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GREAT LAKES WINTER WEATHER
AND ICE CONDITIONS FOR 1982-83

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GREAT LAKES WINTER WEATHER
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Raymond A. Assel, C. Robert Snider†, and Reginald Lawrence*

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. An extremely strong Aleution low that persisted most of the winter was associated with the mild temperatures in the United States. 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%). The 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

Since the early 1960's, the annual Great Lakes ice cycle has been systematically documented 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

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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 figure 1 or in other figures.

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 phenomenon that accompanied it. A detailed description of the climatic significance of that winter is given by Quiroz (1983). Here we will 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 much of the northern hemisphere, with near-normal to slightly 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, with many minor perturbations.

In the Pacific, anomalously warm water (fig. 3) associated with the weak coastal current off Peru and Ecuador (El Niño) dominated the tropical regions and contrasted strongly with the normally cold water of the higher latitudes (Quiroz, 1983). 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 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).

The monthly circulation pattern for the northern hemisphere for November 1982 through April 1983 is illustrated in figure 4; it shows 700-mb heights and departures from normal. The flow pattern over all of the northern continents 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 centered somewhat southeast of its normal position. There were also very significant, though not quite as extreme, anomalies in the

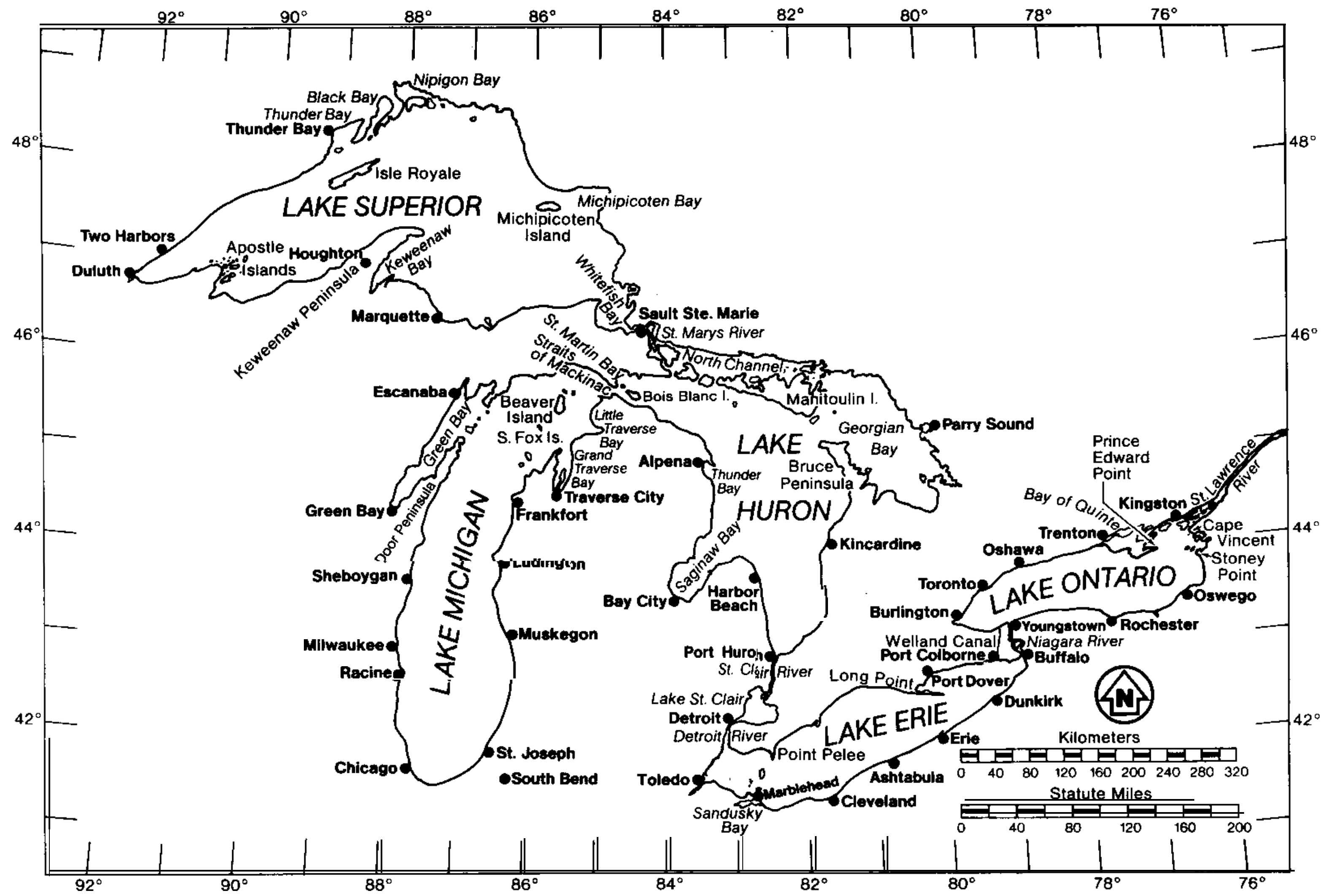


FIGURE 1.--*Place names a the Great Lakes.*

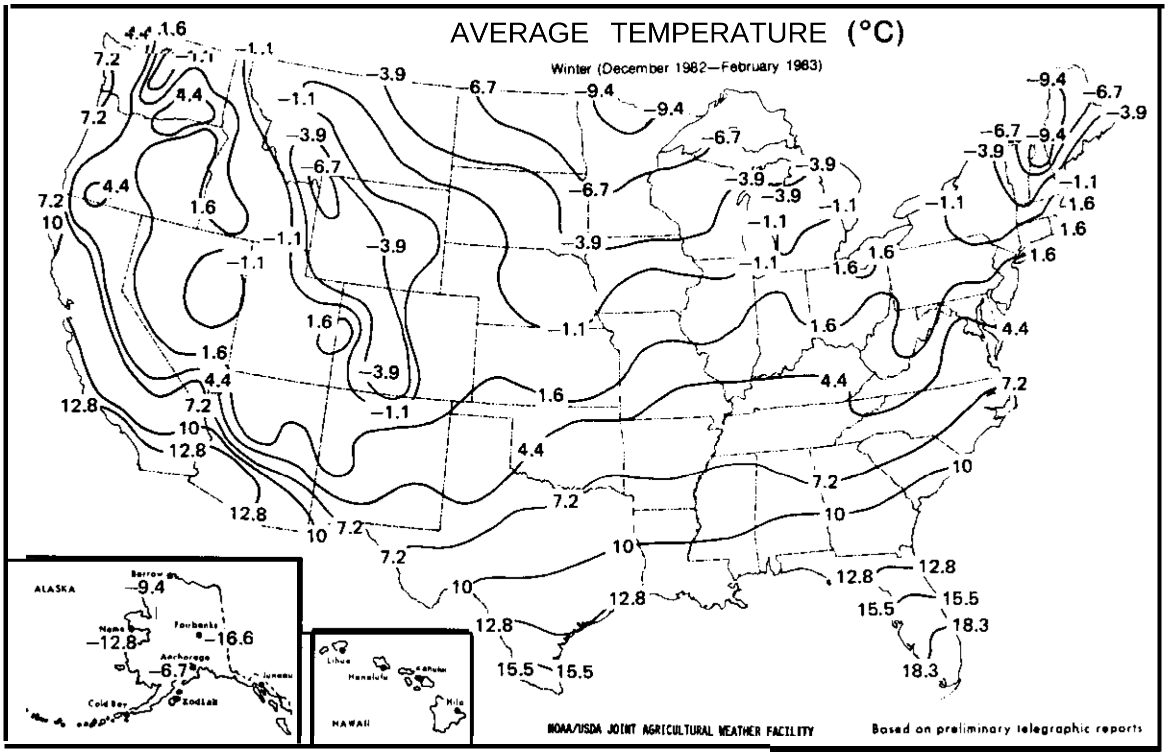


FIGURE 2a .--*Average winter temperature (°C), December 1982-February 1983.*

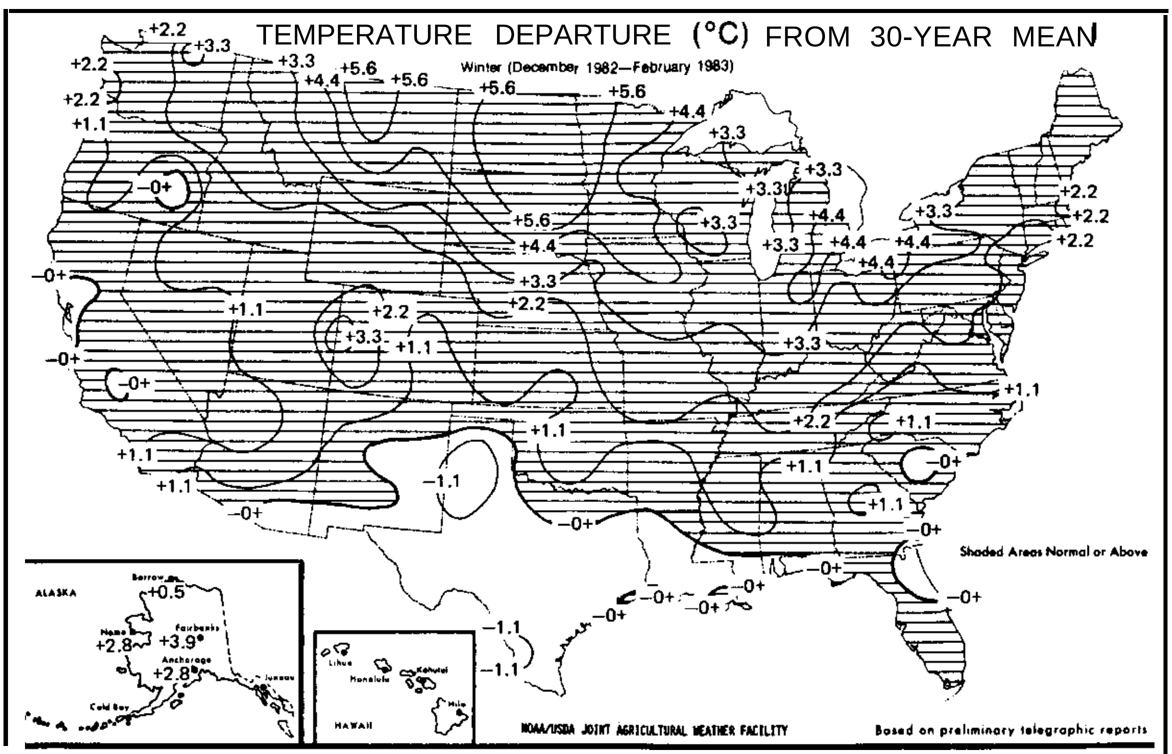


FIGURE 2b.--*Winter temperature departure (°C)* from a *30-year* mean. *Information* on figure 2 *is modified* from Weekly Weather and Crop Bulletin, vol. *70, no. 11, March 15, 1983.*

