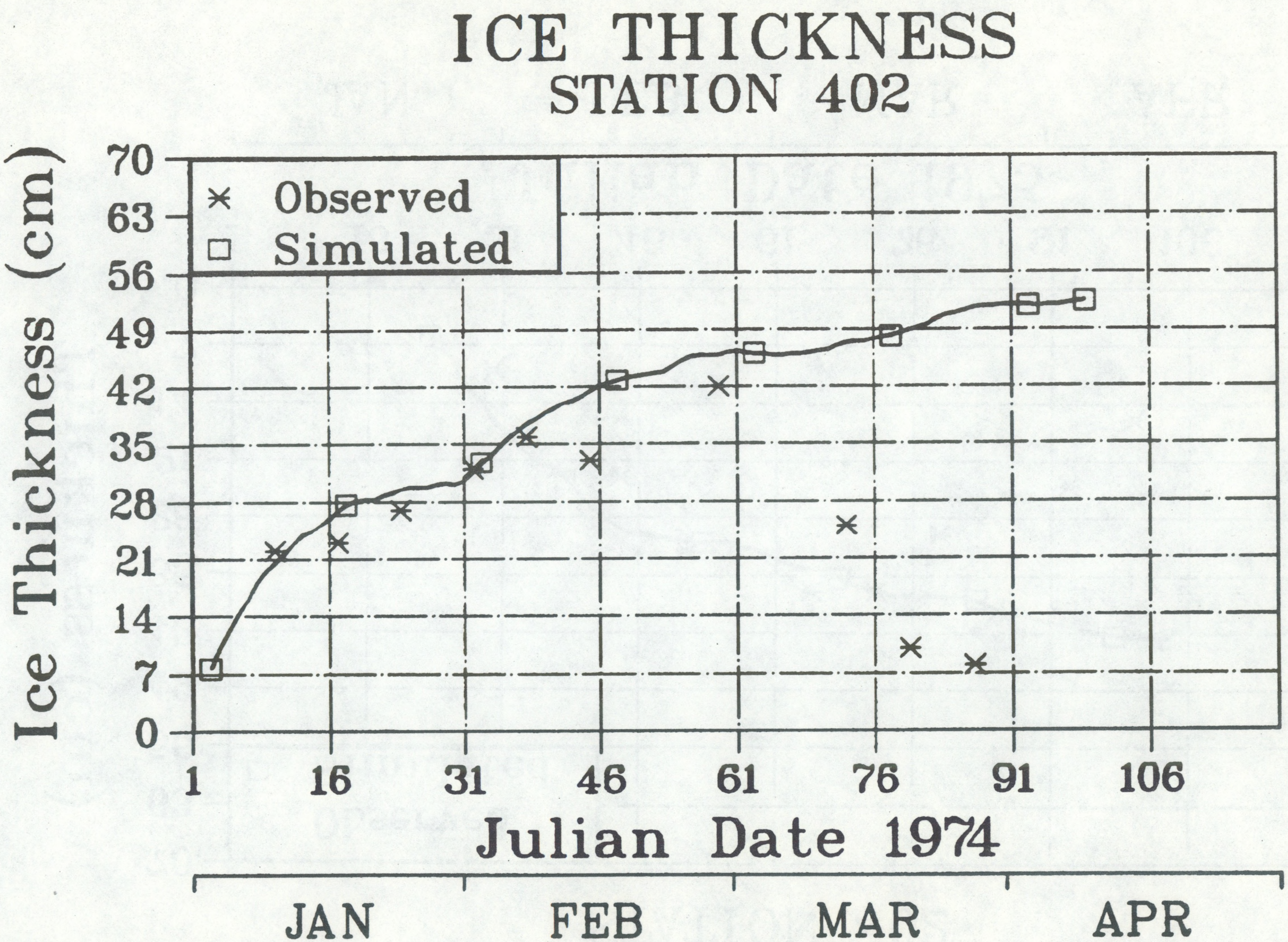


FIGURE 5c.--*Simulated ice-cover thickness at station 402 compared to observed thickness, 1974.*

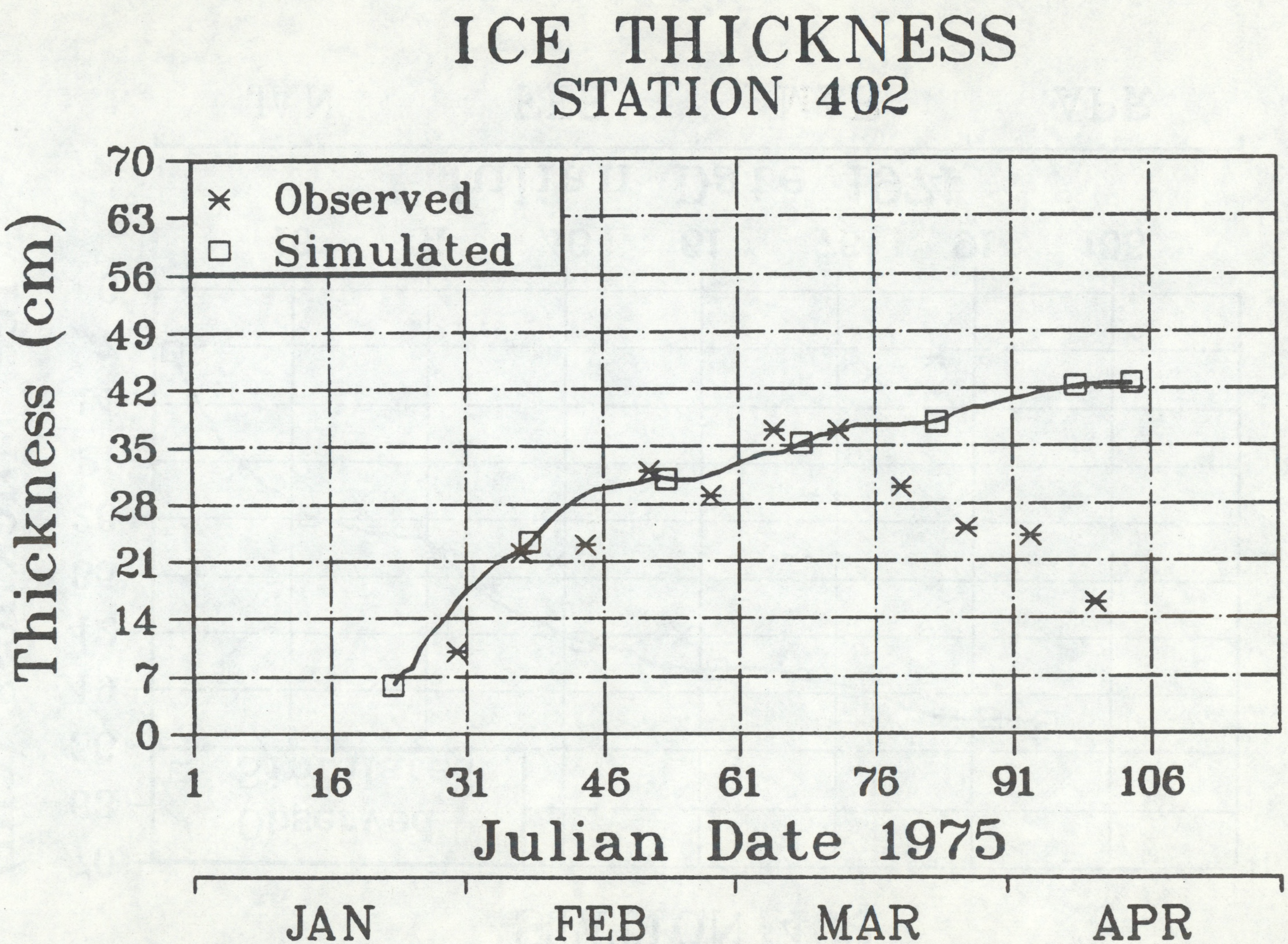


FIGURE 5d.--*Simulated ice-cover thickness at station 402 compared to observed thickness, 1975.*

