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Objective Prediction of Ice Formation, Freeze-up and Breakup on the Great Lakes

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ABSTRACT

Objective predictions of first permanent ice formation and freeze-up on the Great Lakes were made by use of cumulative freezing degree-day totals, by the Lisitzin-Rodhe-Bilello equation, by use of departures from normal air temperature and by use of 30-day temperature outlooks. The four objective methods yield similar improvement over use of the mean date of freeze-up in prediction of these ice events, although freezing degree-day totals appear to represent the best method. Lake Superior ice cover can be predicted using the freezing degree-day method extrapolated to mid-lake locations with better results than a climatological prediction based on the use of long-term mean freeze-up dates.

Ice breakup on the Great Lakes was predicted using thawing degree-day totals and a correlation between stations approach. Both of these predictive techniques are superior to use of the mean date of breakup as a prediction.

1. Introduction

In this study various objective techniques for prediction of ice formation, freeze-up and breakup on the Great Lakes will be compared with predictions based on mean date of the event and with each other to determine their efficacy. Although Great Lakes shipping would benefit from improved ice predictions, only Richards (1964) and Snider (1974) have specifically attempted to deal objectively with Great Lakes ice conditions. Both of these previous studies concentrated on the use of air temperatures, expressed as freezing degree-day (FDD) totals,[1] for objectively predicting freeze-up. This study re-examines FDD's, considers the efficacy of a differential equation to estimate loss of sensible heat from the water body to the atmosphere (Bilello, 1964), the use of departures from normal air temperatures and use of the National Weather Service *Average Monthly Weather Outlook* (30-day temperature outlooks) in prediction of formation of first permanent ice and freeze-up on the Great Lakes.

Little attention has been given to techniques for prediction of breakup on the Great Lakes or other inland water bodies, although Richards (1964) mentions that an analog to the FDD would be a thawing degree-day (TDD)[2], which might be used for predicting breakup. Snider (1974) indicates that solar radiation contributes heavily to ice deterioration and eventual breakup. In general, objective methods to predict breakup have been viewed by most forecasters as more difficult to develop and use than similar methods for freeze-up. This study will evaluate two objective techniques for prediction of ice breakup (use of thawing degree-day totals and a correlation between stations approach) and will compare the efficacy of these techniques with use of the long-term mean date of breakup.

Further refinement of forecast techniques must await accumulation of a data base adequate to permit construction of a physical-dynamic thermal model. Such a model could consider the seasonal cycle of heat storage in lake waters and surpass limited objective models which consider only air and water temperatures.

One of the biggest problems in developing and testing objective prediction techniques for Great Lakes ice cover is the lack of historical records of ice events which are needed for a statistical study. For many Great Lakes harbors, records of ice events have been kept for three to four years and then abandoned, or have just begun recently as part of the Ice Information Demonstration Program. This program was part of the Great Lakes–St. Lawrence Seaway Navigation Season

[1] Since the aim of this research is to aid operational ice forecasting, the definition of a freezing degree-day is the depression of the mean temperature by 1°F below 32°F for one day; where a total in FDD Centigrade is given in the text, it is the FDD Fahrenheit total multiplied by 5/9.

[2] A thawing degree-day is defined as the elevation of the mean temperature by 1°F above 32°F for one day; TDD Centigrade as stated in the text is the TDD Fahrenheit total multiplied by 5/9.

