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LAKE CHAMPLAIN ICE FORMATION AND ICE FREE DATES AND PREDICTIONS--ETC(U)
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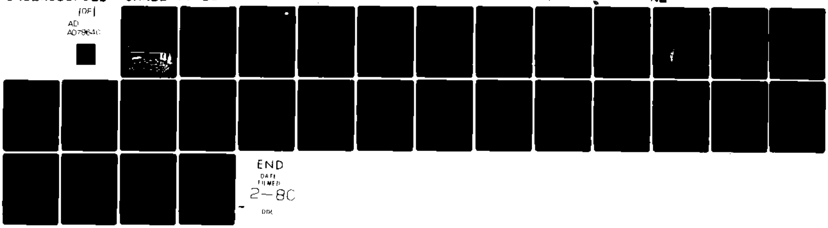

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REPORT 79-26

Lake Champlain ice formation and ice free dates and predictions from meteorological indicators

Cover: Grand Isle Ferry Docking Slip, Gordon Landing, Vermont, on Lake Champlain, February 1977. (Photograph by R. Bates.)

CRREL Report 79-26

Lake Champlain ice formation and ice free dates and predictions from meteorological indicators

Roy E. Bates and Mary-Lynn Brown

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A 19-year record of the annual closing and opening dates of operation of the Lake Champlain ferry at Grand Isle, Vermont, which are controlled by the lake's ice cover, was made available to CRREL. These navigation records accurately approximated the freeze-over and breakup dates for the ferry crossing area between Gordon Landing, Vermont, and Cumberland Head, New York. When compared statistically with water temperature and climatological data for the same years at nearby Lake Champlain locations, the dates allowed accurate predictions of ice formation. From nearby air temperature records, cumulative freezing degree-day (°C) curves were plotted for each year of record and ice formation dates and standard deviations were predicted with considerable accuracy. Several methods of predicting ice formation on Lake Champlain were attempted. The most accurate approach used a combination of

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water temperatures and freezing degree-days. The influence of wind speed on ice cover formation and prediction are also discussed in the report.

PREFACE

This report was prepared by Roy E. Bates, Meteorologist, and Mary-Lynn Brown, Science Aid, of the Snow and Ice Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory.

The study was conducted under DA Program *Ice Engineering,* Subprogram *Ice Decay,* Work Unit CWIS 31361, *Thermal Regimes Disturbed by Man*.

The authors express appreciation to Dr. George D. Ashton and Richard K. Haugen for their helpful suggestions concerning the study and for technical review of the manuscript. They also express appreciation to the Lake Champlain Transportation Company, Burlington, Vt., especially to John Camm, for providing records of the dates of opening and closing of their ferry service and data on water temperature.

The U.S. Army Atmospheric Sciences Laboratory (White Sands, New Mexico) meteorological team based at CRREL furnished and installed the meteorological instrumentation and tabulated the meteorological field data for the winters of 1975-76 at Shelburne, Vt., and 1976-77 and 1977-78 at Grand Isle, Vt.

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LAKE CHAMPLAIN ICE FORMATION AND ICE FREE DATES AND PREDICTIONS FROM METEOROLOGICAL INDICATORS

Roy E. Bates and Mary-Lynn Brown

INTRODUCTION

This report summarizes several climatological variables: freezing degree-days (accumulated below a base of 0°C), air temperatures (1959-78), and water temperatures (1962-78) at or near Burlington, Vermont, which is situated on Lake Champlain (Fig. 1). Annual opening and closing dates of the Lake Champlain Transportation Company (LCT. Co.) Ferry, located at Grand Isle, Vermont, were provided by the company.[1] These opening and closing dates are controlled by ice cover formation and decay on the lake. CRREL established and operated a meteorological station at the Grand Isle site during the winters of 1977 and 1978 and at Shelburne Point, Vermont, also on Lake Champlain, during the winters of 1975 and 1976.

The overall objective of this study was to examine climatic variables, lengths of ice seasons, air and water temperatures, and freezing degree-days. Specific objectives were: 1) to determine the relationships existing between air and water temperatures and ice formation and breakup on Lake Champlain; 2) to determine if any correlations between these variables might be useful tools in the prediction of ice formation and breakup dates; and 3) to determine the effects of wind speed on ice formation. Several ice formation hypotheses were tested from the available data and references with various degrees of success.

DATA TABULATION AND COLLECTION

Air temperatures

Average monthly air temperatures were extracted from Local Climatological Data: Burlington, Vermont[2], for the years January 1959 - May 1978. Air temperature data for this period were measured at the Burlington International Airport, 5 km inland. Although average monthly minimum and maximum temperatures exhibit a greater amplitude range at the airport than on the lake, the average monthly temperatures at both locations are similar[3].

A 17-year mean monthly temperature and standard deviations were computed for each month, as well as a 17-year average annual temperature*. These calculations served three purposes. First, monthly temperature departures from normal for each year were easier to identify. Second, a 17-year monthly mean temperature with corresponding ice data and water temperatures was compared with the 30-year monthly normals for Burlington, Vermont, computed for the years 1941-1970, and presented in Climatography of the United States, No. 81, for New England[4]. Air temperature trend comparisons were also made with the record of

*When comparing air and water temperatures 17 years of air temperature data were used. When computing freezing degree-day curve, to compare freezing degree-days with lake closings 19 years of air temperature data were used (App. A).

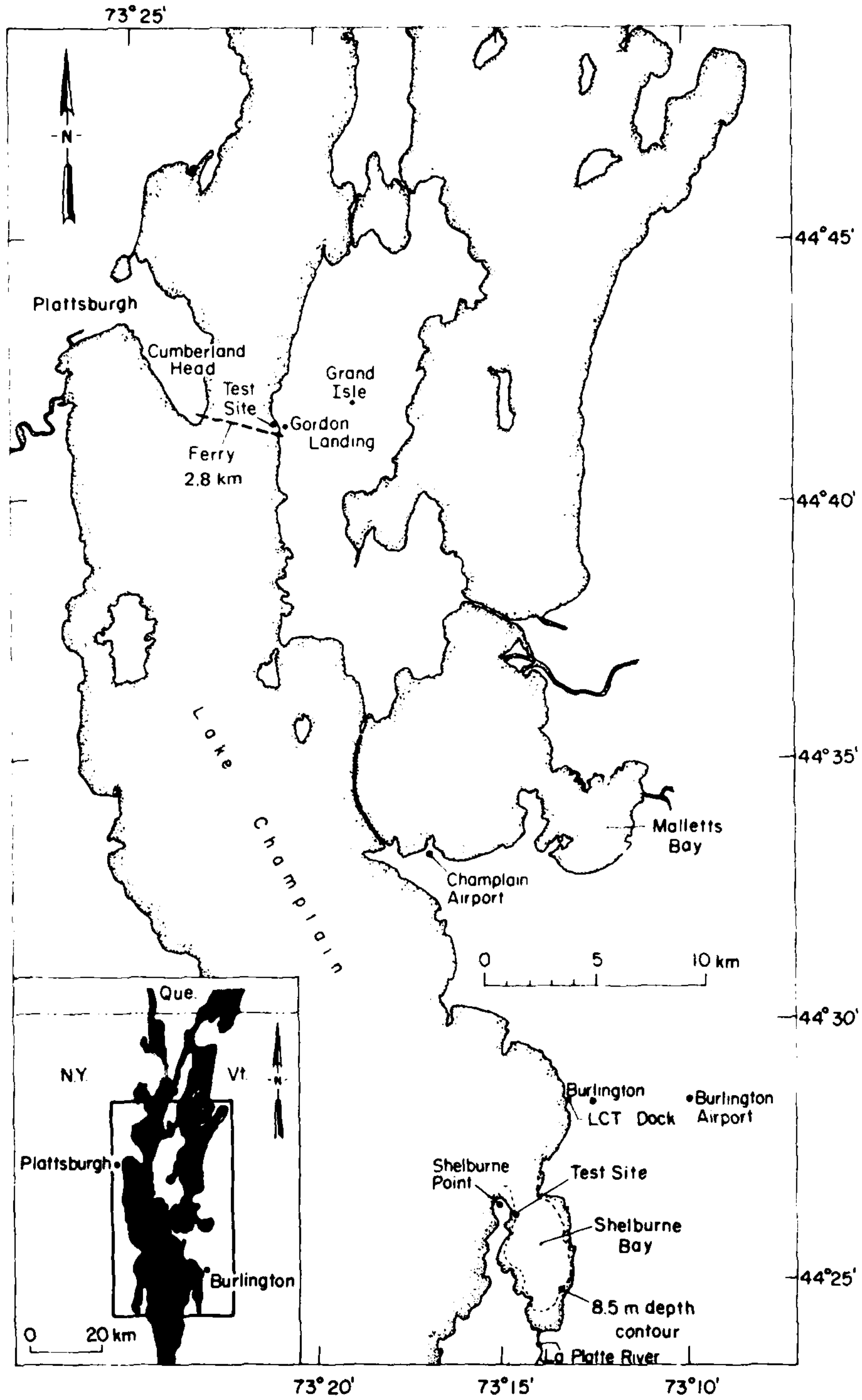

Figure 1. Test site locations in Burlington, Vermont, area.

monthly normal temperatures determined from data collected since 1893[2]. Thus, recent temperature trends became apparent (Table 1); these will be discussed later in this report.

