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LANDSAT fake color image of ice cover on Lake Michigan for 16 February 1977. The winter of 1976-77 produced a record areal ice extent on Lake Michigan.

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration

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SUMMARY OF GREAT LAKES WEATHER AND ICE CONDITIONS, WINTER 1976-77*

The winter of 1976-77 was the fifth coldest in the past 200 years. Record-breaking low temperatures from mid-October to mid-February, associated with an upper air pressure pattern consisting of a strong ridge in the westerly flow over North America, resulted in extraordinary ice cover on the Great Lakes. Ice was produced almost simultaneously in various shallow protected areas of the Great Lakes in early December. The progression of early winter, mid-winter, and maximum ice extent was from 4 to 5 weeks earlier than normal. At the time of maximum ice extent in early February, Lake Superior was approximately 83 percent ice covered, Lake Michigan over 90 percent, Lake Huron approximately 89 percent, Lake Erie 100 percent, and Lake Ontario approximately 38 percent. Spring breakup started in late February in the southern part of the Great Lakes region and in early March in the northern part. The bulk of the ice cover was gone by the fourth week of April. Shipping was severely hampered by the abnormally large amount and duration of the ice cover. Direct icebreaker assistance by the U.S. Coast Guard was up about 55 percent over the previous winter season.

1. INTRODUCTION

F. H. Quinn and R. A. Assel

This report on the 1976-77 winter weather and ice conditions is the first coordinated report to combine the activities of each of the NOAA components responsible for monitoring Great Lakes ice conditions. The participating units are the National Weather Service (NWS), the Environmental Research Laboratories (ERL), and the National Environmental Satellite Service (NESS). Individual publications produced in the past by each of the above units led to an undesirable fragmentation of Great Lakes ice information. R. A. Assel and F. H. Quinn edited the report and all authors reviewed it.

Most geographic locations referenced in this report are shown in Figure 1. The winter of 1976-77 is an appropriate year to begin the combined NOAA ice reports as it was the fifth coldest winter in the Great Lakes in the past 200 years and the coldest since the program to extend winter navigation on the Great Lakes began in 1971. Thus, it will likely serve as the benchmark winter for Great Lakes ice studies for many years to come.

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*GLERL Contribution No. 138.

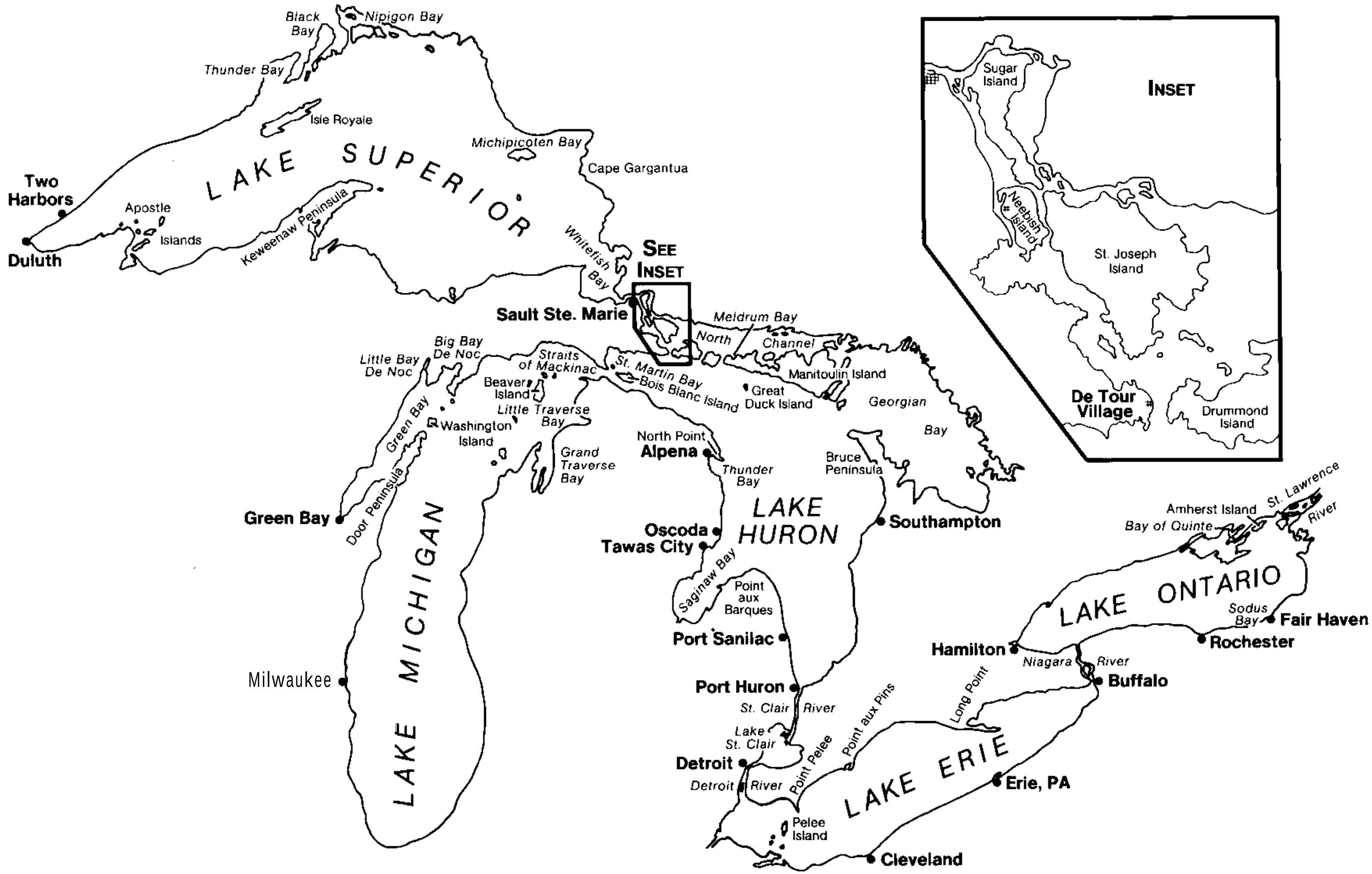

Figure 1. Geographic location chart for the Great Lakes.

The first ice began to form in the Great Lakes in early December. With the continued record cold winter, the ice cover grew rapidly, reaching its maximum extent during the first week of February. At this time the percent of ice cover on each of the lakes was as follows: Lake Superior, 83 percent; Lake Michigan, 90 percent; Lake Huron, 89 percent; Lake St. Clair, 100 percent; Lake Erie, 100 percent; Lake Ontario, 38 percent. The spring breakup started early in March with the last ice being seen in Buffalo Harbor on 30 April. The harshness of the 1976-77 winter ice conditions severely hampered waterborne commerce throughout the Great Lakes.

2. SUMMARY OF METEOROLOGICAL CONDITIONS

C. R. Snider

2.1 Synoptic Study of the Winter

The winter of 1976-77 was the coldest on the Great Lakes since serious attempts at winter navigation began. Record breaking cold weather persisted over the eastern half of North America from mid-October through mid-February.

The meteorological phenomenon responsible for this anomaly was not confined only to the Great Lakes, but was part of a world-wide pattern. Excessively warm weather occurred during the same period on the west coast of North America and in portions of western Europe; the drought over the western states intensified.

The persistent cold was associated with an upper air pressure pattern consisting of a strong ridge in the westerly wind flow that settled over western North America and remained nearly stationary from late autumn to late winter. Figures 2*a*-*c* show the mean height of the 700 millibar surface during November and December 1976 and January 1977. Streamlines coming from the north and northwest directed one frigid air mass after another across the Great Lakes. Figures 3*a*-*c* show the normal mean height of the 700 millibar surface during the same time. In a typical winter, streamlines at this level fluctuate from northwesterly to southwesterly, allowing alternate movement of cold and mild air masses over the Lakes. The cause of these blocking high-pressure centers that occasionally develop in the general circulation of the atmosphere is not well understood, though some statistical relationships useful for forecasting have been derived. Namias (1969, 1971), Rogers (1976b), and Egger (1977) have pointed out that abnormally warm water in the eastern North Pacific Ocean is associated with, and sometimes precedes, the development of such blocking highs. Namias (1978) gives a detailed description of the causes of this abnormal winter.

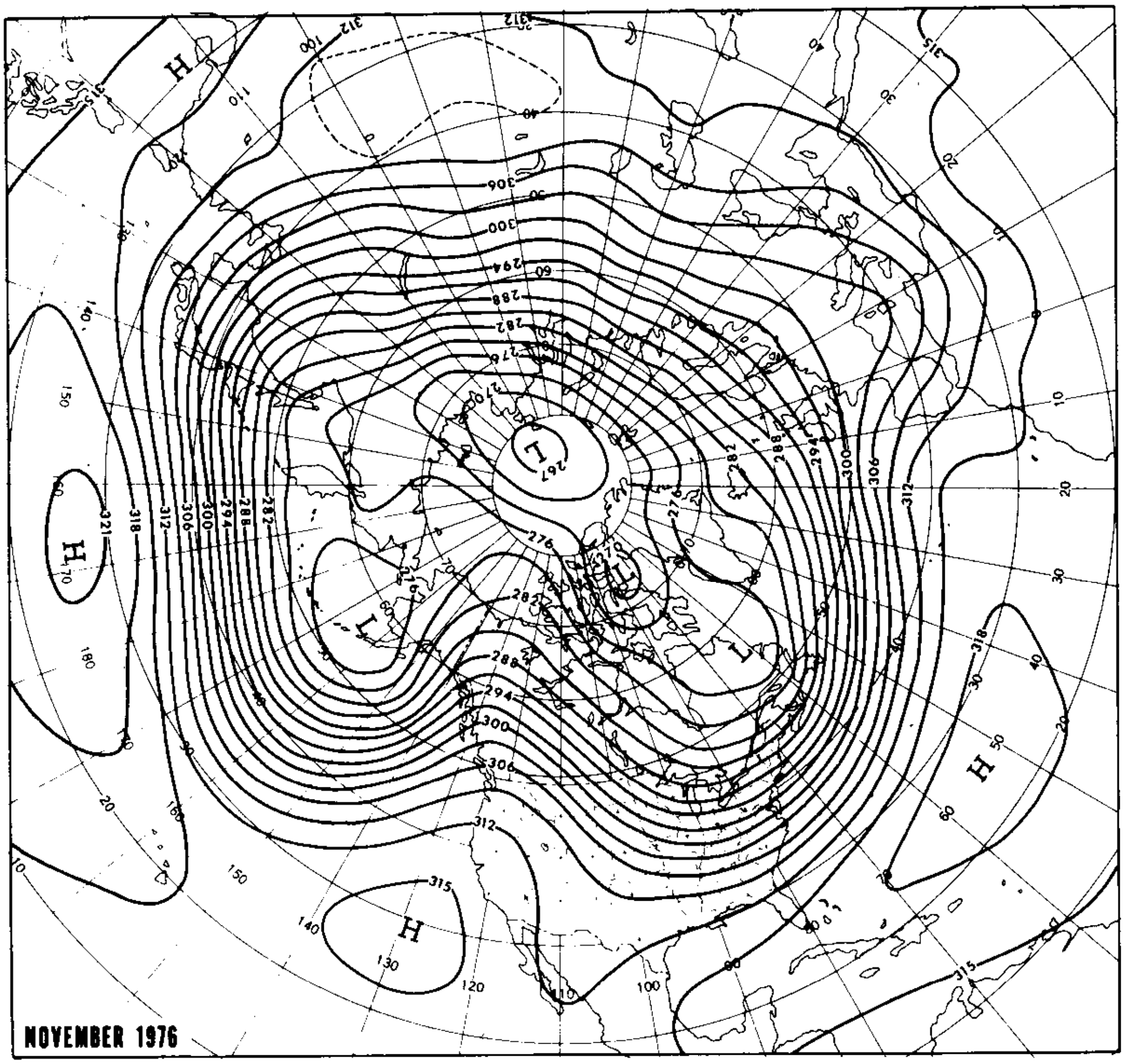

Figure 2a. Mean 700 mb heights, November 1976.

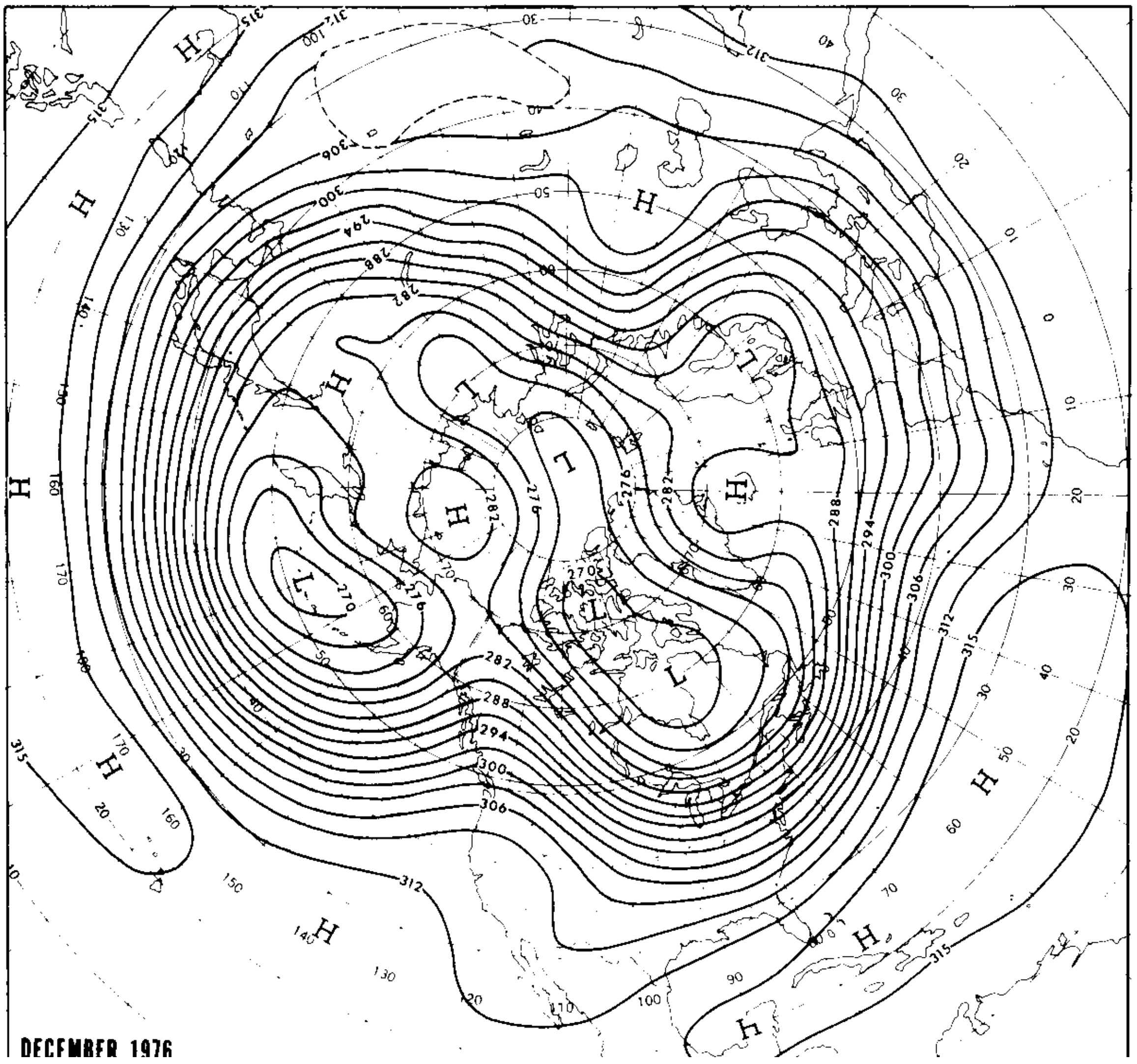

Figure 2b. Mean 700 mb heights, December 1976.

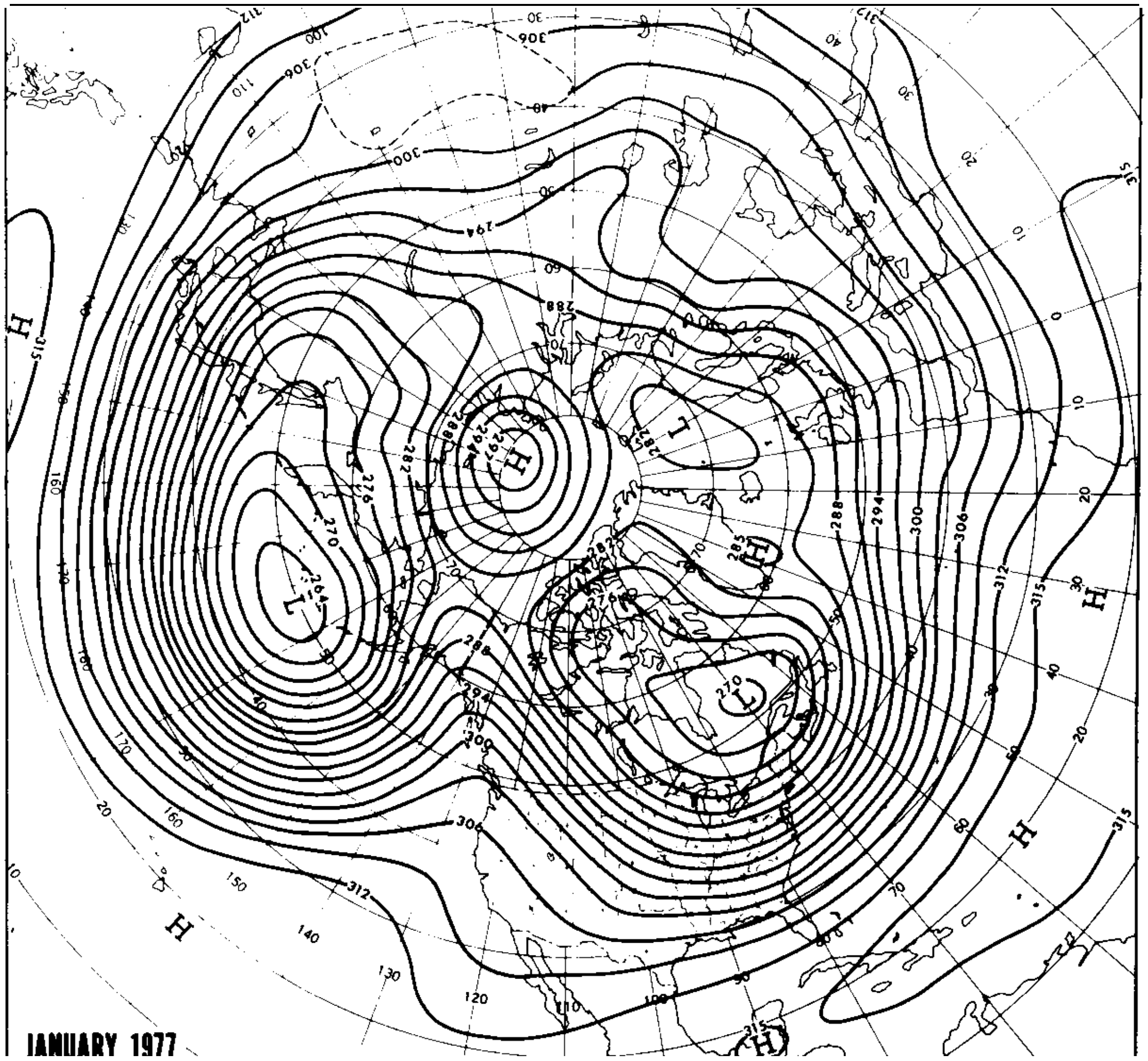

Figure 2c. Mean 700 mb heights, January 1977.

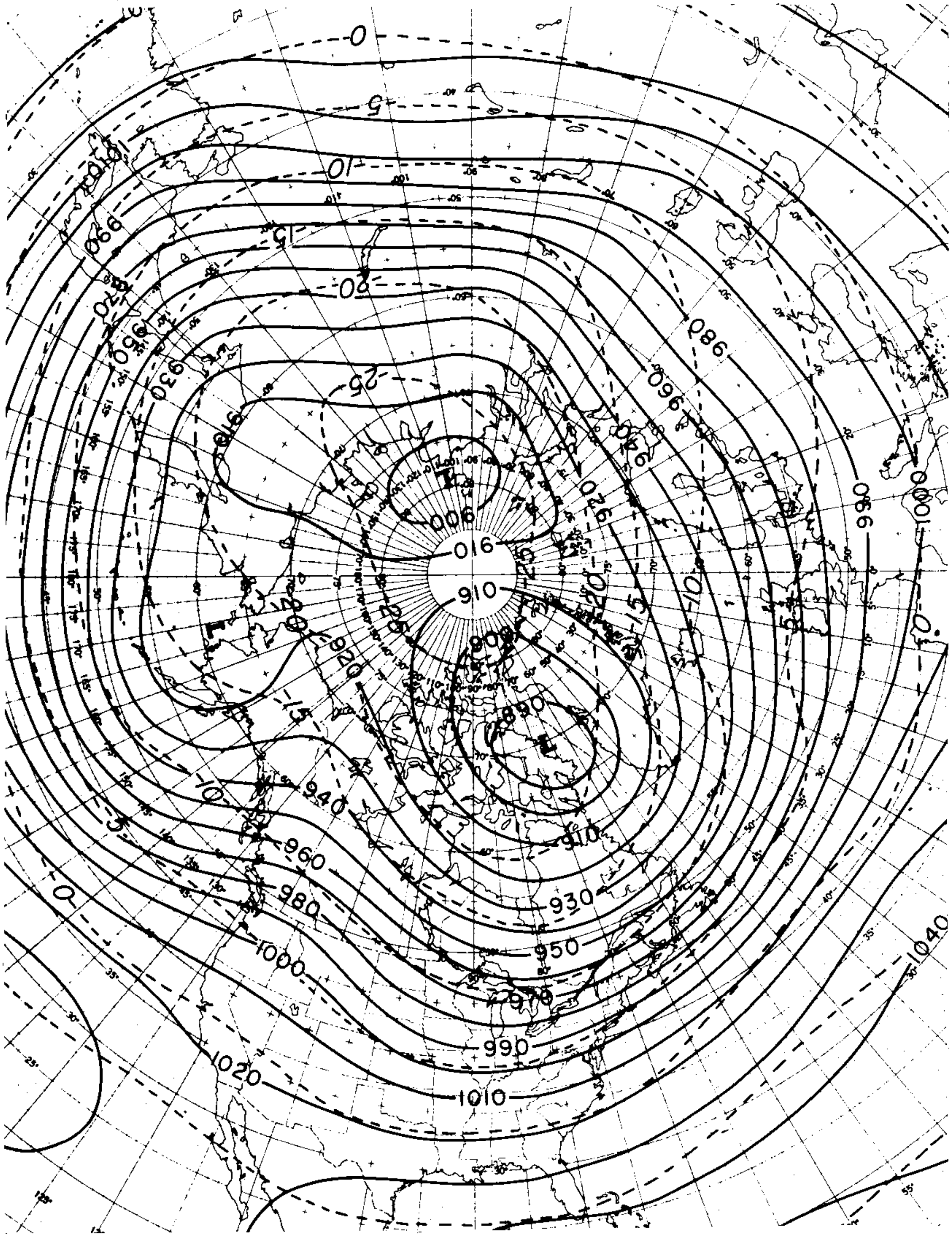

Figure 3a. Normal 700 mb heights, November 1976.

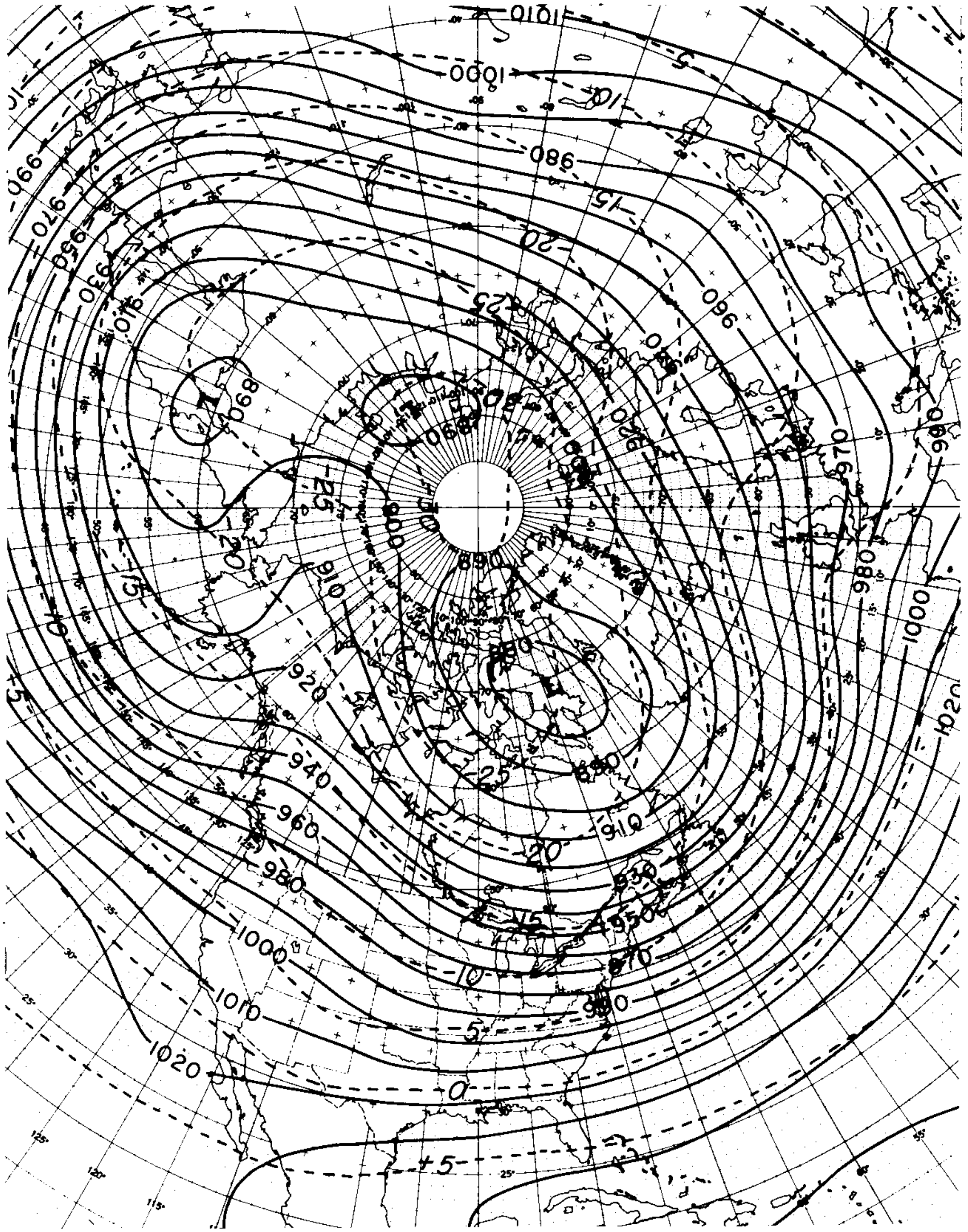

Figure 3b. Normal 700 mb heights, December 1976.

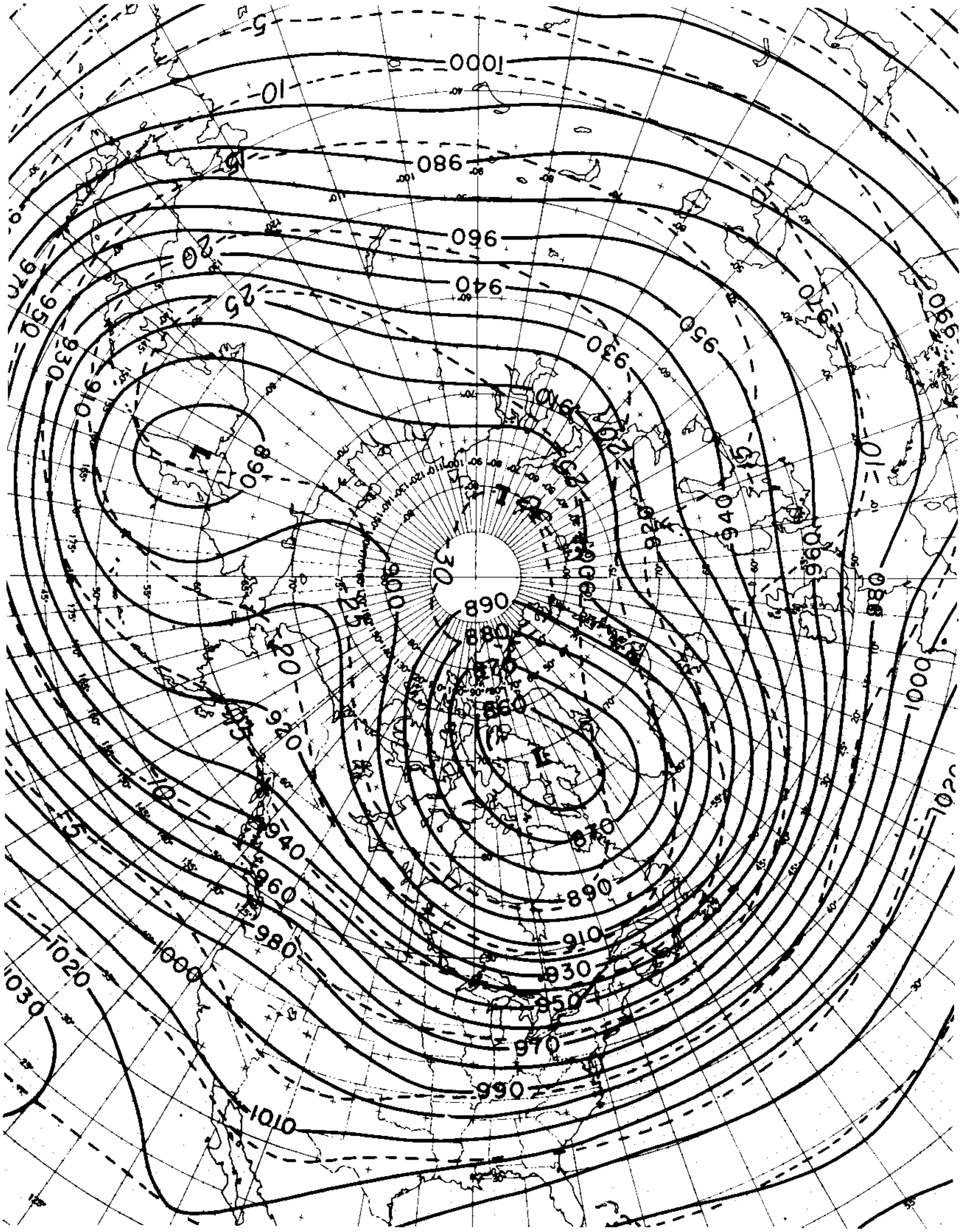

Figure 3c. Normal 700 mb heights, January 1977.

Weather systems at the earth's surface develop and move in response to the configuration of the upper wind flow. Divergence and subsidence in the northern and northeastern portions of the ridge kept skies nearly clear over the continental polar air mass source region in northwestern Canada. Unimpeded terrestrial radiation continuously cooled the surface, which in turn cooled the air near the surface in this snow-covered region. This cooling in combination with the subsidence aloft brought about repeated anticyclogenesis. As each newly generated high cell built to a critical pressure, it broke out of the source region and, steered by the winds aloft, moved across eastern North America.

The winter of 1976-77 can be divided into several phases:

1. The preparatory phase, from August to mid-October,

2. The onset, from mid-October to November,

3. The northern intenstive phase, from December to early January,

4. The core of the winter, or the southern intensive phase, mid-January.

5. The receding phase, from late January to March.

2.1.1 The Preparatory Phase

The roots of the winter can be traced back as far as August 1976. That was the first of a continuous series of months with below normal temperatures over the Great Lakes. Each month from August 1976 through January 1977 had a mean temperature farther below normal than that of the previous month. The anomaly was at first almost imperceptible. The normal cool air masses of late summer were simply a little more persistent than the normal warm air masses. The coolness became a little more noticeable in September and early October.

2.1.2 The Onset of Winter

A cold front swept through the Lakes region during 15 and 16 October. The continental polar air mass that followed was not exceptionally cold for that time of year, but it established a pattern that was to persist for 4 months. No warm front would appear to bring any other type of air mass over the Lakes until mid-February. By late November it had become obvious that an unusually cold winter was in progress. Water temperatures were near freezing throughout the Lakes, and ice was appearing in some areas from 3 to 4 weeks earlier than normal.

The relatively warm waters of the Great Lakes, even when they are ice covered, provide a substantial source of heat to modify cold wintertime air masses. Cold air moving over the lakes is warmed and its pressure lowered. For this reason, the center of highest pressure rarely passes directly over the Lakes. Usually about half of them will go to the north and half to the south. The northerly jet stream of fall 1976 directed most of them well to the south, bringing rather low temperatures to the entire region and the greatest negative departures from normal to the southern part of the region (see Figs. 4a-c).

2.1.3 The Northern Intense Phase

During December and early January the ridge over western North America flattened a little, but remained firmly anchored in place. Cold high centers were then directed through the slot between the Great Lakes and Hudson Bay. This section of Canada suffered extreme cold during this phase. North of the Lakes December monthly means were lower than those in January, a rare occurrence. Cold air masses also persisted throughout this period over and south of the Lakes, but they were only a sample of what was yet to come.

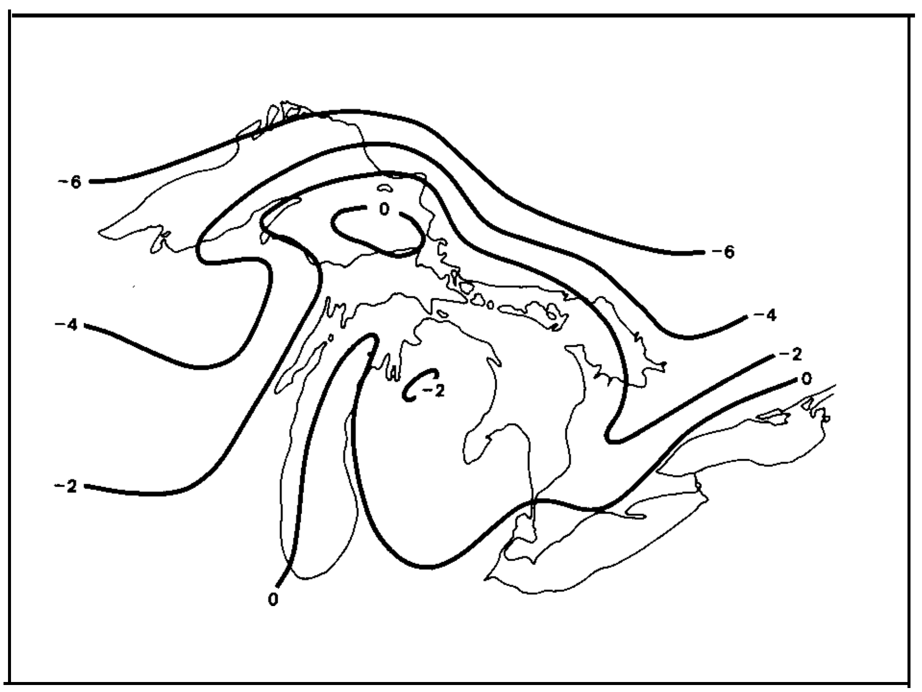

Figure 4a. Mean temperature (°C), November 1976.

Figure 4b. Mean temperature departure from normal ("Cl, November 1976.

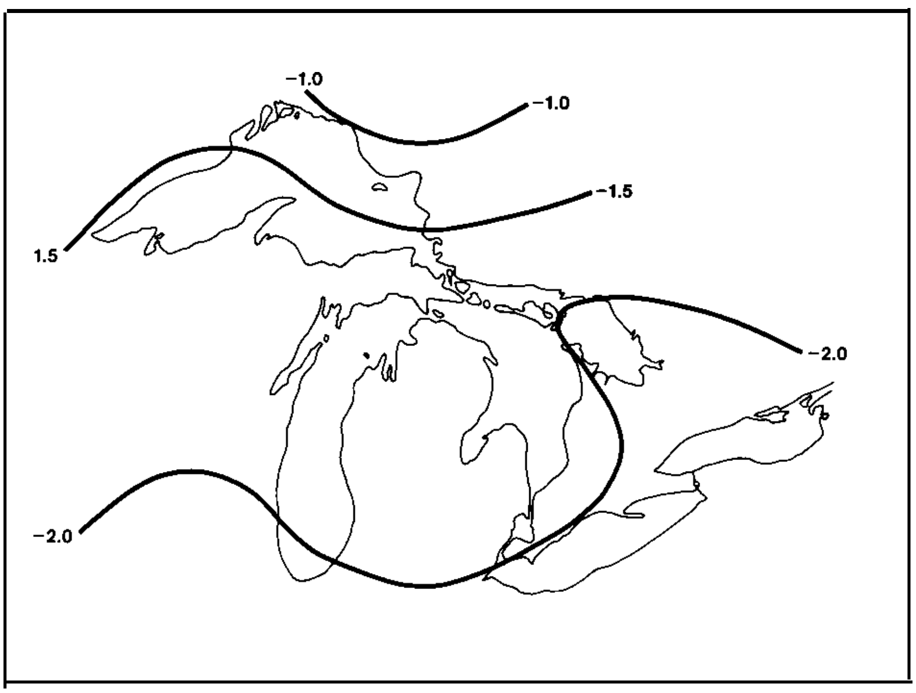

Figure 4c. Mean temperature departure from normal(σ), November 1976.

2.1.4 The Core of the Winter

In early January the Arctic stratosphere underwent a major warming, perhaps fueled by southerly winds from the eastern Pacific. This produced a deep anticyclone centered near the North Pole, (Fig. 2c) which absorbed the shallower anticyclones normally present over the northern portions of Asia and North America. Masses of cold air poured directly from the Arctic into the heart of the continent.

The first cold wave of this intense phase spread across the Great Lakes on 8 January. On the morning of 9 January the highest pressure was just south of Duluth, Minn., and most stations in the northern Lakes region reported their lowest temperatures of the winter (Fig. 5a).

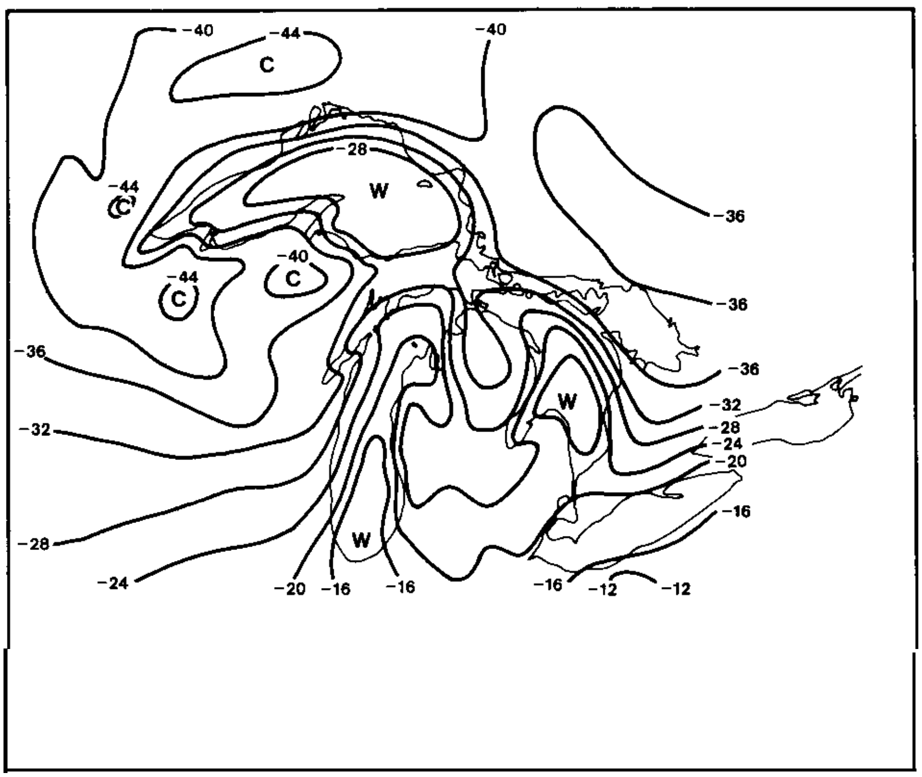

Figure 5a. Minimum temperature, 9 January 1977 (°C).

An even colder air mass swept southward during 15 and 16 January. The center moved through the Plains States, sparing the Great Lakes its greatest cold, but bringing the lowest temperatures of the winter to cities along the southern Lakes and to most of the country farther south (Fig. 5*b*) on the morning of 17 January.

