Ice-Push Damage on Lake Bomoseen, Vermont

Final Report

Submitted by:

Lawrence W. Gatto, Michael G. Ferrick, and Darryl J. Calkins
U.S. Army Corps of Engineers
Engineer Research and Development Center
Cold Regions Research and Engineering Laboratory
72 Lyme Rd.
Hanover, NH 03755-1290

Submitted to:

State of Vermont
Agency of Natural Resources
Department of Environmental Conservation
Water Quality Division
103 S. Main St.
Waterbury, VT 05671-0408

and

U.S. Army Corps of Engineers
New England District
Planning Division
696 Virginia Rd.
Concord, MA 01742-2751

May 2001

TABLE OF CONTENTS

FIGURES

TABLES

Ice-Push Damage on Lake Bomoseen, Vermont

LAWRENCE W. GATTO, MICHAEL G. FERRICK, AND DARRYL J. CALKINS

INTRODUCTION

Background

In cold climates such as Vermont's, where an ice cover forms on lakes and ponds nearly every winter, ice can push horizontally into shorelines and shore structures or vertically lift shoreline materials and in-water structures. The pushing forces result when ice expands or when ice is moved about by wind. The lifting forces are generated when the water level of an ice-covered lake rises. The damage caused by horizontal ice push, which is common along many northern lakes including Lake Bomoseen, is addressed in this report.

Lake Bomoseen is located north of Hydeville in west-central Vermont about 11 miles west of Rutland (Fig. 1). The lake covers 2360 acres, has a drainage area of about 39 square miles, has a maximum depth of 65 feet, and averages about 27 feet deep. The main body of the lake is oriented north-northeast to south-southwest. It is a little more than 3.5 miles long from Indian Point on the south to the Grady Bridge on the north and generally varies from about 0.5 to 0.7 miles wide. The maximum width is 1.2 miles near Neshobe Island, and the minimum width is generally less than 400 feet in the channel section south of Indian Point. The lake is surrounded by rolling topography with local hills less than 1000 feet in elevation, and the lake surface is at an elevation of 411 feet.

Objectives and Limitations of this Study

The general objective of this study as defined in the scope of work was to determine the effect and severity of ice interaction with shorelines and structures along the westerly shore of Lake Bomoseen. The four primary specific objectives in the scope of work were to:

- Inventory shoreline and structure ice damage along a 2-mile section of the westerly shore of the lake;

Figure 1. Location of Lake Bomoseen.

- Synthesize databases to determine if a particular winter climatic pattern exists in this area when ice damage has been reported;
- Install a web camera to document and understand meteorological conditions during ice push at a lakeside home that has experienced ice damage to the property in the past; and
- Identify potential structural and non-structural solutions to ice-damaged structures and natural conditions assuming no drawdown of the winter lake level.

We had three additional objectives not specified in the scope of work:

- Use available literature to provide background information on the causes and effects of ice push, the magnitudes of ice push measured at

various locations, and the prediction of ice push;
- Determine if there are shore conditions that might influence the location, severity, and frequency of ice push within and beyond the 2-mile section of the west shore; and
- Improve the current understanding of cause-and-effect relationships between ice expansion and ice push.

Thermal expansion is the most common cause of ice push along small to medium-sized lakes like Lake Bomoseen in northern New England (Gatto 1982). However, this has never been determined specifically for Lake Bomoseen because the on-site data required have not been available. We measured ice and air temperatures, snow depth, and ice thickness at a site along Lake Bomoseen during the 1999-2000 winter to relate those conditions to ice push.

This study is limited in several ways. First, this was a one-year study, which is far too short for an analysis of the variety of factors that cause ice push.

Second, the study did not include an analysis of other processes that affect the shoreline and shore structures along Lake Bomoseen. The movement and failure of shoreline banks or shore structures are influenced by waves and currents, which erode and redistribute soils and sediments. Shorelines are also affected by lateral soil pressures generated year-round within the soil by groundwater changes and freeze-thaw cycling. These processes can make a shoreline segment or shore structure more susceptible to ice push during the winter. When this occurs, ice is not the sole cause of the observed damage, only the most obvious.

Third, the historical data available to synthesize for patterns were only marginally useful. They consisted of qualitative recollections and eyewitness reports which are inherently inaccurate, data not collected during ice-push events, and data collected some distance from the lake. These shortcomings limited the degree to which cause-and-effect relationships could be defined.

Fourth, the scope of work specified that there will be no winter drawdown of the Lake Bomoseen water level, which eliminates one potential solution for ice-push damage. If the water could be lowered, the ice would push against the lake bed, not the shoreline. However, the Vermont Agency of Natural Resources (VANR) does not allow a winter drawdown because of concerns about the effects on the wetland habitat and wildlife at the north end of the lake.

ICE PUSH ALONG LAKE SHORES

We synthesize here a selection of reports that address ice push along lakes. Much has been written describing ice push effects, but much remains to be learned about cause-and-effect relationships of the ice push process.

Causes and Effects

The horizontal push of ice into a lake shore is caused by static and dynamic forces. Static forces are generated when ice on the water surface expands as it warms. This expansion is often augmented by an increase in ice volume when water in cracks that have formed in ice freezes. But the thermal expansion is by far the primary cause of static ice push. Dynamic forces are generated when wind drives an ice cover into the shore. Generally, water currents under lake ice are insufficient to move ice about (Tsang 1975).

It is generally agreed that ice push due to thermal expansion predominates on lakes and bays less than 2.5 miles across and that wind-driven ice push predominates on lakes and bays wider than 2.5 miles (Gatto 1982). However, Wagner (1970) suggested that lakes less than about 0.5 mile in diameter are too small for appreciable expansion and that the ice on lakes larger than 1.5 miles across generally have weak zones that absorb the expansion and prevent expansion forces from reaching the shore. Laskar and Strenzke (1941) described ridges of boulders pushed up along shores and entire trees and bushes uprooted by wind-driven ice in northern Germany; they concluded that wind thrusts ice into the shore only on larger lakes with adequate fetch.

Montagne (1963) suggested that both processes can occur simultaneously, but it is more likely that one or the other would predominate at a given location because the conditions for each are mutually exclusive. Fetches that are sufficiently long for wind to generate enough momentum in an ice cover to drive the ice into a shoreline would be too great a distance for an expanding ice cover to maintain competency across a water surface. Such an expanding cover would crack and buckle out in the lake, and the expansion forces would never reach the shore.

Ice Expansion

Ice reacts to temperature changes like most solids; it contracts as it cools and expands as it warms (Zumberge and Wilson 1953). If ice completely covers a lake, the expanding ice would push against a shoreline. If the cover is incomplete, the ice could expand into open water areas and not affect the shore. When ice alternately expands and contracts during warm and cold periods, it cracks because of the compression and tension forces set up within the ice. Cracks can also form when a lake level fluctuates (Wortley 1978). The cracks can fill with water, and if they refreeze the new ice adds to the mass of the ice cover. Cracks can also remain dry and accommodate some ice expansion, which mitigates the forces that impact a shore during thermal expansion (Wortley 1978). Ice expansion requires ice temperature fluctuations, which tend to occur less often at high latitudes because of deep snow and few changes in air temperature and solar radiation (Wagner 1970).

Montagne (1963) described linear mounds of sediment, called ramparts, pushed up along the shore of the South Arm of Yellowstone Lake in Yellowstone National Park, Wyoming. These ramparts were composed of angular boulders, some weighing over a ton. He reasoned that the ramparts were formed by ice expansion because South Arm is 1.5 miles across, which is not too great a distance for expanding ice to remain intact and thrust against the shore. He concluded that 1.5 miles was not wide enough for wind to give the ice enough momentum to push such large boulders.

Wagner (1970) reported that the ice ramparts along Shelburne Bay on Lake Champlain, Vermont, that formed by ice expansion when the ice cover was complete were larger than those formed by wind-driven ice when the ice was breaking up. He reasoned that the width of the bay was optimum for ice expansion and that the ice at breakup was too weak to push the same amount of shore sediment. Sommerville and Burns (1968) described reservoir damage near Winnipeg, Canada, caused by ice expansion during a one-day push event. Tesaker (1987) described boulder ramparts pushed up along two lakes in Norway when ice expanded.

Zumberge and Wilson (1953) related ice push along Wamplers Lake, Michigan, to thermal expansion of the ice cover. Their measurements showed that the expansive force of ice is not necessarily directed at a right angle to the shore and that a rise in air temperature of about 1°F per hour for half a day can cause thrusting at the shore. Pessl (1969) related thermal expansion of ice to the formation of a rampart 2–4 feet high and 4–10 feet wide on Gardner Lake, Connecticut. He measured a net shoreward movement of about 3 feet over a 30-day period. He concluded that ice thrusting occurred when the ice temperature increased about 2°F per hour for 6 hours. Gardner Lake is 1.7 long and 0.75 miles across, and Pessl concluded that wind stress on the ice was generally insufficient to push ice into the shore.

Wind

Wind push is generally ineffective where ice completely covers a lake or when ice is too weak to remain intact when it is pushed against the shore (Wagner 1970). Wind moves ice on a lake only when there are ice-free areas into which ice can move. These open areas appear when the surface area of a lake increases during a rise in water level and the existing ice doesn't cover the elevated water surface and when an ice cover starts to melt along the shoreline in the spring.

If an open area appears along a shore during a rise in water level, wind can blow ice directly into the shoreline. However, if the ice cover breaks some distance from the shoreline during a water level rise and a shelf of ice remains attached to the shore, that shore ice can protect the shoreline from wind-blown ice that is free floating.

The degree to which wind-blown ice could push shore structures and sediment in the spring depends on how advanced ice decay and melt are once open areas appear along a shore. Ice decay is the melting of the internal boundaries between ice crystals and grains, and ice melt is the thinning of the ice layer. Both substantially weaken an ice cover. Ice has considerable strength early in the spring before decay and melt are too advanced (Williams 1966).

Gilbert and Glew (1986) and Gilbert (1991) described wind-driven ice push events that occurred on Lake Ontario near Kingston, Ontario, where the fetch was at least 6 miles. A midwinter thaw event piled ice 16 feet high off shore in less than 3 feet of water but did not move sediment. A spring breakup event piled ice 8 feet high on shore in 10 minutes and moved 37- to 450-lb boulders inland up to 21 feet. Overall the shore damage was relatively minor because the ice was decayed and the shoreline was partially armored with riprap up to 5 feet in diameter. They concluded that wind-driven events require moderate onshore winds and enough melting and weakening of the ice to produce open water near shore that is expansive enough for the ice to gain sufficient momentum. They suggested that sufficiently large open areas occur more often at breakup when ice is weak than in midwinter when ice is strong, so that waves and currents active during ice-free seasons are significantly more important in changing shorelines than wind-blown ice.

Tsang (1975) studied wind-driven, ice pile-ups on Lake Simcoe north of Toronto, Canada. He concluded that:

- They form in a short time.

- They require above-freezing air temperatures to weaken the ice in cracks, which allows a cover to break into individual floes.
- They are influenced by the size of ice floes and the condition of the ice.
- Open water nearshore, at least 3–6 feet wide, is required so that ice can gain momentum as it moves shoreward.
- A wind that is sustained and not necessarily more than 5 mph is needed if the ice is strong and ice floes are large.

Magnitudes

Although variation is significant, lake ice push is greatest in the spring when ice is still thick and strong enough to be pushed up shorelines and over obstacles (Sodhi and Kovacs 1984).

The magnitude of the forces applied to a shoreline by wind-driven ice is a function of the momentum of the ice (the speed of the ice times the total mass of the ice) and the strength of the ice (whether it is competent and strong or decayed and weakened). Strong ice will apply a much larger force before it breaks or buckles, while weak ice will crumble into small chunks on impact with the shore. The greatest forces are generated when fast-moving, strong ice hits the shore. The forces applied to a shore by wind-driven ice have not been measured because it is impossible to anticipate where to install instruments before a wind event occurs. Gilbert and Glew (1986) estimated the force required to build ice piles to be about 940 lb/ft, which is significantly less than forces measured during ice expansion.

The magnitudes of ice forces at the shoreline during ice expansion have been measured at numerous places and summarized by Michel (1970) (Table 1). They vary by about an order of magnitude.

Table 1. Ice forces at the shoreline during ice expansion measured at numerous places as summarized by Michel (1970). The highest values represent near-vertical faces.

Location	*Force (lb/ft)*
Tainter gate, Hasting Dam, Mississippi River	3,500
Flat shoreline, Antero and Shadow Mtn. Reservoirs, CO	3,600–5,800
Face of Des Joachims Dam, Ontario	6,900
Dam on Ges Reservoir, Dnieper River	8,300
Moderately steep shoreline, Evergreen Reservoir, CO	9,400
Face of dam, Eleven Mile Canyon Reservoir, CO	14,000–20,000
Steep, rocky shoreline, Tarryall Reservoir, CO	17,000

Cox (1984) measured pressures within the ice about 25 feet from shore in Canaan Street Lake, Canaan, NH, during February and March 1983. He reported maximum compressive pressures of about 3,000 lb/sq.ft. at a right angle to the shore, with some spatial differences that may have been partially due to the location of active cracks in the ice. One could reason that similar pressures were being applied on the shoreline at this site.

The variability in these measurements is caused by the numerous factors that affect ice forces during thermal expansion. These include the rate of change in ice temperature, the coefficient of thermal expansion of ice, the flow and deformation characteristics (rheology) of ice, the size and distribution of wet and dry cracks in the ice, the ice thickness, and the degree of confinement of the ice cover (Bergdahl 1978). The rate of change in ice temperature is controlled by air temperature, wind speed, solar radiation, and the depth, density, and albedo of the snow cover on the ice (Cox 1984). The coefficient of thermal expansion, the rheology, and the cracks are all interrelated and unpredictable. Ice thickness depends on air and water temperatures and snow cover conditions throughout the period of ice growth.

The data listed above suggests that steep and rigid structures and shorelines that tend to confine ice and resist ice expansion receive the highest forces, while those with a gentler slope will allow ice to slip over and not resist the ice. However, Monfore (1952) reported that on the Eleven Mile Canyon Reservoir, ice forces on a shallow sandy beach were nearly the same as those along vertical rock faces; the gently sloping shore did not relieve ice pressure. He suggested that the ice may have been solidly frozen to the shore and that the bond offered substantial resistance to the expanding ice sheet. Sodhi and Kovacs (1984) reported that offshore topography and shoreline roughness also influence ice pressures at the shore, and they reiterated the importance of whether shore ice is frozen to the land or free floating.

Prediction

Because of the complexity of the interplay of the factors that influence ice push, Sodhi and Kovacs (1984) concluded that ice push at a specific site is unpredictable. They equated ice push with such natural occurrences as a large flood or a tornado, which occur yearly in many places but not in any given location. These events are not predictable. Wagner (1970) also concluded that it is not possible to predict where ice expansion ramparts will form. Gilbert and Glew (1986) concluded that the frequency and location of wind-driven ice push are irregular and unpredictable because they depend on the coincidence of a number of weather and ice conditions. Our review of the literature and our field experience lead us to the same conclusion. The current state of knowledge about the cause-and-effect relationships between weather and ice conditions is inadequate, and much work remains to be done before ice push events become predictable.

METHODS

Data Sources for Inventorying Damage

An inventory of shoreline and structure damage was made from information in the files of the State of Vermont, field observations of the lake shore, and discussions with the Lake Bomoseen Association (LBA). Three files were examined: the general Lake Bomoseen file and the construction-permit file at the VANR, Department of Environmental Conservation, Water Quality Division (WQD), Lakes and Pond Section, and a file of written comments submitted to the Vermont Water Resources Board (WRB) during the proceedings that considered the adoption of rules to allow a winter drawdown of Lake Bomoseen.

The field observations were made on 18 October 1999 with Jim Leamy (LBA), Virginia Garrison and Steven Hanna (VANR), and Larry Gatto and Darryl Calkins (CRREL). Jim Leamy marked the LBA map of the lake showing the shorelines where property owners have reported ice push damage during the 1990s. The damage ranged from moderate to serious. These shorelines were in North Cove, in Eagle Bay, in West Castleton Bay, from Avalon Beach to Point of Pines, along the north-facing shore east of Indian Point, and from Green Bay to Neshobe Beach.

Databases Synthesized to Discern Patterns

We evaluated the Lake Bomoseen shoreline to see if damaged reaches have a distinctive orientation, shape, or lake bed slope that is different from undamaged reaches, and we determined if there were unique patterns in water level, air temperature, or snow depth that existed when ice push occurred in the 1990s. Other data that would have been useful in evaluating possible cause-and-effect relationships between weather, ice conditions, and ice push include wind speed and direction, ice thickness, ice temperature, ice type, ice cracks, and degree of confinement of the ice cover, but this information was not available.

Since this was a one-year study, we had to analyze data that were readily available. The shore orientation and shape were available on the LBA map of the lake. The lake bed slopes were taken from a report by Aquatec, *Bathymetric Measurements of Lake Bomoseen* (Luxenberg 1988). Water level data are taken at the dam on the lake and are available from the VANR.

The only long-term record of air temperature and snow depth was available from the National Weather Service (NWS) in Rutland, VT, about 11 miles east of Lake Bomoseen. We compiled that data from 1 December to 1 May each year from 1948 to 1999 (Appendix A). The air temperatures collected at the Fair Haven grade school about 3 miles west of Lake Bomoseen since 1998 are within 5°F of the NWS temperatures. We assumed that the air temperature at the lake, since it is between the NWS site and the Fair Haven school, would also be within 5°F of that recorded by the NWS, although this may not necessarily be true. The NWS site is at 620 feet elevation and the lake is at 411 feet, so the snow depths at the two sites could be within a few inches of one another, with the lake having generally less snow.

Wind speed and direction are highly variable in Vermont's mountainous terrain, so we assumed that wind data collected at the NWS site would not be representative of the winds at the lake. Accordingly, we did not compile the NWS wind data and, without data for the lake site, could not evaluate if wind push is an important process on Lake Bomoseen.

Data Collection During the 1999-2000 Ice Season

In preparation for an ice push event during the 1999-2000 ice season, we made detailed observations and measurements of the ice to evaluate possible relationships between ice push, weather, and ice conditions. We selected the Cook property (Fig. 2) in the middle of the heavy damage zone along the west shore of Avalon Bay to make observations of ice thickness and conditions, measure temperatures of the air, ice, and water, and record ice push. We installed a digital camera to document site conditions and observe ice push. The camera took up to five pictures a day, which were immediately available for viewing on the CRREL web page from 23 November 1999 to 30 March 2000.

We installed thermistors on 27 January 2000 to measure the air temperature five feet above the ice surface and the ice temperature about 2 inches below the ice surface. We installed stakes in the ice on 7 February to monitor shoreward ice movement. The distances between the stakes and the house were known, allowing us to measure the ice push.

Jim Leamy arranged to have snow depth measured at three nearby locations: Castleton Town Garage, Eagle Bay on Lake Bomoseen, and Hooker Hill. We also measured on-site snow depth during site visits. We took ice cores to define the ice type and thickness, and we measured water temperatures about 125–135 feet offshore of the Cook property. The water temperatures were measured at the ice-water interface and every 3 feet down to 23 ft.

a. camera location in second story window of house on the right.

b. air temperature thermistor.

c. ice temperature thermistor.

d. ice-push stakes.

Figure 2. Cook property site.

RESULTS

Shore and Structure Damage

The water level on Lake Bomoseen is usually maintained wihin 3 inches of a defined elevation. It is unlikely that such small vertical changes would produce significant vertical lifting forces. Uplift forces associated with greater increases in water level may damage structures left in the water, but damage of this type has not been reported on the lake and was not evaluated during this study.

Table 2 lists the information on ice push damage available in the general VANR and WRB files. The files contained no quantitative information on ice damage but did provide photographs of the damage reported during the 1989-90, 1990-91, and 1997-98 ice seasons. The WRB file showed that ice damage was also reported for 1995-96, but the VANR construction-permit file gave no additional information. The VANR files have no record or discussion of when ice push damage did or did not occur prior to the 1990s.