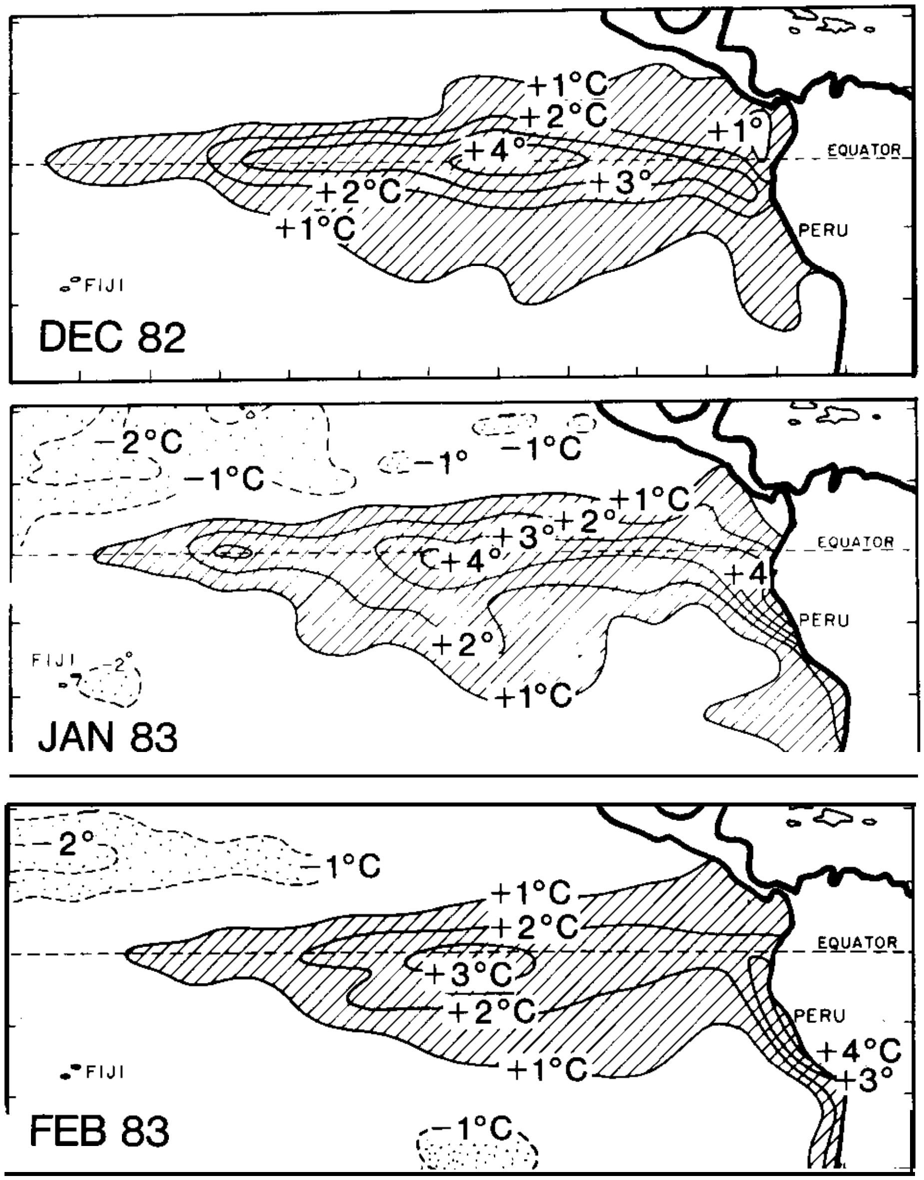


FIGURE 3.--*Anomaly* of *sea* surface *temperatures (°C)*, Pacific Ocean, *(a) December 1982, (b) January 1983, (c) February 1983,* **modified** *from* Storm Data, *vol.* 24-25, no. *12-1,2*.

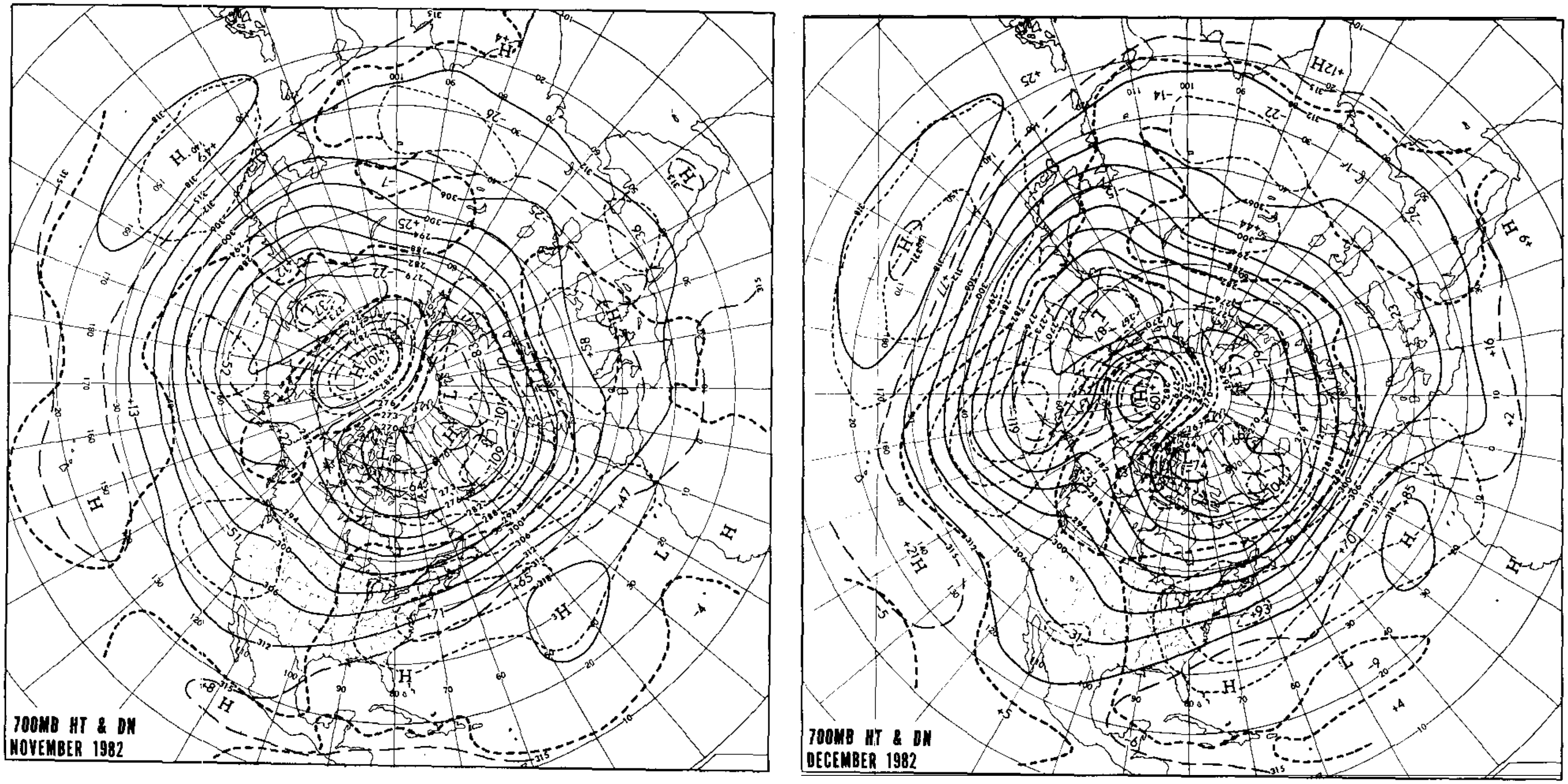
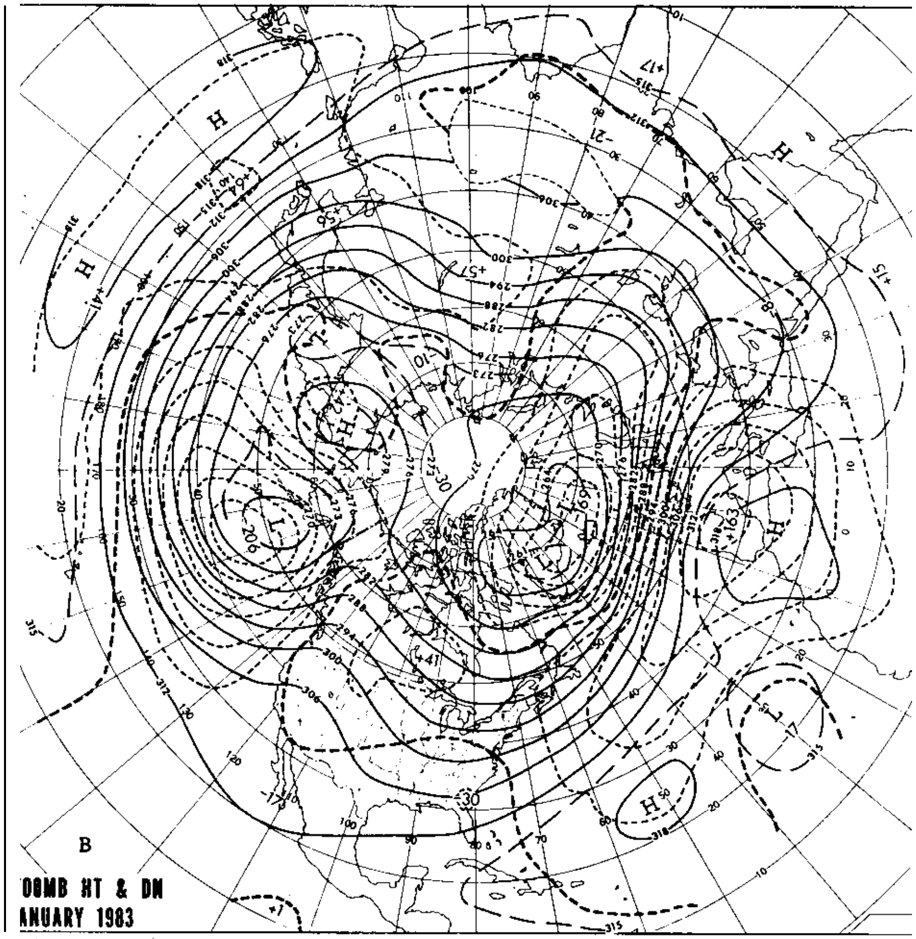