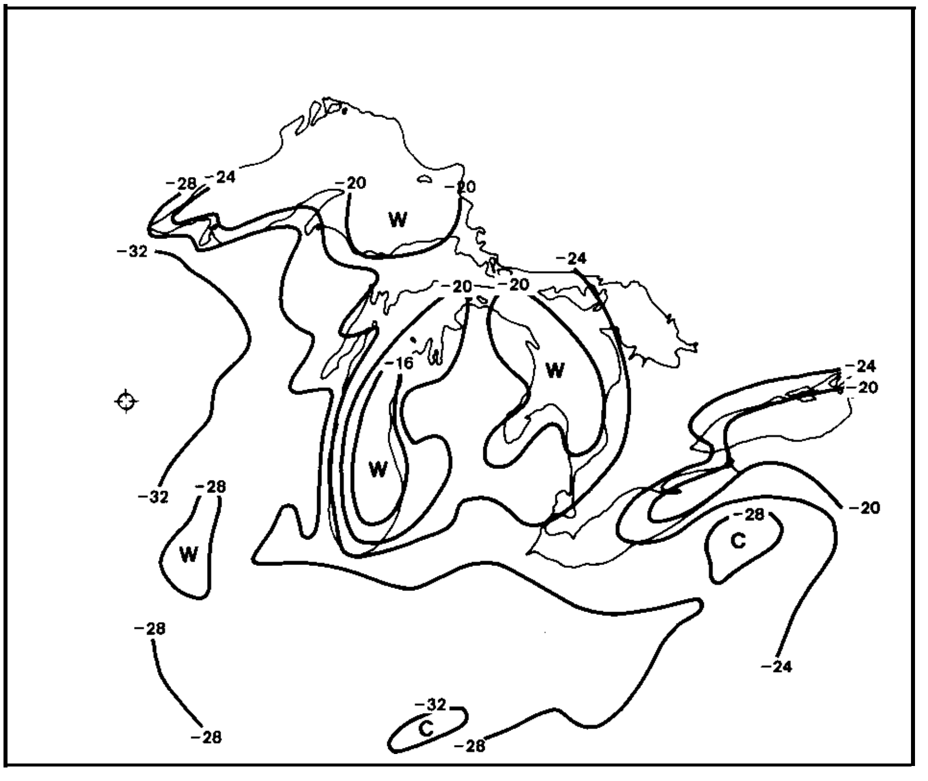

Figure 5b. Minimum temperature, 17 January 1977 (°C).

The great temperature anomalies over the Great Lakes (Section 2.3), and the massive ice cover that resulted, were due not so much to extremely low individual temperature readings as to the long continuance of well below normal temperatures. The lowest temperature of the winter at Detroit, Mich., was -23°C, not as cold as is experienced in many milder winters. The -34°C extreme at Sault Ste. Marie, Mich., was only a little more unusual.

2.1.5 The Receding Phase

Warmer air masses began pushing intermittently into the Lakes region in mid-February. Temperatures averaged near normal during the last half of February and March. But normal temperatures were still below freezing during much of this period, so that with the exception of portions of the southern Great Lakes the massive ice cover already present continued to thicken slowly. A few warm days during March started the melting, which proceeded at a more rapid than usual rate during the warm month of April. Shallow waters cleared rapidly, but many ice formations on deeper water were so thick that it was well into May before the last vestige was gone.

2.1.6 The Precipitation Pattern

Each of the cold air masses that burst across the Lakes was preceded by a rather weak cold front, weak because the air mass ahead of it was only slightly warmer than the air mass following it. These weak fronts can produce only small amounts of precipitation. Average snowfall over the Great Lakes Basin was considerably less than normal, with the spectacular exception of a few localities on the lee shores. Much publicity was given the heavy snowfall that paralyzed Buffalo, N.Y. Similar heavy snow fell locally at Watertown, N.Y., and at Sault Ste. Marie (Fig. 6).

2.2 Freezing Degree-Days

The concept of freezing degree-day (FDD) accumulations is useful in forecasting a wide range of phenomena: the usage of heating fuel, the maturation of crops, etc. The growth of fresh water ice is closely correlated with the accumulation of FDD's (Richards, 1963; Snider, 1974; Assel, 1976).

FDD calculations are sensitive to minor changes in computational procedures. Various workers have used different methods of computing daily mean temperature, negative FDD's (thawing degree-days), and determination of the beginning of the freezing season. Data presented here were derived as described below.

A. Thawing degree-days (defined as positive departures of mean daily air temperatures from 0°C) are subtracted from the FDD total. It is possible for the accumulated FDD total to fall below zero owing to an extended mild spell. If this happens, FDD's and thawing degree-days continue to be added or subtracted algebraically.

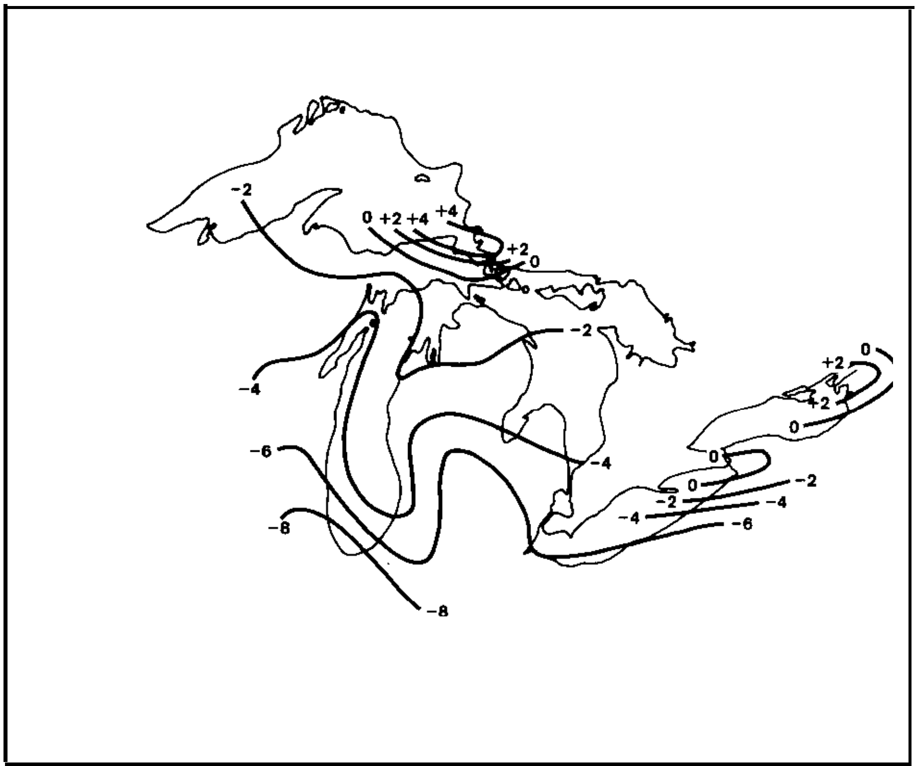

Figure 6. Precipitation excess or deficiency (cm water equivalent), December 1976 through February 1977.

B. A determination must be made as to when to begin the FDD tabulations in the fall. The method used at NWS, Detroit, begins the tally on the first fall date on which one or more FDD's occur (a mean temperature of -1°C or below). If this occurs before the mean (or normal) date of the first occurrence (Table 1), an algebraic summation process is initiated and continued up through that mean date, which is based on normals currently being used. If on this mean date the accumulated total is negative, the total is dropped and the FDD tally will begin on the first date after this mean date that a -1°C or lower mean daily temperature occurs. If the total is positive, the summation process continues to build upon this total for the remainder of the winter. Of course, if no FDD's occur before this mean (normal) date, the tally is routinely initiated on the first day thereafter with an FDD occurrence.

Table 1. Mean Date of First Freezing Degree-Day Occurrence

Location	Date
Duluth, Minn.	9 Nov.
Marquette, Mich.	19 Nov.
Sault Ste. Marie, Mich.	24 Nov.
Green Bay, Wis.	23 Nov.
Milwaukee, Wis.	27 Nov.
Muskegon, Mich.	29 Nov.
Alpena, Mich.	27 Nov.
Detroit, Mich.	29 Nov.
Toledo, Ohio	29 Nov.
Cleveland, Ohio	10 Dec.
Buffalo, New York	1 Dec.
Rochester, New York	1 Dec.

Figures 7a-j show normal FDD curves (solid line) and curves representing winter 1976-77 (dashed line) at several Great Lakes cities. The most pertinent data from the NWS and the Great Lakes Environmental Research Laboratory (GLERL) are summarized in Table 2. The accumulation of FDD's during winter 1976-77 was everywhere greater than normal, with the excess above normal being greatest in the southern part of the Great Lakes region. At Cleveland, Ohio, the accumulation reached 330 percent of normal. The maximum was reached considerably earlier than normal everywhere except at Sault Ste. Marie. Temperatures during the breakup season were above normal except in the northeastern part of the region, where the onset of spring was retarded by the ice cover itself.

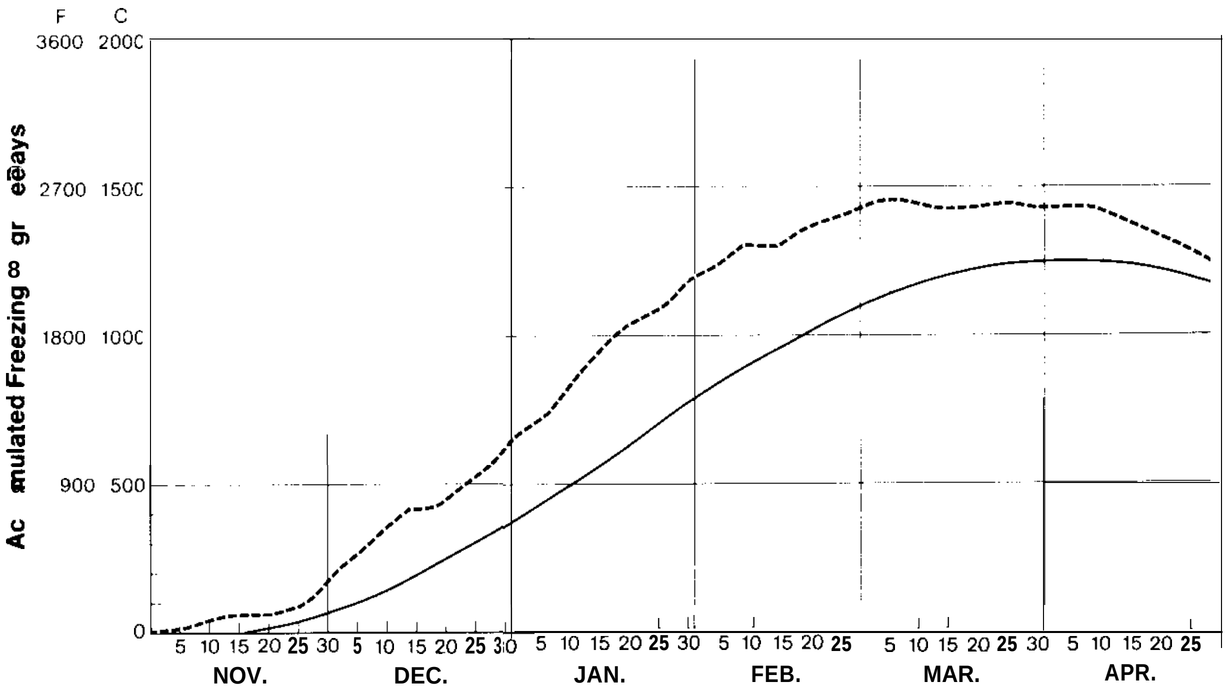

Figure 7a. Freezing degree-day accumulations, Duluth, Minn.

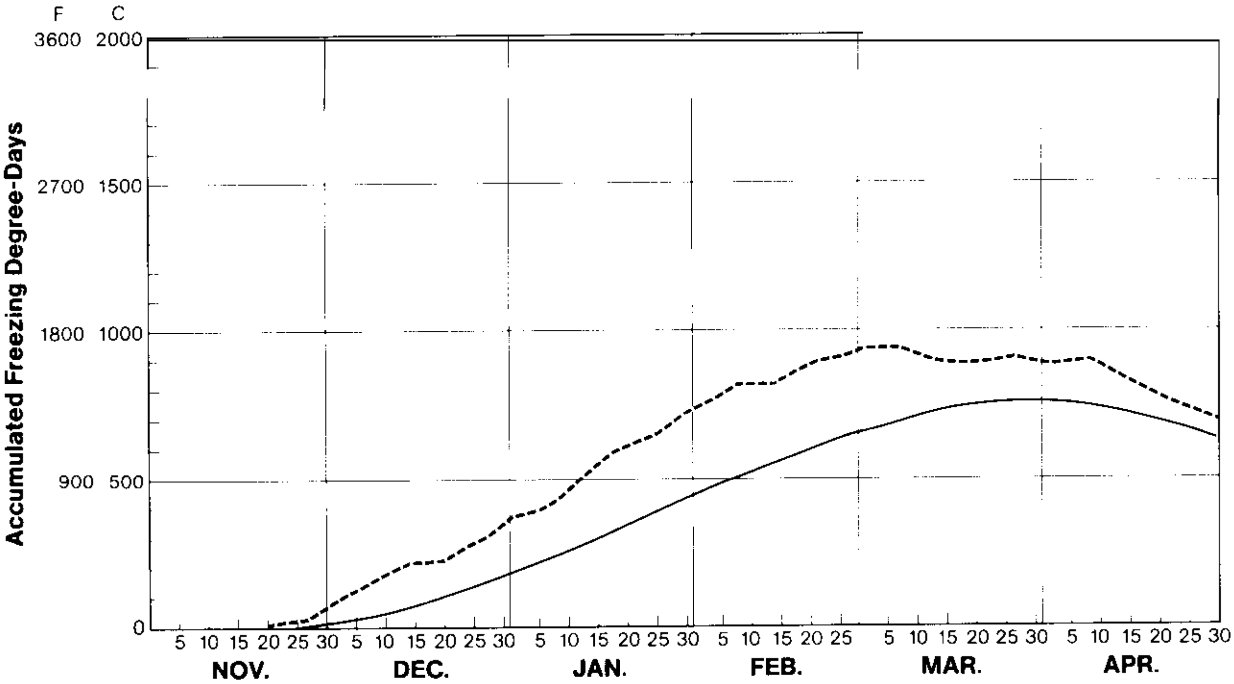

Figure 7b. Freezing degree-day accumulations, Marquette, Mich.

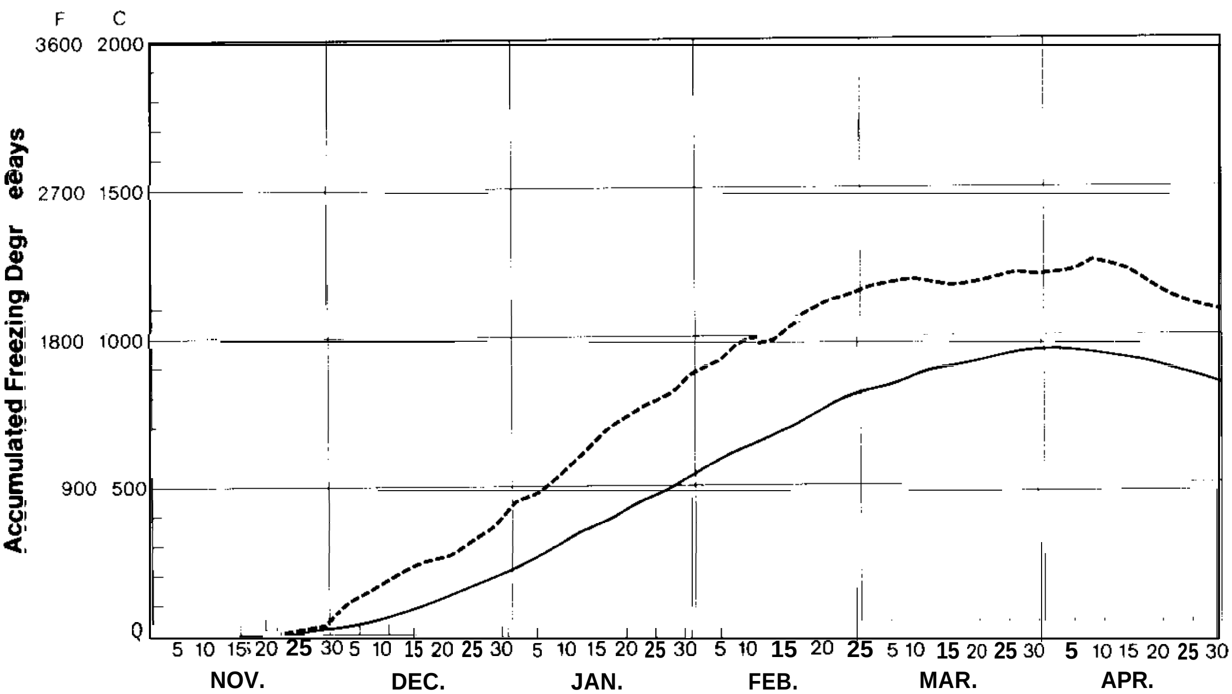

Figure 7c. Freezing degree-day accumulations, Sault St. Marie, Mich.

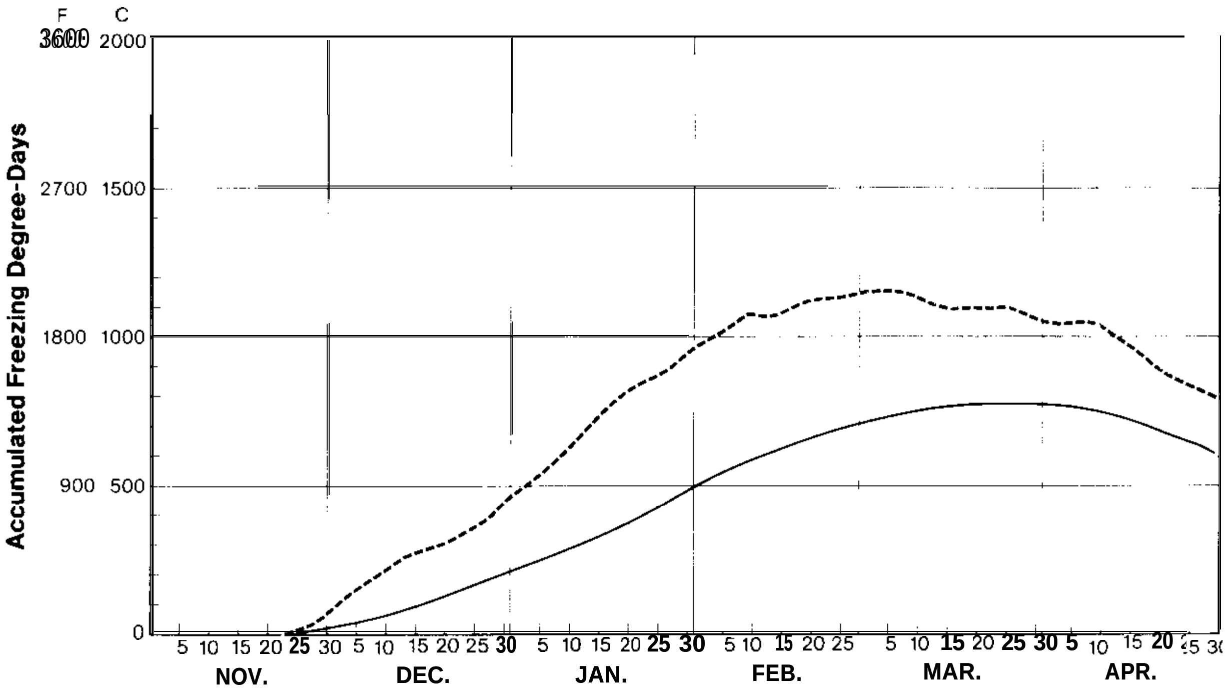

Figure 7d. Freezing degree-day accumulations, Green Bay, Wis.

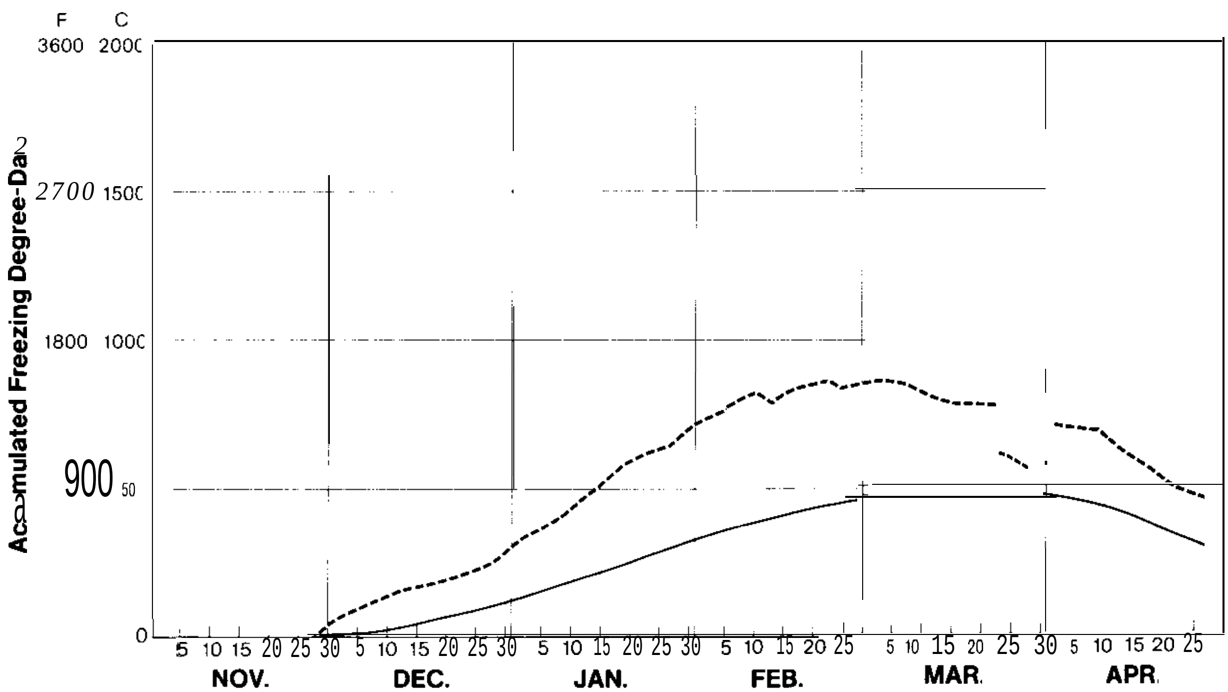

Figure 7e. Freezing degree-day accumulations, Milwaukee, Wis.

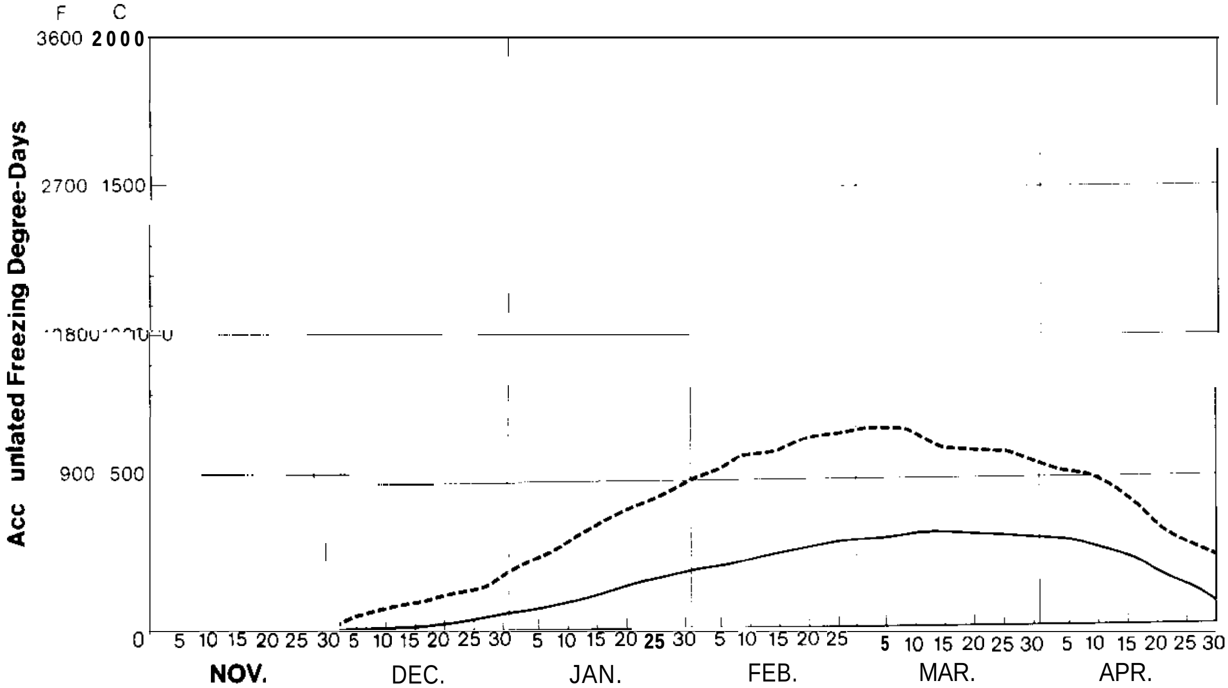

Figure 7f. Freezing degree-day accumulations, Muskegon, Mich.

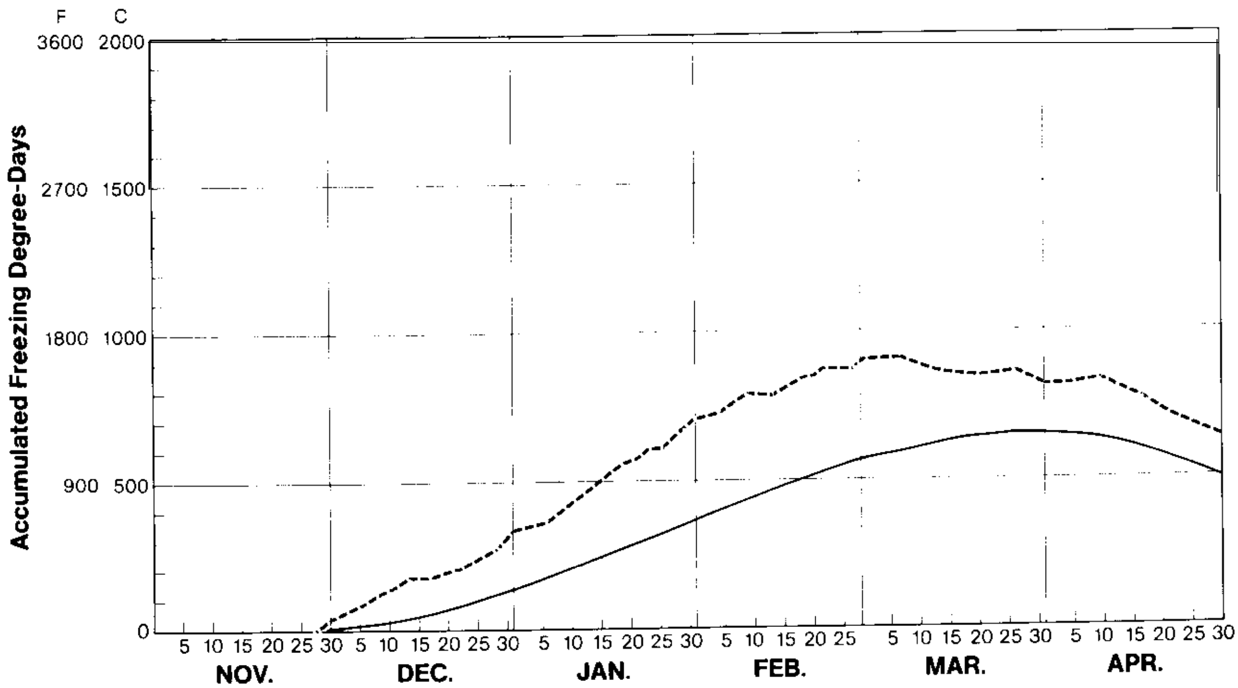

Figure 7g. Freezing degree-day accumulations, Alpena, Mich.

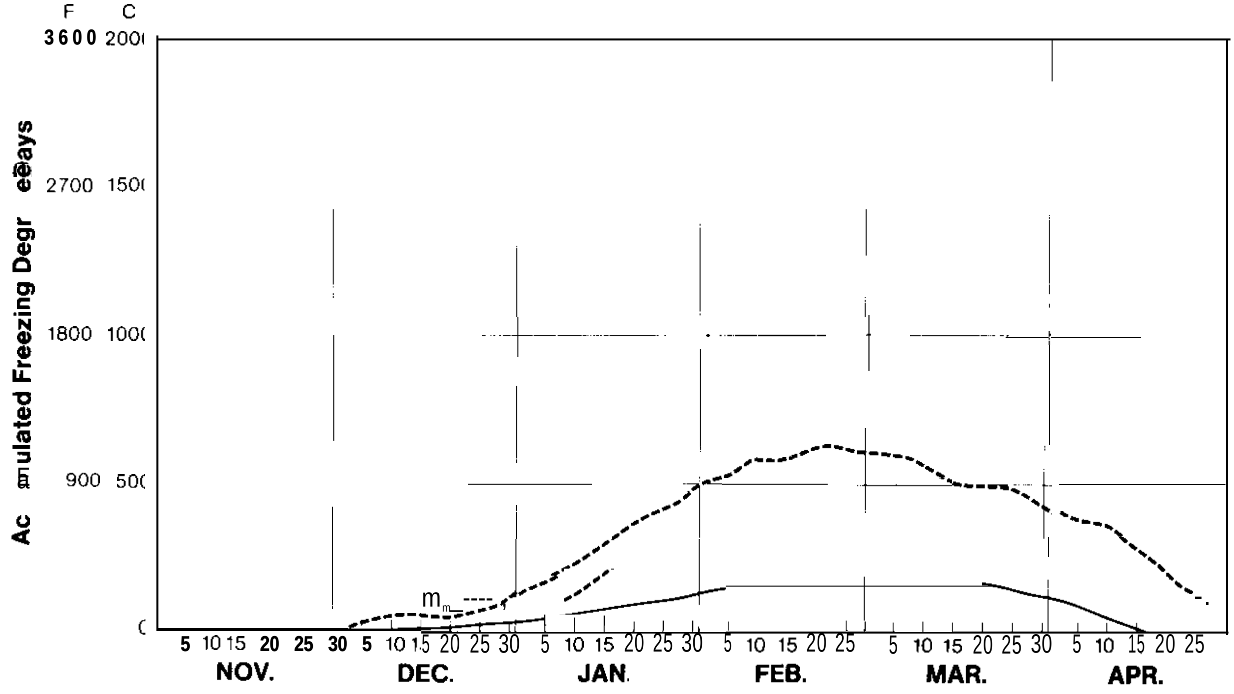

Figure 7h. Freezing degree-day accumulations, Cleveland, Ohio.

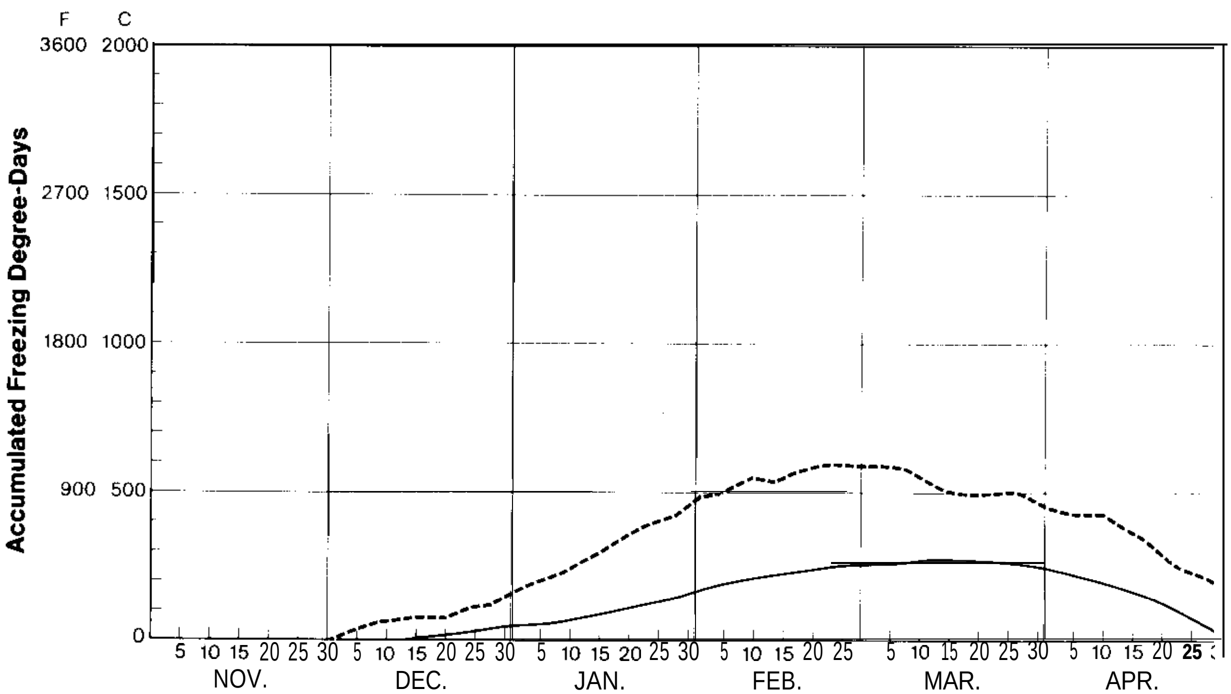

Figure 7i. Freezing degree-day accumulations, Buffalo, N.Y.

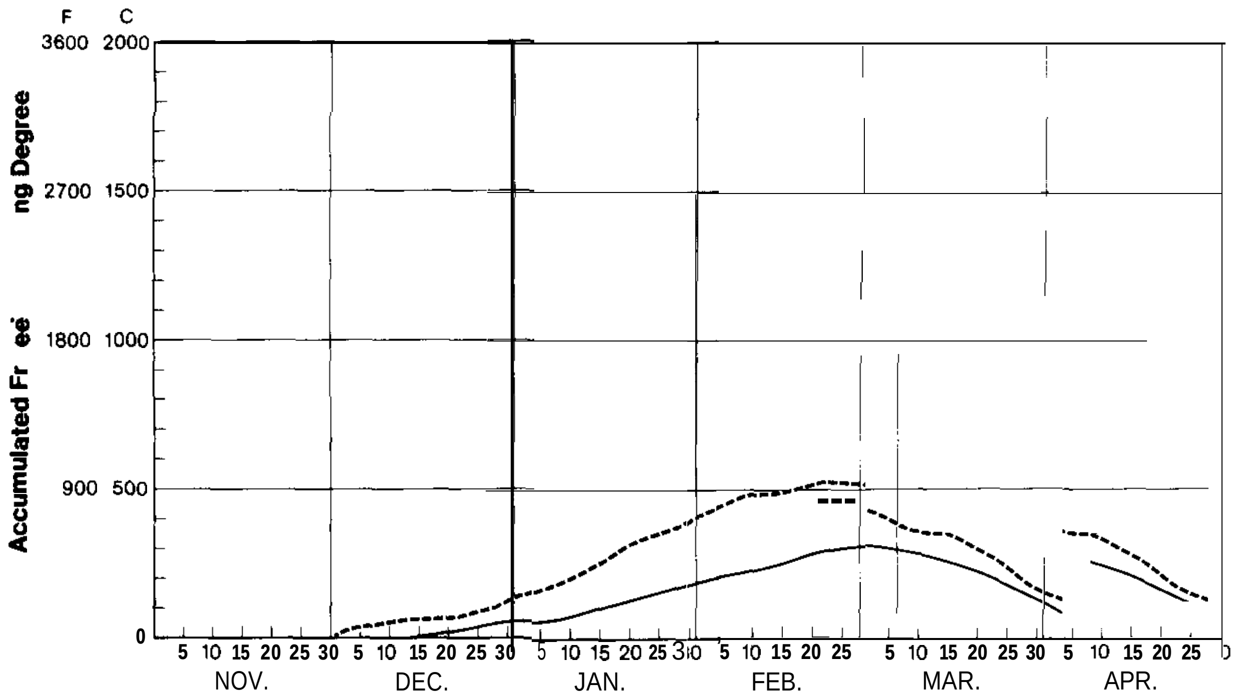

Figure 7j. Freezing degree-day accumulations, Rochester, N.Y.

2.3 Climatic Anomalies and Comparisons

Figures *4a*, *8a*, and *9a* show mean temperatures for November and December 1976 and January 1977. The well-known effect of the Lakes in warming the lee shores shows up strongly on these charts.

Figures *4b*, *8b*, and *9b* show the same data expressed in terms of degrees Celsius departure from normal. Even here the lake affect is quite evident, for the normal variability is much greater inland than along the lakeshore.

Figures *4c*, *8c*, and *9c* show the same data expressed in terms of standard deviations departure from normal. This transformation removes the lake effect and gives a realistic 'picture of the anomalous nature of the cold weather during these 3 months. A departure more than 3 standard deviations below normal will occur 13 times in 10,000 occasions.

Table 2. *Maximum Freezing Degree-Day Values*

Location	Normal* maximum FDD's (°C)	Maximum** FDD's (°C) 1976-77	Normal* maximum date	Maximum** date 1976-77
Duluth, Minn.	1267	1453	3 Apr.	7 Mar.
Marquette, Mich.	756	933	30 Mar.	6 Mar.
Sault Ste. Marie, Mich.	946	1246	3 Apr.	9 Apr.
Green Bay, Wis.	787	1157	27 Mar.	3 Mar.
Milwaukee, Wis.	489	852	17 Mar.	2 Mar.
Muskegon, Mich.	329	673	17 Mar.	2 Mar.
Alpena, Mich.	647	904	29 Mar.	3 Mar.
Cleveland, Ohio	191	631	1 Mar.	21 Feb.
Buffalo, N. Y.	272	594	18 Mar.	23 Feb.
Rochester, N. Y.	326	527	18 Mar.	23 Feb.

*From GLERL records.

**From NWS, Detroit, records.

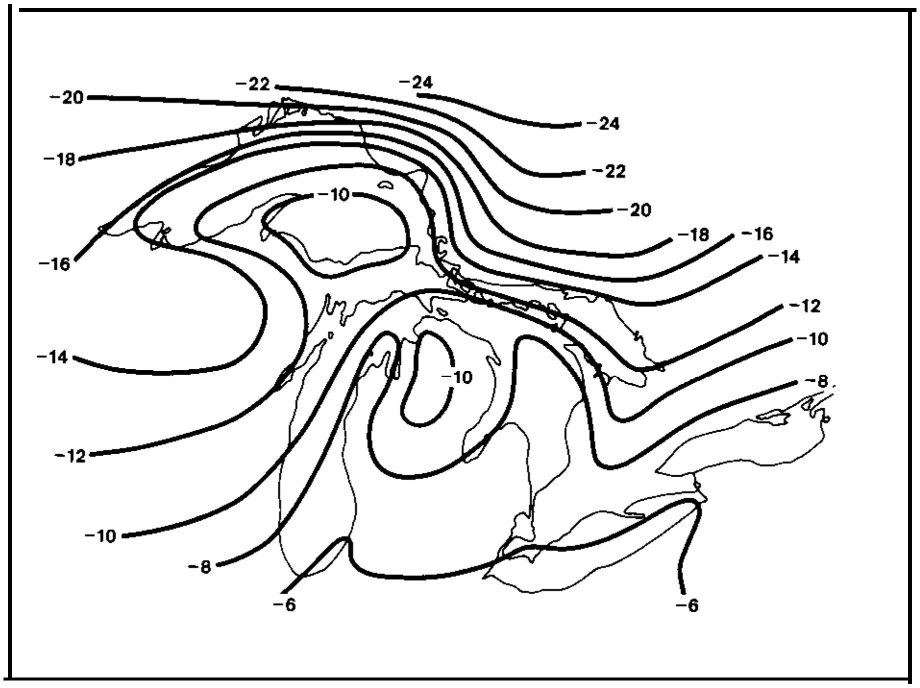

Figure 8a. Mean temperature (°C), December 1976.

