Comparison of 1983 Great Lakes Winter Weather and Ice Conditions with Previous Years[1]

RAYMOND A. ASSEL

NOAA, Great Lakes Environmental Research Laboratory, Ann Arbor, MI 48104

C. ROBERT SNIDER

NOAA, National Weather Service, Ann Arbor, MI 48107

REGINALD LAWRENCE

NOAA, National Environmental Satellite and Data Information Service, Washington, DC 20233

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ABSTRACT

Winter 1983 was one of the mildest winters in the past 200 years. One result of the unusual winter weather was the mildest overall ice season on the Great Lakes since systematic observations of ice cover extent on the Lakes were initiated some 20-odd years ago. The 1983 winter developed during the peak of one of the most intense El Niño–Southern Oscillation events of this century. Associated with the mild temperatures in the United States was an extremely strong Aleution low that persisted most of the winter. Monthly Northern Hemispheric circulation patterns were generally weak; no general long wave patterns were able to persist; and 700 mb heights were above normal. Annual maximum ice coverage on the Great Lakes was much below normal: Lake Superior 21% (normal is 75%), Lake Michigan 17% (normal is 45%), Lake Huron 36% (normal is 68%), Lake Erie 25% (normal is 90%), and Lake Ontario less than 10% (normal is 24%). Economic impact of the below-normal ice cover included reduced U.S. Coast Guard ice breaking assistance to commercial vessels, reduced U.S. Coast Guard flood relief operations in connecting channels of the Great Lakes, and virtually no ice-related winter power losses at hydropower plants on the St. Marys, Niagara and St. Lawrence Rivers.

1. Introduction

The annual Great Lakes ice cycle has been systematically documented since the early 1960s by charts showing the general pattern of ice cover extent and concentration. Reports describing most of the ice cycles for the past 20 years are cited in *Glaciological Data* (Institute of Arctic and Alpine Research, 1980). The 1977, 1978, 1979 and 1982 ice cycles were among the most severe in the past 20 years; the 1983 ice cycle was among the mildest. Winter 1983 is of particular significance because of the record low amount and extent of ice cover; it establishes a lower limit of synoptic ice extent on portions of the Great Lakes for the period of well-documented ice cover. In this paper, we review the synoptic meteorology that was the primary cause of the much-below-normal 1983 ice cover; we compare the temperature severity of the 1983 winter to past winters; and we describe the normal progression of ice cover on the Great Lakes and compare seasonal maximum ice coverage for winter 1983 with maximum ice cover climatology. The significance of the mild 1983 weather and ice conditions is reviewed with respect to economic impacts attributable to this benchmark winter. Place names used in this article are shown in Fig. 1 or in the figure in which they appear.

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2. Synoptic description of the winter

Winter 1983 was one of the most noteworthy winters this century because of the strong El Niño–Southern Oscillation (ENSO) phenomenon that accompanied it. The climatic significance of ENSO relative to winter 1983 is given by Quiroz (1983) and Barrientos (1984). Here we describe some of the more salient features of the synoptic meteorology of that winter relative to the Great Lakes.

In sharp contrast to the recent severe winters of 1977, 1978, 1979 and 1982, the Great Lakes had a very mild winter in 1983. Most of the contiguous United States had above-normal mean temperatures, with the greatest positive anomaly along the northern border (Fig. 2). The same pattern prevailed throughout

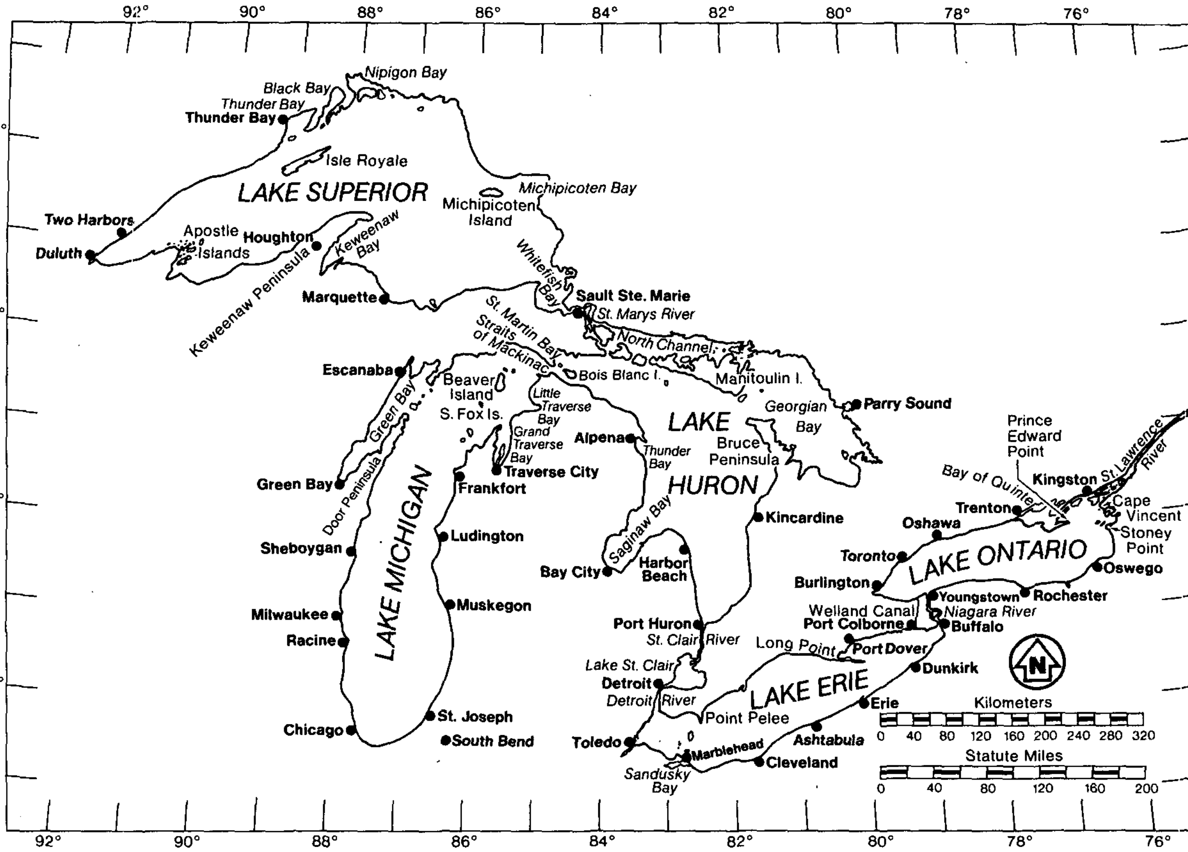

FIG. 1. Place names on the Great Lakes.

much of the Northern Hemisphere, with near-normal to a little below-normal temperatures in the tropics and unusual mildness in the far north. The greatest and most persistent positive temperature anomaly was in Eurasia (Quiroz, 1983).

The weakened south-to-north temperature gradient was associated with a weakened westerly wind flow over most of the hemisphere. No general long wave pattern was able to persist. The basic wind flow over eastern North America was mostly from the west, rather weak, and contained many minor perturbations.