As follow-up to the field survey of damage, Jim Leamy reported that serious damage, which he defined as "widespread and substantial," had occurred in 1989-90, 1990-91, 1997-98, and 1998-99. The locations that the LBA identified as having been moderately to seriously damaged are shown in Figure 3. Thus, the five winters for which damage was reported, as determined from the files and the LBA, are 1989-90, 1990-91, 1995-96, 1997-98, and 1998-99. Figure 4 shows some of the shorelines and structures that were damaged in the 1990s.

Table 2. Lake Bomoseen ice damage reports (from WQD and WRB files).

March, 1990	Lake Bomoseen Ice Damage Report
	most extensive damage: west side from state fishing access area (Green Dump) to Avalon Beach
	some damage: from VT Conservation Camp to Point of Pines, W. Castleton Bay along the Cedar Mt. road
	shoreline damage in 1990 was greater than normal
	lake level fluctuated between +3 and -3 in Dec and Jan, and between +1 and -2 in Feb and into mid-March
3.12.90	Notes: snowmelt and 1-3" rain in Rutland on 1.30.90
3.20.90	Memo:
3.12.90	calls re ice damage
3.13.90	photos; some claimed damage was due to water level management
3.15.90	photos of ice break-up at Lakes St. Catherine, Bomoseen, Dunmore; damage not a new occurrence
3.16.90	photos from Gatto/Sodhi shoreline survey
4.12.90	photos taken; no written documentation or report
1991	Sauerbrei letter (1 July 1996)
3.29.91	photos taken; no written documentation or report
1996	Inpassia letter (10 July 1996); Crist letter (29 June 1996); Sauerbrei letter (1 July 1996); Skinner letter (8 July 1996)
	Root Engineering letter report (September 1997)
1.28.98	photos show ice ride up along Point of Pines, shoreline to the north; no written complaints, documentation, or report
2.98	Root Engineering letter report (23 May 1998)
	Kosloffsky letter (28 February 1998)

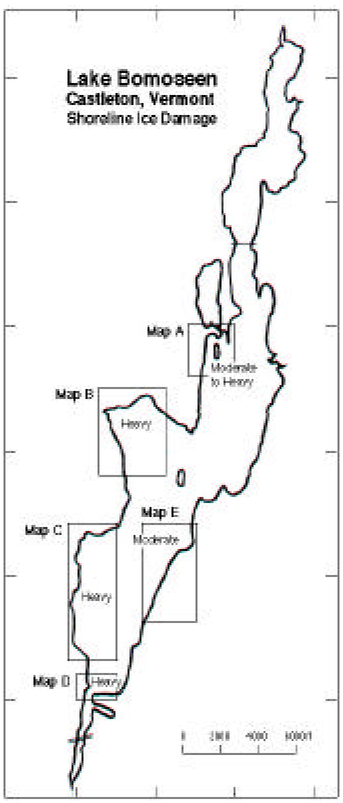


Figure 3. Shore locations where moderate to heavy (serious) ice damage occurred in the 1990s (from Jim Leamy); base map used was the LBA Map of Lake Bomoseen (1987).

Damage during a single season along Lake Bomoseen has ranged from none to substantial, depending on how all the factors discussed earlier interacted. For example, during March 1990 ice pushed shoreline soils into 3-foot-high ramparts at some locations along Avalon Beach and completely destroyed a large, concrete platform on the southwest shore of Avalon Bay at what is now the Cook property (Fig. 5). Elsewhere along the bay and the lake, damage was less or did not occur. Conversely, at the Cook property during the 1999-2000 ice season, the only damage was some small patches of grass that were scraped from the soil when a southerly wind drove decayed ice up and onto the southwest-facing shore. The degree of damage that occurs at a given location and the locations where damage occurs are highly variable from year to year, and the degrees of damage that occur along the lake shore during the same season vary significantly.

A letter report in the ANR files describing the damage from the March 1990 ice push event attributed the push to thermal expansion. The ice in the first half of March 1990 completely covered the lake, so wind could not have moved the ice around. The report stated that water levels were between +1 and –2 inches in February and into mid-March, which was very similar to the levels during the previous several years, excluding the legislatively mandated drawdown of 1988-89.

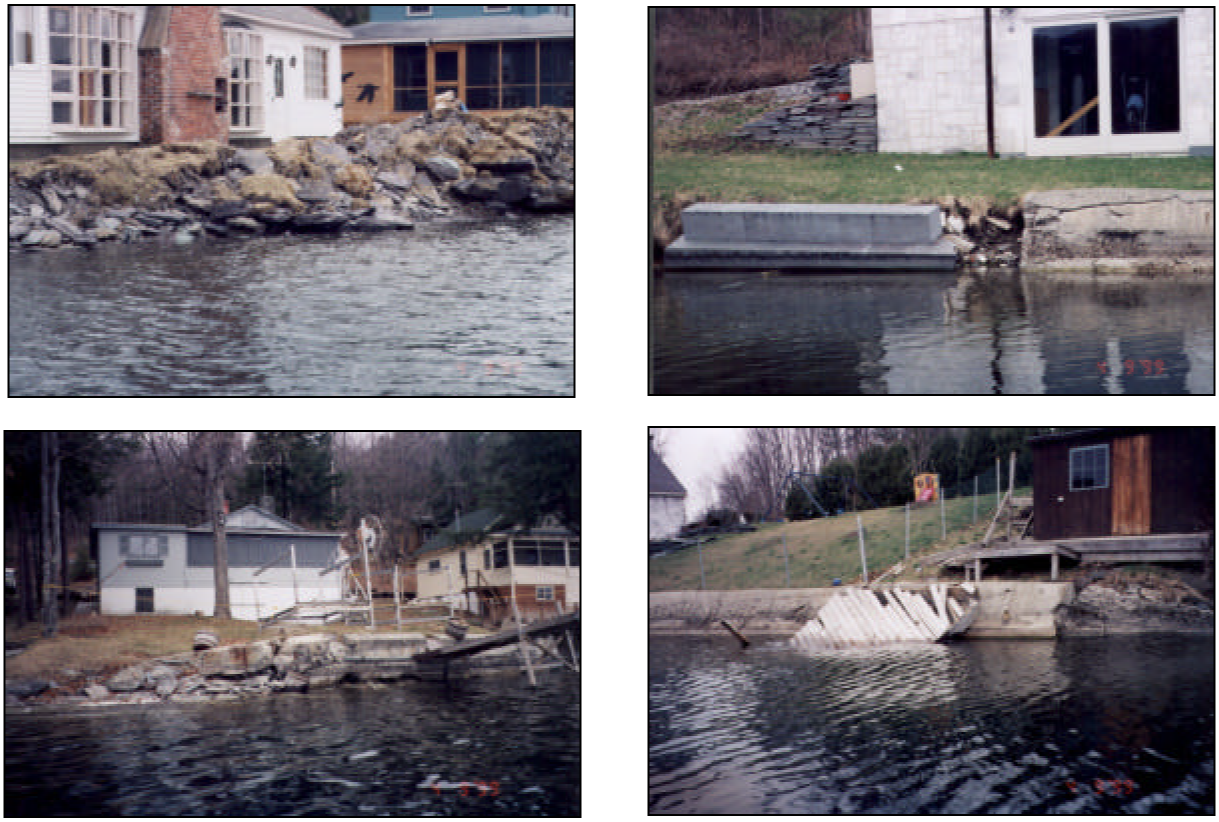


Figure 4. Shorelines and structures where damage has been moderate to heavy.

Figure 5. The most severe single-season damage caused by ice push in the 1990s, March 1990 (photos by L. Gatto); a and b. Avalon Beach, c and d. south shore, Avalon Bay.

Measurements of the distances that ice moved inland along Lake Bomoseen because of ice expansion in March 1990 were made by Larry Gatto and Devinder Sodhi of CRREL during a visit on 16 March, four days after the damage was first reported. The distances varied from 2 feet near the fishing access on the west shore to 7 feet in Avalon Bay southeast of St. Matthews church. The leading edge of the pushed ice may have partially melted between the time of maximum inland movement and the time measurements were made; the air temperature during the four days was 40–60°F.

Root Engineering (in a letter report dated 23 May 1998) observed damage that occurred during the February 1998 ice push event along the west shore from Point of Pines to the northern end of Avalon Bay and in Eagle Bay, where damage had been previously reported. They measured ice advances at five locations, which varied from 1.5 feet at Point of Pines and Eagle Bay to 6.5 feet in the north end of Avalon Bay. Root concluded that water-filled cracks added to the volume of ice on the lake, contributing to ice push and that the water level, which varied from +2 to +11 inches from 8 to 14 January 1998, allowed ice to form higher on the shoreline and exert more pressure. Root suggested that high water in January 1990 and 1996 resulted in damaging ice push in March 1990 and 1996. The mechanism of how ice that formed higher on a shore would necessarily exert more pressure to the shore was not explained.

Root Engineering[*] later implied that the ice advances that occurred in February 1998 were caused by wind push. If wind was the cause of that push, it would have had to blow from the northeast quadrant to push ice into Point of Pines, from the east quadrant to push ice into the west shore, and from the southeast quadrant to affect both Eagle Bay and the north end of Avalon Bay. Previous studies confirm that a sustained wind is required to give enough momentum to an ice cover to push it into a shore with sufficient force to drive the ice up onto the shoreline. The multiple wind directions that would have been required in February 1998 to push the ice into the three locations is contrary to current understanding of the wind push process. In addition, the fetch east of the shore along the fishing access is 0.5–0.7 miles, and that southeast of Eagle Bay is 0.9 miles. Both are much less than previous investigators have said is required for wind push to occur. However, without wind speed and direction data for the lake, one can only speculate about the likelihood of wind as the cause of the February 1998 event or any other ice push event on Lake Bomoseen.

Shore Characteristics and Ice Push

We compared the shoreline orientation and offshore topography along the shorelines where ice damage has been reported as moderate to heavy (Fig. 6) to determine if there are any obvious differences between these locations and those where no damage has been reported. Any differences of this type could help explain why ice push would preferentially damage one location and not another.

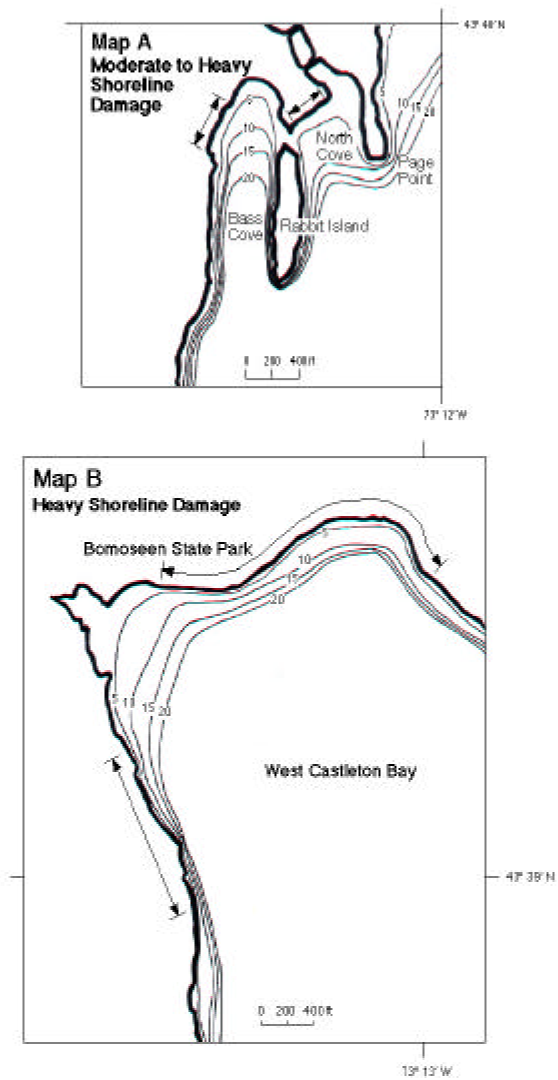


Figure 6. Lake bed slopes in the locations shown in Figure 3; contour intervals are in feet.

[*] Personnel communication, 30 November 2000.

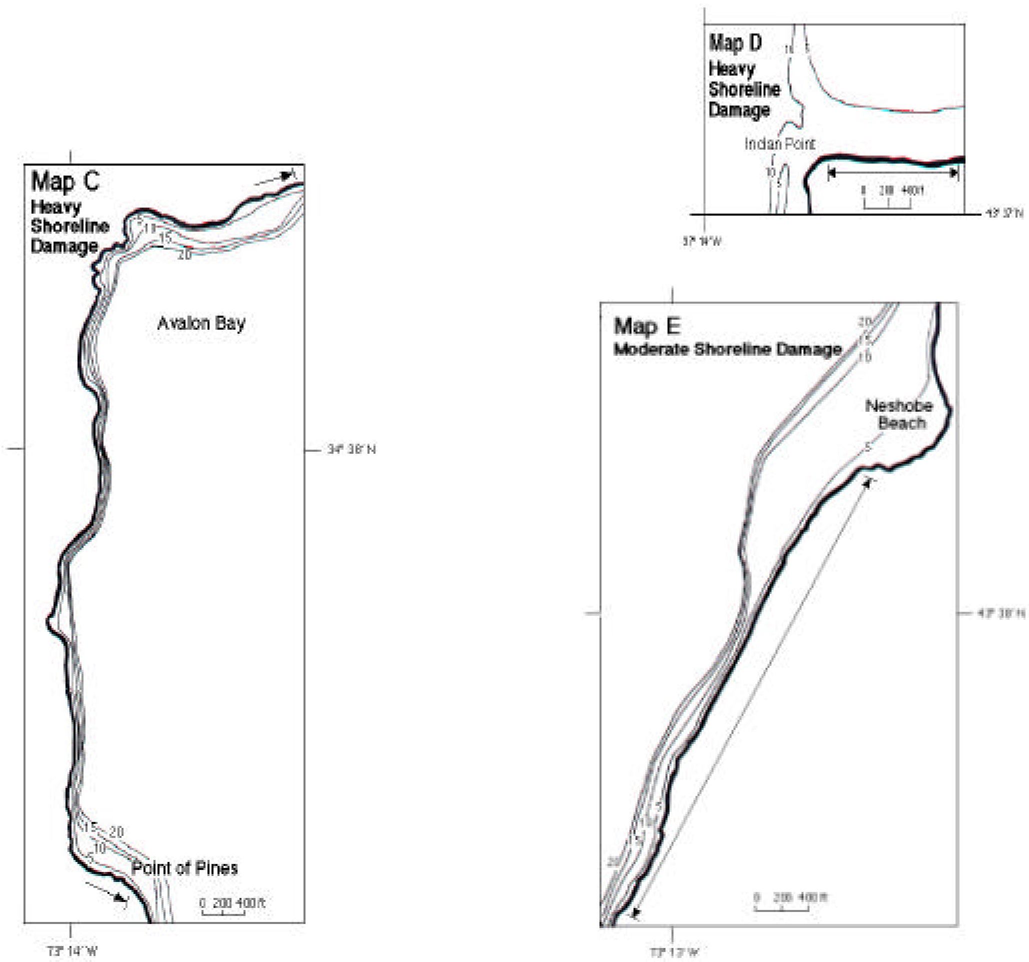


Figure 6 (cont.). Lake bed slopes in the locations shown in Figure 3; contour intervals are in feet.

The orientations of the shorelines at map areas A to E (Fig. 6) are highly variable. They are southeast-facing along North Cove; east facing in Eagle Bay (Bass Cove); south-, southeast-, northeast-, and east-facing in West Castleton Bay; south-, southeast-, northeast-, and east-facing from Avalon Bay to Point of Pines; north-facing east of Indian Point; and northwest-facing from Green Bay to Neshobe Beach. There appears to be no orientation of the shoreline that is more susceptible to ice push than any other. The only observation that can be made based on the distribution of moderate to heavy damage zones shown in Figure 3 is that the zones are in bays or border the main body of the lake south of Spooners Point.

The offshore slopes at the five locations are highly variable (Fig. 6). The lake bed slopes as gradually as 0.03 ft vertically for each foot of horizontal distance along the shore east of Indian Point (Fig. 6d) and as steeply as 0.3 ft vertically for each foot horizontally between Avalon Bay and Point of Pines (Fig 6c). Inspection of the bed slopes along the shorelines that have not been damaged shows no consistent pattern.

Air Temperature, Snow Depth, and Ice Push, 1948 to 1999

A visual inspection of the NWS air temperature and snow depth graphs (Fig. 7) for four of the winters (1990-91, 1995-96, 1997-98, and 1998-99) shows that the air temperature and snow cover patterns were not obviously different from the years when no ice push was reported (see graphs in Appendix A). However, the pattern of air temperature in March 1990 (Fig. 7a) was quite different from the others.

The average daily temperature from January to early March 1990 remained below freezing except for eight 1- to 5-day intervals. The snow cover had been generally less than 5 inches deep except for the latter half of December and a 5-day period in early February when the snow was 5–11 inches deep. This generally thin snow cover and the predominantly sub-freezing temperatures would favor substantial ice growth. The ice in early March 1990 was probably thick and strong.

In early March the snow, which was only 1 inch deep, would have had very little insulating value. Rather abruptly the air temperature rose 54°F from 11° to 65°F over a 10-day period in early March. With the shallow snow, the warm air would readily increase the ice temperature.

The ice would have expanded significantly in response to the rapid and extreme warming, and the ice push in March 1990 caused some of the worst shore damage of the decade. Note that none of the other four winters in the 1990s (Fig. 7b-e) have similar air temperature and snow cover patterns, and the ice push damage reported during those winters was less.

Daily air temperatures expressed as freezing degree-days (FDD) can be used to compare the severity of one winter with the next. One FDD means that the average daily air temperature for a day was one degree below freezing. By accumulating FDDs the "coldest" winter is apparent. The FDDs were accumulated using the NWS air temperature data beginning on 1 December each winter to produce Figure 8.

The five winters when damage was reported were not particularly cold. Some of the colder winters, such as 1993-94, had no ice damage reported, and other winters that were as cold as the five with damage had no damage. This strongly suggests that there is little correlation between ice push damage caused by expanding ice and air temperature alone, especially when using data not from the lake.