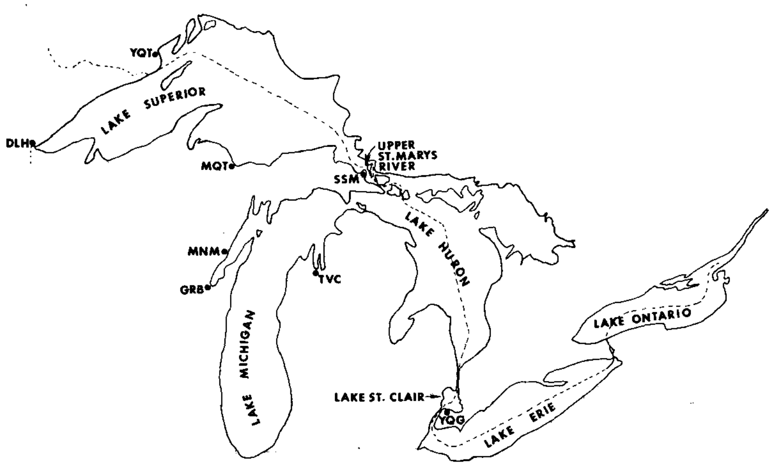


FIG. 1. Map of the Great Lakes and connecting waterways. Meteorological stations indicated are DLH (Duluth), YQT (Thunder Bay), MQT (Marquette), SSM (Sault Ste. Marie), MNM (Menominee), GRB (Green Bay), TVC (Traverse City) YQG (Windsor).

Extension Demonstration Program which was authorized by Congress in the River and Harbor Act of 1970, and amended by the Water Resources Development Act of 1974. The program was undertaken to demonstrate the practicability of extending the navigation season on the Great Lake–St. Lawrence Seaway System. The U. S. Army Corps of Engineers was designated as the lead agency to manage the program with the assistance of other key federal and state agencies. The research presented in this paper deals with development of improved ice forecasting techniques which would benefit navigation.

The statistical nature of the present study required sequences (chronologies) of ice events for specific ports of at least 10-years length. Ports and waterways in the Great Lakes having such records include Thunder Bay, Menominee, Grand Traverse Bay, the Upper St. Marys River and Windsor (see Fig. 1 for locations). Another input for prediction of ice formation and freeze-up is water temperature. The authors have met with considerable success in obtaining daily water temperatures for Thunder Bay, Menominee and Sault Ste. Marie (a city located on the Upper St. Marys River) from municipal water treatment plant records. However, available water temperature records covered a shorter span of years than the ice chronologies for these three locations. Air temperatures for all locations are readily available.

TABLE 1. Comparison of various objective methods for predicting date for formation of first permanent ice on the Upper St. Marys River. Probability given is that of being within x number of days of the observed date.

Method	50% Probability	80% Probability
Mean date of freeze-up (1962–72)	12 days	16 days
Freezing degree-day totals (1962–72)	7 days	9 days
Lisitzin-Rodhe-Bilello equation with observed 1 November water temperatures (1963–72)	8 days	11 days
Lisitzin-Rodhe-Bilello equation with an assumed 1 November water temperature of 49°F (9.4°C) (1963–72)	8 days	9 days

2. Predictive techniques for freeze-up

Two ice formation events which are predicted are 1) formation of first permanent ice and 2) total freeze-up. The approach used for predicting these events is the same—developing and using empirical relationships between meteorological and limnological parameters and information from ice chronologies.

For the Upper St. Marys River (often called the "Soo Waterway"), the date of first ice formation has been recorded continuously since 1962 by the Canadian Meteorological Service (Allen and Cudbird, 1971). During the period 1962–72, the climatological mean date of first permanent ice formation was 17 December. Using this date as a predictor, and the dependent data set, predictions of first permanent ice were within 12 days of the observed 50% of the time, and within 16 days, 80% of the time (see Table 1). Statistics, such as the standard deviation, are not used for comparisons of the methods since several years have dates of freeze-over which are questionable and which dominate any summation of squares. Since no solid evidence could be found that these dates were in fact in error, it did not appear to be justifiable to discard the questionable years. In the comparison method given here, each year has equal weight in the verification.

Two objective methods for predicting first permanent ice formation were tested on the Upper St. Marys River ice chronology: use of FDD's and use of a differential equation (the Lisitzin-Rodhe-Bilello equation) to estimate loss of sensible heat from the water body to the atmosphere (Bilello, 1971). For use in predicting ice formation on the Upper St. Marys River (and other Great Lakes ports and waterways) the FDD method is applied as follows: an estimate of how many FDD's accumulated in an average year before first permanent ice appeared was made by calculating cumulative FDD totals beginning 1 November, then the cumulative FDD totals for each year on the date of first permanent ice formation were averaged. It was found that an average of 133 FDD Centigrade (240 FDD Fahrenheit) were accumulated at Sault Ste. Marie before formation of first permanent ice. Based on observations, a hindcast was made of when first permanent ice would form. Fifty percent of the predictions verified within 7 days, representing a significant improvement over the use of mean data of freeze-up as a predictor (see Table 1).