In the Pacific, anomalously warm water associated with the weak coastal current off Peru and Ecuador called El Niño, dominated the tropical regions and contrasted strongly with the normally cold water of the higher latitudes (U.S. Department of Commerce, 1982–83). A stronger-than-normal jet stream south of its normal position (Barrientos, 1984) steered storm after storm into California. These storms then moved eastward and weakened, bringing 150–200% above-normal winter rainfall, December to February, to the Gulf States and portions of the Pacific coast but barely affecting the Great Lakes (U.S. Departments of Agriculture and Commerce, 1983).

Winter 1983 700 mb pattern over the northern continents, Fig. 3, was weak, and in general the above-normal 700 mb heights reflected the presence of mild air masses. In November there was weak blocking on the west coast of North America and a modest broad ridge off the east coast. This established warmer-than-normal air masses in the eastern states and cooler-than-normal air masses in the north-central and far west. A strong trough developed in the eastern Pacific during December and set the pattern for the winter. During January, February and most of March, an extremely strong Aleutian low was somewhat southeast of its normal position. There were also very significant, though not quite as extreme, anomalies in the Atlantic. A strong Icelandic low was north of its normal position, displaced by a well-developed ridge in the eastern part of the ocean. An intense jet stream between them forced large quantities of mild maritime air into the northern parts of Europe and Asia. The established circulation pattern broke down completely in late March and early April and was replaced by a nondescript and seemingly unstable pattern. Perhaps its most significant feature is a weak trough over the Great Lakes, a reflection of the prevailing cool weather.

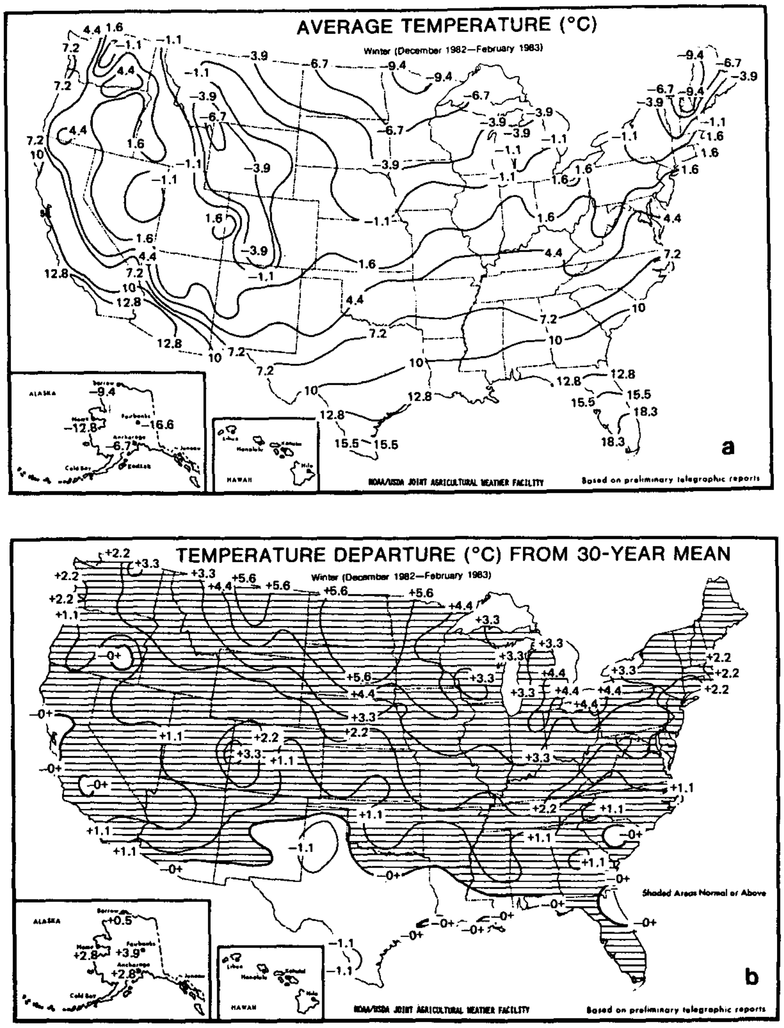

FIG. 2. (a) Average winter temperature (°C) December 1982–February 1983. (b) Winter temperature departure (°C) from a 30-year mean. Information on Fig. 2 is modified from *Weekly Weather and Crop Bulletin*, Vol. 70, No. 11, 15 March 1983.

Maritime polar air masses of Pacific origin covered the Lakes most of the winter. Precipitation was primarily due to overrunning from warmer air masses to the south. The total seasonal precipitation around the Great Lakes was near normal; however, except around western Lake Superior, an abnormally high percentage of it came in the form of rain. Snow cover was a short-lived rarity in the southern Lakes region. A storm center moved east-northeastward just south of the lower Great Lakes on 21 March, pushing floodwaters into the southwest shore of ice-free Saginaw Bay, and ushering in an extended period of colder weather. Freezing began again on the upper Great Lakes. The mild winter was followed by a decidedly cold spring. However, the change to colder weather came too late to have much effect on Great lakes ice.

3. Winter severity

a. Monthly mean temperatures and anomalies

Winter started early around Lake Superior. Below-normal November temperatures in that area are the only negative anomalies listed in Table 1. Early season low air temperatures and persisting December snow cover along the shore of Lake Superior seemed to augur a severe ice season on that Lake, but it was not to be. The strong positive air temperature anomaly, which had been centered along the southern edge of the Great Lakes region in early winter, spread northwestward and was centered northwest of the Lakes by winter's end.

Monthly mean temperatures more than one standard deviation above normal occurred over all the Lakes during each of the winter months. March also