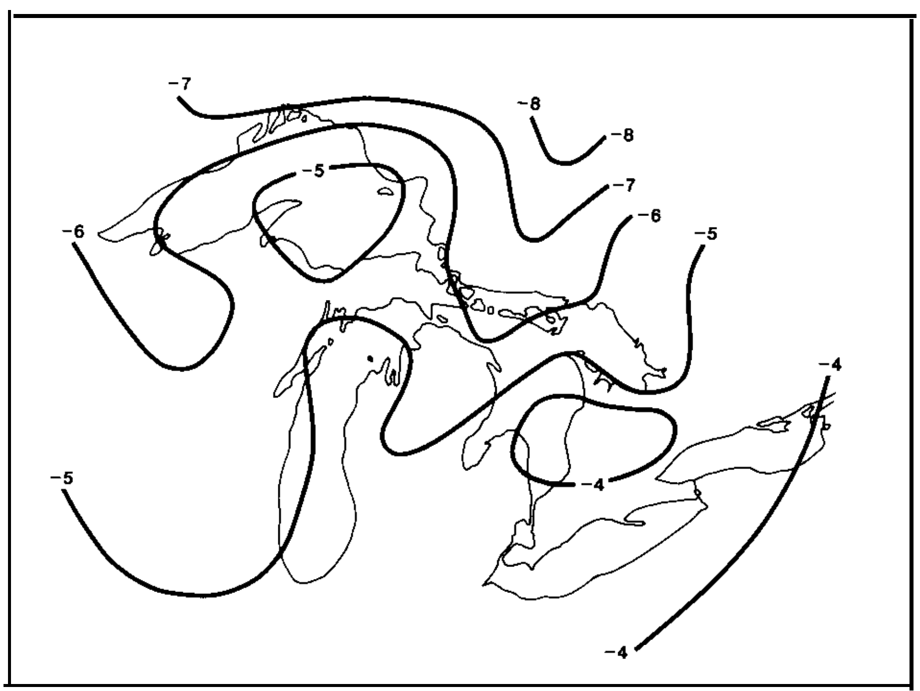

Figure 8b. Mean temperature departure from *normal ("Cl, December 1976*

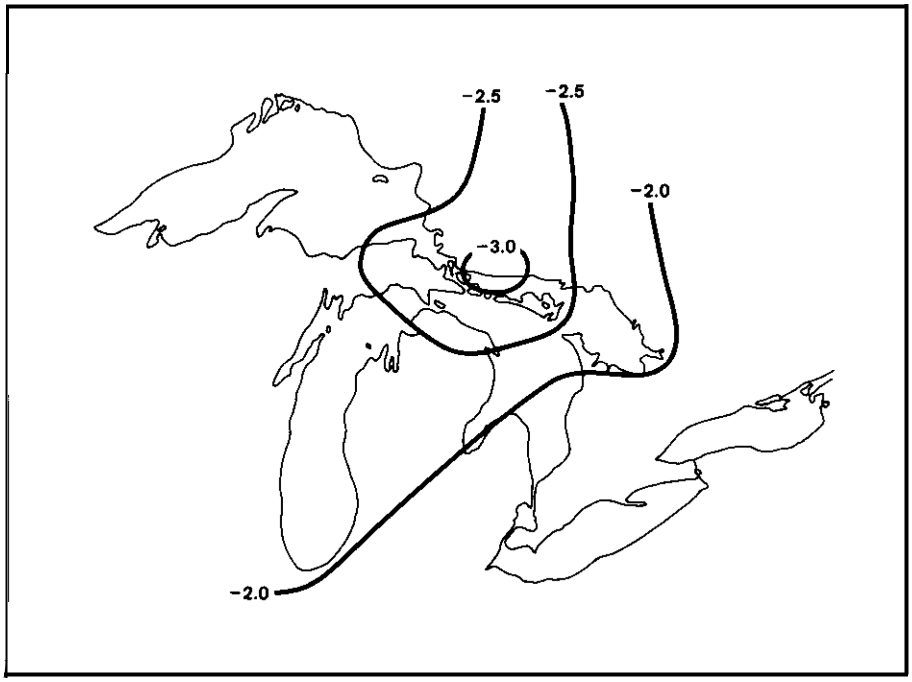

Figure 8c. Mean temperature departure from normal(σ), December 1976.

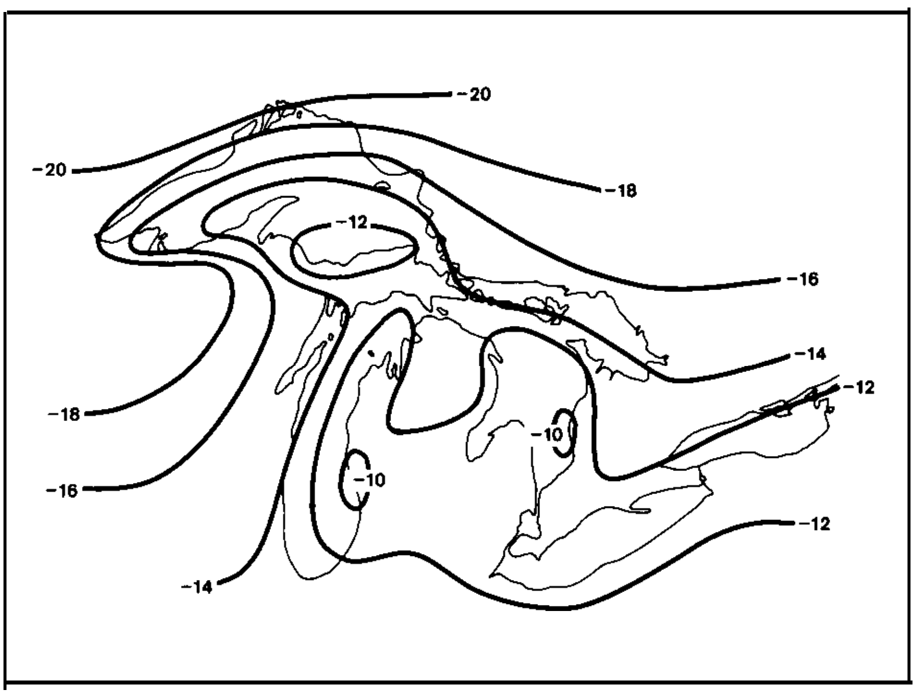

Figure 9a. Mean temperature (°C), January 1977.

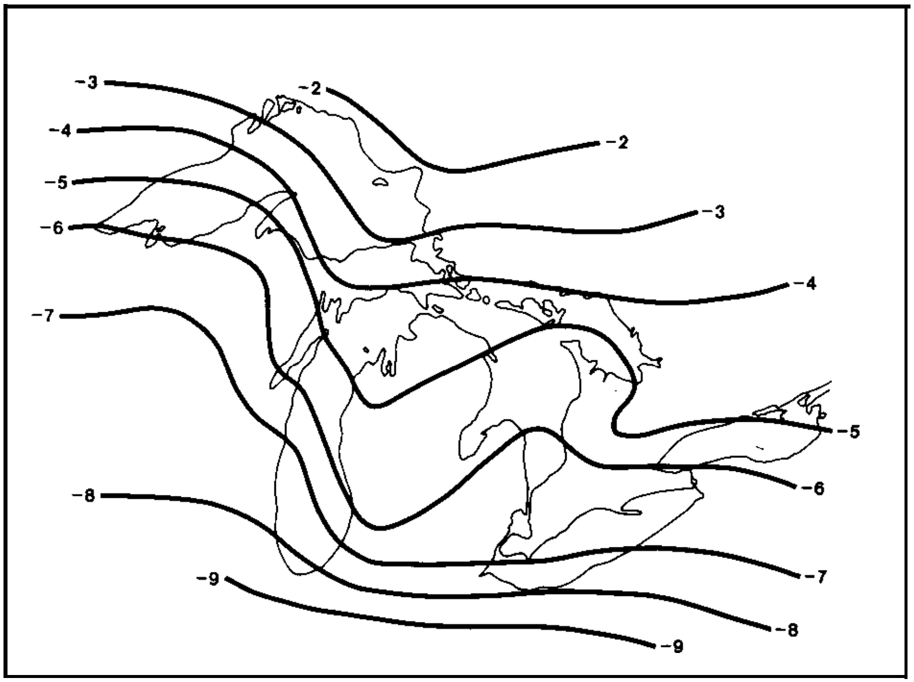

Figure 9b. Mean temperature departure from normal (°C), January 1977.

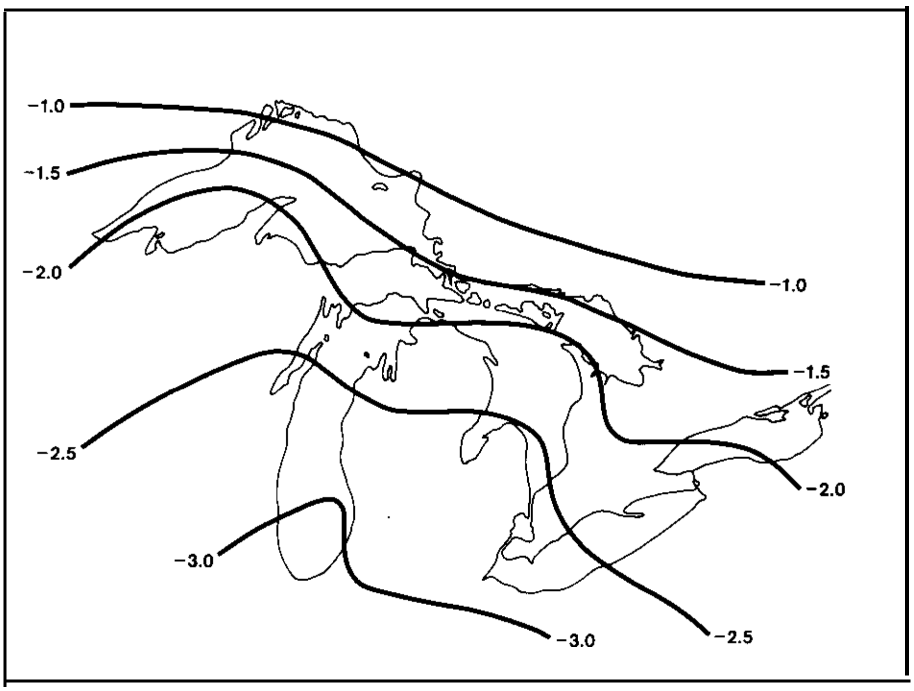

Figure 9c. Mean temperature departure from normal (σ), January 1977.

Such departures did occur on the northern shore of Lake Huron in December 1976 and over the southern end of Lake Michigan and a broad area to the south in January 1977.

Figures 10*a* and *b* show the mean temperature and the departure from normal for the entire 3-month period. The mean trajectory of the cold air masses to the west and south of the Lakes is well illustrated, as is the effect of the Lakes on air temperature.

2.4 Comparison with Previous Winters

As most of the extraction of sensible and latent heat from the water occurs during November, the date of initial ice formation is well correlated with the November mean air temperature. Ice forms and thickens during December and January and reaches its greatest mass during February. The date of the final melting, usually in April, is well correlated with the February mean air temperature. The rate of melting during March and April is not as well correlated with ambient air temperatures as one might expect. Apparently absorption of solar radiation plays as important a role in conductive heat transfer. From the above statements, it can be concluded that the mean temperature of the 4-month period from November through February is a satisfactory indicator of the severity of a winter season.

Most of the major meteorological observatories in the region have instrumental records about 100 years in length. All of them have been relocated at least once, and none of the records are completely homogeneous. Changes in observational and computational procedures require that early records be carefully studied and adjusted if necessary before comparing them with modern records. Unofficial observations can extend the record back many more years in a few places, but these observations must be used with even more care. Noninstrumental observations can also be used to indicate the severity of a winter. The ice cover itself is an excellent integrator of mean winter temperatures over broad areas.

The mean temperature of these 4 months is averaged over four widely separated stations, Duluth, Sault Ste. Marie, Detroit, and Buffalo, to obtain a single index of winter severity on the Great Lakes. High quality data from these four stations are available back to 1888. There is nearly continuous data of somewhat lesser quality back to 1820 for Minneapolis, Minn.; Detroit; and Albany, N. Y. These were normalized to the same base. For earlier data the nearest continuous record is from New Haven, Conn., which goes back to 1780. These records were also normalized to the same base, but were used very cautiously. Their indications were compared to the continuous ice record back to 1807 at Buffalo, to temperature records at Detroit between 1781 and 1786, and to various narrative weather summaries from the Great Lakes, mostly around Lake Erie.

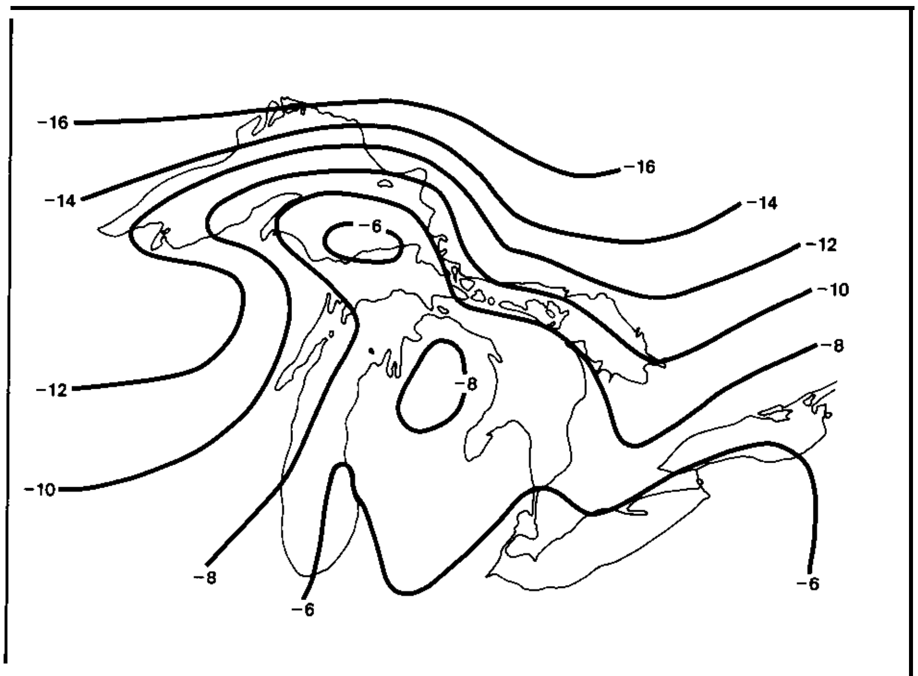

Figure 1 Oa. Mean Temperature ("Cl, November 1976 through January 1977.

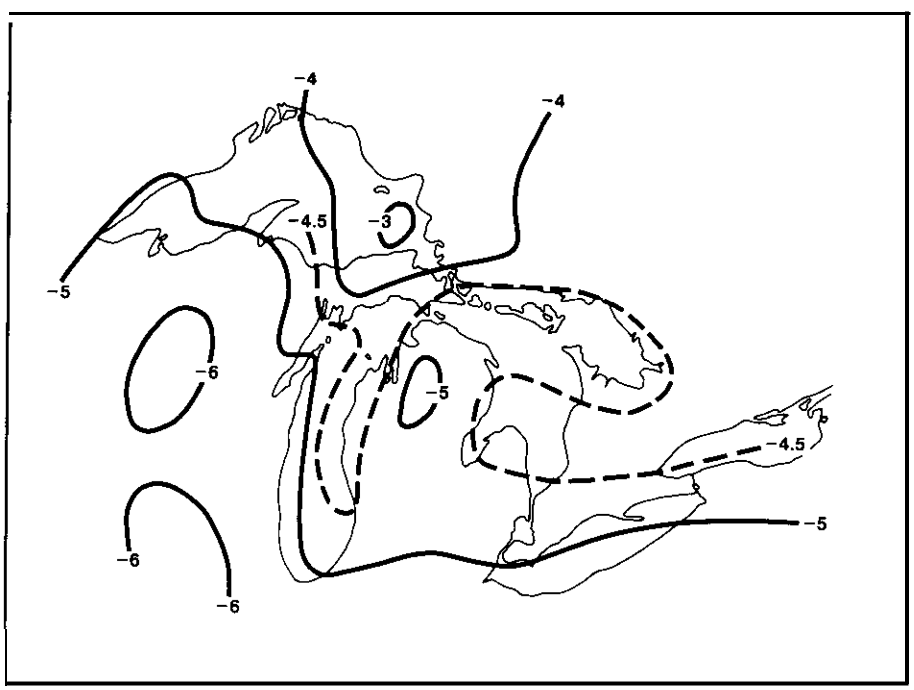

Figure 1 Ob. Mean temperature departure from normal(°C), November 1976 through January 1977.

It was thus possible to classify as severe, ordinary, or mild the 200 winters from 1777 through 1977 over the Great Lakes, and to list in order of severity the 20 (first decile) coldest of the two centuries. This listing is given in Table 3 and each of the winters that proved to be colder than 1976-77 is discussed briefly.

2.4.1 The Winter of 1903-04

November, December, and January of this winter each averaged just a little warmer than the corresponding months of 1976-77. February of 1904 was much colder than February 1977 (-10.9 vs. -3.7°C). Ice formed a little later than in 1976-77, but continued to thicken rapidly through February. Navigation out of Cleveland was not possible before 1 April, the Soo Locks opened 30 April, and Duluth Harbor opened 8 May. There had been no attempt to extend the previous navigation season and closing dates were normal for that era.

2.4.2 The Winter of 1783-84

November and the first part of December were mild. The last 11 days of December were continuously below freezing at Detroit. After a brief thaw the first few days of January, very cold weather set in for the rest of the month. The Detroit River froze over on 7 January. The temperature at Detroit was -27 or -28°C each morning from 27 through 30 January. Another brief thaw the first of February was again followed by cold weather, which continued into March. On 6 March the ice on Lake St. Clair was 3-feet thick. On 22 March the river could still be crossed by sledge.

2.4.3 The Winter of 1874-75

This winter was quite similar to that of 1903-04. November and January were a little warmer than in 1976-77; December considerably warmer. February was extremely cold, -11.4°C. As might be expected, this sequence of weather events had a major effect on the springtime opening of navigation. The 12 May opening of the Soo Locks was the latest date in the 121 years the facility has been operating.

2.4.4 The Winter of 1779-80

It may seem presumptuous to give a temperature value for this winter, and especially to categorize it as colder than any of the others discussed, as there was not a single thermometer in the Great Lakes region at the time. Nevertheless, the evidence seems overwhelming. All the weather diarists in New England (and there were many) agreed that this was one of the two coldest winters of the eighteenth century. (The other was 1739-40). Diarists in Detroit agreed it was the coldest they had experienced at that location. (None of them had been there prior to 1760.) Only January and February 1780 temperatures are available for

Table 3. The 20 Coldest Winters on the Great Lakes, 1777-1977

Rank	Winter	Nov.-Feb. mean temp. (°C)	Nov.-Jan. mean temp. ("C)	Character
1	1779-80	-9	-10	E
2	1874-75	-9	-6.5"	L
3	1783-84	-8	-6.5*	L
4	1903-04	-7.9	-6.2	L
5	197677	-7.7	-8.2	E
6	1872-73	-7.5*	-7.5"	
7	1831-32	-7.5"	-6.5*	L
8	1855-56	-7.5"	-6	L
9	1919-20	-7.4	-7.0	L
10	1880-81	-7.3	-7.2	
11	1917-18	-7.2	-6.8	L
12	1820-21	-7	-7	
13	1856-57	-7	-7	
14	1822-23	-7	-4.5"	L
15	1892-93	-6.8	-5.8	L
16	1962-63	-6.5	-6.3	L
17	1791-92	-6.5"	-6	L
18	1835-36	-6.5"	-5.5*	L
19	1817-18	-6.5*	-5	L
20	1796-97	-6	-7	E

Each of the 20 coldest winters was characterized as early (E), intermediate, or late (L), according to the timing of its coldest period.

*Data prior to 1888 were not of sufficient quality to justify means with 0.10°C precision. They have been rounded off to the nearest 0.5°C.

New Haven, and these are not particularly cold. This can be reconciled with narrative reports only by assuming extremely low temperatures for November and December 1779.

A noninstrumental record kept at the British Naval Shipyard on the St. Clair River shows the same general trend. Extreme cold in November and December continued through mid-January, but February was quite mild. Frost persisted through the afternoons the last week in November. Ice was flowing in the St. Clair River on 16 December, and on the following day the river froze over. Only light snow was recorded during the very cold weather through December and early January. Mild periods during late January and February were accompanied by heavier snow. A significant thaw was noted 21 February. The first rain was reported 7 March. Late March and April were cool. Small boats were first able to cross Lake St. Clair on 16 April. The ice bridge above Port Huron, Mich., broke 20 April, and the river was jammed with ice until at least 11 May. Further east the supply ship from Fort Erie could not get through to Detroit until 16 May.

2.4.5 Character of Winters

Each of the 20 coldest winters (Table 3) was characterized as late (L), intermediate, or early (E), according to the timing of its coldest period. In 13 of the 20, February was the coldest month; in 4 the cold weather was rather evenly distributed throughout the season; and in only 3 did the major part of the cold weather come before February.

We conclude that during the last 200 years only four winters are likely to have produced more massive ice cover on the Great Lakes than did the winter of 1976-77, and in only one of those winters did the heavy ice cover appear early enough to have had a more inhibitory effect on extended season navigation.

3. SUMMARY OF ICE CONDITIONS

R. A. Assel, G. A. Leshkevich, C. R. Snider, and D. Weisnet

3.1 Data Collection Platforms and Processes

Primary sources of ice-cover information used to document the 1976-77 Great Lakes ice cover include: visual aerial ice reconnaissance, side looking airborne radar (SLAR), and satellite imagery. A comparison of SLAR and NOAA-4 and LANDSAT-1 satellite imagery is given by Leshkevich (1976). Ice charts are the end product resulting from interpretation of this data. Ice charts depicting ice distribution and concentration, as well as size and age of floes, were received at GLERL throughout the winter from the Ice Navigation Center, Cleveland, and Ice Forecasting

Central, Ottawa, Ont., Canada. Interpretations of ice conditions made from NOAA-5, Very High Resolution Radiometer (VHRR) satellite, and Geostationary Operational Environmental Satellite (GOES) imagery on a weekly basis were received from NESS in Washington, D.C. SLAR imagery and ice charts based on it were received from the Ice Navigation Center, Cleveland. In addition to this primary data, weekly and daily surface reports of ice conditions and thickness were received from observers for GLERL and the U.S. Coast Guard.

3.1.1 Visual Aerial Ice Reconnaissance

Trained ice observers for the U.S. Coast Guard and the Canadian Department of the Environment record visually observed ice conditions on the Great Lakes periodically during winter. GLERL receives copies of most of the ice charts produced during a given winter season; during winter 1976-77, 196 ice charts were received from the U.S. Coast Guard and 72 ice charts from the Canadian Department of the Environment. In addition, GLERL produced two ice charts as a result of visual reconnaissance flights made over southern Lake Michigan in February.

U.S. Coast Guard aircraft used for visual ice reconnaissance include the Grummand HU-16 Albatross and smaller fixed wing craft and rotary (helicopter) aircraft. Flights are made from Chicago, Ill.; Detroit, Mich.; and Traverse City, Mich. A detailed description of the U.S. Coast Guard 1976-77 visual aerial ice reconnaissance program is given in the Ninth Coast Guard District, Domestic Icebreaking Plan, Annex W to Commander Coast Guard District Nine Operation Plan No. 1-(FY) (1976a). Canadian aircraft used to support visual aerial ice reconnaissance include a Douglas DC-3 and a Lockheed Electra L188C. For information on the Canadian 1976-77 visual observation program, see Noble (1976).

3.1.2 Side Looking Airborne Radar

The National Aeronautics and Space Administration Lewis Research Center, in cooperation with the U.S. Coast Guard and NOAA, has developed a SLAR system for ice surveillance on the Great Lakes. The system, mounted aboard a HC-130B aircraft operating out of Cleveland, operates in the X-band at a frequency of 9.245 GHz (3.245 cm wave length). Flight altitude for SLAR missions is 3.35 km (11,000 ft) with an average ground speed of 280 knots. Flights are made regularly over all of the Great Lakes with the exception of Lake Ontario. The advantage of SLAR over visual reconnaissance and satellite imagery is its all-weather capability and ability to "see" through clouds. A history of the development of the current system is given by Schertler et *al.* (1975). The operational plan for U.S. Coast Guard missions for 1976-77 is given in the joint United States Coast Guard-Canadian Coast Guard Guide to

Great Lakes Ice Navigation (1976b). During winter 1976-77, 82 interpreted SLAR images (ice charts) covering 24 missions were received by GLERL. Owing to mechanical difficulties with the HC-130B aircraft, no flights were made during February and most of March.

3.1.3 Satellite Imagery

NOAA-5 and GOES-l satellite imagery were used in ice-cover documentation. The NOAA-5 satellite represents the third generation of environmental satellites in the National Operational Environmental Satellite System. The orbit is near polar and sun synchronous so the satellite always crosses the equator at the same local solar time, in this case 0830 and 2030. This orbit is a typical polar orbit, providing a twice-daily thermal infrared image and a one-time visible band image of an area.

This type of orbital coverage permits detection of changes at 12-hour intervals for dynamic snow and ice events. Cloudiness commonly reduced these observations, but in most of the U.S. it is possible to secure at least one cloudless view per week. The primary sensor for hydrologic use aboard NOAA-5 is the VHRR, dual channel scanner (visible, 0.6-0.7 μm; infrared, 10.5-12.5 μm).

NOAA's GOES has demonstrated the value of a 35,000-km geosynchronous orbit, in which the satellite appears to hover "motionless" over a point on the earth. The advantages of this type of orbit are as follows:

1. The viewing station is constant.

2. Almost 1/6 of the earth may be observed almost synoptically.

3. Observations may be more frequent, e.g., every 30 minutes.

4. "Telescopic" observations can be made of those areas where high resolution is required for detailed observations.

5. Time-lapse imagery of ice movement, storms, floods, snow cover, etc., can be prepared to study the genesis and dynamic aspects of these important hydrologic events.

6. The satellite can collect and relay data in real time from instruments located at remote inaccessible sites upon command 24 hours a day. Furthermore, these readouts can be programmed to coincide with scheduled detailed imagery, if desired.

7. Processed data products can be retransmitted from central processing and analysis centers via satellite to local forecast/warning centers in near real time.

The VHRR images of the Great Lakes presented here have been specially processed to improve their quality and to rectify and correct the distortions due to earth curvature, earth rotation, and spacecraft roll-attitude errors. This rectification and correction was accomplished by using an algorithm developed by Legeckis and Pritchard (1976) in which the digital tape data are rerun and reformatted. The corrected tape is then processed through a Digital Muirhead Device (DMD) to prepare new images. Standard NESS snow and ice enhancement programs were applied to the tapes to bring out details of the snow and ice areas.

The GOES images were prepared from Visible Spin Scan Radiometer (VISSR) negatives stored at NOAA Environmental Data Service (EDS). Tapes were not archived for GOES/VISSR images. The GOES images presented here have not been enhanced or rectified. North-south foreshortening is noticeable in images taken in higher latitudes such as those of the Great Lakes.

3.2 General Description

The ice cycle that occurs on the Great Lakes each winter can be divided into three phases (Rondy, 1971): a cooling phase, an ice formation phase, and a breakup or fragmentation phase. In brief, the cooling phase starts in fall as air temperatures drop below water temperatures and the water begins to lose heat. Ice formation starts after fall overturn is completed and a stable water density gradient enables rapid cooling to take place in the surface layer. During the ice formation phase, both stable and dynamic ice is formed. Even though the net energy balance of the lake is negative during this time, i.e., the water mass is losing heat, rapid and extensive changes in ice extent and thickness can occur due to wind and current induced ice movement, upwelling of warmer waters, and even mid-winter thaws on some portions of the Great Lakes. The breakup period begins when the energy balance of the ice cover becomes positive and may be well defined and short if a warming trend starts and is persistent, or it my drag on as cold and warm periods alternate in frequency and intensity in spring. In this report the end of the ice formation period is defined as the date the running sum of FDD accumulations at representative stations for each lake reaches its maximum value.

3.2.1 Fall Cooling Phase

As an indication of the intensity of the fall cooling phase the NWS Forecast Office at Detroit has developed an index of antecedent heat content of lake waters. This index is based upon the following three types of water temperature data available on the Great Lakes:

1. Surface temperature, measured by satellite-borne infrared sensors.

2. Near-surface temperatures measured at municipal and ship water intakes.

3. Occasional expendable bathythermograph soundings from Lake Superior.

Each of these observational tools provides data useful in some phase of the ice forecasting program. However, indirect methods must still be used to approximate the heat content of the lake as prediction of heat content based on models is still in the developmental stage.

Each lake goes through an isothermal stage twice each year, usually in April or early May, and again in early December. At these times the lake is isothermal at precisely 4°C. The heat content associated with this temperature may be taken as the base heat content of the lake.

Any excess or deficiency above or below this base heat content has been absorbed from or lost to the atmosphere since the last isothermal stage. Average air temperatures, integrated over periods of several months, have been found to give useful indications of the water's heat content.

Several different methods of integrating air temperature have been used. The most useful attempted so far, incorporating a "decay factor" to give greater weight to more recent data, is calculated as follows:

$$S_m = \frac{\Delta T_m + S_{m-1}}{2},$$

where

S_m is the heat storage factor at the end of a month,

ΔT_m is the departure from normal of the average air temperature for the month,

S_{m-1} is the heat storage factor at the end of the previous month.

The physical meaning of the heat storage factor cannot be precisely defined. It approximates the excess heat, sensible and latent, or a unit water mass within the epilimnion. Units are degrees farenheit.

At the end of August 1976, the heat storage factor was still positive over most of the upper lakes despite below normal air temperatures everywhere except over Lake Superior. By the end of September, positive factors were present only over small portions of the upper lakes, and increasingly negative heat storage was indicated everywhere else. This was the first significant harbinger of an early freezeup. By the end of October, large negative heat storage factors were apparent throughout the Lakes; they continued to increase through January. Table 4 summarizes the changes in the heat storage factor during the cooling and freezing period of 1976-77.

Table 4. Heat Storage Factor at Month's End

City	Aug.	Sept.	Oct.	NOV.	Dec.	Jan.
Duluth, Minn.	+1.15	+1.03	-3.59	-4.95	-7.43	-8.06
Green Bay, Wis.	+0.71	-0.25	-3.08	-5.39	-8.60	-10.45
Chicago, Ill.	-0.89	-1.15	-3.97	-5.79	-7.10	-10.52
Sault Ste. Marie, Mich.	+1.10	-0.30	-2.60	-4.05	-7.13	-7.51
Detroit, Mich.	+0.22	-0.64	-3.17	-4.89	-5.95	-8.88
Buffalo, N.Y.	-0.55	-1.03	-3.12	-4.41	-5.12	-7.53

3.2.2 Ice Formation and Breakup Phases

The general seasonal pattern of ice formation and decay is illustrated by a series of 21 weekly composite ice charts (Fig. 11*a-u*). These charts were compiled from available ice charts and supplementary ice-cover data as described in Section 3.1. FDD accumulations (°C) at eight representative locations are included as an indication of winter severity. The FDD's were calculated from average weekly temperatures given in the *Weekly Weather and Crop Bulletin*. In addition to the composite ice charts, 54 satellite images (Figs. 12*a-bbb*) document synoptic ice conditions for given dates throughout the 1976-77 ice cycle.

Two methods were used to estimate the percent of each lake that was ice covered. From ice charts, measurements of areas of different ice concentrations were made directly by planimeter. From satellite imagery, the percent of ice cover was estimated by visual observation.

At almost the same time in early December the winter of 1976-77 produced ice in various shallow protected areas of the Great Lakes. Lake St. Clair was virtually frozen over by early January. The remainder of the Great Lakes neared maximum area1 ice coverage by the first week of February. Spring breakup started in the last half of February on the southern part of the Great Lakes and in the first week in March on the northern part of the Great Lakes. In general, open water areas first appeared lakeward of the western and northern shores

Figure 11a. *Composite ice chart for 5 December 1976.*

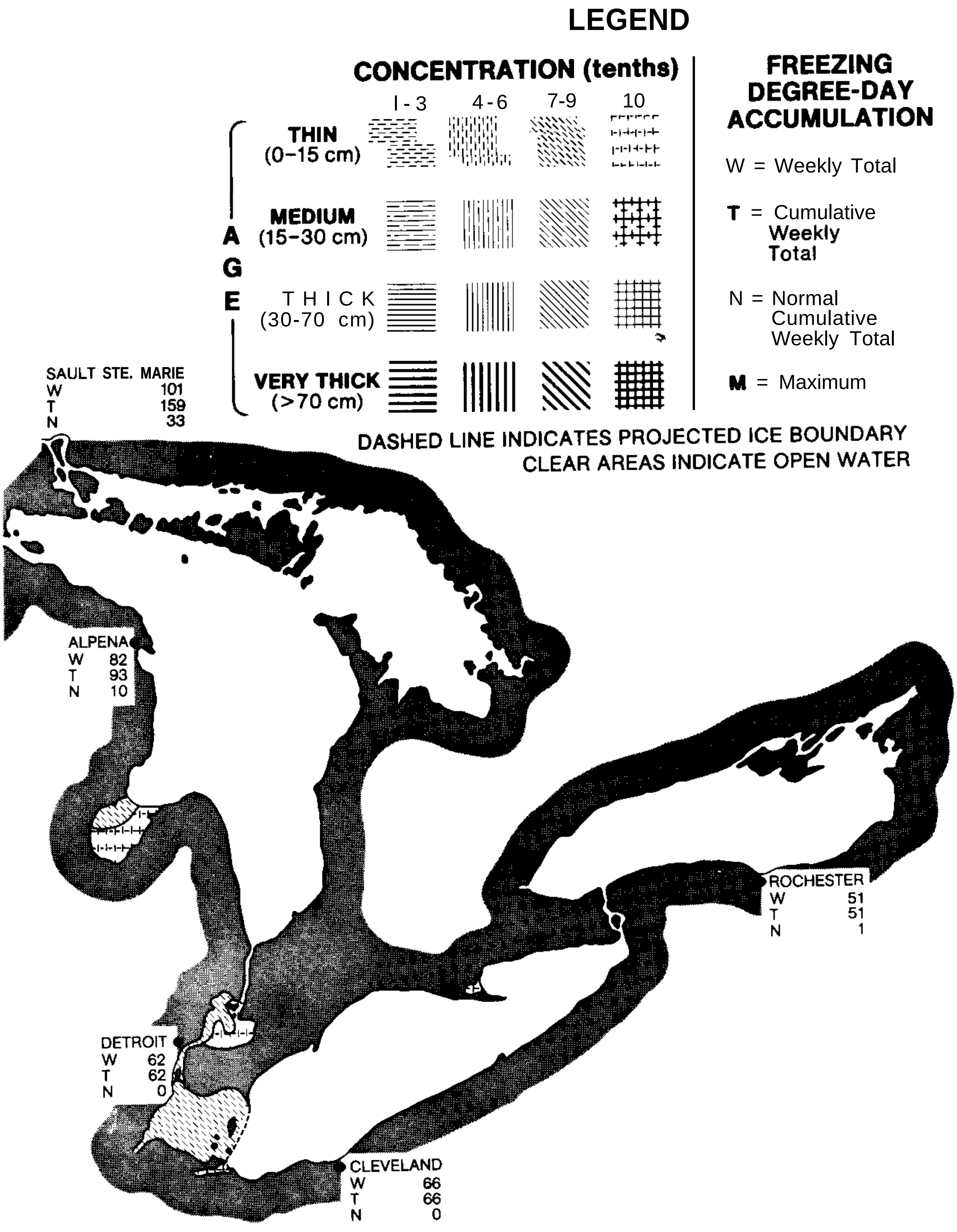

Figure 11a. Composite ice chart for 5 December 1976 (continued).

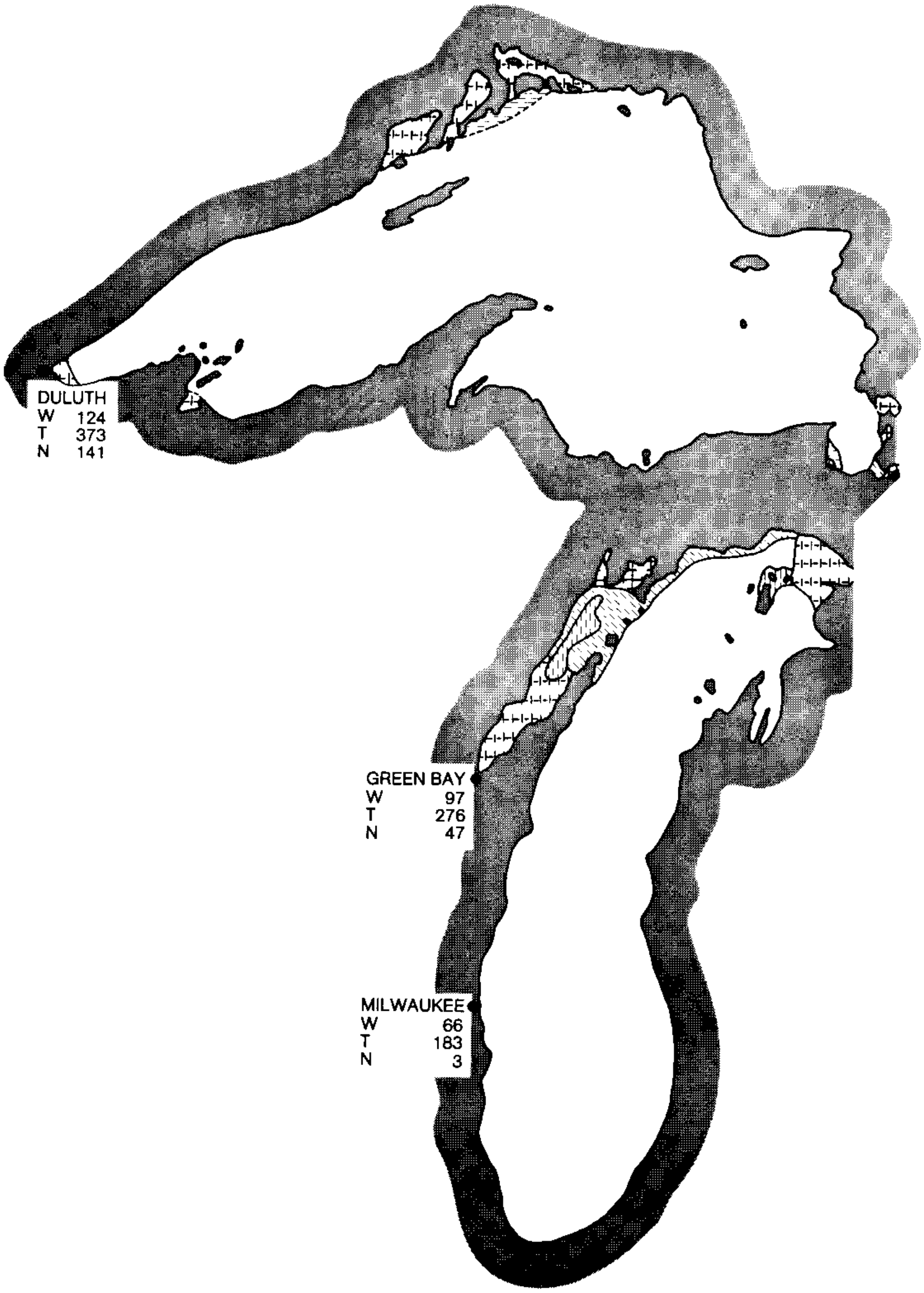

Figure 11b. Composite ice chart for 12 December 1976.

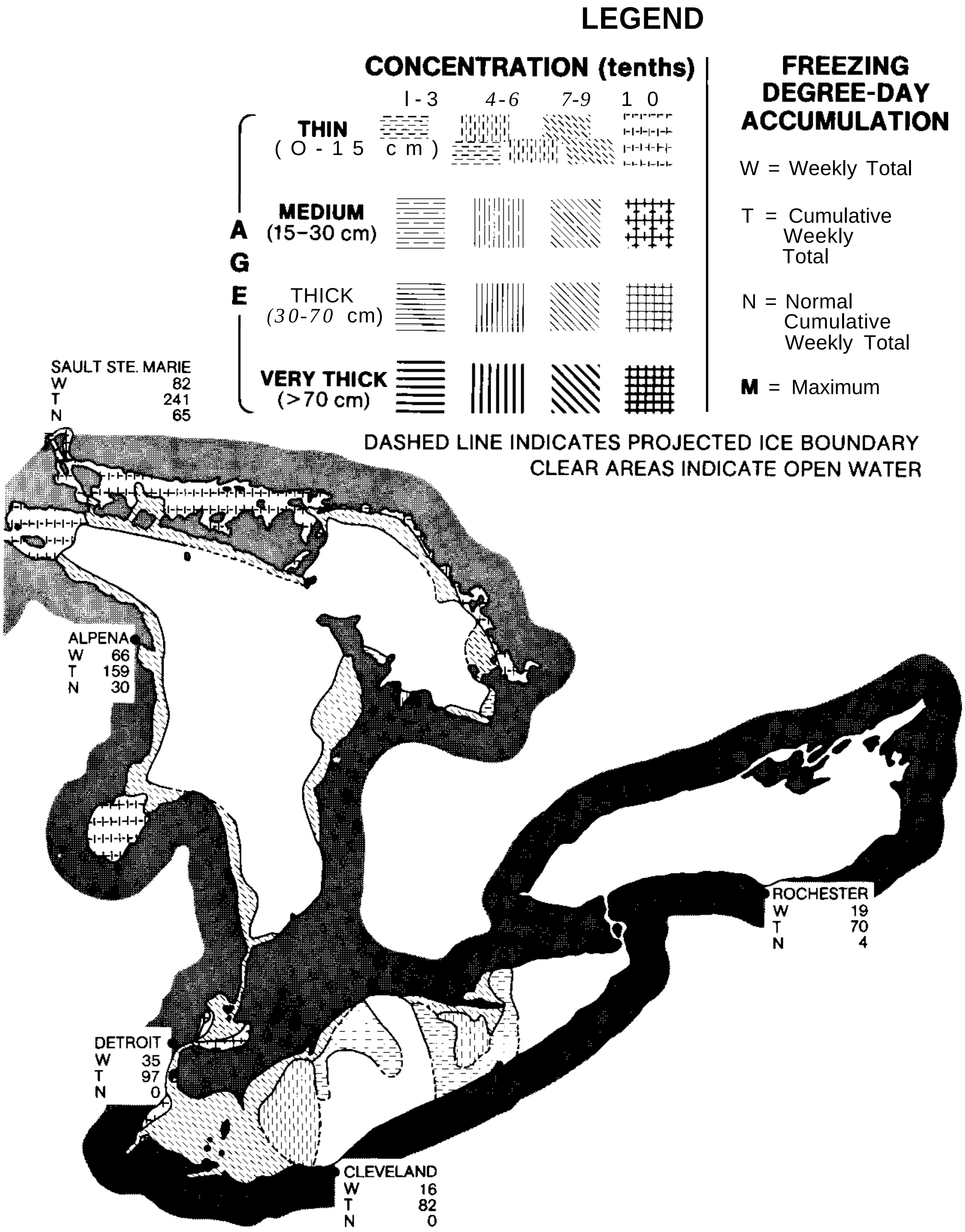

Figure 11b. Composite ice chart for 12 December 1976 (continued).