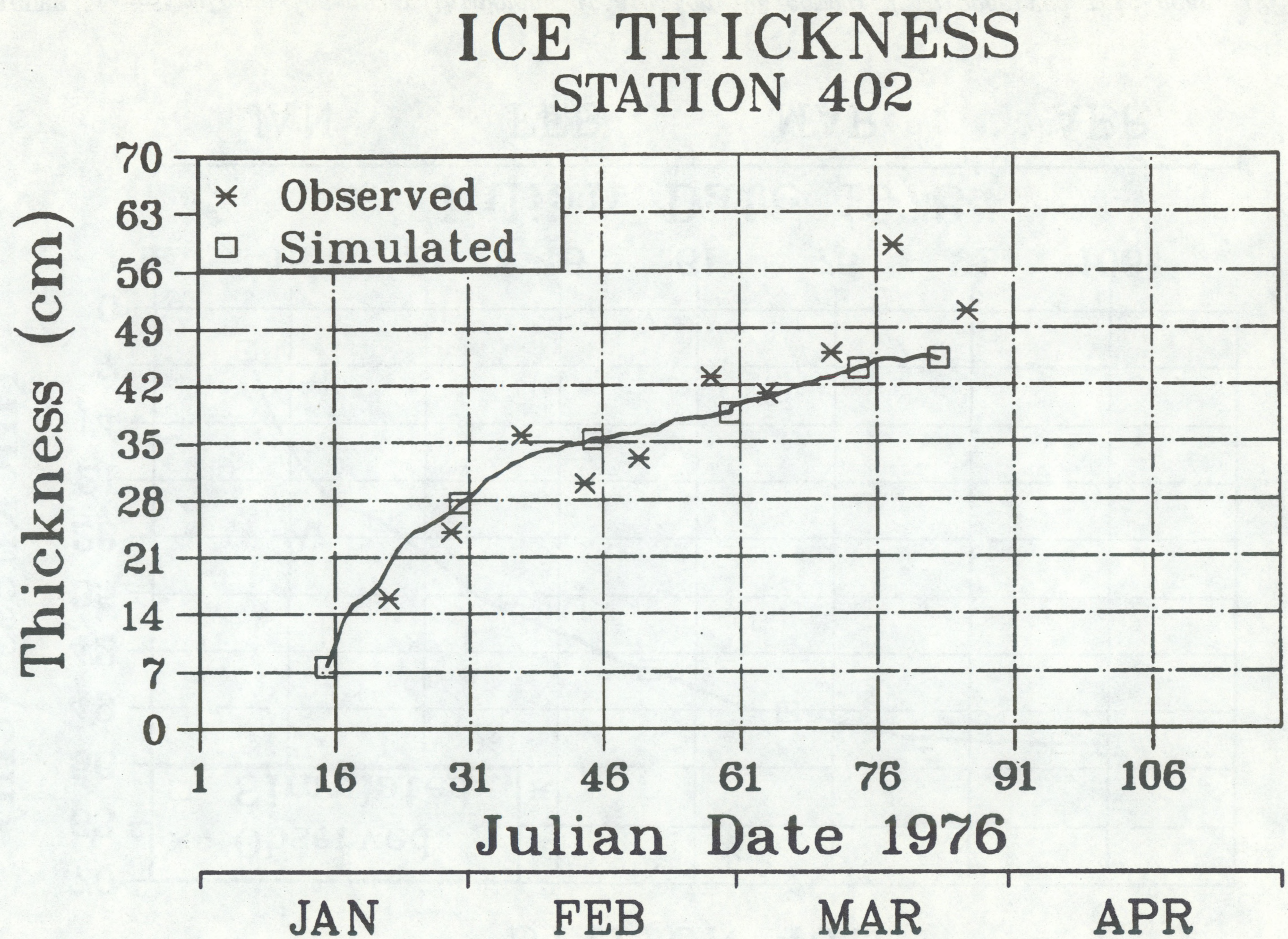


FIGURE 5e.--*Simulated ice-cover thickness at station 402 compared to observed thickness, 1976.*

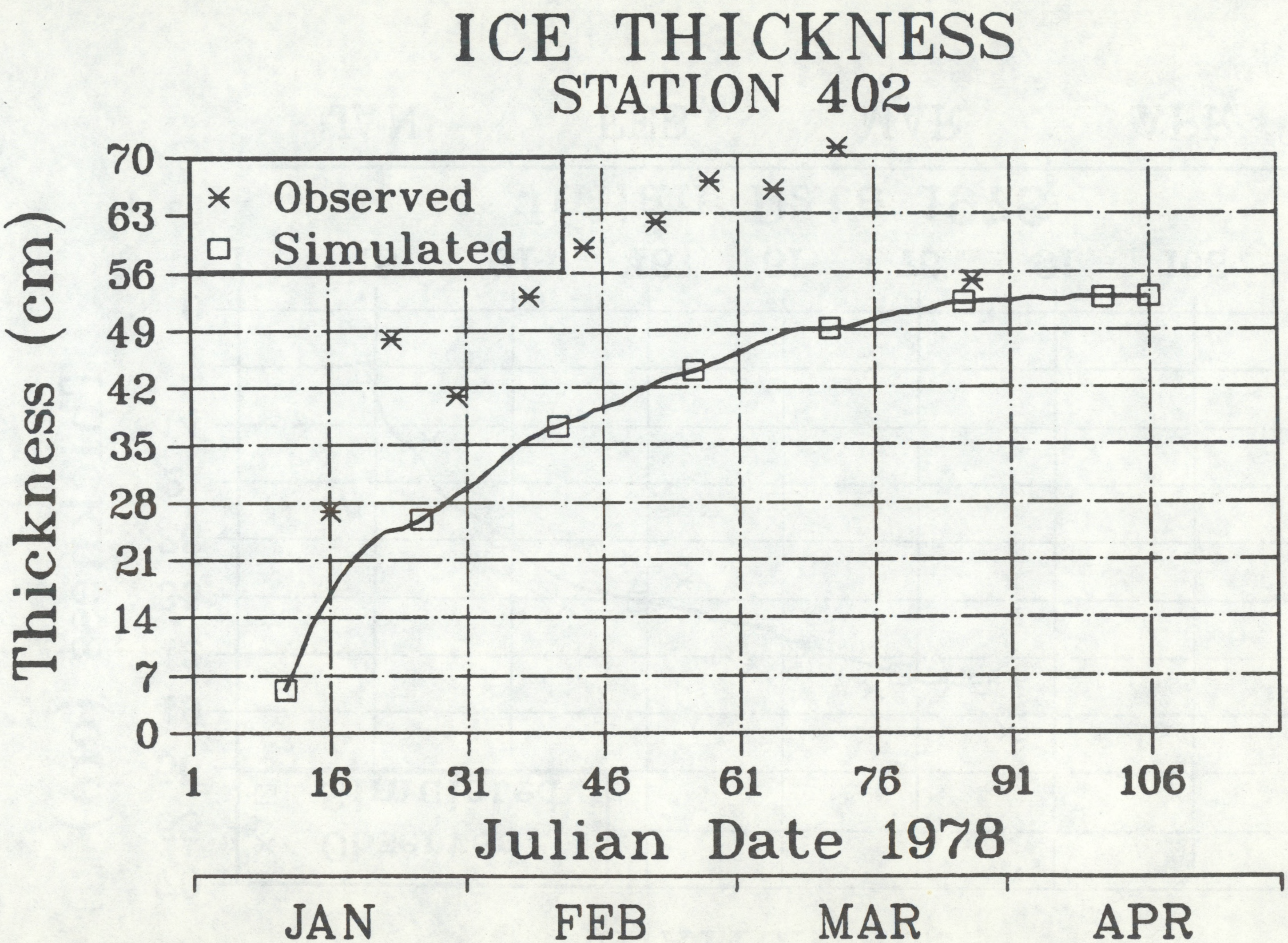


FIGURE 5f.--*Simulated ice-cover thickness at station 402 compared to observed thickness, 1977.*