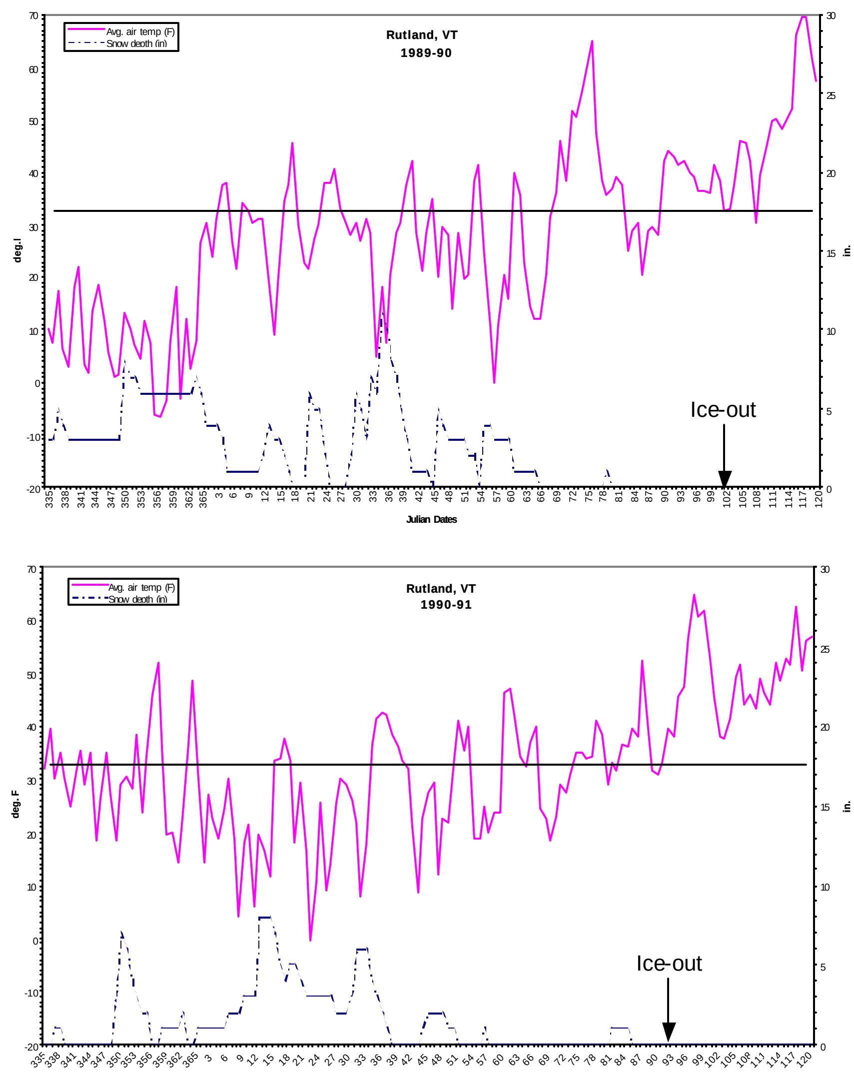
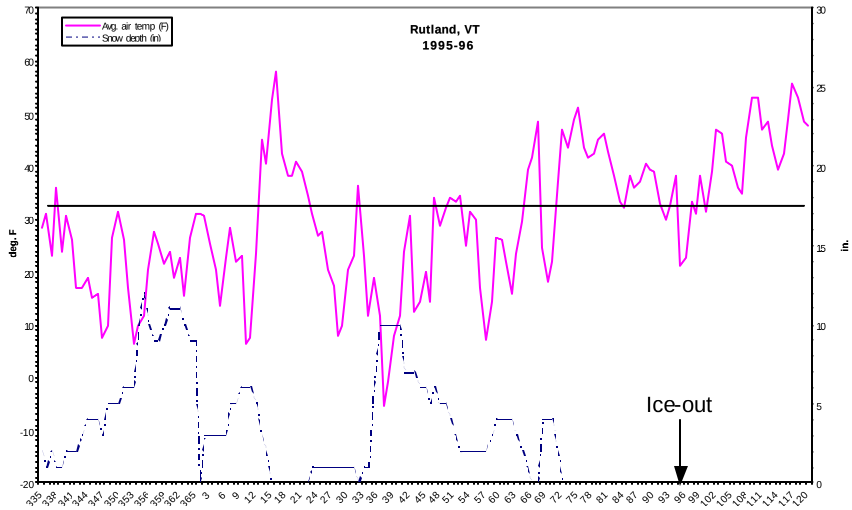
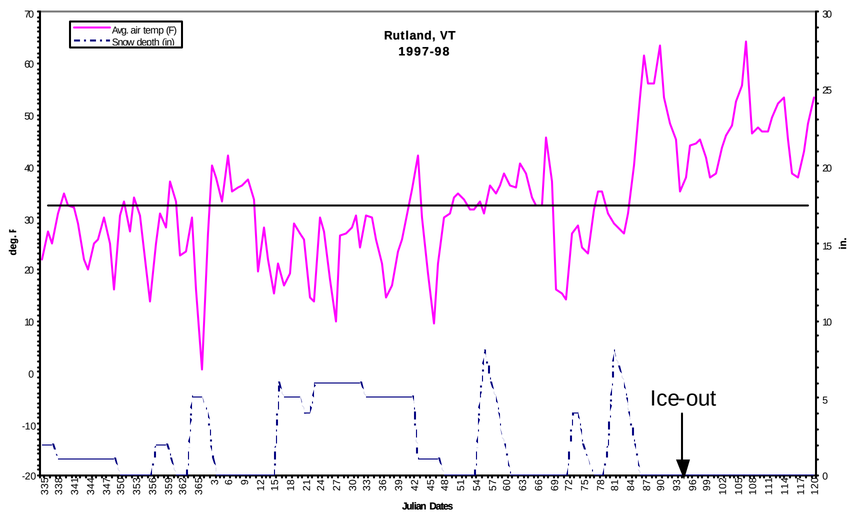


Figure 7. Air temperature and snow-depth measurements, NWS, Rutland, VT.





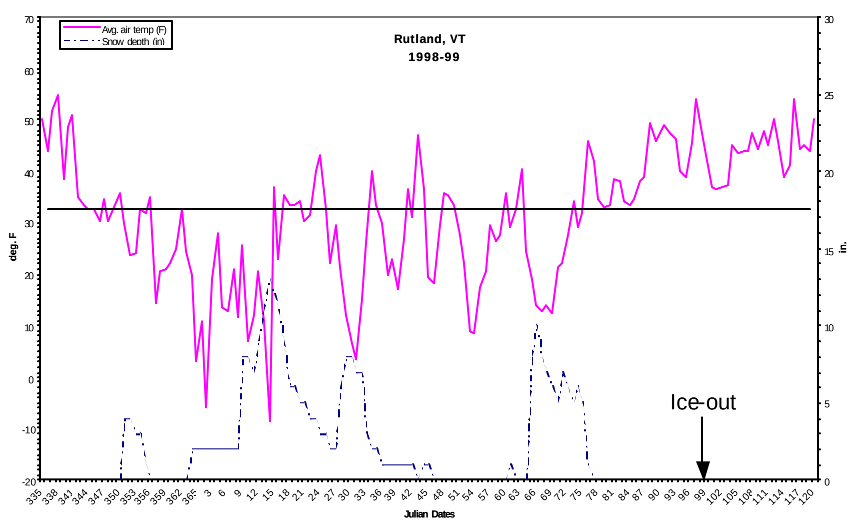


Figure 7 (cont.). Air temperature and snow-depth measurements, NWS, Rutland, VT.

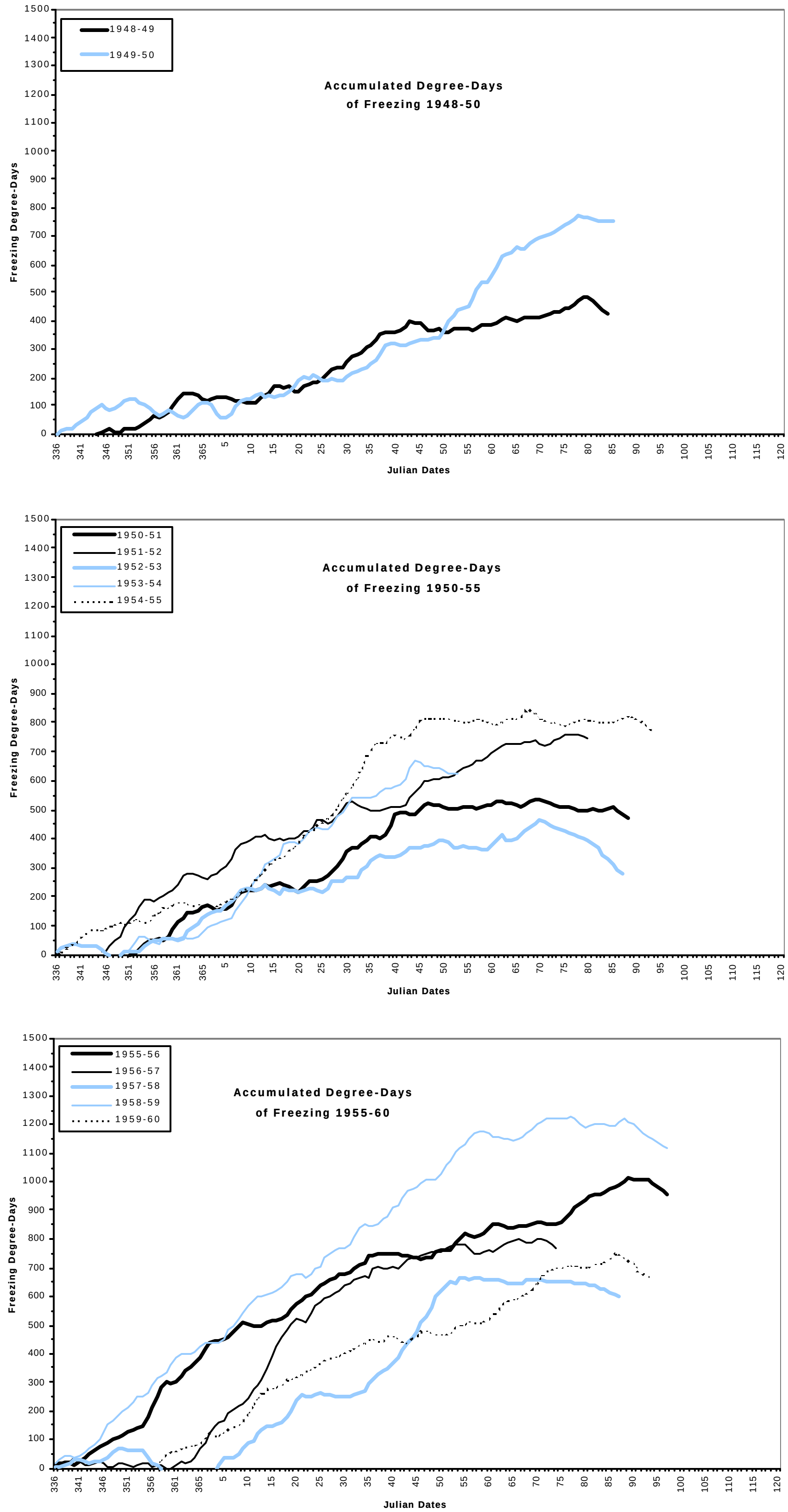


Figure 8. Accumulated freezing degree-days using the NWS air temperature record.

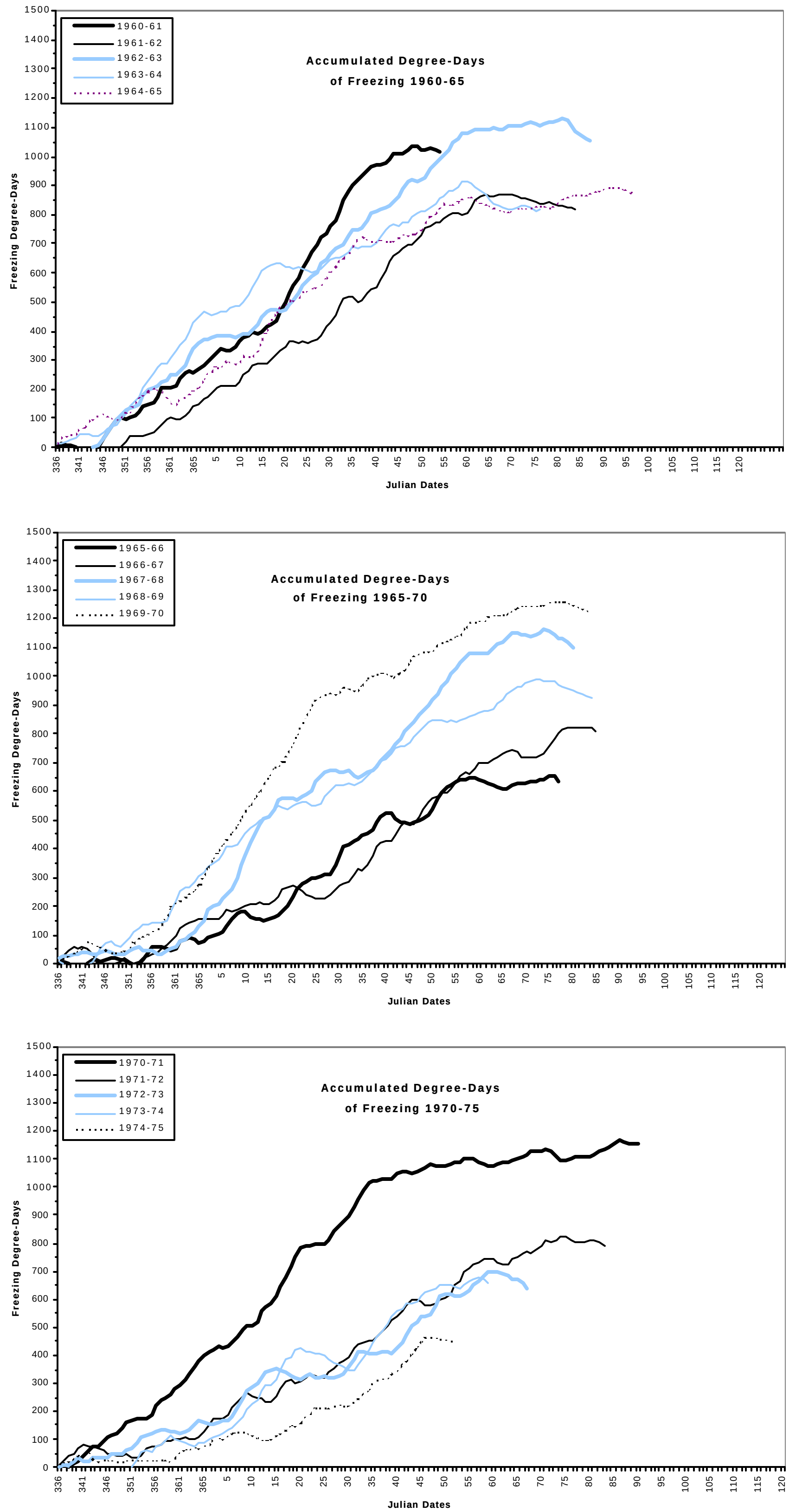
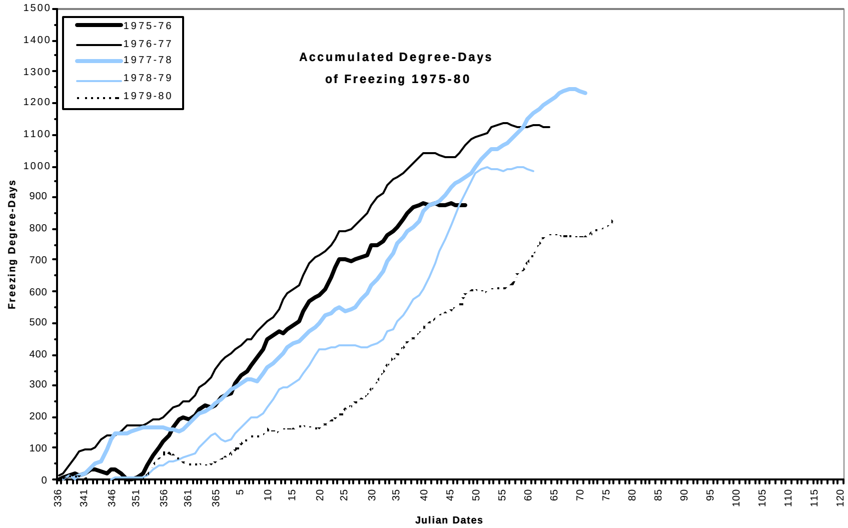
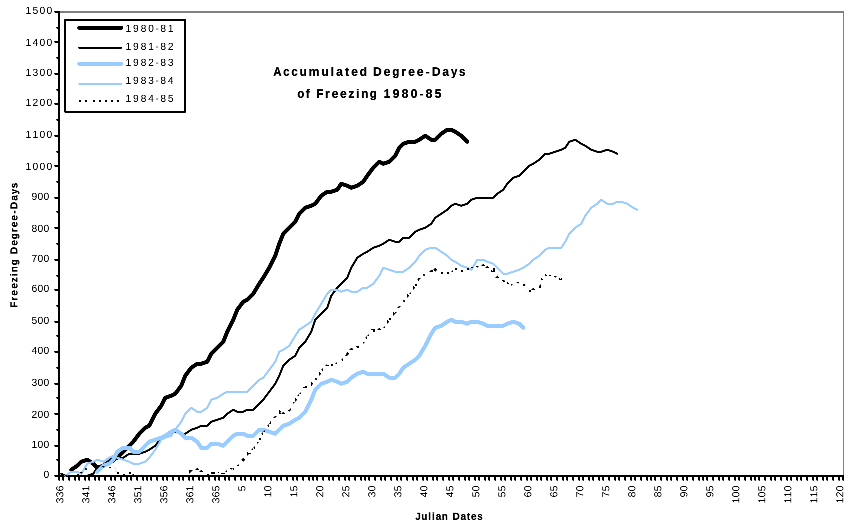


Figure 8 (cont.). Accumulated freezing degree-days using the NWS air temperature record.





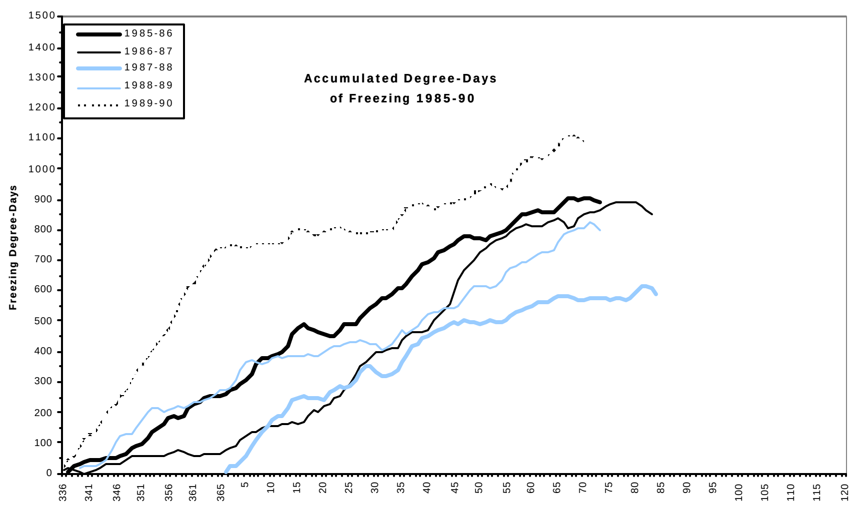


Figure 8 (cont.). Accumulated freezing degree-days using the NWS air temperature record.

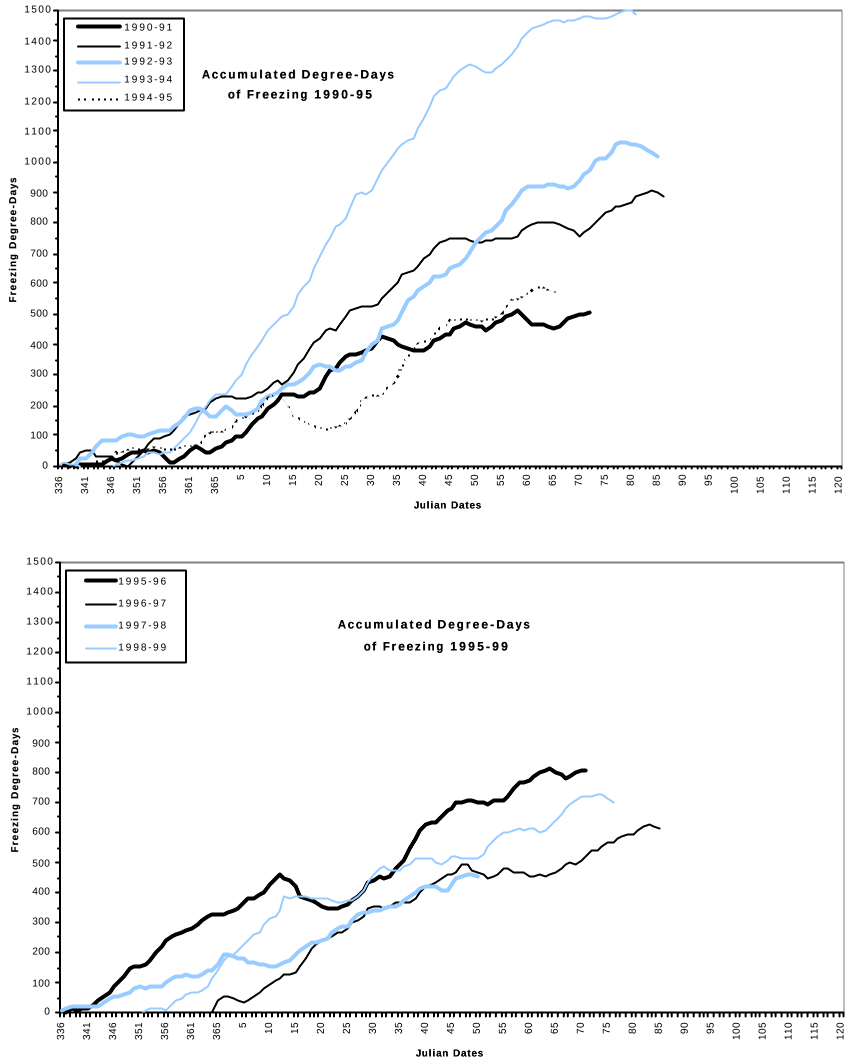


Figure 8 (cont.). Accumulated freezing degree-days using the NWS air temperature record.

