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

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ABSTRACT

A 19-year record of annual closing and opening dates of the Lake Champlain ferry season was found to accurately approximate the freeze-over and breakup dates for the ferry crossing area between Gordon Landing, Vermont, and Cumberland Head, N.Y. These lake navigation records, when compared statistically with the lake's wintertime thermal structure and climatological data for the same years at nearby Lake Champlain locations, 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 water temperatures and freezing degree-days. A method of predicting ice growth rates is shown and the influence of wind speed on ice cover formation and prediction on a large body of water such as this is also discussed.

INTRODUCTION

This report examines four years of continuous field measurements on the climate, water temperature, and ice conditions of Lake Champlain near Burlington, Vermont (Fig. 1). Results are compared to long-term climatology records for nearby stations. A unique data set of annual opening and closing dates of the Lake Champlain Transportation Company (LCT Co.) Ferry was provided by the company (LCT Co. 1962-78). These opening and closing dates are controlled by ice cover formation and decay on the lake. The U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) has operated a winter meteorological station at the ferry terminal at Gordon Landing from 1977 to the present and previously operated a station at Shelburne Point, Vermont (Fig. 1) during the winters of 1975 and 1976.

The CRREL site at Gordon Landing (Fig. 2) is ideally sited as it: 1) provided a location for the instrumentation with access to power, 2) had a dock bubbler system that we could observe, and 3) gave us an opportunity to observe and conduct physical measurements during the LCT Company's first attempt at year-round navigation at their ferry crossing site on Lake Champlain.

Three reports, Bates (1976), Bates and Brown (1979), and Bates (1980), have been published on Lake Champlain ice conditions. This report gives an overview of findings to date of the wintertime research being conducted by CRREL on Lake Champlain.

OBJECTIVES

The main objectives of this research were the following:

1. To measure the heat transfer budget of a large temperate zone lake during ice formation, growth, and decay.

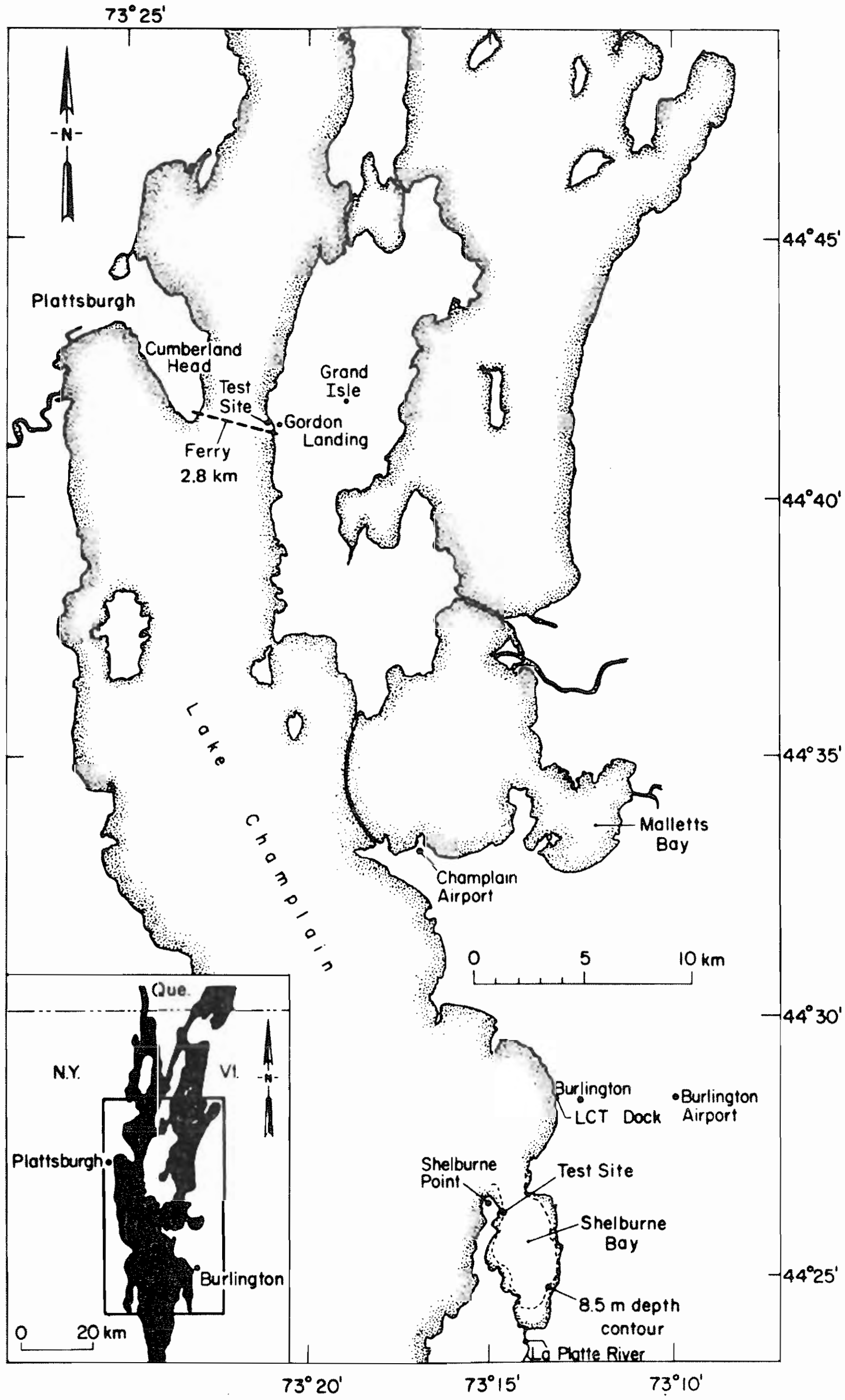

Figure 1. Test site locations in Burlington, Vermont, area.