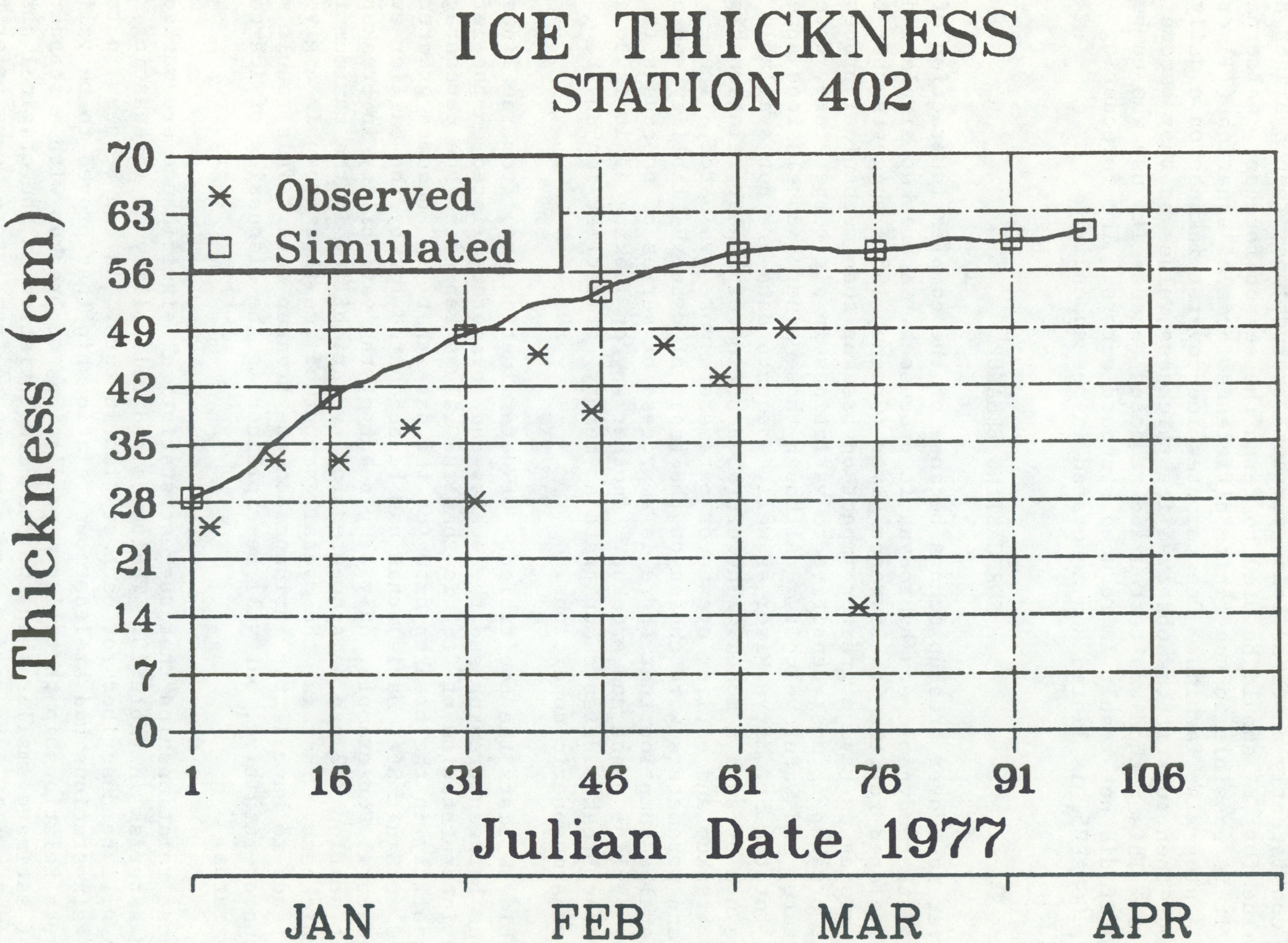


FIGURE 5g.--*Simulated ice-cover thickness at station 402 compared to observed thickness, 1978.*

formation forecast; that is, equation (1) can be used to determine each day's normal air temperature, which is then raised or lowered based on the extended 30-day air temperature forecast.

If, as the season progresses, one finds that the simulated ice thickness is consistently above or below current observations, then a higher or lower value for "F" should be used to rerun the season forecast. Alternatively, it is possible to use finite difference forms of equation (11) or (12) in a step-wise fashion. One computes ice-cover thickness on a daily basis, but then substitutes observed ice thickness values as they become available. This method was tested and rejected because its use was cumbersome and it did not result in reduced standard errors. The forecasting program, GGMAPP5, is listed and annotated in the appendix.

5. FORECASTING BREAKUP

River ice-cover breakup occurs because of the complex interaction of a number of thermodynamic and hydrodynamic processes. A breakup simulation model developed for the St. Lawrence River (Greene, 1981) suggests that the thermal processes have a greater impact on breakup than mechanical processes and that breakup is most sensitive to variations in air temperature, water temperature, and water velocity. Although these general conclusions appear to hold for the St. Marys River as well, adequate data are not available to test the use of such a model. Therefore, a series of linear relationships between breakup and earlier events or parameters were evaluated. These events and parameters were chosen on the basis of data availability and on the general assumption that there is a process or series of processes that link the earlier event and breakup. Another way of looking at it is to ask whether the breakup dates demonstrate a "memory" of earlier ice-cover, river, or atmospheric conditions.

Table 10 lists the coefficients of determination (r^2) from the linear relations between breakup and the events and parameters listed on the left. A valid interpretation of "r^2" is that the values represent the percentage of variability in the breakup date (or the date that "T_w" becomes greater than 0°C at Sault Ste. Marie) that can be accounted for by the earlier event or parameter. For example, only 21 percent of the variability in breakup dates at station 302 can be accounted for by variability in the maximum ice-cover thickness. That is, the overall amount of ice that grows in a given season tends to have little influence on the breakup date. This result may seem counter-intuitive, but will be explained in the discussion of ice-cover melting rates.

Those relationships that suggest statistical significance are marked with an asterisk in table 10. Their use and reliability as forecasting devices will be described for each station in turn. As can be seen in table 10, all six stations had at least one relationship that proved to be valid, that is, a relationship that allows predictions of breakup with a standard error of estimate smaller than the standard deviation in the original observations. Overall, forecasting lead time ranges from 1 to 4 weeks prior to mean date of breakup.

TABLE 10.--*Coefficients of determination for linear breakup relations*

	r^2					
	SSM[†]	108	302	303	401	402
Number of years	11	6	7	9	9	7
Date SSM $T_w > 0°C$	-	0.92*	0.53**	0.78*	-	-
Maximum $\sum$FDD	0.36	0.25	0.02	0.12	-	-
Date of max $\sum$FDD	0.69*	0.53	0.33	0.71*	-	-
Max ice-cover thickness	-	0.12	0.21	0.00	0.06	0.52
Date of max ice-cover thickness	-	0.10	0.25	0.86*	0.01	0.20
Mean Feb. air temperature	0.18	0.53	0.04	0.00	0.14	0.08
Max % ice cover on Lake Superior	0.30	0.56	-	-	-	-
Melt rate = f (date of max ice-cover thickness)	-	0.17	0.58**	0.28	0.87*	0.82*

[†]Sault Ste. Marie.

*Statistical significance at 0.005 level or lower.

**Statistical significance at 0.05 level.

Before describing specific station relations, it is of interest to look at the general patterns in table 10. The two most important parameters appear to be the date on which water temperature at Sault Ste. Marie rises above (and then remains above) 0°C and the melt rate as determined from the date of maximum ice thickness. The water temperature date is significant both because it occurs within 7-10 days of breakup and because water temperatures at all sites, although unknown, are clearly related to water temperatures at Sault Ste. Marie. Stations 401 and 402 probably have a strong relationship with water temperatures, but their ice-cover breakup generally occurs prior to the date of warming at Sault Ste. Marie, reflecting the additional significance of current velocity at those two sites.

Another general pattern is that breakup is more likely to be a function of the dates of maximums, such as accumulated freezing degree-days (FDD) or ice thickness, than of the numerical values of the maximums. This point is emphasized by the significance of melt rates at stations 401 and 402. As will be seen, the linear relationships show that the later the date of maximum ice-cover thickness, the greater the melting rate of the ice cover, probably because the ice cover is melting while air and water temperatures are rising.

One might expect ice conditions on Lake Superior to influence breakup and the water temperatures at the stations upstream from Sault Ste. Marie. The maximum percent of ice cover on all of Lake Superior is an inadequate measure, however, and should be replaced by ice concentrations and water temperatures in Whitefish Bay. The ice concentrations will soon be available in the revised *Great Lakes Ice Atlas* (Assel, 1983).

Mean February air temperatures were tested as an indicator in the hope that they might allow an early forecast. Their failure and that of the maximum ice-cover thickness reflect the influence of later conditions.

A final caution before proceeding with the forecasts: these linear relations were developed over a specific range of data and have no applicability outside that range. For example, the melt rate relationship at station 401 has a negative "a" value for the general relationship

$$Y = a + bX \tag{17}$$

Technically, if "X" was 0 (January 1), the melt rate "Y" would be negative. However, the date of maximum ice-cover thickness is much later than January 1; hence, such a result is meaningless.