Commencing in December 1974, CRREL installed an instrument shelter and a water temperature remote recording system on Lake Champlain at Shelburne Point, Vermont. This instrumentation was installed to monitor the thermal structure of Lake Champlain (Fig. 1). A hygrothermograph provided a continuous record of air temperatures at Shelburne Point from December 1974 through April 1975, and from December 1975 through April 1976.

In November 1976, the meteorological station was moved from Shelburne Point to the Grand Isle (Gordon Landing) Ferry Dock at South Hero, Vermont. A Doric data logger, with a water temperature profiling device, attached by cable to a buoy approximately 100 m from shore, was also installed. The Doric data logger provided a printout, every four hours, of air temperature, and the temperature profile from the surface through the ice down through the water and into the mud, where the cable with built-in thermistors was attached to the buoy anchor. This equipment was in service on Grand Isle for the winters of 1976-77[5] and 1977-78.

Freezing degree-days

Daily temperatures were used to compute accumulated freezing degree-days for the winters of 1960-78 at the Burlington Airport, for the winters of 1974-75 and 1975-76 at Shelburne Point; and for the winters of 1976-77 and 1977-78 at Grand Isle. These accumulated freezing degree-days were then fed into a computer program at CRREL; the resulting curves are shown in Appendix A. Mean daily air temperatures were entered into the program and accumulated beginning with the first date that the mean daily temperature remained below 0°C. Furthermore, each graph (App. A) illustrates the accumulated freezing degree-days experienced during a particular year, as compared with the 19-year average cumulative winter curve and the 30-year normal curve. These curves demonstrate year-to-year air temperature fluctuations and common tendencies. In addition, they compare conditions at the two CRREL sites and the Burlington Airport. Finally, they were used in the ice prediction methods to be described later in the report.

Water temperatures

CRREL recently (1974-1978) began to measure wintertime water temperatures on Lake Champlain. The Lake Champlain Transportation Company at the Burlington Ferry Dock (Fig. 1) has tabulated daily water temperatures since July 1962, with the exception of the months (usually January-March) that the lake has been ice covered. Monthly average water temperatures were computed for these data. Long-term monthly water temperatures (17 years), including standard deviations, were also calculated (Table 2).

In addition to the monthly averages, graphs were made of the water temperature readings taken on the 1st and 15th of each month for the years 1962-78. However, in analyzing these data, it was found that year-to-year water temperature fluctuations have little effect on the dates of ice formation. Thus, these diagrams were omitted except for two curves that demonstrate the normal range of water temperature that might be expected and the average curve (Fig. 2). Figure 2 gives an envelope of water temperatures that can be experienced during any year.

Closing and opening dates

The Lake Champlain Transportation Company also provided invaluable data from their ferry log records (1960-78) of the closing and opening dates of the Ferry at Grand Isle; these are shown in Table 3. The dates shown, especially the closing dates of the ferry, served as the base dates for many of the calculations performed for the prediction of ice formation and decay on the lake. The average number of days between closing and opening of the ferry approximates the number of days navigation on the lake is restricted due to ice cover.

RESULTS

Air temperature

The primary objective for analyzing air temperatures was to calculate the freezing degree-days. A further use of the air temperatures was to test the hypothesis (see Analysis, p. 8) that summer water or air temperatures might affect ice formation the following winter. However, Table 1 also illustrates some interesting trends resulting from the air temperature records.

Table 1. Air temperatures (°C), Burlington, Vermont.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg
1962	-9.2	10.2	1.7	5.5	13.2	18.1	17.8	18.6	13.2	7.9	0.2	6.6	5.6
1963	-8.6	11.8	3.3	4.6	11.3	18.6	21.3	16.9	11.9	10.9	4.6	10.6	5.5
1964	-5.6	8.2	0.5	6.3	14.8	17.2	20.9	17.2	13.2	7.4	2.1	4.0	6.7
1965	-10.2	-6.7	2.6	4.1	14.0	17.2	18.4	18.9	14.8	8.[illegible]	0.5	1.9	6.2
1966	[illegible]	7.8	-0.9	5.2	10.7	18.5	20.9	19.7	13.2	8.3	4.8	4.8	6.5
1967	[illegible]	11.3	3.7	4.8	8.7	19.8	21.2	19.4	14.5	9.3	0.5	3.6	6.3
1968	-13.1	-11.7	-1.3	7.9	10.9	16.0	20.4	17.6	16.1	9.9	0.1	7.8	5.4
1969	-8.6	7.5	4.3	5.2	10.7	17.8	19.9	20.4	14.[illegible]	7.7	2.4	7.4	5.9
1970	-15.8	-8.4	3.4	5.9	12.3	17.6	21.4	20.2	15.6	10.3	3.9	9.8	5.8
1971	-12.4	-6.7	-4.4	2.9	12.5	18.3	20.5	19.5	17.5	12.1	0.8	4.3	6.4
1972	-6.1	-8.3	4.0	2.0	13.4	17.3	20.8	18.5	14.8	5.8	0.1	5.3	5.8
1973	-5.8	-9.7	2.8	7.0	12.0	19.4	21.4	22.3	14.7	9.6	2.9	-2.6	7.8
1974	-7.4	9.1	1.6	6.9	10.7	19.2	21.2	20.6	14.6	6.3	2.3	1.9	6.8
1975	-4.7	6.3	-2.2	2.8	16.8	19.1	23.7	20.6	14.4	10.2	5.6	6.6	7.8
1976	-11.6	4.1	0.8	8.6	12.6	20.7	20.3	18.7	13.9	6.5	0.6	8.7	6.5
1977	-11.6	6.4	3.1	7.4	15.6		20.9	19.7	14.8	8.1	4.4	5.3	7.4
1978	-9.4	-12.5	3.3	3.7	15.6								
17-Yr Mean	-9.0 ± 3.2*	8.5 ± 2.3	1.9 ± 2.2	5.3 ± 1.8	12.7 ± 2.1	18.3 ± 1.2	20.7 ± 1.3	19.3 ± 1.3	14.5 ± 1.3	8.7 ± 1.7	2.2 ± 1.9	5.7 ± 2.6	6.4 ± 1.9
30-Yr Mean	-8.4	-6.9	-1.6	6.1	12.7	18.4	21.0	19.7	15.2	9.3	2.8	5.2	6.9
Mean Since 1893	-7.8	7.6	1.5	5.9	12.9	18.3	20.9	19.6	15.3	9.3	2.6	4.9	6.9

*Indicates standard deviation from 17 year mean

Table 2. Monthly average water temperatures: Lake Champlain (°C).

Year	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Fol Yr	Jan	Feb
1962					20.5	20.3	18.1	12.6			1963		
1963		2.8	6.0	16.1	21.3	19.9	16.2	12.6	9.0	5.5	1964		
1964	1.2†	2.9	8.1	14.1	21.5	19.3	17.9	12.5	8.8	4.4	1965	*†	
1965		4.2†	8.2	15.6	18.7	20.8	17.3	12.6	7.9	5.1	1966	*†	
1966		4.3†	6.6	14.6	20.4	21.1	17.6	12.0	8.4	5.9	1967	2.4	*†
1967		2.7	5.8	13.7	20.8	21.7	18.0	12.8	8.1	5.0	1968	†	
1968		4.7	8.9	14.7	20.7	19.7	19.0	15.3	9.6	4.4	1969	*	
1969		3.6	6.8	14.6	19.6	22.2	*	*	8.9	5.7	1970		
1970		4.1†	7.1	15.6	*	*	*	14.9	10.3	6.1	1971	*†	
1971		2.2†	*	13.7	19.8	21.1	19.2	14.8	9.8	5.0	1972	*†	
1972		2.2†	6.4	13.0	19.9	20.1	18.1	10.8	6.2	2.6	1973	†	
1973	1.7	3.6	7.5	15.6	21.2	23.6	19.6	13.7	8.7	4.7	1974	2.4	
1974		2.7	6.4	14.6	19.9	21.7	17.9	11.7	8.2	4.6	1975	2.4	†
1975	2.2†	2.2	8.8	15.4	22.3	22.1	17.1	13.6	10.2	5.4	1976	†	
1976	1.2†	3.8	7.6	15.1	21.0	20.2	17.6	12.4	7.4	3.0	1977		
1977	1.9†	4.3	9.6	14.8	20.1	20.7	17.9	12.7	7.1	4.7	1978	1.1	†0.7
1978	1.1	2.2											
Avg		3.2±0.8	7.4±1.1	14.7±0.8	20.5±0.9	20.9±1.1	17.9±0.9	13.0±1.3	8.6±1.1	4.8±0.9			

* < 15 days of data available due to equipment difficulties not included in average calculations
† < 15 days of data available due to freezing

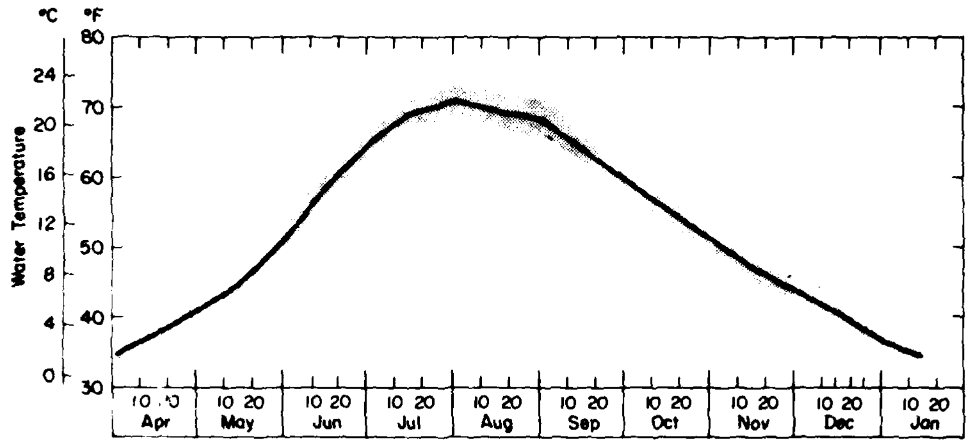

Figure 2. Water temperatures at Lake Champlain. Solid line is average for years 1962-1978

Table 3. Data tabulated from LCT Co. freeze-over and open dates.