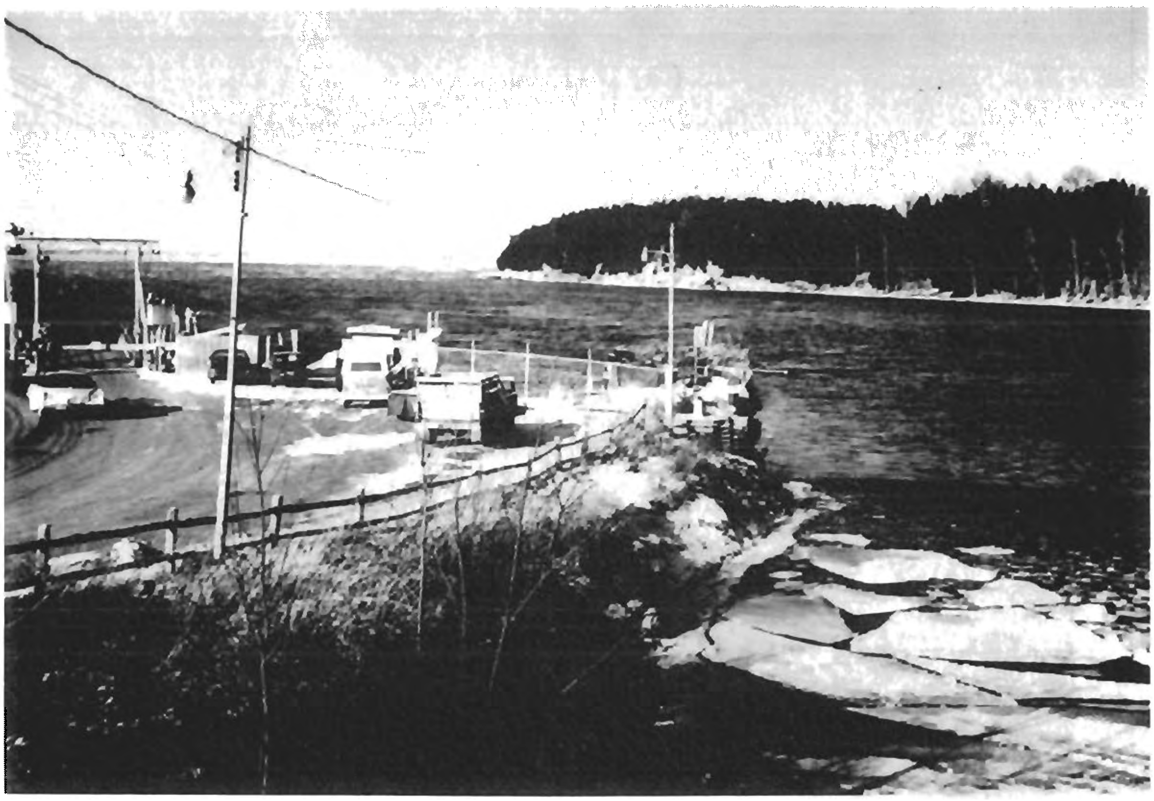

Figure 2. Lake Champlain Transportation Company ferry slip at Gordon Landing, Vermont.

2. To further develop a catalog of wintertime water thermal profiles that characterize the natural thermal environment of water bodies such as lakes and reservoirs.

3. To gather complete meteorological data in order to modify or better understand predictive models for ice formation, growth, and decay of mid-latitude water bodies.

4. To test several available ice formation hypotheses with known meteorological and water temperature data as well as with ice formation dates.

5. To observe the Lake Champlain wintertime ferry crossing in ice with a bubbler and flusher system installed at the Gordon Landing ferry slip and extending out from shore.

METHODOLOGY AND DATA ACQUISTION

Instrumentation, Measurements and Location:

In early December each winter a string of thermistors and a Doric 30-channel data logger recording system with a constant current source were installed. These thermistors were the same as used the previous winter and were installed at nearly the same water depth levels as described in Bates (1976). The temperature sensing instrumentation was designed to monitor the water temperature profile from the bottom sediment of the lake to the top of the data buoy extending 40 cm above the water and/or ice surface 100 m out from shore.

In early December 1976, CRREL meteorological instrumentation and water temperature recording systems were installed at Gordon Landing. This site offered us an excellent opportunity to observe the first attempt of year-round navigation of Lake Champlain by LCT Co. and to document the concurrent ice conditions, climate, and thermal influences of the lake. Figure 3 shows the ice mooring water temperature sensing device, solar radiation equipment and hot wire annemometer installed on site.