The Lisitzin-Rodhe-Bilello equation (Bilello, 1964, 1967; Rodhe, 1955) can be stated as

$$\frac{d\tau}{dt}=K(T-\tau),$$

where T is the air temperature, τ the surface water temperature, t the time in days and K a constant (day^{-1}).

Water temperatures for the Upper St. Marys River were available for the years 1963–72, thus allowing 10 years of data to be used for hindcasting. A K of 0.03 day^{-1} for this locality was determined empirically, and iteration of the equation was conducted for each year beginning with the 1 November water and air temperatures. Fifty percent of the time the prediction of date of first permanent ice formation on the Upper St. Marys River verified within 8 days (Table 1).

Since water temperatures are often difficult to obtain, use of the Lisitzin-Rodhe-Bilello equation with an average 1 November water temperature was explored. Prediction of date of formation of first permanent ice on the Upper St. Marys River using this modified Lisitzin-Rodhe-Bilello method was found to verify within 8 days 50% of the time (Table 1).

Comparison of the use of the observed and average water temperatures in the Lisitzin-Rodhe-Bilello equation at the 80% level indicate that using the average 1 November water temperature may yield better predictions for formation of first permanent ice on the Upper St. Marys River than using the observed 1 November water temperature. Recorded water temperatures from 1 November represent point observations, while the conditions of the water body during late October and early November are highly variable. Stratification is growing less pronounced with the onset of colder air temperatures. Use of the average of all 1 November water temperatures apparently provides a method for coping with unusual upwelling or downwelling conditions during several years which would otherwise bias the calculations.

TABLE 2. Comparison of various objective methods for predicting freeze-up at Menominee, Mich., for the years 1945–62. Probability given is that of being within x number of days of the observed date.

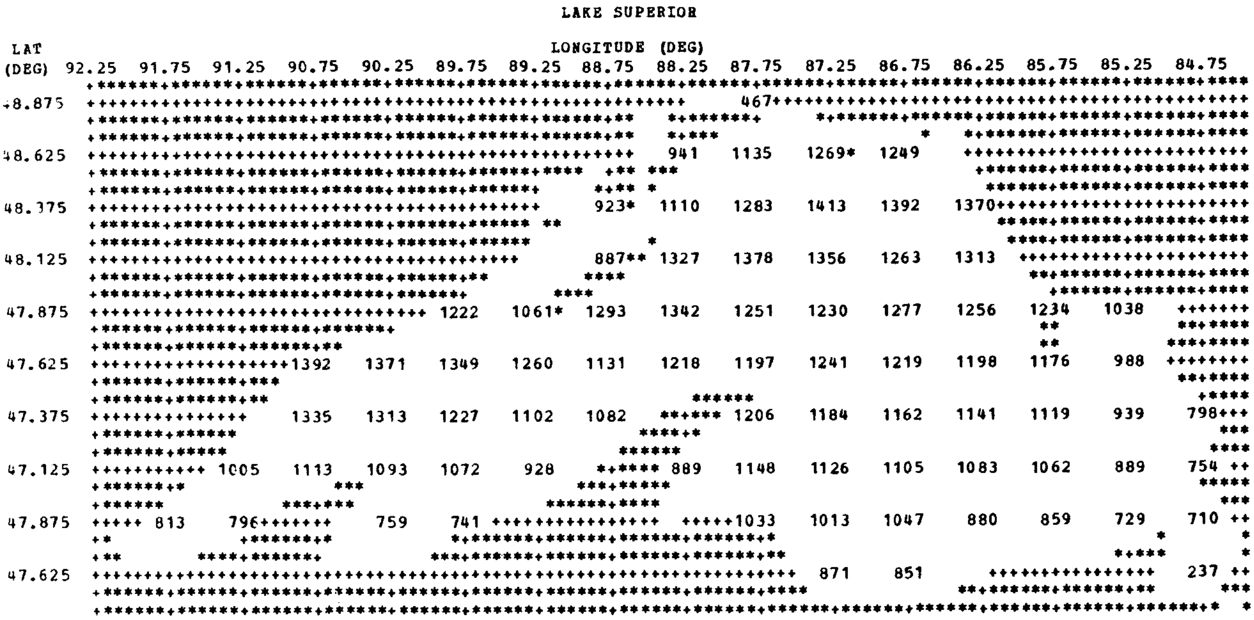
Method	50% Probability	80% Probability
Mean date of freeze-up	8 days	14 days
Freezing degree-day totals	4 days	8 days
Departure from normal air temperatures	5 days	10 days
30-day temperature outlook	5 days	11 days
Lisitzin-Rodhe-Bilello equation with observed 1 November water temperatures	4 days	12 days
Lisitzin-Rodhe-Bilello equation with 1 November water temperature of 11.1°C (52°F)	4 days	11 days