Ice cover dates provided by Lake Champlain Transportation Company (LCT). Temperature data from Burlington Airport, Vermont

Closed dates (Freeze-over at ferry)	*Open dates (Ferry start)*	*Days lake closed*	*Freezing degree-days (°C) to ice cover*	*Date lake completely frozen*	*Freezing degree-days (°C) to close of entire lake*
8 Jan 60	2 Apr 60	85	260	Did not close	
10 Jan 61	15 Apr 61	89	330	27 Jan 61	560
31 Dec 61	14 Apr 62	104	180	16 Feb 62	640
30 Dec 62	15 Apr 63	107	220	8 Feb 63	580
31 Dec 63	26 Mar 64	87	290	Did not close	
15 Jan 65	15 Apr 65	91	300	Did not close	
26 Jan 66	25 Mar 66	59	310	7 Feb 66	480
6 Feb 67	5 Apr 67	59	400	13 Feb 67	505
8 Jan 68	3 Apr 68	87	340	16 Feb 68	770
9 Jan 69	8 Apr 69	90	425	2 Mar 69	780
5 Jan 70	19 Apr 70	105	370	21 Jan 70	650
17 Jan 71	27 Apr 71	101	550	2 Feb 71	760
29 Jan 72	26 Apr 72	89	405	10 Feb 72	510
9 Jan 73	16 Mar 73	67	310	21 Feb 73	630
7 Feb 74	26 Mar 74	48	480	15 Feb 74	570
4 Feb 75	29 Mar 75	54	370	21 Feb 75	520
13 Jan 76	31 Mar 76	79	370	Did not close	
28 Dec 76	21 Mar 77*	83	250	18 Jan 77	490
16 Jan 78	8 Apr 78*	82	320	13 Feb 78	600
Average					
15 Jan (± 13 days)	5 Apr (± 13 days)	82 (± 18 days)	342 (± 87 deg-days)	11 Feb (± 12 days)	603 (± 99 deg-days)

* LCT ferry navigated in ice cover these two winters

First, monthly air temperatures exhibit the smallest standard deviations during the summer months (June through September), whereas the greatest range of fluctuations occurs in the coldest months of the year (December through February). Second, air temperatures show a recent slight cooling trend for Burlington (Table 1). However, there is negligible difference between the mean monthly temperatures for the 30-year period of 1941-1970 and the mean since 1893. As a result, these long-term average temperatures for the two periods are essentially the same: 6.9°C (44.5°F).

In contrast, air temperatures for the past 17 years have averaged 0.5°C colder than the long-term averages, or 6.4°C (43.5°F). Records for every month, averaged for the past 17 years and compared with the 30- or 85-year average, showed slightly colder temperatures than the 30-or 85-year average. One item that partially explains some of this temperature difference is that the meteorological station was moved from downtown city offices to Burlington Airport in May 1943.

Freezing degree-days

The freezing degree-day curves in Appendix A also illustrate the recent cooling trend. The "normal" curve (30 years) begins on 1 December and peaks around 690 freezing degree-days °C. In contrast, the 19-year average curve begins on 16 November and peaks at 810 freezing degree-days °C. This averages out to a daily temperature difference approximately 0.5°C (1°F) colder during the winter for the past 19 years than during the previous period.

Excluding the data from Shelburne Point and Grand Isle, a wide range of accumulated freezing degree-days °C has been reported since 1960. The greatest number was 1125 freezing degree-days in the winter of 1969-70 (App. A, Fig. A11), whereas the lowest number was 700 freezing degree-days °C in the winter of 1973-74 (App. A, Fig. A15). Other pertinent freezing degree-day °C information is summarized in Table 3. For instance, freeze-over at Grand Isle normally occurs at 342 accumulated freezing degree-days °C (± 87° degree-days), whereas final freeze-over of the entire lake, in the winters that experience complete freeze-over, normally occurs after 603 freezing degree-days °C (± 99 degree-days).

An additional use of the freezing degree-day curves concerns the comparison between various stations near or on Lake Champlain. The air temperature records of Shelburne Point, Vermont, were compared with those of the Burlington Airport for the winters of 1974-75 and 1975-76. In the first winter, Shelburne averaged 97 fewer freezing degree-days °C than Burlington, and 202 fewer in the 1975-76 winter (App. A, Figs. A16a-A17b). This is explained by the persistence of open-water areas later in the winter near the Shelburne Point measurement site and by the larger geographical size, width and depth of the lake in this area (Fig. 1).

In the winters of 1976-77 and 1977-78, a similar study was done, utilizing data from Grand Isle, as the CRREL measurement site was moved from Shelburne Point to Grand Isle in the fall of 1976. The Grand Isle freezing degree-days data, when compared with the Burlington data, show a difference of only 45 freezing degree-days °C in the 1976-77 winter, and 105 in the 1977-78 winter (App. A, Figs. A18a-A19b).

It has previously been established (Bates 1976[3]; and Bates, in preparation[5]) that the normal winter temperature curve for the Burlington Airport approximates curves for the Shelburne Point and Grand Isle measurement sites. Therefore, the difference in the annual plots from site to site must be attributed to the tempering influence of the lake. This is especially apparent at Shelburne Point, which is situated between a bay and the main lake and is thus more sensitive climatically to the lake's influence. In contrast, Grand Isle is situated on a large island in the lake, but its shoreline and surroundings are more typical of the rest of the lake. Thus, the data obtained from Grand Isle probably more accurately represent the wintertime climatic regime of Lake Champlain.

Water temperatures

On the other hand, water temperatures, as expected, do not exhibit the extremes that typify air temperatures. The average monthly standard deviation is 1.0°C (1.8°F) for the 17-year period (Table 2). The largest month-to-month increase occurs from May to June (7.3°C) (13°F). The average date of the warmest water temperature, 23.8°C (74.8°F), is 31 July. The water temperature slowly cools in late August and September, then begins to drop more rapidly as winter commences (Table 2; Fig. 2).

This rapid cooling trend leads to the freeze-over of Lake Champlain at the Grand Isle Ferry site normally on 15 January and the lake is normally closed for navigation approximately 81 days, opening again on 5 April (Table 3).

ANALYSIS: ATTEMPTED METHODS OF PREDICTING ICE FORMATION

Predicting air temperatures

Although many meteorological and geographical factors affect the date of ice formation, subfreezing air is the primary determinant of water temperature. If a means of making more accurate long range, 15-to-30-day, air temperature forecasts were possible, the accuracy of predicting ice formation would then be greatly increased. Rogers[6] analyzed four methods of forecasting air temperatures on the Great Lakes, but when these techniques were applied to Lake Champlain, the resulting predictions were not as accurate as those obtained using the degree-day or water temperature decrease-in-time method for predicting ice formation. The latter two methods are described later in this report (see page 9). Bilello[8] discussed methods for prediction of ice formation growth and decay in Canada using the Rodhe[9] relationship between weighted air temperatures and ice formation. This method was attempted for several years of temperature data including the long-term average for Burlington Airport, near Lake Champlain. Utilizing a derived (k) value of 0.02 (see Bilello[8] or Rodhe[9] for experimental theory), dates of freeze-over at Grand Isle were computed within 3 days of the observed date. However, although this method demonstrates a high degree of accuracy, it depends on reliable air temperature forecasts. The advantage of methods described later in this report are that 15-to-30-day air temperature forecasts are not a necessary requirement.

Summer water temperatures

The thermal structure of a lake is mostly influenced by air temperature, radiation and winds, and by the geographical setting of the lake. These variables directly affect the date of ice occurrence. Therefore, our second approach utilized summer and/or fall water temperatures as indicators of the closing dates of the Grand Isle ferry (freeze-over).

However, this method was also rejected. After examining a few years of recent data, inconclusive results were obtained. If only the year 1973 were used, apparently summer water temperatures and freeze-over could be correlated. Water temperatures (Table 2) were exceptionally high in June, August and September 1973, but only August experienced warmer than normal air temperatures. In contrast to the normal 31 July latest summer date of the warmest water temperature, the latest date of the warmest water temperature in 1973 was 6 September. Accompanying this warming trend was the latest ferry closing date (7 February 1974) and the lowest number of days (48) the lake was unnavigable due to ice on record (Table 3).