Water Level and Ice Push

The Vermont Water Resources Board changed the water level operating scheme on Lake Bomoseen in May 1983 in response to concern about impacts on wetlands and wildlife. Prior to 1983 the level of the lake was kept at 0 to +3 inches from May to November, lowered to –12 to –18 inches from 1 November to ice-out, and raised to +3 inches by mid-May. Beginning in 1983 the water surface was kept at ±3 inches year-round except during the 1988-89 winter, when the water level was lowered. The Vermont Department of Environmental Conservation issued 53 permits for new shore-wall construction and wall repairs in 1988, and most of those projects were conducted during that 1988-89 drawdown.

It is relevant to note that all ice damage reported has occurred after the elimination of the winter drawdown and after the extensive construction of new shore walls. The absence of ice damage prior to 1983 suggests that the winter drawdown prevented ice from pushing at the shore, so ice damage did not occur. There was also no reported ice damage from 1983 to 1988, when the water was at the new higher level. One could then reason that damage reported in the 1990s resulted from the higher winter levels combined with all the new walls that were in place after the 1988-89 drawdown. However, no definite cause-and-effect relationship can be determined.

The water surface levels during the five ice seasons when damage was reported are shown in Table 3. The water surface was above the +3-inch level only in January 1990, April 1991, January 1996, January 1998, and April 1998. During all the other months the level was within or slightly below the ±3-inch range. This suggests that a water surface higher than the +3 level is not necessarily required for ice damage to shorelines and shore structures and that ice on a water surface within the prescribed range can do damage.

Table 3. Lake Bomoseen water levels.

Years/ Months	*Maximum Range (ft)*	*Most-Frequent Range (ft)*
During Winters When Serious Ice Damage Occurred in the 1990s		
1989-90/Jan	–0.2 to +0.35	–0.1 to +0.1
/Feb	–0.3 to +0.1	–0.2 to 0
/Mar	–0.3 to –0.1	–0.3 to –0.15
/Apr	–0.35 to +0.15	–0.3 to 0
1990-91/Jan	–0.5 to 0	–0.35 to 0
/Feb	–0.35 to –0.2	–0.3 to –0.2
/Mar	–0.5 to 0	–0.4 to –0.1
/Apr	–0.55 to +0.3	–0.2 to +0.2
1995-96/Jan	–0.4 to +0.4	–0.2 to 0
/Feb	–0.4 to 0	–0.35 to –0.15
/Mar	–0.3 to –0.2	–0.3 to –0.2
/Apr	no data	
1997-98/Jan	–0.25 to +0.9	–0.2 to 0
/Feb	–0.25 to +0.1	–0.2 to –0.1
/Mar	–0.35 to +0.05	–0.2 to –0.1
/Apr	–0.2 to +0.4	–0.2 to +0.1
1998-99/Jan	–0.2 to 0	–0.15 to 0
/Feb	–0.25 to –0.1	–0.2 to –0.15
/Mar	–0.2 to –0.05	–0.15 to –0.1
/Apr	–0.3 to 0	–0.3 to –0.1
During the 1999-2000 Winter		
1999-00/Jan	–0.3 to –0.05	–0.25 to –0.15
/Feb	–0.2 to +0.2	–0.15 to –0.05
/Mar	–0.4 to +0.25	–0.4 to 0
/Apr	no data	

The 1999-2000 Ice Season

The pictures taken by the on-site digital camera showed that ice did not form on the lake within the camera's field of view from 23 November to early January. By 5 January ice had formed on the eastern portion of the lake but not in front of the site. By 7 January thin ice had formed at the site, and there was a dusting of snow estimated to be less than 1 inch deep. The ice had melted along the shore at the site by 8 January and was gone until 15 January, when it re-formed. Ice thickened through mid-January. The site was snow free on 19 January, but by 24 January the snow appeared to be 1–2 inches deep. By 27 January snow was 7–10 inches deep at the other sites (Fig. 9), and snow on the ice was wind blown and drifted from 2 to 8 inches deep and was of low density. The ice on 27 January was 12 inches thick and clear. Snow continued to blow and drift at the site and was 8–10 inches deep on 7 February; the ice remained 12 inches thick and clear.

Air temperatures stayed below freezing most of the time until 23 February (day 54 on Fig. 10), when the air warmed and stayed above freezing until 29 February (day 60). Snow and ice melt occurred during this warm period, and most of the snow was gone by 1 March. The ice continued to melt through mid-March, and on 10 March (day 70) the ice was 8–9 inches thick nearshore and 10–11 inches thick at our offshore site. No ice push occurred at the stakes over the entire period. We also surveyed the other sites where moderate to heavy damage had been reported in the past (Fig. 3) on 10 March. We saw no evidence of ice push.

On 16 March (day 76) the ice at the offshore site was 11 inches thick, but it had deteriorated in the lower 3 inches and the surface had a layer of snow ice less than 1 inch thick. (Snow ice is partially melted or flooded snow that has refrozen. It has a frothy appearance because of the air bubbles frozen in it.) A trace of snow fell overnight on 16 March, as observed on the web-camera pictures, but the snow was never deeper than 2 inches on the ice through March. Snowdrifts up to an estimated 4 inches deep were observed on the shore in the pictures taken on 17 March. By 24 March (day 84) the ice was 10 inches thick and had deteriorated throughout its thickness. Our water temperature measurements showed that the ice deterioration was accompanied by the warming of the water column.

When we installed the thermistor in the ice on 27 January, the ice was already at its maximum thickness (12 inches). The ice temperature record in Figure 10 shows that the ice never got below –2°C from 27 January to 15 February, even though the air temperature got as low as –32°C. The snow insulated the ice and reduced ice growth to near zero.

On 10 February 2000 a pressure crack was reported to extend northeast from the fishing access on the west shore to the east side of Neshobe Island and then southeast toward Mason Point. This crack could have helped reduce the likelihood of ice push. Such pressure cracks and ridges tend to absorb ice expansion movements, which reduces horizontal movement of ice at the shoreline, and they retard the development of contraction cracks, which ordinarily promote net expansion movements (Wagner 1970).

Around 23 February (day 54) there was sufficient snow and ice melting underway that the ice thermistor was no longer 2 inches deep and was exposed on the ice surface. We re-set the thermistor into the ice at the 2-inch depth on 10 March (day 70).

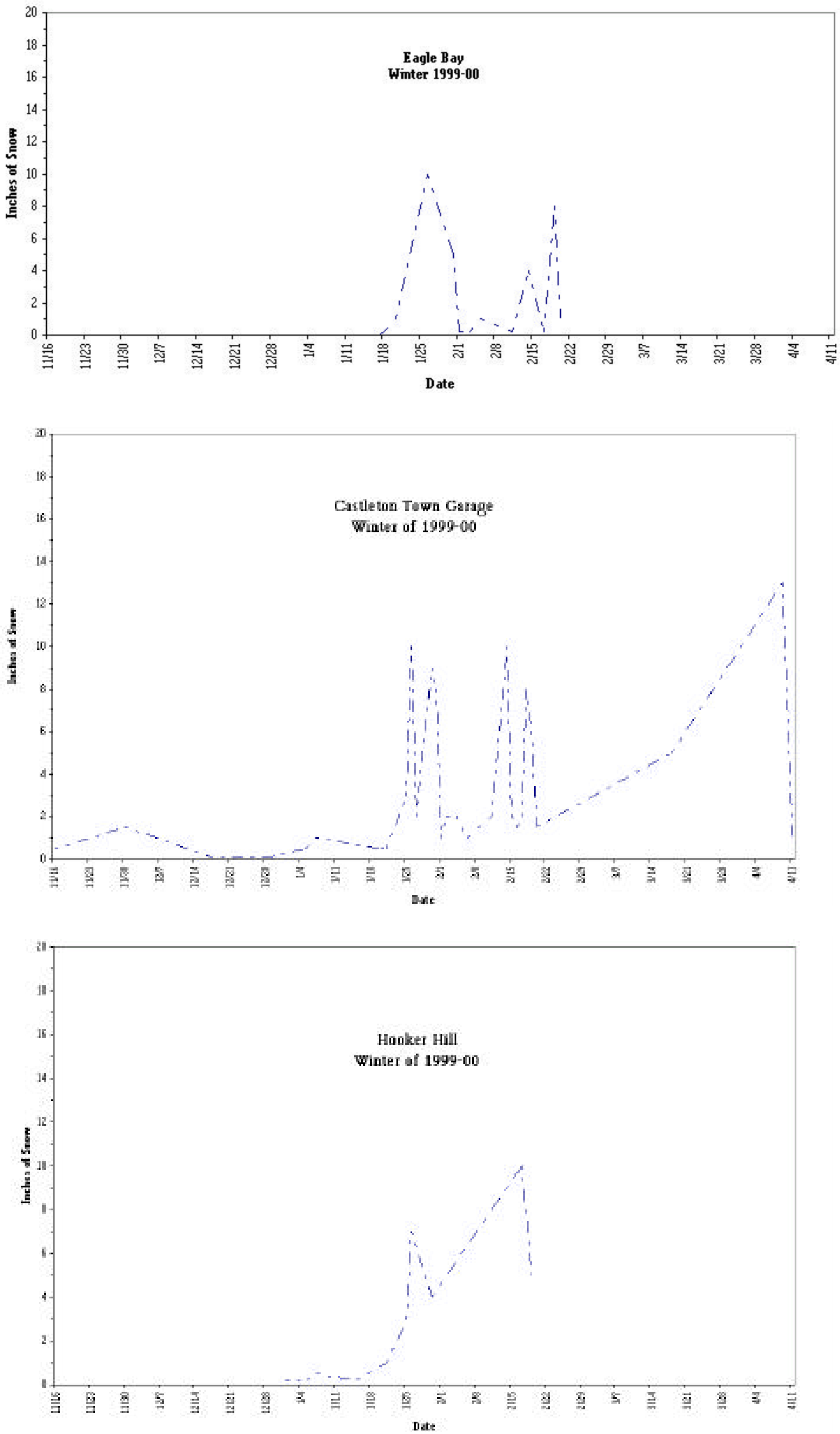


Figure 9. Snow depths measured from 16 November 1999 to 11 April 2000.

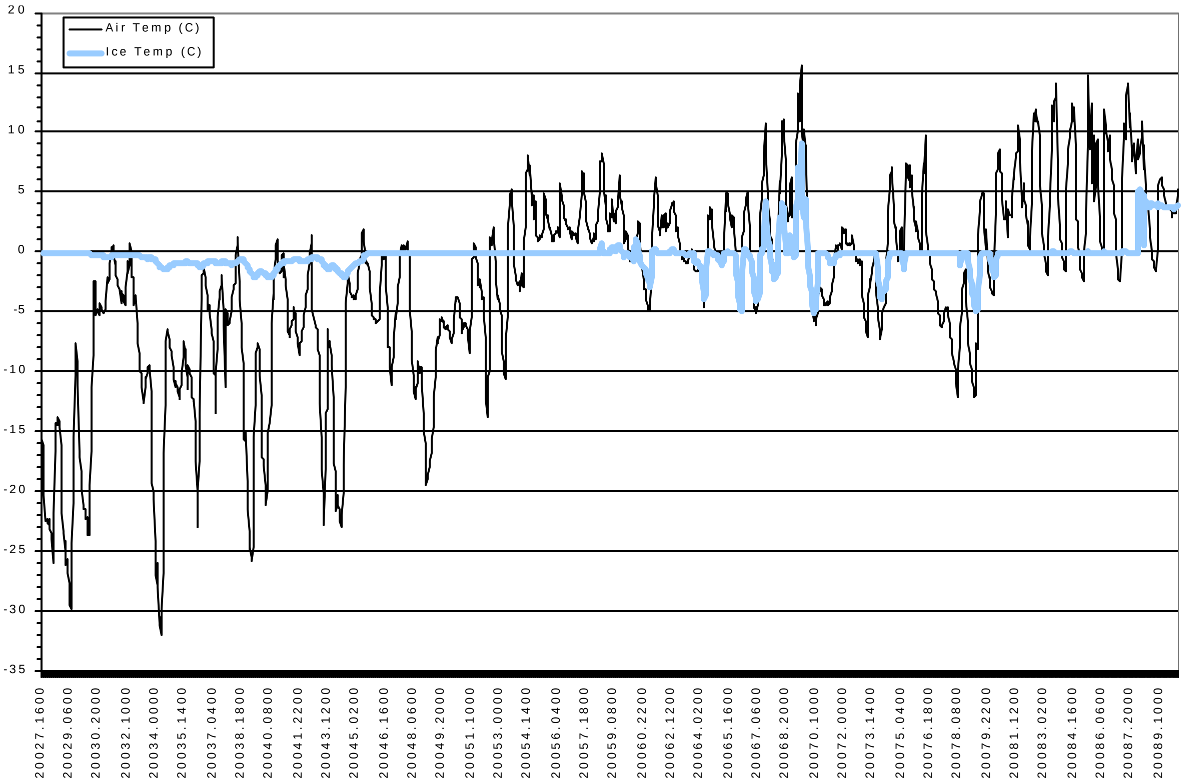


Figure 10. Air and ice temperatures from 27 January to 30 March 2000; the nomenclature for the numbers along the bottom is: 20027.1600 stands for year 2000, day 27 (27 January), 1600 hours (4 p.m.).

When the air temperature dropped to –12°C on 19 March (day 79), the ice that was snow free dropped to –5°C. This ice temperature was the lowest of the year and illustrates how ice temperature is affected more by fluctuations in air temperature when the ice is snow free. The ice temperature remained at 0°C until 28 March (day 88), when the ice had melted enough to expose the thermistor once again.

Figure 11. Brash ice pile along Cook property, 28 March 2000.

The pictures taken on March 28 (day 88) show that the nearshore ice had melted, and by the afternoon the wind had blown the decayed ice sheet into the shore at the Cook property, where it broke into variably sized chunks, piled up (Fig. 11), and scraped the soil surface (Fig. 12). On March 30 (day 90) we visited the site for the final time. The water temperature at a depth of 2 feet was 3.9°C. The decayed ice piled on the shore was 4–4.5 inches thick. We observed similar ice pileups on other south-facing shores along the lake. The official ice-out date in 2000 was April 4.

Figure 12. Scraped soil surface when decayed ice was pushed up and piled on shore.

Discussion and Conclusions

Ice has shoved soils and vegetation into piles, pushed riprap materials out of place, and damaged shore structures along Lake Bomoseen, and the damage at the same location has varied dramatically from year to year, as has the damage between sites during the same year. This variability results from the complex interrelationships of ice conditions, weather, and shore characteristics at different locations and from one year to the next. However, some variability may occur because some of the damage reported as ice damage may have resulted from other processes that weaken or undermine banks and shore structures without being detected. Where this undetected damage has been significant, the ice would appear to be very damaging; elsewhere the ice may appear less destructive.

Many landowners along the lake are not year-round residents, so they report damage to their shore upon their return to the lake well after an ice-push event. Even when property owners were present and see the damage as it is happening, on-site data needed to relate weather and ice conditions to the push event are not available. Consequently, in none of the reported cases of ice push damage could we relate the conditions at the time of the push to the amount of push and the resulting damage.

This lack of data needed for definitive conclusions means that we, and others who have evaluated ice-push on the lake, must make educated guesses or anecdotal conclusions about the cause-and-effect relationships of weather and ice conditions and ice push on Lake Bomoseen. We relied on existing knowledge from other investigations and available observations to frame the following conclusions.

1. Ice-push damage on Lake Bomoseen is like that on other lakes with seasonal ice cover. It occurs during some winters and not others and can be localized along small reaches of the shore or widespread.

2. Most reports of ice push come in the late winter or early spring while the ice cover is still intact and completely covers the lake. This complete ice cover cannot move about on the lake, so the most frequent cause of ice push must be thermal expansion augmented by an increase in the volume of the ice caused by refreezing of water-filled cracks.

3. Open water usually appears on the lake in late spring when ice along the shore melts. By this time ice throughout the lake has begun to thin and decay as well. This weakened ice can be blown onshore but is often too weak to hold together and cause significant damage. This scenario occurred in March 2000.

4. A rise in lake level that creates open water along the shoreline would allow wind to drive an ice cover into a shore. If the open areas exist while the ice is still strong, the potential for wind-driven ice damage could be substantial.

5. Shoreline shape, slope of the lake bed, air temperature and snow depth patterns, and post-1983 lake levels during the ice season do not correlate with ice damage locations or severity.

6. Ice damage was not reported before 1983, when winter drawdown was allowed.

7. Existing databases are inadequate to determine cause-and-effect relationships between weather patterns and ice push on Lake Bomoseen.

8. Ice push events are unpredictable.

9. In general, a shore or structure that does not resist the movement of ice shoreward when the ice is driven by wind or the expansion of ice will receive lower forces and be damaged less during an ice push event.

MITIGATING OR LIVING WITH ICE DAMAGE

A property owner can either attempt to reduce ice push or live with the ice damage. The following should be considered when deciding to try to reduce the push. First, there are no guarantees that any method will always be effective. A winter will come along during which all factors come together to cause more severe ice push than ever before. A shore protection method that has worked previously may not then. Second, the unpredictability of ice push precludes any cookbook solutions for ice-damage mitigation. Third, the methods proposed here are based on the best available knowledge, which we have compiled from scattered field observations of ice push events and short-term lab tests, neither of which provides a comprehensive basis for selecting options or engineering designs.

Maintaining the Natural Setting

A shore-property owner can choose to live with the changes that ice push makes on the shoreline and leave the shore natural. The changes such as pushed-up mounds of soil could be accounted for in landscape designs. This may be the least expensive and most environmentally acceptable approach. Buildings should be 20 feet or more from the shore to be far enough from where the ice would likely advance.

A setback distance can be estimated using Figure 13, which shows the expansion of ice based on the coefficient of thermal expansion of ice. (This graph does not account for the numerous factors that affect ice expansion discussed earlier, such as increases in the volume of ice that occur when water in cracks freezes.) The figure shows that on a lake that is 4000 feet wide, ice will expand 1–2 feet when the ice temperature increases 10°F, 2–3 feet with a 20°F rise, 3–4 feet with a 30°F rise, and 4–5 feet with a 40°F rise. It also shows that ice expansion can be greater where a lake is wider and when the ice temperature increases more.

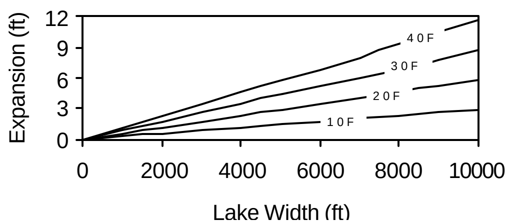


Figure 13. Estimated expansion in ice when the ice temperature increases.

A setback distance for wind-driven ice push cannot be estimated, as no equation exists to do so. The distance that ice will move inland when driven by wind depends on the momentum of the ice as it moves on shore, the shape of the shore zone, and the strength and condition of the ice. The only data we have seen for wind-driven lake ice push are from Gilbert and Glew (1986). They reported that wind-driven ice moved inland 21 feet when the wind speed was about 18 mph at Kingston, Ontario, where the fetch was at least 6 miles.

A setback for wind push on Lake Bomoseen can be established as follows. If we look at the orientation of the lake, the maximum fetch is about 3.3 miles along the north-northeast–south-southeast axis of the lake. This is about half the fetch reported in the Gilbert and Glew (1986) study. One could speculate that a sustained wind of 18 mph from the north-northeast or south-southeast directions could drive ice up the shore some 10 feet along the north-facing shore east of Indian Point or along the south-facing shores in the vicinity of Eckley Point. Most of the fetches at the damaged locations are Lake Bomoseen are less than the 2.5 miles, the distance cited as the minimum necessary for wind push.

So a 10-foot setback appears reasonable as a safe setback distance for expansion and wind push. Of course, the distance an expanding or wind-driven ice cover actually moves inland at a particular site will depend on the shape of the shoreline. Where the shore has a vertical or near-vertical bank or structure, the inland movement of the ice will likely be reduced. Where the shoreline has a gentle slope, the ice can move over it more readily, so it will move inland a greater distance.