FIGURE 4.--*Mean contours of the 700-mb surface (meters x10 above sea level) and departure from normal, November 1982 to April 1983 (from Climatic Analysis Center, National Weather Service).*



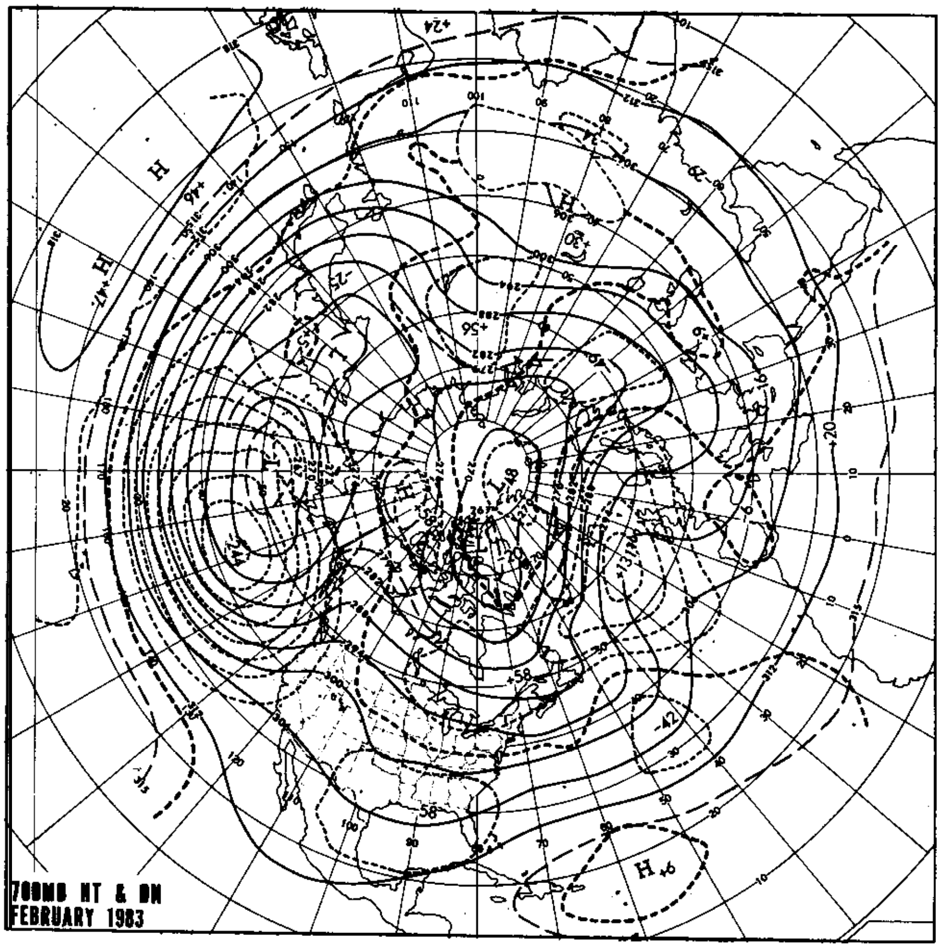


FIGURE 4.--*Mean contours of the 700-mb surface (meters x10 above sea level) and departure* from *normal, November 1982* to *April 1983* (from *Climatic Analysis Center, National Weather Service) (cont.).*

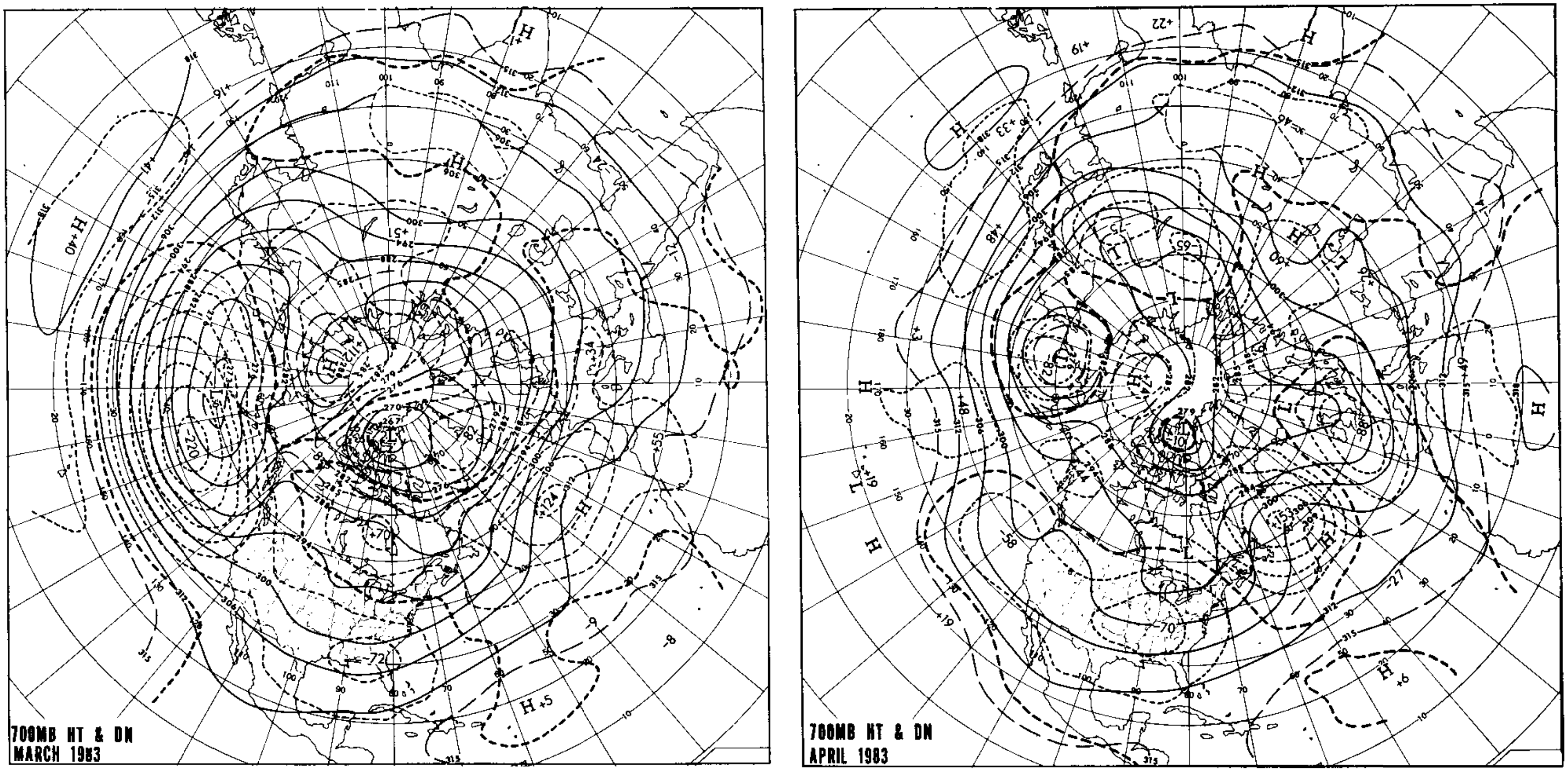


FIGURE 4.--*Mean contours of the 700-mb surface (meters x10 above sea level) and departure from normal, November 1982 to April 1983 (from Climatic Analysis Center, National Weather Service) (cont.).*

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.

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 "ear normal, however, except around western Lake Superior, where a" abnormally high percentage of precipitation 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 March 21, 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

3.1 Monthly Mean Temperatures and Their Anomalies

Winter started early around Lake Superior. Below-normal November temperatures in that area are the only negative anomalies listed in table 1. The contrast between cold air masses over Lake Superior and warmer air masses in the south and east produced a storm track that brought major snow storms to the lake on October 20-21 (fig. 5a) and on November 11-12 (fig. 5b). Although warmer air advanced over all of the lakes during December, a brief reestablishment of this patter" brought another similar storm on December 27-28 (fig. 5c).

Extraction of heat from the lake water to melt all this snow, in addition to the early season low air temperatures and the persisting snow cover on the surrounding land, seemed to augur a severe ice season on Lake Superior, but it was not to be. The strong positive air temperature anomaly that 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 averaged above normal everywhere, though by the end of that month considerably colder weather had set in.