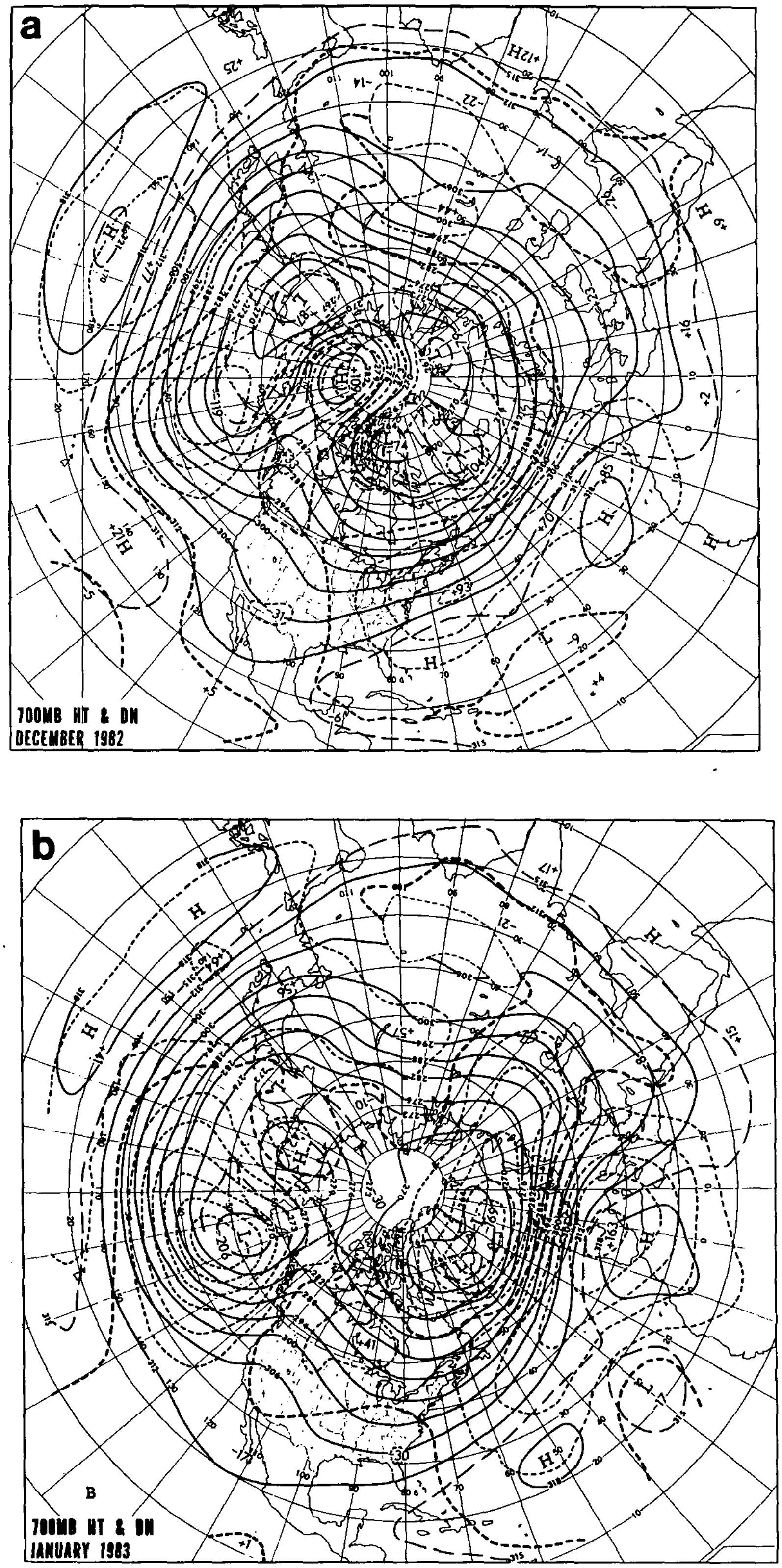

FIG. 3. Mean contours of the 700 mb surface (meters ×10 above sea level) and departure from normal, December 1982 to February 1983. (From Climatic Analysis Center, National Weather Service.)

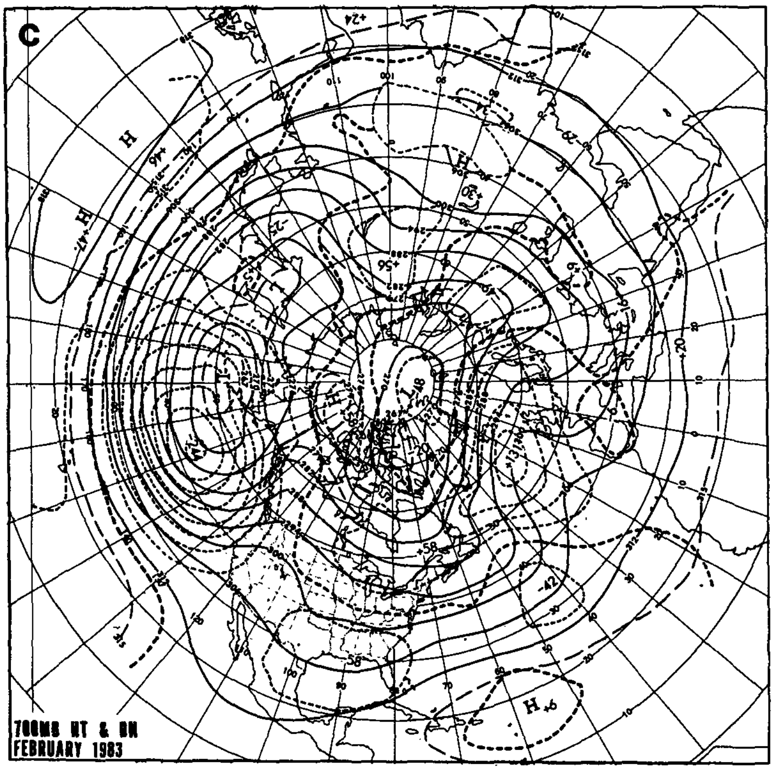

FIG. 3. (*Continued*)

averaged above normal throughout the region, although considerably colder weather had set in by the end of that month.

b. Freezing degree-days

The accumulation of freezing degree-days (FDDs) began early—3 November at Duluth, Minnesota; 4 November at Marquette, Michigan. By the end of November, accumulations were 198% of normal at Duluth, 68% at Sault Ste. Marie, Michigan, 164% at Green Bay, Wisconsin, and 230% at Alpena, Michigan. As usual there were at this time no accumulations of FDDs at more southerly locations.

Freezing took place more slowly during December and was interrupted by thawing on several occasions.

TABLE 1. Monthly mean air temperature and anomalies in °C (Fahrenheit in parentheses).