All of the following techniques are in the form

$$Y = a + (bX) \pm (\text{standard error}) \tag{18}$$

5.1 Station 108 (Table 11)

5.1.1 Techniques

Y = predicted Julian date ice free,

X = observed Julian date that Sault Ste. Marie T_w rises above 0°C,

a = −8.65,

b = 1.13,

r^2 = 0.92,

TABLE 11.--*Breakup at station 108*

Season	Date ice free	Date SSM T_w > 0°C	Max $\sum$FDD (°C)	Date of max $\sum$FDD	Max Z_i (cm)	Date of max Z_i	Melt rate (cm day^{-1})	ΣTDD (°C)	Max % of ice cover Lake Superior
1968-69	Apr. 15	Apr. 9	874	Apr. 3	36	Mar. 23	1.6	48	40
1969-70	Apr. 19	Apr. 20	1114	Apr. 12	38	Mar. 7	0.9	27	80
1970-71	-	-	-	-	-	-	-	-	-
1971-72	May 13	May 1	1102	Apr. 11	48	Mar. 18	0.9	193	95
1972-73	-	-	-	-	-	-	-	-	-
1973-74	Apr. 26	Apr. 21	1021	Apr. 9	56	Mar. 27	1.9	77	70
1974-75	Apr. 20	Apr. 14	848	Apr. 13	35	Mar. 16	1.0	19	30
1975-76	Apr. 3	Mar. 30	966	Mar. 22	46	Mar. 12	2.1	20	40
$\overline{X}$	Apr. 21	Apr. 16	987	Apr. 7	43	Mar. 17	1.4	64	59

standard deviation of observed dates ice free = 13 days,

standard error of estimate = 3.8 days,

mean observed date ice free = April 21,

mean observed date $T_w > 0°C$ = April 13,

average forecast lead time = 8 days.

5.1.2 Discussion

The standard error of estimate tells us that use of this linear relationship allows us to considerably reduce the uncertainty in the date of breakup; rather than a 68-percent chance that breakup occurs within a 26-day period, we can predict such that there is roughly a 68-percent chance that breakup occurs within a predicted 8-day period. However, one must know the date when water temperatures at Sault Ste. Marie rise above (and stay above) 0°C.

This relationship has a very short lead time and probably is of little use unless one can forecast the date that $T_w > 0°C$ and use that forecast date in place of "X" above. Forecasting water temperature at Sault Ste. Marie is discussed at the end of this section.

5.2 Station 401 (Table 12)

5.2.1 Techniques

Y = estimated melt rate (cm day^{-1}),

X = date of observed maximum ice-cover thickness,

a = -5.76,

b = 0.146,

r^2 = 0.87,

standard deviation of observed melt rates = 1.8 cm day^{-1},

standard error of estimate = 0.6 cm day^{-1},

mean observed melt rate = 2.0 cm day^{-1}.

To compute the date ice free

$$\text{date}_{\text{ice free}} = \text{date}_{\max} + (Z_{\max}/Y), \quad (19)$$

TABLE 12.--*Breakup at station 401*

Season	Date ice free	Date SSM T_w > 0°C	Max $\sum$FDD (°C)	Date of max $\sum$FDD	Max Z_i (cm)	Date of max Z_i	Melt rate (cm day^{-1})
1968-69	Mar. 24	Apr. 9	874	Apr. 3	41	Feb. 19	1.2
1969-70	Mar. 5	Apr. 20	1114	Apr. 12	27	Feb. 12	1.3
1970-71	Apr. 9	-	1133	Apr. 6	53	Feb. 25	1.2
1971-72	-	-	-	-	-	-	-
1972-73	Mar. 14	Mar. 23	719	Feb. 28	30	Feb. 21	1.4
1973-74	Mar. 21	Apr. 21	1021	Apr. 9	32	Feb. 14	0.9
1974-75	Apr. 10	Apr. 14	848	Apr. 13	25	Feb. 13	0.4
1975-76	Mar. 26	Mar. 30	966	Mar. 22	51	Mar. 17	5.7
1976-77	Mar. 22	Apr. 11	1265	Apr. 9	69	Mar. 7	4.6
1977-78	Mar. 28	Apr. 24	1154	Apr. 9	55	Feb. 13	1.3
$\overline{X}$	Mar. 25	Apr. 11	1010	Apr. 2	43	Feb. 22	2.0

where $date_{max}$ = the date of maximum ice-cover thickness,

Z_{max} = maximum ice thickness (cm),

Y = melt rate computed above.

mean observed date ice free = March 25,

mean observed date of maximum ice-cover thickness = February 22,

average forecast lead time = less than 31 days.

5.2.2 Discussion

This is a two-stage forecast in which one first forecasts the melt rate and then computes how long it takes to melt the observed amount of ice.

Note that the uncertainty in the melt rate has been reduced by more than 50 percent. For example, assume that the observed date of maximum ice cover occurs on February 25 (day 56) and that the maximum ice-cover thickness is 53 cm.

$$Y = -5.765 + 0.1465\ (56),$$

$$= 2.4 \text{ cm day}^{-1},$$

$$\text{melt rate} = 2.4 \pm 0.6 \text{ cm day}^{-1},$$

$$\text{date ice free} = 56 + (53 \text{ cm}/(2.4 \pm 0.6 \text{ cm day}^{-1}))$$

$$= 78 \pm 6 \text{ days for 68-percent confidence interval.}$$

The forecasting lead time available with this relationship is actually less than 31 days because one needs a certain amount of elapsed time to see whether the maximum ice thickness has indeed been achieved. Unfortunately, as one can see in figures 5a-g, there are instances when ice thickness decreased and then increased, but this is most likely related to the natural spatial variability in ice-cover thickness rather than to actual reductions in thickness. Another caution is that the observed melt rates are clustered into two groups, one around 5 cm day^{-1} and the other around 1.3 cm day^{-1}.

5.3 Station 402 (Table 13)

5.3.1 Techniques

Y = estimated melt rate (cm day^{-1}),

X = date of observed maximum ice-cover thickness,

$a = -2.495$,

$b = 0.076$,

$r^2 = 0.82$,

standard deviation of observed melt rates = 1.1 cm day^{-1},

standard error of estimate = 0.5 cm day^{-1},

mean observed melt rate = 2.3 cm day^{-1},

mean observed date ice free = March 30,

mean observed date of maximum ice-cover thickness = March 4,

average forecast lead time = less than 26 days.

TABLE 13.--*Breakup at station 402*

Season	Date ice free	Date SSM T_w > 0°C	Max ∑FDD (°C)	Date of max ∑FDD	Max Z_i (cm)	Date of max Z_i	Melt rate (cm day^{-1})
1968-69	Mar. 24	Apr. 9	874	Apr. 3	38	Feb. 17	1.1
1969-70	-	-	-	-	-	-	-
1970-71	Apr. 9*	-	1133	Apr. 6	59	Mar. 24	3.7
1971-72	-	-	-	-	-	-	-
1972-73	Mar. 14*	Mar. 23	719	Feb. 28	40	Feb. 27	2.7
1973-74	Apr. 4*	Apr. 21	1021	Apr. 9	42	Feb. 28	1.2
1974-75	-	-	-	-	-	-	-
1975-76	Apr. 2*	Mar. 30	966	Mar. 22	59	Mar. 18	3.9
1976-77	Mar. 29	Apr. 11	1265	Apr. 9	49	Mar. 7	2.3
1977-78	-	-	-	-	-	-	-
1978-79	Apr. 3	Apr. 12	1146	Apr. 10	53	Feb. 14	1.1
$\overline{X}$	Mar. 30	Apr. 8	1018	Mar. 31	49	Mar. 4	2.3

*"Unsafe cover," not ice free.

5.3.2 Discussion

This forecast takes the same form as the one for station 401. It is likely to be more accurate than the relation for 401 because the standard error of estimate is smaller and the observed melt rates are not clustered as they are for 401. Again, one must have some certainty that the ice cover is beginning to melt before this relation can be applied.

5.4 Station 302 (Table 14)

5.4.1. Techniques

There are two potential methods of forecasting the date when station 302 will be ice free, but they are only marginally significant as measured by their respective "r^2" values of 0.53 and 0.58. They are included here because they are the best currently available.