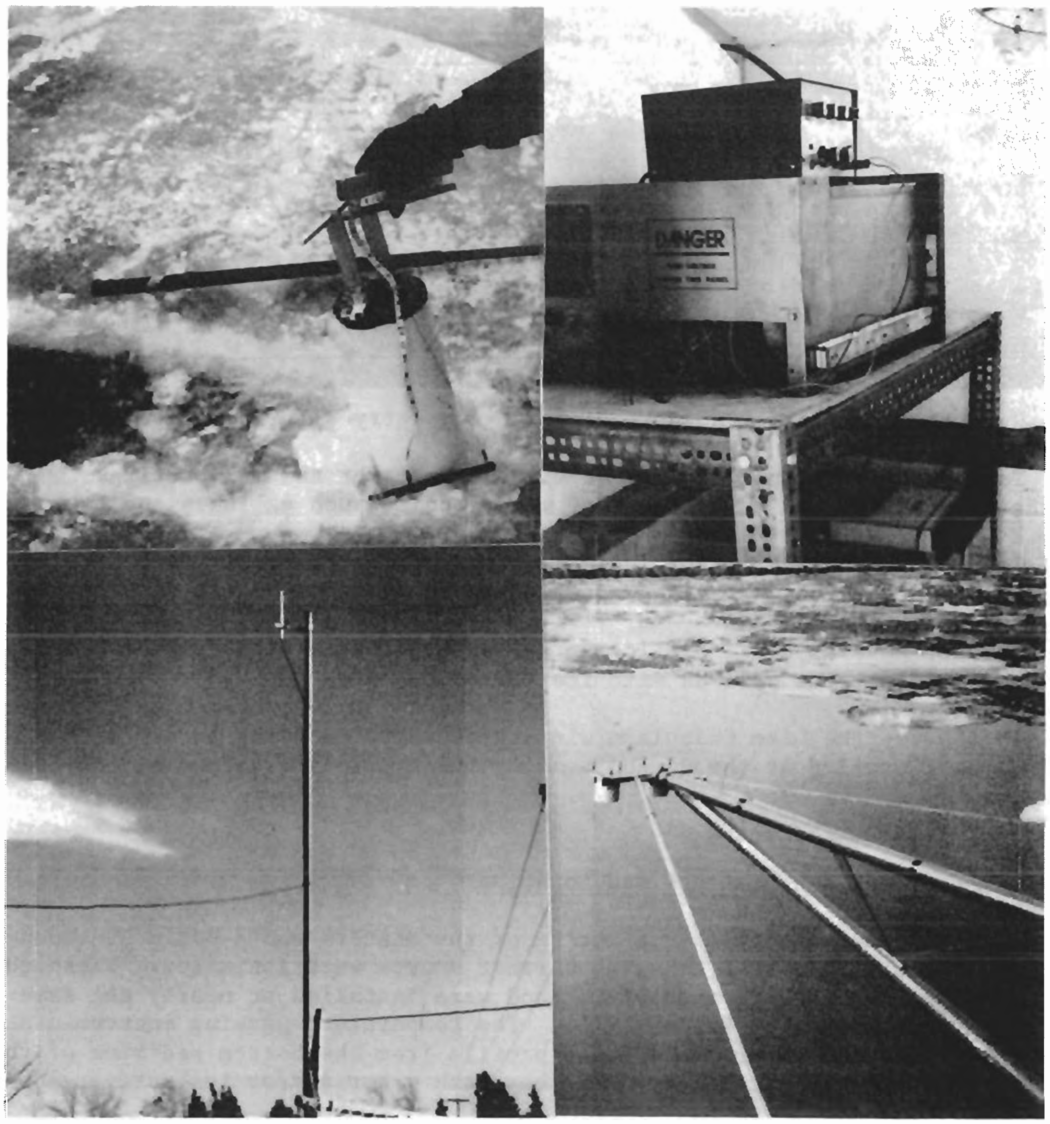

Figure 3. Instrumentation at Gordon Landing, Vt. Measurement Site.

TABLE 1. Location of thermistors installed 100 m offshore from Gordon Landing ferry dock.

Data logger channel	Thermistor location with respect to initial air/water interface
2	Top of ice buoy (40 cm above interface)
3	Above surface installed in snow
4	Above surface installed in snow-ice
5	Initial air/water interface
6	5 cm below interface
7	10 cm below interface
8	15 cm below interface
9	20 cm below interface
10	25 cm below interface
11	30 cm below interface
12	35 cm below interface
13	40 cm below interface
14	45 cm below interface
15	50 cm below interface
16	55 cm below interface
17	75 cm below interface
18	100 cm below interface
19	150 cm below interface
20	200 cm below interface
21	400 cm below interface
22	770 cm below interface
23	800 cm below interface

Table 1 gives the data logger channel numbers and water depth locations. The data logger provided an automatic printout every four hours of the water temperature profile throughout the winter. Discussions on thermistor calibration, the water temperature data collection system, construction of the ice-free mooring, and the computer program through which the data were entered every four hours are all presented in Bates (1976). The temperature error for the thermistors was $\pm$ 0.16°C in the region around 0°C.

ICE CONDITIONS AND PERTINENT PHOTOGRAPHY

Ice samples were obtained at the Gordon Landing site on 2 March 1977. These samples were taken to help determine the structure and type of ice that the Grand Isle Ferry was breaking while traversing the lake throughout the winter. In situ beam tests of the flexural strength of the ice cover were performed at this time in conjunction with other ice property studies. A representative sample (Fig. 4) of the ice cover was subsequently examined for structural characteristics and found to be composed of 14 cm of frazil ice overlain by 9-10 cm of snow-ice and underlain by 18-19 cm of congelation ice. A full cross section of the structural characteristics of this ice cover is shown in Figure 4.

Landsat imagery was obtained from the EROS Data Center (Sioux Falls, South Dakota) for the Lake Champlain area during the winter of 1976-77 to determine whether the open water area of the LCT Co.'s ferry crossing was discernible. Two pertinent photographs were received and enlargements made of the area under consideration for use in this report (Figs. 5 and 6). Figure 5 shows solid ice cover conditions on Lake Champlain on 9 March 1977 except for the ferry crossing area when the ice measured 38 cm at the Gordon Landing ferry installation. Figure 6 shows Lake Champlain ice conditions on 27 March 1977 at breakup of the main lake ice cover. The ferry crossing site is marked by an arrow in both photographs. Throughout all winters a complete chronological account of visual ice conditions and photographs was obtained. Some of these photographs are shown by Bates (1980).

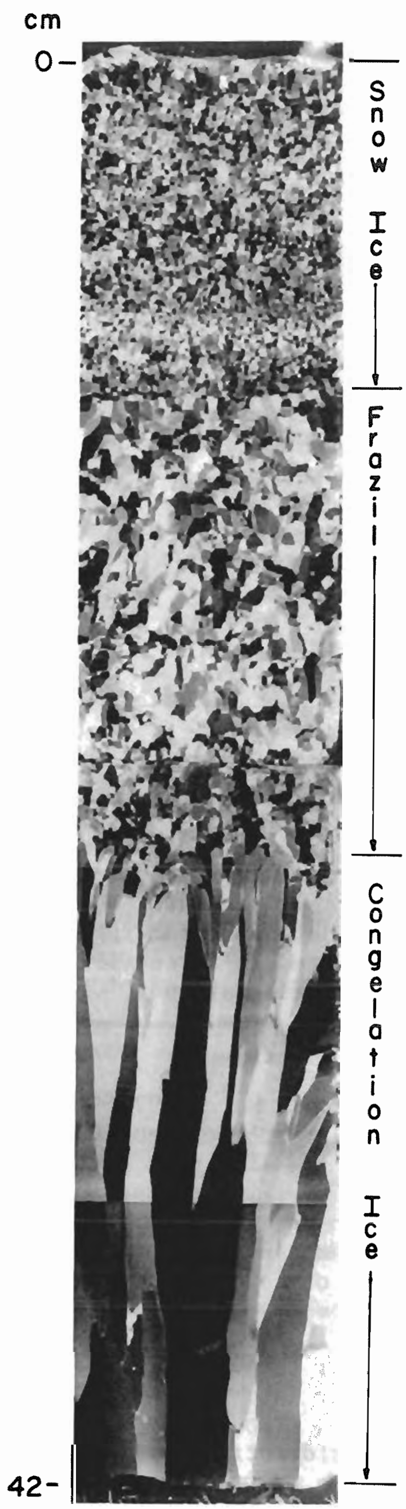

Figure 4. Crystal structure of Lake Champlain ice cover, Grand Isle, 3 March 1977. (Furnished by Dr. Anthony Gow, CRREL)

DATA ACQUISTION

Air Temperature:

Average monthly air temperatures were extracted from Local Climatological Data: Burlington, VT (U.S. Department of Commerce 1959-1978). Air temperature data for this period were measured at the Burlington International Airport, 5 km inland. 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), taken from Climatology of the United States, No. 81, for New England (U.S. Department of Commerce 1973). Third, these air temperatures were used for calculations of freezing degree-days.