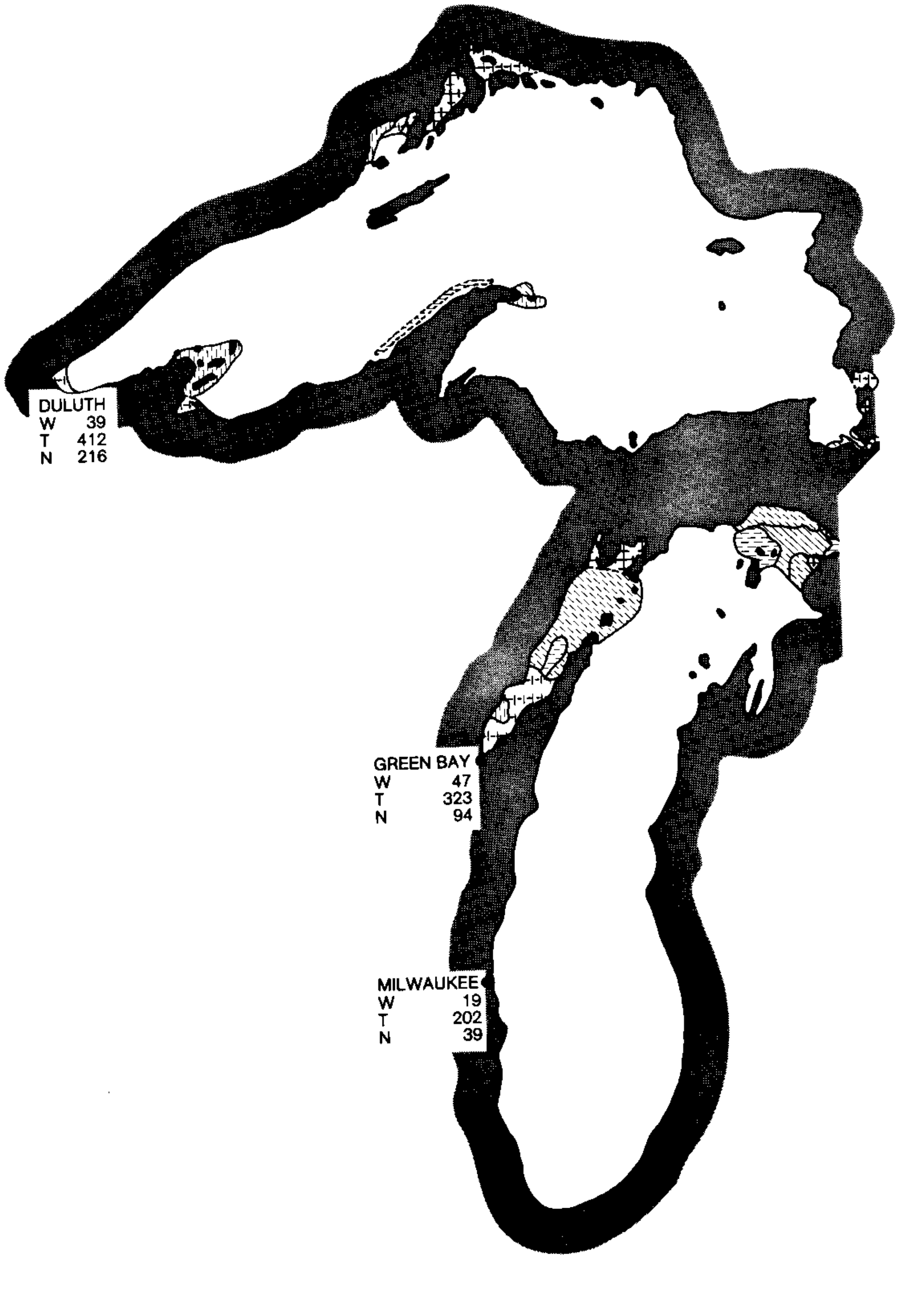

Figure 11c. Composite ice chart for 19 December 1976.

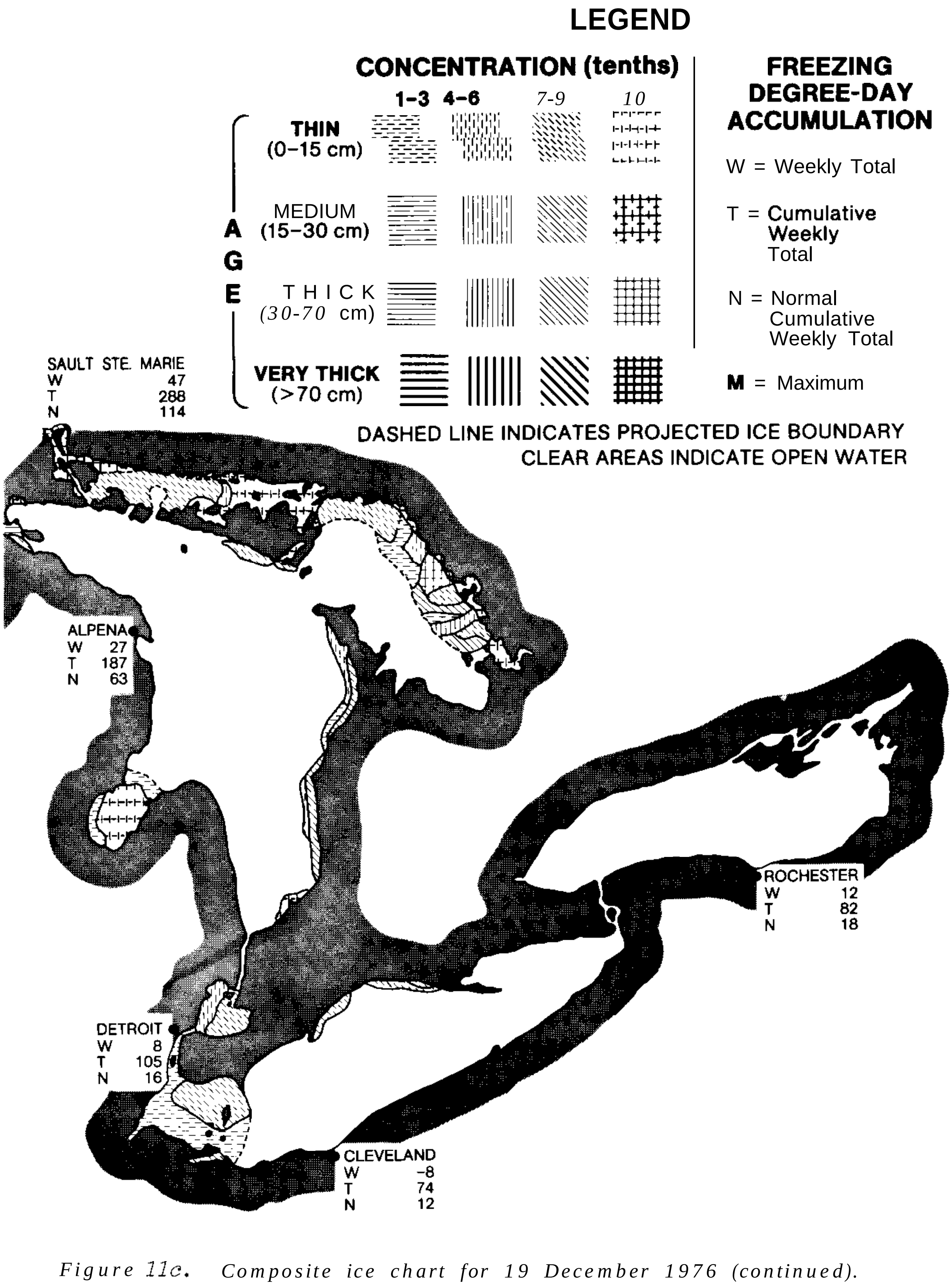

Figure 11c. Composite ice chart for 19 December 1976 (continued).

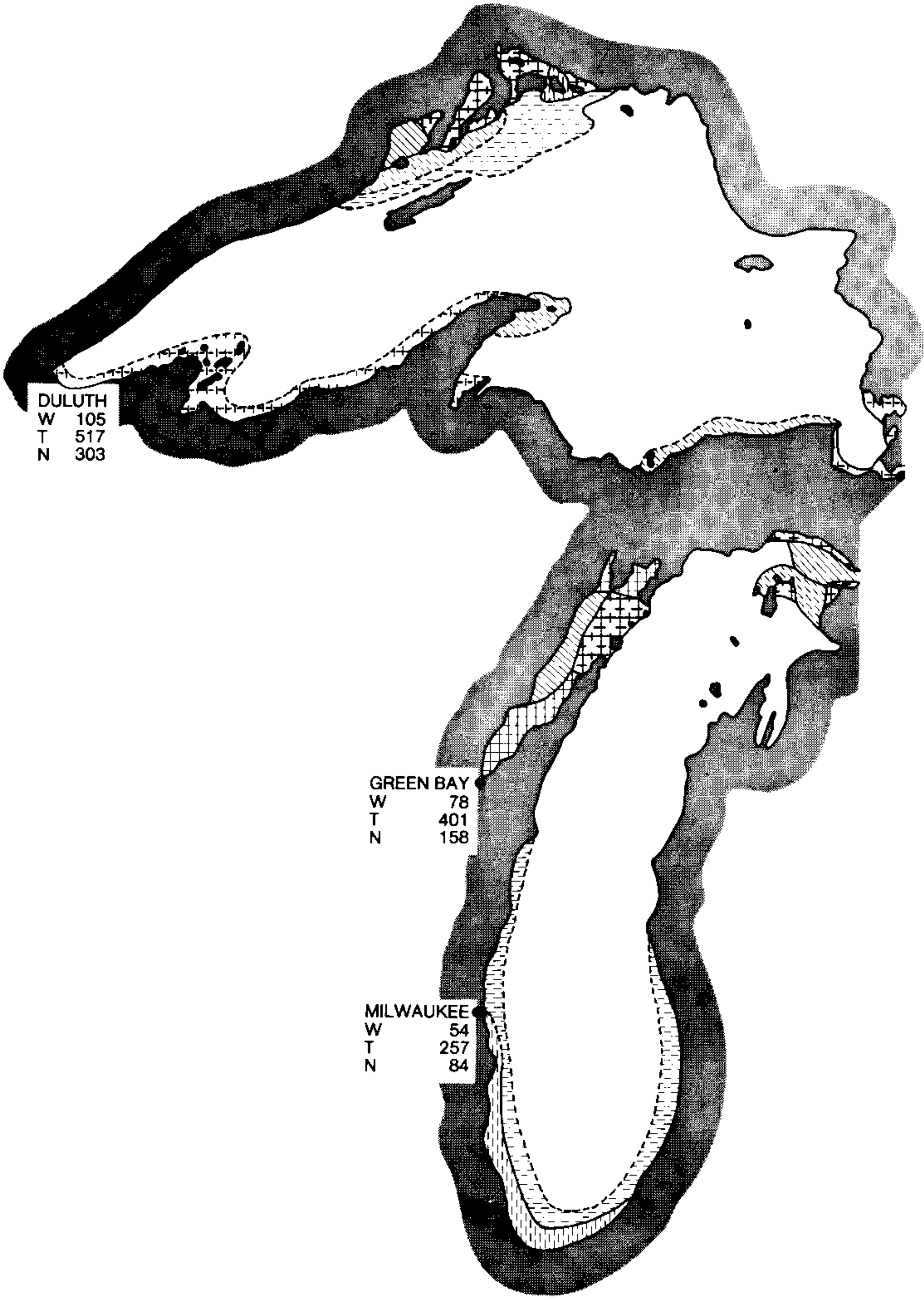

Figure 11d. Composite ice chart for 26 December 1976.

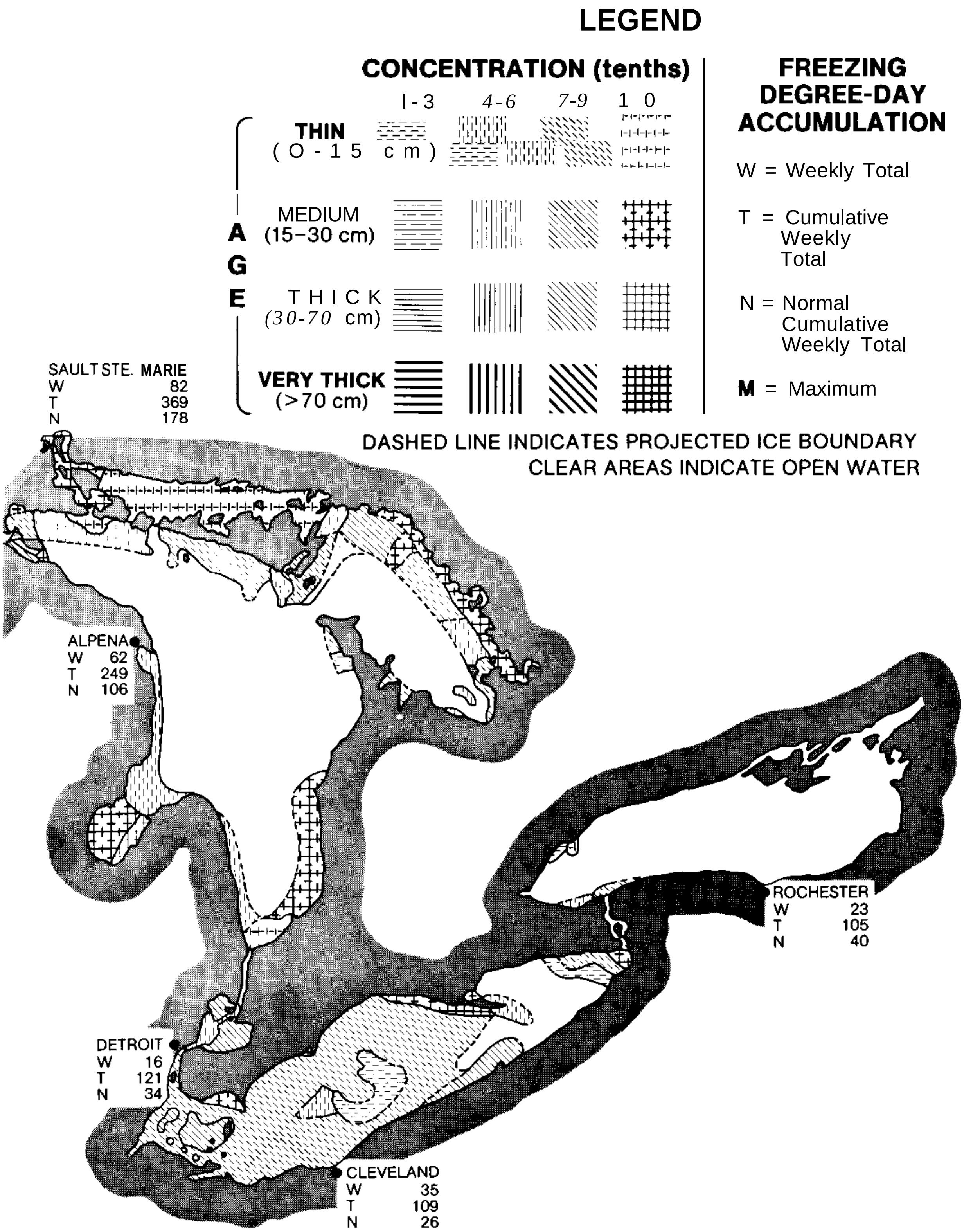

Figure 11d. Composite ice chart for 26 December 1976 (continued).

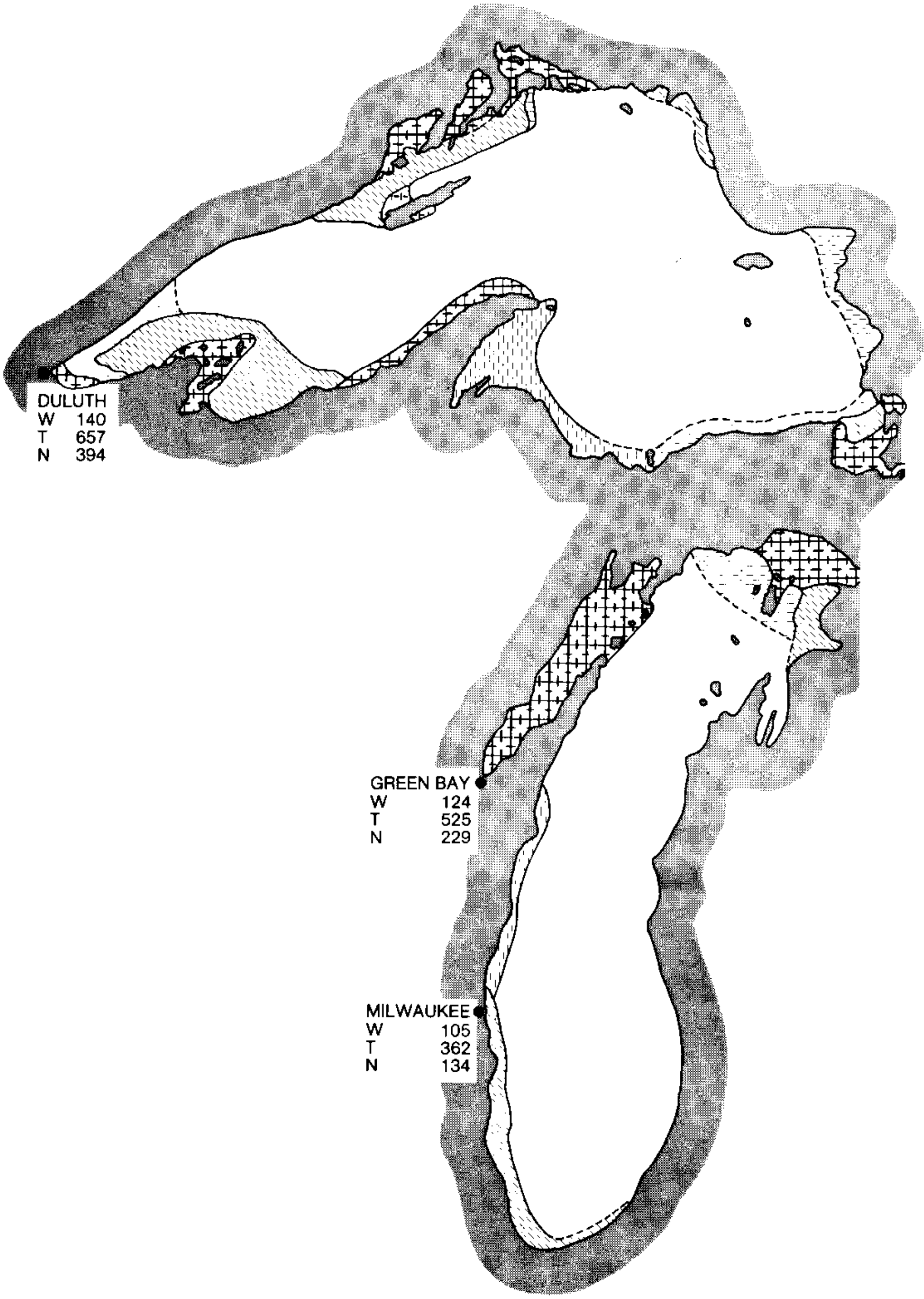

Figure 11e. Composite ice chart for 2 January 1977.

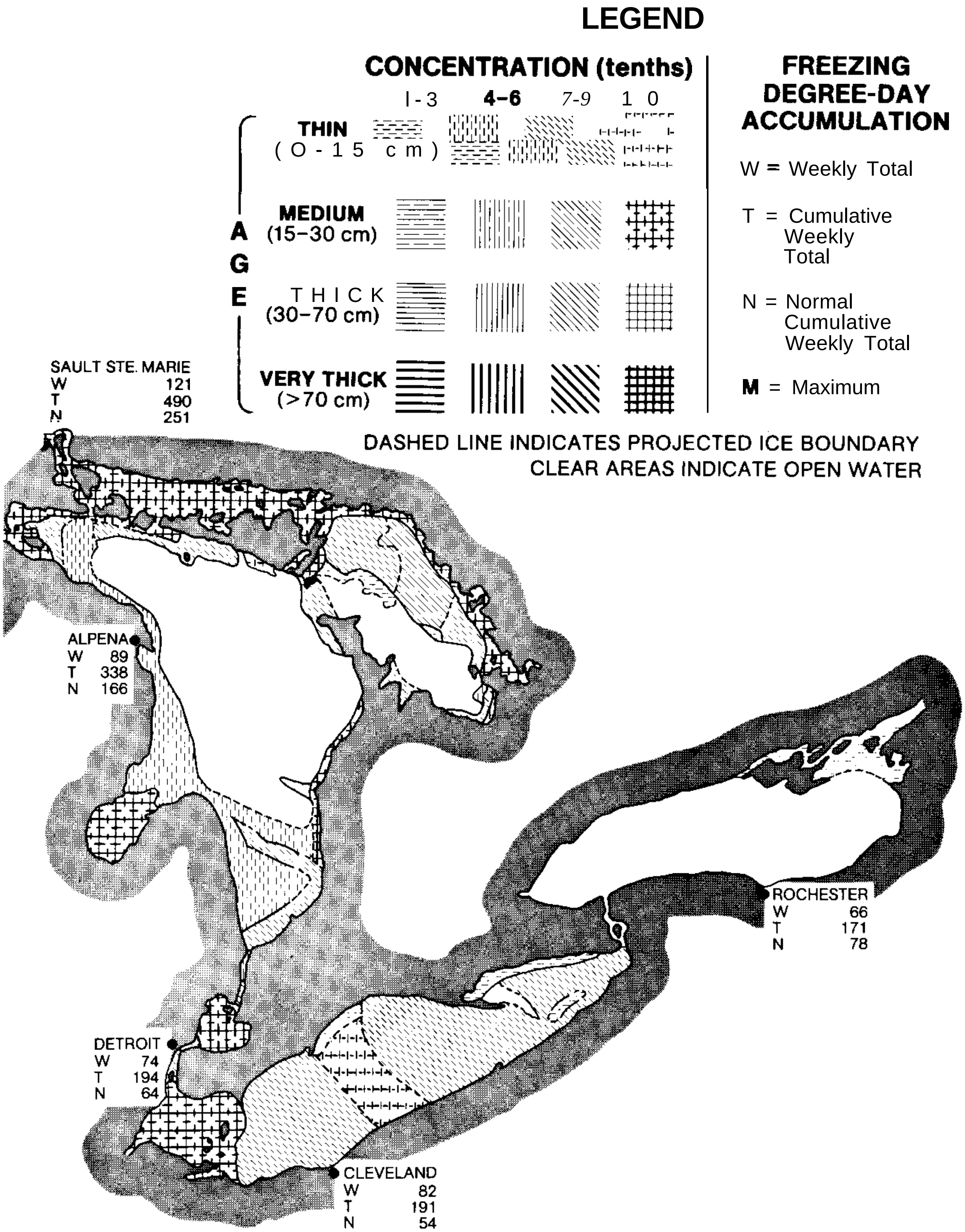

Figure 11e. Composite ice chart for 2 January 1977 (continued).

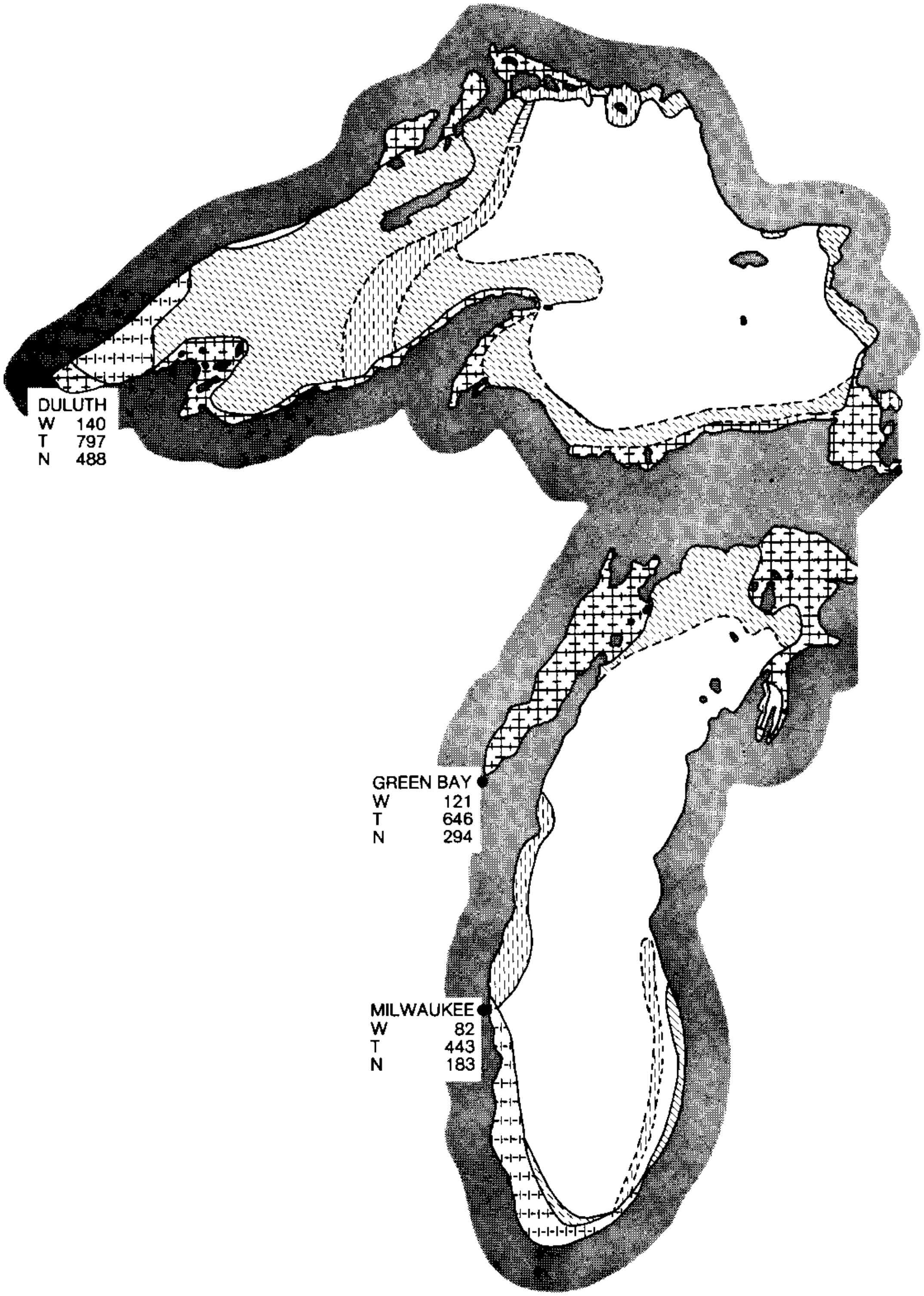

Figure 11f. Composite ice chart for 9 January 1977.

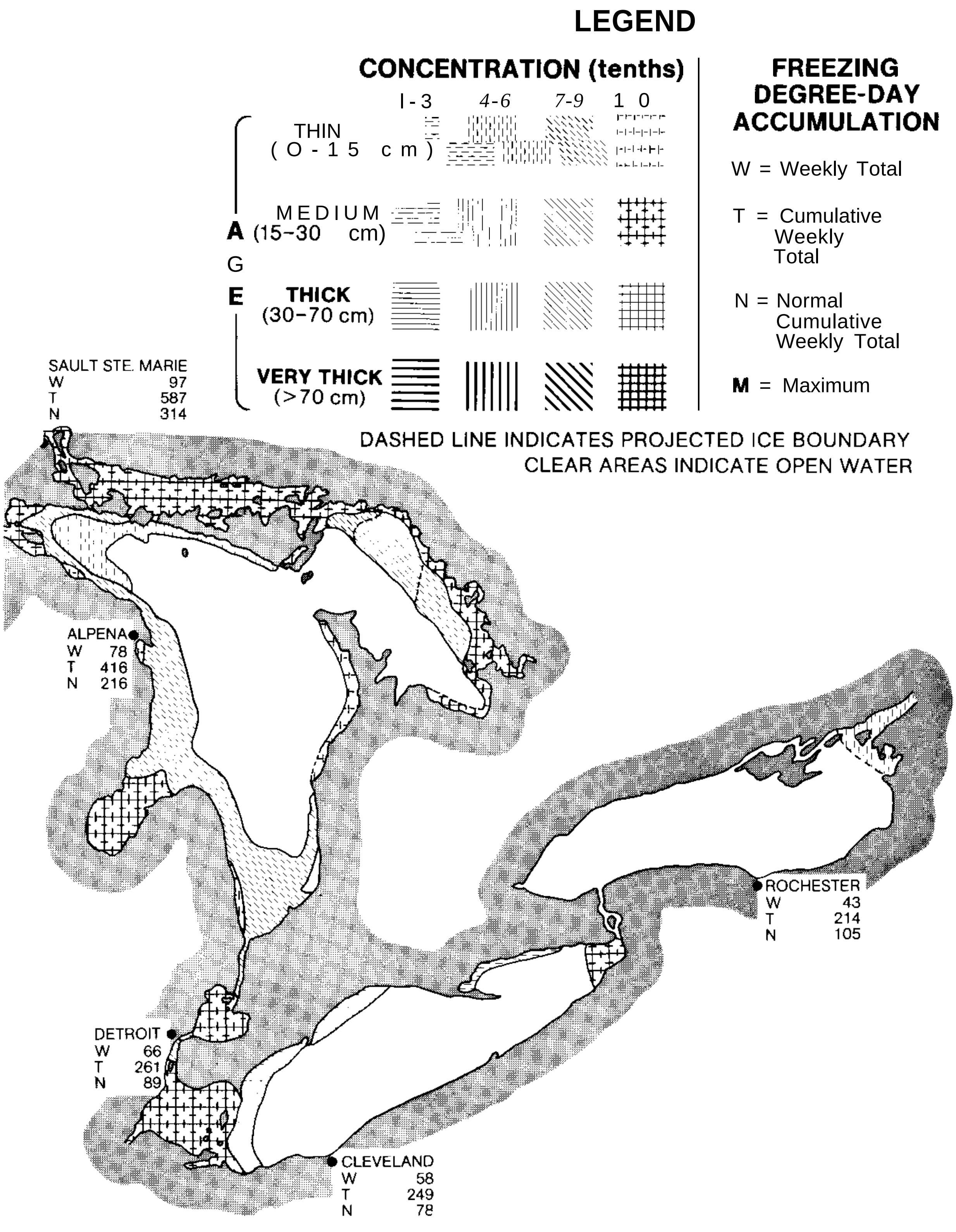

Figure 11f. Composite ice chart for 9 January 1977 (continued).

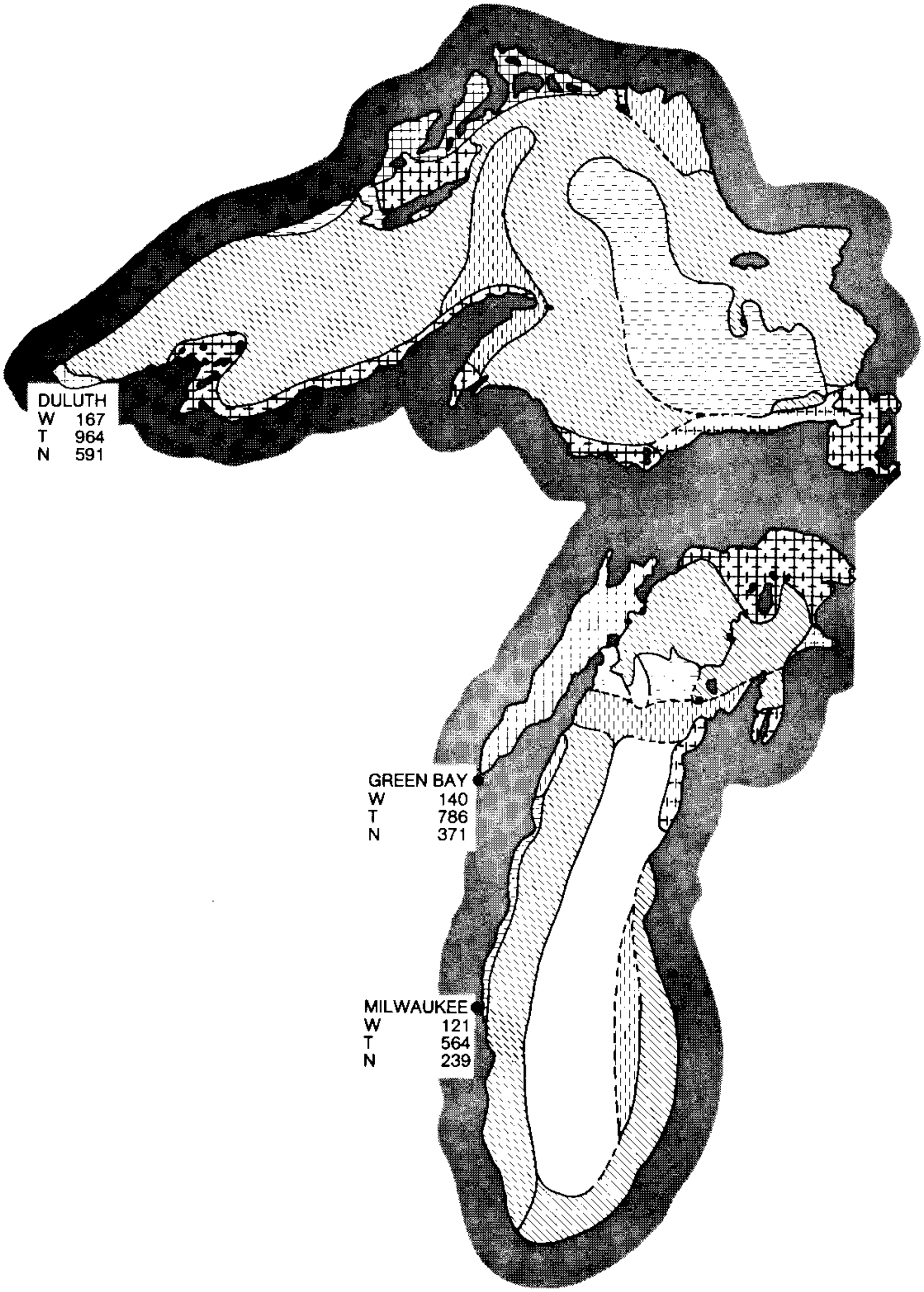

Figure llg. Composite ice chart for 16 January 1977.

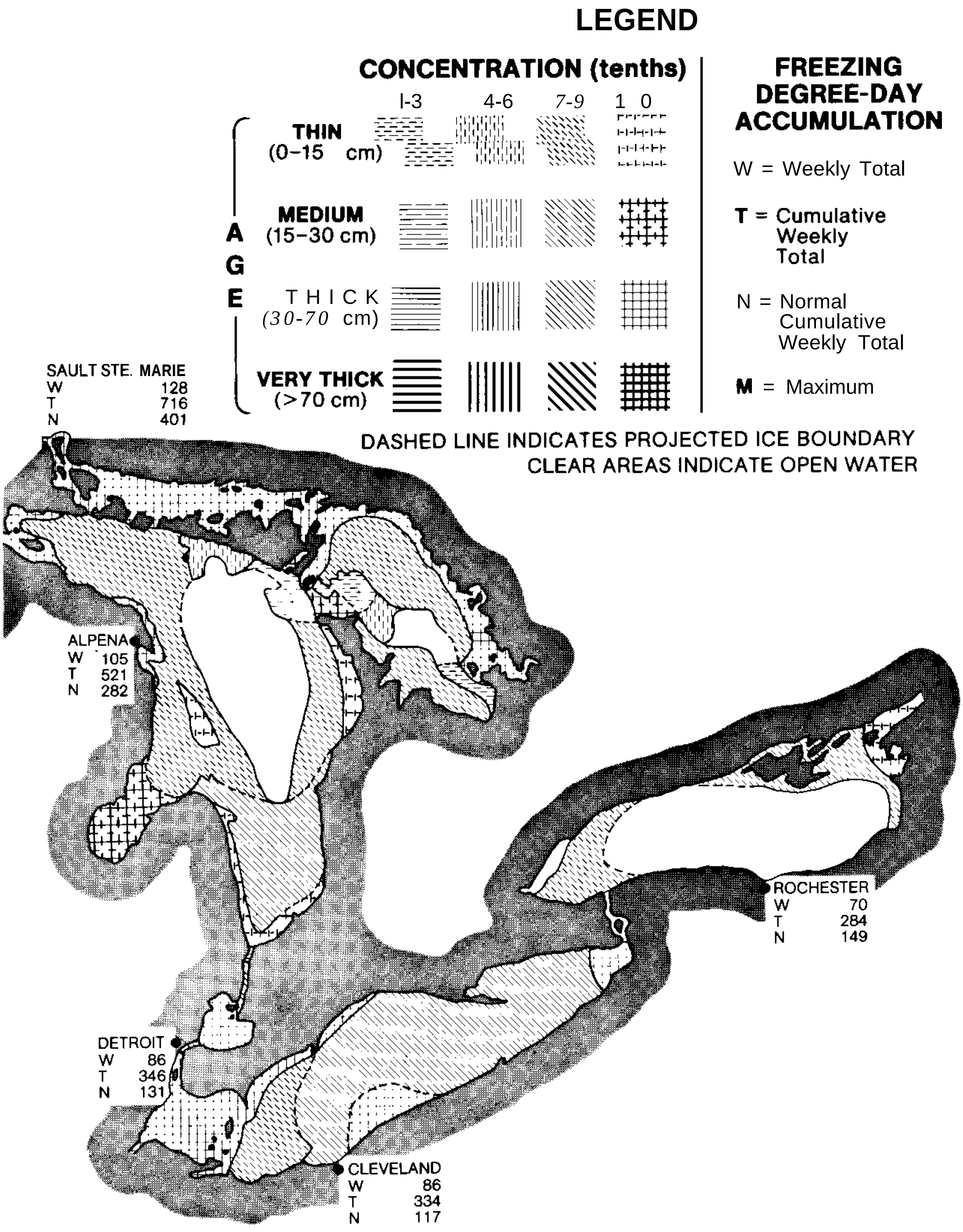

Figure 11g. Composite ice chart for 16 January 1977 (continued).