	1982				1983					
	November		December		January		February		March	
Station	Mean	Anomaly	Mean	Anomaly	Mean	Anomaly	Mean	Anomaly	Mean	Anomaly
Duluth, MN	−4.2 (24.4)	−2.2 (−4.0)	−6.9 (19.6)	2.9 (5.2)	−10.4 (13.2)	3.8 (6.9)	−6.1 (21.1)	5.1 (9.1)	−3.6 (25.6)	1.5 (2.7)
Marquette, MI	−1.6 (29.1)	−0.2 (−0.3)	−2.7 (27.2)	2.1 (3.7)	−7.8 (18.0)	3.3 (5.9)	−5.6 (21.9)	4.2 (7.6)	−3.3 (26.0)	1.6 (2.8)
Sault Ste. Marie, MI	0.2 (32.3)	−0.3 (−0.5)	−4.2 (24.5)	2.4 (4.4)	−8.9 (15.9)	1.4 (2.6)	−5.7 (21.7)	3.7 (6.7)	−2.5 (27.5)	2.0 (3.6)
Green Bay, WI	0.7 (33.3)	−0.4 (−0.8)	−2.2 (28.0)	3.9 (7.1)	−5.9 (21.4)	4.1 (7.4)	−3.2 (26.3)	4.7 (8.5)	−0.5 (31.1)	1.4 (2.5)
Milwaukee, WI	3.3 (38.0)	0.8 (1.5)	0.7 (33.2)	5.0 (9.0)	−3.1 (26.4)	4.3 (7.7)	−1.4 (29.4)	3.6 (6.4)	1.7 (35.0)	1.6 (2.9)
South Bend, IN	5.8 (42.5)	1.6 (2.9)	3.9 (39.0)	6.0 (10.8)	−1.5 (29.3)	3.4 (6.1)	0.7 (33.2)	3.8 (6.8)	4.6 (40.2)	2.3 (4.2)
Muskegon, MI	4.6 (40.3)	0.6 (1.1)	2.1 (35.7)	4.0 (7.2)	−2.8 (26.9)	2.1 (3.8)	−1.0 (30.2)	3.3 (6.0)	2.4 (36.4)	2.0 (3.6)
Alpena, MI	2.2 (36.0)	0.6 (1.1)	−0.3 (31.4)	4.4 (8.0)	−5.4 (22.2)	2.7 (4.8)	−3.8 (25.1)	3.9 (7.1)	−0.7 (30.8)	2.2 (4.0)
Detroit, MI	5.3 (41.6)	0.8 (1.5)	2.9 (37.3)	4.9 (8.8)	−1.8 (28.7)	2.9 (5.3)	−0.2 (31.6)	3.2 (5.8)	3.6 (38.4)	1.9 (3.4)
Toledo, OH	5.4 (41.8)	1.2 (2.2)	2.6 (36.6)	4.8 (8.6)	−2.4 (27.6)	2.5 (4.5)	−0.8 (30.5)	2.6 (4.7)	3.3 (37.9)	1.4 (2.5)
Cleveland, OH	7.4 (45.4)	2.1 (3.8)	4.7 (40.5)	5.7 (10.2)	−0.7 (30.7)	2.9 (5.2)	1.1 (33.9)	3.6 (6.5)	4.9 (40.8)	2.3 (4.2)
Buffalo, NY	6.1 (43.0)	1.8 (3.2)	3.1 (37.5)	5.3 (9.6)	−2.8 (27.0)	1.9 (3.5)	−1.3 (29.6)	2.8 (5.1)	2.6 (36.7)	2.1 (3.7)
Rochester, NY	6.3 (43.4)	1.6 (2.9)	3.0 (37.4)	5.1 (9.1)	−2.6 (27.4)	2.1 (3.8)	−1.6 (29.1)	2.6 (4.7)	2.9 (37.2)	2.2 (3.9)

TABLE 2. Freezing degree-days in °C (Fahrenheit in parentheses).

Station	Maximum FDDs	Date	Normal maximum	Percent of normal	Normal date	Winter severity class*
Duluth, MN	929 (1672)	30 Mar	1267 (2281)	73	02 Apr	MN
Marquette, MI	703 (1265)	30 Mar	—	—	—	—
Sault Ste. Marie, MI	634 (1141)	23 Mar	1008 (1814)	63	03 Apr	M
Green Bay, WI	366 (659)	30 Mar	790 (1422)	46	21 Mar	M
Milwaukee, WI	186 (335)	13 Feb	500 (900)	37	10 Mar	M
Chicago, IL	167 (301)	13 Feb	—	—	—	—
Muskegon, MI	141 (253)	13 Feb	370 (666)	38	11 Mar	M
Alpena, MI	326 (587)	31 Mar	670 (1206)	49	28 Mar	M
Detroit, MI	107 (192)	14 Feb	—	—	—	—
Toledo, OH	143 (258)	14 Feb	307 (553)	47	10 Mar	MN
Cleveland, OH	71 (128)	13 Feb	246 (443)	29	02 Mar	MN
Buffalo, NY	161 (290)	14 Feb	361 (650)	32	11 Mar	MN
Rochester, NY	154 (277)	14 Feb	364 (655)	42	11 Mar	MN

* After Assel (1980): M—mild, MN—milder than normal.

During the first few days of the month, FDD accumulations fell below normal everywhere except on western Lake Superior and by 23 December even Duluth was below normal. This pattern continued through January with very slow freezing on Lake Superior and periods of thawing elsewhere. Cleveland, Ohio had zero accumulation as late as 11 January.

Stations throughout the Lakes reached peak FDD accumulations, averaging about half the normal, on 13 or 14 February. The seasonal thaw then began, although some further freezing took place on Lake Superior and Green Bay late in the month.

After the cold frontal passage on 21 March, significant accumulations began again at northern stations, and higher peaks were reached there on 30 or 31 March. These, among the largest accumulations of the winter, were still too small to permit the formation of any significant ice.

Maximum FDD accumulations for the 1982/83 season are given in Table 2 and were used to classify winter severity by Assel's (1980) method for those stations in Table 2 that did not have a discontinuity in station location. Using that classification on ten stations, the winter was classified as mild at five stations and milder than normal at the remaining five stations.

c. *Comparison with previous winters*

In an earlier study (Quinn *et al.*, 1978), Snider defined an index of winter severity. This index, the average of the monthly mean temperatures from November through February at Duluth, Sault Ste. Marie, Detroit and Buffalo, was found to correlate with the mass of ice formed on the Great Lakes (Table 3). Indices were calculated for all the mild winters between 1783 and 1983. The 20 warmest (first decile) years of the two centuries are tabulated in Table 4. Note that 1982/83 was the tenth warmest winter of the 200 years; 95% of all winters were colder. Winter severity indices for the warmest 10% of winters range from +0.1 to −3.4 and correspond to 0–41% ice coverage. Indicies for the coldest 10% of the winters range from −6 to −9 and correspond to 73–100% ice coverage.

TABLE 3. Correlation between winter severity index and regional ice cover.

Year	Winter severity index	Regional ice cover*: Observed	Regional ice cover*: From regression†
1963	−6.7	88.8	81.8
1964	−3.6	31.8	43.9
1965	−5.0	63.7	61.0
1966	−4.2	40.8	51.3
1967	−4.9	70.3	59.8
1968	−5.4	60.6	65.9
1969	−4.5	38.4	54.9
1970	−5.9	57.4	72.0
1971	−5.3	44.0	64.7
1972	−5.0	71.1	61.0
1973	−4.5	49.9	54.9
1974	−4.9	56.0	59.8
1975	−3.3	36.7	40.3
1976	−3.6	41.9	43.9
1977	−7.7	84.4	94.0
1978	−6.0	76.5	73.2
1979	−6.8	99.6	83.0
1980	−4.0	65.4	48.8
1981	−5.0	75.9	61.0
1982	−5.8	87.0	70.8
1983	−2.2	23.3	26.8

* Percentage of combined total surface area of the five Great Lakes that was ice covered, based on information given in DeWitt *et al.* (1980) and for winters past 1979 from U.S. Coast Guard (personal communication, 1983).

† A linear regression of the form, ice cover = winter severity index · coefficient, was calculated, where coefficient = −12.203, correlation coefficient = −0.83, and standard error of estimate is 11.6% ice cover.

TABLE 4. The 20 mildest winters on the Great Lakes, 1783–1983.