Shoreline Stabilization

To stabilize a shoreline in more or less the same position would require:

- The shore or a structure with a gentle slope to allow ice to ride up and over the shoreline (buildings should be 20 feet or more from the shore);
- A structure to deflect the ice up; or
- A structure to stop the ice altogether.

Figure 14 shows a schematic of a gently sloping shore that allows ice to move inland with low impact to the soil at the shoreline. Sodhi (personal communication) recommended a slope of 1 vertical foot for each 3 or more horizontal feet (1V:3H). Establishing

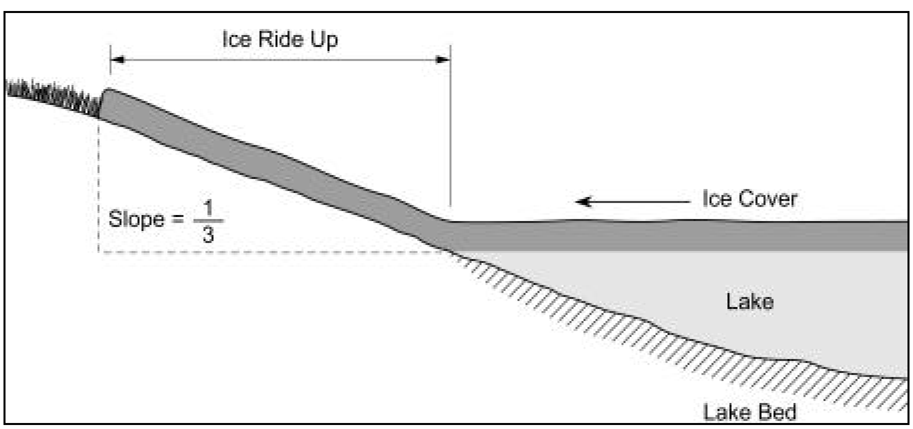


Figure 14. Gently sloping shore offers little resistance to ice movement and allows ice to ride up onto the shore. There is less potential for ice damage to the shore itself.

the shore at such a slope reduces the resistance to ice push and allows the ice to ride up onto the land rather than plow into it. However, even this low-impact shoreline would require some reshaping and revegetating over time, because some damage to the vegetation and soil surface will likely occur.

Figure 15 shows a gently sloping, bedrock shoreline along the west side of Avalon Bay where the ice has ridden up the shore. On shorelines susceptible to ice damage, a riprap revetment (Fig. 16), gabion blanket, or concrete slab could be installed with a gentle slope to simulate the bedrock and allow the same type of ice ride-up. If riprap is used, Sodhi and others (1996) recommended a maximum rock size of twice the ice thickness when using a 1V:3H slope and a maximum size of three times the ice thickness for steeper slopes (1V:1.5H).

To provide more protection for upland areas, a structure can be designed that deflects incoming ice upward so the ice eventually falls back on itself and piles up on the lake side of the structure. Figure 17 shows a concrete wall along the west shore of Avalon Bay that works this way. The steep slope of the wall facing the lake forces the ice to ride up, and the ice does not get on the shore. Such a structure could be made of many different materials, but the key element is to shape the structure to deflect ice.

A vertical structure or bank that stops inland ice movement as shown in Figure 18 will have to withstand greater forces than the above options. Such a structure must be constructed well to remain stable and effective.

Vermont law does not allow any work beyond the shoreline of a lake without a permit from the Department of Environmental Conservation (DEC). Precautions must be taken to stay back from the edge of the lake during reshaping work, or a permit must be obtained prior to starting a project.

Figure 15. Bedrock shoreline along Avalon Bay.

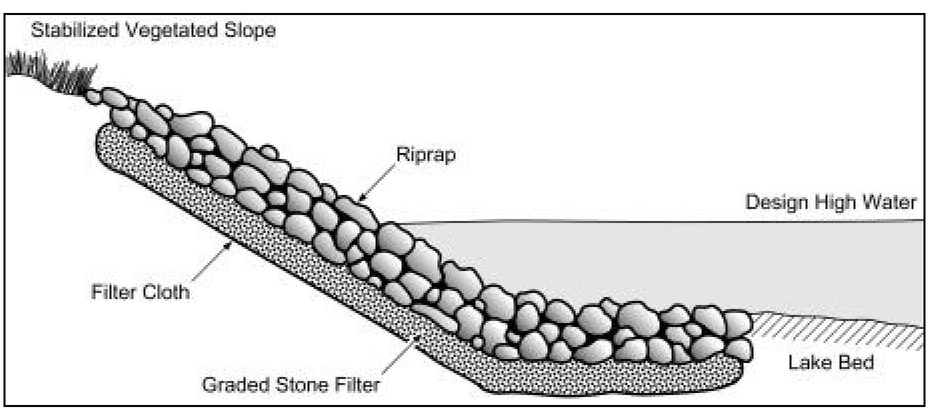


Figure 16. Gently sloping structure offers little resistance to ice.

Figure 17. Sloping structure along Avalon Bay.

Ice Suppression or Weakening

A bubbler system can maintain an ice-free area or can weaken an ice cover. Ice moving shoreward can then move into the open water and not reach the shore. A zone of weakened ice can fail when ice forces are generated and will not transmit the force to shore. Bubbler systems need permits from the Vermont DEC and would only be allowed if a public purpose outweighed the negative impacts of the system on winter uses of the lake. Incorporating ways to focus and minimize the extent of the area of open water or weakened ice would increase the likelihood that a permit could be issued. Wortley (1978) lists other ice suppression and weakening methods, including insulating ice with snow or man-made insulation, melting ice with dark material placed on the ice surface or with electrical resistance methods, and mechanically creating weak zones in the ice that would easily fail. Any material placed on the ice would have to be retrieved in the spring before ice-out.

RECOMMENDATIONS

An extensive and long-term investigation of the processes causing changes to shorelines and damage to structures along Lake Bomoseen is necessary to determine the amount of damage caused by ice alone.

A systematic, long-term study to relate weather, ice conditions, shore-zone conditions, and water level to ice push so as to understand the differences between years when ice push occurs and when it does not is required to advance current understanding of the cause-and-effect relationships. Without such a study, predictions of ice push will never be possible.

A systematic program is needed to evaluate and demonstrate methods to suppress and weaken ice so as to reduce ice push on shorelines and structures.

A long-term study is needed to determine the effects of an incremental lowering of the Lake Bomoseen water level during the winter on riparian and wetland habitats and wildlife.

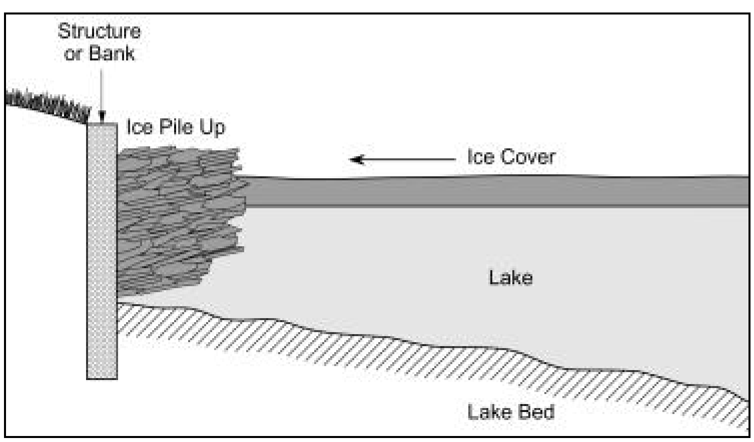


Figure 18. Vertical structure or bank tends to resist ice movement.

ACKNOWLEDGMENTS

We thank the following for their assistance during this study: Steven Hanna for coordinating the project with State of Vermont personnel and providing data on past ice damage and water levels; Jim Leamy for providing data on past ice damage, leading the shore reconnaissance in October, coordinating our study with the LBA, and providing numerous objective and useful insights; Clarence Decker, Jim Leamy, and Jeff Freeman for collecting snow cover data during the 1999-2000 ice season; Jim and Linda Cook for allowing us to use their house and property for the 1999-2000 data collection; John Gagnon (CRREL) for installing and maintaining the web camera to ensure that it functioned properly; and Lauren Raymond (CRREL) for preparing the freezing degree-day, air temperature, and snow depth graphs.

REFERENCES

Bergdahl, L. (1978) Thermal ice pressure in lake ice covers. Report Series A2, Department of Hydraulics, Chalmers University of Technology, Goteborg, Sweden.

Cox, G.F.N. (1984) A preliminary investigation of thermal ice pressures. *Cold Regions Science and Technology,* **9**(3):221–229.

Gatto, L.W. (1982) Reservoir bank erosion caused and influenced by ice cover. U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H., Special Report 82-31.

Gilbert, R. (1991) Ice pile-up on shores in northwestern Lake Ontario during winter 1990. *Geographie Physique at Quaternaire,* **45**(2):241–244.

Gilbert, R., and J.R. Glew (1986) A wind-driven ice-push event in eastern Lake Ontario. *Journal of Great Lakes Research,* **12**(4):326–331.

Laskar, K., and K. Strenzke (1941) Ice thrust on shores of north German lakes and its effect. *Natur und Volk (Nature and Man),* **71**:63–70. Also available as CRREL Draft Translation 405, 1973.

Luxenberg, R.R. (1988) Bathymetric measurements on Lake Bomoseen. Prepared for the Town of Castleton, Vermont, by Aquatec, Inc., South Burlington, Vermont.

Michel, B. (1970) Ice pressure on engineering structures. U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H., Monograph III-B1b.

Monfore, G.E. (1952) Ice pressure against dams: Experimental investigations by the Bureau of Reclamation. *Proceedings, American Society of Civil Engineers,* vol. 78, Separate No. 162, p. 1–13.

Montagne, J.D.L. (1963) Ice expansion ramparts on South Arm of Yellowstone Lake, Wyoming. *Wyoming University Contributions to Geology,* **2**(1):43–46.

Pessl, F. (1969) Formation of a modern ice-push ridge by thermal expansion of lake ice in southeastern Connecticut. U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H., Research Report 259.

Sodhi, D.S., S.L. Borland, and J.M. Stanley (1996) Ice action on riprap, small-scale tests. U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H., CRREL Report 96-12.

Sodhi, D.S., and A. Kovacs (1984) Forces associated with ice pile-up and ride-up. *Proceedings, International Association of Hydraulic Research Symposium on Ice, Hamburg, Germany, August 1984*, p. 239–262.

Sommerville, R.C., and G.E. Burns (1968) Damage to a Winnipeg reservoir due to ice. *Proceedings, National Research Council Conferences on Ice Pressures Against Structures*, Technical Manual 92, p. 143–150.

Tesaker, E. (1987) The role of thermal expansion of ice in forming lake shoreline profiles. Norwegian Hydrotechnical Laboratory Bulletin No. 27, p. 249–257.

Tsang, G. (1975) A field study on ice piling on shores and the associated hydro-meteorological parameters. *Proceedings, Third International Symposium on Ice Problems, Hanover, NH, 18-21 August 1975,* p. 93–110.

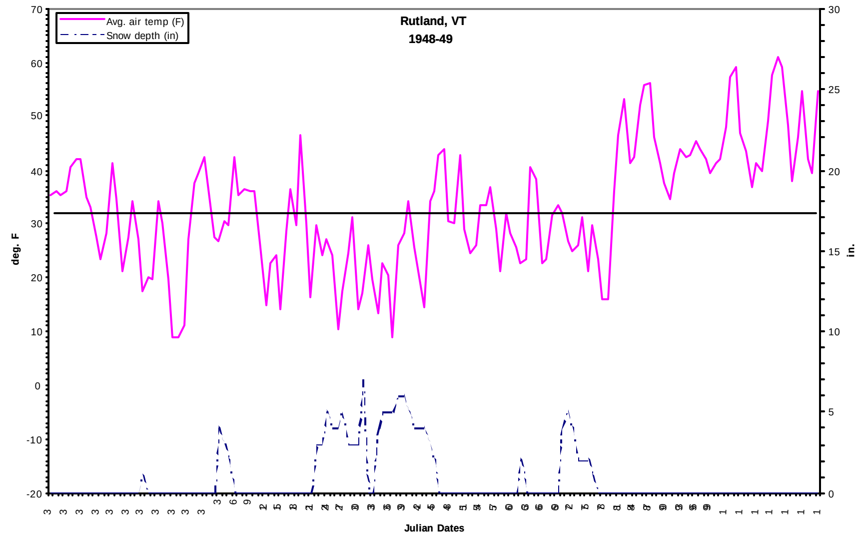
Wagner, W.P. (1970) Ice movement and shoreline modification, Lake Champlain, Vermont. *Geological Society of America Bulletin,* **81**:117–126.

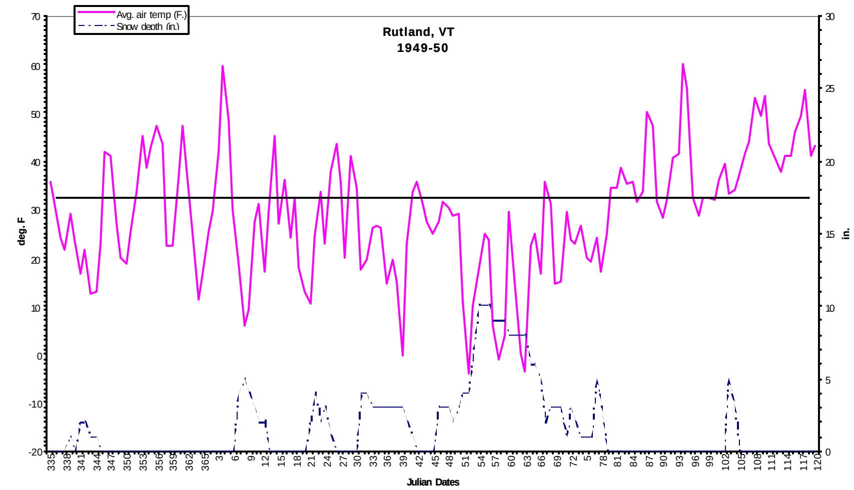
Williams, G.P. (1966) Freeze-up and break-up of fresh-water lakes. *Proceedings, National Research Council Conferences on Ice Pressures Against Structures*, Technical Manual 92, p. 203–215.

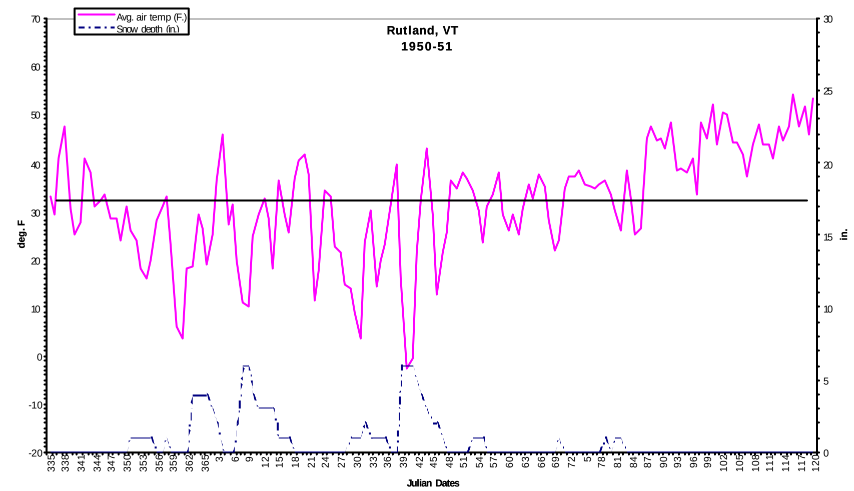
Wortley, C.A. (1978) Ice engineering guide for design and construction of small craft harbors. University of Wisconsin, Madison, Wisconsin, Advisory Report WIS-SG-78-417.

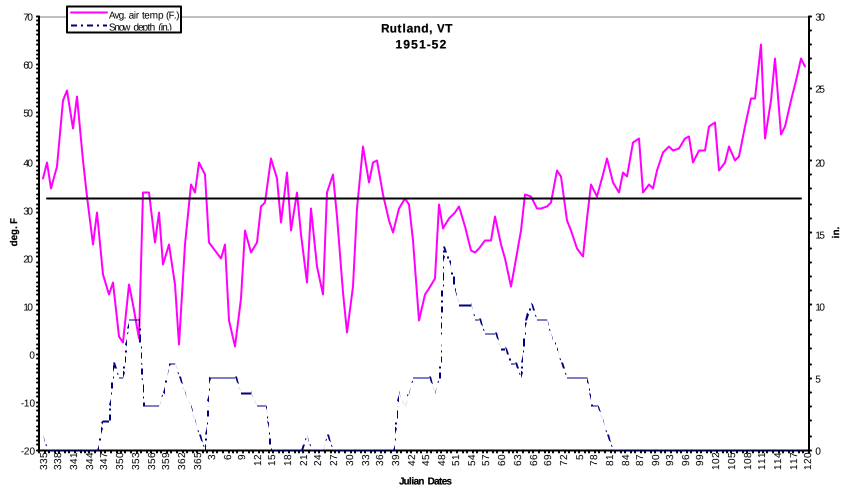
Zumberge, J.H., and J.T. Wilson (1953) Quantitative studies on thermal expansion and contraction of lake ice. *Journal of Geology,* **61**(4):374–383.

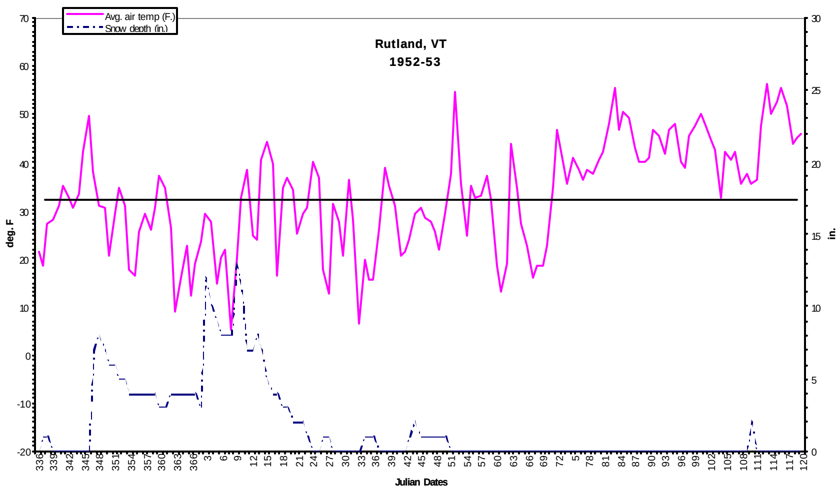
APPENDIX A. AVERAGE DAILY AIR TEMPERATURES AND SNOW DEPTHS, 1 DECEMBER (JULIAN 335) TO 30 APRIL (JULIAN 120), FROM THE NWS RECORDS. THE ARROWS ON GRAPHS STARTING IN 1956-57 SHOW THE DATE OF ICE-OUT.