Comparisons of air temperature trends were also made with the long-term monthly normal temperatures determined from data collected since 1893 by the U.S. Department of Commerce (1952). Comparison of these data with air temperature measurements taken near the lake shore by Bates (1976, 1979, 1980) showed that Burlington Airport's average monthly winter air temperatures (Table 2) were representative of Lake Champlain. This is reasonable as the lake, especially while void of ice, has a large effect of the overall meso-climate of nearby areas of Vermont and New York.

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 and the resulting curves are shown in Bates (1979). 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. An example of the type of diagram available for each year is shown on (Fig. 7). These curves demonstrated year-to-year air temperature fluctuations and common tendencies. In addition, they compare conditions

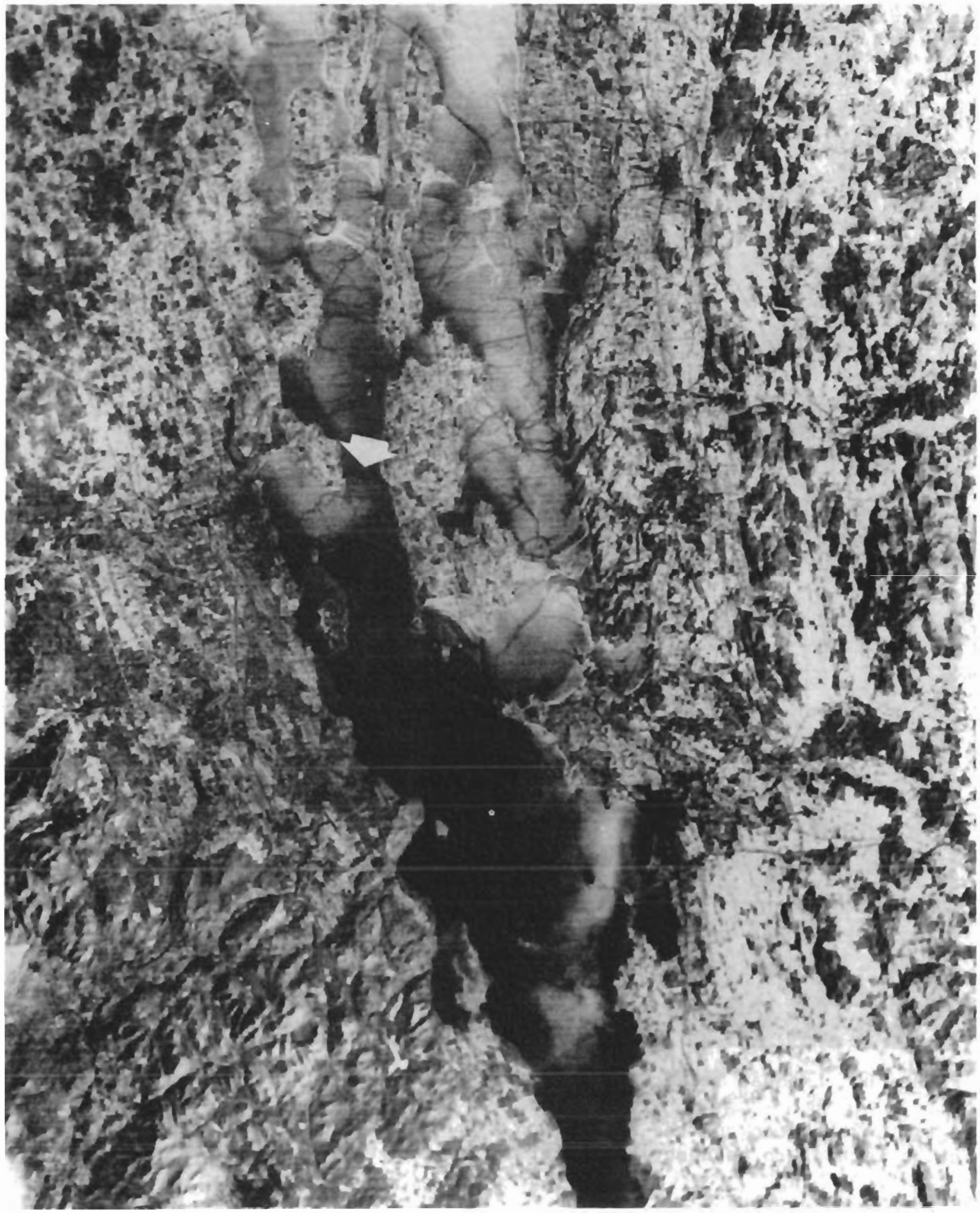

Figure 5. Landsat imagery of ice conditions on Lake Champlain on 9 March 1977.