TABLE 14.--*Breakup at station 302*

Season	Date ice free	Date SSM T_w > 0°C	Max ∠FDD (°C)	Date of max ∠FDD	Max Z_i (cm)	Date of max Z_i	Melt rate (cm day^{-1})	∠TDD (°C)
1971-72	Apr. 29	May 1	1102	Apr. 11	66	Mar. 10	1.3	85
1972-73	Apr. 4	Mar. 23	719	Feb. 28	56	Mar. 2	1.7	68
1973-74	May 1	Apr. 21	1021	Apr. 9	71	Mar. 22	1.8	115
1974-75	Apr. 25	Apr. 14	848	Apr. 13	45	Apr. 11	3.2	38
1975-76	Apr. 19	Mar. 30	966	Mar. 22	54	Mar. 19	1.7	101
1976-77	Apr. 15	Apr. 11	1265	Apr. 9	50	Mar. 11	1.4	40
1977-78	-	-	-	-	-	-	-	-
1978-79	Apr. 6	Apr. 12	1146	Apr. 10	54	Mar. 17	2.7	NA
$\overline{X}$	Apr. 19	Apr. 12	1009	Apr. 2	57	Mar. 18	2.0	74

5.4.1.1 Method 1--Y = estimated date ice free,

X = observed date that Sault Ste. Marie T_w > 0°C,

a = 48.2,

b = 0.594,

r^2 = 0.53,

standard deviation of observed dates ice free = 11 days,

standard error of estimate = 6.4 days,

mean date ice free = April 19,

mean date T_w > 0°C = April 12,

average forecast lead time = 7 days.

For example, if $X = 104$ (April 14),

$$Y = 48.2 + (0.594 \times 104)$$

$$= 110 \pm 6.4 \text{ days},$$

meaning that the forecast interval is April 17-20.

This interval is not sufficiently later than April 14 to lend much usefulness to this method.

5.4.1.2 Method 2--Y = estimated melt rate (cm day^{-1}),

X = observed date of maximum ice-cover thickness,

$a = -1.31$,

$b = 0.043$,

$r^2 = 0.58$,

standard deviation of observed melt rates = 0.71 cm day^{-1},

standard error of estimate = 0.4 cm day^{-1},

mean observed melt rate = 2.0 cm day^{-1},

mean observed date ice free = April 19,

mean observed date of maximum ice-cover thickness = March 18,

average forecast lead time = less than 32 days.

For example, assume that X is 70 (March 11) and that Z_{max} is 50 cm.

$$Y = -1.31 + (0.043 \times 70)$$

$$= 1.7 \text{ cm day}^{-1},$$

melt rate = 1.7 ± 0.4 cm day^{-1},

date ice free = $70 + (50 \text{ cm}/(1.7 \pm 0.4 \text{ cm day}^{-1}))$

$$= 99 \pm 8 \text{ days}.$$

5.5 Station 303 (Table 15)

5.5.1 Techniques

This station is the easiest to forecast because it has three different relationships between breakup and earlier events, with average lead times of approximately 10 days, 21 days, and 24 days.

5.5.1.1 Method 1--Y = estimated date ice free,

X = observed date Sault Ste. Marie $T_w > 0°C$,

a = 41.6,

b = 0.697,

$r^2 = 0.78$,

TABLE 15.--*Breakup at station 303*

Season	Date ice free	Date SSM T_w > 0°C	Max ∑FDD (°C)	Date of max ∑FDD	Max Z_i (cm)	Date of max Z_i	Melt rate (cm day^{-1})	∑TDD (°C)
1967-68	Apr. 12	Apr. 8	991	Mar. 25	69	Mar. 21	3.1	54
1968-69	Apr. 25	Apr. 9	874	Apr. 3	58	Apr. 2	2.5	96
1969-70	Apr. 26	Apr. 20	1114	Apr. 12	58	Apr. 2	2.4	69
1970-71	Apr. 24	-	1133	Apr. 6	81	Apr. 7	4.5	62
1971-72	May 6	May 1	1102	Apr. 11	78	Apr. 12	3.2	131
1972-73	Apr. 9	Mar. 23	719	Feb. 28	66	Mar. 2	1.7	71
1973-74	Apr. 28	Apr. 21	1021	Apr. 9	73	Apr. 4	3.0	100
1974-75	May 1	Apr. 14	848	Apr. 13	50	Apr. 11	2.5	81
1975-76	-	-	-	-	-	-	-	-
1976-77	Apr. 21	Apr. 11	1265	Apr. 9	66	Mar. 25	2.4	107
$\overline{X}$	Apr. 24	Apr. 14	1007	Apr. 3	66	Mar. 30	2.8	86

standard deviation of observed date ice free = 9 days,

standard error of estimate = 4.5 days,

mean observed date ice free = April 24,

mean observed date $T_w > 0°C$ = April 14,

average forecast lead time = 10 days.

<u>5.5.1.2 Method 2</u>--Y = estimated date ice free,

X = date of observed maximum $\sum$FDD,

a = 65.6,

b = 0.518,

$r^2 = 0.71$,

standard deviation of observed dates ice free = 9 days,

standard error of estimate = 3.6 days,

mean observed date ice free = April 24,

mean observed date of maximum $\sum$FDD = April 3,

average forecast lead time = 21 days.

<u>5.5.1.3 Method 3</u>--Y = estimated date ice free,

X = date of maximum ice-cover thickness,

a = 58.2,

b = 0.621,

$r^2 = 0.86$,

standard deviation of observed dates ice free = 9 days,

standard error of estimate = 3.6 days,

mean observed date ice free = April 24,

mean date of observed maximum ice-cover thickness = March 30,

average forecast lead time = 25 days.

5.5.2 Discussion

The advantage of forecasting at this site is that there are two additional independent checks on the original forecast from the date of maximum ice-cover thickness. This point is significant in that it allows one to incorporate more recent meteorological trends into the forecasts. It is possible that additional methods will eventually be found to be valid at other ice-cover stations, given additional years of measurements and observations.

5.6 Sault Ste. Marie (Table 16)

5.6.1 Techniques

Stations 108, 302, 303 all have significant relations between the rise in water temperature at Sault Ste. Marie and the observed date of ice-free conditions. A logical question is whether it is possible to forecast the rise in water temperature in order to gain forecasting lead time for those stations listed above. The answer is a qualified "no." As table 10 shows, there is a statistically significant relation between the observed date of maximum freezing degree-days and the rise in water temperature.

Y = estimated date $T_w > 0°C$,

X = observed date of maximum $\sum$FDD,

a = 38.2,

b = 0.698,

$r^2 = 0.69$,

standard deviation of observed dates of temperature rise = 11 days,

standard error of estimate = 5.7 days.

5.6.2 Discussion

Strictly speaking, the average forecast lead time is 10 days, but given the difficulty of immediately pinpointing the date of maximum $\sum$FDD, that lead time is reduced. When one considers that the error in estimating "Y" would then be amplified by the error in forecasting ice-free conditions from the date of water temperature rise, the attempt makes little sense.

6. RECOMMENDATIONS

There are two general approaches for improving forecasting ability on the St. Marys River: first, extension of the techniques described by use of

TABLE 16.--*Spring warming of water temperature at Sault Ste. Marie*

Season	Date SSM T_w > 0°C	Max $\sum$FDD (°C)	Date of max $\sum$DD	$\sum$TDD (°C)	Max. % ice cover Lake Superior
1967-68	Apr. 8	991	Mar. 25	36	-
1968-69	Apr. 9	874	Apr. 3	16	40
1969-70	Apr. 20	1114	Apr. 12	30	80
1970-71	-	1133	Apr. 6	-	48
1971-72	May 1	1102	Apr. 11	106	95
1972-73	Mar. 23	719	Feb. 28	17	55
1973-74	Apr. 21	1021	Apr. 9	45	70
1974-75	Apr. 14	848	Apr. 13	1	30
1975-76	Mar. 30	966	Mar. 22	13	40
1976-77	Apr. 11	1265	Apr. 9	14	83
1977-78	Apr. 24	1154	Apr. 9	30	82
1978-79	Apr. 12	1146	Apr. 10	3	100
$\overline{X}$	Apr. 13	1018	Apr. 3	28	68

additional data, and second, evaluation of processes other than those considered here for their impact on ice events. It should be noted that both approaches have the potential to narrow the standard error of estimate, but would not affect the previously described lead times with the same impact as improved air temperature forecasts.