Both the FDD method and the Lisitzin-Rodhe-Bilello equation can be used to forecast freeze-up of a lake, harbor or river. Using the freeze-up chronology for Menominee, Mich. (a harbor situated on Green Bay, Lake Michigan) and weather records for Green Bay, Wisc., hindcasts of freeze-up were made for the years 1945–62. During this period an average of 210 FDD Centigrade (378 FDD Fahrenheit) were accumulated when freeze-up was recorded. Fifty percent of the hindcasts verified within 4 days, compared with a prediction based on mean date of freeze-up, which verified within 8 days 50% of the time (Table 2).

The 1 November water temperatures were obtained from records of the Menominee Municipal Water Treatment plant for the years 1945–62. These water temperatures and the recorded Green Bay air temperatures were used as input into the Lisitzin-Rodhe-Bilello Equation. A value of K of 0.024 day^{-1} was determined empirically, and iterations perfomed to yield a prediction for each year.

Fifty percent of the time the hindcast verified within 4 days, while 80% of the time it was within 12 days. Thus, the Lisitzin-Rodhe-Bilello equation is not quite as good as the FDD method for predicting freeze-up at Menominee (Table 2).

Because of the length of the ice chronology for Menominee (begun in 1899), relatively elaborate predictive techniques based on air temperatures can be used to predict ice formation. Since freeze-up should occur earlier than normal in years when air temperatures are below normal, a predictive scheme utilizing departures from normal air temperatures was developed. The objective scheme was quantified by determining the number of degrees above or below the



KEY WATERWAYS AND SELECTED PORTS

DULUTH	SAULT STE. MARIE	MARQUETTE	KEWEENAW WATERWAY	WHITEFISH BAY
400	221	872	894	234

FIG. 2. Total FDD (°C) accumulation from 1 November to freeze-up based on 20 years of data.

daily mean temperature accumulated since 1 November at Menominee each year for the period 1914–63. This value was then related to the actual date of freeze-up each year using a linear regression technique. To enable a forecaster to use this technique operationally, the degree departure total accumulated to the mean date of freeze-up (24 December) was used. The following regression equation was determined:

$$F=56.6+0.233D,$$

where F is the date of freeze-up (number of days elapsed from 1 November), and D the accumulated departure (°C) on 29 December. The correlation coefficient was 0.6 for the data set used to establish the regression. For the period 1945–62, this method for predicting freeze-up at Menominee verified within 5 days 50% of the time, a 3-day improvement over use of mean date of freeze-up as a predictor (Table 2).

Another similar predictive technique for forecasting freeze-up was developed so that objective use of the National Weather Service *Average Monthly Weather Outlook* could be made. This 30-day temperature guidance specifies departures from normal air temperatures as 1) above normal (30% of the years), 2) normal (40% of the years) and 3) below normal (30% of the years). Inspection of Menominee temperatures departures for the period 1914–62 showed that in a December with below-normal temperatures, on the average, freeze-up occurred on 22 December, while with above-normal December temperatures, on the average, freeze-up occurred on 9 January. Years in which the air temperatures during December were normal experienced freeze-up on the average on 26 December (Table 2). Fifty percent of the time during the period 1914–62, this hindcast technique verified within 5 days using the Menominee chronology.