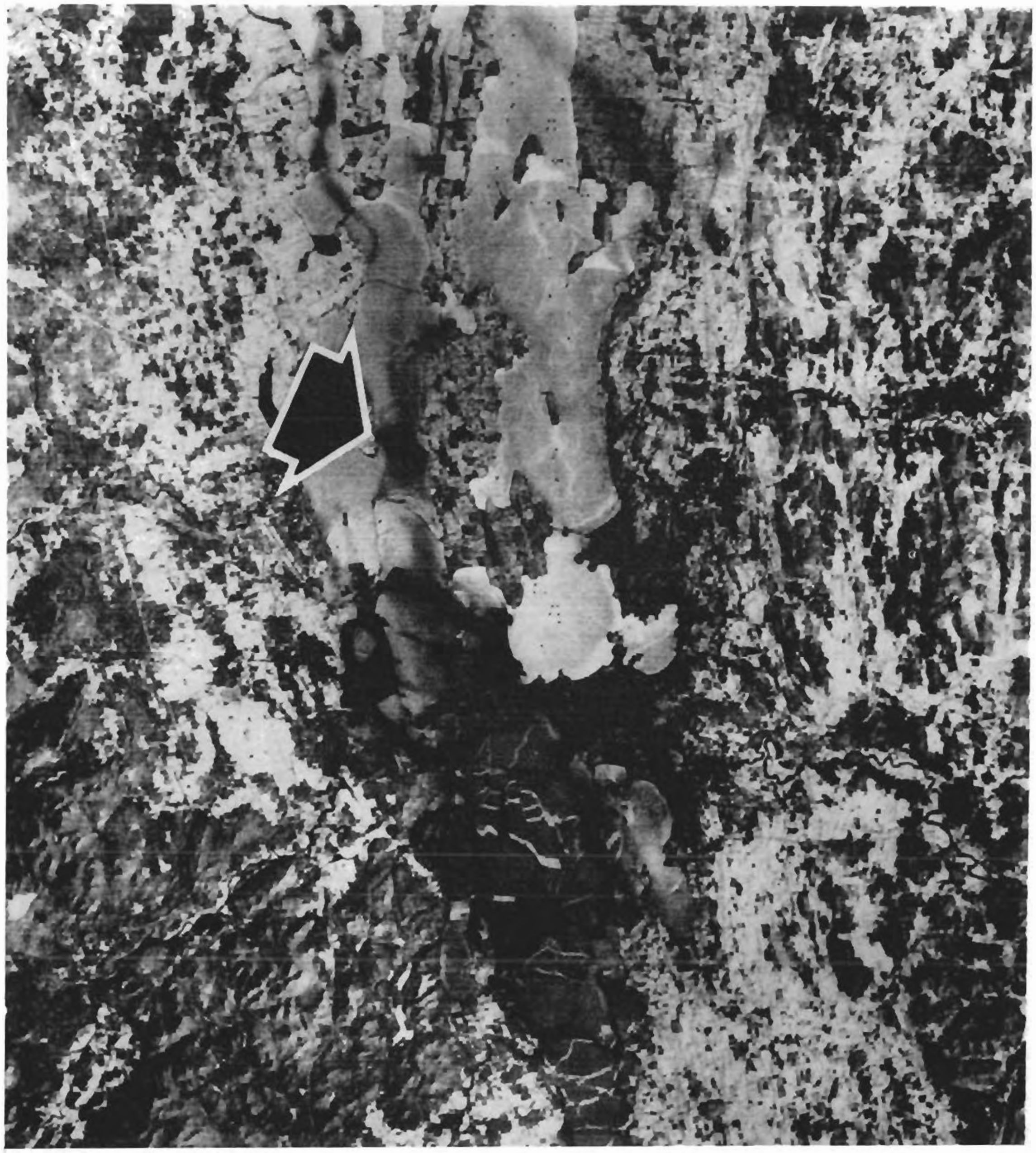

Figure 6. Landsat imagery of ice conditions on Lake Champlain on 27 March 1977.

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:

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. These data have been compiled and will be correlated with water temperatures measured by CRREL (1974-present) later in the report for ice prediction purposes.

Closing and Opening Dates:

The Lake Champlain Transportation Co. 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

Table 2. 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	8.2	0.5	-1.9	6.2
1966	-9.2	-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	-4.5	-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	14.4	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	-7.4	-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 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.

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.

ANALYSIS

Air Temperature Comparisons:

A continuous record of air temperature was measured by CRREL for four winters at Shelburne Point during 1974-75 and 1975-76 and at Gordon Landing (Fig. 1) during 1976-77 and 1977-78. Average daily and monthly air temperature in degrees Celsius were determined for each winter and reported in previous reports.

Comparison of each site's annual winter temperature regime and the three-year long-term normal (see Table 2 for long-term normal) showed the following:

1. The ice growth period during 1974-75 was warmer than normal.

2. During 1975-76, December and January were 1.2° and 0.3°C colder than normal, and February and March were 7.1° and 3.4°C warmer than normal, so that the winter season of 1975-76 averaged 2.2°C warmer than normal.

3. In comparing long-term normal values to the 1976-77 season at Gordon Landing, it was found that temperatures were 1.6° and 3.2°C colder than normal in December and January, respectively.

4. February and March 1977 temperatures were 1.3° and 3.6°C warmer than normal. Thus, the overall winter season was near normal, since the ice growth period was colder but the ice decay period was warmer.

5. The winter of 1977-78 (December-March) averaged 1.3°C colder than normal with February recording 5°C colder than normal.

Table 2 shows that 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). Also, air temperatures show a recent slight cooling trend for Burlington (Table 2). However, there is a 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 (Table 2) 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 Burlington meteorological station was moved from downtown city offices to Burlington Airport in May 1943.

Freezing Degree-Days:

The freezing degree-day curves (Fig. 7) illustrate the recent cooling trend. The 30-year normal or average curve 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.

An example of one year's degree-day curve is plotted in Figure 7 for the 1976-77 season at the Gordon Landing site. First ice formed on 15 December after 186 freezing degree-days. The curve for 1976-77 in Fig. 7 for Gordon Landing nearly approximates the

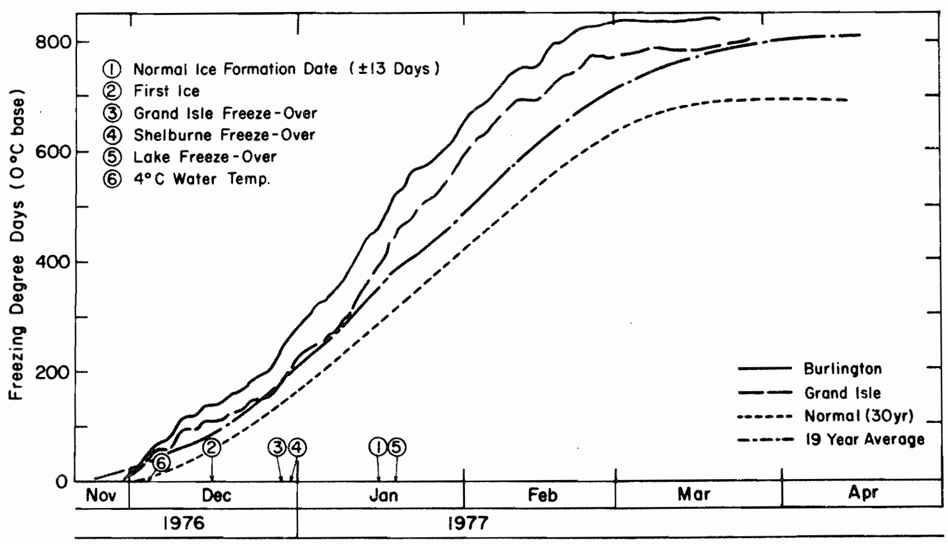

Figure 7. Accumulated degree-days of freezing $0^{o}C$ base.