The first general approach to be considered is the extension or improvement of the existing techniques. The identification of freeze-up and breakup dates was done solely from published reports, with a resulting 6-10 years of observations. It certainly would be possible to extend this period to 15-20 years by using local newspaper accounts and carefully constructed interviews. The advantage of this additional work would be that the derived parameters would not be so heavily influenced by the relatively severe winters that occurred during the 1970's.

A second group of desirable data is ice thickness measurements and water velocity measurements beneath the ice cover. These measurements are currently being performed by field teams from the Detroit District of the Corp of Engineers and should continue. Consistent ice thickness measurements will allow an improved evaluation of ice thickness variability over time and space.

Water velocity measurements and water temperature monitoring at additional sites would allow an evaluation of thermal models of the water temperature regime, particularly during the breakup period. Careful consideration should be given to the siting, maintenance, and accuracy of two additional temperature sensors, one located near the upstream end of the river and the other at the narrows between Lake Munuscong and Raber Bay. The average value for the fall heat transfer coefficient is quite similar to the same empirical coefficient used on the St. Lawrence River. Deviations did occur, however. Water temperature measurements in the Whitefish Bay area may help to pinpoint changes in thermal conditions that could not be adequately simulated from local meteorology.

There are three areas of additional analysis not addressed in this report that could be of value in future forecasting efforts. The first topic of interest is a comparison of the ice conditions in Whitefish Bay with ice events in the river. There are 20 years of ice charts in the material used by Assel to prepare the revised *Great Lakes Ice Atlas* (Assel, 1983). The data would be of greatest value if they could be correlated with water temperature, wind speed, and direction.

A second topic for analysis is the effect of snow-ice formation on the growth rates of the ice cover. Deviations from the simulated ice cover growth were most likely due to the retarding effects of heavy snowfall or the growth-inducing effect of snow-ice formation. Such a study would best be performed by careful study of a small area of the ice cover in Raber Bay, with continuous monitoring of micrometeorological conditions as well.

The final suggestion for future analysis is to evaluate breakup from a mechanical and a thermal viewpoint, that is, to give adequate consideration both to those processes that significantly affect ice strength and to the relationship between ice strength and breakup. Two justifications for this approach are that it provides a more realistic view of the breakup process and it has much greater relevance to the movement of ships through the waterway than does the simple appearance or disappearance of the ice cover.

7. REFERENCES

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Appendix A.--FORTRAN PROGRAM FOR COMPUTING BILELLO COEFFICIENTS AND SAMPLE RUN BASED ON FREEZE OVER DATE OF DECEMBER 9, 1973

```
/JOB
/NOSEQ
S,T10.  GREENE
ACCOUNT(GL15,HYDRO,GERL)
CHARGE,W82002,GREENE.
GET,TAPE5=GGMESSS.
FTN.
LGO.
REPLACE,OUTPUT=GGMAP3A.
CALL,BYE.
EXIT.
/EOR
      PROGRAM BILL(INPUT,OUTPUT,TAPE5,TAPE6=OUTPUT)
C
C
C  FILE GGMAPP3
C
C
C  PROGRAM TO COMPUTE BILELLO COEFFICIENT FOR ANY
C  GIVEN STATION AND YEAR
C
C
C  DECEMBER 1981
C  GORDON M. GREENE
C  GREAT LAKES ENVIRONMENTAL RESEARCH LABORATORY
C  ANN ARBOR, MICHIGAN 48104
C  PHONE 313-668-2249   (FTS  378-2249)
C
C
C
   20  FORMAT(1X,3I3,18X,F8.1)
   21  FORMAT(" SIMULATED WATER TEMP. ON DAY OF FREEZE-OVER ",
      +F8.2)
   22  FORMAT(" BILELLO COEF. (XN) FOR THIS STATION AND YEAR ",
      +F8.4)
   23  FORMAT(" NUMBER OF ITERATIONS TO OBTAIN VALID XN ",I8)
   24  FORMAT("1")
   25  FORMAT(" YEAR, MONTH, AND DAY OF FREEZE-OVER ",3I8)
       DIMENSION INUM(13)
       DIMENSION XN(15),F(15)
       DATA INUM/0,31,59,90,120,151,181,212,243,273,304,334,365/
       ICOUNT=0
C
C
C  SET INITIAL GUESSES FOR XN, THE BILELLO COEFFICIENT
C
C
       XN(1)=0.05
       XN(2)=0.01
C
C
C  IDENTIFY THE YEAR, MONTH, AND DAY THAT FREEZE-OVER OCCURS
C  OR THE DATE UPON WHICH WATER TEMPERATURE DROPS TO AND
C  THEN REMAINS AT O (C) IF YOU ARE COMPUTING XN FOR SSM
```

```
C
C
      IYR1=73
      KMO=12
      KDA=9
      KDAY=INUM(KMO)+KDA
      IF(KMO.EQ.1) KDAY=KDAY+365
      IF(KMO.EQ.1) IYR1=IYR1-1
   10 ICOUNT=ICOUNT+1
      IF(ICOUNT.GE.14) GO TO 95
      TAJ=0.
      REWIND 5
   12 DO 100 J=1,5000
C
C
C  MEAN DAILY AIR TEMP. (TA) INPUT FROM FILE GGMAPP2
C   (THIS PROGRAM IS STRUCTURED TO READ FROM A MULTIYEAR FILE,
C  BUT WILL WORK WITH ONLY A SINGLE YEAR OF DATA)
C
C
      READ(5,20) IYR,IMO,IDAY,TA
      IF(EOF(5)) 90,15
   15 CONTINUE
      IF(IMO.EQ.1) IMO=13
      IF(IMO.EQ.13) IYR=IYR-1
      IF(IYR.EQ.IYR1.AND.IMO.GE.6) GO TO 50
      GO TO 100
   50 IF(IMO.EQ.6) TAJ=TAJ+TA
      IF(IMO.EQ.6) GO TO 100
      IF(IMO.EQ.7.AND.IDAY.EQ.1) F(ICOUNT)=TAJ/30.
      JDAY=INUM(IMO)+IDAY
      IF(JDAY.GT.KDAY) GO TO 10
      IF(ICOUNT.LE.2) GO TO 51
C
C
C  THIS PROGRAM USES A SECANT ALGORITHM TO COMPUTE A NEW
C  VALUE FOR XN BASED ON THE TWO PREVIOUS VALUES FOR XN
C  AND THE TWO PREVIOUS VALUES FOR THE SIMULATED WATER
C  TEMPERATURE - F(ICOUNT) - ON THE DATE THAT FREEZE-OVER
C  WAS EXPECTED TO OCCUR.
C  THAT IS, WE PICK A VALUE FOR XN AND THEN PLUG IT INTO
C  THE BILELLO ALGORITHM TO SEE IF IT DROPS WATER TEMPERATURE
C  TO 0 (C) ON THE DATE WE SPECIFIED ABOVE.  IF THE SIMULATED
C  WATER TEMPERATURE ON THAT DATE IS MORE THAN 0.2 (C) ABOVE
C  OR BELOW 0.0 (C), THEN WE PICK A SECOND VALUE FOR XN AND
C  REPEAT THE BILELLO ALGORITHM.  ONCE WE HAVE TWO GUESSES
C  FOR XN AND THE TWO SUBSEQUENT WATER TEMPERATURES ON THE
C  DATE OF FREEZE-OVER, WE THEN INVOKE THE SECANT ALGORITHM
C  TO MAKE CONVERGING GUESSES FOR THE VALUE OF XN
C
C
      J3=ICOUNT
      J2=ICOUNT-1
      J1=ICOUNT-2
```

```
      XN(J3)=XN(J2)-((XN(J2)-XN(J1))*F(J2))/(F(J2)-F(J1))
   51 B=TA
      C=F(ICOUNT)
      D=B-C
C
C
C  COMPUTE THE NEW WATER TEMPERATURE (F(ICOUNT)) BASED ON
C  THE PREVIOUS DAY'S WATER TEMPERATURE ("C"), AND XN
C  TIMES THE DIFFERENCE BETWEEN THE  AIR TEMPERATURE ("B"),
C  AND WATER TEMPERATURE ("C").
C
C
      E=D*XN(ICOUNT)
      F(ICOUNT)=C+E
      FABS=ABS(F(ICOUNT))
      IF(JDAY.EQ.KDAY.AND.FABS.LE.0.2) GO TO 95
      IA=IYR
      IB=IMO
      IC=IDAY
  100 CONTINUE
   90 CONTINUE
   95 CONTINUE
      WRITE(6,24)
      IF(KMO.EQ.1) IYR1=IYR1+1
      WRITE(6,25) IYR1,KMO,KDA
      WRITE(6,21) F(ICOUNT)
      WRITE(6,22) XN(ICOUNT)
      WRITE(6,23) ICOUNT
      STOP
      END
/EOF
```

```
YEAR, MONTH, AND DAY OF FREEZE-OVER          73        12          9
SIMULATED WATER TEMP. ON DAY OF FREEZE-OVER          .08
BILELLO COEF. (XN) FOR THIS STATION AND YEAR .0892
NUMBER OF ITERATIONS TO OBTAIN VALID XN          6
??
```