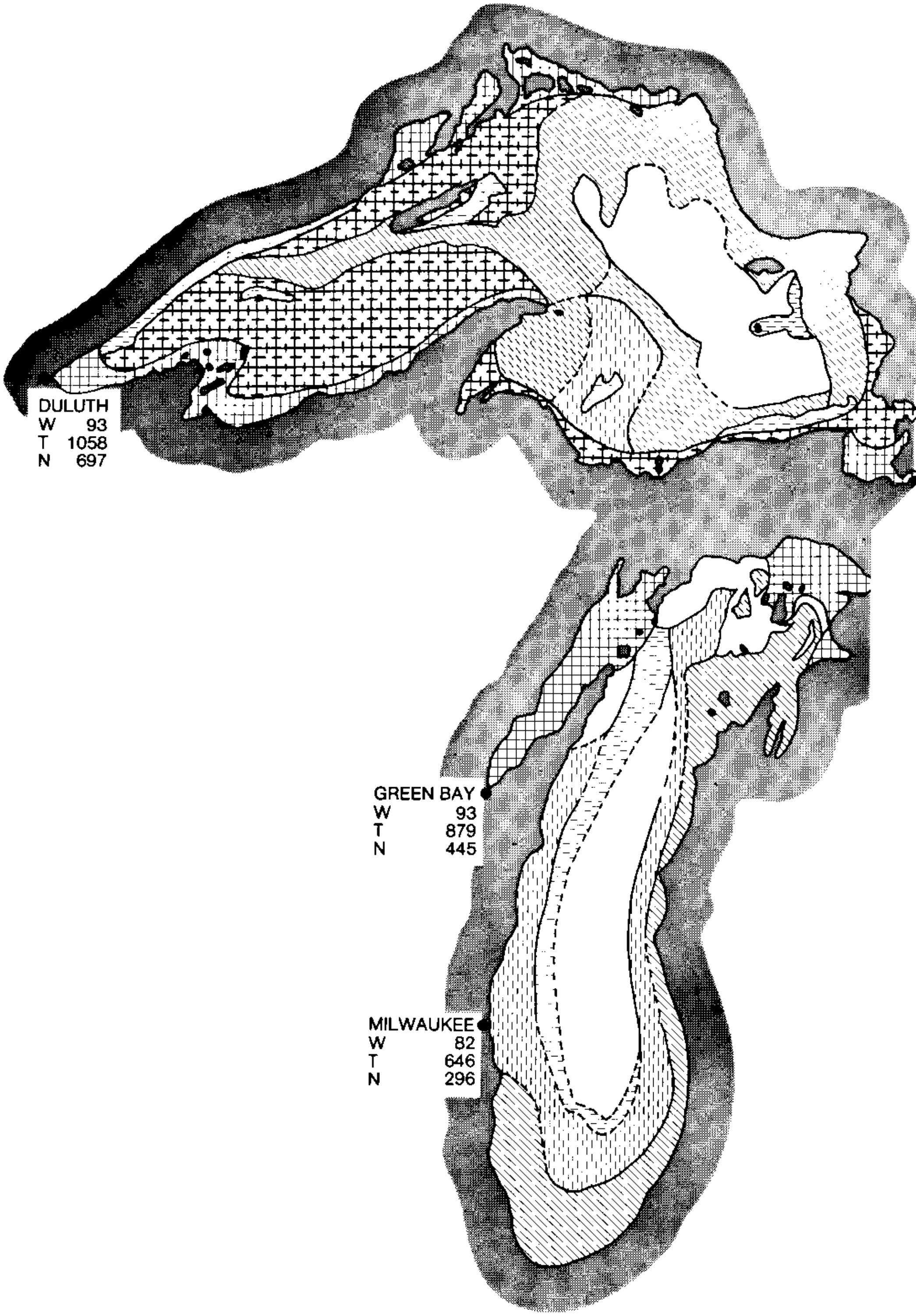

Figure llh. Composite ice chart for 23 January 1977.

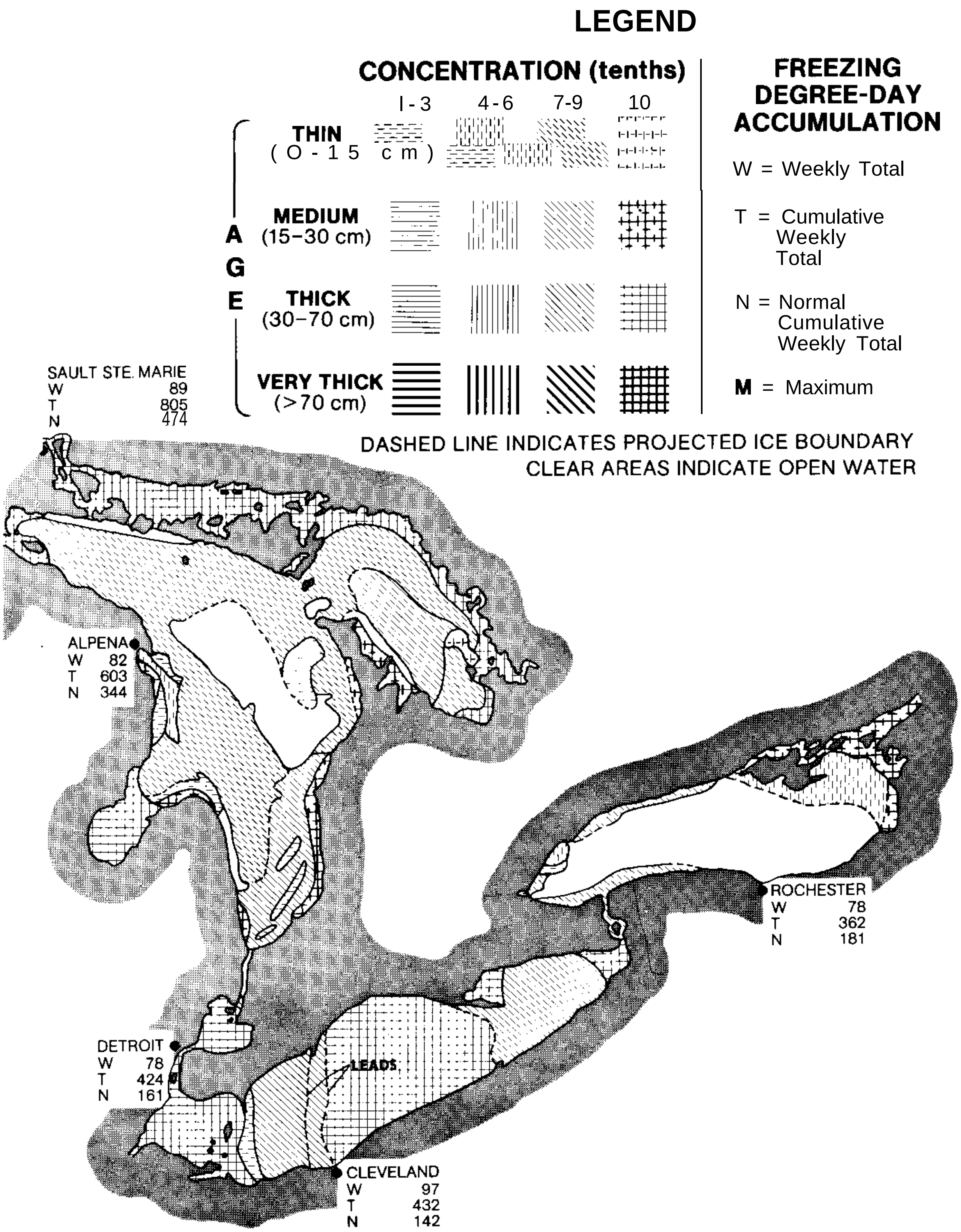

Figure llh. Composite ice chart for 23 January 1977 (continued).

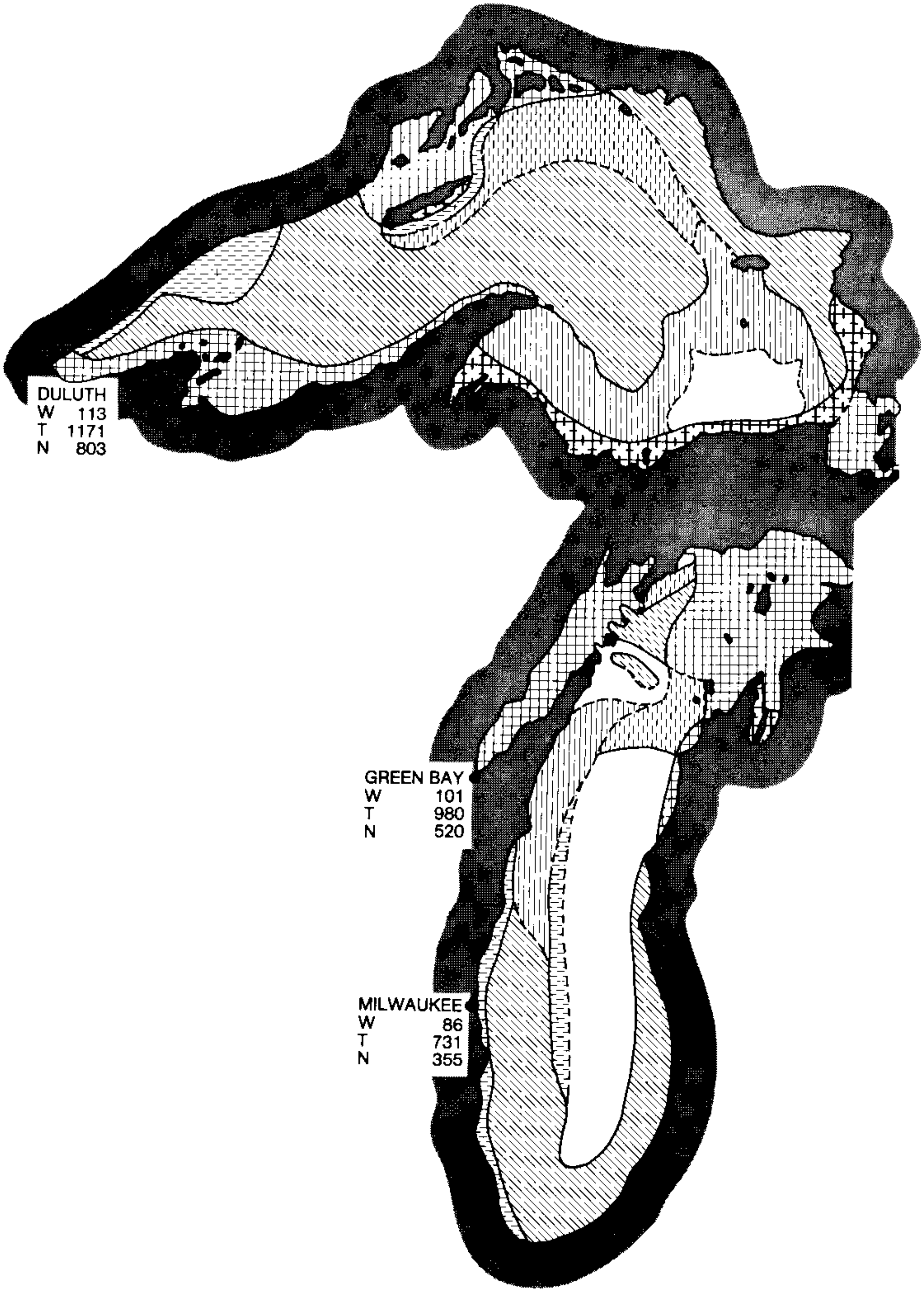

Figure lli. Composite ice chart for 30 January 1977.

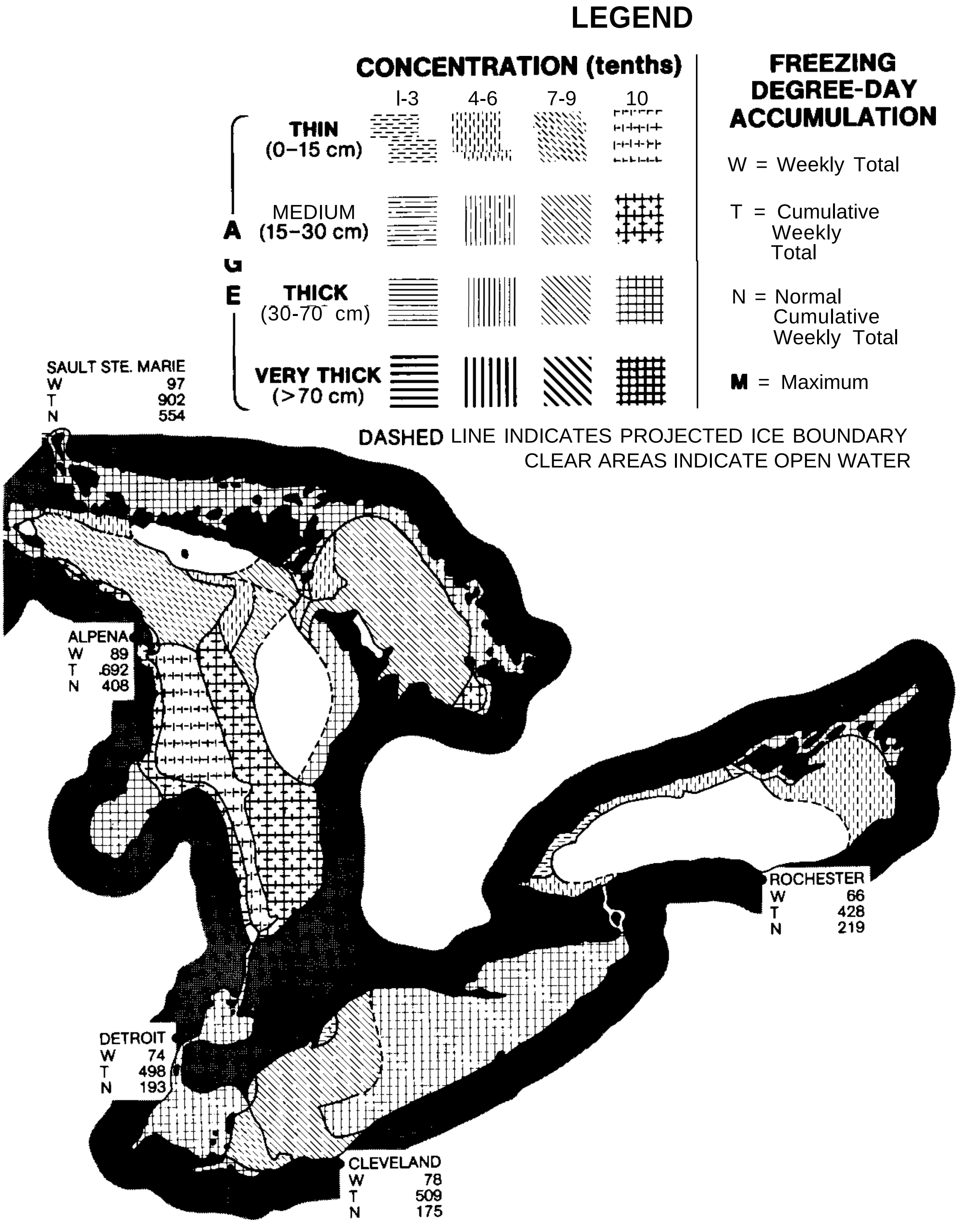

Figure lli. Composite ice chart for 30 January 1977 (continued).

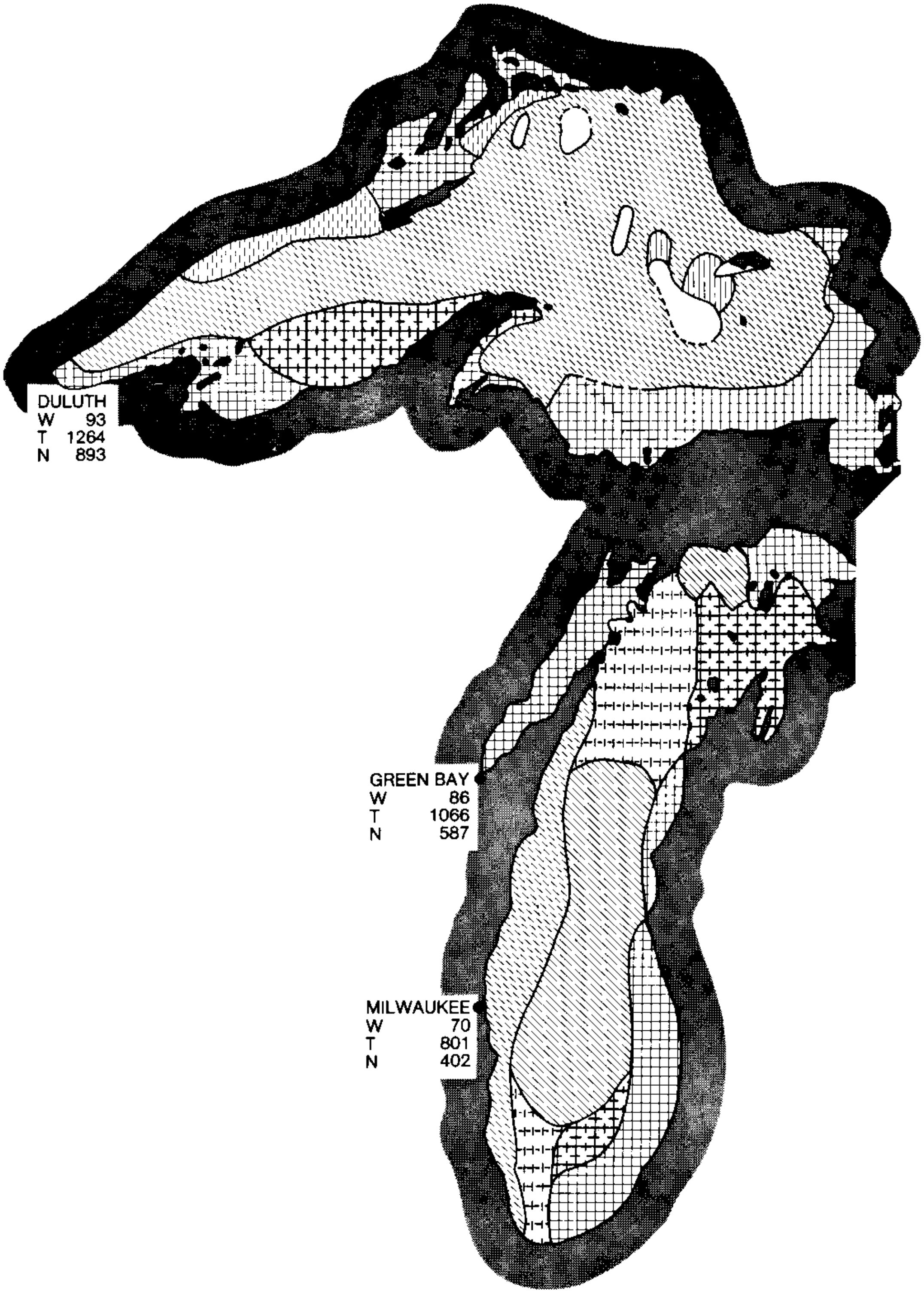

Figure 11j. Composite ice chart for 6 February 1977.

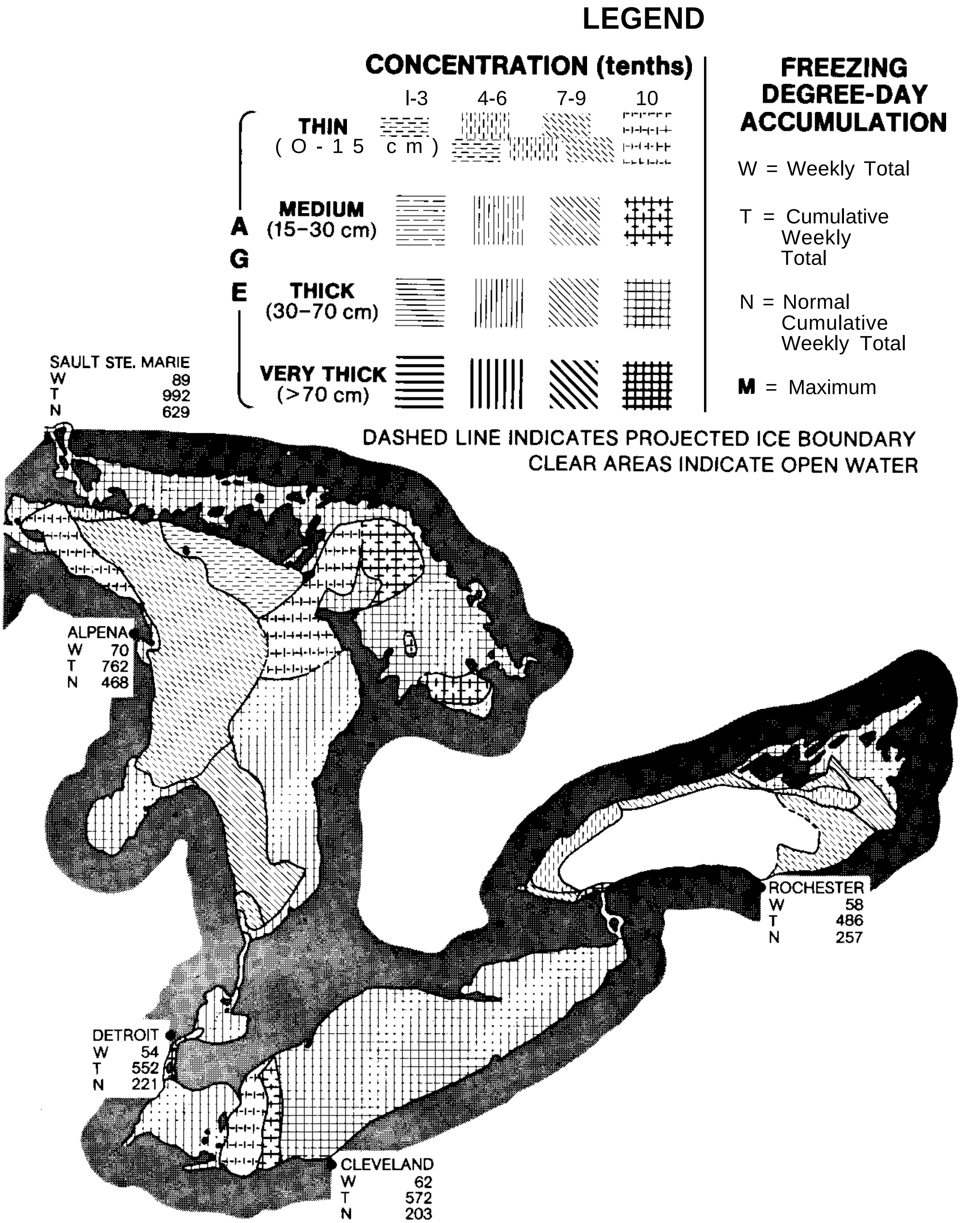

Figure 11j. Composite ice chart for 6 February 1977 (continued).

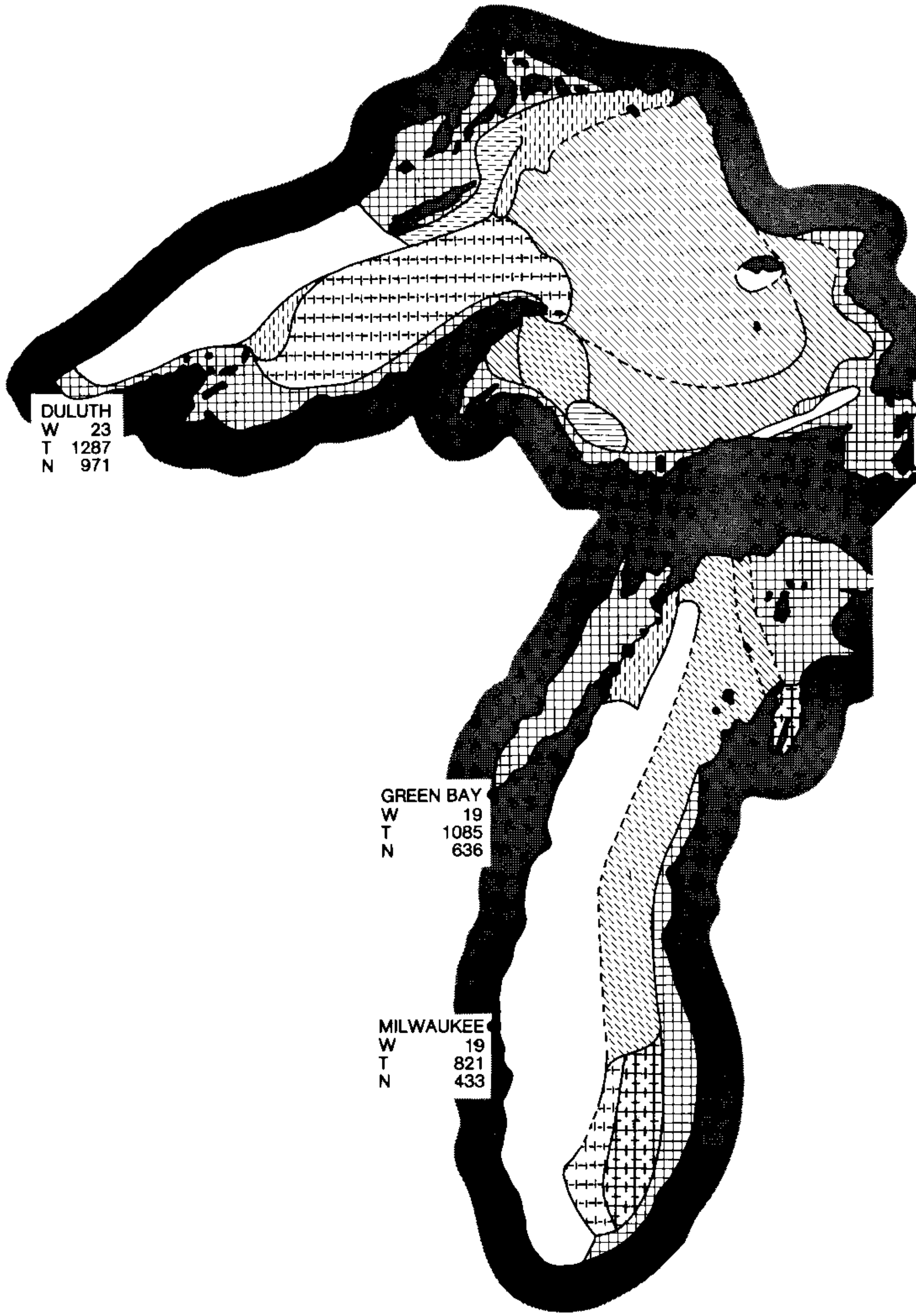

Figure 11k. Composite ice chart for 13 February 1977.

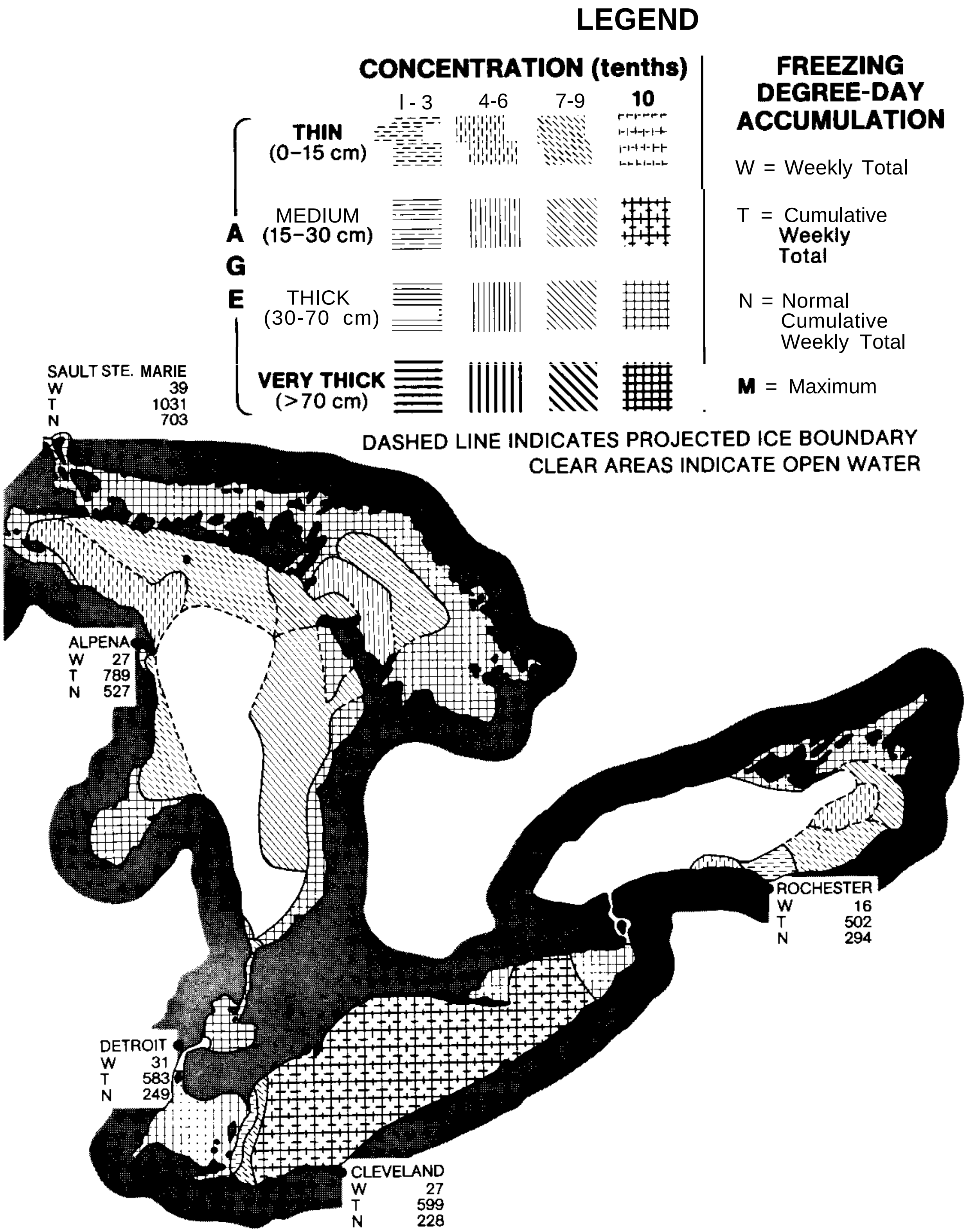

Figure 11k. Composite ice chart for 13 February 1977 (continued).

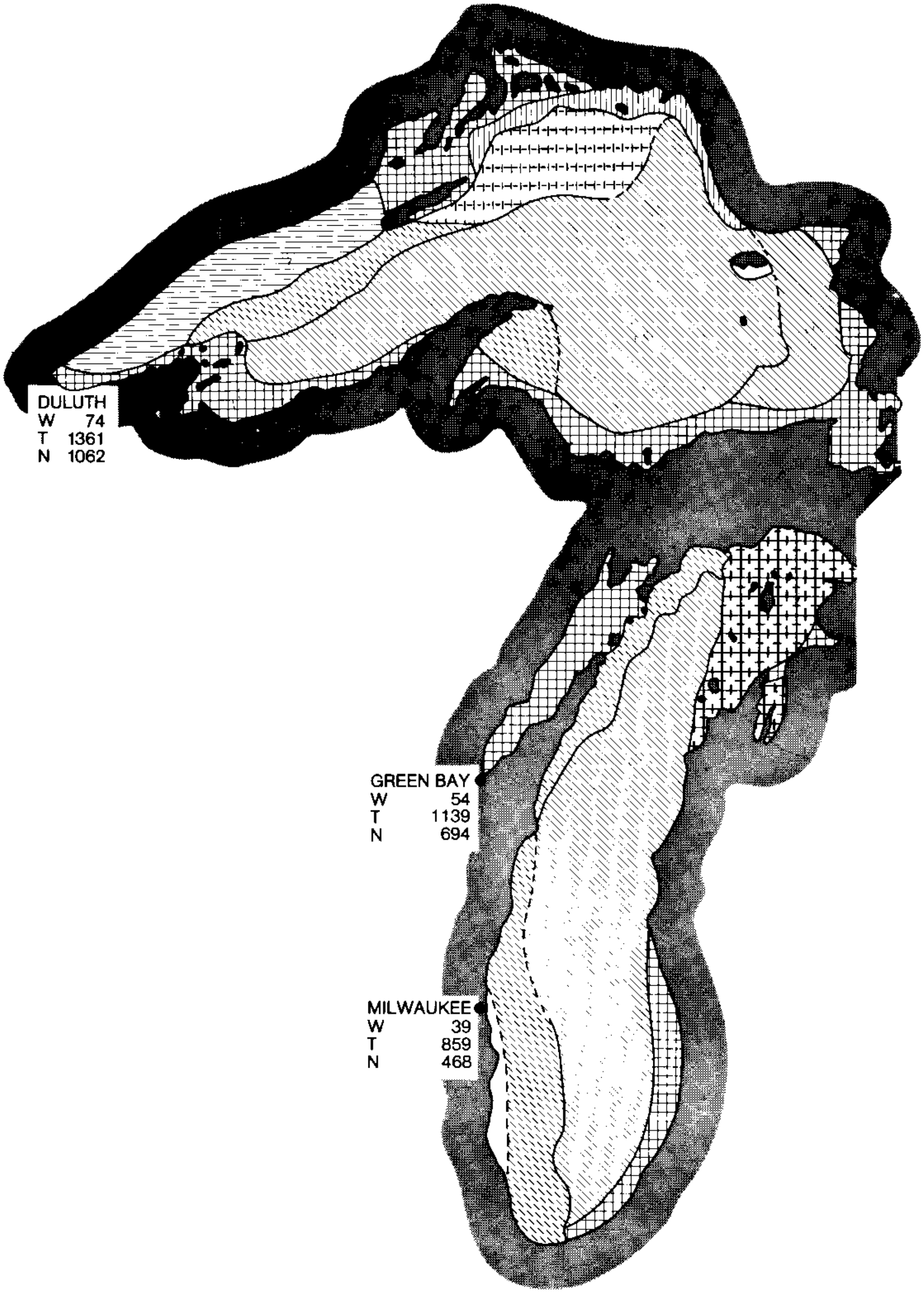

Figure 111. Composite ice chart for 20 February 1977.

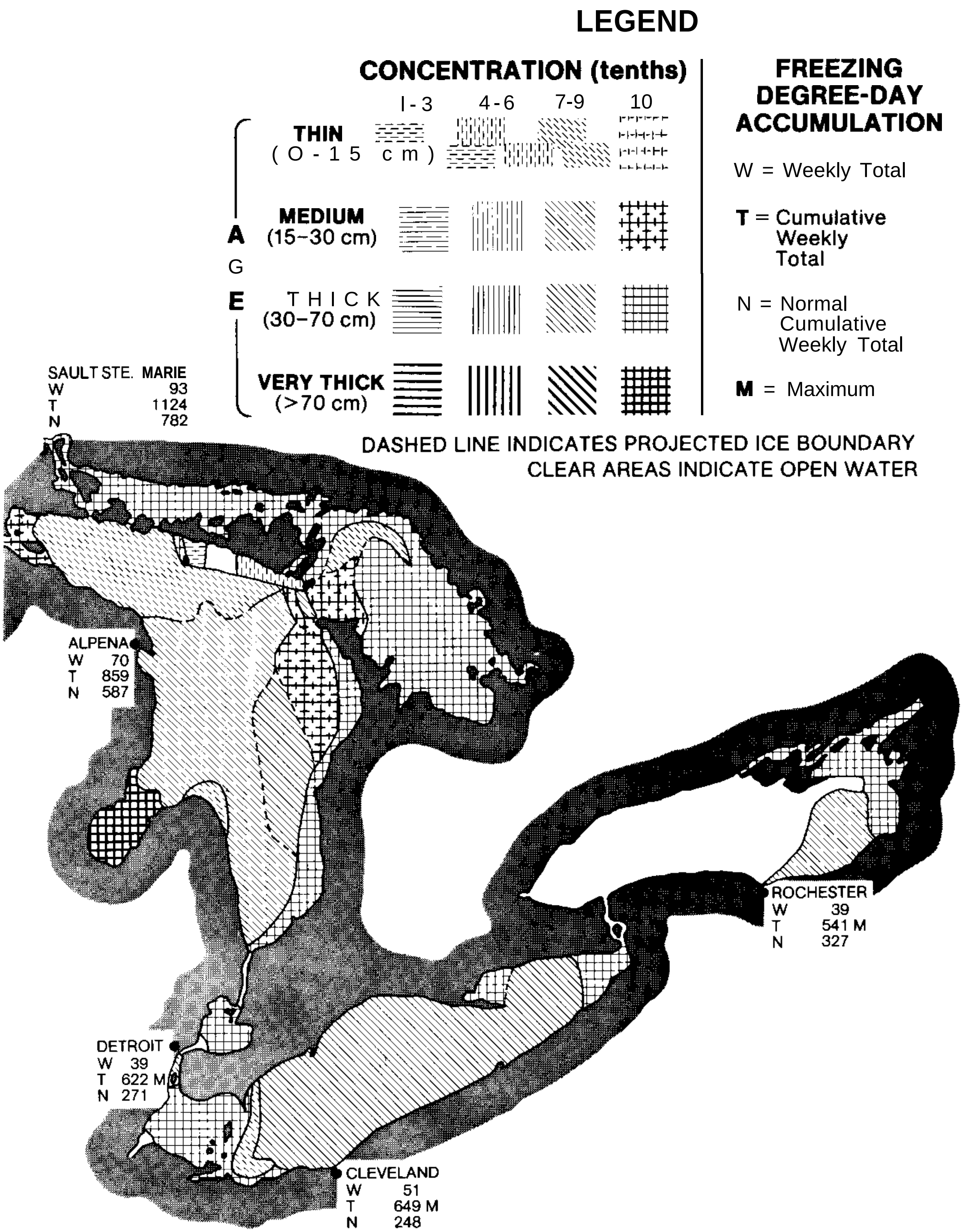

Figure 111. Composite ice chart for 20 February 1977 (continued).

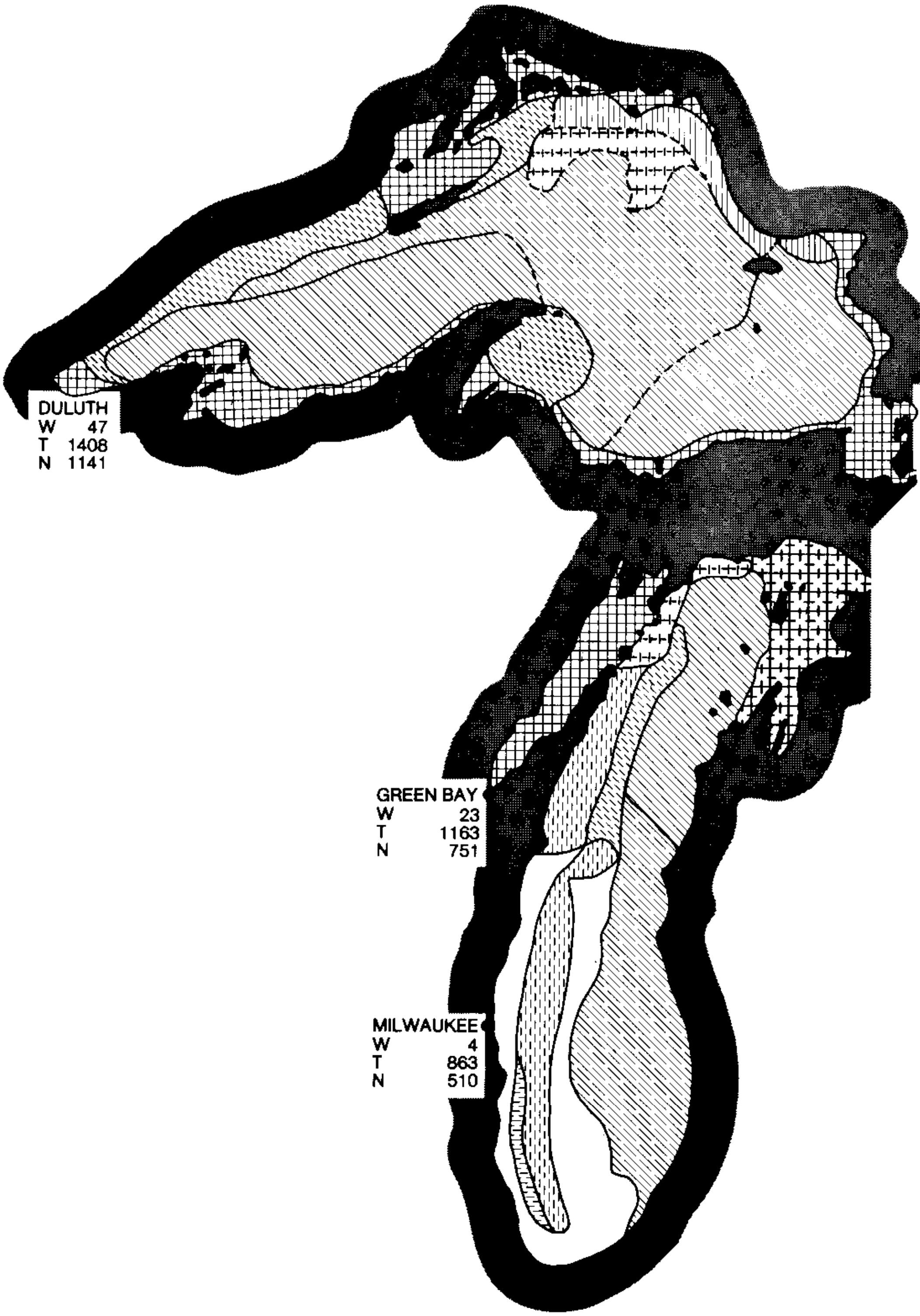

Figure 1 1m. Composite ice chart for 27 February 1977.