3.2 Freezing Degree-Days

The accumulation of freezing degree-days (FDD's) began early--November 3 at Duluth, MN, and November 4 at Marquette, MI. By the end of November,

TABLE 1.--*Monthly mean* air *temperature and* anomalies

	November 1982		December 1982		January 1983		February 1983		March 1983	
	Mean C° (F°)	Anomaly C° (F°)	Mean C° (F°)	Anomaly C° (F°)	Mean C° (F°)	Anomaly C ° (F)	Mean C° (F°)	Anomaly C° (F°)	Mean C° (F°)	Anomaly C° (F°)
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)

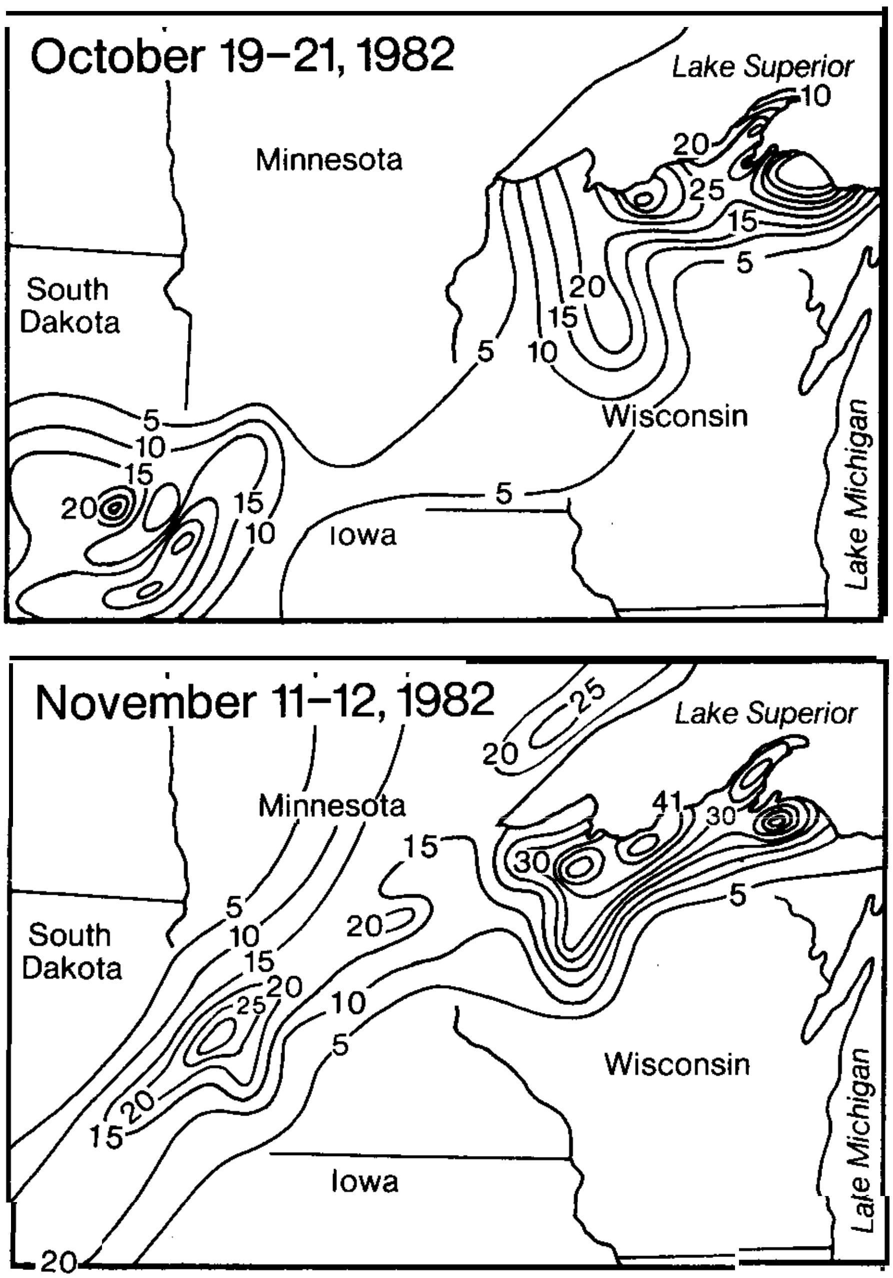


FIGURE 5.--Upper midwest snow in centimeters (a) October 19-21, 1982, (b) November 11-12, 1982, (c) December 27-28, 1982, modified from Storm Data, vol. 24, no. 10-12.

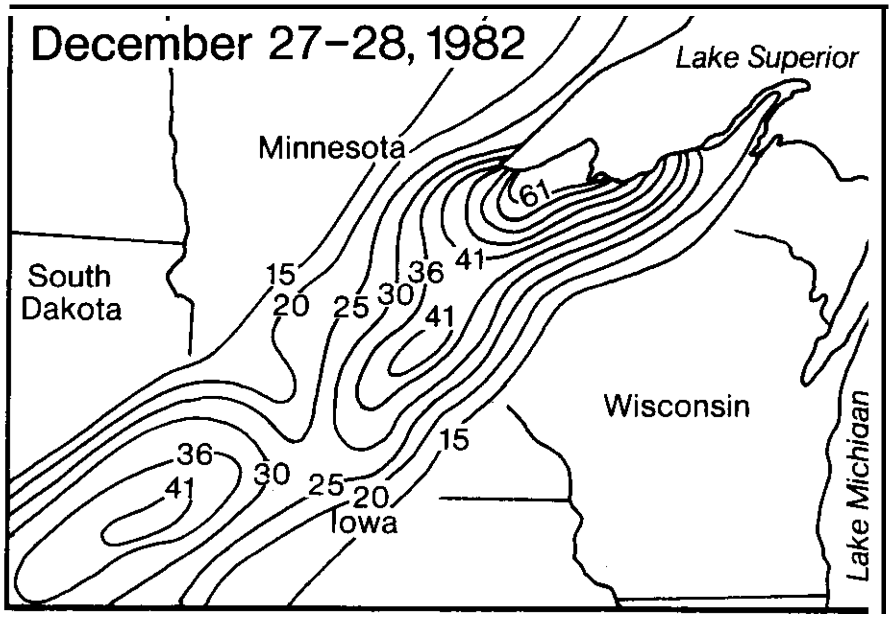


FIGURE 5.--*Upper midwest snow in centimeters (a) October 19-21, 1982, (b) November 11-12, 1982, (c) December 27-28, 1982, modified* from Storm Data, *vol.* 24, no. *10-12 (cont.).*

accumulations were 198% of normal at Duluth; 68% at Sault Ste. Marie, MI; 164% at Green Bay, WI; and 230% at Alpena, MI. As usual, there were at this time no accumulations of FDD's at more southerly locations.

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

On February 13 or 14, stations throughout the lakes reached peak FDD accumulations, averaging about half the normal. 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 March 21, significant accumulations began again at northern stations, and higher peaks were reached there on March 30 or 31. 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; they 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.

TABLE 2.--Freezing degree-days for winter 1982-83

station	Maximum FDD's °C	(°F)	Date	Normal maximum °C	(°F)	% of normal	Normal date	Winter severity class*
Duluth, MN	929	(1672)	3/30	1267	(2281)	73	4/02	MN
Marquette, MI	703	(1265)	3/30	--	--	--	--	--
Sault Ste. Marie, MI	634	(1141)	3/23	1008	(1814)	63	4/03	M
Green Bay, WI	366	(659)	3/30	790	(1422)	46	3/21	M
Milwaukee, WI	186	(335)	2/13	500	(900)	37	3/10	M
Chicago, IL	167	(301)	2/13	--	--	--	--	--
Muskegon, MI	141	(253)	2/13	370	(666)	38	3/11	M
Alpena, MI	326	(587)	3/31	670	(1206)	49	3/28	M
Detroit, MI	107	(192)	2/14	--	--	--	--	--
Toledo, OH	143	(258)	2/14	307	(553)	47	3/10	MN
Cleveland. OH	71	(128)	2/13	246	(443)	29	3/02	MN
Buffalo, NY	161	(290)	2/14	361	(650)	32	3/11	MN
Rochester, NY	154	(277)	2/14	364	(655)	42	3/11	MN

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

Using that classification on 10 stations, the winter was classified as mild at 5 stations and as milder than normal at the remaining 5 stations.

3.3 Comparison With Previous Winters

In an earlier study (Quinn et al., 1978), Snider defined an index of winter severity. This index combines monthly mean temperatures from November through February at Duluth, Sault Ste. Marie, and Detroit, MI, and Buffalo, NY. The index was found to correlate strongly with the mass of ice formed on the Great Lakes during an unusually cold winter. Details given below suggest that the correlation is not quite so high in a mild winter. Nevertheless, for the sake of uniformity, indices were calculated by the method described in that earlier study for all the mild winters between 1783 and 1983. The 20 warmest (first decile) years of the two centuries are tabulated in table 3. Note that 1982-83 was the 10th 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. For the coldest 10%, they range from -6 to -9. Each of the winters that proved to be warmer than 1982-83 is described briefly below in order of their rank.

3.3.1 winter 1931-32

January 1932 was the warmest in history at Buffalo, Detroit, and Sault Ste. Marie. February was the ninth consecutive month of above-normal temperatures throughout the Great Lakes. The 1931 shipping season closed December 16, with the crew on the final ship reporting no ice between Duluth and Cleveland. At the end of February, the Straits of Mackinac were still "pen and there was no ice at all in the southern lakes.' This mildest of all winters ended abruptly with a severe cold frontal passage on March 7. March was the coldest month of the year, and well below normal temperatures persisted through April. Western Lake Erie and Lake St. Clair froze over on March 9, and new ice was observed everywhere. The last windrow across the head of the St. Marys River cleared on April 29.