The warm water temperatures, coupled with warm air temperatures in the fall of 1971, also probably had some bearing on the late closing date in the winter of 1971-72. Accordingly, the winters of 1968-69, 1970-71, and 1975-76 should have experienced later than normal ice formation (Table 3). However, in all three cases, freeze-over at Grand Isle occurred well within the normal boundaries.

Additional evidence of the limitations of this approach occurred during the winters of 1972-73 and 1974-75. Water temperatures in June, October, November, and December of 1972 (Table 2) were all significantly below normal, as were air temperatures in October and November, yet the closing date of the ferry was normal. The 1974-75 winter had the late closing date of 4 February, but neither water nor air temperatures can entirely account for this occurrence. In fact, the water temperature reached its highest peak of 22.8°C (73°F) (Fig. 2) on 10 July 1975, versus the normal peak temperature of 23.8°C (74.8°F) on 31 July.

In summary, summer water temperatures measured on Lake Champlain have little bearing on water temperatures in late December and January. As expected, water temperature is primarily dependent on air temperature, but other variables complicate the overall picture.

Fall water temperatures and freezing degree-days

Because of the limited success encountered with the long-term prediction methods described thus far, it was decided to use a more direct, yet more accurate, means of ice prediction. Utilizing the available recent air temperature dat.

namely the 17 year normals, since they are more representative of recent trends, an accurate (± 7 days) closing date can be predicted a month ahead. The model incorporates water temperatures and freezing degree-days in the determination of the closing date. By closely monitoring these, the date of ice formation can be more closely pinpointed as it approaches.

The dates of the occurrence of these three particular water temperatures in the late fall-early winter were of interest. Of primary importance was the date the temperature of the lake cooled to 4°C (39°F) and remained at or below this temperature. The first temperature limit was chosen because 4°C is the temperature at which water reaches its maximum density and the lake's thermal profile is nearly isothermal at this time. The average date of 4°C water temperature is 19 December; this corresponds to 100 freezing degree-days (App. B). On the average, 29 days (± 7 days) and 250 freezing degree-days elapse between the occurrence of the 4°C reading and freeze-over at Grand Isle (Table 4). This represents an accuracy range of almost 75% (Table 4). Therefore, it can be estimated that, when the water temperature reaches 4°C (39°F), freeze-over will occur approximately 29 days (± 7 days) and 250 freezing degree-days later. The results of this prediction method for each year are summarized in Table 5.

From the calculations shown in Table 4, it is evident that when winter air temperature trends are colder than normal, thus accumulating freezing degree-days at a faster rate, freeze-over occurs from 1 to 7 days earlier than normal. The accuracy of this ice prediction model is excellent (± 7 days) when it is noted that other important meteorological and mechanical factors have not been considered.

However, as a further demonstration of the ice formation-freeze-over date at Grand Isle, the same type of analysis is presented for water temperatures at 2°C (36°F) and 1°C (34°F) respectively. Appendix B summarizes the average dates and corresponding accumulated freezing degree-days for the occurrence of 2°C (31 December, 200 freezing degree-days) and 1°C (9 January, 280 freezing degree-days). In addition, the average number of days from those dates until the closing date of the lake at Grand Isle were also calculated (17 days and 8 days, respectively). Table 4 summarizes these results.

Thus, similar to the predictions made using 4°C (39°F) water temperature as a base, freeze-over will occur 17 days (± 6 days) and 150 freezing degree-days after the lake reaches 2°C (36°F), and 8 days (± 4 days) and 70 freezing degree-days after it reaches 1°C (34°F) (Table 4). There is the advantage of more accurate prediction with decreasing temperature. However, the decreased accuracy in using, for instance, 4°C as the basis for prediction is compensated for by the fact that a forecast of the closing date can be made further in advance (29 days versus 17 and 8 days, respectively). See Appendix B for a combined summary.

The significance of the accumulated freezing degree-day curves for an area is that if, for some reason, water temperatures are not available a freeze-over date could still be approximated by matching a previous winter's freezing degree-day curve from Appendix A with the start of the current winter's accumulation of freezing degree-day data.

In a further effort to more accurately estimate a closing date, two actual accumulated freezing degree-day curves (App. A) (for 1975-76 and 1976-77) were compared at 2°C (36°F) and 1°C (34°F) with curves of similar shapes and slopes through the end of December, rather than with the normal curve. The 1975-76 curve was compared with the 1968-69 curve, using the technique previously described. Likewise, the 1976-77 curve was compared with the 1962-63 curve. The results, shown in Table 6, demonstrate that these approximations do not represent any significant improvement over using the normal curve.

Finally, observations from other stations were examined in order to determine whether the dates of the ice formation predicted by this method hold true for other sites on Lake Champlain. The approach thus far used air temperatures from the Burlington Airport and water temperatures from the Lake Champlain Transportation Company (LCT Co.) records. Therefore, air and water temperatures, as well as observances of dates of ice formation, measured by CRREL at Shelburne Point (1974-75, 1975-76) and Grand Isle (1976-77 and 1977-78), were compared with the water temperature data from the LCT Co. files. Comparisons between water temperature of 2 and 1°C and actual ice formation dates are shown in Table 7; this analysis and Table 5 illustrate the validity of the approach to ice prediction for locations on Lake Champlain. For the most part, the dates correspond within a day

Table 4. Days to closing of ferry at Grand Isle due to ice after occurrence of 4, 2, and 1°C water temperatures.

	Date 4°C (39°F)	*No. of days to close*	*Date 2°C (36°F)*	*No. of days to close*	*Date 1°C (34°F)*	*No. of days to close*
1962-63	12 Dec	18	15 Dec	15	26 Dec	4
1963-64						
1964-65	17 Dec	29	7 Jan	8	11 Jan	4
1965-66	1 Jan	25	8 Jan	18	13 Jan	13
1966-67	1 Jan	36	18 Jan	18	30 Jan	7
1967-68	18 Dec	21	21 Dec	18	3 Jan	5
1968-69	10 Dec	30	26 Dec	14	27 Dec	13
1969-70						
1970-71	24 Dec	24	8 Jan	9	11 Jan	6
1971-72	20 Dec	40	6 Jan	23	19 Jan	10
1972-73	2 Dec	38	11 Dec	29	6 Jan	3
1973-74	17 Dec	52	13 Jan	25	21 Jan	17
1974-75	25 Dec	41	21 Jan	14	22 Jan	13
1975-76	19 Dec	25	29 Dec	15	5 Jan	8
1976-77	3 Dec	25	15 Dec	13	22 Dec	6
1977-78	26 Dec	21	30 Dec	17	10 Jan	6
Average	19 Dec	29 ± 7 days	31 Dec	17 ± 6 days	9 Jan	8 ± 4 days

Table 5. Predicted freezing degree-days and closing date of Ferry as compared with actual, *using water temperature occurrence of 4, 2, and 1°C*.

	Estimated from 4°C (39°F)		*Estimated from 2°C (36°F)*		*Estimated from 1°C (34°F)*		*Actual*	
Winter	*Closing date*	*Z°* to close*	*Closing date*	*Z°* to close*	*Closing date*	*Z°* to close*	*Closing date*	*Z°* to close*
1962-63	9 Jan	245	1 Jan	210	3 Jan	230	30 Dec	220
1963-64		Insufficient water temperature data					31 Dec	290
1964-65	14 Jan	350	24 Jan	375	19 Jan	320	15 Jan	300
1965-66	30 Jan	360	25 Jan	300	21 Jan	280	26 Jan	310
1966-67	30 Jan	440	4 Feb	410	7 Feb	400	6 Feb	400
1967-68	16 Jan	360	7 Jan	260	10 Jan	300	8 Jan	340
1968-69	8 Jan	380	12 Jan	390	4 Jan	320	9 Jan	425
1969-70		Insufficient water temperature data					5 Jan	370
1970-71	22 Jan	500	25 Jan	540	19 Jan	510	17 Jan	550
1971-72	18 Jan	390	23 Jan	410	27 Jan	410	29 Jan	405
1972-73	31 Dec	320	28 Dec	250	14 Jan	330	9 Jan	310
1973-74	16 Jan	283	30 Jan	410	29 Jan	440	7 Feb	480
1974-75	23 Jan	370	7 Feb	390	30 Jan	340	4 Feb	370
1975-76	17 Jan	320	13 Jan	350	13 Jan	330	13 Jan	370
1976-77	1 Jan	280	1 Jan	280	30 Dec	250	28 Dec	250
1976-77†	1 Jan	270	1 Jan	240	30 Dec	200	28 Dec	250
1977-78	24 Jan	410	16 Jan	310	18 Jan	330	16 Jan	320

* Z° = Freezing degree-days (°C)

† CRREL Site

Table 6. Predicted closing date of lake for two winters from a similar winter versus "normal."

Winter	Estimated from 2°C (36°F)		Estimated from 1°C (34°F)		Actual	
	Closing date	Z°* to close	Closing date	Z°* to close	Closing date	Z°* to close
1975-76 From 1968-69	13 Jan	370	19 Jan	440	13 Jan	370
1975-76 From normal	13 Jan	350	13 Jan	330	13 Jan	370
1976-77 From 1962-63	31 Dec	300	26 Dec	230	28 Dec	250
1976-77 From normal	1 Jan	280	30 Dec	250	28 Dec	250

* Z° = Freezing degree-days (°C).