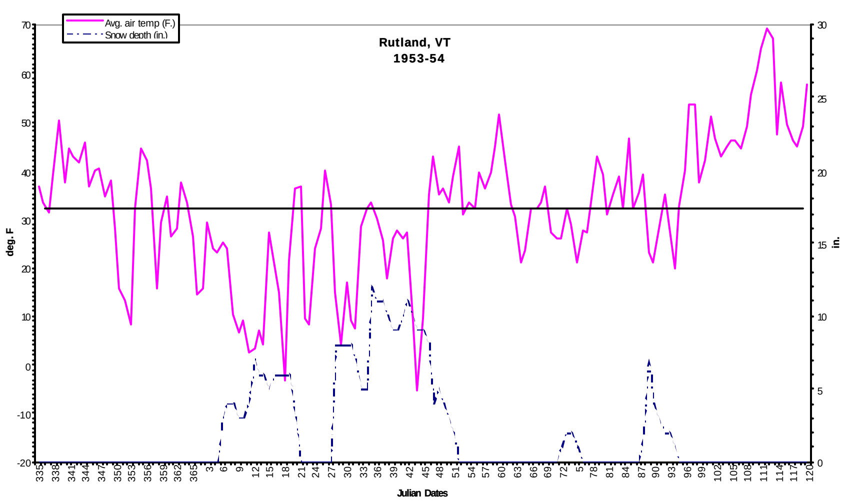


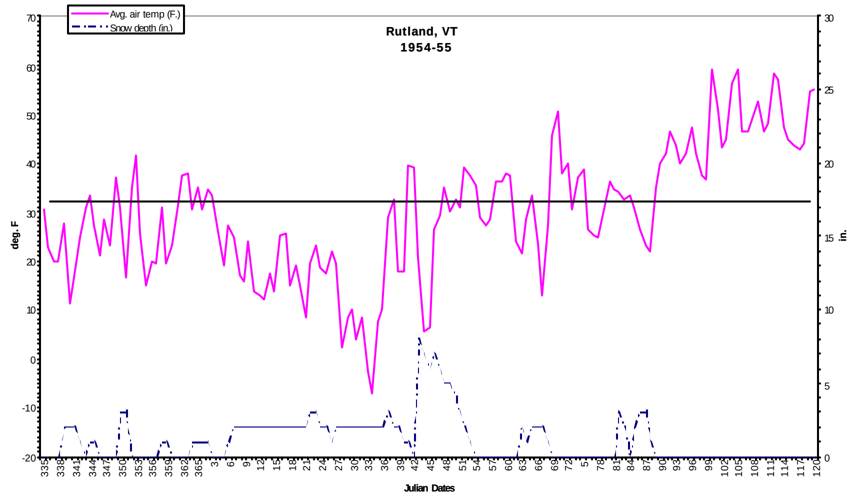


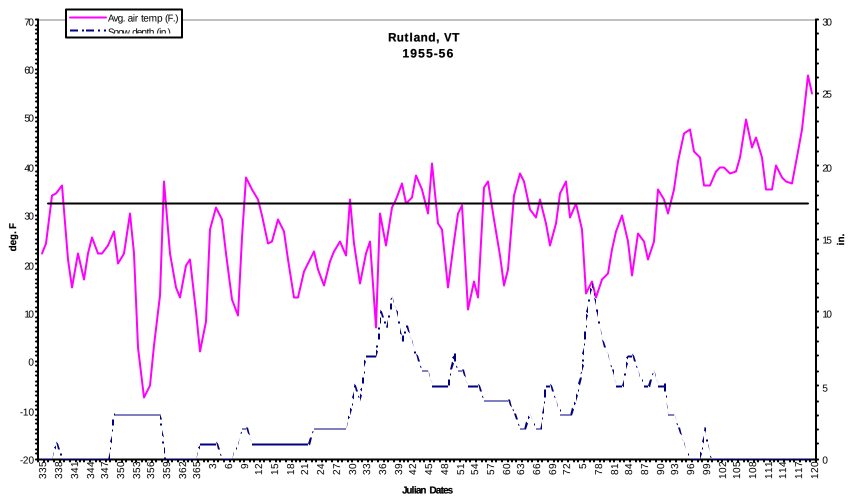


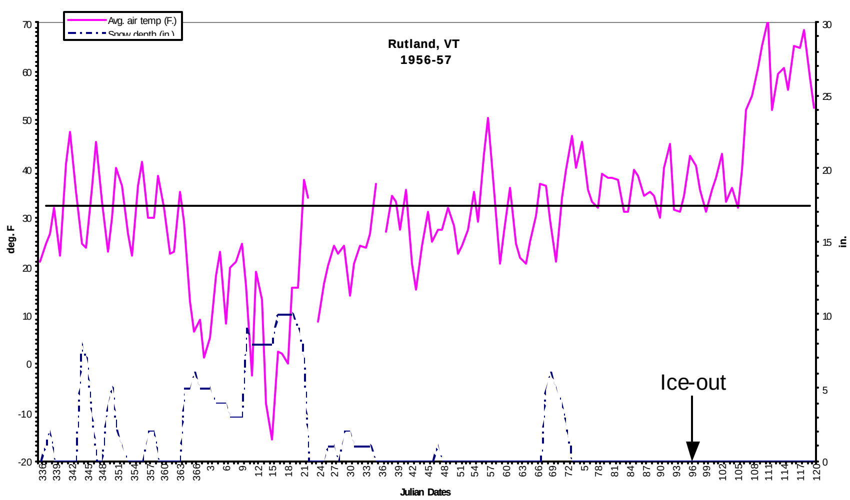

Avg. air temp (F.)
Snow depth (in.)
Rutland, VT
1951-52
deg. F
in.
Julian Dates

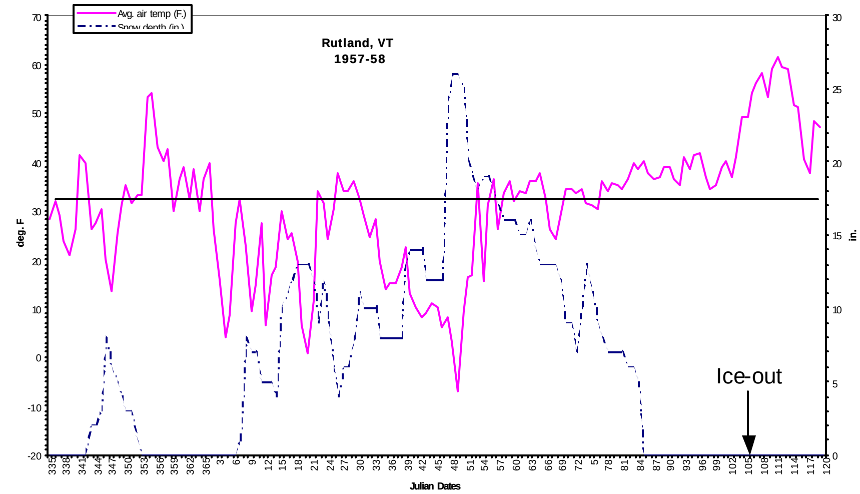

Avg. air temp (F.)
Snow depth (in.)
Rutland, VT
1952-53
deg. F
in.
Julian Dates

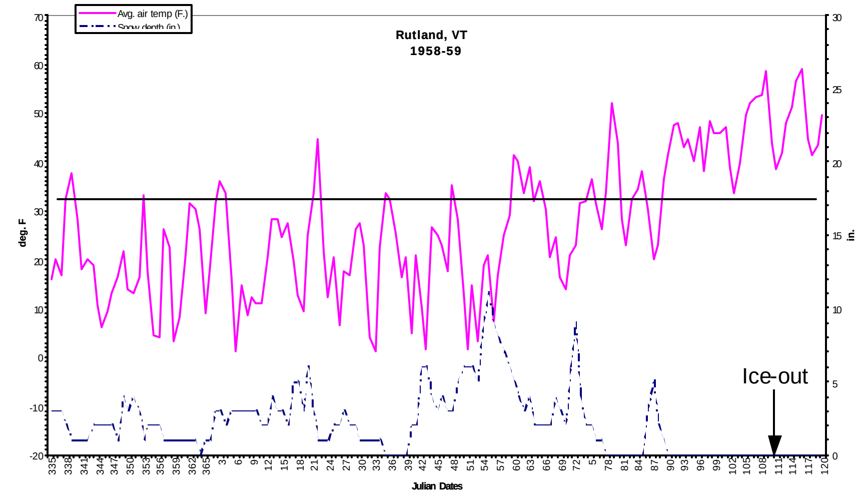

Avg. air temp (F.)
Snow depth (in.)
Rutland, VT
1953-54
deg. F
in.
Julian Dates

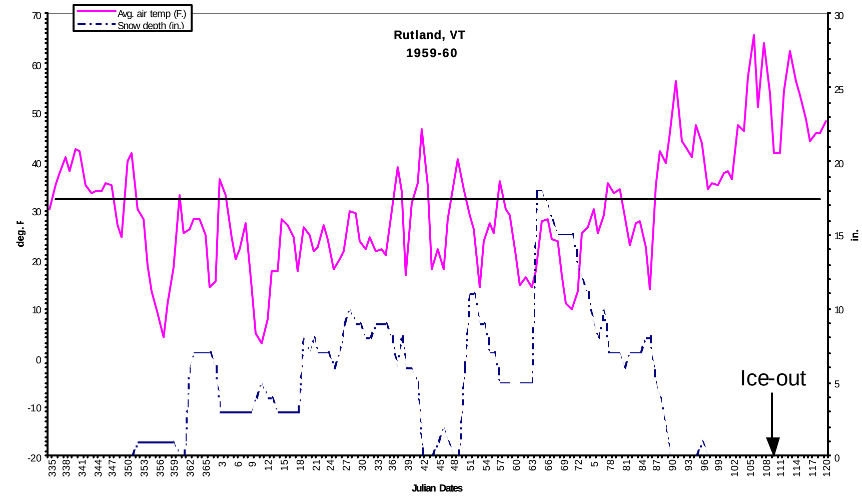

Avg. air temp (F.)
Snow depth (in.)
Rutland, VT
1954-55
deg. F
in.
Julian Dates

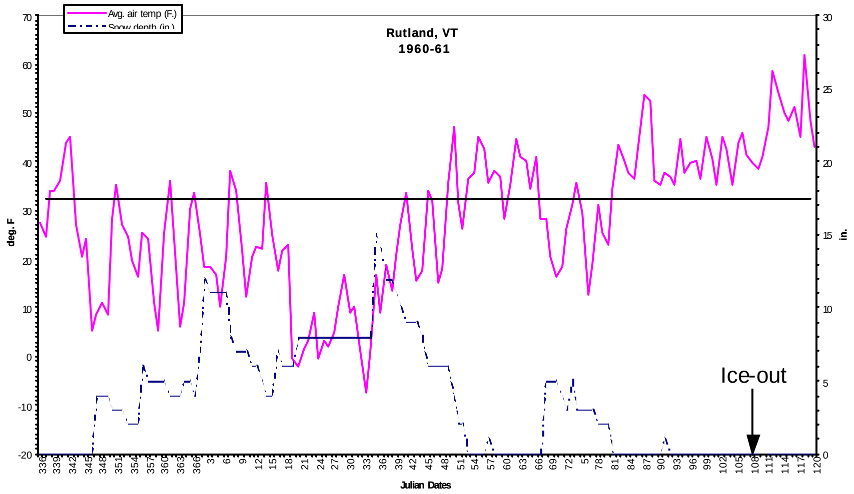

Avg. air temp (F.)
Rutland, VT
1955-56
deg. F
in.
Julian Dates

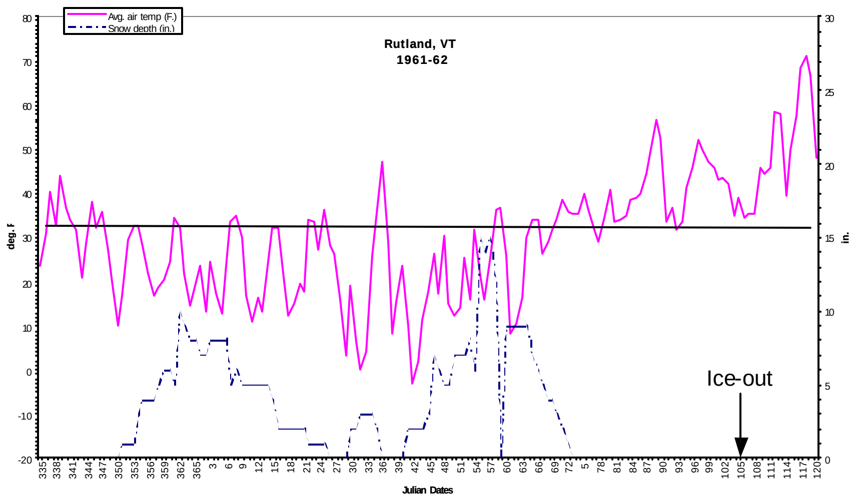

Avg. air temp (F.)
Rutland, VT
1956-57
deg. F
in.
Ice-out
Julian Dates

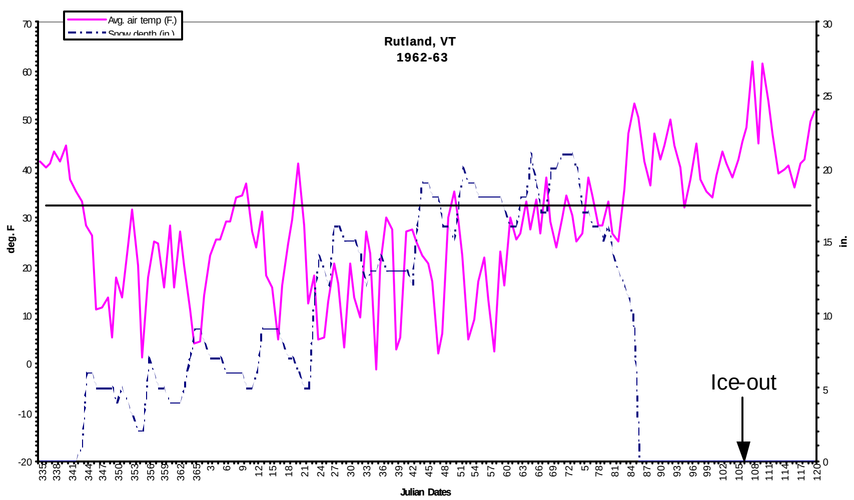

Avg. air temp (F.)
Rutland, VT
1957-58
deg. F
in.
Julian Dates
Ice-out

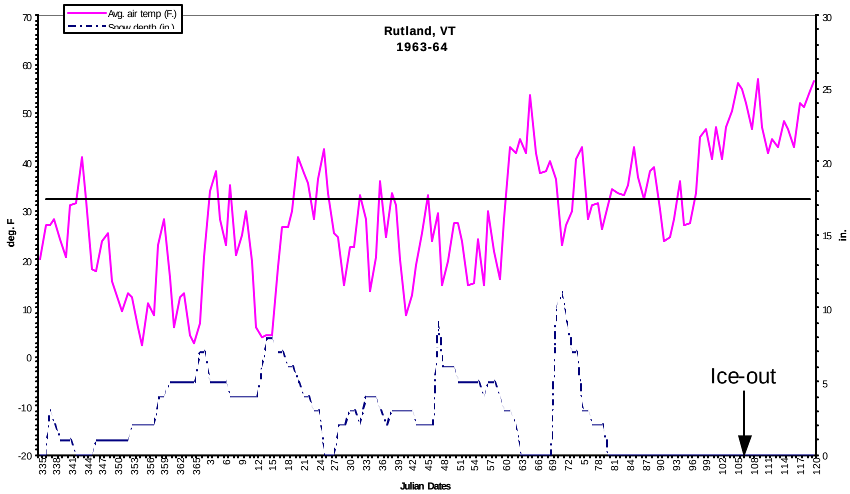

Avg. air temp (F.)
Rutland, VT
1958-59
deg. F
in.
Julian Dates
Ice-out

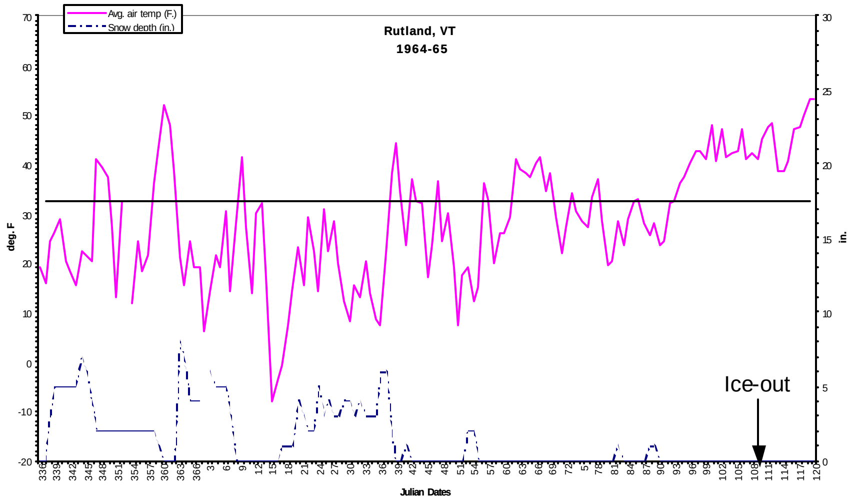

Avg. air temp (F.)
Snow depth (in.)
Rutland, VT
1959-60
deg. F
in.
Julian Dates
Ice-out

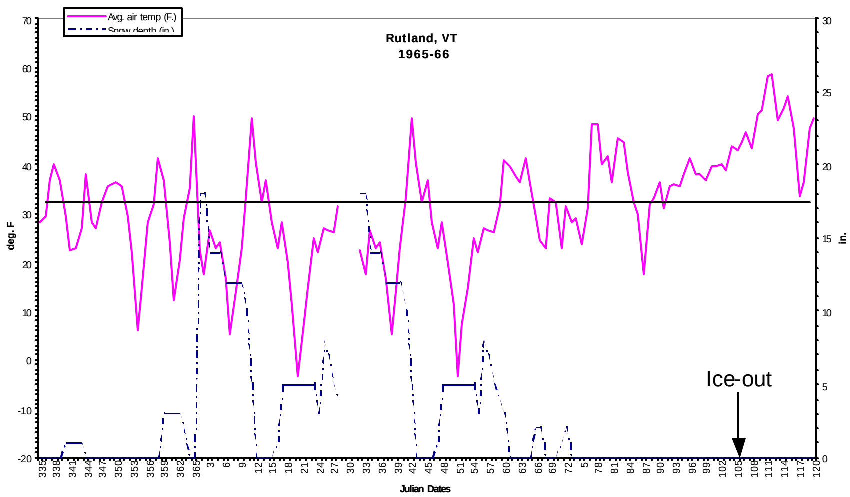

Avg. air temp (F.)
Snow depth (in.)
Rutland, VT
1960-61
deg. F
in.
Ice-out
Julian Dates

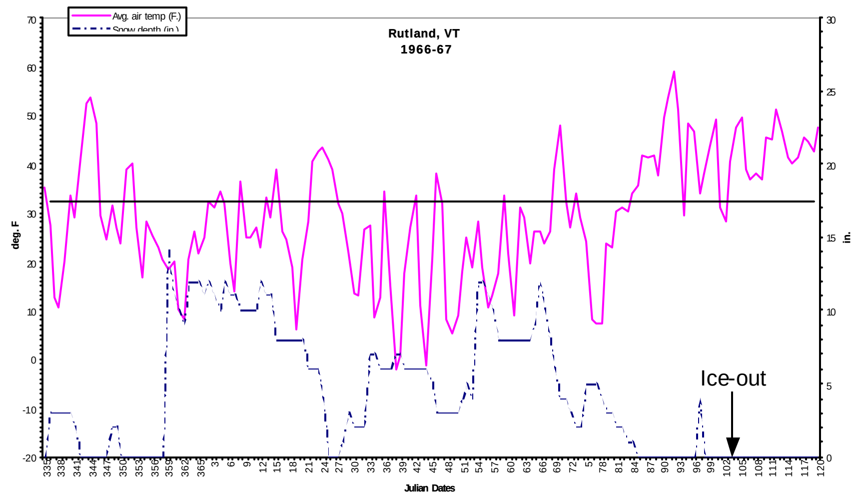

Avg. air temp (F.)
Snow depth (in.)
Rutland, VT
1961-62
deg. F
in.
Ice-out
Julian Dates

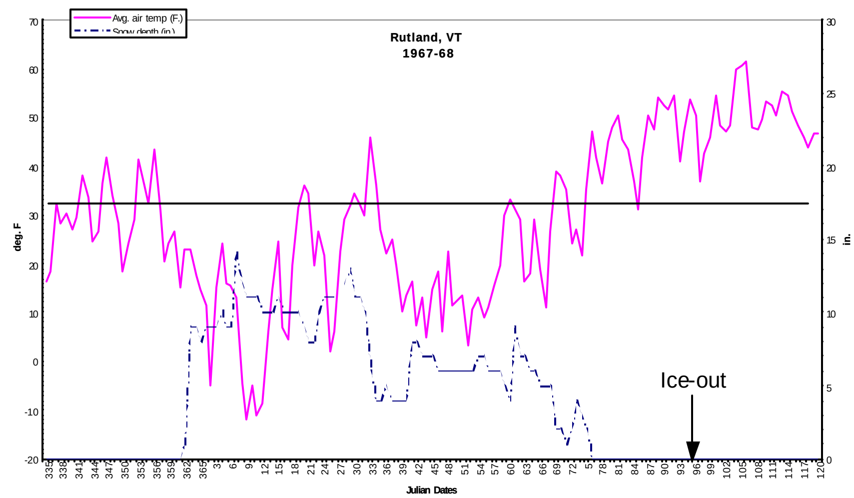

Avg. air temp (F.)
Snow depth (in.)
Rutland, VT
1962-63
deg. F
in.
Ice-out
Julian Dates