3.3.2 Winter 1877-78

This winter was especially mild on Lake Superior. February was warmer at Duluth than at either Detroit or Buffalo. Ice cleared from Duluth harbor February 18, and the first ship arrived March 17. Marquette Harbor was only intermittently ice covered during January and February. Lake Michigan, except Green Bay, was ice free throughout the winter. The Port of Escanaba opened March 5 and Green Bay was ice free by March 16. The first transit of the straits, on March 15, encountered no ice. Lower Great Lakes ports opened early. Buffalo was ice free from February 28.

3.3.3 Winter 1881-82

Mean temperatures during December 1881 and February 1882 were the highest recorded during those months in 156 years of observations at Detroit. Navigation was essentially unhindered except for minor problems on Lake superior. Ports opened whenever cargoes were ready, beginning at Alpena on March 2. Ice disappeared from Duluth and Marquette Harbors by March 3, but was encountered drifting on Lake Superior until at least March 20.

3.3.4 Winter 1850-51

November was very warm, and the below-normal temperatures of December failed to produce much ice. January was stormy, with rapid variations in temperature. Well above normal mea" temperatures in January were followed by

TABLE 3.--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	-0.3	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.

progressively larger positive departures from normal in February and March. By the time any prudent mariner was ready to venture onto the lakes, no significant ice remained.

3.3.5 Winter 1918-19

The winter months all had above-average temperatures. Lake Erie ports were never closed by ice. Ice at Duluth and Sault Ste. Marie was much thinner than normal. By March 27 nearly all of the ice was gone from the upper Great Lakes. The Soo Locks opened on April 9.

3.3.6 Winter 1889-90

A ship arrived at Milwaukee, WI, from Port Huron, MI, on January 6. The straits were still open January 31. The first ice appeared on Soo Harbor January 9. Thunder Bay had intermittent partial ice cover from January 16, but did not freeze over until March 15. The Port of Alpena opened March 31. Regular service between Detroit and Cleveland began February 28. The straits froze over April 1 and opened April 16.

3.3.7 Winter 1952-53

A voyage from Detroit to Ashtabula, OH, was made on February 10, 1953. This is the mildest winter for which aerial reconnaissance is available. In late February, less than 20% of Lake Superior was ice covered; the other lakes had ice only near shore.

3.3.8 Winter 1948-49

The lower Great Lakes remained practically ice free throughout the winter. The straits never froze solid. The Soo Locks opened March 26, and Duluth Harbor opened March 27.

3.3.9 Winter 1930-31

Port openings everywhere were early. About 46 cm of fast ice formed in the Straits of Mackinac, and heavy windrowing caused local problems.

3.4 Typical Ice Conditions in a Mild Winter

In all of the winters discussed above, ice cover was minimal at the end of February. 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 as applicable to spring opening as it is to fall freeze-up.

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.

Eve" in the mildest winter know" on the Great Lakes, enough heat is extracted from the water by the end of February that ice can form quickly whenever FDD's 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--1889-90 and 1931-32--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

4.1 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 from ice charts (1) 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, ON, Canada, and (2) from satellite images made from the Geostationary Operational Environmental Satellite (GOES) and provided by the National Environmental Satellite, Data, and 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. 6). 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 in figure 7. A series of detailed ice charts that contain information on ice concentration and distribution patterns of the Great Lakes ice cover is available from NESDIS, National Snow and Ice Data Center, Boulder, CO, and from AES, Ice Branch.

4.2 Lake Superior

Ice cover on this most northerly and westerly of the Great Lakes is usually confined to bays, harbors, and the exposed lakeshore through the end of January. The areas in the shore zone where ice formation occurs in December and January are the waster" tip of the lake; the Apostle Islands; Nipigon, Black, and Thunder Bays along the north-central shore; Keweenaw Bay along the south-central shore; Whitefish Bay at the southeastern end of the Lake; and Michipicoten Bay along the east-central shore. During the first half of February, ice normally forms in the open lake area of the western half

FIGURE 6a.--GOES VISSR (visible) image for January 21, 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. Mary8 River, Straits of Mackinac eastward, portions of North Channel, Georgian Bay, Saginaw Bay, lakeward of other shores).

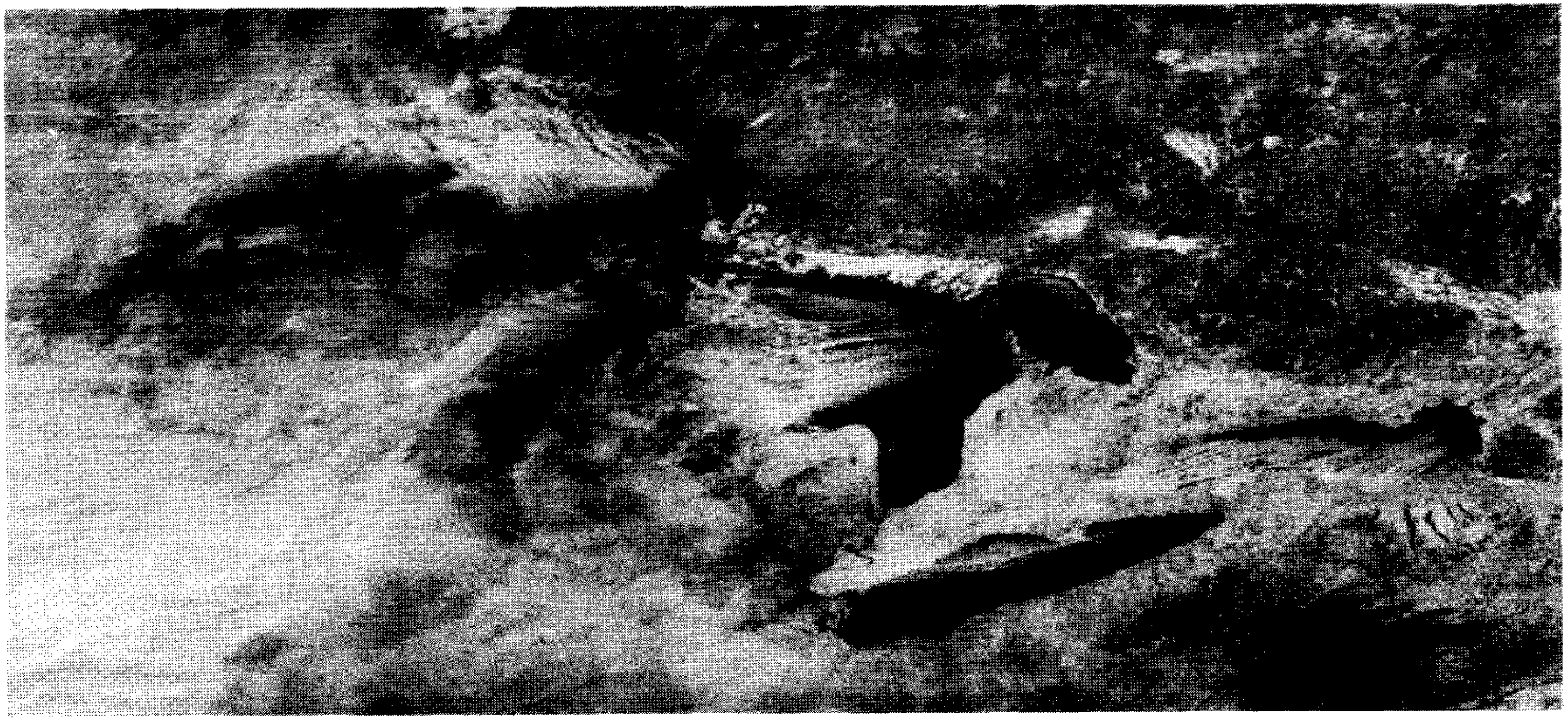


FIGURE 6b.--*GOES VISSR (visible) image for February IO, 1983. Ice cover is still confined primarily to shore* zone: *Lake Superior (Apostle Islands, southeastern shore, and Whitefish Bay), Lake Michigan (Straits* of Mackinac *westward, Green Bay), Lake Huron (St. Marys River, North* Channel, *much of* Georgian *Bay, Saginaw Bay, the entire* lake *perimeter). Lake St. Clair (almost completely covered), Lake Erie (the western* end of *the* lake *and possibly along the* northern *shore), Lake Ontario (the Bay* of *Quinte and the extreme northeastern section* of *the lake.)*