curve for the same period at Burlington Airport. Shelburne Point reported freeze-over on 30 December (Fig. 7) which was after 270 freezing degree-days (°C) at Burlington Airport. The curves also show that colder-than-normal air temperatures prevailed at Burlington Airport, 5 km inland from the lake, until ice formation. The two seasonal curves are similar for the rest of the ice growth period. Finally, both seasonal curves show much colder temperatures than normal during December and January, with the entire lake freezing over on 16 January after 450 freezing degree-days (°C). This is the earliest freeze-over of the entire lake in this century. An earlier report, Bates (1979), shows that the greatest number of accumulated freezing degree-days °C for the years 1960-1978 is 1125 in the winter of 1969-70 with the least being 700 freezing degree-days in 1973-74.

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 (0°C) degree-days (± 87 degree-days), whereas final freeze-over of the entire lake in the winters that experience complete freeze-over normally occurs after 603 freezing (0°C) degree-days (± 99 degree-days).

It was previously established that the normal winter temperature curve for the Burlington Airport approximates curves for the Shelburne Point and Gordon Landing measurement sites. Therefore, the difference in the annual freezing degree-day totals from site to site must be attributed to the tempering influence of the lake. This is especially apparent at Shelburne Point (Fig. 1) which is geographically situated between a bay and the main lake and is thus more sensitive to the lake's influence. In contrast, Gordon Landing 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 the Gordon Landing site probably more accurately represent the wintertime climatic regime of Lake Champlain.

Ice Formation Predictions From 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. Bilello (1960, 1964) discussed methods for prediction of ice formation growth and decay in Canada using the Rodhe (1952) relationship between weighted air temperatures and ice formation. This method was attempted for several years of air temperature data including the long-term average for Burlington Airport, near Lake Champlain. Utilizing a derived (k) value of 0.02 (see Bilello, 1964 and Rodhe, 1952 for experimental theory), dates of freeze-over at Grand Isle were computed within three days of the observed date. However, although this method demonstrates a high degree of accuracy, it depends on reliable air temperature forecasts.

Ice Formation Predictions From Fall Water Temperatures And Freezing Degree-Days:

Ice predictions are attempted in this section using the date of occurrence of a specific water temperature and corresponding freezing degree-days °C. Utilizing the available recent air temperature data, 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.

Of primary importance was the date the temperature of the lake cooled to 4°C (39°F) and remained at or below this temperature. This water 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 (17-year record) of 4°C water temperature is 19 December; this corresponds to 100 freezing degree-days. On the average, 29 days (± 7) and 250 freezing degree-days elapse between the occurrence of the 4°C reading and freeze-over at Gordon Landing (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

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.

250 freezing degree-days later. The results of this prediction method for each year are summarized in Table 5 along with results from selections of water temperature base temperatures of 2°C (36°F) and 1°C (34°F) and their corresponding freezing degree-days.

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

There is an advantage of more accurate prediction with decreasing temperature. However, the slightly decreased accuracy in using, for instance, 4°C water temperature as the basis for prediction is compensated for by the fact that a forecast of the ice formation date can be made further in advance (i.e., 29 days). This is compared to 17 days for 2°C and 8 days for 1°C (Table 5).

Other ice prediction models were attempted using the Lake Champlain closing and opening dates with limited success and are presented in Bates (1979).

Water and Ice Temperature:

The water/ice temperature automatic profiling system was installed in early November 1976 at Gordon Landing and temperatures were accurately recorded at all depths listed in Table 6 during the 1976-77 winter period.

Figure 8 gives the water temperature/ice temperature profiles measured during the month of February 1977. This figure shows both the profile nearest the time of measured ice thickness and the average profile for each selected date. Each date was selected to correspond with weekly ice thickness measurements. However, a profile could be drawn for any daily mean or four-hour period throughout the winter. Table 6 is an example of the computer printout of temperature for one day.

The 0°C point of water or ice on the three profiles (Fig. 8) does not necessarily correspond to the measured ice thickness because the thickness was measured weekly within 3 m of the buoy and not exactly where the buoy was frozen into the ice. However, it can be assumed that the approximate ice thickness at the buoy approximates the 0°C point of the plotted profile, as this is generally at the ice/water interface. Further analysis shows that:

Table 6. Representative water temperature printout for Lake Champlain, 11 February 1977.

		Hour								
Chn	*Loc Depth*	*0*	*400*	*800*	*1200*	*1600*	*2000*	*Min*	*Max*	*Ave*
2	Air temp	-7.4	-3.0	-0.5	2.9	4.5	2.1	-7.4	4.5	-0.2
3	Snow	-2.8	-2.3	-1.6	-0.3	0.0	0.1	-2.8	0.1	-1.2
4	Snow/ice int	-3.3	-2.5	-1.7	-0.4	0.1	0.1	-3.3	0.1	-1.3
5	0	-3.9	-2.4	-1.0	0.4	1.0	0.6	-3.9	1.0	-0.9
6	5 cm	-3.1	-2.1	-1.1	0.1	0.3	0.2	-3.1	0.3	-1.0
7	10 cm	-3.3	-2.9	-2.1	-0.6	-0.2	-0.1	-3.3	-0.1	-1.5
8	15 cm	-2.8	-2.6	-2.1	-0.9	-0.5	-0.2	-2.8	-0.2	-1.5
9	20 cm	-2.2	-2.3	-1.9	-1.1	-0.6	-0.3	-2.3	-0.3	-1.4
10	25 cm	-1.8	-2.0	-1.8	-1.2	-0.7	-0.4	-2.0	-0.4	-1.3
11	30 cm	-1.4	-1.5	-1.5	-1.1	-0.7	-0.4	-1.5	-0.4	-1.1
12	35 cm	-1.1	-1.3	-1.3	-1.0	-0.6	-0.4	-1.3	-0.4	-0.9
13	40 cm	0.2	0.4	0.5	0.5	0.5	0.3	0.2	0.5	0.4
14	45 cm	0.4	0.5	0.6	0.6	0.6	0.5	0.4	0.6	0.5
15	50 cm	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
16	55 cm	0.7	0.7	0.7	0.7	0.6	0.7	0.6	0.7	0.7
17	75 cm	0.9	0.8	0.7	0.8	0.7	0.8	0.7	0.9	0.8
18	100 cm	0.9	0.9	0.8	0.9	0.8	0.8	0.8	0.9	0.8
19	150 cm	0.9	0.9	0.8	0.9	0.9	0.8	0.8	0.9	0.9
20	200 cm	0.9	1.0	0.8	1.0	1.0	0.9	0.8	1.0	0.9
21	400 cm	1.1	1.2	1.1	1.0	1.0	1.0	1.0	1.2	1.1
22	770 cm	1.0	1.1	1.0	1.0	1.0	1.0	1.0	1.1	1.0
23	800 cm	1.1	1.1	1.1	1.0	1.0	1.0	1.0	1.1	1.0