Rank	Winter	Severity index	Coldest month
1	1931/32	+0.1	March
2	1877/78	−0.5*	January
3	1881/82	−1.0*	January
4	1850/51	−1.0*	December
5	1918/19	−1.3	February
6	1889/90	−1.5	March
7	1952/53	−1.9	January
8	1948/49	−2.0	February
9	1930/31	−2.1	January
10	1982/83	−2.2	January
11	1920/21	−2.3	January
12	1794/95	−2.5*	January
13	1879/80	−2.5*	December
14	1896/97	−2.9	January
15	1862/63	−3.0*	February
16	1843/44	−3.0*	January
17	1902/03	−3.2	January
18	1954/55	−3.4	January
19	1939/40	−3.4	January
20	1943/44	−3.4	December

* Data prior to 1888 were not of sufficient quality to justify means with 0.1 precision. They have been rounded off to the nearest 0.5°C.

d. Typical ice conditions in a mild winter

In all of the winters milder than 1983, ice cover was minimal at the end of February (Assel *et al.*, 1984). But conditions varied considerably during the March and April opening of the navigation season. The Winter Severity Index, which was developed for the study of extended winter navigation, is not so applicable to the spring opening.

Oak (1955) found that no meteorological parameter, or combination of parameters, available in early March correlated as well with port opening dates as did the February mean temperature. The present study substantiates his conclusion. Conditions earlier in the winter have little effect on the progress of ice breakup.

Even in the mildest winter known on the Great Lakes, enough heat has been extracted from the water by the end of February that ice can form quickly whenever FDDs occur. This can continue well into spring.

Only four times in 200 years has March been the coldest month of the winter. On two of these occasions, March followed an extremely mild winter, and each time new ice formed on previously open water during the season when melting normally occurs.

4. Normal seasonal ice cover progression and the 1983 Great Lakes ice cycle

a. Data

Information on the normal maximum ice cover and normal seasonal progression of the Great Lakes ice cover was abstracted from Assel *et al.* (1983) and data on yearly maximum percentage ice cover was abstracted from DeWitt *et al.* (1980). Information for the 1983 ice cycle was abstracted (i) from ice charts produced by the National Weather Service and the Navy as described by Jacobs *et al.* (1980), and by the Atmospheric Environment Service (AES), Ice Branch, Ottawa, Ontario, Canada, and (ii) from satellite images made from the Geostationary Operational Environmental Satellite (GOES) and provided by the National Environmental Satellite and Data Information Service (NESDIS), Washington, DC.

The seasonal progression of the 1983 Great Lakes ice cover is illustrated in a series of GOES visible images (Fig. 4). Estimates of the generalized distribution pattern of ice concentration, near the time of seasonal maximum ice cover, for the 1983 winter and for a normal winter, are given as Fig. 5. Also, although space does not permit in this report, a detailed description of 1983 ice conditions is given in Assel *et al.* (1984).

b. Lake Superior

Ice cover on this most northerly and westerly of the Great Lakes is usually confined to bays, harbors, and the exposed lake shore through the end of January. Ice normally forms in the open lake area of the western half of the lake during the first half of February, and during the last half of February, ice normally forms in the deeper, eastern half of the lake. Maximum aerial extent of ice usually occurs in the last half of February or early March but ice formation can continue in the open lake through March. Midlake ice cover is usually dissipated the second half of March and the first half of April most years. Shore ice can last into May.

In 1983 the midlake area of Lake Superior remained virtually ice free. The percentage of lake surface covered by ice was estimated to be at its greatest seasonal extent on 8 February, at which time 21% of the surface area of the lake was ice covered. This is much below the normal seasonal maximum ice cover of 75%. The only two other winters during the past 20-odd years that had less than 40% maximum ice covers for Lake Superior are the 1965 and 1975 winters, when the lake was estimated to be 31 and 30% ice covered, respectively.

c. Lake Michigan

Lake Michigan has the longest north-to-south axis (494 km) of the five Great Lakes. Ice formation on the northern half of the lake starts earlier, lasts longer, and is more extensive than it is on the southern half of the lake. Ice cover usually forms first during the last half of December in shallow shore areas located in the northern end of the lake. Ice formation occurs along the entire lake perimeter in January and the first half of February. From the second half of Feb-

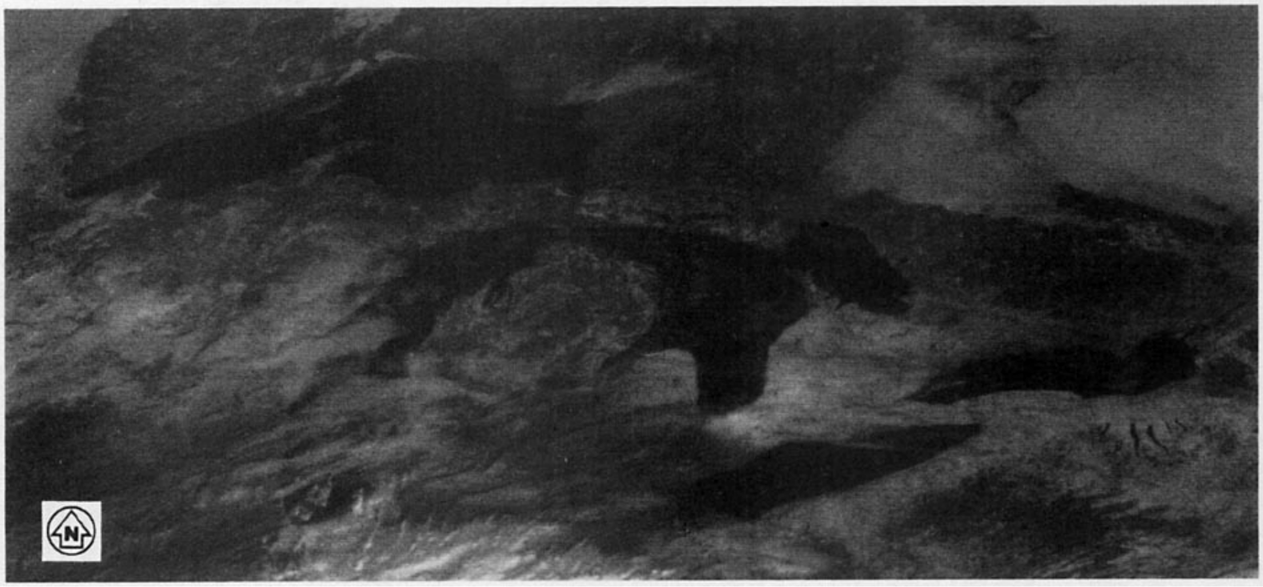

FIG. 4a. GOES VISSR (visible) image for 21 January 1983. Note ice covers in shore areas: Lake Superior (Thunder Bay, Black Bay, Nipigon Bay, Apostle Islands, shore of Whitefish Bay), Lake Michigan (portions of Green Bay, the Straits of Mackinac westward), Lake Huron (the St. Marys River, Straits of Mackinac eastward, portions of North Channel, Georgian Bay, Saginaw Bay, lakeward of other shores).

ruary through the middle of March, ice forms in the open lake. The lake usually attains its greatest seasonal ice cover extent the last half of February. Ice formation usually ends on the southern half of the lake by mid-March, while below freezing air temperatures prolong the ice formation period on the northern half of the lake through the end of March. Ice cover also begins to deteriorate in March as longer and more intensive thaw periods gradually advance from the southern to the northern end of the lake as the month progresses. By the middle of April, the bulk of the ice left in the lake is located once more in shallow shore areas at the north end of the lake. Ice in these areas can last through the end of April.