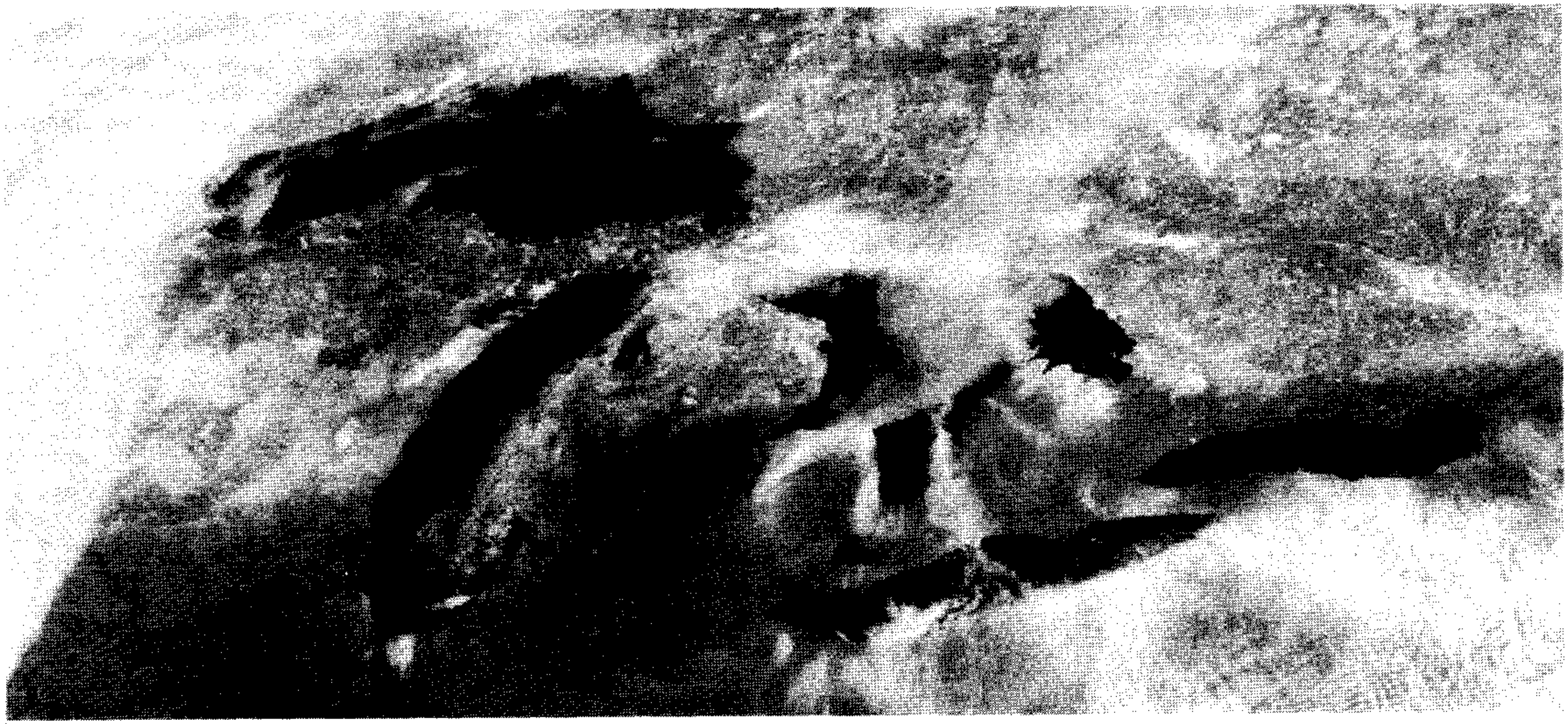


FIGURE 6c.--*GOES VISSR (visible) image* for *February 26, 1983. Ice is observed in Lake Superior (the three north-central bays, eastern* half of Whitefish *Bay), Lake* Michigan *(Green Bay--with large area* of open' water or new ice in the *northern end* of the *Straits* of Mackinac *westward), Lake Huron (St. Mary8 River, Straits* of *Mackinac eastward, North Channel, shore* of Georgian *Bay,* Saginaw Bay now showing open *water or new ice along the western shore), and Lake8 St. Clair, Erie, Ontario (ice deteriorating rapidly).*

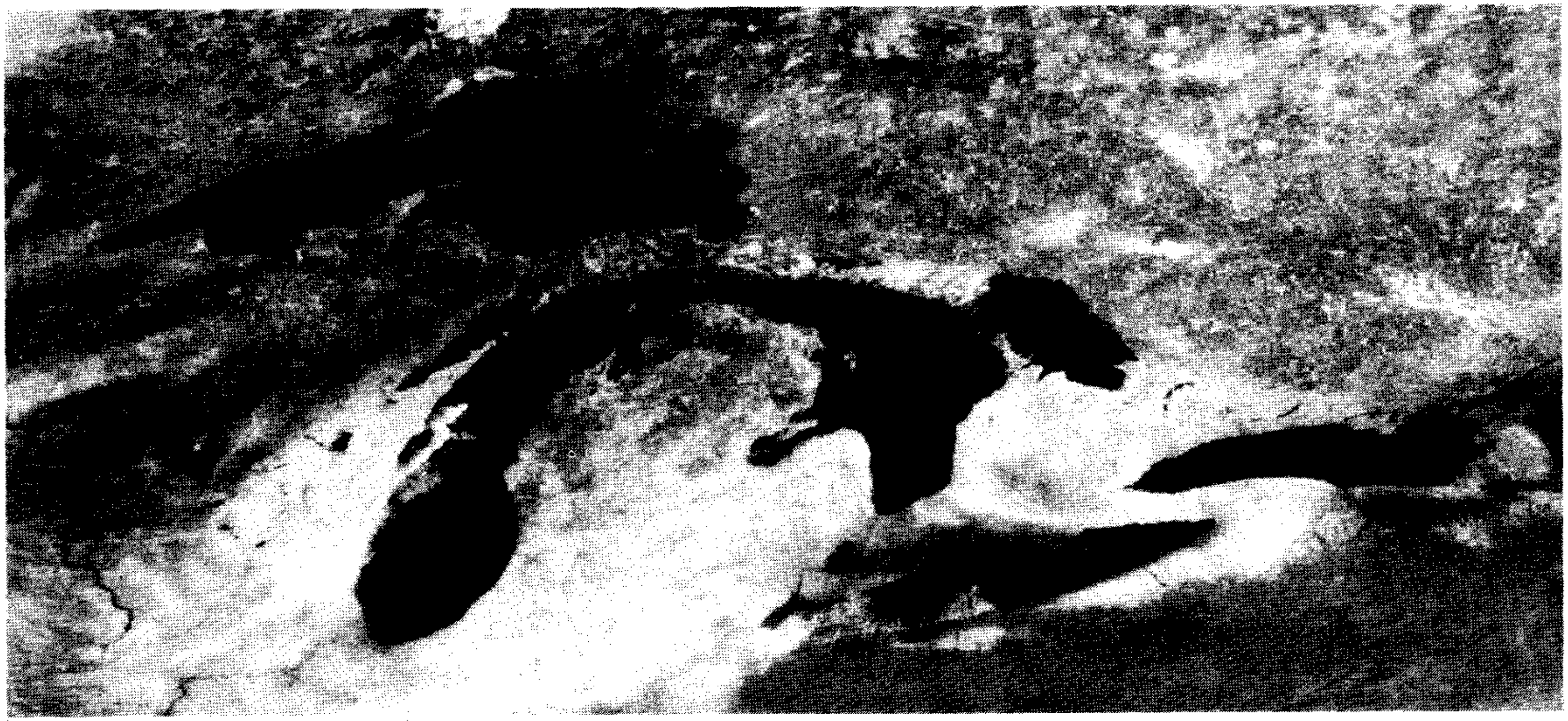


FIGURE 6d.--*GOES VISSR (visible) image* for *March 25, 1983. The remaining ice is confined to the northern Great Lakes: Lake Superior (south of Apostle Islands, between Isle Royal and the mainland, the three north-central bays, and in Whitefish Bay), Lake Michigan (northern and southern* shore area8 of Green *Bay, shore area* of *Strait8* of *Mackinac westward), Lake Huron (St. Mary8 River, Straits of* Mackinac *to Bois Blanc Island, North* Channel--ice now showing *signs* of *deterioration--northeastern* Georgian *Bay and shores* of *Saginaw Bay).*

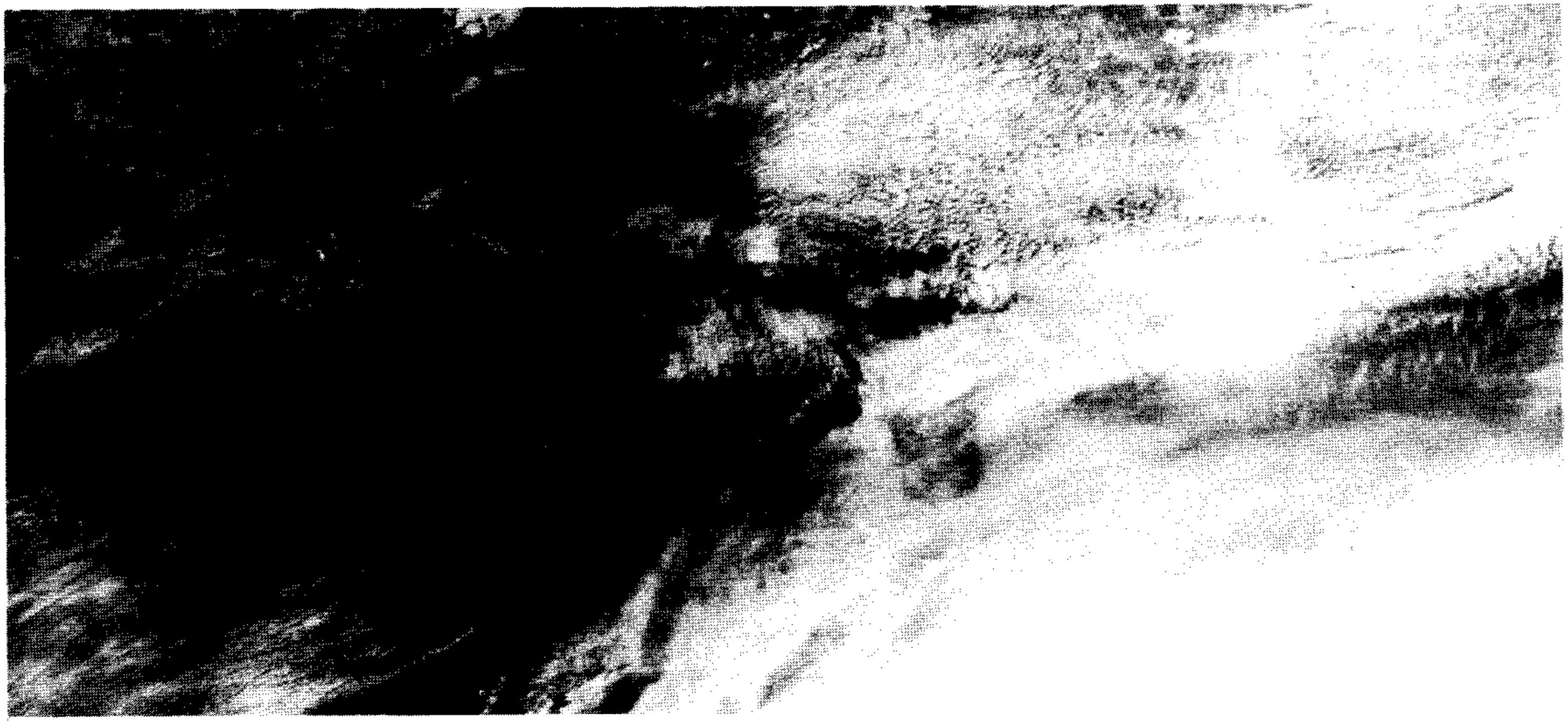


FIGURE 6e.--*GOES VISSR (visible) image* for *April 8, 1983. Lakes Superior and Michigan are virtually ice free except* for *the three north-central bays and south* of *the Apostle Islands on Lake Superior and the extreme northern and southern tips* of *Green* Bay *on Lake Michigan.*

FIGURE 6f.--*GOES VISSR (visible) image* for *April 20, 1983. The Great Lakes are virtually ice* free *(except for ice in Thunder, Black, and Nipigon Bays along the north-central shore* of *Lake* Superior).