3. Objective prediction of ice cover

The objective prediction methods for freeze-up show promise for operational use both in port forecasting and in providing 30-day outlook guidance of Great Lakes ice cover. The applicability of these techniques for predicting ice cover over deep-water locations was investigated for Lake Superior. This test used the FDD method for predicting freeze-up for the whole lake, and produced results in the graphic form shown in Figs. 2–4, with a summary for key ports and waterways on Lake Superior. For the test, air temperature data from the shore stations at Duluth, Thunder Bay, Sault Ste. Marie and Marquette (Fig. 1) were used, with air temperatures for mid-lake locations obtained from a planar fit of the shore data. The paucity of input data probably does not justify further sophistication in the objective analysis technique at this stage.

For numerical manipulation, Lake Superior was divided into a grid, with each grid unit being $\frac{1}{2}$° longitude by $\frac{1}{4}$° latitude. An estimate of freeze-up using the FDD method was made by finding the average FDD's accumulation from 1 November to freeze-up based on 24 years of data. Dates of freeze-up for each block were

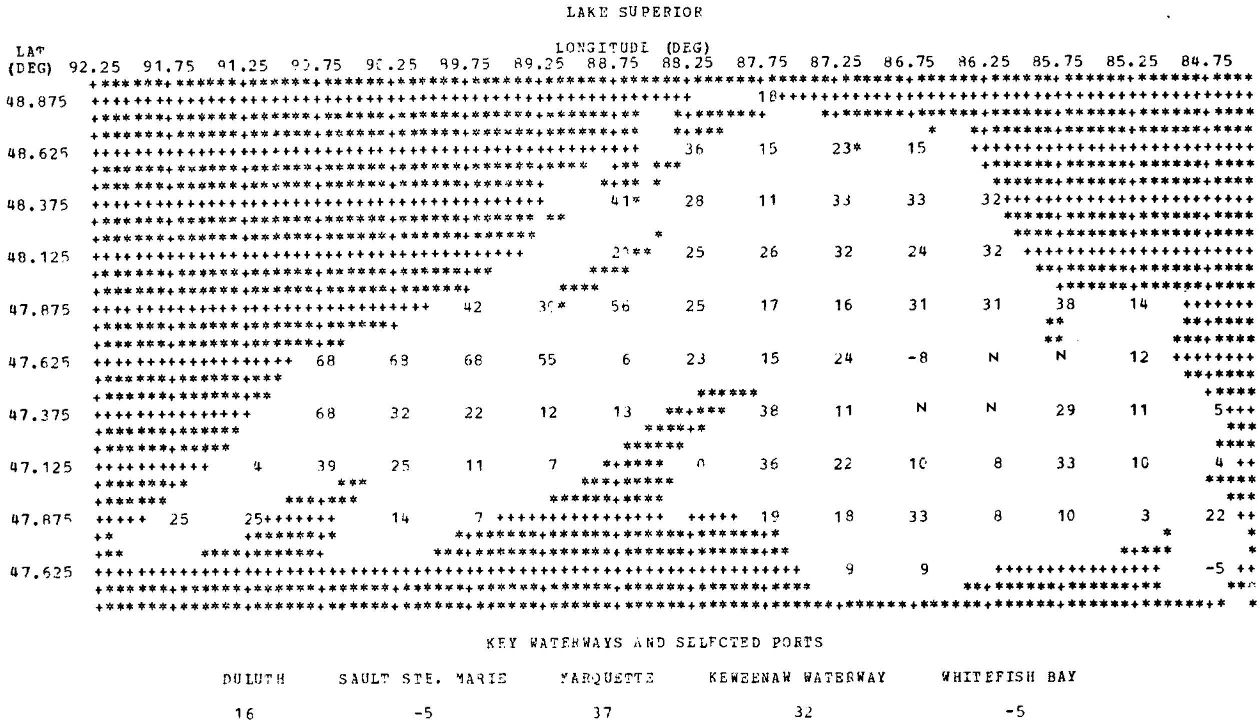


Fig. 3. Departure in days of date of freeze-up using FDD method from verification for the 1973–74 ice season. An N means that freeze-up was predicted, but did not occur.