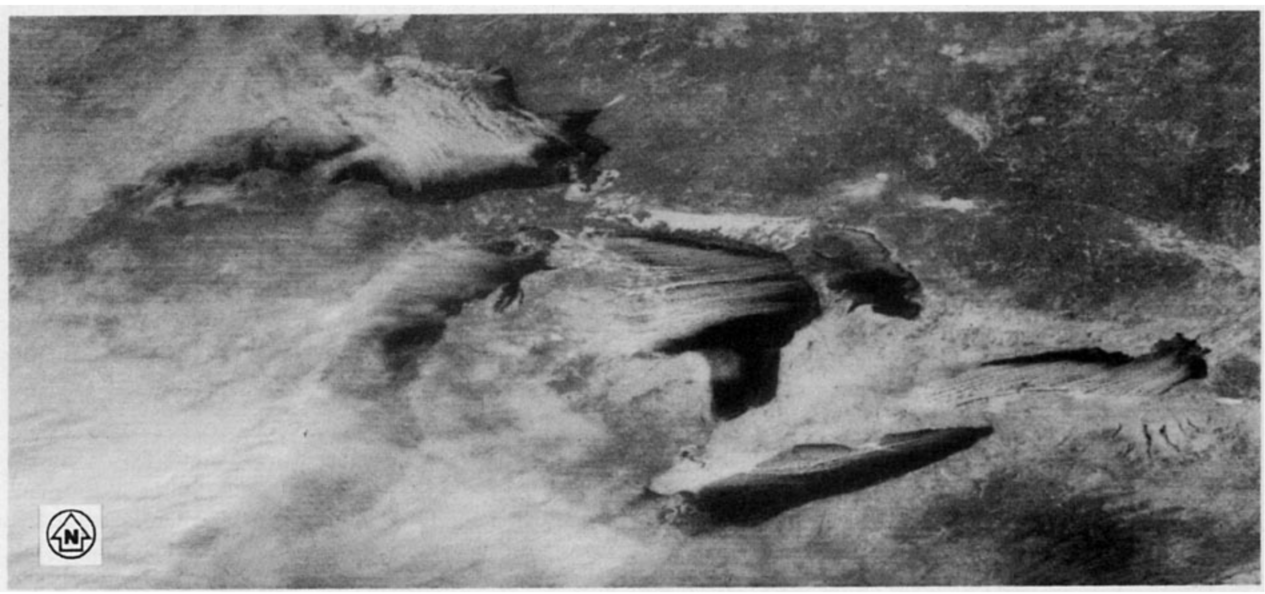

FIG. 4b. GOES VISSR (visible) image for 10 February 1983 showing ice cover still confined primarily to shore zone: Lake Superior (Apostle Islands, southeast shore and Whitefish Bay), Lake Michigan (Straits westward, Green Bay), Lake Huron (St. Marys River, North Channel, much of Georgian Bay, Saginaw Bay, the entire lake perimeter), Lake St. Clair (almost completely covered), Lake Erie (the west end of the lake and possibly along north shore), Lake Ontario (the Bay of Quinte and the extreme northeast section of the lake.)

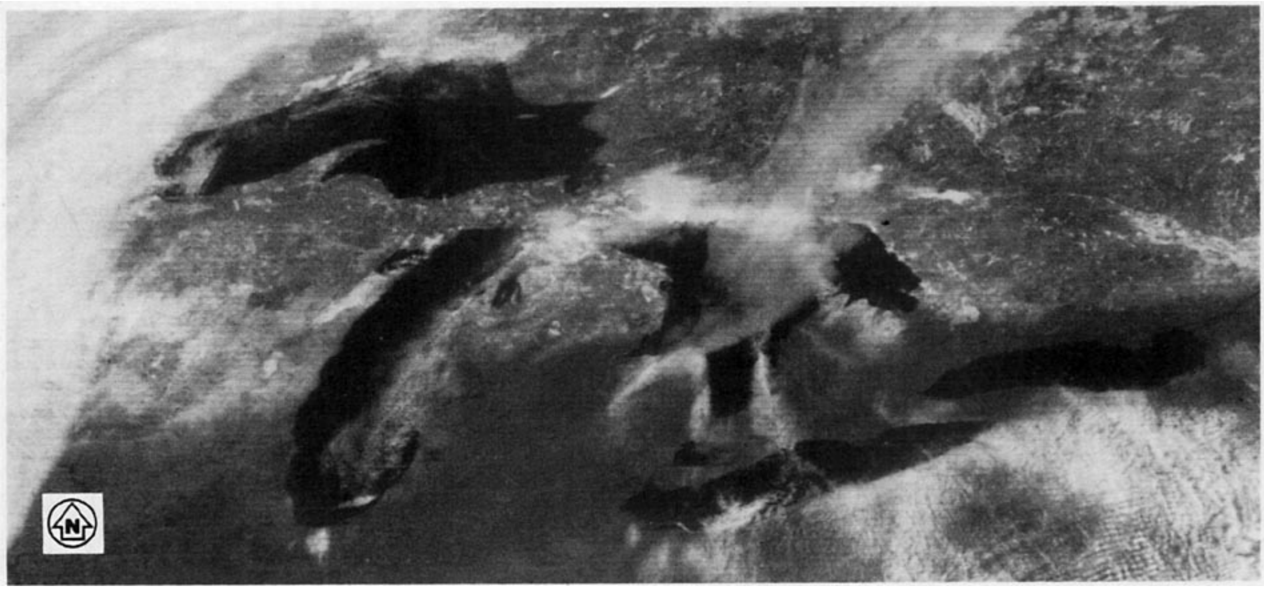

FIG. 4c. GOES VISSR (visible) image for 26 February 1983. Ice is observed in Lake Superior (the three north central bays, eastern half of Whitefish Bay), Lake Michigan (Green Bay—with large area of open water or new ice in north end the Straits of Mackinac westward) Lake Huron (St. Marys River, Straits of Mackinac eastward, North Channel, shore of Georgian Bay, Saginaw Bay now showing open water or new ice along west shore), Lakes St. Clair, Erie, Ontario (ice deteriorating rapidly).