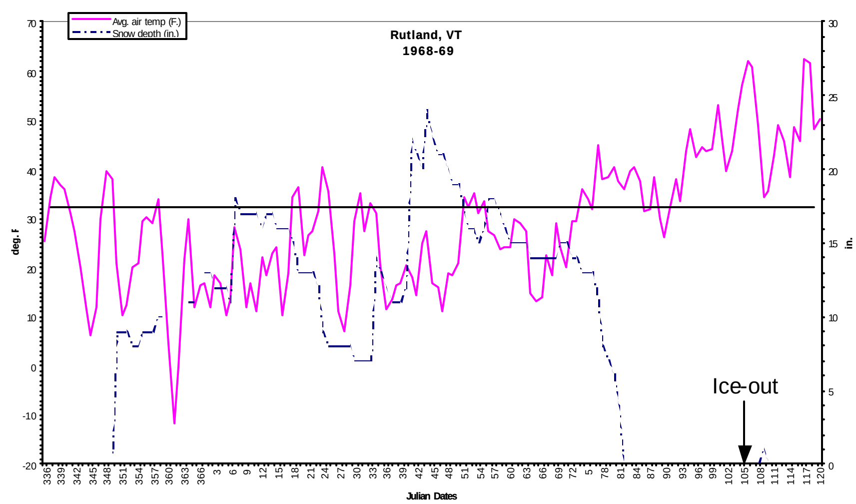

Avg. air temp (F.)
Snow depth (in.)
Rutland, VT
1963-64
deg. F
in.
Julian Dates
Ice-out

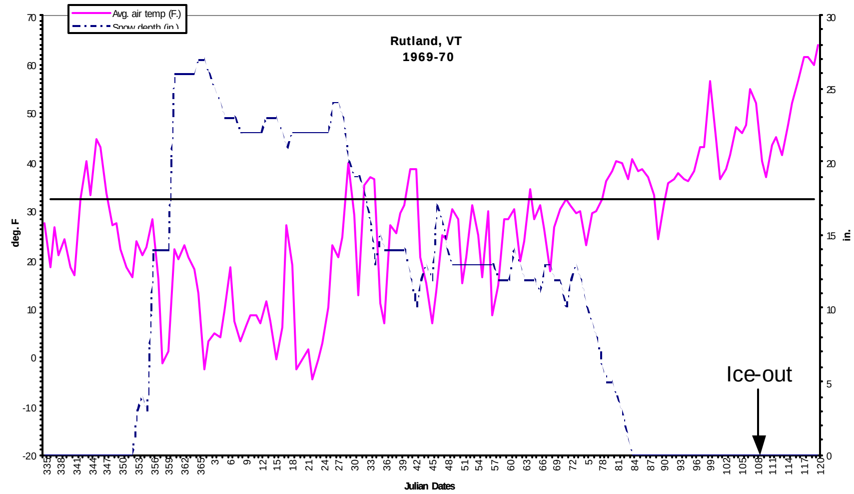

Avg. air temp (F.)
Snow depth (in.)
Rutland, VT
1964-65
deg. F
in.
Julian Dates
Ice-out

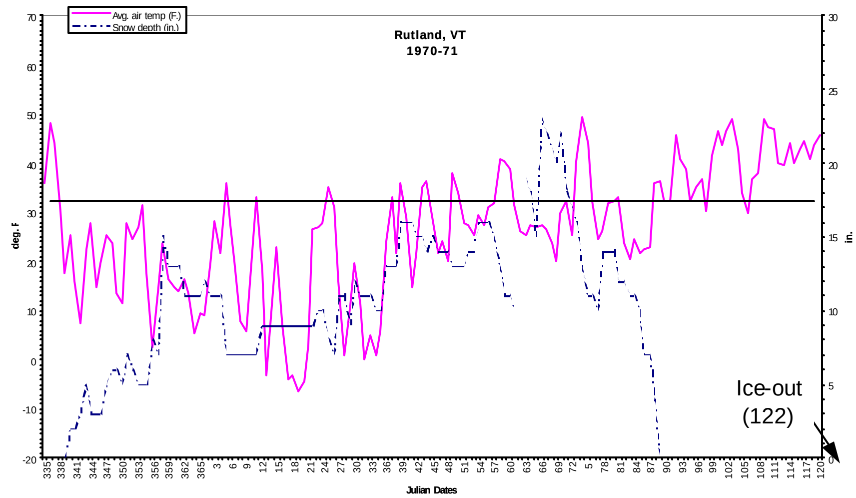

Avg. air temp (F.)
Rutland, VT
1965-66
deg. F
in.
Julian Dates
Ice-out

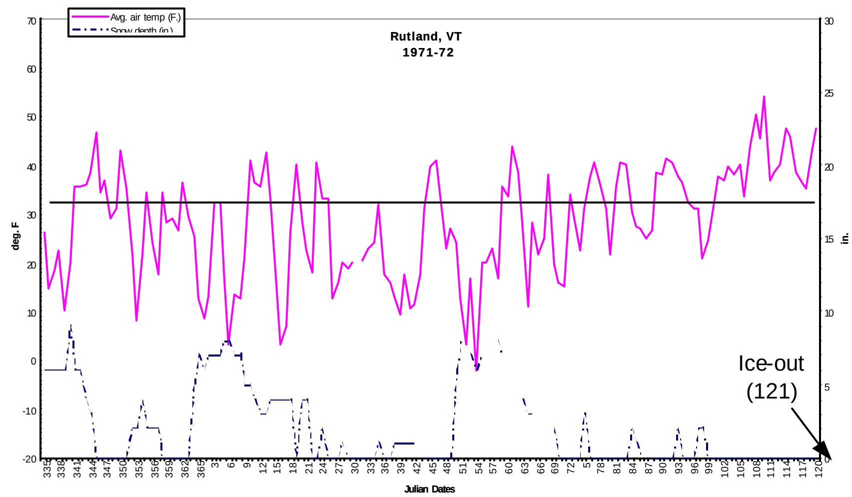

Avg. air temp (F.)
Snow depth (in.)
Rutland, VT
1966-67
deg. F
in.
Ice-out
Julian Dates

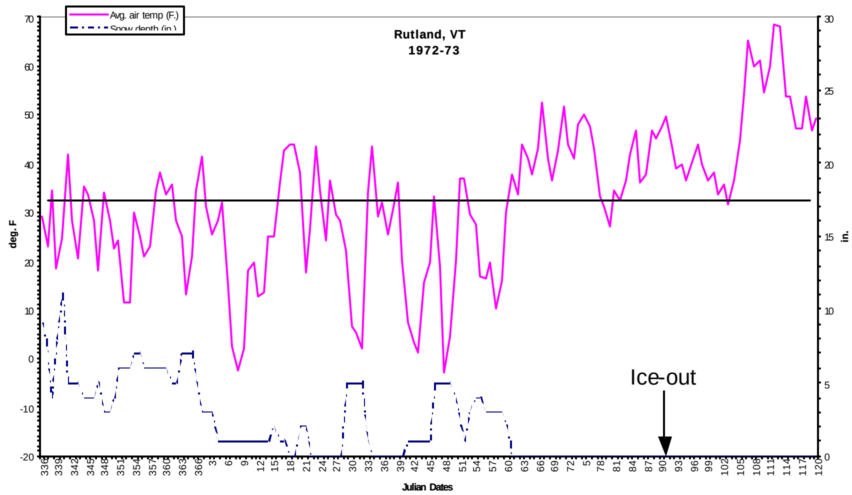

Avg. air temp (F.)
Snow depth (in.)
Rutland, VT
1967-68
deg. F
in.
Ice-out
Julian Dates

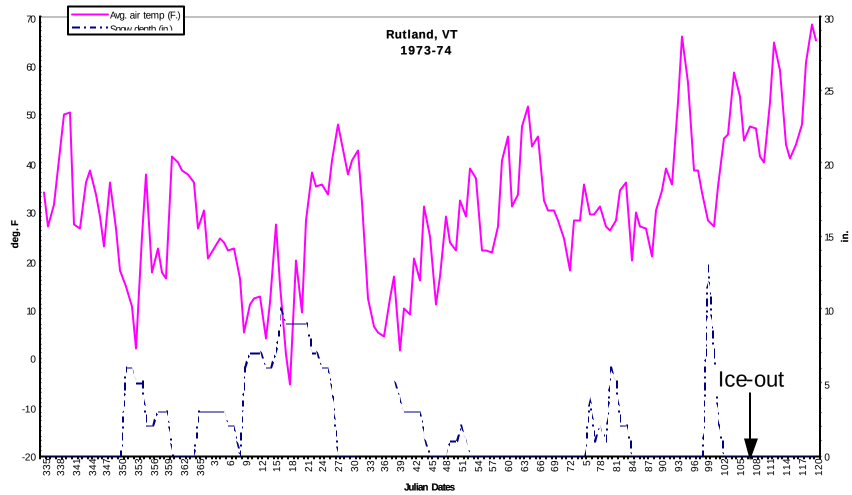

Avg. air temp (F.)
Snow depth (in.)
Rutland, VT
1968-69
deg. F
in.
Ice-out
Julian Dates

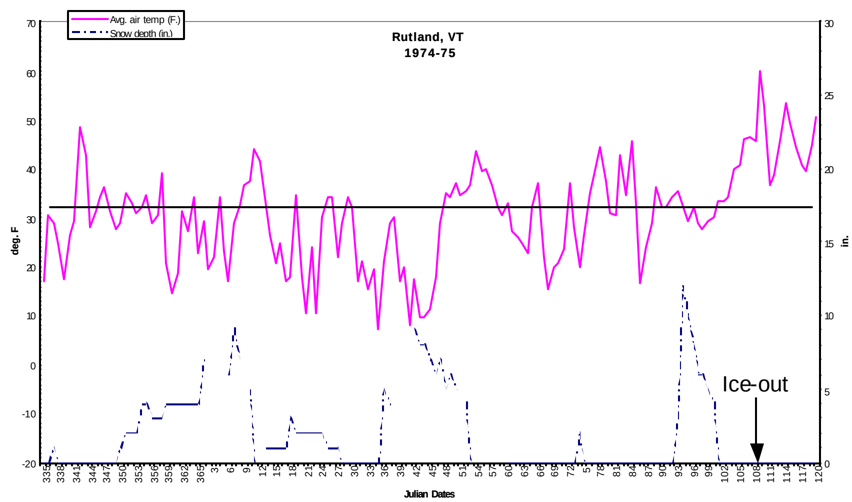

Avg. air temp (F.)
Snow depth (in.)
Rutland, VT
1969-70
deg. F
in.
Ice-out
Julian Dates

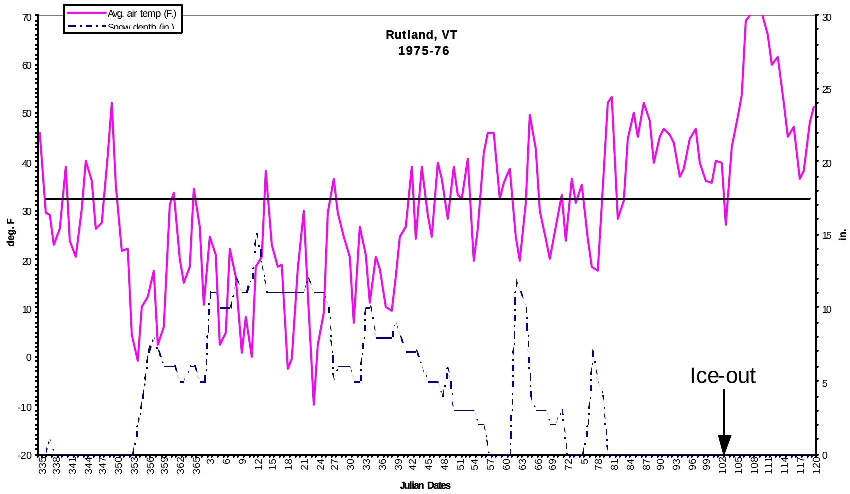

Avg. air temp (F.)
Snow depth (in.)
Rutland, VT
1970-71
deg. F
in.
Ice-out
(122)
Julian Dates

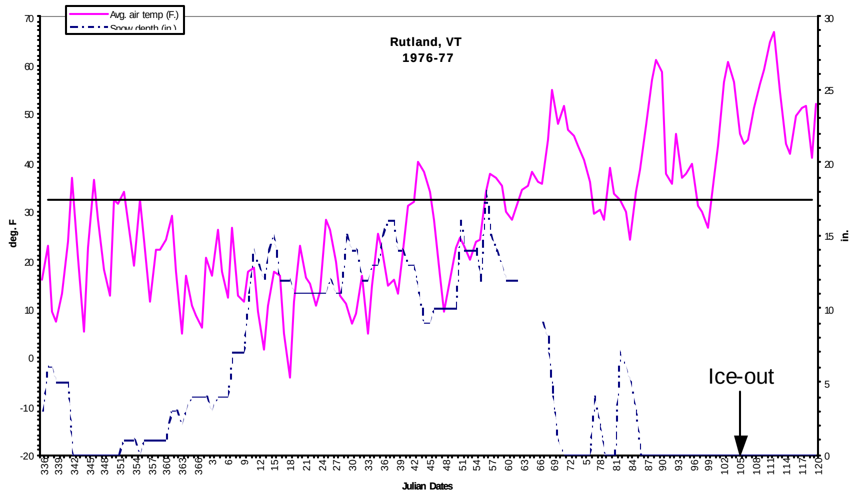

Avg. air temp (F.)
Snow depth (in.)
Rutland, VT
1971-72
deg. F
in.
Ice-out
(121)
Julian Dates

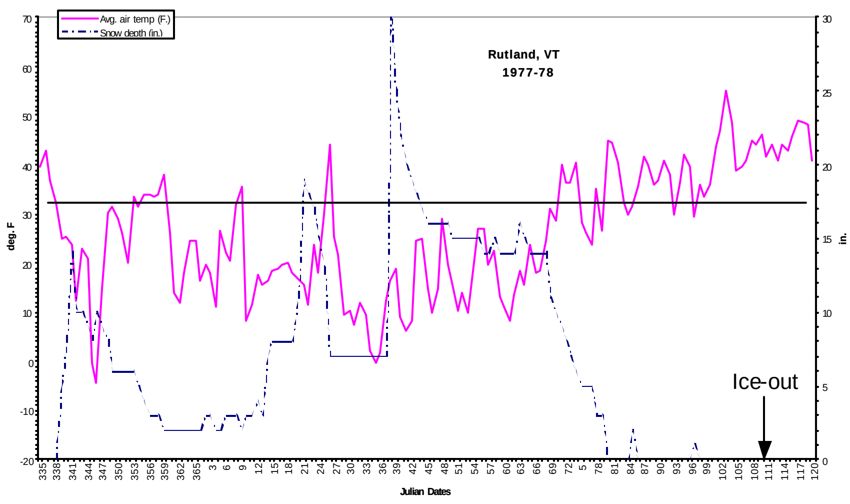

Rutland, VT
1972-73
Avg. air temp (F.)
deg. F
in.
Julian Dates
Ice-out

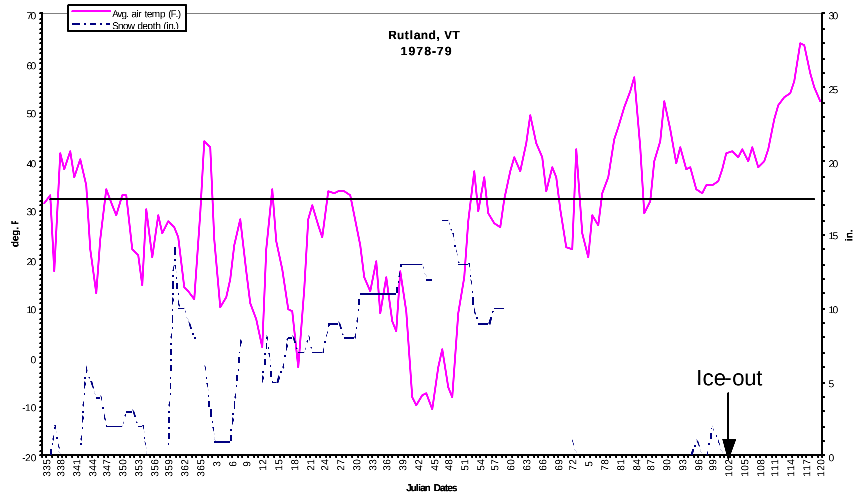

Rutland, VT
1973-74
Avg. air temp (F.)
deg. F
in.
Julian Dates
Ice-out

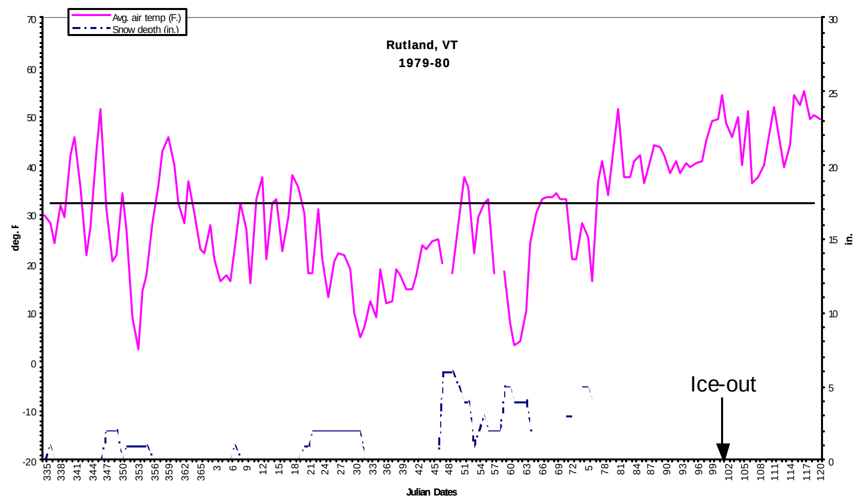

Rutland, VT
1974-75
Avg. air temp (F.)
Snow depth (in.)
deg. F
in.
Julian Dates
Ice-out