Appendix B.--FORTRAN PROGRAM TO FORECAST DATE OF FREEZE OVER AND SAMPLE FORECAST FOR SAULT STE. MARIE AS OF DECEMBER 1, 1982

```
/JOB
/NOSEQ
TOMMY.          GREENE
ACCOUNT(GL15,HYDRO,GERL)
CHARGE,W82002,GREENE.
GET,TAPE5=GGM82MD.
FTN,PMD.
LGO.
REPLACE,OUTPUT=GGMAP4A.
CALL,BYE.
EXIT.
CALL,BYE.
/EOR
      PROGRAM FORE(INPUT,OUTPUT,TAPE5,TAPE6=OUTPUT)
C
C   FILE GGMAPP4
C
C
C   PROGRAM TO FORECAST DATE THAT WATER TEMP. DROPS TO
C   0 (C) FOR SAULT STE. MARIE OR DATE THAT ICE COVER
C   FREEZE-OVER OCCURS AT ALL OTHER STATIONS FOR ANY
C   GIVEN YEAR.
C
C
C   JANUARY 1982
C   GORDON M. GREENE
C   GREAT LAKES ENVIRONMENTAL RESEARCH LABORATORY
C   ANN ARBOR, MICHIGAN 48104
C   PHONE 313-668-2249  (FTS  378-2249)
C
C
C
      DIMENSION MON(12),XN(5)
      DATA MON/0,31,59,90,120,151,181,212,243,273,
     +304,334/
      DATA XN/0.0198,0.0188,0.0268,0.0290,0.0154/
   20 FORMAT(2X,2I2,2X,I2,4X,I2,8X,I2)
   22 FORMAT("1")
   23 FORMAT(" STATION CODE AND (MO/DAY/YR) OF LAST OBSERVATION"
     +,I2,4X,3I3)
   24 FORMAT(" OBSERVED WATER TEMP AT SAULT STE. MARIE (C) ",F6.2)
   25 FORMAT(" PROJECTED JULIAN DATE OF FREEZEOVER ", F8.0)
C
C
C   SPECIFY:
C
C   TAJ = AVERAGE JUNE AIR TEMPERATURE
C   ICODE = STATION NUMBER FOR LOCATION TO BE FORECAST
C           VALUES FOR ICODE:
C           1 = WATER TEMPERATURE AT SAULT STE. MARIE
C           2 = FREEZE-OVER AT 108
C           3 = FREEZE-OVER AT 302
C           4 = FREEZE-OVER AT 303
C           5 = FREEZE-OVER AT 401
```

```
C  JYR = YEAR DURING WHICH FORECAST IS ISSUED
C  DEPN = PREDICTED NUMERICAL DEPARTURE OF AIR TEMPERATURES
C          OVER THE NEXT 30 DAYS ABOVE (+) OR BELOW (-)
C          NORMAL  (SEE MONTHLY WEATHER OUTLOOK)
C
C
      TAJ=11.06
      ICODE=1
      JYR=82
      DEPN=0.
      K=0
      KYR=JYR+1
      XXN=XN(ICODE)
C
C
C   INPUT DATA FILE CONTAINS:
C    IDAY = DAY OF MONTH
C    IMO  = MONTH (INPUT DATA MUST START BY JULY 1 FOR ANY GIVEN
C            FORECAST YEAR BUT INPUT DATA FILE MAY CONTAIN MORE
C            THAN ONE YEARS DATA)
C    IYR  = YEAR
C    ITA  = MEAN DAILY AIR TEMPERATURE (F)
C    ITW  = DAILY OBSERVED WATER TEMP AT SAULT STE. MARIE (F)
C
C
      DO 100 I=1,3650
      READ(5,20) IDAY,IMO,IYR,ITA,ITW
C
C
C   CONVERT MEAN DAILY AIR TEMPERATURE AND WATER TEMPERATURE
C   FROM FARENHEIT TO CENTIGRADE
C

C
      TA=FLOAT(ITA-32)*5/9
      TWOBS=FLOAT(ITW-32)*5/9
      IF(EOF(5)) 90,15
   15 CONTINUE
      IF(IYR.EQ.KYR.AND.IMO.EQ.1)GO TO 16
      IF(IYR.EQ.KYR.AND.IMO.GT.1)GO TO 90
      IF(IYR.LT.JYR)GO TO 100
      IF(IMO.LT.7)GO TO 100
      K=K+1
   16 JDAY=MON(IMO)+IDAY
      IF(IMO.EQ.1) JDAY=JDAY+365.
      B=TA
      IF(K.EQ.1) C=TAJ
      D=B-C
      E=D*XXN
      TW=C+E
      TWS=TW
      C=TW
  100 CONTINUE
   90 CONTINUE
```

```
      CALL FCAST(DEPN,JDAY,TWS,XXN,DAY)
      WRITE(6,22)
      WRITE(6,23) ICODE,IMO,IDAY,JYR
      WRITE(6,24) TWOBS
      WRITE(6,25) DAY
      STOP
      END
C
C
      SUBROUTINE FCAST(DEPN,JDAY,TW,XXN,DAY)
C
C
C   COMPUTATION OF DATE UPON WHICH WATER TEMP REACHES
C   0 (C) - EQUIVALENT TO DATE OF ICE-COVER FORMATION
C
C
C
C
      DAY=FLOAT(JDAY)
C
C
C    DEPN IS RESET TO 0. AFTER 30 DAYS BECAUSE NWS ONLY PROJECTS
C    THE DEPARTURE FROM NORMAL ONE MONTH IN ADVANCE
C
C
      DAYL=FLOAT(JDAY)+30.
      DO 100 I=1,500
      DAY=DAY+1.
      CALL TNORM(DAY,TA)
      IF(DAY.GT.DAYL)DEPN=0.
      TA=DEPN+TA
      B=TA
      IF(I.EQ.1) C=TW
      D=B-C
      E=D*XXN
      TW=C+E
      C=TW
      IF(I.EQ.499) GO TO 50
      IF(TW.LE.0.) GO TO 51
  100 CONTINUE
  50  PRINT*,"   I = 499  "
  51  CONTINUE
      RETURN
      END
C
C
      SUBROUTINE TNORM(DAY,TA)
C
C    ALPH AND BETA ARE THE COEFICIENTS FOR THE FIRST HARMONIC
C    OF THE SAULT STE. MARIE NORMAL AIR TEMPERATURE SERIES.
C    THE FIRST HARMONIC CAPTURES 99.6 PERCENT OF THE VARIANCE OF
C    THE ORIGINAL.
C
C
```

```
      TN=4.492
      ALPH=-12.588
      BETA=-5.839
      PI=3.14159
      XI=2.*PI*DAY/365.
      TA=TN+(ALPH*COS(XI)+BETA*SIN(XI))
      RETURN
      END
/EOF
```

```
STATION CODE AND (MO/DAY/YR) OF LAST OBSERVATION 1     12  1 82
OBSERVED WATER TEMP AT SAULT STE. MARIE (C)     5.56
PROJECTED JULIAN DATE OF FREEZEOVER      368.
??
```