The Lake Michigan ice cover was estimated to be at its greatest areal extent for the 1983 winter on 8 February. On that date the lake was estimated to be 17% ice covered. This is about one-third the normal maximum ice cover of 45%. The only other winters with seasonal maximum ice cover of less than 20% during the last 20 years were 1964 (13%), 1966 (15%) and 1969 (15%).

d. Lake Huron

Lake Huron, excluding Georgian Bay, is similar to Lake Michigan in that its major axis is in a north–south direction, facilitating ice formation and ice loss simultaneously at the north and south ends of the lake during late winter and early spring. This lake is the second shallowest of the Great Lakes, deeper only than Lake Erie. Saginaw Bay to the south and the North Channel, the shore areas of Georgian Bay and the Straits of Mackinac to the north begin to form ice covers in December. Most of these areas, excluding the deeper section of Georgian Bay, by mid-January, are 90 to 100% ice covered. Ice formation continues in embayments and along the more exposed areas of the lake perimeter during the last half of January and the first half of February. Georgian Bay usually becomes 90% ice covered the first half of February. Significant ice formation in the deep midlake areas of Lake Huron begins the second half of February and the ice cover is normally at its seasonal maximum extent during that period. Ice covers in midlake and the southern end of the lake begin to decline the first half of March. Bay and harbor ice covers usually start to break up the second half of that month. The midlake area is usually ice free by the first half of April and the main body of ice remaining in the lake by mid-April is usually located in the North Channel and Georgian Bay at the northern end of the lake and against windward shores along the entire length of the lake. Ice covers continue to dissipate the second half of April and into early May, ending the ice season.

The seasonal maximum ice extent on Lake Huron in 1983 occurred near 8 February, when the lake was estimated to be 36% ice covered. This is about half the normal maximum seasonal ice cover extent of 68%. Georgian Bay did not form a 90% ice cover the first half of February as it normally does, and the midlake area did not form significant ice cover the second half of February as it normally does. The only other winters during the past 20 years with less than 40% ice cover on Lake Huron include the winter of 1964 (34%) and the winter of 1966 (29%).

e. Lake St. Clair

This lake has a mean depth of 3.6 m and a surface area of only 1113 km^2, putting it in a different class of lake relative to the five Great Lakes. Discussion of Lake St. Clair ice cover is included here because this lake is part of the connecting link of waterways between Lake Huron and Lake Erie. Diurnal air temperature changes can cause significant ice cover changes over virtually the entire lake's surface area

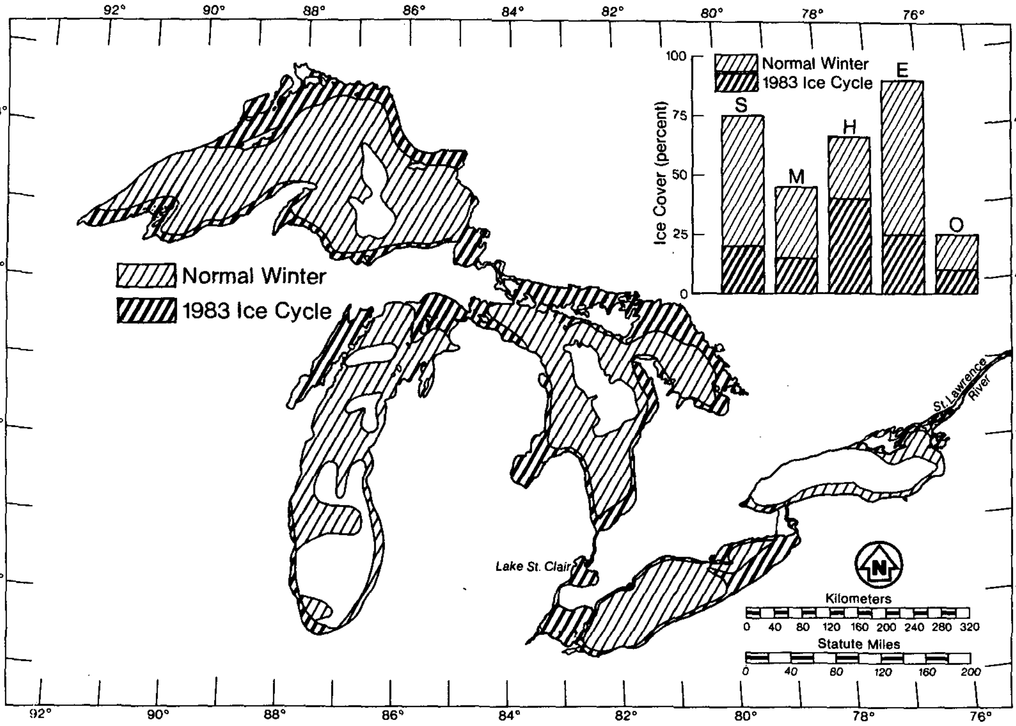

FIG. 5. Estimated maximum ice cover for 1983 compared to normal maximum ice cover modified from Assel *et al.* (1983). Maximum ice cover in 1983 occurred the first half of February; it normally occurs the second half of the month. Normal and 1983 estimated seasonal maximum ice covers are: Lake Superior 75% (21% in 1983), Lake Michigan 45% (17% in 1983), Lake Huron 68% (36% in 1983), Lake Erie 90% (25% in 1983), and Lake Ontario 24% (10% or less in 1983).

because Lake St. Clair is so shallow and small compared to the Great Lakes. Lake St. Clair is normally near 100% ice covered in January and February and about 75% ice covered the first half of March. It normally loses most of its ice cover the second half of March.

During winter 1983, initial ice formation is estimated to have occurred the second week of December. The periods of extensive ice cover included the first week of January, 18–21 January, and most of the second and part of the third week of February. The lake was estimated to be 70% or greater ice covered during these periods. Mild air temperatures the second half of February brought an abrupt halt to any further significant ice formation. And Lake St. Clair was virtually ice free by March 11.

f. Lake Erie

This is the shallowest of the Great Lakes, with a mean depth of only 19 m. Its shallow west basin is usually the first midlake area of the lake to form ice, and the deep east basin is usually last. The western end of the lake is also first to lose its ice cover and the eastern end the last because this lake is oriented with its length axis approximately parallel to the prevailing westerly winds.

The first half of January the lake west of Point Pelee is usually 90% or more ice covered. The midlake basin between Point Pelee and Long Point usually becomes 70–90% ice covered the second half of January. In February the entire lake is normally 90–100% ice covered and at its greatest areal ice extent for the winter. By the end of the second half of March, the western half of the lake is usually ice free and the lake is only 26% ice covered. The remaining ice cover east of Long Point is gradually dissipated over the next month and normally covers only 3% of the lake by the end of April.

Lake Erie was estimated to be near its seasonal maximum ice cover extent 8 February 1983, when approximately 25% of its surface area was ice covered. The next lowest maximum ice cover over the past 20 years occurred during the winters of 1975 (80%) and 1969 (80%). Thus, the 1983 ice cover is virtually without parallel over the period of well-documented ice cover and so establishes a historic benchmark of minimum ice cover extent for a given winter season for at least the past two decades.

g. Lake Ontario

Lake Ontario has the second greatest mean depth of the five Great Lakes and the smallest surface area.