Table 7. Comparison of water temperatures and ice formation at several sites on Lake Champlain.

Site	Date 2°C	Date 1°C	Date ice-covered	Remarks
Winter 1974-75				
A Burlington (LCT Co.)	21 Jan	22 Jan	4 Feb	Ferry closed, Grand Isle
B Shelburne Pt (CRREL)	—	~29 Jan	4 Feb	Ice formed, Shelburne Pt
Winter 1976-76				
A Burlington (LCT Co.)	29 Dec	5 Jan	13 Jan	Ferry closed, Grand Isle
B Shelburne Pt (CRREL)	30 Dec	6 Jan	14-15 Jan	Ice formed, Shelburne Pt.
Winter 1976-77				
A Burlington (LCT Co.)	15 Dec	22 Dec	28 Dec	Ice formed
B Grand Isle (CRREL)	—	20-21 Dec	28 Dec	Ice formed at recording buoy, Grand Isle
C Shelburne Pt	—	—	30 Dec	Ice formed, Shelburne Pt.
Winter 1977-78				
A Burlington (LCT Co.)	30 Dec	10 Jan	16 Jan	Ice formed
B Grand Isle (CRREL)	28 Dec	14-15 Jan	10-11 Jan	Ice formed at recording buoy, Grand Isle
C Shelburne Pt	—	—	16 Jan	Ice formed, Shelburne Pt.

or two to the closing dates of the ferry or when it would have been closed due to permanent freeze-over.*

Wind speed influence on closing of the lake

Average daily wind speeds ($m\ s^{-1}$) were accumulated each fall, starting with the date of 0°C average daily air temperature occurrence until the ferry closing date due to ice for each winter from 1959 to 1978. These values give the total wind run during lake cooling below a base of 0°C air temperature for each winter. These values are shown with accumulated freezing degree-days base (0°C) in ascending order in Table 8, for the purpose of ranking analysis, which will be discussed later in this section.

As mixing by wind appeared to be the next significant variable in prediction of freeze-over, wind values (independent variables) were then correlated with total accumulated freezing degree-days from Table 8 (dependent variable) for corresponding years using a computer regression analysis for each winter. The results and a computer plot are shown in Figure 3.

The formula used is:

$$y = a + bx$$

where y = accumulated freezing degree-days (°C) until ice formation and x = accumulated average daily wind speeds ($m\ s^{-1}$) until ice formation. The computed values of a and b are given in Figure 3; Figure 3 also gives the calculated correlation coefficient (r) of 0.63 between accumulated freezing degree-days and accumulated daily average wind speed.

The ranking order of accumulated freezing degree-days to closing of the ferry (a_i, Table 8), and the accumulated average daily wind from the starting date of freezing degree-days (b_i, Table 8), are ranked against the actual yearly observations of earliest to latest closing dates of the lake. A ranking correlation (Smillie[10]) was computed for the data in Table 8, using the expression:

$$r_s = 1 - \frac{6}{n(n^2-1)} \Sigma^2_{d_i}$$

where r_s is the rank correlation, n is the number of input values and $\Sigma^2_{d_i}$ is the sum of the squares of the rank differences $(a_i - b_i)^2$. The above expression, using the data in Table 8, reduces to

$$r_s = 1 - \frac{6}{6840} \cdot \frac{436}{1} \text{ or}$$

Rank correlation (r_s) = 0.62

The analyses shown in Figure 3 and Table 8, and the similar correlation coefficients obtained by both methods, indicate that 1) after air temperature, wind speed is probably the next most significant variable in prediction of ice formation dates, 2) a greater number of freezing degree-days are needed to close navigation on the lake if wind speeds are high — in other words, freeze-over is more likely to occur with lower wind speeds and cold temperatures, and 3) after the lake is cooled to near 0°C, strong winds delay the occurrence of freeze-over on a large lake such as Lake Champlain. When mechanical mixing of the surface area of a lake is reduced during low wind speeds, and 300 freezing degree-days have been accumulated (Table 3) on Lake Champlain, the next cold air mass with low wind speeds will most likely induce freeze-over.

Water temperature vs surface air temperature analysis

To relate the water and surface air temperature analysis for Lake Champlain to other large lake areas, the report "Lake Ontario Atlas: Lake Temperatures (Chermack 1977[11])" was obtained. This report gives average monthly lake and surface air temperature variations near two sites, Rochester and Oswego, New York, on Lake Ontario. The period of record covered was 18 years (1950-1968), or approximately the same number of years as the Lake Champlain study. The Lake Champlain water temperature data are from the period 1962-1978, which encompasses only 7 of the same years as the Ontario study; but the analysis shows some similarities.

Lake Ontario, New York, temperature curves taken from Figures 5 and 6 of Chermack[11] are replotted in this report in Figures 4a and b. The air temperature scale is expanded to accommodate a similar plot for Lake Champlain, Vermont, for comparison. In order to plot the diagram (Figs. 4a and b) for Lake Champlain, data from Tables 1 and 2 were used. However, water temperatures were not measured under the ice

* The Grand Isle Ferry operated in ice throughout the winters of 1977 and 1978 by breaking a channel through the land-fast ice cover (Bates[5]).

Table 8. Ranking order of accumulated freezing degree-days and accumulated wind vs closing of Lake Champlain at Grand Isle, Vermont.

Least to greatest Z° days to closing a*		*Least to greatest accumulated wind from start Z°* days to closing b*		*Actual earliest to latest closing of lake (yr)*	*Ranking a*	*Ranking b-d*
1961-62	180	1962-63	91	1976-77†	3	3-0
1962-63	220	1963-64	124	1962-63	2	1-1
1976-77	250	1976-77	149	1961-62	1	4-3
1959-60	260	1961-62	167	1963-64	5	2-3
1963-64	290	1969-70	171	1969-70	12	5-7
1964-65	300	1960-61	175	1959-60	4	8-4
1972-73	310	1975-76	180	1967-68	11	11-0
1965-66	310	1959-60	184	1968-69	17	14-3
1977-78	320	1970-71	191	1972-73	7	12-5
1960-61	330	1977-78	200	1960-61	10	6-4
1967-68	340	1967-68	206	1975-76†	13	7-6
1969-70	370	1972-73	210	1964-65	6	13-7
1975-76	370	1964-65	230	1977-78†	9	10-1
1974-75	370	1968-69	231	1970-71	19	9-10
1966-67	400	1973-74	273	1965-66	8	17-9
1971-72	405	1966-67	297	1971-72	16	19-3
1968-69	425	1965-66	305	1974-75†	14	18-4
1973-74	480	1974-75	325	1966-67	15	16-1
1970-71	550	1971-72	363	1973-74	18	15-3

* Z° = Freezing degree-days (°C)

† CRREL observed conditions during these years, also, the ferry operated during the entire winters of 1976-77

Closing dates are when ferry normally would have closed

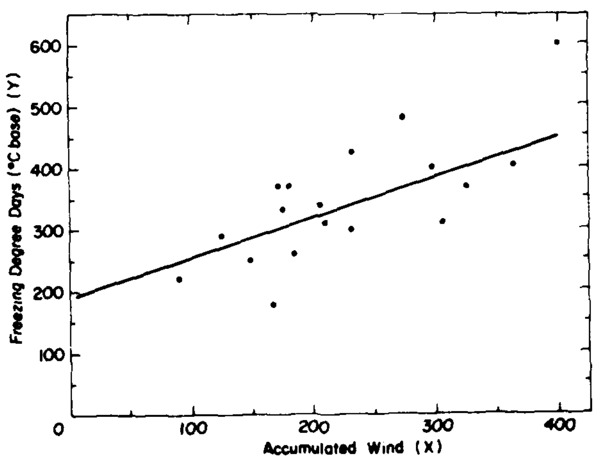

Figure 3. Computer regression analysis plot, Burlington Airport Data. y = a + bx, a = 188.4, b = 0.654 and correlation coefficient = 0.63

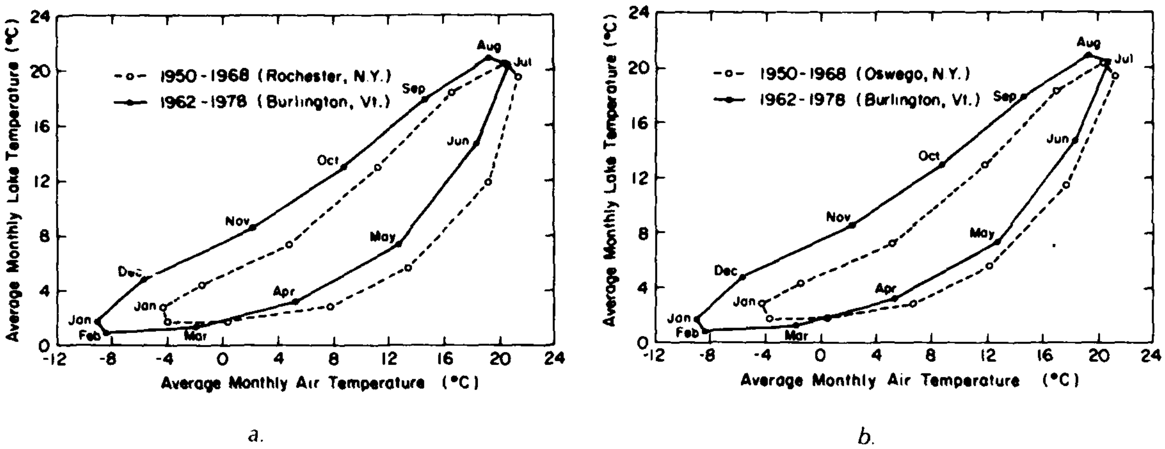

Figure 4. Average lake water temperatures vs air temperatures for Burlington, Vermont vs Oswego and Rochester, New York.

cover most winters (January-March). A combination of the LCT Co. data for the years available with the CRREL measurements on water temperature of the past 4 winters is included in the averages for Burlington in Figure 4. A slope analysis was computed of air vs water temperature (Table 9). This shows the similarities between the curves for Burlington vs. Oswego and Burlington vs. Rochester in Figures 4a and b. Table 9 shows that the slope differences between months are the greatest in the summer and that the slopes of the curves are similar.