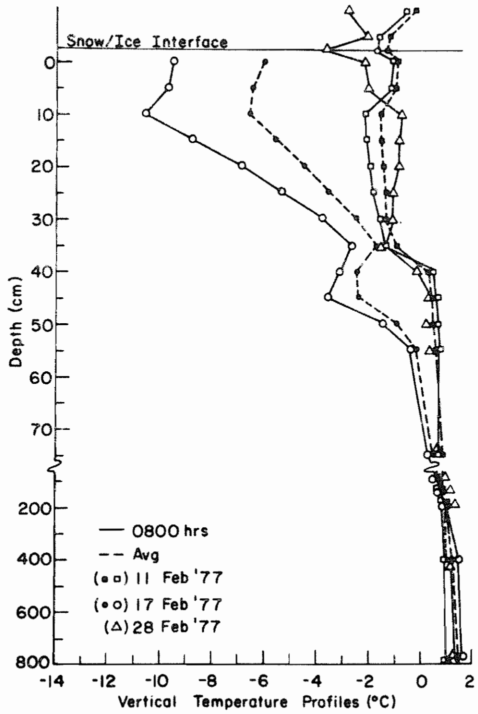

Figure 8. Water temperature/ice temperature profiles for February 1977. (Ice thickness varied between 43-48 cm during the month.)

1. The lake bottom temperature was cooled to 0.7°C in early February. This bottom temperature warmed to 1.6°C by 28 February even though the ice thickness remained fairly constant throughout the month (43-48 cm). A possible explanation of this is the gain in net solar radiation received at the surface of a clear ice cover, with no snow depth and less than 3 cm of snow-ice at this time of year, together with increased lake circulation.

2. Ice temperatures colder than air temperatures are occasionally measured in the ice cover both on a single profile and on the average plot for the day.

3. These colder air temperatures can remain for a few hours or 24 to 48 hours depending on the surface (snow/ice) atmospheric heat exchange, which is controlled by both mechanical and thermodynamic processes within the particular air mass over the site.

Wind and Its Influence on Closing of the Lake:

Summaries of 20-year average wind speed were compiled by Bates et al. (1979). These data, calculated from local climatological data at Burlington Airport (U.S. Department of Commerce 1973), show that the wintertime (November - March) wind speeds average 4.1 m/s, prevailing from the south from November through February, with March reporting a northerly wind direction. During 1976-77, the Gordon Landing site recorded westerly winds as compared to those from the west-southwest at Plattsburg AFB. Maximum hourly wind speed for the two winter periods reached 17 m/s during 1975-76 and 16 m/s during 1976-77.

Average daily wind speeds (m/s) 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.

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 for corresponding years using a computer regression analysis for each winter. The results and a computer plot are shown in Figure 9.

The formula used for the regression analysis is:

$$y = a + bx$$

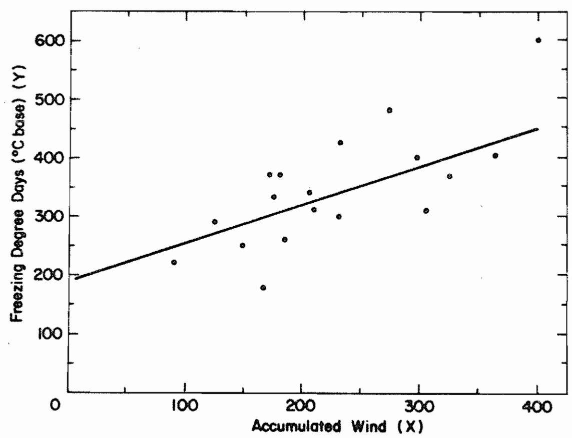

Figure 9. Computer regression analysis plot, Burlington Airport Data. y=a + bx, a=188.4, b=0.654 and correlation coefficient=0.63.

where y = accumulated freezing degree-days (°C) until ice formation and x = accumulated average daily wind speeds (m/s) until ice formation. The computed values of a and b are given in (Fig. 9). Figure 9 also gives the calculated correlation coefficient (r) of 0.63 between accumulated freezing degree-days and accumulated daily average wind speed.

The analyses shown in Figure 9 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.

Predictions of Ice Growth:

In earlier reports ice growth curves were computed from the date of initial ice cover using the simplified Stefan equation:

$$t = \alpha(\Sigma\Delta T\theta)^{1/2}$$

where t is ice thickness, α is the coefficient, ΔT is air temperature below 0°C and θ is time. In the most simplified treatment of this equation, as described by Ashton (1978), the maximum theoretical value of α is calculated as

$$\alpha = (2k_i/\rho_i\lambda)^{1/2}$$

where k_i is thermal conductivity, ρ_i is ice density and λ is latent heat of fusion. This expression equals 0.000121 m $s^{-1/2}$ $°C^{-1/2}$ for typical lake ice. This derivation assumes that the surface temperature T_s of the ice sheet is the same as air temperature T_a. Since T_s differs substantially from T_a for thin ice sheets (<0.2 m) in the initial growth period (Ashton 1978), an additional correction factor (β) had to be included to achieve better agreement between predicted and observed ice thicknesses. Thus, the equation for the coefficient α becomes:

$$\alpha = \beta(2k_i/\rho_i\lambda)^{1/2} = \beta(0.000121 \text{ m s}^{-1/2} \text{ °C}^{-1/2})$$

In Bates (1980) and from the above analysis, β was determined to equal 0.6 at both the Shelburne and Gordon Landing sites, giving a coefficient α of 0.00007 m $s^{-1/2}$ $°C^{-1/2}$. This coefficient falls within the bounds of typical empirical values of 0.00006 to 0.00010 m $s^{-1/2}$ $°C^{-1/2}$ obtained by investigators using this equation (Ashton 1978).