Its southerly and easterly exposure provides it with milder air temperatures relative to Lake Superior and the northern portions of Lakes Michigan and Huron. The large heat reservoir of this lake and relatively mild air temperatures combine to produce the least extensive ice cover of the five Great Lakes. Ice cover usually forms first in the Bay of Quinte and the embayments along the northeastern shoreline. By the end of January, the shore areas and northeastern section of the Lake form an extensive ice cover, but the midlake area of the Lake remains relatively ice free for the entire winter. The maximum seasonal ice extent usually occurs the second half of February, when the Lake is normally 24% ice covered. By 15 March the Lake is usually only 10% ice covered and a month later, 15 April, the lake is virtually ice free.

Due to the extremely mild weather during winter 1983, there was no regularly scheduled observation of ice cover extent on Lake Ontario. However, a limited number of observations were made during the month of February. From these observations and air temperature records at Kingston, Ontario, it is estimated that the maximum seasonal ice cover extent on Lake Ontario occurred during the second week of February and that during that week ice was present in the shore zone in the vicinity of Burlington, Ontario, in the western end of the lake and in the Bay of Quinte and the head of the St. Lawrence River in the northeastern section of the lake. While no calculations of percentage ice cover were made because of this limited data record, it is safe to say that at most only 10% of the lake was ice covered. The winters with 10% ice cover or less on Lake Ontario during the past 20 years were those of 1965 (10%), 1968 (10%), 1969 (10%) and 1971 (10%).

5. Economic impact of a mild winter

The primary economic impact of the below normal ice cover on the Great Lakes relates to winter navigation, shore flooding, hydropower generation, and possibly shore erosion. During this past decade, attention has been given to extending the navigation season on the Great Lakes and St. Lawrence Seaway as a result of a Congressionally-funded program to demonstrate the feasibility of winter navigation on the Great Lakes (U.S. Army Corps of Engineers, 1979). During winter 1983, winter navigation would have been possible with only a minimal amount of ice breaking assistance for virtually the entire winter, resulting in savings in the hundreds of thousands of dollars in operating and fuel costs associated with ice breaking operations and aircraft costs for ice reconnaissance flights. The cost of operating an arctic-class U.S. Coast Guard ice breaker in the Great Lakes is $3,085 per hour, while helicopter operation cost for ice reconnaissance is $1,883 per hour (Lt. E. Funk, U.S. Coast Guard, Cleveland, Ohio, personal communication, 1984). During winter 1983, only five cases of direct U.S. Coast Guard assistance were made; this compares to 139 direct assistance cases in winter 1982 (U.S. Coast Guard, 1983). In spring, connecting channels of the Great Lakes and smaller rivers that feed into the lakes may become jammed with ice as the ice on the river moves downstream during the breakup period. When this occurs, there is always the potential for flooding upstream of the ice jam and the jam also impedes navigation and may also cause a reduction in hydropower generating capacity. The U.S. Coast Guard did not report any ice-jam breaking operations during the mild 1983 winter as ice cover on rivers was less than normal and the ice breakup period was earlier than normal. Thus there was a cost savings associated with the operational cost of ice breakers and ice reconnaissance aircraft. In sharp contrast, in 1984 a major ice jam did form on the St. Clair River in late March and most of April and there was a prolonged disruption of navigation and also some flooding. Estimated navigation cost associated with the ice jam included 1.1 million dollars per day (U.S. Army Corps of Engineers, Detroit District, personal communication, 1984). There was also the cost of operating ice breakers on the river for nearly one month in 1984.

Ice control structures such as the ice boom located at the east end of Lake Erie, described in International Niagara Working Committee (1983), near the head of the Niagara River are installed each winter to aid in forming a stable ice cover upstream of hydroelectric power plants and thus help prevent or reduce the severity of ice-related problems such as the 1984 ice jam on the St. Clair River. The average annual cost savings in hydrogenerating capacity associated with the ice boom at the head of the Niagara River is estimated to be 414 000 megawatt hours of electric energy (International Niagara Working Committee, 1983). Thus in mild winters, such as 1983, when ice control structures may not have been needed, this potential electric energy cost savings is directly related to the below-normal ice cover. And, although it is difficult to assess the dollar amount savings, the average annual savings in electric energy noted above can be used to give a "ball park" estimate of the potential savings. There were no reported ice-related hydroelectric power generating capacity losses in winter 1983 on the St. Marys, Niagara, or St. Lawrence Rivers as indicated by annual reports by U.S. Army Corps of Engineers (1983), International Niagara Working Committee (1983) and St. Lawrence Power Project Report on Winter Operations 1982–83 (1983).

A certain type of shore ice formation, called an ice foot, described by Zumburge (1953), acts as a protective barrier against high energy waves that would otherwise cause shore erosion. The formation of ice foots has been documented along the southeastern shore of Lake Superior by Marsh *et al.* (1973), along the central shore of Lake Michigan, and the southern end of that lake by Evenson (1973) and Seibel *et al.* (1976), respectively, and along the south shore of Lake Erie by Fahnestock *et al.* (1973). Shore erosion in many of the above areas has been reported in winter 1983 (Martin Jannereth, Michigan Department of Natural Resources; Donald Guy, Ohio Department of Natural Resources; personal communications, 1983) indicating that ice foot formation in these areas in winter 1983 was below normal. However, the economic impact of the shore erosion in winter 1983 is difficult to assess because of the lack of systematic measurement and documentation of shore erosion rates in most of the above areas in 1983 and prior years.

6. Summary and observations

The 1983 Great Lakes winter was exceptional because of the high air temperatures that resulted in one of the mildest winters during the past 200 years. Ice cover on the Great Lakes was at or near record low amounts on all five Lakes. The economic impact of the mild winter would have been much greater had the U.S. economy been stronger; in the winter of 1983 the economy was in a period of recession. This is particularly true for winter navigation where the cost savings associated with operational support activities such as ice breaker assistance and ice reconnaisance would have been large as indicated in the per hour operating costs of ice breakers and reconnaisance aircraft given in the previous section.

There were three relatively long periods of low air temperature favorable for ice formation during winter 1983. The first period was associated with the passage of high pressure centers over the Great Lakes 16–21 January; the second period of sustained low temperatures, 8–12 February, was associated with an anticyclone centered over James Bay that drifted slowly eastward. The third period of low temperatures, 22–26 March, was associated with an anticyclone that followed the passage of a late winter cyclone that produced high winds and significant snowfall over the Great Lakes.

Bay and harbor ice formation begin the second week of December. Mild air temperatures in December, much of January and February, and March confined significant ice formation to the shore zone of the Great Lakes. Ice usually forms in the midlake areas of the Great Lakes in February and March and normally reaches its greatest areal extent the second half of February. However, during February and March 1983, periods of ice formation alternated with prolonged periods of ice decay, resulting in much below-normal ice cover in this two month period. The main body of water in each of the Great Lakes and much of the shore zone as well was ice free by the end of the first week of March, virtually ending the 1983 ice season, although the cold spell in the last week of the month did produce some short-lived new ice cover on Lake Superior and the northern portions of Lakes Huron and Michigan. By the end of the third week of April, the Great Lakes were ice free except for some bay and harbor ice along the northern shore of Lake Superior, ending one of the mildest ice seasons during the past 20 years.

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