The curves in Figures 4a and b demonstrate the similarity between a large lake (Ontario) and a smaller one (Champlain) in similar temperate climates. However, there are notable differences; for instance on a larger lake, the mechanical effects of wind are greater, therefore breaking up the primary ice cover and delaying freeze-over. Also, on Lake Champlain (Figs. 4a and b) air temperature means are colder, especially in winter, and exhibit a greater monthly range than they do at Oswego and Rochester on Lake Ontario.

A further comparison of Lake Champlain and Lake Ontario involved an examination of annual air and water temperatures at both lakes. For this analysis, Oswego, New York, was selected from Chermack[11] as it is nearer in mileage to Lake Champlain. The mean annual air temperature for Oswego was 8.5°C vs 6.4°C for Burlington. The mean annual water temperature for Oswego was 9.0°C vs 9.6°C for Burlington. The Burlington values are plotted on Figure 5. Table 9, Figures 4a and b, and Figure 5 show that, even though the mean annual air temperature is 2.1°C warmer at Oswego than at Burlington, the mean water temperature on Lake Champlain is 0.6°C warmer than on Lake Ontario. One factor that must be considered in this comparison is that Oswego (Lake Ontario) records are for the period 1950-1968, whereas the Burlington (Lake Champlain) data are for the period 1960-1978. Another possibility for this 0.6°C difference is that Lake Ontario has a much larger water volume that has to be cooled or warmed.

Further studies on lake surface relationships between annual water temperatures and near-surface air temperatures need to be completed. This may be a way of comparing one lake or reservoir with another where no records of ice formation or breakup are available. Also, it may be an indicator of the length of the ice season. Finally, as previously stated, the geographical size, depth and exposure of the water body will have to be considered.

Prediction of ice-out dates

Freezing degree-days graphs were also used in an attempt to predict the opening date of the ferry (ice free at Grand Isle). The average date of the maximum accumulated freezing degree-days is 20 March (App. B), and the number of days from this date until the opening of the lake were computed. Approximately 15 days (±5 days) elapse between the date of above 0°C average

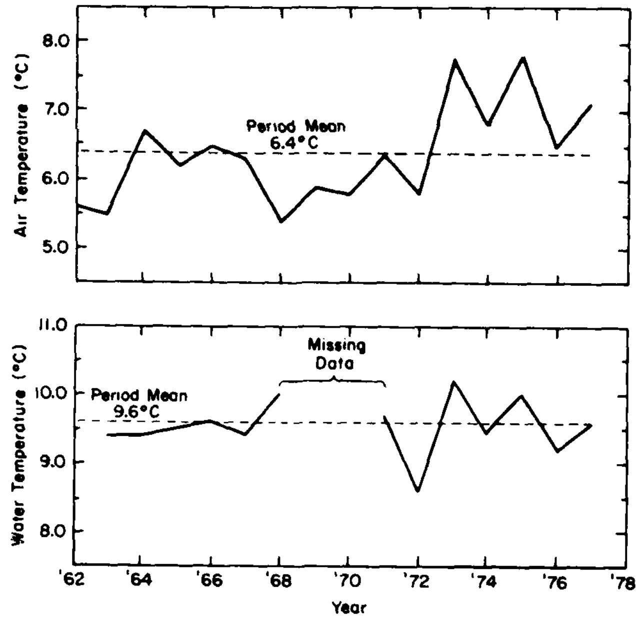

Figure 5. Mean annual water and air temperatures, Burlington, Vermont, 1962-1978.

Table 9. Slopes of air vs water temperature determined from Figure 4.

Slopes	*Burlington*	*Oswego*	*Rochester*
Dec→Jan	0.94	0.56	0.57
Jan→Feb	-1.60	-2.50	-2.75
Feb→Mar	0.06	0.03	0.04
Mar→Apr	0.26	0.15	0.16
Apr→May	0.57	0.52	0.52
May→Jun	1.30	1.05	1.02
Jun→Jul	2.42	2.32	3.62
Jul→Aug	-0.29	-1.25	-1.10
Aug→Sep	0.62	0.62	0.58
Sep→Oct	0.84	0.98	1.01
Oct→Nov	0.68	0.86	0.85
Nov→Dec	0.48	-0.44	0.46
	6.28/12	3.78/12	4.98/12
Avg. slope	0.523	0.315	0.415

daily air temperatures and the opening of the ferry. This figure exhibits too great a variation to be seriously considered as a viable means of predicting an ice-out date. Since Lake Champlain is large, other influences (i.e., solar radiation, wind, water currents, etc.) also affect the rate of ice deterioration. Further work needs to be done on the identification of these parameters and their influences regarding ice breakup.

CONCLUSIONS

The basic data obtained on the annual opening and closing dates of the Lake Champlain Transportation Company (LCT Co.), Grand Isle, Ferry Crossing made this report possible. The LCT Co., from 1960 to the present, maintained an extremely accurate account of the ferry closing and opening dates each year that are essentially the freeze-over and breakup dates of the ice cover of this area of Lake Champlain.

These data were invaluable when compared statistically with available water temperature and climatological data for the same years at nearby Lake Champlain locations. Freezing degree-day curves (0°C base) for each year are given in Appendix A. Each yearly plot has notations of dates of freeze-over at Grand Isle, complete lake freeze-over and occurrence of water temperature at 4°C (39°F), 2°C (36°F) and 1°C (34°F).

From these freezing degree-day curves and their associated information, ice formation dates and standard deviations were predicted with considerable accuracy (Table 3). Several methods of predicting ice formation on Lake Champlain were studied. The most accurate approach involved the use of a combination of water temperatures and freezing degree-days. If the past 17 winters are considered, a water temperature of 4°C (39°F) and 100 freezing degree-days normally occurred on 19 December. Thus, freeze-over at Grand Isle, Vermont, can be expected approximately 29 days later at nearly 350 freezing degree-days °C, which falls normally on 15 January with a standard deviation of 7 days. Although this calculation is for Grand Isle, the value is representative (see Table 7) of other areas of the lake. Finally, this predicted date (15 January) can be approximated starting with the average date of occurrence of 2°C and 1°C water temperature, which corresponds to 200 and 280 freezing degree-days °C, respectively (see App. B).

Analysis on wind speed influence on the ice cover formation of Lake Champlain was made for the years of the study. A computer regression analysis using wind speeds and freezing degree-days °C as variables gave a correlation coefficient (r) of 0.63. Also, a ranking analysis (Table 8), using the same variables, gave a similar rank correlation (rs) of 0.62, indicating to the authors that a greater number of freezing degree-days are needed to close a large lake to navigation due to ice if wind speeds are high. In other words, freeze-over is more likely to occur with lower wind speeds and cold temperatures.

Another analysis (Table 9, and Figs. 4a and b) was completed in which surface air temperature was plotted against water temperature for Lake Champlain and compared with a similar analysis for Lake Ontario at two locations. The slopes resulting from this analysis are similar for both Lake Champlain and Lake Ontario. Indications are that this might be a way of comparing one reservoir's ice cover history with that of another where records of climate and/or water temperatures are available and dates of ice formation and breakup are unavailable.

Further heat budget studies on the interaction at the air/water or ice interface need to be completed to further confirm the above analysis.