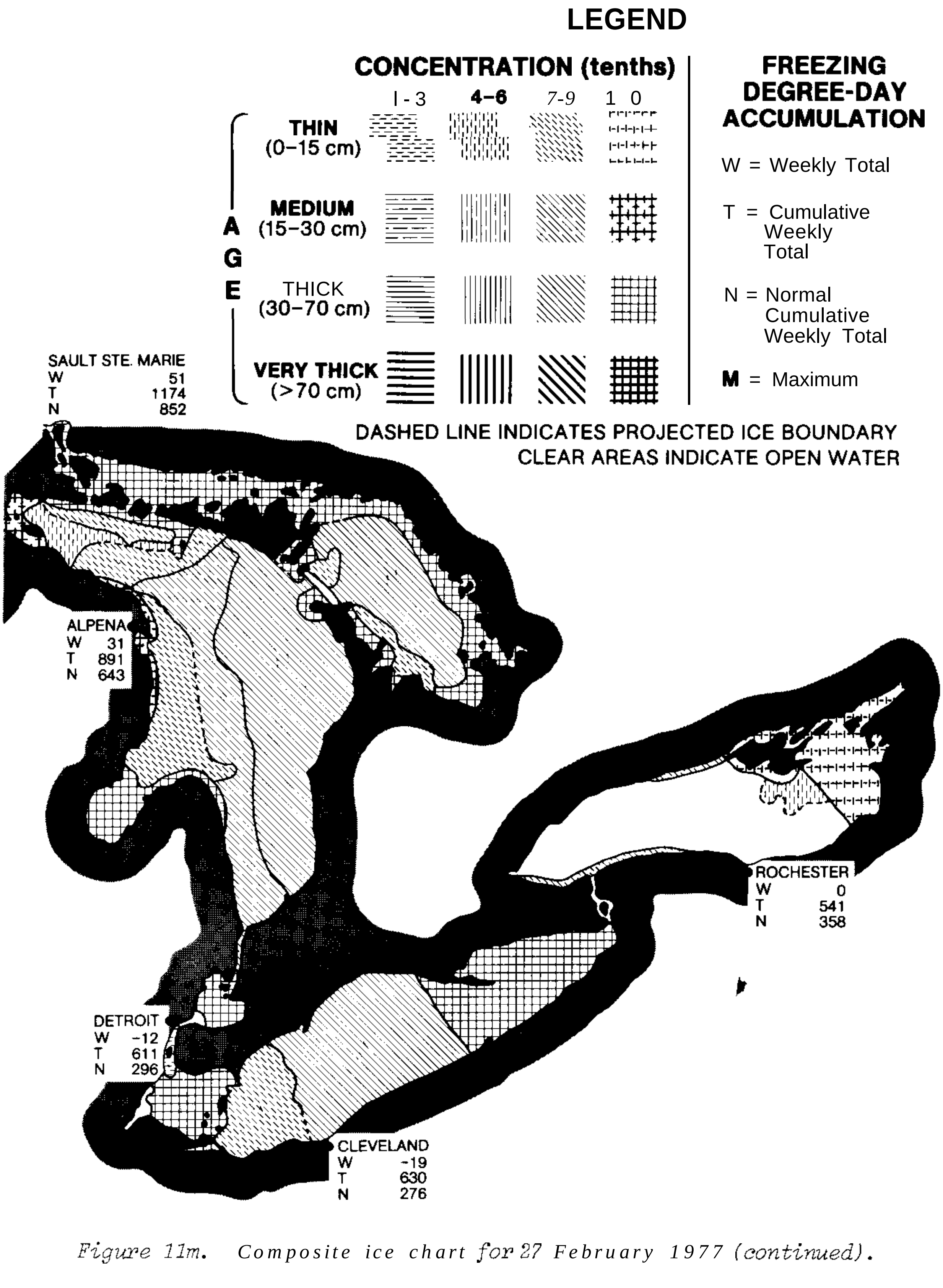

Figure 11m. Composite ice chart for 27 February 1977 (continued).

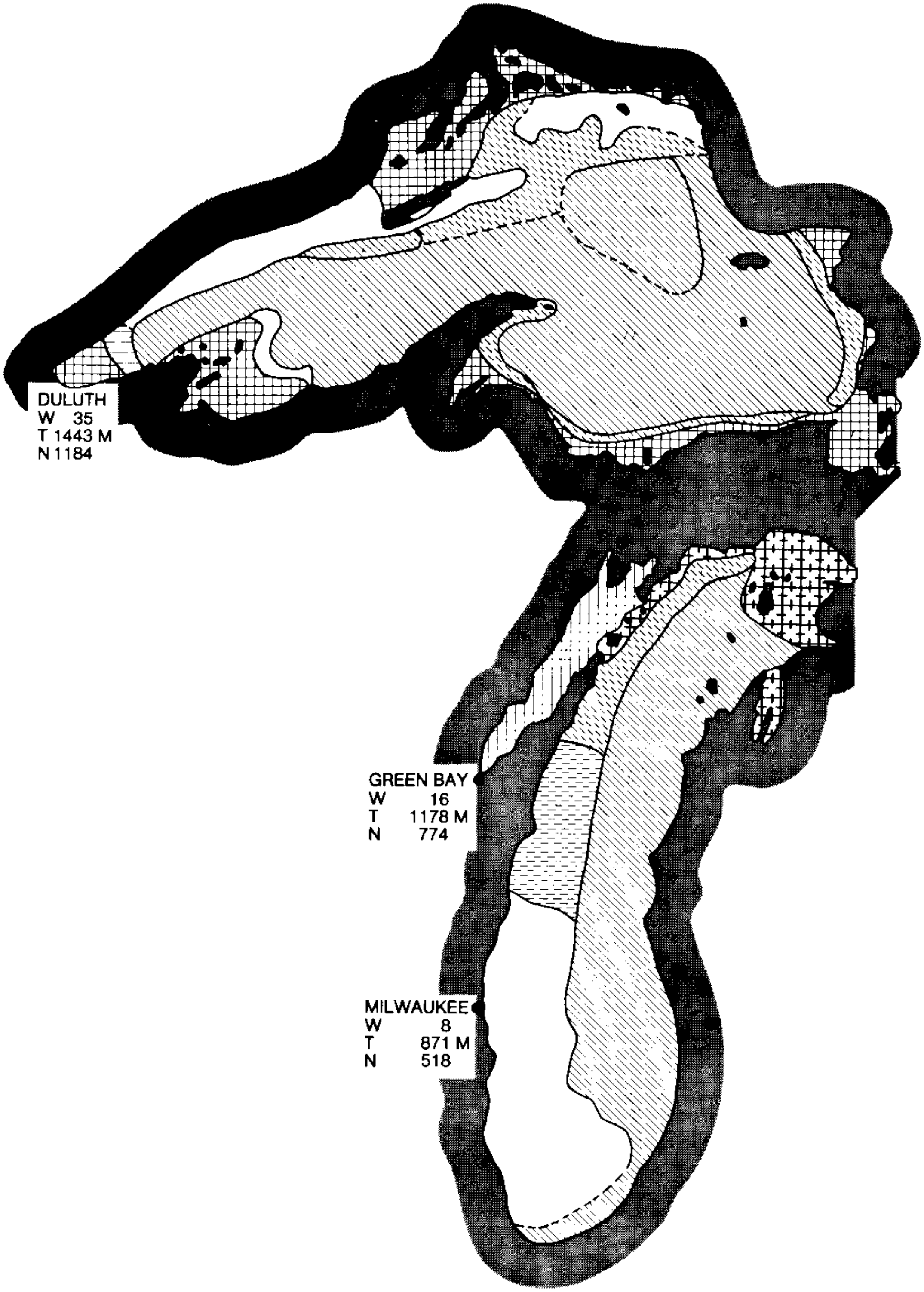

Figure 11n. Composite ice chart for 6 March 1977.

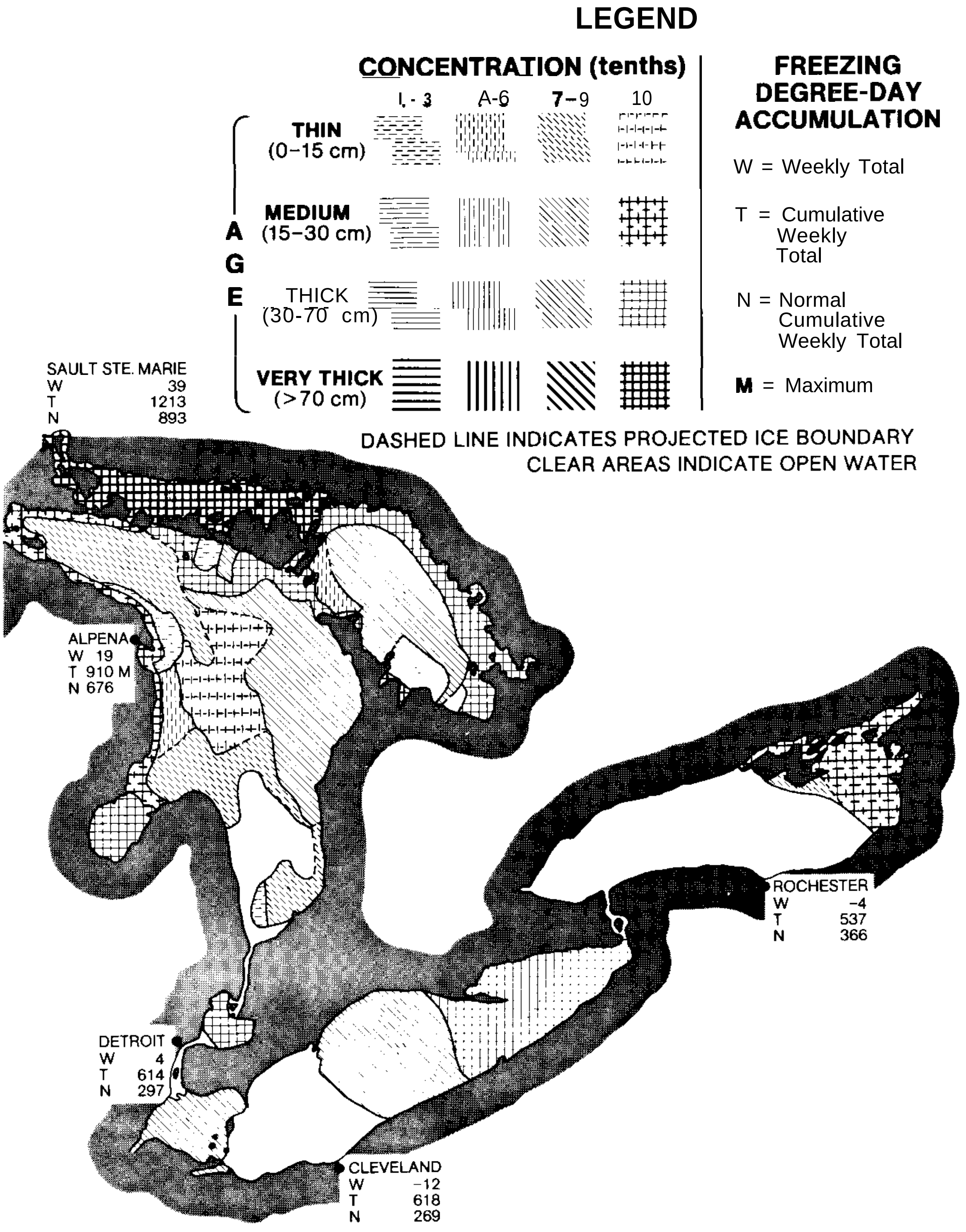

Figure 11n. Composite ice chart for 6 March 1977 (continued).

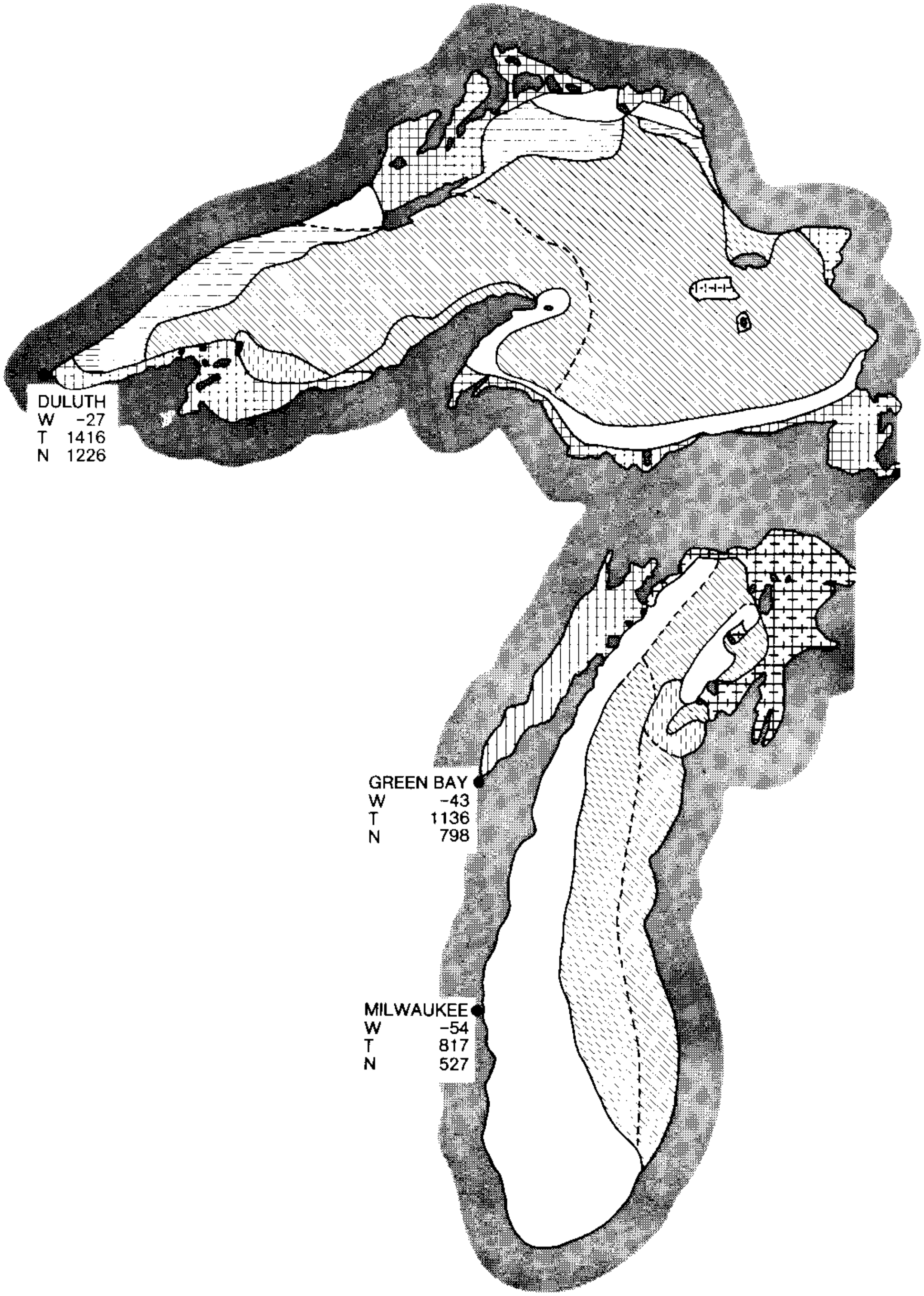

Figure 110. Composite ice chart for 13 March 1977.

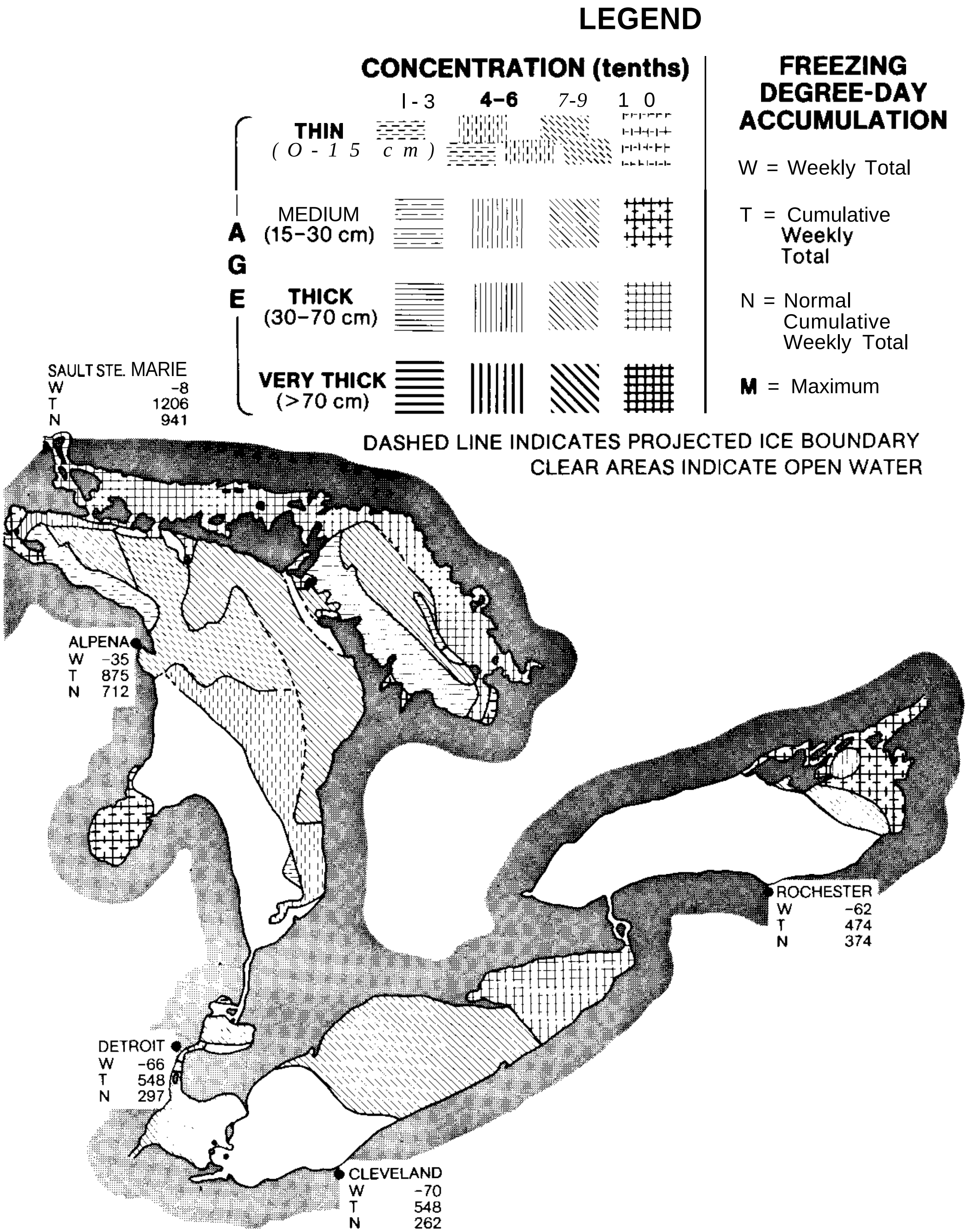

Figure 110. Composite ice chart for 13 March 1977 (continued).

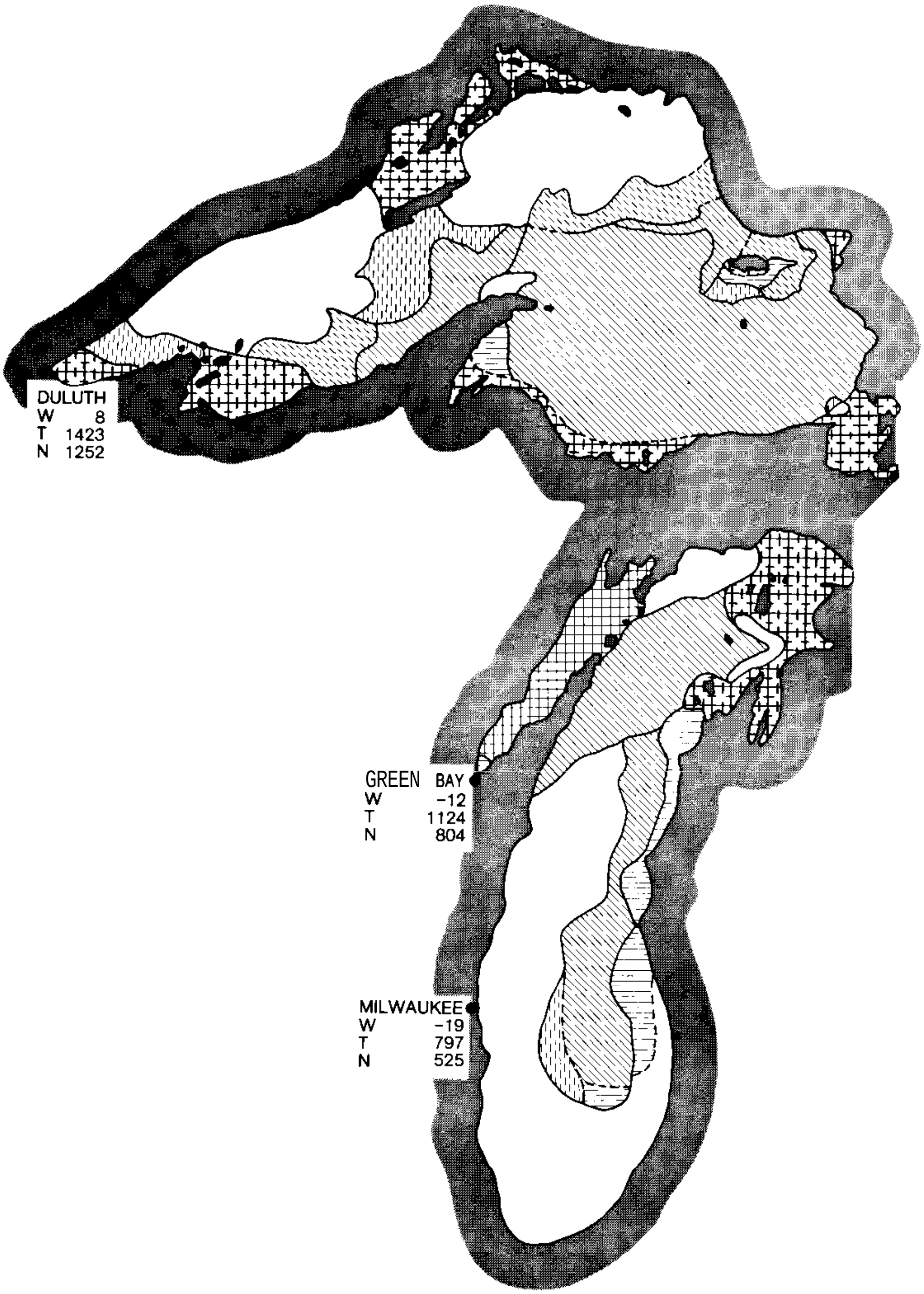

Figure 11p. Composite ice chart for 20 March 1977.

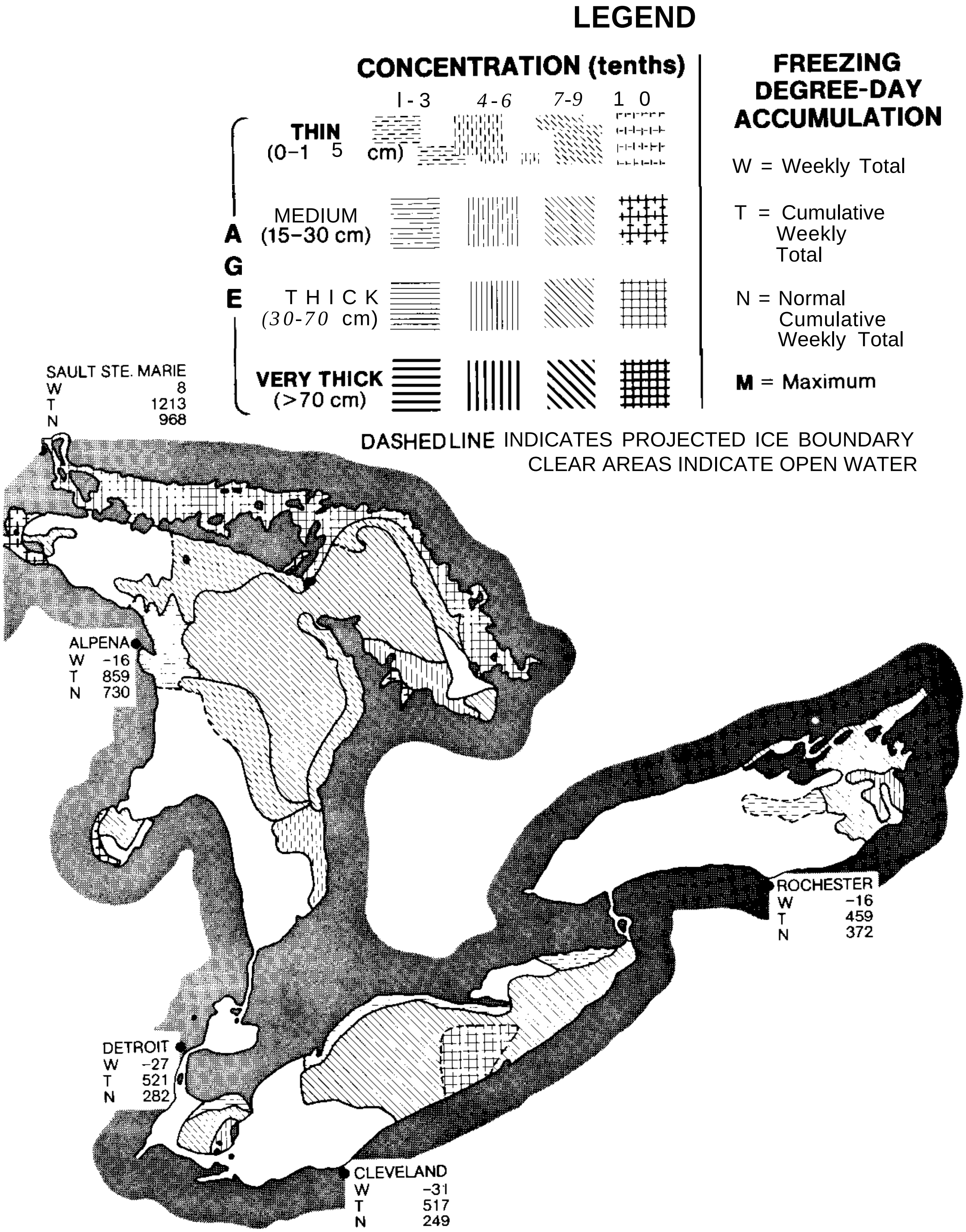

Figure 11p. Composite ice chart for 20 March 1977 (continued).

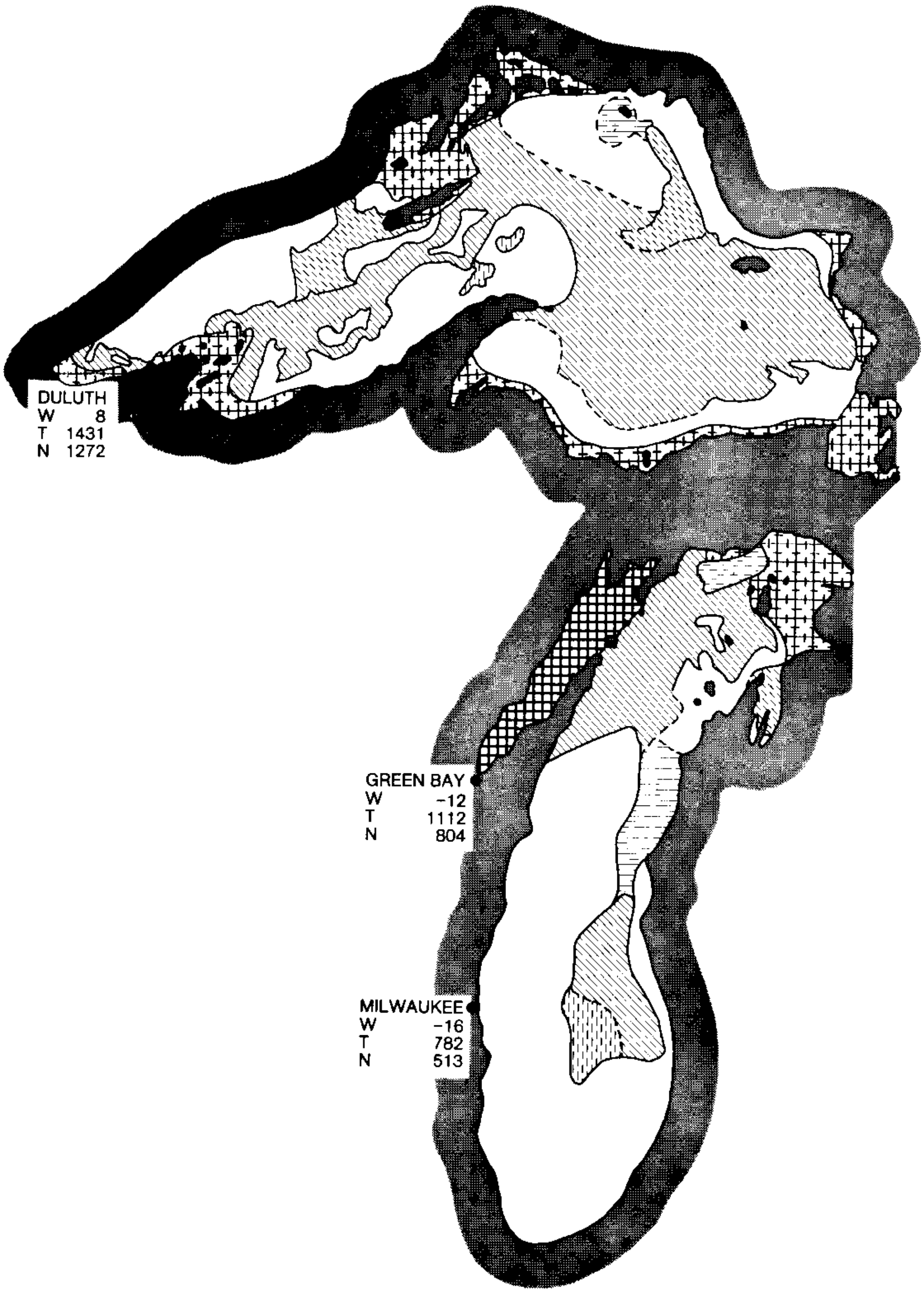

Figure llq. Composite ice chart for 27 March 1977.

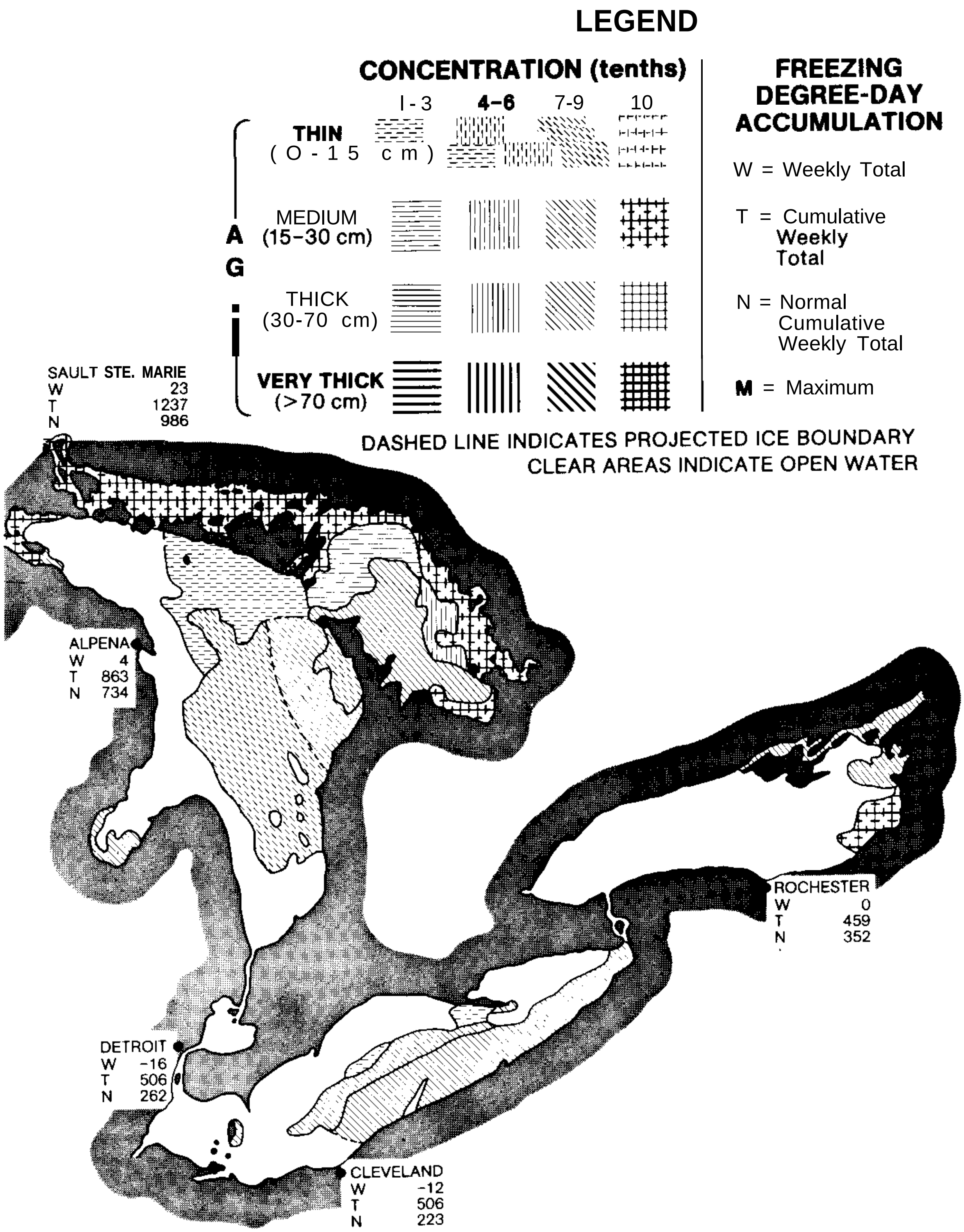

Figure 11q. Composite ice chart for 27 March 1977 (continued).

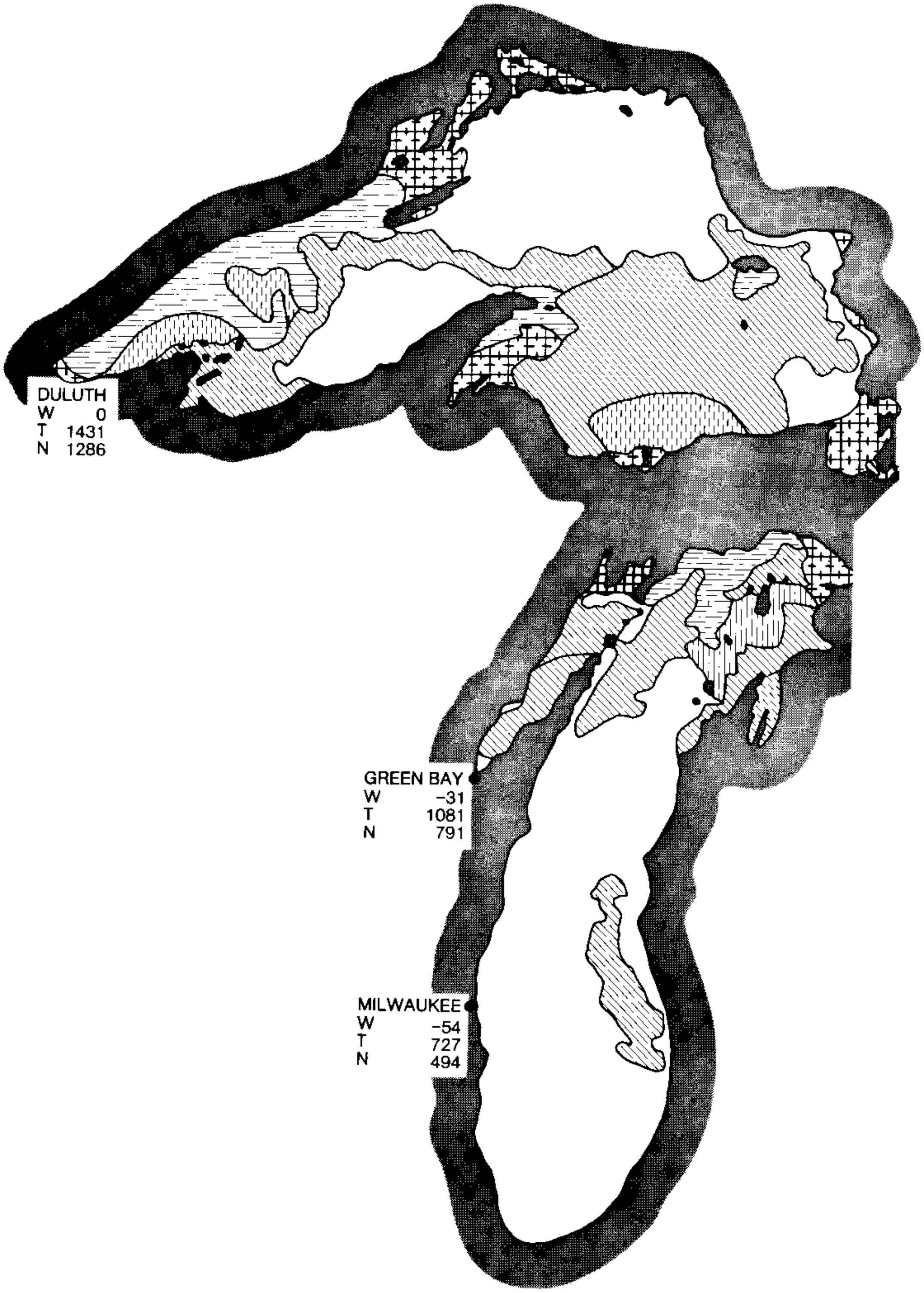

Figure 11r. Composite ice chart for 3 April 1977.

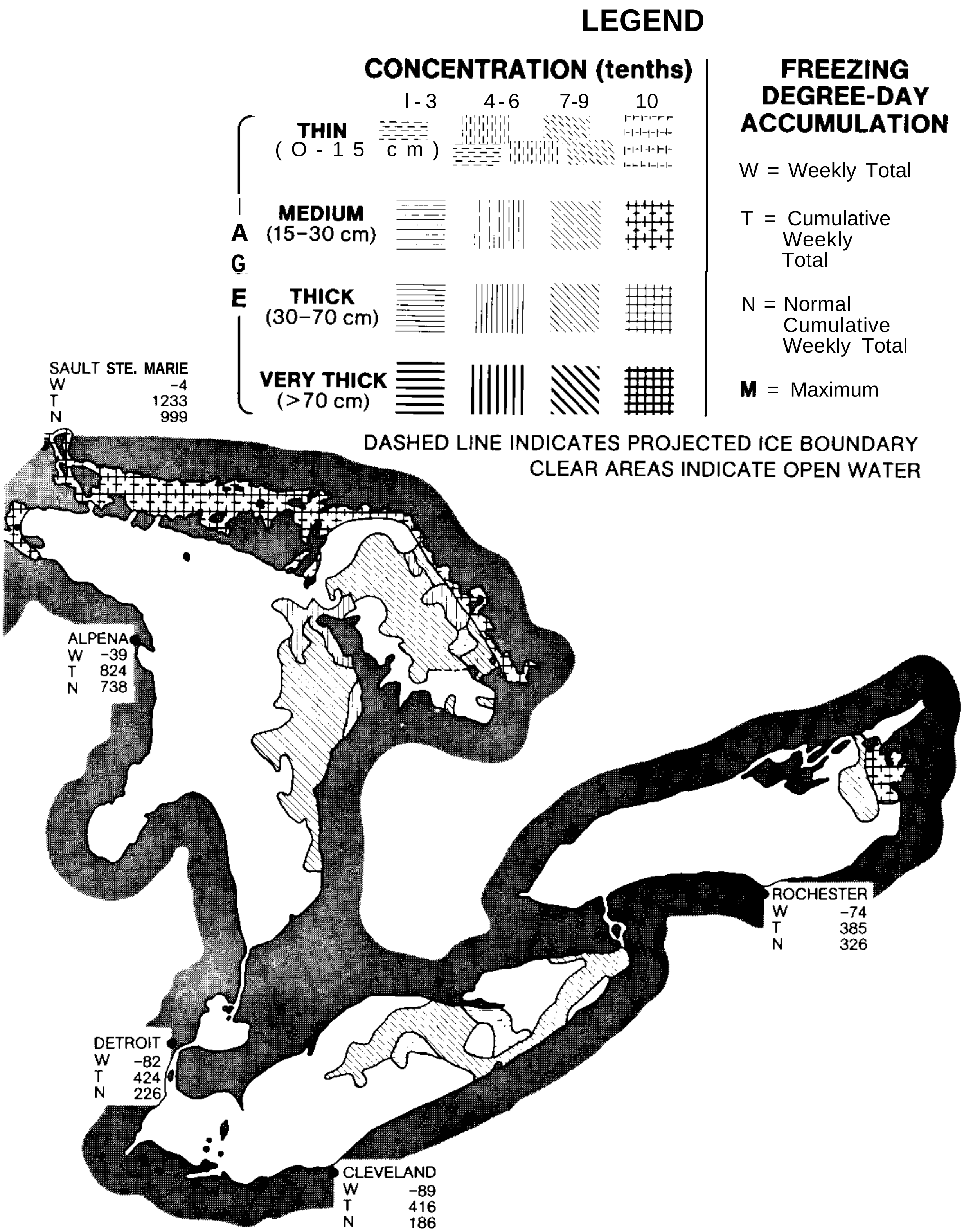

Figure 11r. Composite ice chart for 3 April 1977 (continued).