Appendix C.--FORTRAN PROGRAM TO FORECAST ICE-COVER THICKNESS AND SAMPLE FORECAST AT STATION 108 AS OF FEBRUARY 15, 1976

```
/JOB
/NOSEQ
S.   GREENE
ACCOUNT(GL15,HYDRO,GERL)
CHARGE,W82002,GREENE.
GET,TAPE5=GGA5AUX.
FTN,PMD.
LGO.
REPLACE,OUTPUT=GGMAP5A.
CALL,BYE.
EXIT.
CALL,BYE.
/EOR
      PROGRAM DEGD(INPUT,OUTPUT,TAPE5,TAPE6=OUTPUT)
C  FILE GGMAPP5
C
C
C  JANUARY 1982
C  GORDON M. GREENE
C  GREAT LAKES ENVIRONMENTAL RESEARCH LABORATORY
C  ANN ARBOR, MICHIGAN 48104
C  PHONE  313-668-2249   (FTS 378-2249)
C
C
C  PROGRAM TO FORECAST ICE-COVER THICKNESS AT SELECTED STATIONS
C  ON THE ST MARYS RIVER ONCE ICE-COVER HAS FORMED
C
C
      DIMENSION MON(12)
      DATA MON/0,31,59,90,120,151,181,212,243,273,
     +304,334/
   20 FORMAT(1X,3I3,16X,F8.1)
   21 FORMAT(2X,5I6,2F8.2)
   22 FORMAT(2X,2I6,12X,I6,2F8.2)
   23 FORMAT("1")
   24 FORMAT(" STATION  YEAR MONTH   DAY  JDAY    FDD       ZI")
   25 FORMAT(" FDD = SUM FREEZING DEGREE DAYS SINCE FREEZEOVER")
   26 FORMAT(" ZI = SIMULATED ICE COVER THICKNESS (CM)")
   27 FORMAT(" START OF FORECAST AIR TEMPERATURES ")
C
C
C
C  SPECIFY:
C  ICODE = STATION CODE FOR LOCATION TO BE FORECAST
C          VALUES FOR ICODE
C          1 = ICE THICKNESS AT 403
C          2 = ICE THICKNESS AT 108
C          3 = ICE THICKNESS AT 302
C          4 = ICE THICKNESS AT 303
C          5 = ICE THICKNESS AT 401
C          6 = ICE THICKNESS AT 402
C
C
C  JDAY = JULIAN DATE OF INITIAL ICE COVER FORMATION
```

```
C          AT FORECAST SITE
C   DEPN = EXPECTED DEPARTURE FROM NORMAL AIR TEMPERATURES
C          (SEE MONTHLY WEATHER OUTLOOK)
C
C
      ICODE=2
      DEPN=0.
      JDAY=15
      FAC=3.47
      SUMT=0.
      F=0.6
      IF(ICODE.EQ.2) F=0.5
      WRITE(6,23)
      WRITE(6,25)
      WRITE(6,26)
      WRITE(6,24)
C
C
C   COMPUTE DAILY TOTAL ICE THICKNESS UNTIL END OF
C   OBSERVED AIR TEMPERATURES
C
C
      DO 100 K=1,500
C
C
C   INPUT FILE:
C   IYR = YEAR
C   IMO = MONTH
C   IDAY = DAY
C   TA = AIR TEMP IN CENTRIGRADE
C
C
      READ(5,20) IYR,IMO,IDAY,TA
      IF(EOF(5)) 90,15
   15 CONTINUE
      JXDAY=MON(IMO)+IDAY
      IF(JXDAY.LT.JDAY) GO TO 100
      SUMT=SUMT+(0.-TA)
      IF(SUMT.LE.0.) SUMT=0.
      ZICE=F*FAC*SQRT(SUMT)
      WRITE(6,21) ICODE,IYR,IMO,IDAY,JXDAY,SUMT,ZICE
  100 CONTINUE
   90 CONTINUE
      ICOUNT=0
C
C
C   CONTINUE COMPUTING DAILY TOTAL ICE THICKNESS BASED
C   ON NORMAL OR EXPECTED AIR TEMPERATURES
C
C
      WRITE(6,27)
      DO 200 J=1,500
      ICOUNT=ICOUNT+1
      JXDAY=JXDAY+1
```

```
      IF(JXDAY.GT.120) GO TO 290
      XDAY=FLOAT(JXDAY)
      CALL TNORM(XDAY,TA)
      IF(ICOUNT.LE.30) TA=TA+DEPN
      SUMT=SUMT+(0.-TA)
      ZICE=F*FAC*SQRT(SUMT)
      WRITE(6,22) ICODE,IYR,JXDAY,SUMT,ZICE
  200 CONTINUE
  290 CONTINUE
      STOP
      END
C
      SUBROUTINE TNORM(DAY,TA)
C
C    ALPH AND BETA ARE THE COEFICIENTS FOR THE FIRST HARMONIC
C    OF THE SAULT STE. MARIE NORMAL AIR TEMPERATURE SERIES.
C    THE FIRST HARMONIC CAPTURES 99.6 PERCENT OF THE VARIANCE OF
C    THE ORIGINAL TIME SERIES.
C
C
      TN=4.492
      ALPH=-12.588
      BETA=-5.839
      PI=3.14159
      XI=2.*PI*DAY/365.
      TA=TN+(ALPH*COS(XI)+BETA*SIN(XI))
      RETURN
      END
/EOF
```

FDD = SUM FREEZING DEGREE DAYS SINCE FREEZEOVER
ZI = SIMULATED ICE COVER THICKNESS (CM)

STATION	YEAR	MONTH	DAY	JDAY	FDD	ZI
2	76	1	15	15	16.10	6.96
2	76	1	16	16	29.00	9.34
2	76	1	17	17	50.30	12.31
2	76	1	18	18	64.70	13.96
2	76	1	19	19	71.00	14.62
2	76	1	20	20	78.20	15.34
2	76	1	21	21	88.80	16.35
2	76	1	22	22	111.50	18.32
2	76	1	23	23	134.80	20.14
2	76	1	24	24	151.20	21.33
2	76	1	25	25	162.70	22.13
2	76	1	26	26	169.20	22.57
2	76	1	27	27	177.70	23.13
2	76	1	28	28	187.10	23.73
2	76	1	29	29	198.90	24.47
2	76	1	30	30	214.00	25.38
2	76	1	31	31	223.20	25.92
2	76	2	1	32	240.10	26.88
2	76	2	2	33	260.80	28.02
2	76	2	3	34	270.80	28.55
2	76	2	4	35	282.10	29.14
2	76	2	5	36	294.30	29.76
2	76	2	6	37	304.80	30.29
2	76	2	7	38	315.70	30.83
2	76	2	8	39	322.20	31.14
2	76	2	9	40	327.40	31.39
2	76	2	10	41	327.70	31.41
2	76	2	11	42	335.80	31.79
2	76	2	12	43	340.30	32.01
2	76	2	13	44	344.90	32.22
2	76	2	14	45	353.20	32.61
START OF FORECAST AIR TEMPERATURES						
2	76			46	361.71	33.00
2	76			47	370.13	33.38
2	76			48	378.46	33.75
2	76			49	386.70	34.12
2	76			50	394.84	34.48
2	76			51	402.88	34.82
2	76			52	410.82	35.17
2	76			53	418.65	35.50
2	76			54	426.36	35.83
2	76			55	433.97	36.14

??

2	76	56	441.45	36.45
2	76	57	448.81	36.76
2	76	58	456.04	37.05
2	76	59	463.15	37.34
2	76	60	470.12	37.62
2	76	61	476.96	37.89
2	76	62	483.65	38.16
2	76	63	490.21	38.41
2	76	64	496.61	38.66
2	76	65	502.87	38.91
2	76	66	508.98	39.14
2	76	67	514.92	39.37
2	76	68	520.71	39.59
2	76	69	526.34	39.80
2	76	70	531.81	40.01
2	76	71	537.10	40.21
2	76	72	542.23	40.40
2	76	73	547.18	40.58
2	76	74	551.95	40.76
2	76	75	556.55	40.93
2	76	76	560.96	41.09
2	76	77	565.19	41.25
2	76	78	569.23	41.39
2	76	79	573.09	41.53
2	76	80	576.75	41.67
2	76	81	580.21	41.79
2	76	82	583.48	41.91
2	76	83	586.55	42.02
2	76	84	589.42	42.12
2	76	85	592.08	42.22
2	76	86	594.54	42.30
2	76	87	596.80	42.38
2	76	88	598.84	42.46
2	76	89	600.67	42.52
2	76	90	602.28	42.58
2	76	91	603.68	42.63
2	76	92	604.87	42.67
2	76	93	605.83	42.70
2	76	94	606.58	42.73
2	76	95	607.10	42.75
2	76	96	607.40	42.76
2	76	97	607.48	42.76
2	76	98	607.32	42.76

??