interpolated from those given in the climatology of Rondy (1971) for a normal winter. For localities where the lake does not normally freeze, an assignment of the FDD total on 31 March was made. Average FDD totals at freeze-up are given in Fig. 2. Using interpolated temperatures, FDD's for the 1973–74 ice season were

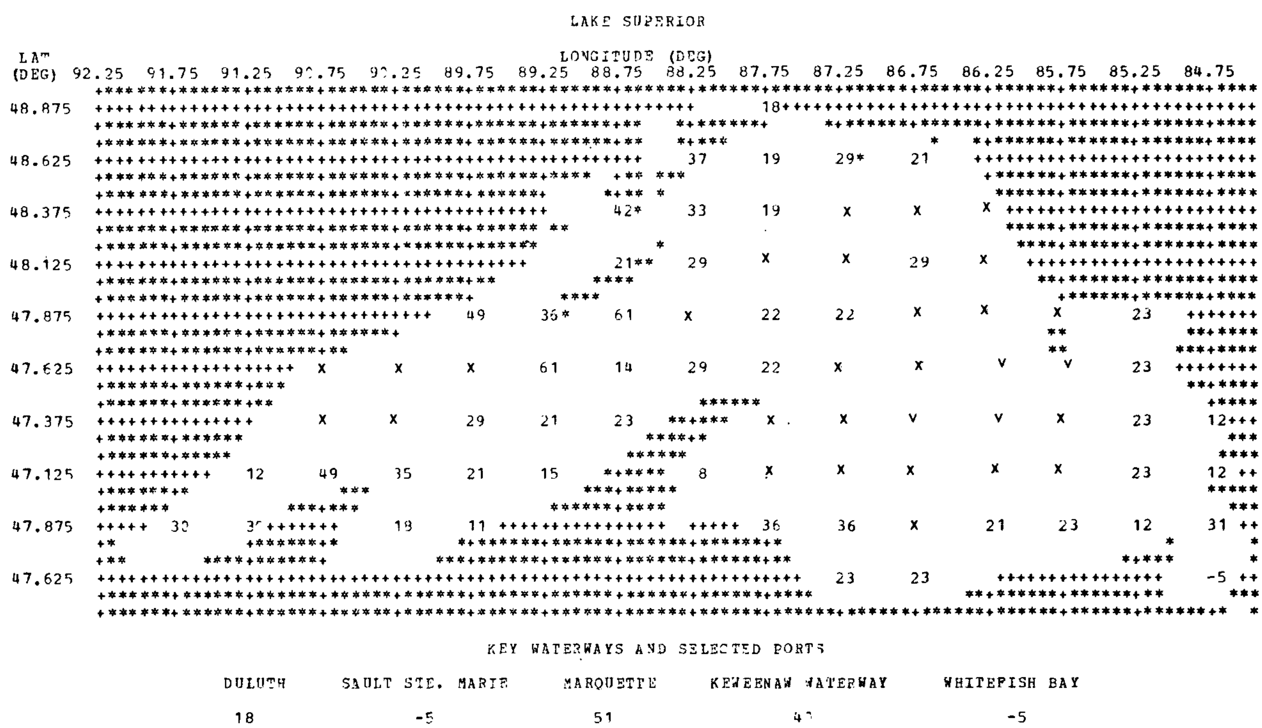


Fig. 4. Departure in days of date of freeze-up from verification using climatology for the 1973–74 ice season. An X means freeze-up occurred even though it was not predicted. A V means freeze-up did not occur even though it was predicted.