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APPENDIX A: FREEZING DEGREE-DAY CURVES WITH ICE NOTATIONS AND WATER TEMPERATURE NOTATIONS

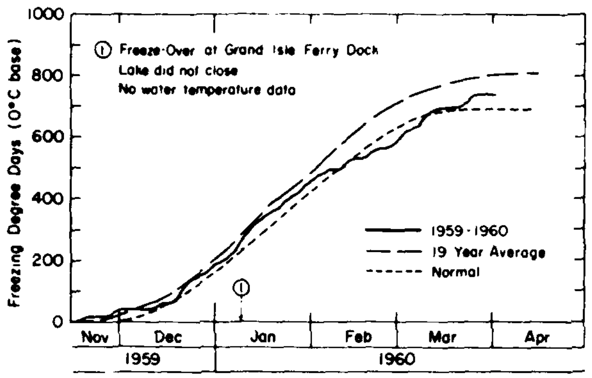


Figure A1

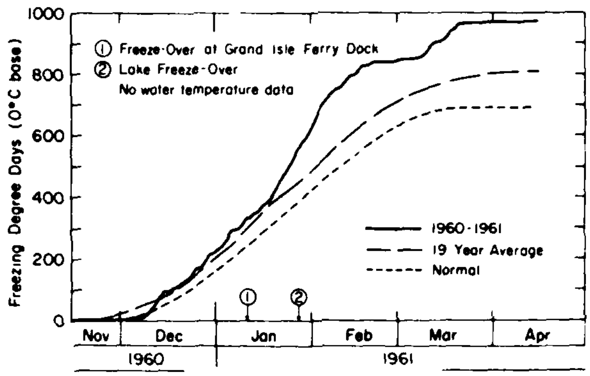
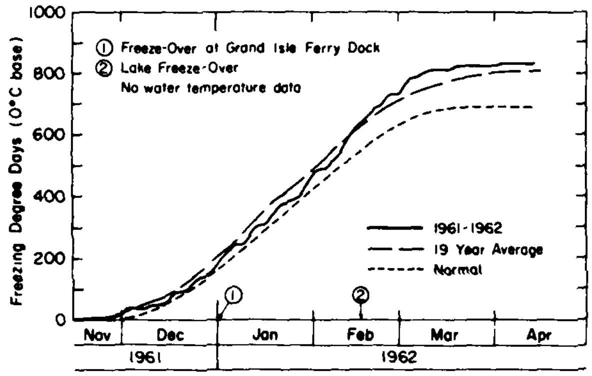


Figure A2



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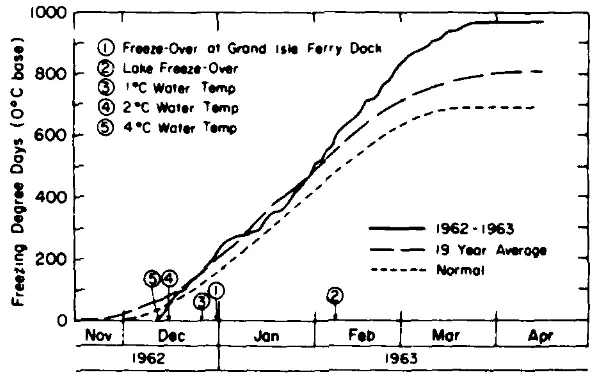

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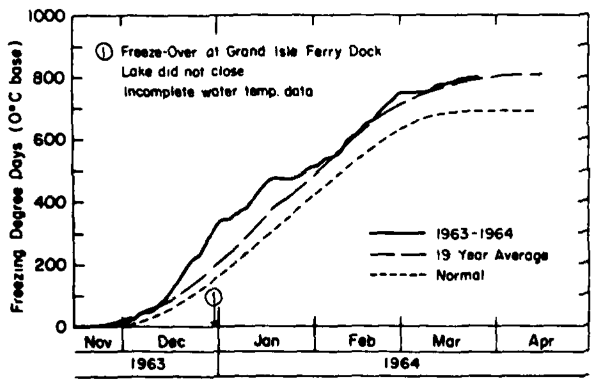

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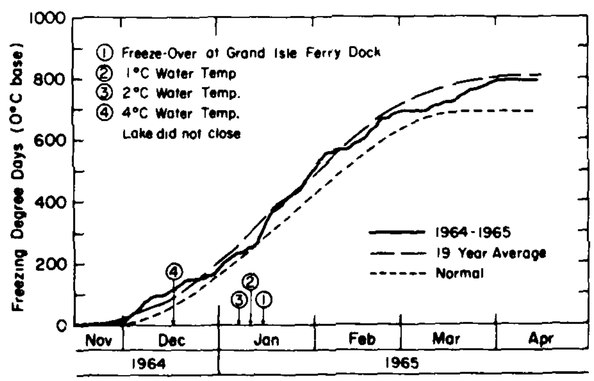

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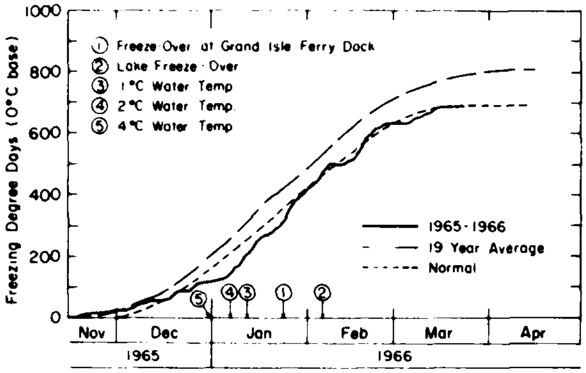

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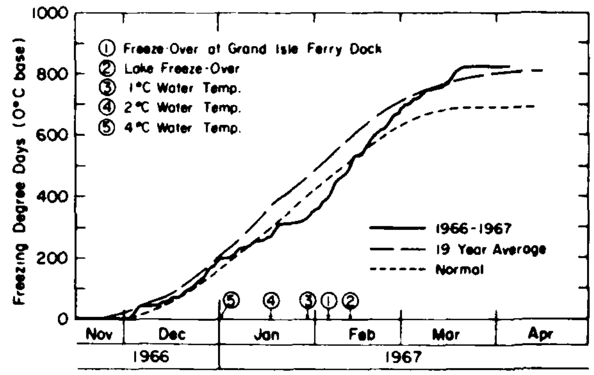

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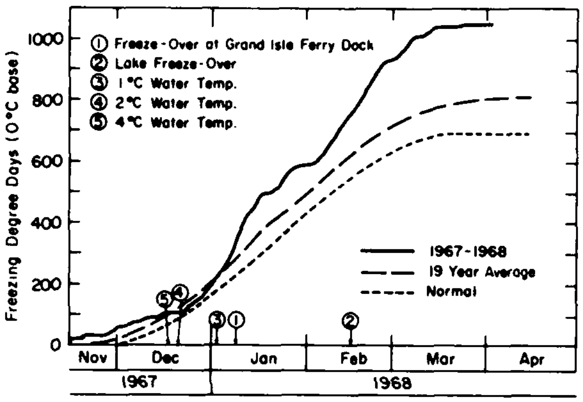

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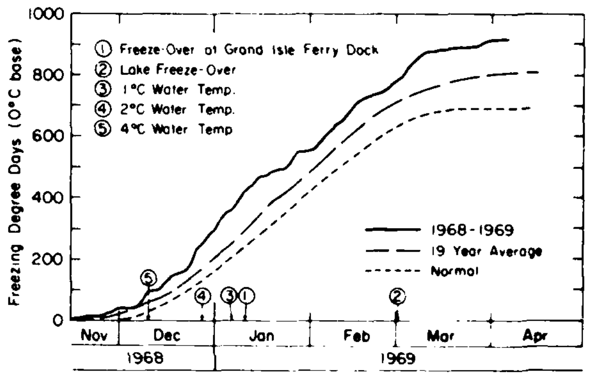

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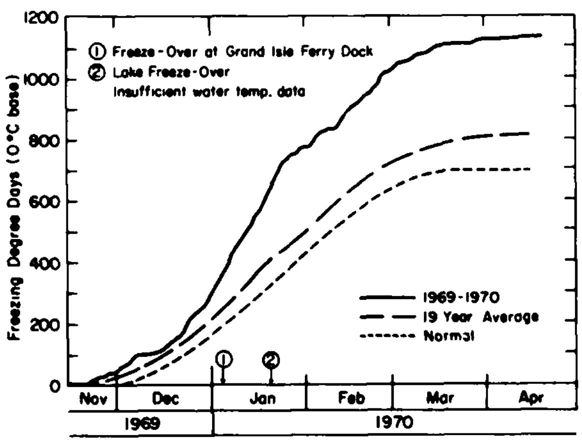

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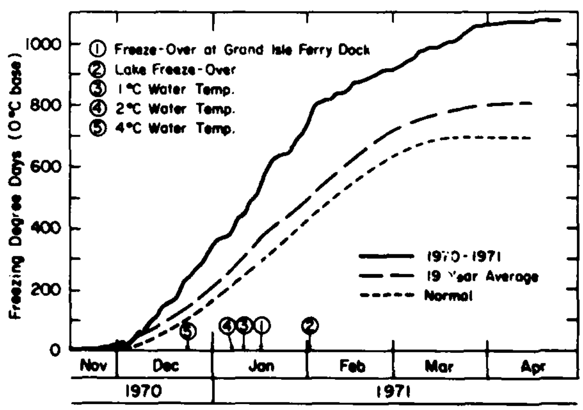

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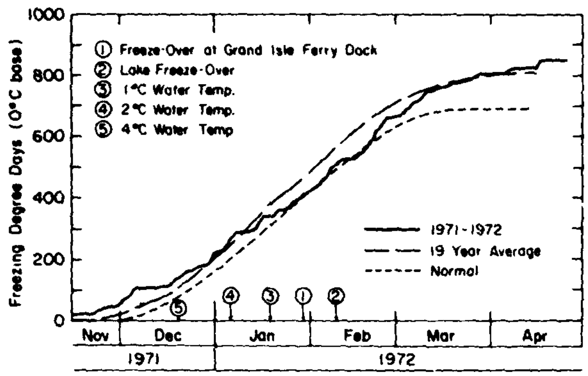