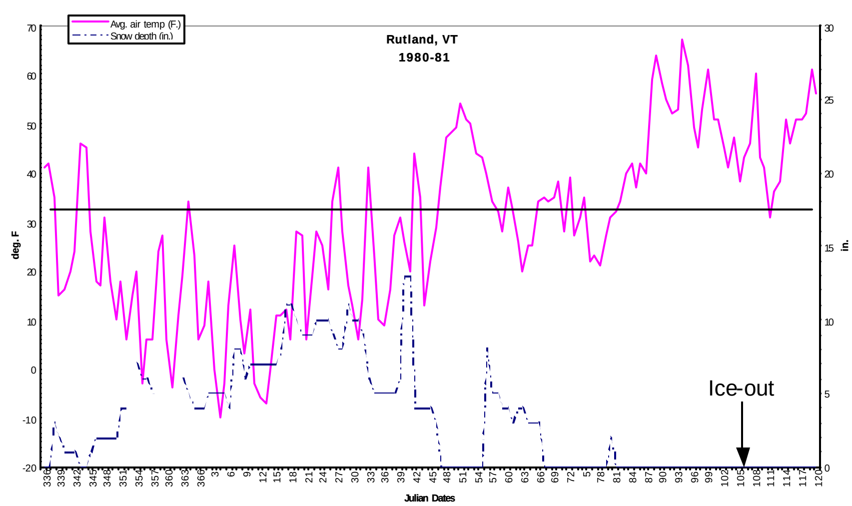

Avg. air temp (F.)
Rutland, VT
1975-76
Ice-out
deg. F
in.
Julian Dates

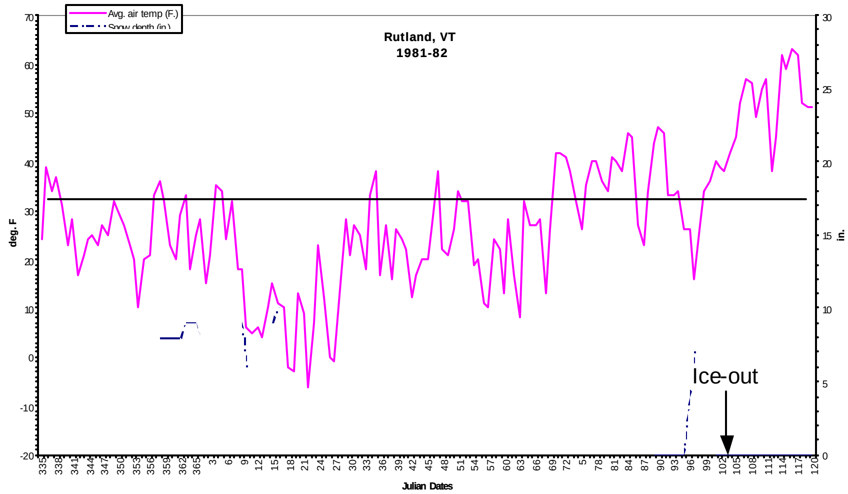

Avg. air temp (F.)
Rutland, VT
1976-77
Ice-out
deg. F
in.
Julian Dates

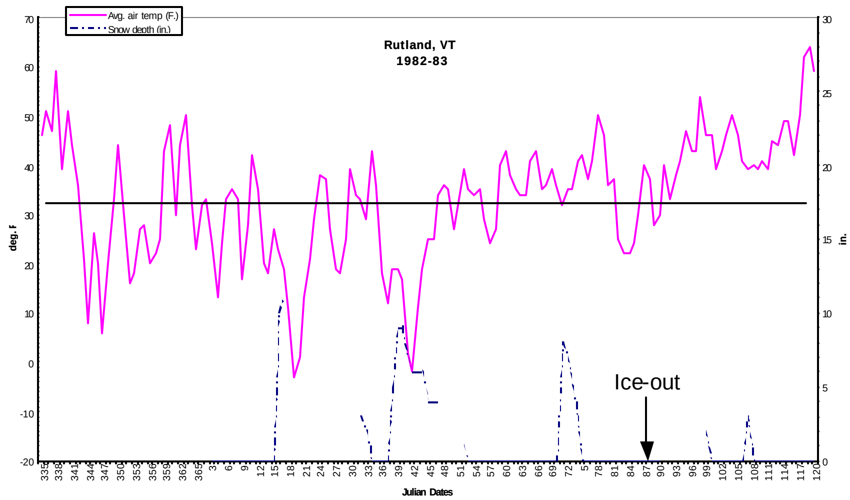

Avg. air temp (F.)
Snow depth (in.)
Rutland, VT
1977-78
Ice-out
deg. F
in.
Julian Dates

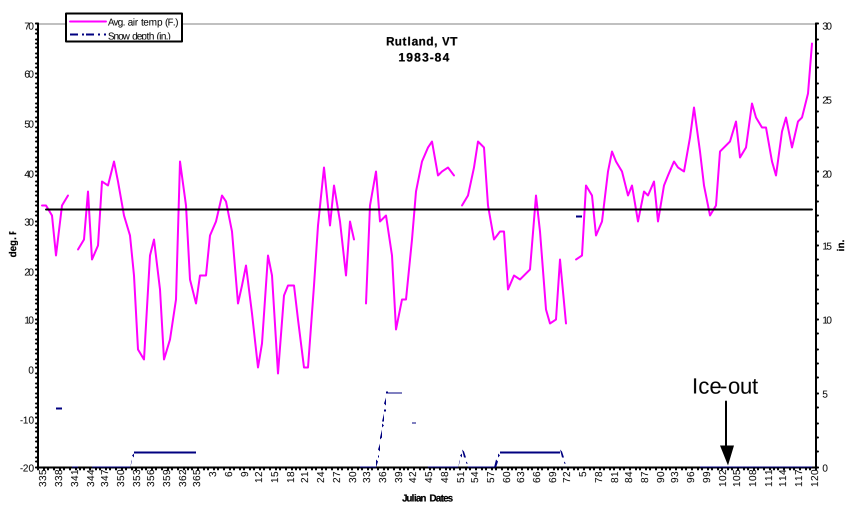

Avg. air temp (F.)
Snow depth (in.)
Rutland, VT
1978-79
deg. F
in.
Ice-out
Julian Dates

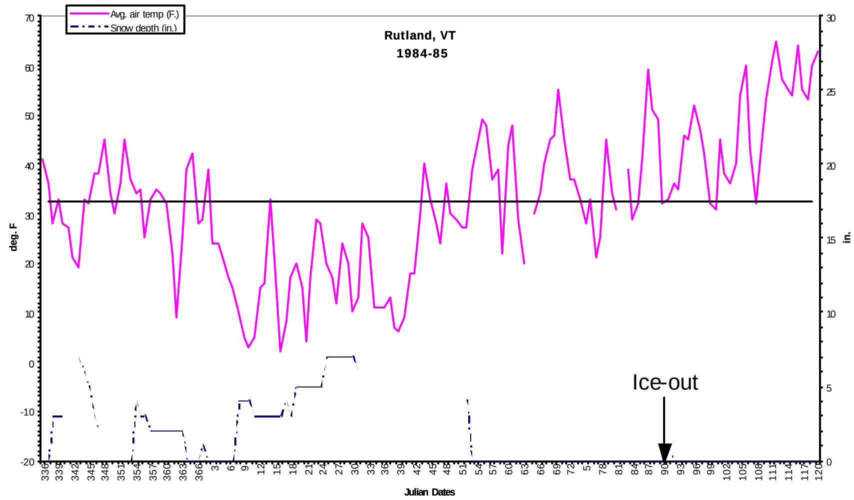

Avg. air temp (F.)
Snow depth (in.)
Rutland, VT
1979-80
deg. F
in.
Ice-out
Julian Dates

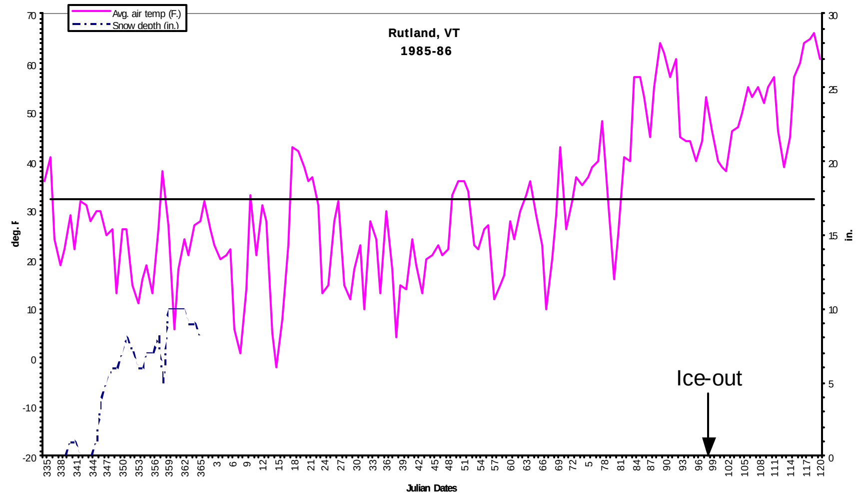

Avg. air temp (F.)
Snow depth (in.)
Rutland, VT
1980-81
deg. F
in.
Ice-out
Julian Dates

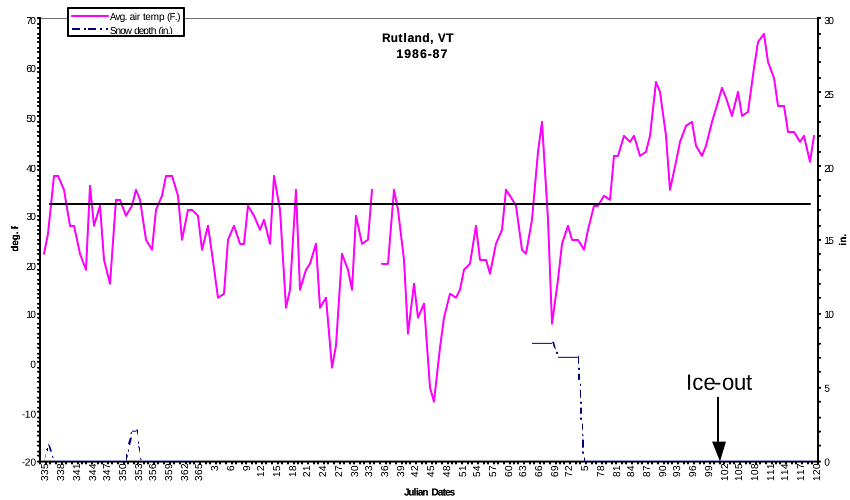

Avg. air temp (F.)
Rutland, VT
1981-82
deg. F
in.
Julian Dates
Ice-out

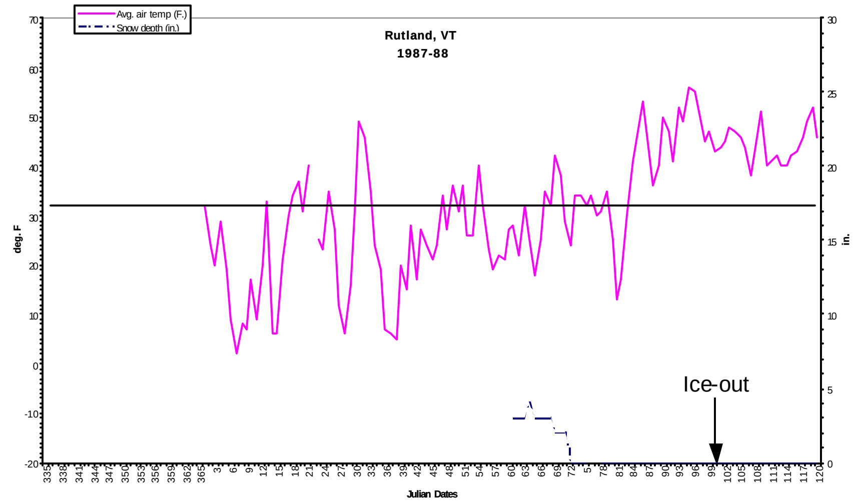

Avg. air temp (F.)
Snow depth (in.)
Rutland, VT
1982-83
deg. F
in.
Julian Dates
Ice-out

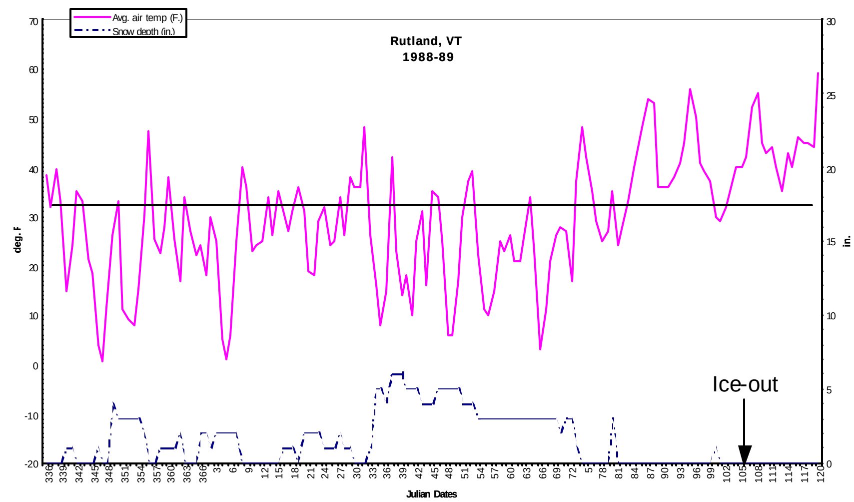

Avg. air temp (F.)
Snow depth (in.)
Rutland, VT
1983-84
deg. F
in.
Julian Dates
Ice-out

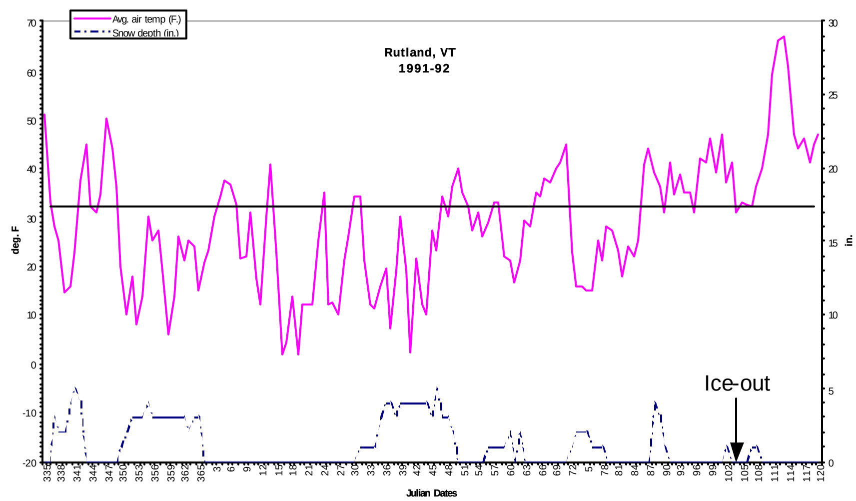

Avg. air temp (F.)
Snow depth (in.)
Rutland, VT
1984-85
deg. F
in.
Julian Dates
Ice-out

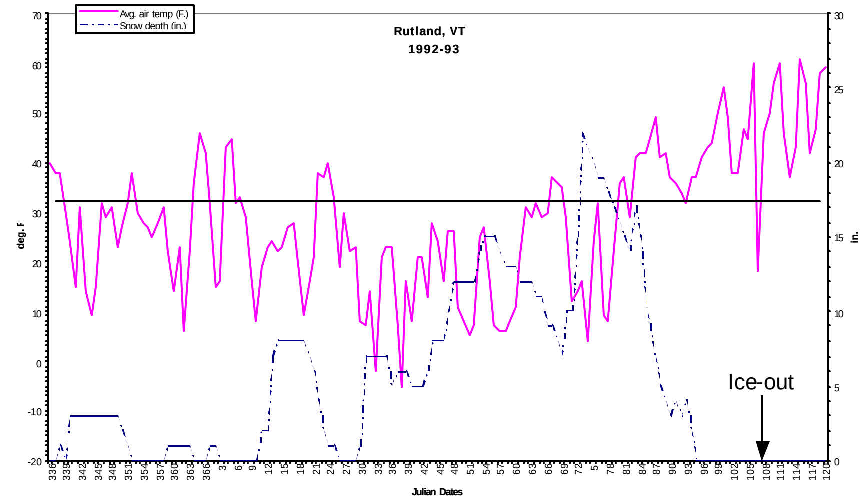

Avg. air temp (F.)
Snow depth (in.)
Rutland, VT
1985-86
deg. F
in.
Julian Dates
Ice-out

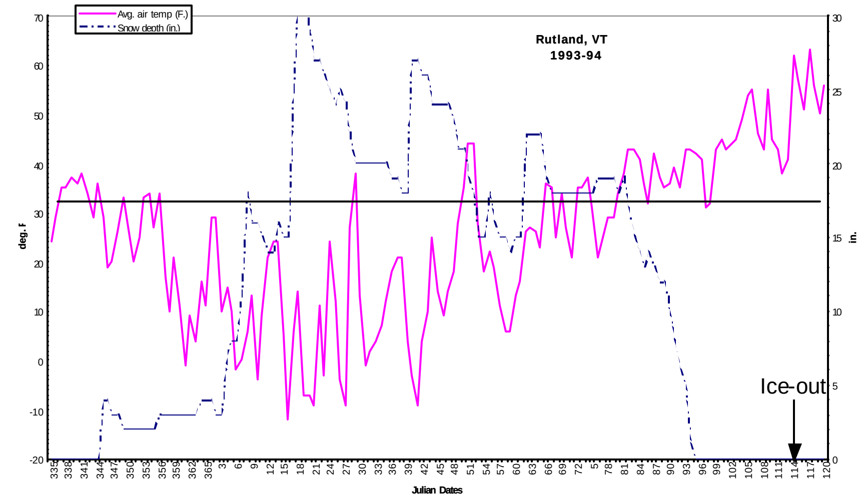

Avg. air temp (F.)
Snow depth (in.)
Rutland, VT
1986-87
deg. F
in.
Julian Dates
Ice-out

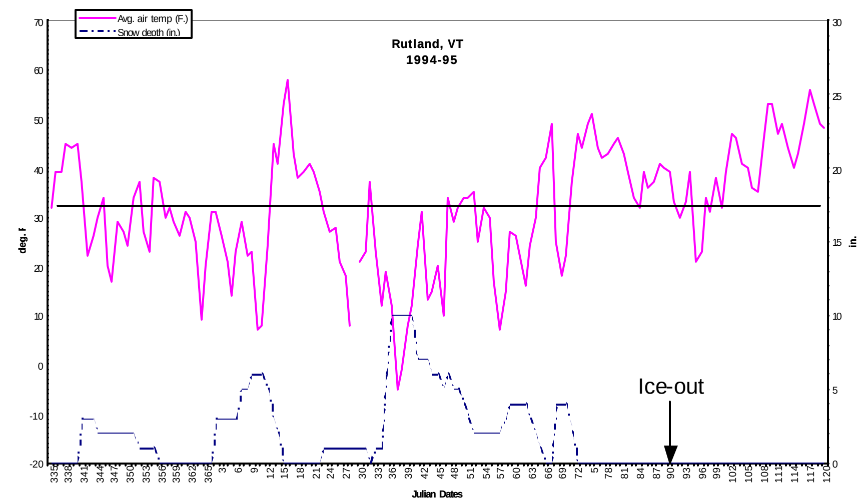

Avg. air temp (F.)
Snow depth (in.)
Rutland, VT
1987-88
deg. F
in.
Ice-out
Julian Dates

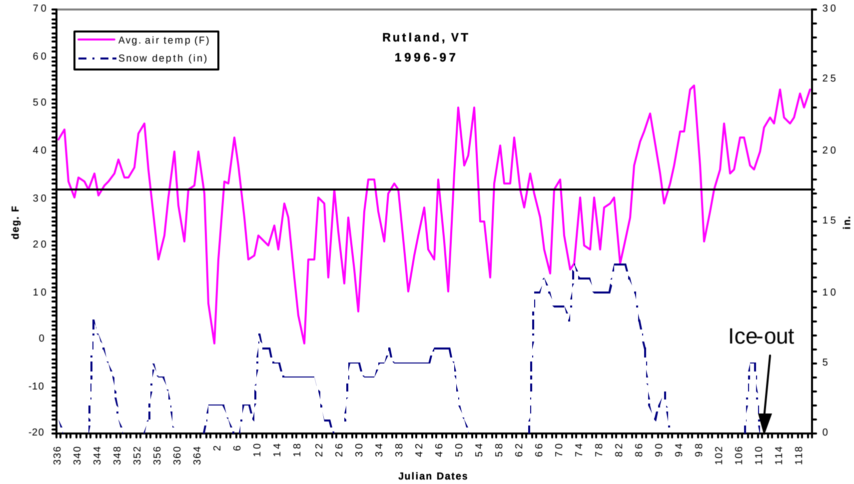

Avg. air temp (F.)
Snow depth (in.)
Rutland, VT
1988-89
deg. F
in.
Ice-out
Julian Dates


Avg. air temp (F.)
Snow depth (in.)
Rutland, VT
1991-92
deg. F
in.
Ice-out
Julian Dates


Avg. air temp (F.)
Snow depth (in.)
Rutland, VT
1992-93
deg. F
in.
Ice-out
Julian Dates


Avg. air temp (F.)
Snow depth (in.)
Rutland, VT
1993-94
deg. F
in.
Ice-out
Julian Dates


Avg. air temp (F.)
Snow depth (in.)
Rutland, VT
1994-95
deg. F
in.
Ice-out
Julian Dates



Rutland, VT
1996-97
Avg. air temp (F)
Snow depth (in)
deg. F
in.
Julian Dates
Ice-out