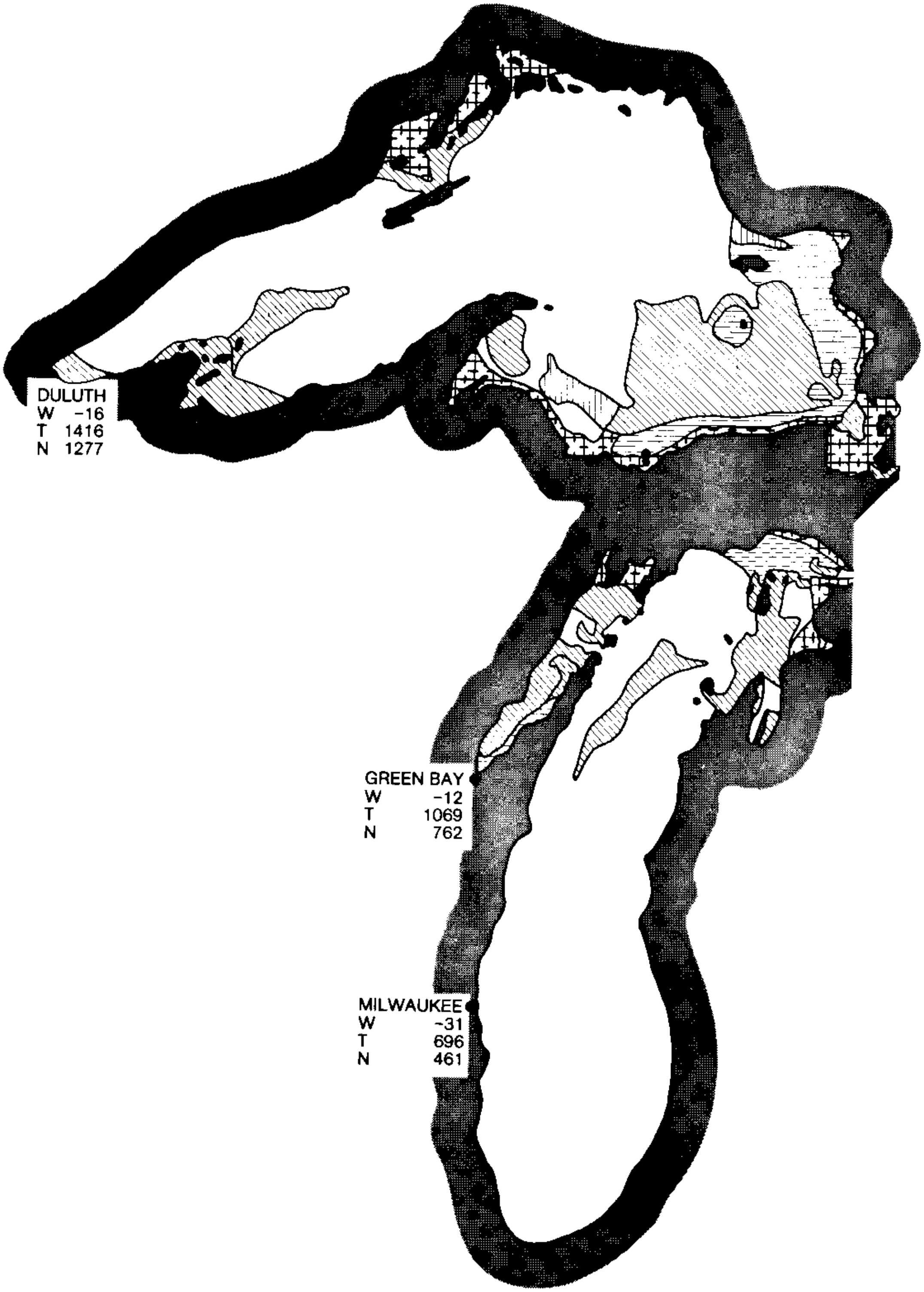

Figure 11s. Composite ice chart for 10 April 1977.

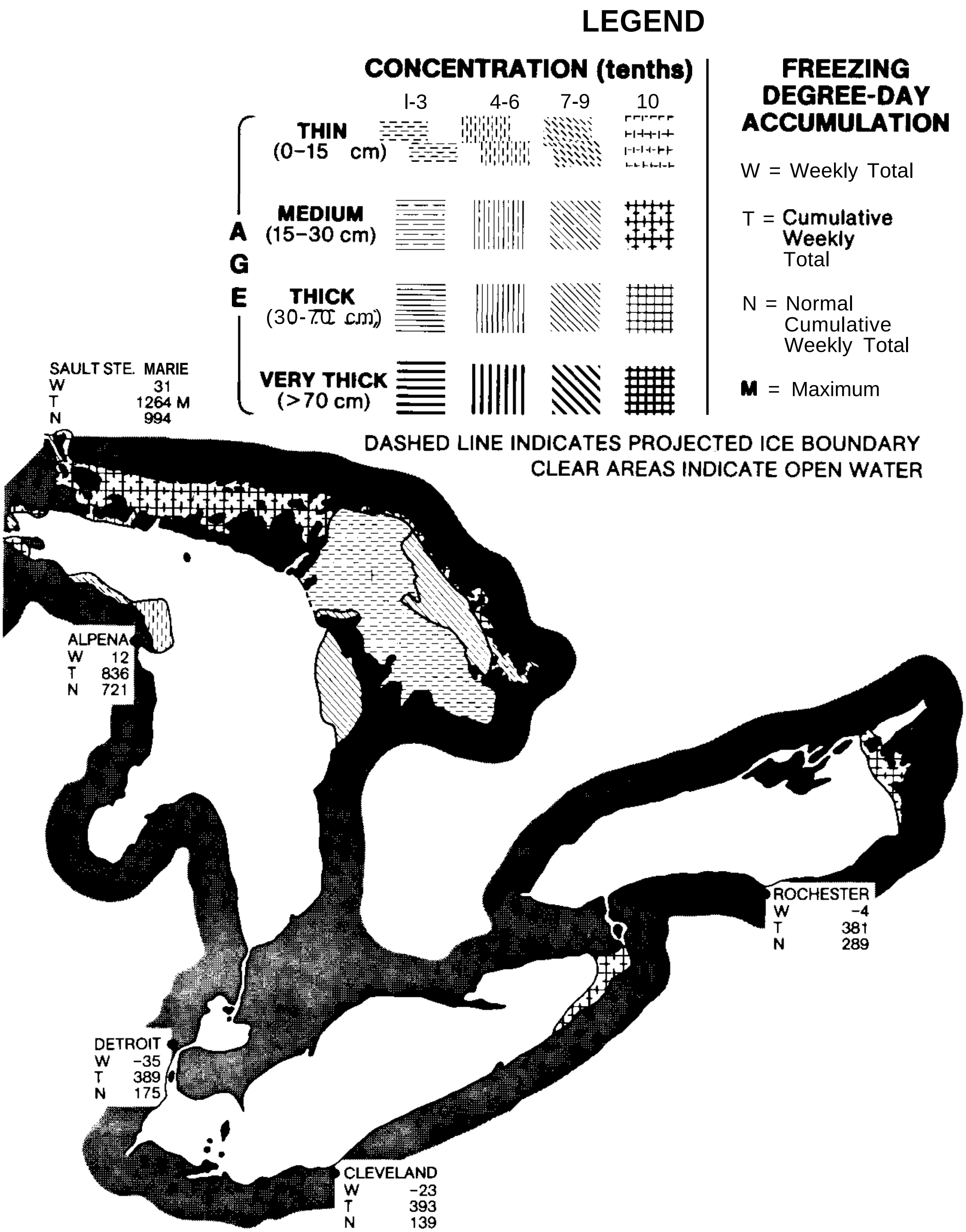

Figure 11s. Composite ice chart for 10 April 1977 (continued).

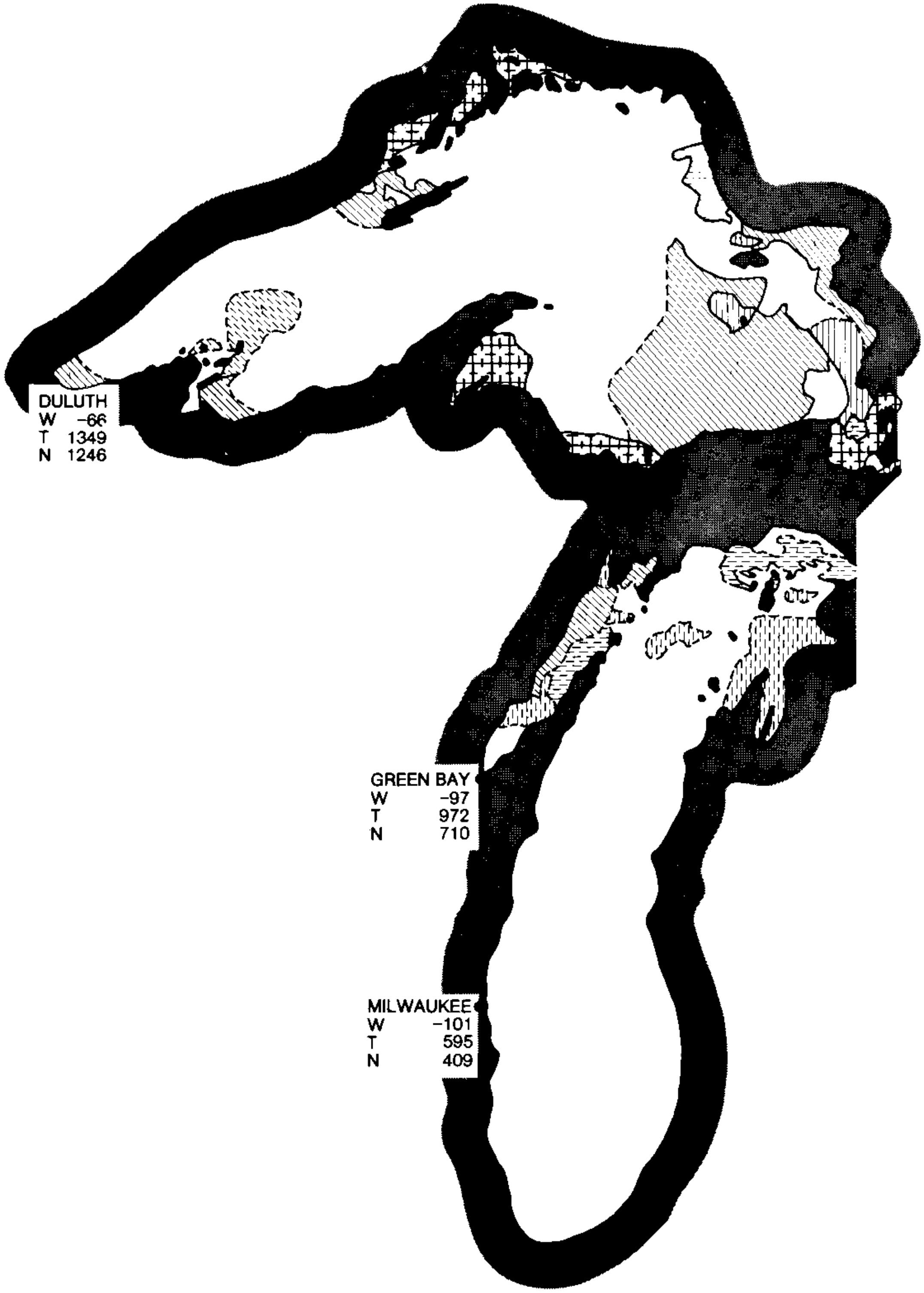

Figure 11t. Composite ice chart for 17 April 1977.

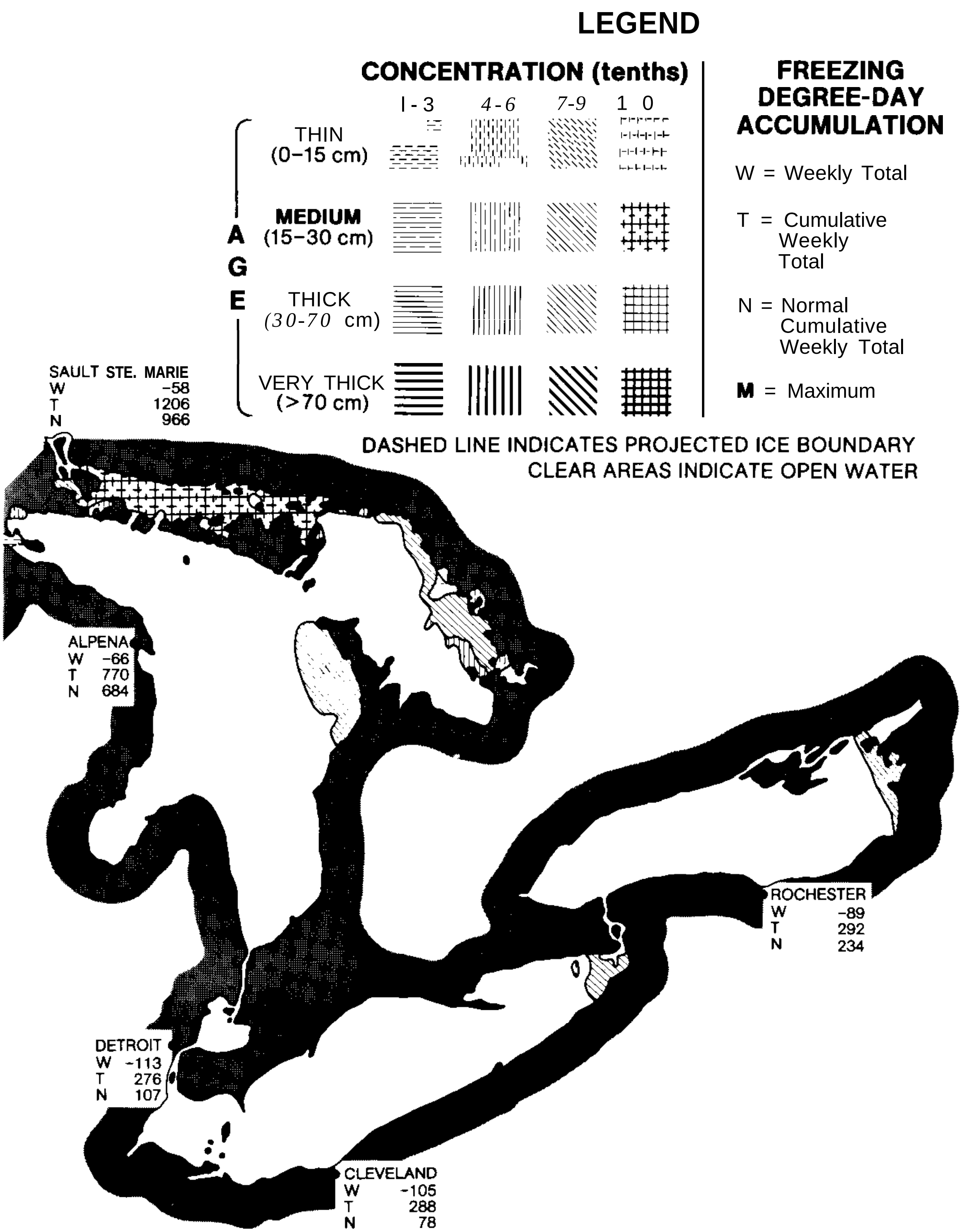

Figure 11t. Composite ice chart for 17 April 1977 (continued).

Figure 11u. Composite ice chart for 24 April 1977.

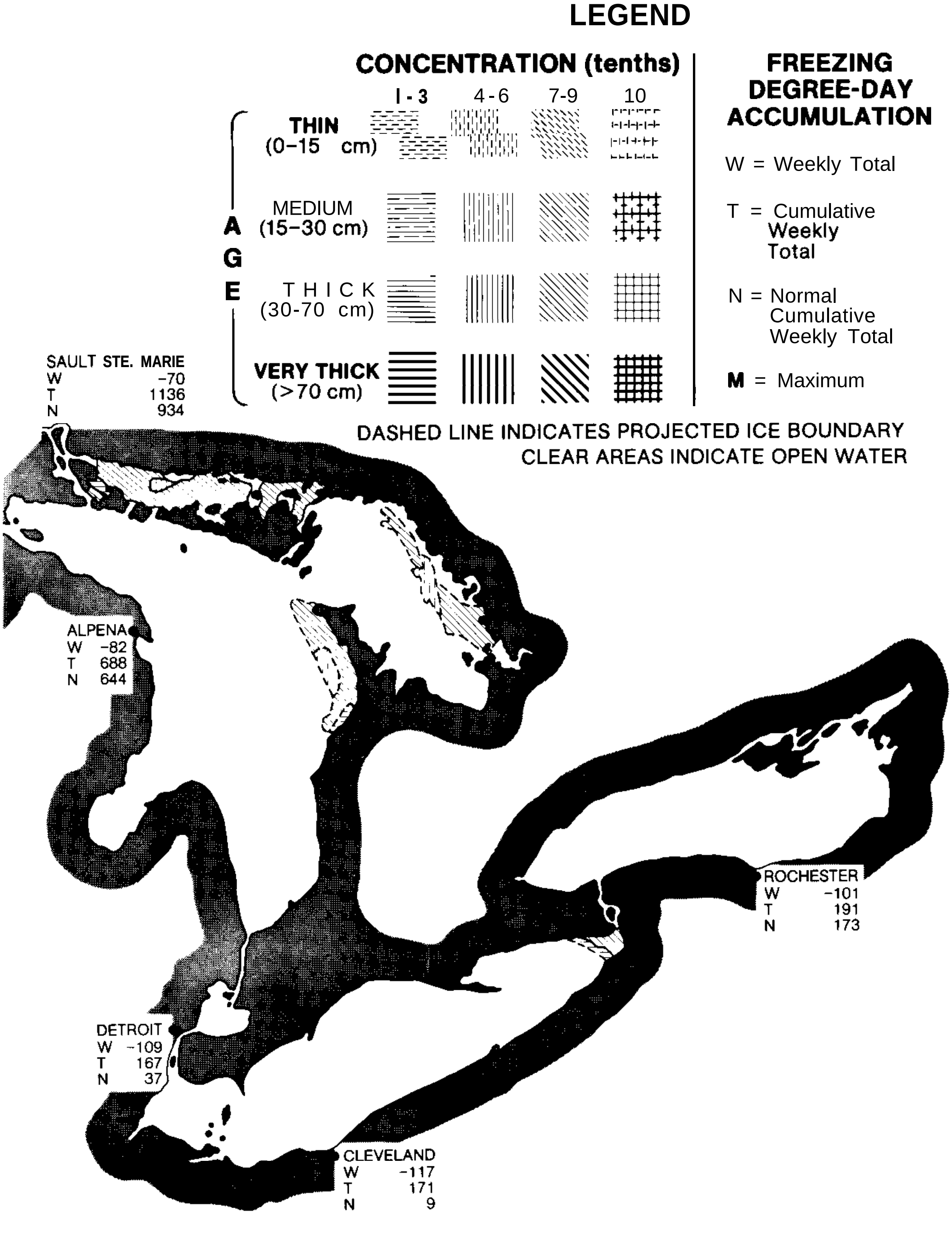

Figure llu. Composite ice chart for 24 April 1977 (continued).

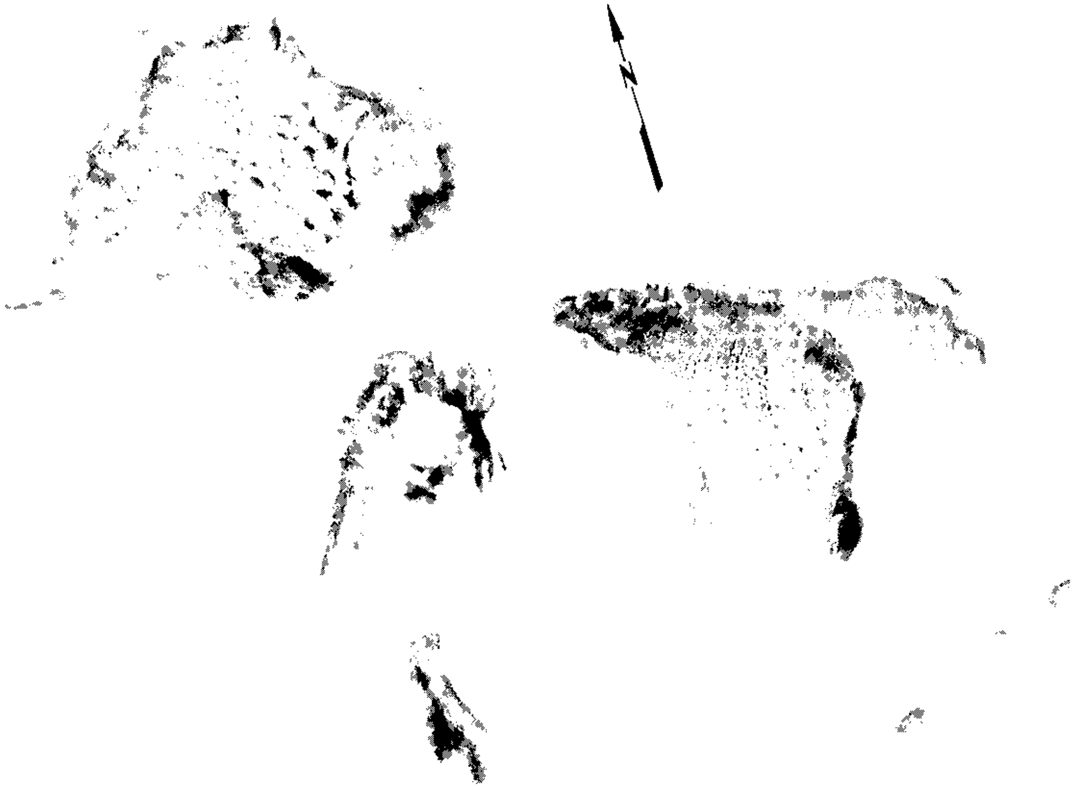

Figure 12a. NOAA-5 VHRR-IR image for 9 January 1977.

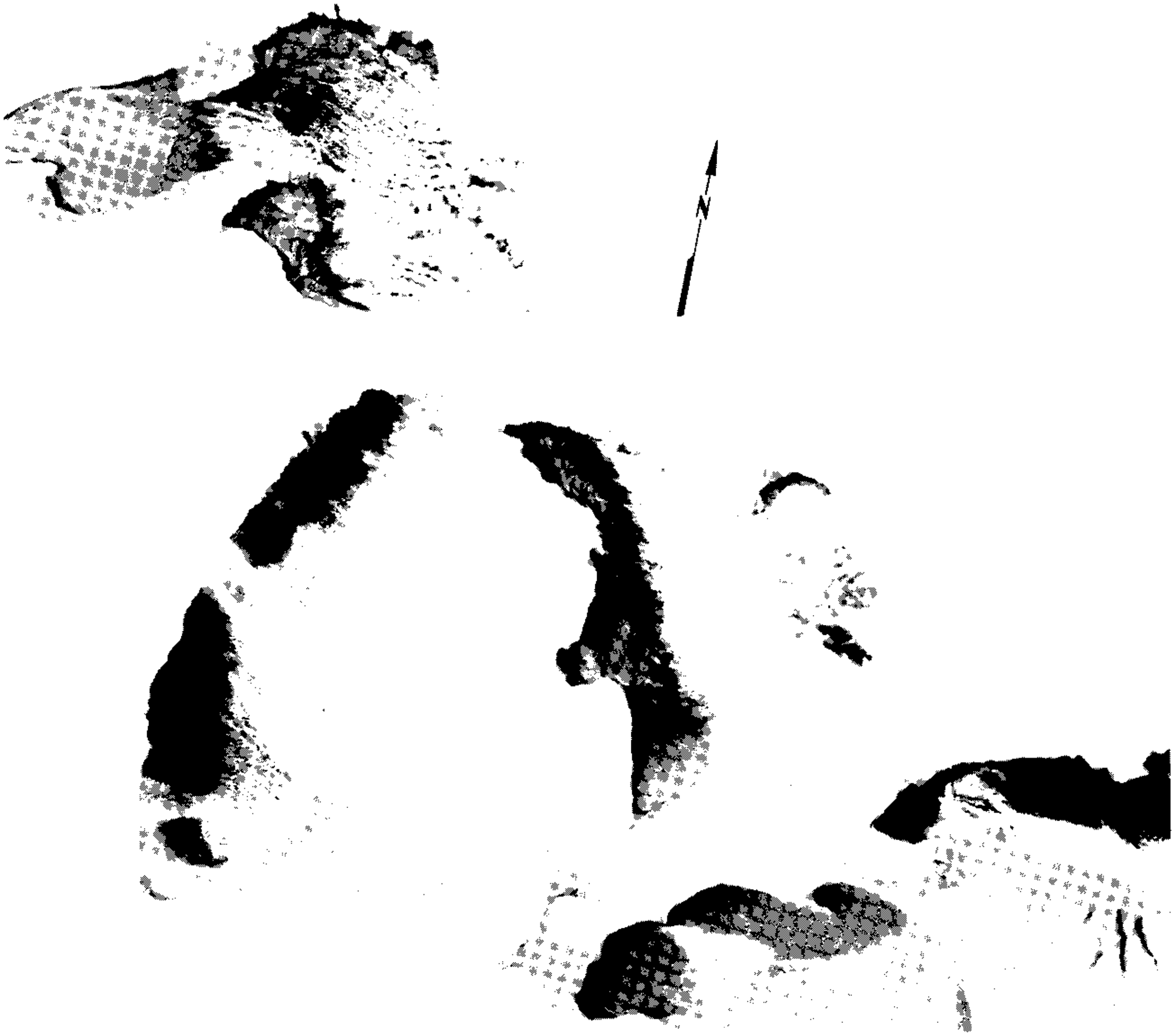

Figure 12b. NOAA-5 VHRR-IR image for 13 January 1977.

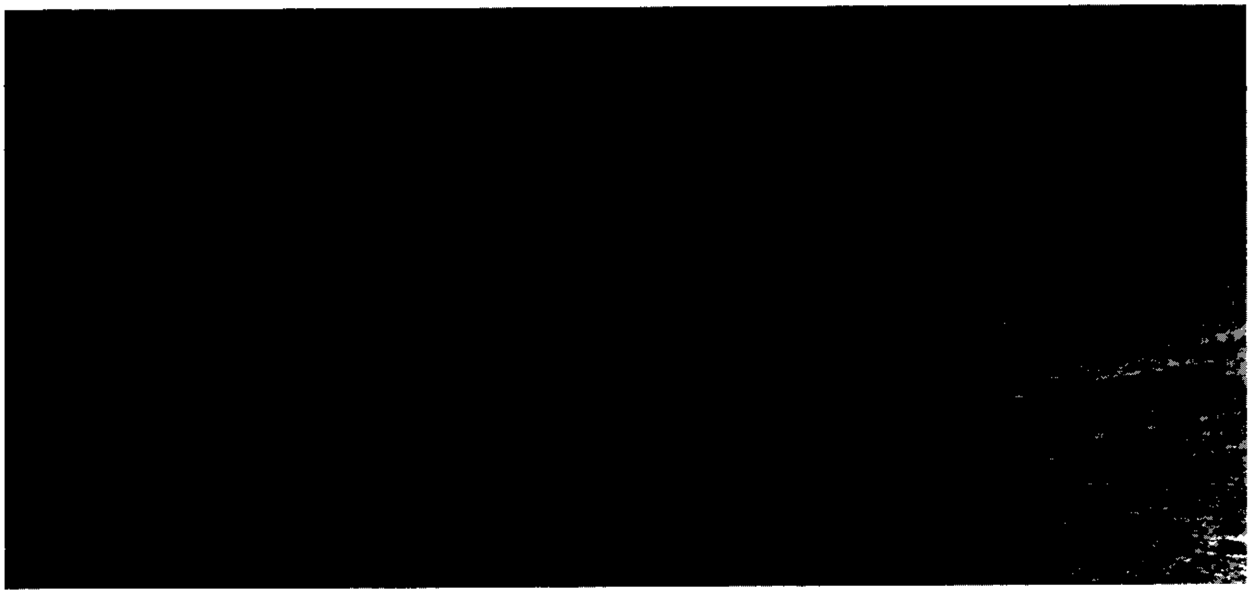

Figure 12c. GOES VISSR(visible)image for 16 January 1977.

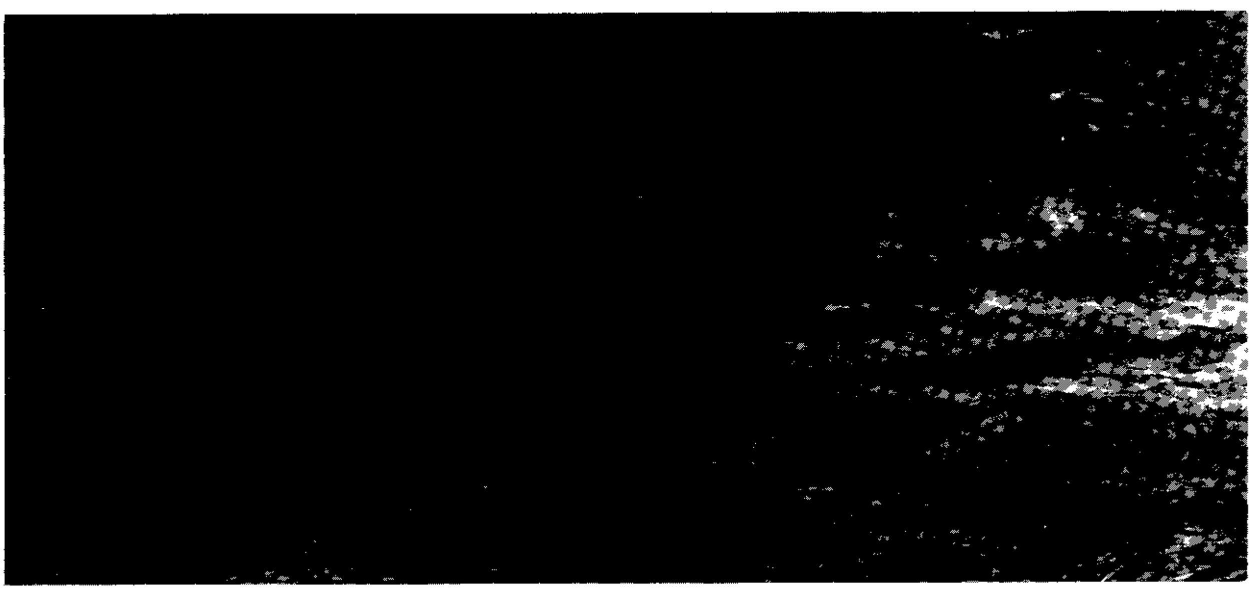

Figure 12d. GOES VISSR (visible) image for 18 January 1977.

Figure 12e. GOES VISSR (visible) image for 25 January 1977.

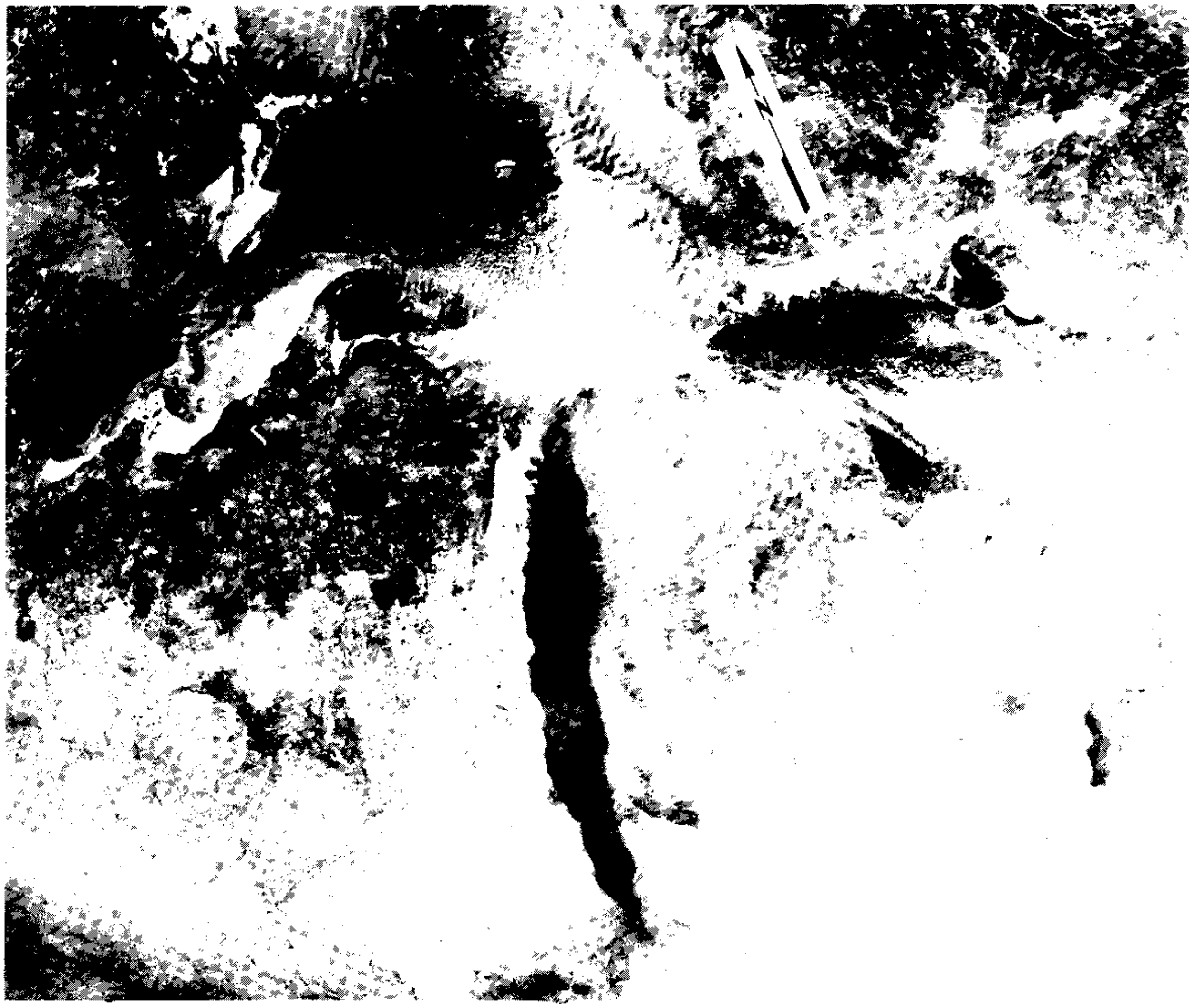

Figure 12f. NOAA-5 VHRR (visible) image for 1 *February 1977.*

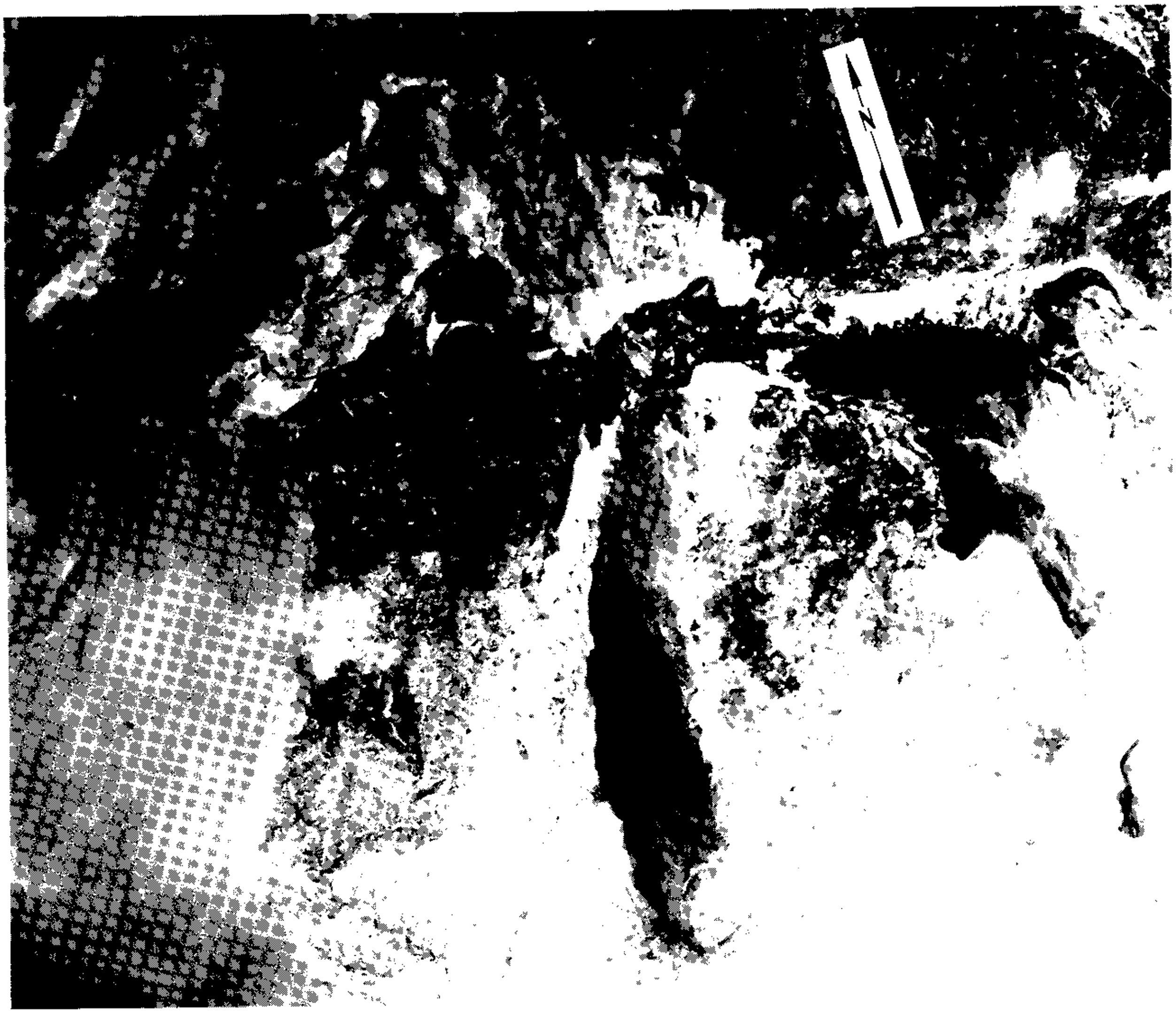

Figure 12g. NOAA-5 VHRR (visible) image for 7 February 1977.

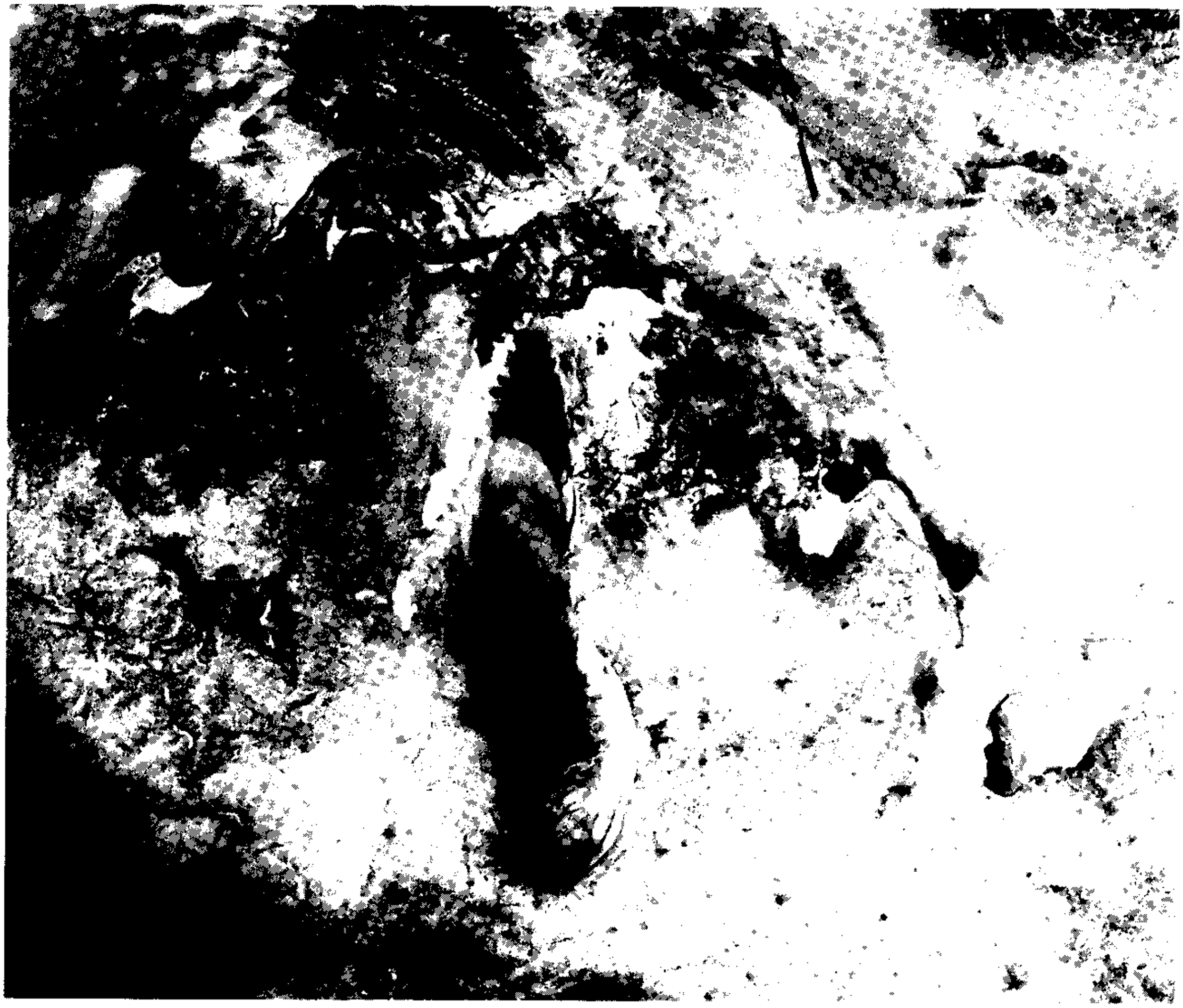

Figure 12h. NOM-5 VHRR (visible) image for 10 February 1977.