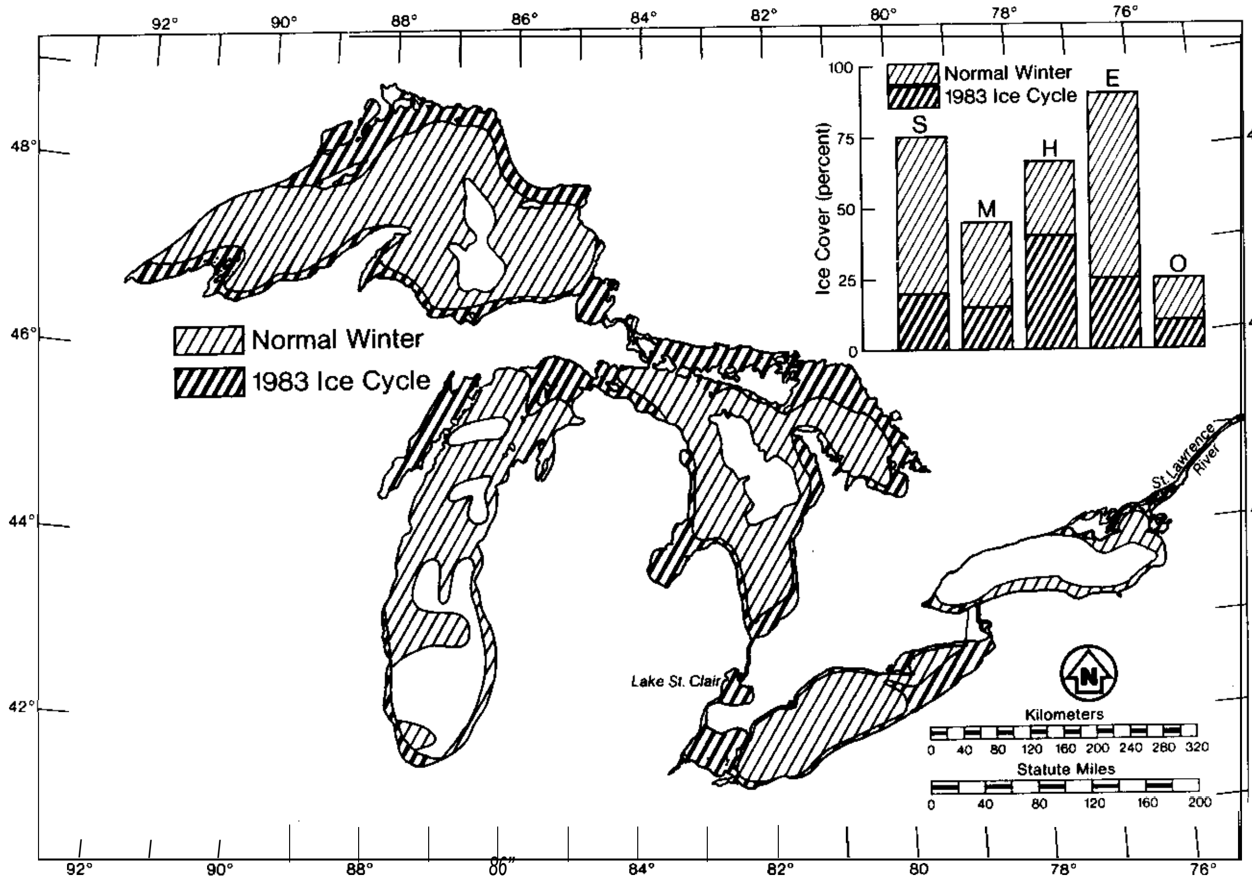


FIGURE 7.--*Estimated maximum ice* cover for *1983 compared to normal maximum ice cover* modified from *Assel* et al.*(1983). Maximum ice cover* in *1983 occurred the first* half of February; *it normally occurs the second* half of *the month. Normal and 1983 estimated* seasonal *maximum* ice cover8 are: *Lake* Superior *75% (21% in 19831, Lake Michigan 45% (17% in 19831, Lake Huron 68% (36% in 1983), Lake Erie 90% (25% in 1983), and Lake Ontario 24% (10% or less in 19831.*

of the lake. During the last half of February, ice normally forms in the deeper, eastern half of the lake. Although ice usually reaches its maximum area1 extent in the last half of February or early March, ice sometimes continues to form in the open lake through March. Midlake ice cover is usually dissipated by the second half of March or the first half of April. Bay and harbor ice can last into May.

The initial ice formation period in the shore zone of Lake Superior was discontinuous during the 1983 ice cycle as episodes of ice formation and increasing ice cover extent alternated with episodes of no ice growth and even some ice loss. Early in the new year, mild air temperatures and high winds reduced ice cover that had formed in December in such areas as Thunder Bay and Whitefish Bay. A large high-pressure center drifted across the Great Lakes from January 17 to January 20, bringing below-normal air temperatures and low winds--ideal ice-forming weather. Accordingly, ice cover in the shore zone of Lake Superior increased in most bay and harbor locations and along many exposed sections of the shoreline as well. There were two other episodes of mild temperatures centered around January 23 and January 29 and one period of below-normal temperatures centered around January 26. The net result was a" increase in ice cover along the southwestern shore from Duluth to the Keweenaw Peninsula, between Isle Royale and the mainland, and eastward from there along the northern shore to Marathon, ON. At the mouth of Whitefish Bay there was actually a net loss of ice cover. Generally below normal temperatures the first week in February brought new ice formation along the southeastern shore from Keweenaw Bay to Whitefish Bay and along the northeastern shore from Nipigon Bay to Michipicote" Bay. The existing ice cover in other areas of the shore zone increased in concentration or lakeward extent or both, but 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 February 8, 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%. Other winters during the past 20-odd years with similar 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.

Above-freezing air temperatures for much of the second and third weeks of February resulted in the loss of much of the existing ice cover. By the 22nd of February, most of the shore zone was ice free, with the exceptions of the Duluth vicinity and the Apostle Islands in the western end of the Lake, the lake between Isle Royale and the mainland and Thunder, Black, and Nipigon Bays along the north-central shore; and Keweenaw Bay and the shore areas of Whitefish Bay along the south-central and southeastern shores.

The abnormally springlike temperatures continued through the first week of March and effectively ended prospects for any significant new ice formation on Lake Superior. The deterioration and loss of existing ice covers continued so that by March 8 the bulk of existing ice cover on Lake Superior was located in the three northern shore bays and the Apostle Islands. Thus, during the first half of March, when Lake Superior is normally 67% ice covered, the lake was well under 10% ice covered, and much below the 20-year norm. A period of much below normal air temperatures, March 20-25, came too late to have any significant effect on the 1983 ice cycle. The existing ice covers on bays and harbors gradually deteriorated during April and early May, ending the mildest ice season on Lake Superior since the beginning of systematic observations of Great Lakes ice cover in the early 1960's.

4.3 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 that on the southern half of the lake. Ice cover usually forms first during the last half of December in Green Bay, in the shore area of the Straits of Mackinac, and in other 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, and during this period Green Bay and the Straits of Mackinac out to Beaver Island usually freeze over. From the second half of February through the middle of March, ice forms in the "pen lake. The lake usually attains its greatest seasonal ice cover extent the last half of February. The normal seasonal maximum ice cover is 45%. 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 progressively deteriorates throughout 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 Green Bay and from the Straits of Mackinac to Beaver Island. Ice cover in these and other shore areas can last through the end of April.

The 1983 Lake Michigan ice season began in a normal enough manner, with ice formation taking place in the shallow areas of Green Bay during the second week of December 1982. However, above-normal air temperatures during the last half of December prevented further significant ice formation. Air temperatures continued to be above normal over Lake Michigan during the first half of January. Despite the mild weather, an extensive ice cover formed over Green Bay. Assel et *al.* (1983) indicate that, during a 20-year base period (1960-79), the shallow waters of Green Bay have persistently formed ice cover during the first half of January; thus the 1983 ice cover was not unusual. Below-normal air temperatures and low wind speeds at Green Bay brought a new spurt of ice formation on the northern portion of Lake Michigan from January 16 to January 19. New ice formed from the Straits of Mackinac to Beaver Island during this time. The second half of January, however, brought above-normal daily average temperatures and daily maximum values of greater than 0°C (32°F), reducing the concentration of existing ice cover in Green Bay and the straits. There was little or no significant ice formation over the remainder of Lake Michigan. Two episodes of low air temperatures in the first week of February (February 4-5 and February 7-8) were associated with new ice formation in the northeastern section of the lake from Beaver Island to South Fox Island and along the southwestern shore from just north of Milwaukee to South Bend, IN.