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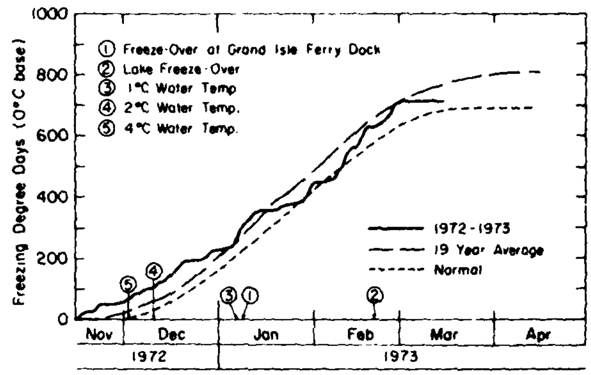

Figure A14

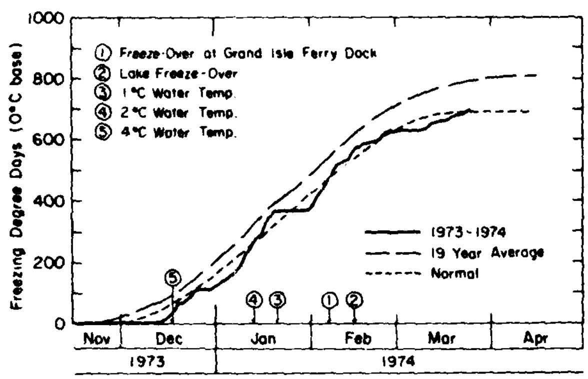

Figure A15

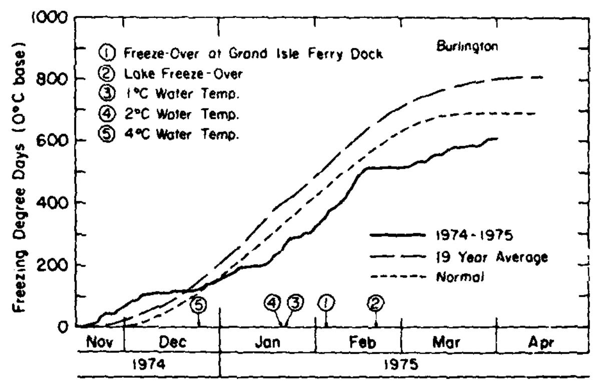

Figure A16a

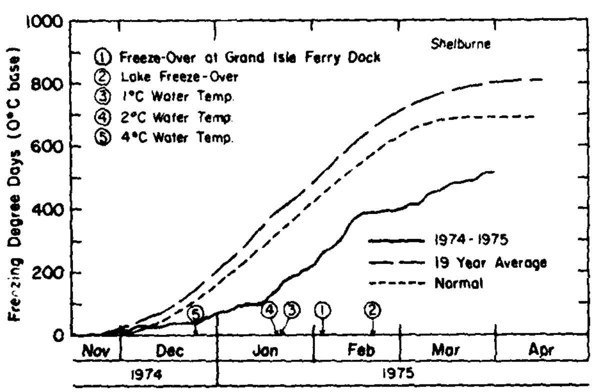

Figure A16b

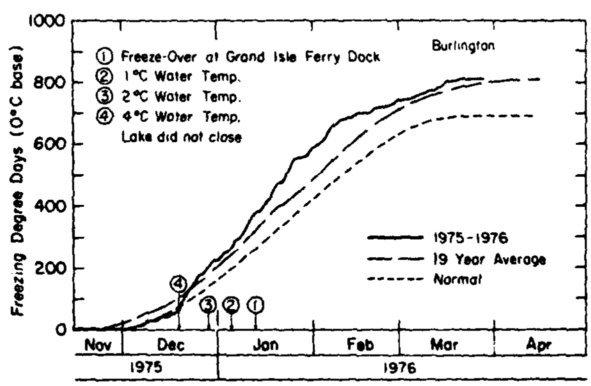

Figure A17a

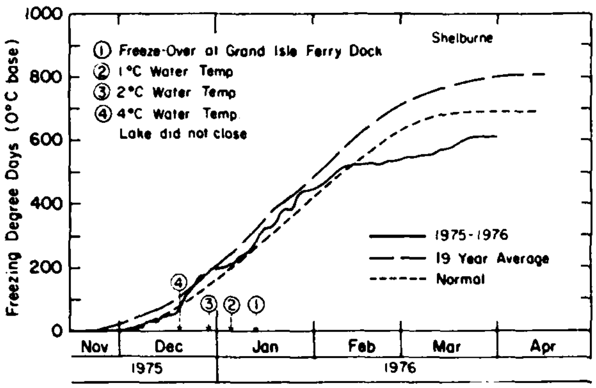

Figure A17b

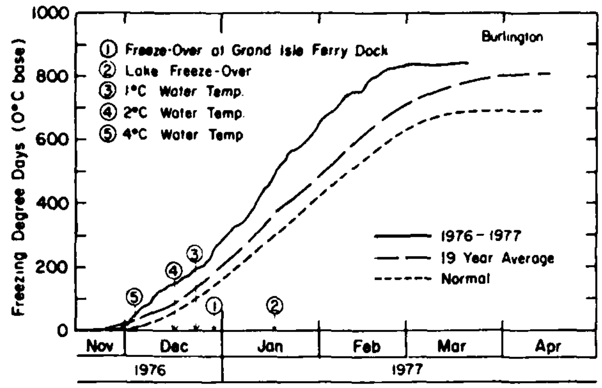

Figure A18a

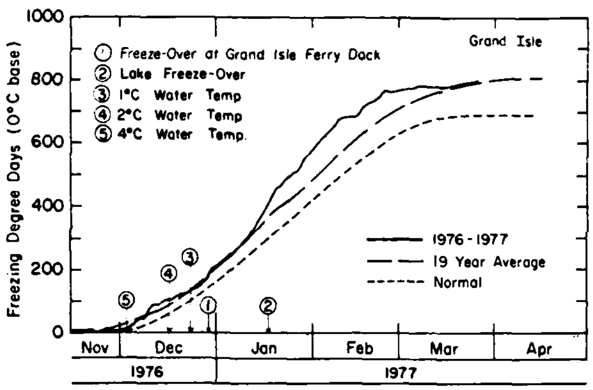

Figure A18b

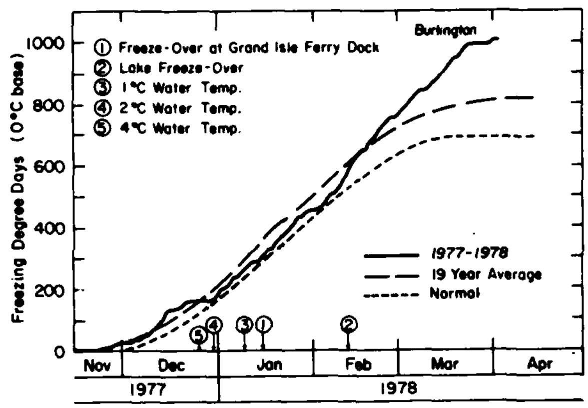

Figure A19a

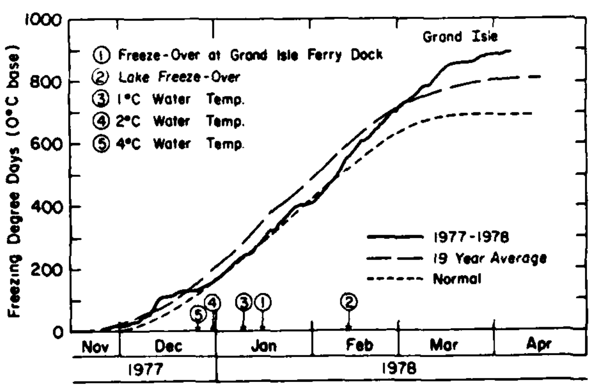

Figure A19b

APPENDIX B SUMMARY

Average date 4°C (39°F): 19 December, 29 ± 7 days to close of ferry
Average number of freezing degree-days on 19 December: 100, 250 freezing degree-days to close.

Average date 2°C (36°F): 31 December, 17 ± 6 days to close of ferry
Average number of freezing degree-days on 31 December: 200, 150 freezing degree-days to close.

Average date 1°C (34°F): 9 January, 8 ± 4 days to close of ferry
Average number of freezing degree-days on 9 January: 280, 70 freezing degree-days to close.

Average closing date at Grand Isle: 15 January
Average number of freezing degree-days on 15 January: 342.

Average date of maximum accumulated freezing degree-days: 20 March
Average number of days to opening at Grand Isle: 15 ± 5 days.
Average opening date: 5 April

Bates, Roy E.
Lake Champlain ice formation and ice free dates and predictions from meteorological indicators / by Roy E. Bates and Mary-Lynn Brown. Hanover, N.H.: U.S. Cold Regions Research and Engineering Laboratory; Springfield, Va.: available from National Technical Information Service, 1979.
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