The winter of 1976-77 is the first winter of observations at the Gordon Landing site. Figure 10 shows two ice growth curves determined from weekly measurements at the site. The in-shore ice was established a few days earlier and grew faster at the beginning of the ice season. The maximum thickness near shore measured 53 cm, while the ice maximum at the temperature profiling buoy measured 48 cm. The ice at the near-shore measurement site candled and melted out due to the influence of the bubbler system and ferry operations by 8 March. Measurements continued at the buoy site until melt-out at the buoy which was recorded on 21 March 1977. The aerial Landsat photograph (Fig. 6) taken on 27 March shows ice breakup of the main lake and melt-out at the Gordon Landing site with a large open area (arrow) in the lake ice from ferry operations and increased solar radiation (discussed in Bates 1980).

The estimated ice thickness prediction curve for 1976-77 using the Stefan equation and the correction factor of 0.00007 m $s^{-1/2}$ °C is also shown in Figure 10. Again, the predicted and actual ice growth curves demonstrate a high degree of correlation until the latter part of February when ice deterioration began.

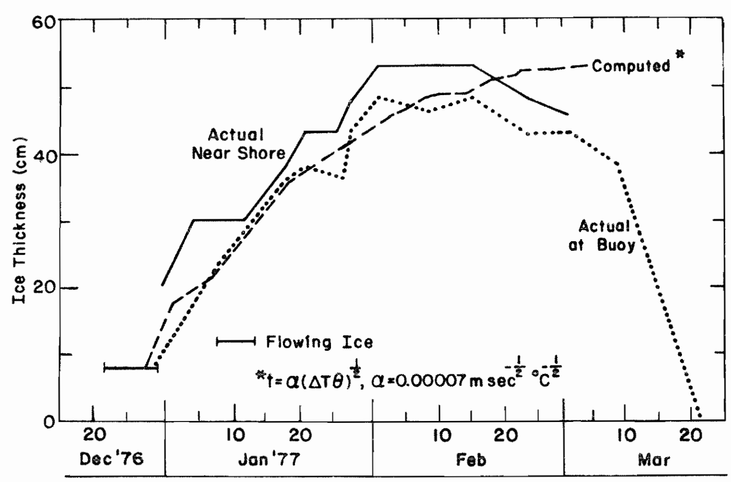

Figure 10. Ice growth curves (actual and computed) for Gordon Landing in 1977.

Shelburne typically experiences a later freeze-over date than Gordon Landing, perhaps due to the difference in the geography of the two sites; i.e., the width of the lake at Shelburne Point is approximately 17 km as compared to 3.2 km at Gordon Landing. This wider part of the lake at Shelburne is prone to greater wind and wave disturbance, thus delaying land-fast ice formation. However, despite this difference in the initial date of ice formation, ice growth proceeded at a similar rate at both sites as demonstrated by the computed empirical coefficient of 0.00007 m $s^{-1/2}$ $°C^{-1/2}$.

Grand Isle Ferry Operations 1976-77:

The Lake Champlain ferry crossings at Gordon Landing during the winter of 1976-77 are discussed and documented in Bates (1980), Table A2. The extremely cold temperatures during the fall and winter of 1976-77 cooled the surface water temperature of the lake to near 0°C by 25 December, which is approximately 20 days earlier than normal. The land-fast ice formed from Gordon Landing, Vermont, to Cumberland Head, New York, on 28 December; thus, LCT Co.'s first attempt at winter navigation commenced on this date.

Lake Champlain completely froze over by 16 January 1977 which was the earliest date this century. Earlier dates of complete freeze-over were 7 January 1868 and 15 January 1893. This shows the severity of the winter through January 1977.

The first year's operation of the Grand Isle ferry throughout an entire winter season was successful, although some problems were encountered during breakup when wind caused ice floes to drift across the normal channel. However, the ferry was able to navigate around these floes and accomplish its crossing routine with only minor delays.

The bubbler system installed in the Gordon Landing slip was very efficient in keeping the slip relatively ice-free throughout the winter. Also, the ferry did not have to break itself free of overnight ice formations each morning when starting its daily schedule.

SUMMARY AND CONCLUSIONS

The basic data obtained on the annual opening and closing dates of the Lake Champlain 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 (base 0°C) for each year are compared with dates of freeze-over at Grand Isle, and complete lake freeze-over and the occurrence of water temperatures at 4°C (39°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 Gordon Landing, 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 of other areas of the lake. Further analysis (Fig. 10) showed that ice growth could be predicted with considerable accuracy.

Analysis of 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 of 0.63. This indicates that freeze-over is more likely to occur on a large lake with lower wind speeds and cold temperatures.

After three winters of study, it is reasonably established that the Burlington Airport long-term average temperatures and winds are representative of areas of Lake Champlain studied. The lake, when unfrozen, has a moderating influence on the climate of nearby areas of New York and Vermont.

The winter of 1976-77 was much colder than the previous two winters studied at Shelburne. This is indicated by colder fall water temperatures, and by December and January air temperatures that averaged 1.6° and 3.2°C colder than normal, respectively. The date of 16 January 1977 is the earliest complete freeze-over of the lake in this century. Freeze-over was observed on 28 December 1976 after 186 freezing degree-days (°C) at the Gordon Landing, Vermont, to Cumberland Head, New York, Grand Isle ferry crossing area. This is one of the earliest dates recorded for this area of the lake.

LCT Co's ferry operations throughout the cold winter of 1976-77 were a success. Documentation of these operations is discussed in a previous report. Landsat photos are presented which show the open water channel caused by ferry operations and document the exact breakup of Lake Champlain in March 1977.

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ACKNOWLEDGEMENTS

The author acknowledges the capable assistance of Mary L. Brown for data tabulation, Bryan Harrington for electronic instrumentation and Gary Decoff for computer programming.