The Lake Michigan ice cover was estimated to be at its greatest area1 extent for the 1983 winter on February 8. On that date the lake was estimated to be 17% ice covered. This is about one-third the normal maximum ice cover of 45%. Other winters with seasonal maximum ice cover of less than 20% include the winters of 1964 (13%), 1966 (15%), and 1969 (15%). The ice cover in northern Lake Michigan began to recede and decrease in concentration the second week of February. With the exception of 4 days, daily average temperatures at Green Bay were above freezing every day during the last half of February, and as a result, ice covers continued to decline. By March 1 there was a large area of open water at the mouth of Green Bay, and ice cover in the straits had receded to the north and to the east of the northern half of Beaver Island. Ice continued to melt in March because of continuing mild temperatures. One last episode of low air temperatures, March 22-25, produced a very transitory ice cover on Green Bay and perhaps other shallow areas of the lake, but for all practical purposes, the 1983 ice season was over. By March

25 the straits were virtually ice free. Ice continued to linger in the shore areas of Green Bay to about the middle of April. Green Bay was observed to be ice free on April 21, ending one of the mildest Lake Michigan ice seasons on record.

4.4 Lake Huron

Like Lake Michigan, Lake Huron (excluding Georgian Bay) also has its major axis in a north-south direction, facilitating ice formation at the northern end of the lake during early winter and ice loss at the southern end of the lake during early spring. This lake is the second shallowest of the Great Lakes, deeper only than Lake Erie. Typically, Saginaw Bay to the south and the North Channel and the shore areas of Georgian Bay and the Straits of Mackinac to the north begin to form ice covers in December. By mid-January most of these areas, excluding the deeper section of Georgian Bay, are 90-100% ice covered. Ice formation continues in embayments and along the more exposed areas of the lake perimeter 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. The lake is normally 68% ice covered at the time of maximum areal ice coverage. Ice covers in midlake areas and the southern end of the lake begin to decline the first half of March, while bay and harbor ice covers usually start to break up during the second half of the month. There is usually no ice in the midlake area by the first half of April. The main body of ice left 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.

During winter 1983, shore ice that had formed at the head of Saginaw Bay during the second half of December 1982 melted before the end of the month because of above-freezing air temperatures. Average daily air temperatures at Alpena remained above normal through mid-January, with daily maximum temperatures above freezing on eight occasions. Despite these mild temperatures, Saginaw Bay, the North Channel, and the northeastern shore of Georgian Bay had formed significant ice covers by midmonth. The period of below-normal air temperature, January 16-21, was associated with the passage of an intense high-pressure area over the Great Lakes and caused ice to from over the entire perimeter of Lake Huron. The straits to Bois Blanc Island and the North Channel were virtually 100% ice covered by the end of the third week in January. With the exception of February 7-12 and March 20-25, temperatures at Alpena were above normal and often above freezing during February and March. The maximum seasonal ice extent on Lake Huron occurred near February 8, 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. Other winters during the past 20 years with less than 40% ice cover on Lake Huron include winter 1964 (34%) and winter 1966 (29%). A period of extremely mild air temperatures occurred February 13-23, effectively ending any further significant ice formation on Lake Huron. During this period, daily average air temperatures at Alpena only dipped below freezing on two occasions and minimum daily temperatures were above freezing on four occasions. By February 22 the only significant ice in the shore zone was located in Saginaw Bay on the southern half of the lake and in the Straits of Mackinac, the North Channel, and the northeastern shore of Georgian Bay on the northern half of the lake. March ice cover was much below normal. Usually, Lake Huron is 53% ice covered the first half of March and 41% ice covered the second half of March. During March 1983, the lake was well below 20% ice covered the entire month. By April 8 the only significant ice on Lake Huron was located on the North Channel. By April 22 even the North Channel was virtually ice free, ending the 1983 Lake Huron ice cycle.

4.5 Lake St. Clair

This lake has a mean depth of 3.6 m and a surface area of only 1,113 km^2, putting it in a class of lakes different from 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. Because Lake St. Clair is so shallow and small compared to the Great Lakes, diurnal air temperature changes can cause significant ice cover changes over virtually the entire lake surface. Lake St. Clair is normally nearly 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.

It is estimated that, during winter 1983, ice initially formed the second week of December. The period of extensive ice cover included the first week of January, January 18-21, and most of the second and part of the third week of February. Air temperatures were below normal and below freezing for all or part of each of these periods, and the lake was estimated to be at least 70% ice covered during these periods. Mild air temperatures the second half of February brought an abrupt halt to any further significant ice formation. Lake St. Clair was virtually ice free by March 11.

4.6 Lake Erie

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

The first half of January, the lake west of Point Pelee is usually at least 90% ice covered. The midlake basin usually becomes 70-90% ice covered during the second half of January. In February the entire lake is normally 90-100% ice covered and at its greatest area1 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. The ice on the eastern end of the lake is usually lost in the second half of April or the first half of May.

Ice formation in the shore zone of Lake Erie began the second week in December 1982. By mid-January the lake west of Point Pelee was 70-90% ice covered. Below-normal air temperatures January 16-20 accompanied a spurt of new ice formation in the eastern end of the lake, east of approximately Dunkirk, NY, as well as in shallow areas along the lake perimeter. The ice in the eastern end of the lake was gone by the first of February. A second significant period of ice formation occurred the first half of February, February 4-14, during which time air temperatures were predominately below normal. Average daily air temperatures the second half of the month were above normal and, with the exception of 2-3 days, they were also above freezing, effectively ending ice formation.

Lake Erie was estimated to be near its seasonal maximum ice cover extent February 8, when approximately 25% of its surface area was ice covered. The next lowest maximum ice cover during the last 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. During the first half of February, the lake west of Point Pelee was 70-90% ice covered, the lake east of Long Point was 10-20% ice covered, and the perimeter of the lake was lined with various amounts of shore ice. The second half of February ice cover diminished so that by month's end the only large area of ice cover was located west of Point Pelee. The ice continued to dissipate the first week of March so that by the end of that week the ice season on lake Erie was at an end for all practical purposes.

4.7 Lake Ontario

Lake Ontario has the second greatest mean depth and the smallest surface area of the five Great Lakes. In addition, its southerly and easterly exposure provides it with milder air temperatures than those of Lake Superior and of the northern portions of Lakes Michigan and Huron. The large heat reservoir formed by 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 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 March 15 the lake is usually only 10% ice covered and a month later, April 15, the lake is virtually ice free.

Because of 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 February. From these observations and air temperature records at Kingston, ON, 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, ON, in the western end of the lake and in the Bay of Quinte end the heed 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. Winters during which Lake Ontario had 10% ice cover or less during the last 20 years include the winters 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 the 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 for virtually the entire winter with only a minimal amount of icebreaking assistance, resulting in savings of 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 the cost of operating a helicopter for ice reconnaissance is $1.883 per hour (Lt. E. Funk; U.S. Coast Guard, Cleveland, personal communication, 1984). During winter 1983 there were only five cases of direct U.S. Coast Guard assistance, in comparison 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. The jam impedes navigation and may also cause a reduction in hydropower generating capacity. Further, there is always the potential for flooding upstream of the ice jam. The U.S. Coast Guard did not report any ice jam breaking operations during the mild 1983 winter because 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. During most of April there was some flooding and prolonged disruption of navigation. Estimated navigation costs associated with the ice jam included 1.1 million dollars per day (U.S. Army Corps of Engineers, Detroit District; personal communication, 1984) in addition to the cost of operating ice breakers on the river for nearly 1 month in 1984.

Ice-control structures 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 such ice-related problems. One such structure, the ice boom, is located at the eastern end of Lake Erie near the head of the Niagara River, and is described in a report by the International Niagara

Working Committee (1983). 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 MWh 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. Further, 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 losses in winter 1983 on the St. Marys, Niagara, or St. Lawrence Rivers as indicated by annual reports issued by the U.S. Army Corps of Engineers (1983), the International Niagara Working Committee (1983). or the St. Lawrence Power Project Report on Winter Operations 1982-83 (New York Power Authority, 1983).

A certain type of shore ice formation called an ice foot, described by Zumberge and Wilson (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 along the southern end of that lake by Evenson (1973) and Seibel et at. (1976). respectively, and along the southern shore of Lake Erie by Fahnestock et *al.* (1973). Shore erosion has been reported in many of the above areas (see fig. 8) during winter 1983 (Martin Jannereth; Michigan Department of Natural Resources, Lansing, MI; and Donald Guy; Ohio Department of Natural Resources; Sandusky, OH, personal communications, 1984). indicating that ice foot formation in these areas was below normal in winter 1983. However, the economic impact of shore erosion in that year 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. CONCLUDING REMARKS AND OBSERVATIONS

6.1 Winter 1983

Winter 1983 on the Great Lakes was exceptional because of high air temperatures, which caused 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 causes of this benchmark winter in the Great Lakes Region is a topic for future studies. Certainly the record El Nino of 1982-83 (described by Quiroz [1983]) and the eruption of El Chichon in spring 1982 (see Wendler [1984]) affected the weather and likely the climate on a global scale. These events should be considered in studies of the root causes of the exceptionally mild 1983 Great Lakes winter.

The economic impact of the mild winter would have been much greater if the U.S. economy had been stronger; in winter 1983 the economy was in a recession. Winter navigation was particularly depressed, and this is where the cost savings associated with operational support activities such as ice breaker assistance and ice reconnaissance would have been large as indicated in the per-hour operating costs of ice breakers and reconnaissance aircraft given in the previous section.

FIGURE 8.--House south of St. Joseph, MI, abandoned because of shore erosion (photograph courtesy of M. Jannereth).

6.2 The 1983 Great Lakes Ice Cycle

There were three relatively long periods of low air temperatures favorable for ice formation during winter 1983. The first period, January 16-21, was associated with the passage of high-pressure centers over the Great Lakes. The second period of sustained low temperatures, February 8-12, was associated with an anticyclone that was centered over James Bay and drifting slowly eastward. The third period of low temperatures, March 22-26, 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 began the second week of December. Mild air temperatures in December and much of January, 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. The main body of water in each Great Lake, and much of the shore zone as well, was ice free by the end of the first week of March, except for bay and harbor ice; this virtually ended 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.

7. ACKNOWLEDGMENTS

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