Table 6. Correlation coefficients for date of breakup at Thunder Bay, Menominee, Traverse City and Windsor for the years 1962–68, with 1964 undefined, since Menominee and Traverse City were open all season that year.

Variable	Breakup at Thunder Bay	Breakup at Menominee	Ice went out at Traverse City	Breakup at Windsor
Breakup at Thunder Bay	1.00			
Breakup at Menominee	0.72	1.00		
Ice went out, Traverse City	0.74	0.92	1.00	
Breakup at Windsor	0.69	0.91	0.99	1.00

only requirement for such a technique to be of operational value is that the time lag between breakup events be large enough for the forecaster to use. This requirement was met with the ice chronologies from Windsor, where the mean date of breakup is 29 March, and from Menominee, where the mean date of breakup was 7 April for the period 1962–70. For this period, the coefficient of correlation between these chronologies was 0.87. A scatter plot of the dates of breakup at Windsor and Menominee is shown in Fig. 5. The easiest way to exploit this relationship in developing a predictive technique is to make a least-squares linear regression. The equation thus produced is

$$\mathrm{MNM} = -6.9 + 1.5\ \mathrm{YQG},$$

where MNM and YQG are the number of days after 1 March until breakup at Menominee and Windsor, respectively. Verification of this method at the 50 and 80% levels is given in Table 4, comparing favorably with use of mean date of breakup.

5. Concluding summary

Ice formation and freeze-up on the Great Lakes can be objectively predicted by four different techniques

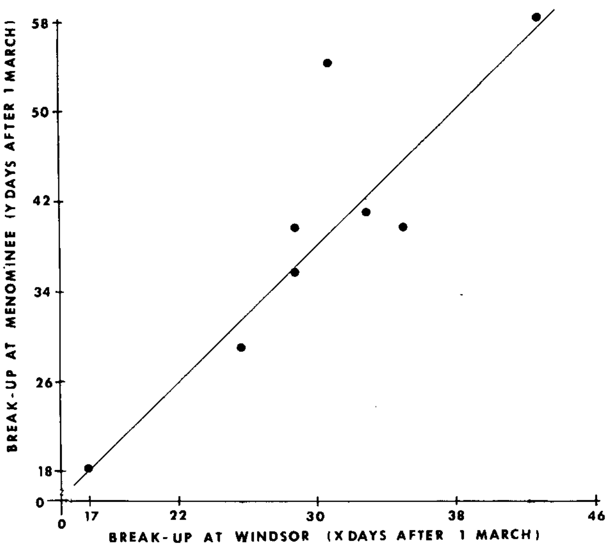


Fig. 5. Scatter plot showing breakup dates at Menominee and Windsor for the years 1962–64, 1966–70. The year 1965 is omitted, since freeze-up at Menominee did not occur that year.

which are superior to use of long-term mean dates: freezing degree day totals, departures from normal air temperatures, 30-day temperature outlooks and the Lisitzin-Rodhe-Bilello equation. Use of freezing degree day totals appears to be the best of these four methods in predicting both formation of first permanent ice on the Upper St. Marys River and freeze-up at Menominee (Tables 1 and 2). The Lisitzin-Rodhe-Bilello equation, using either observed or average 1 November water temperatures, appears to be a good predictive technique. The use of departures from normal air temperatures and 30-day temperature outlooks in forecasting freeze-up are feasible only when a sufficiently long ice chronology is available for the port or waterway of interest.

Extension of the use of freezing degree-day totals to provide 30-day forecast guidance on ice cover on Lake Superior yields results superior to use of mean date of freeze-up.

Thawing degree-day totals provide a promising objective technique for predicting breakup of ice on the Great Lakes, yielding results that are much superior to use of mean date of breakup (Tables 3 and 4). Use of correlation between stations for predicting breakup is promising for those localities on the Great Lakes possessing extensive ice chronologies.

The objective techniques for forecasting ice formation, freeze-up and breakup which have been discussed can be adapted for immediate application. However, development of a physical-dynamic heat flux model which could be run on an AFOS-type minicomputer should be contemplated when AFOS is implemented.

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