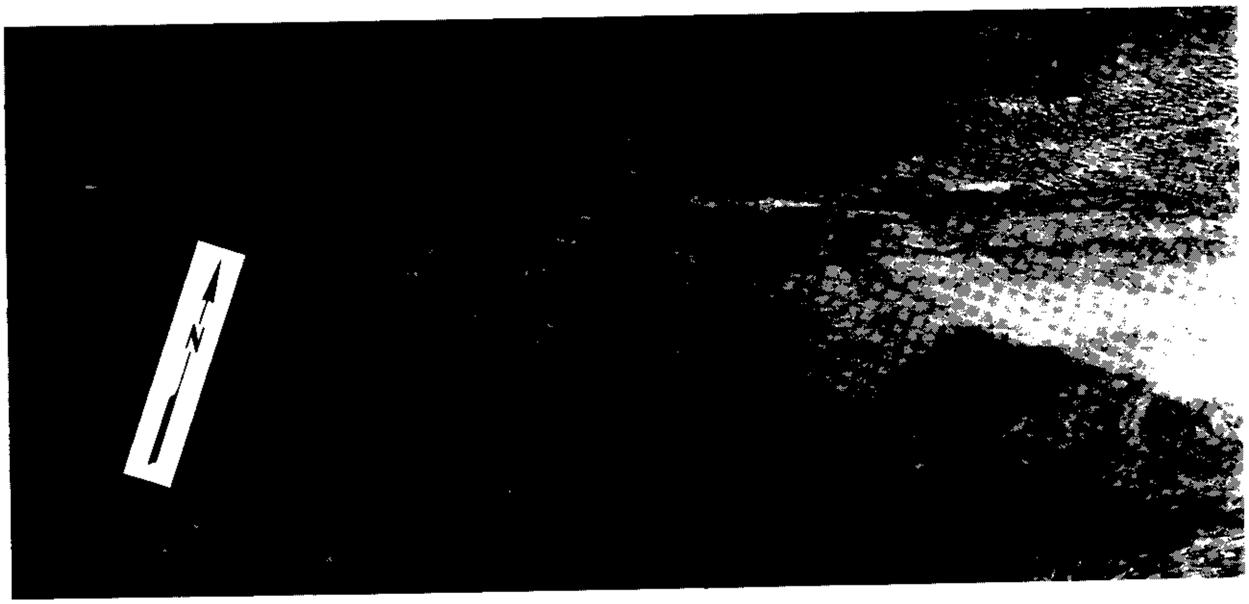

Figure 12i. GOES VISSR (visible) image for 22 February 1977.

Figure 12j. NOM-5 VHRR (visible) image for 1 March 1977.

Figure 12k. GOES VISSR (*visible*) image for 7 March 1977.

Figure 121. NOAA-5 VHRR (visible) image for 8 March 1977.

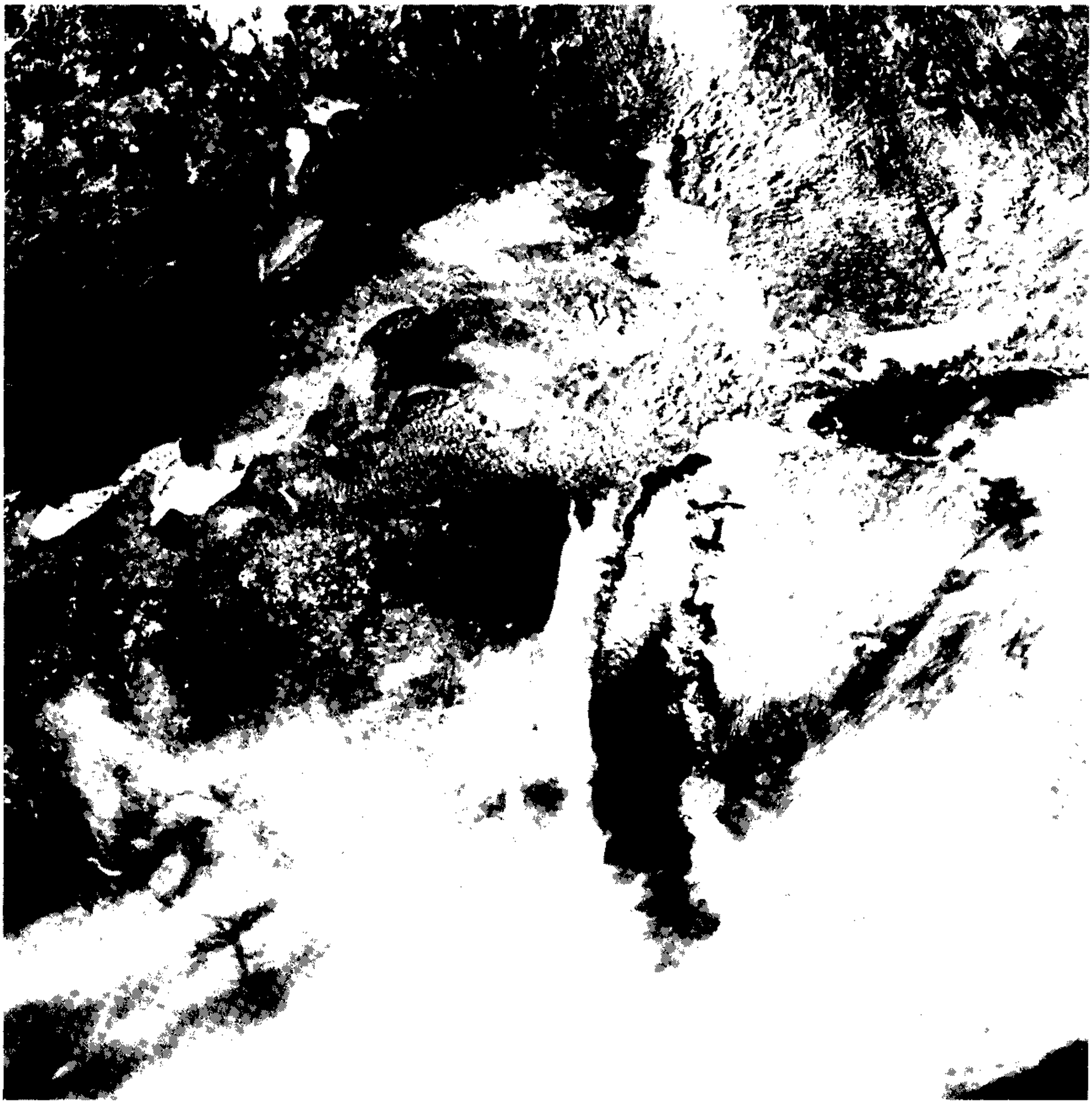

Figure 12m. NOAA-5 VHRR (visible) image for 21 March 1977

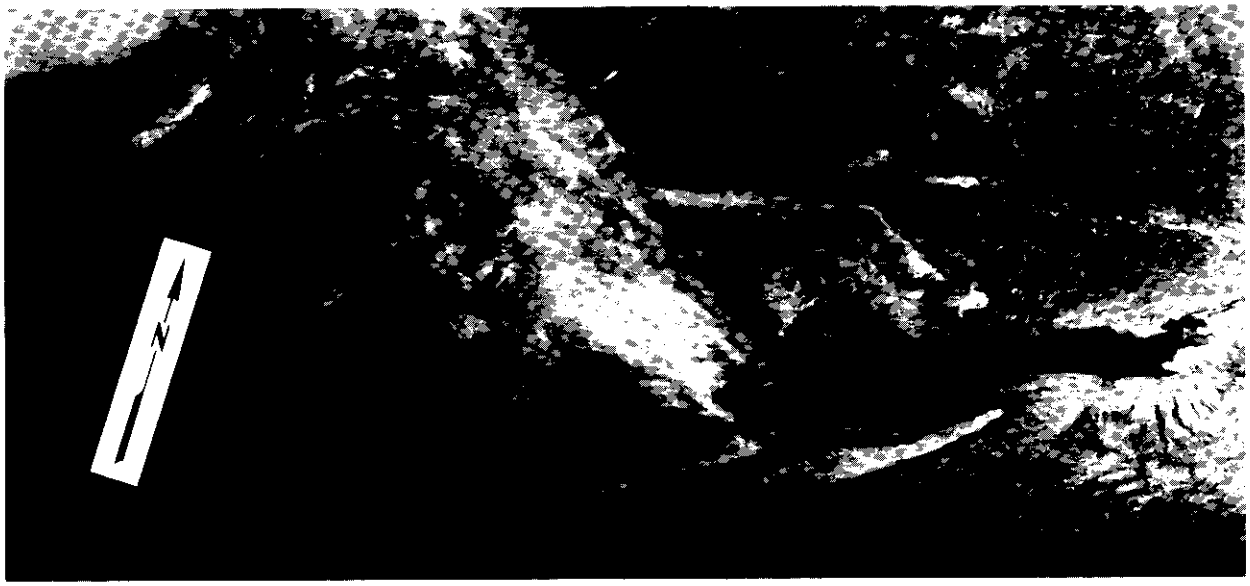

Figure 12n. GOES VISSR (visible) image for 25 March 1977.

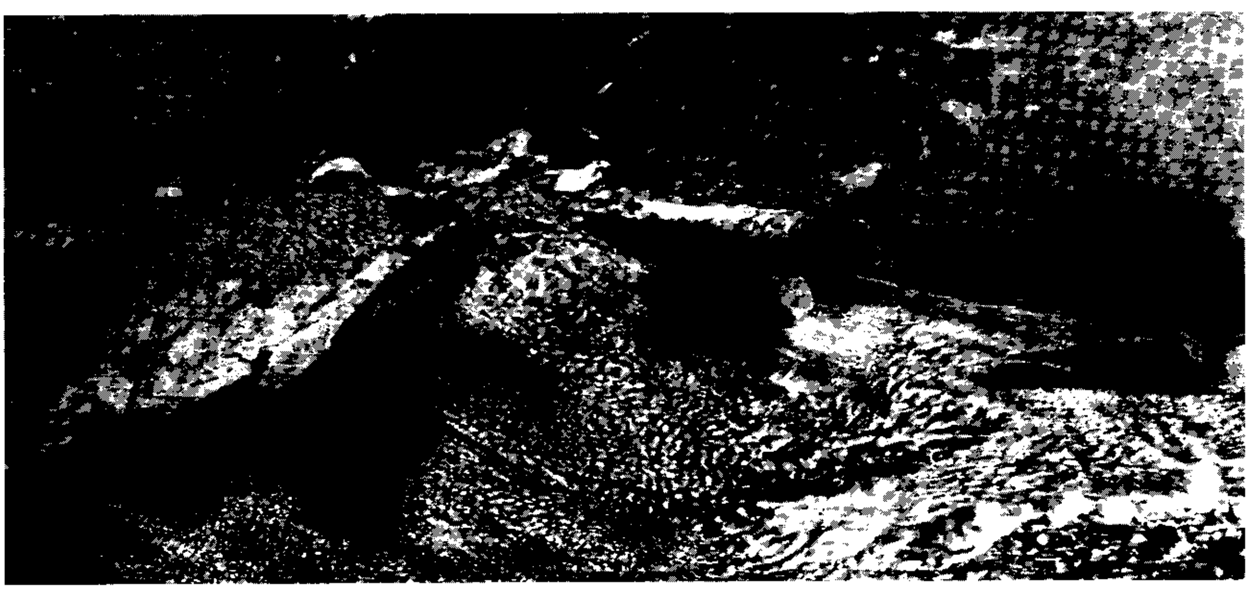

Figure 12o. GOES VISSR (visible) image for 6 April 1977.

Figure 12p. NOM-5 VHRR (visible) image for 9 April 1977.

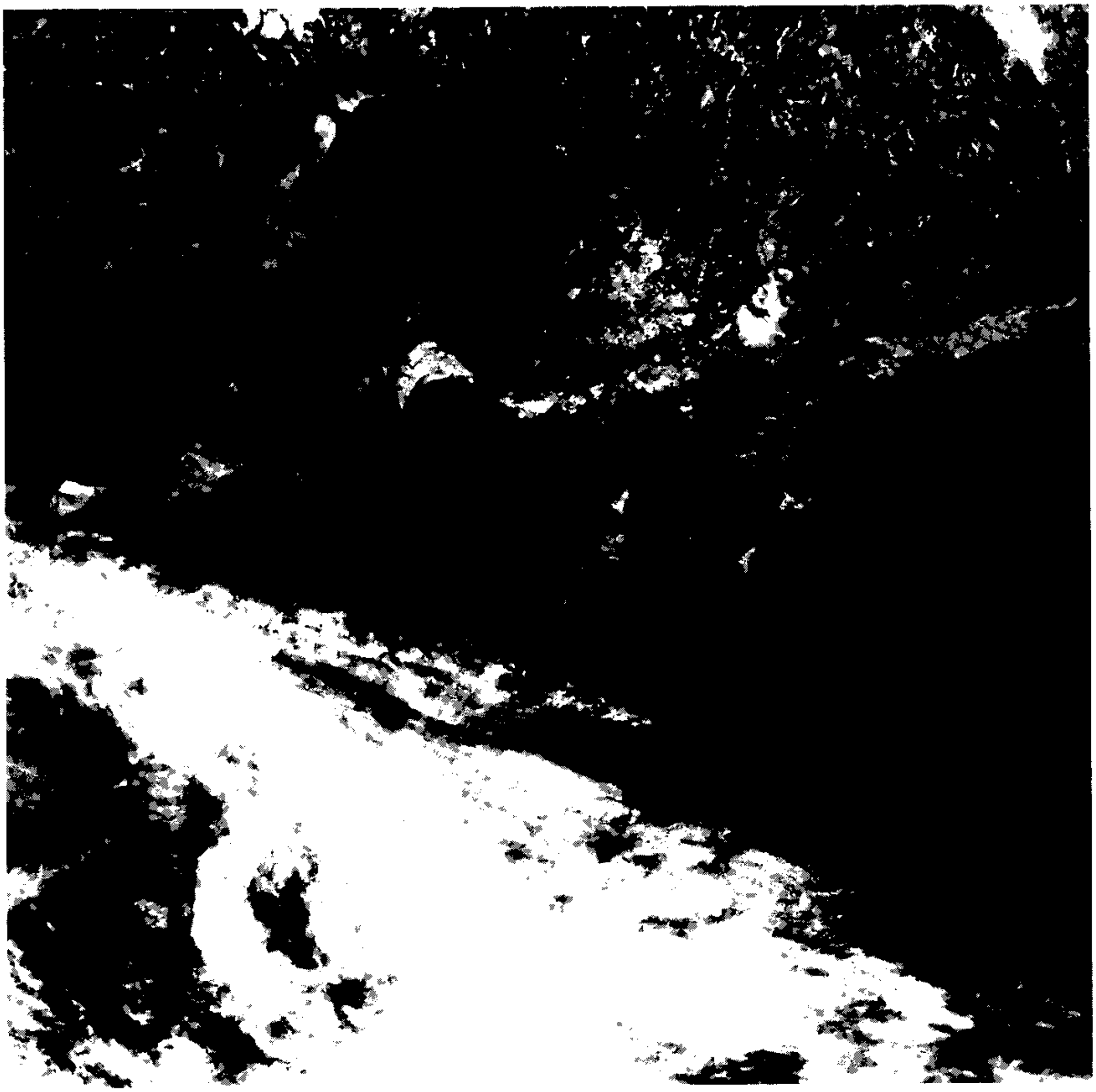

Figure 12q. NOAA-5 VHRR (visible) image for 14 April 1977.

Figure 12r. NOAA-5 VHRR (visible) image for 22 April 1977.

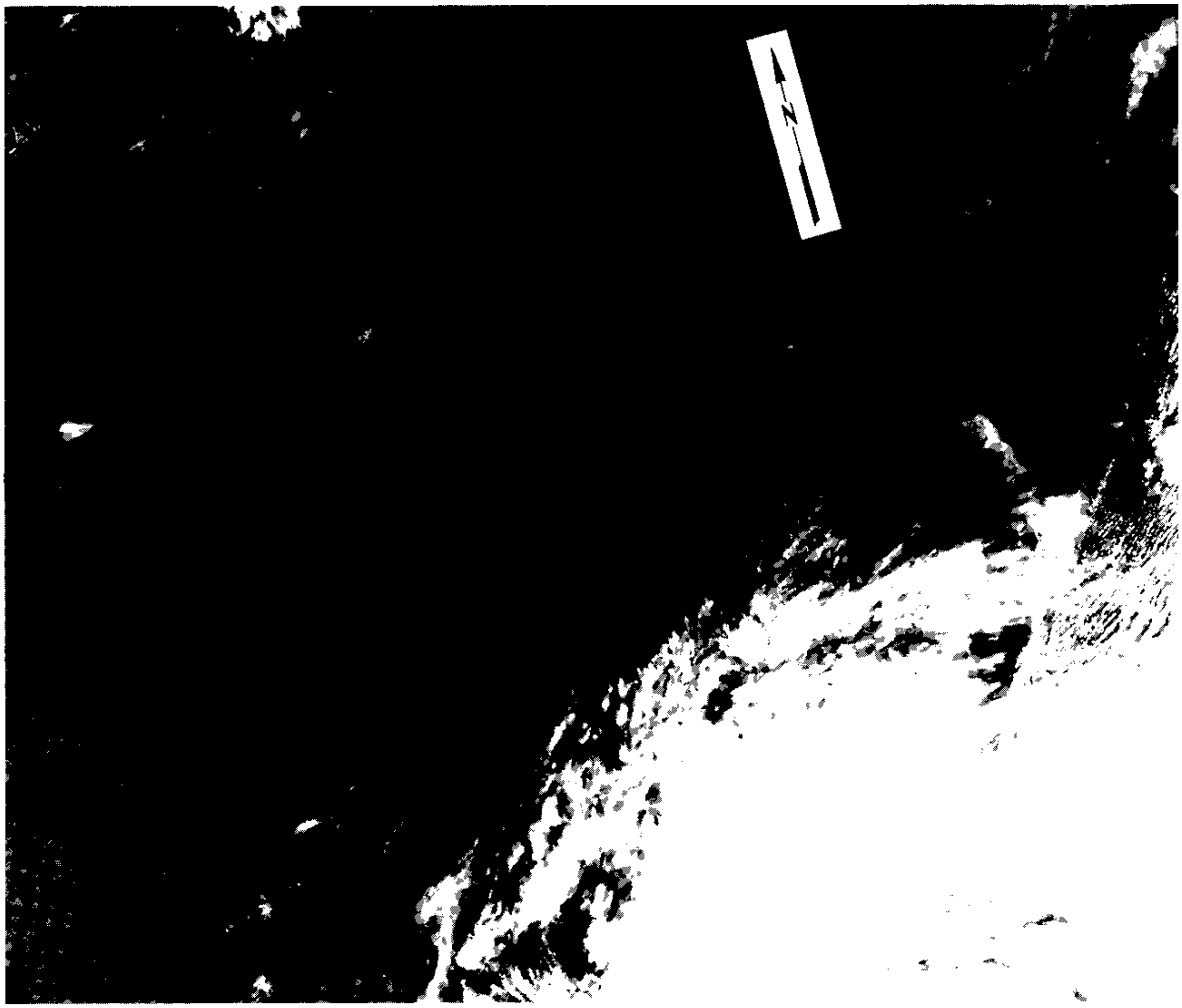

Figure 12s. NOAA-5 VHRR (visible) image for 25 April 1977.

Figure 12t. NOAA-5 VHRR-IR (nighttime) image for 13 December 1977

Figure 12u. **NOAA-5** *VHRR-IR (daytime) image for 11 January 1977.*

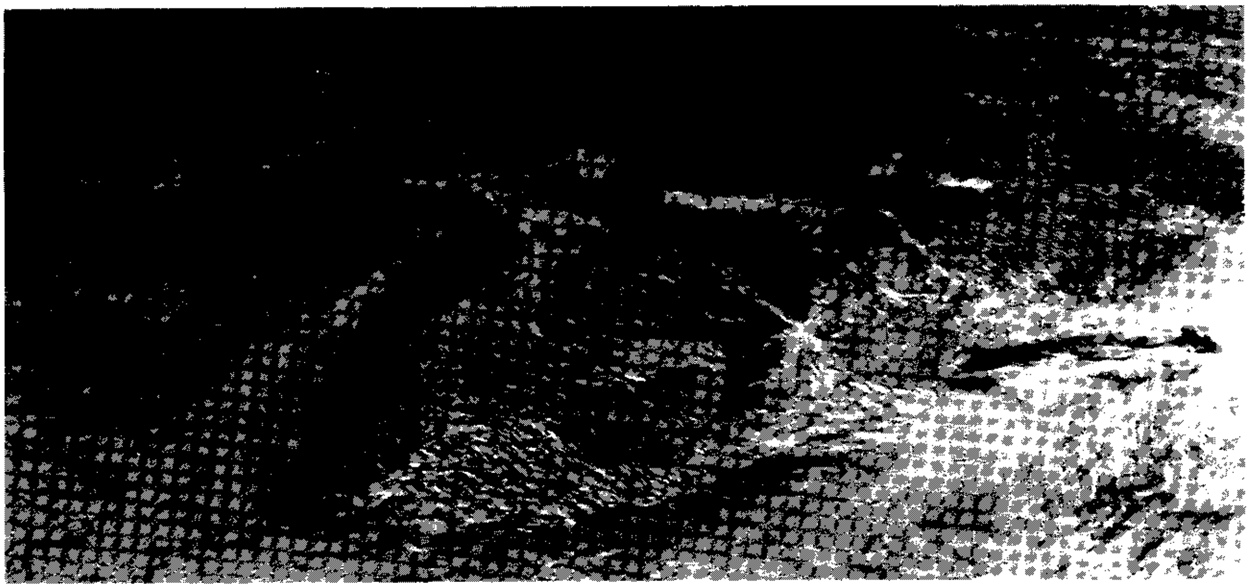

Figure 12v. GOES VISSR (visible) image for 21 January 1977.

Figure 12w. GOES VISSR (visible) image for 27 January 1977.

Figure 12x. GOES VISSR(visible) image for 16 February 1977.

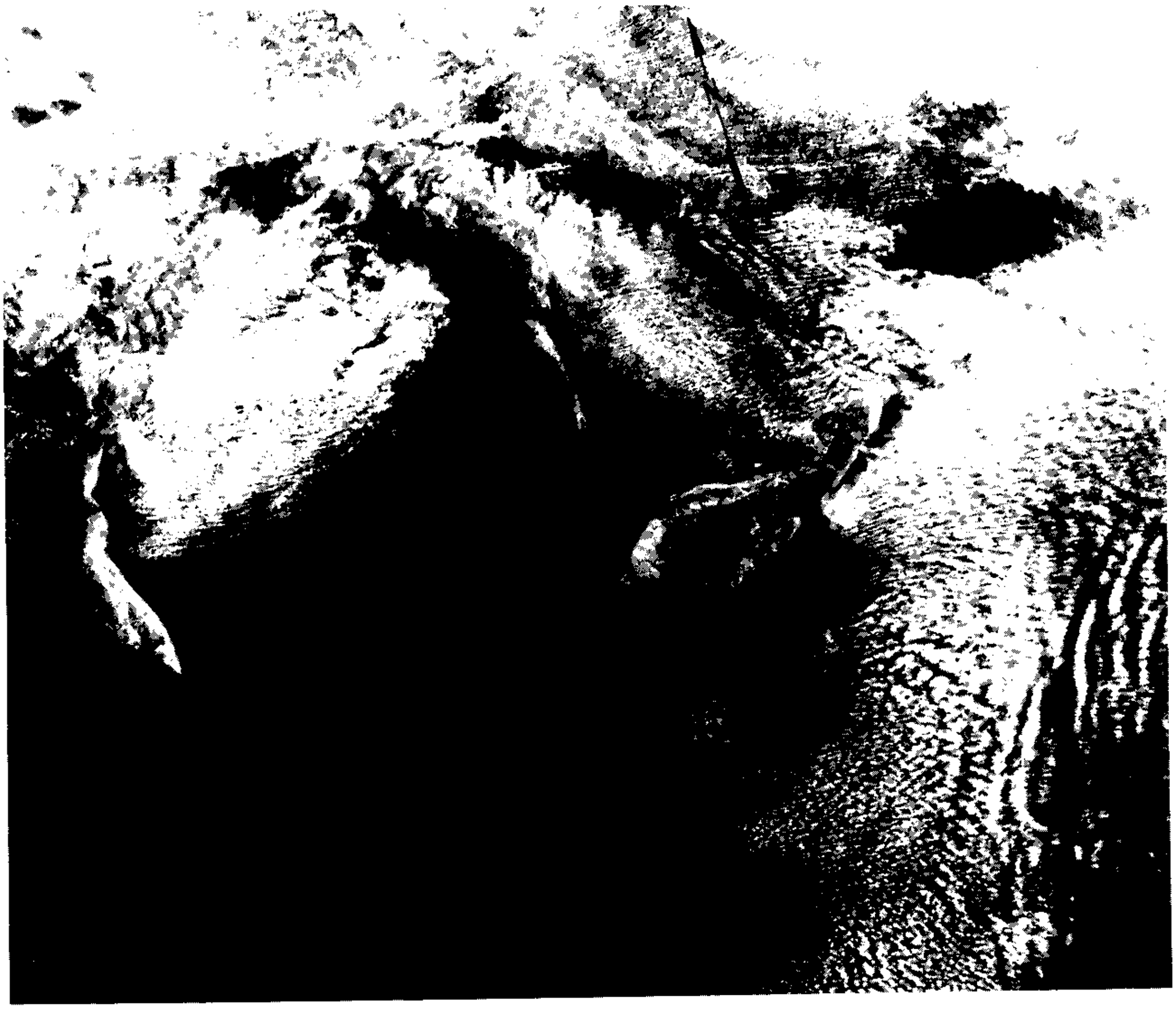

Figure 12y. NOAA-5 VHRR (visible) image for 16 March 1977.

Figure 12z. NOAA-5 VHRR (visible) image for 22 March 1977.

Figure 12aa. NOM-5 VHRR-IR (nighttime) image for 8 December 1977.

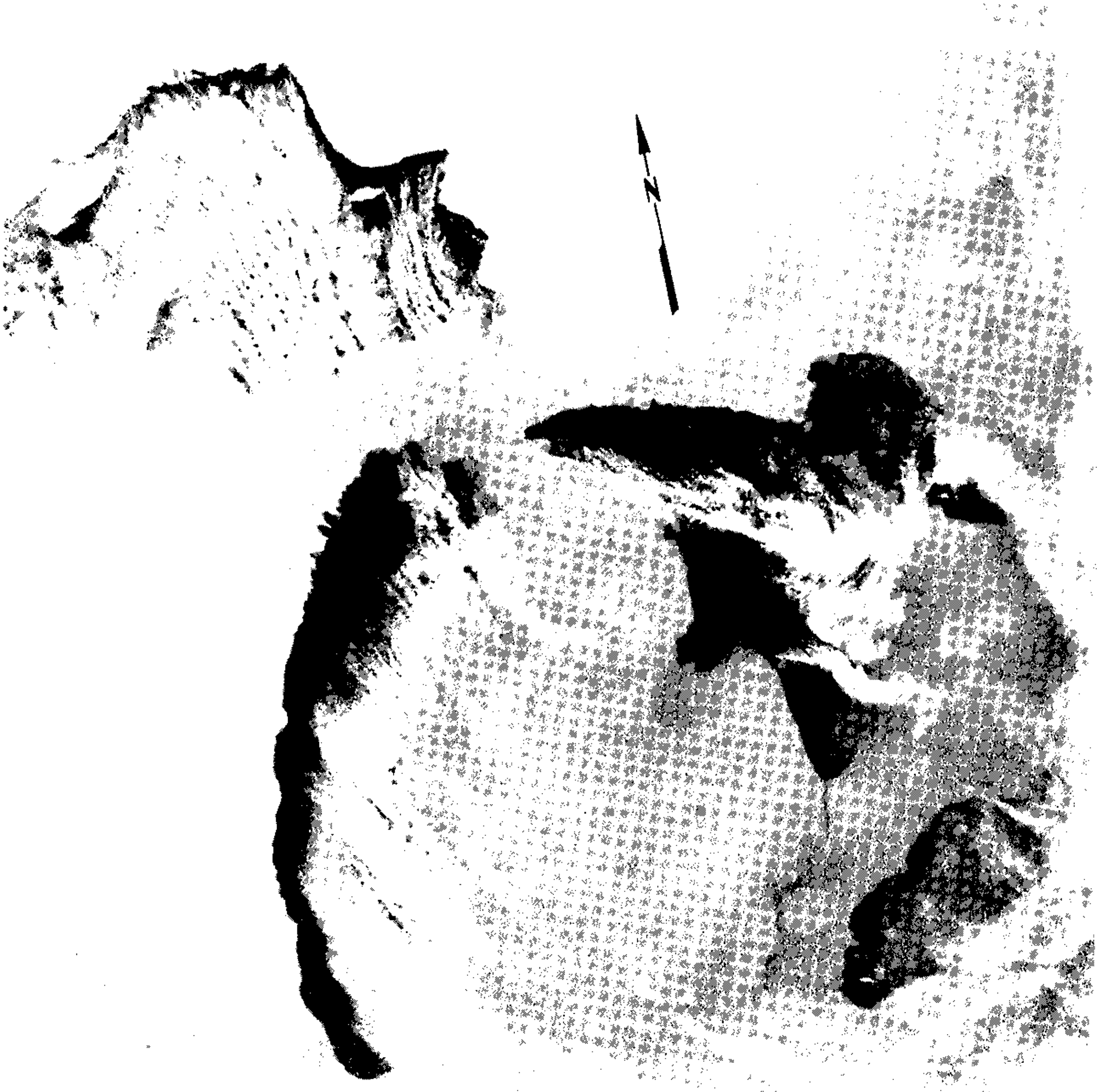

Figure 12bb. NOAA-5 VHRR-IR image for 7 January 1977.

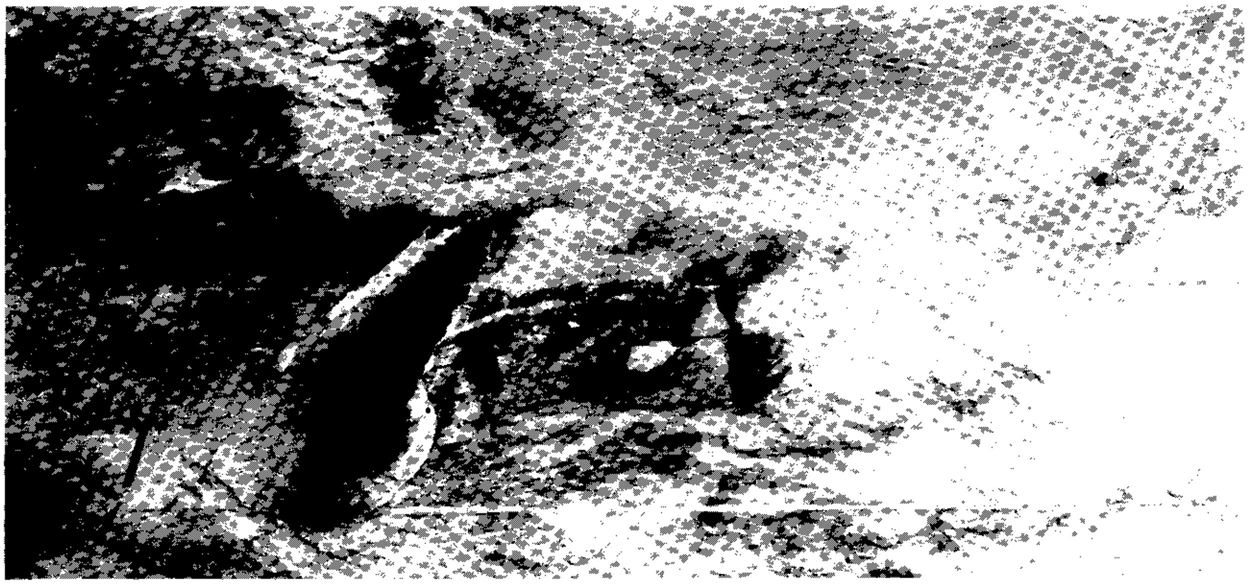

Figure 12cc. GOES VISSR (visible) image for 9 February 1977.

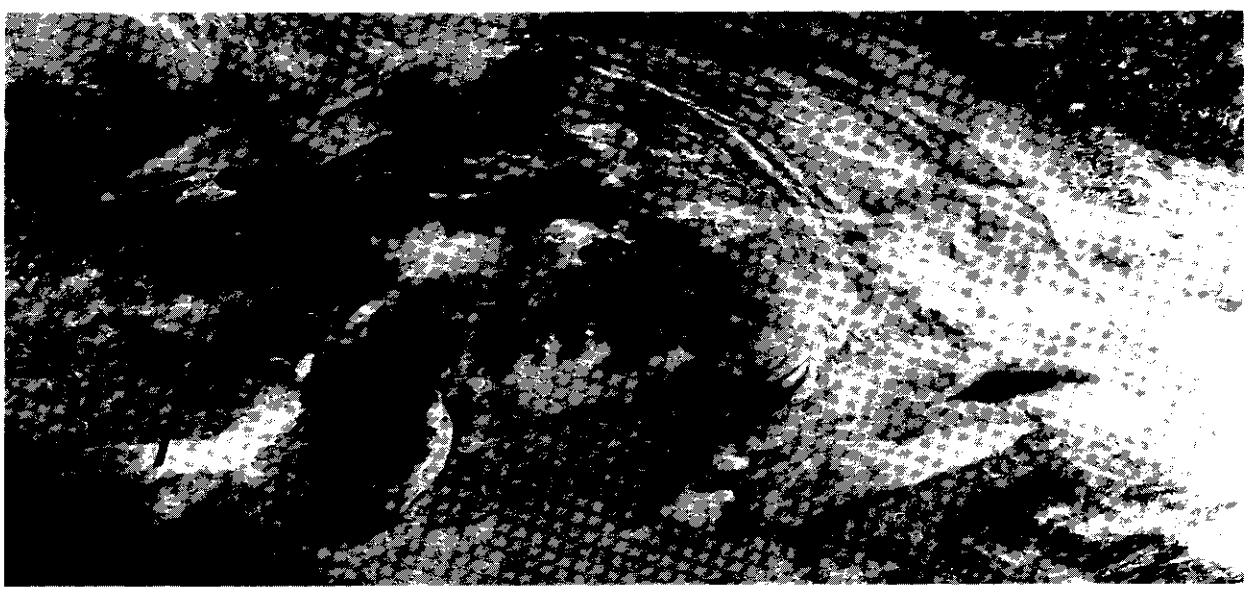

Figure 12dd. GOES VISSR (visible) image for 10 February 1977.

Figure 12ee. GOES VISSR (visible) image for 15 February 1977.

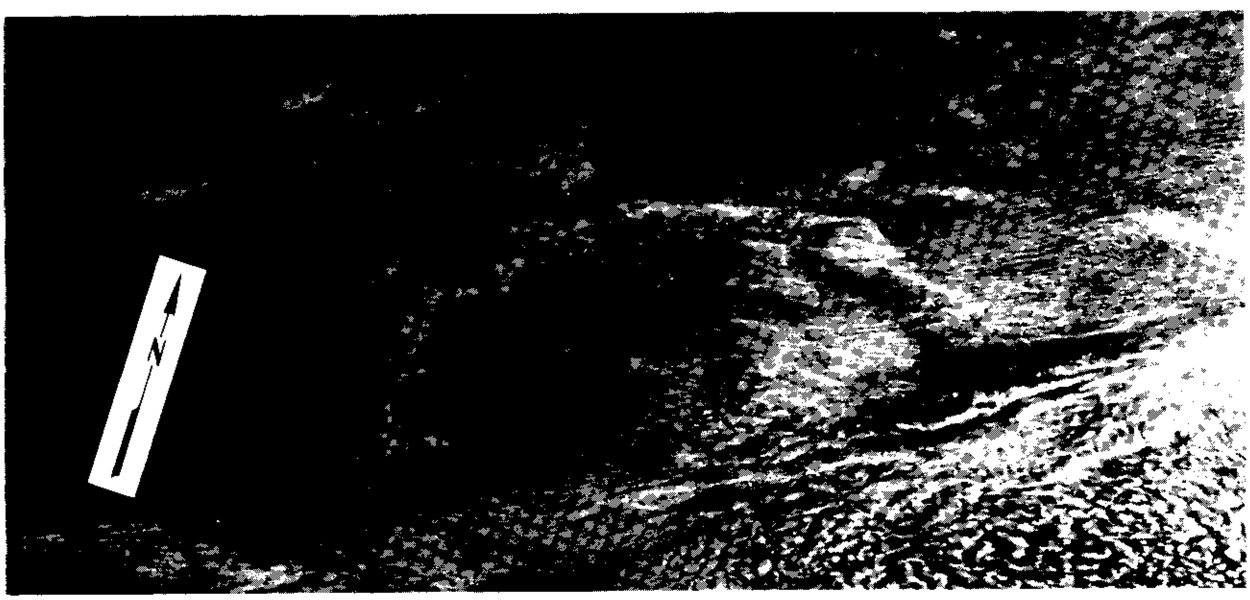

Figure 12ff. GOES VISSR (visible) image for 28 February 1977.

Figure 12gg. GOES VISSR (visible) image for 17 March 1977.

Figure 12hh. NOAA VHRR (visible) image for 24 March 1977.

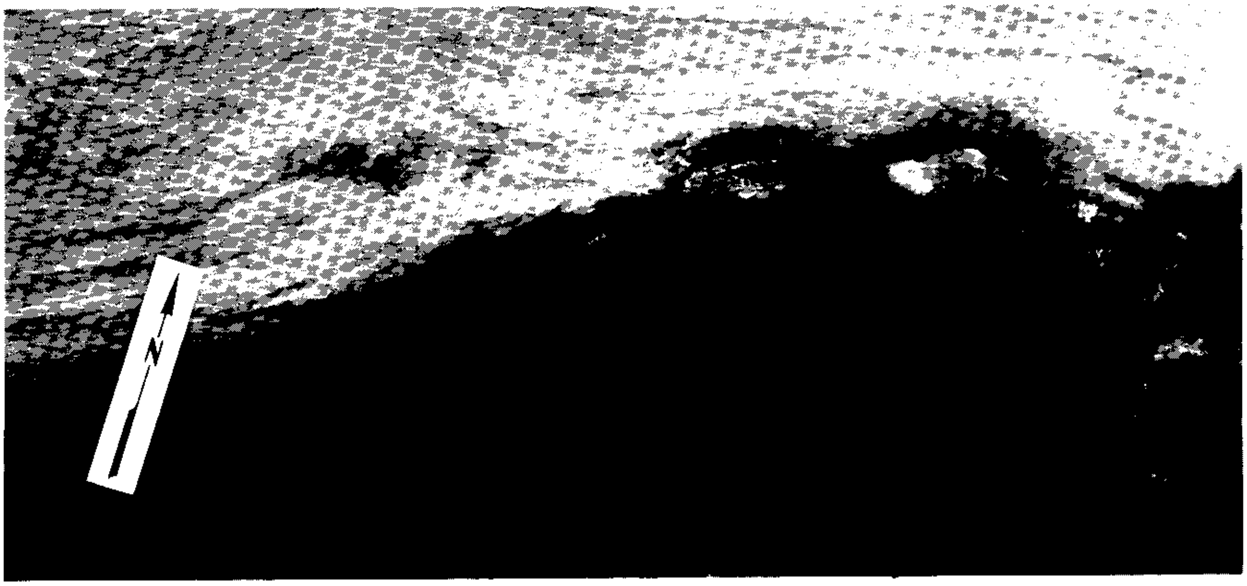

Figure 12ii. GOES VISSR (visible) image for 29 March 1977.

Figure 12jj. GOES VISSR (visible) image for 3 April 1977.

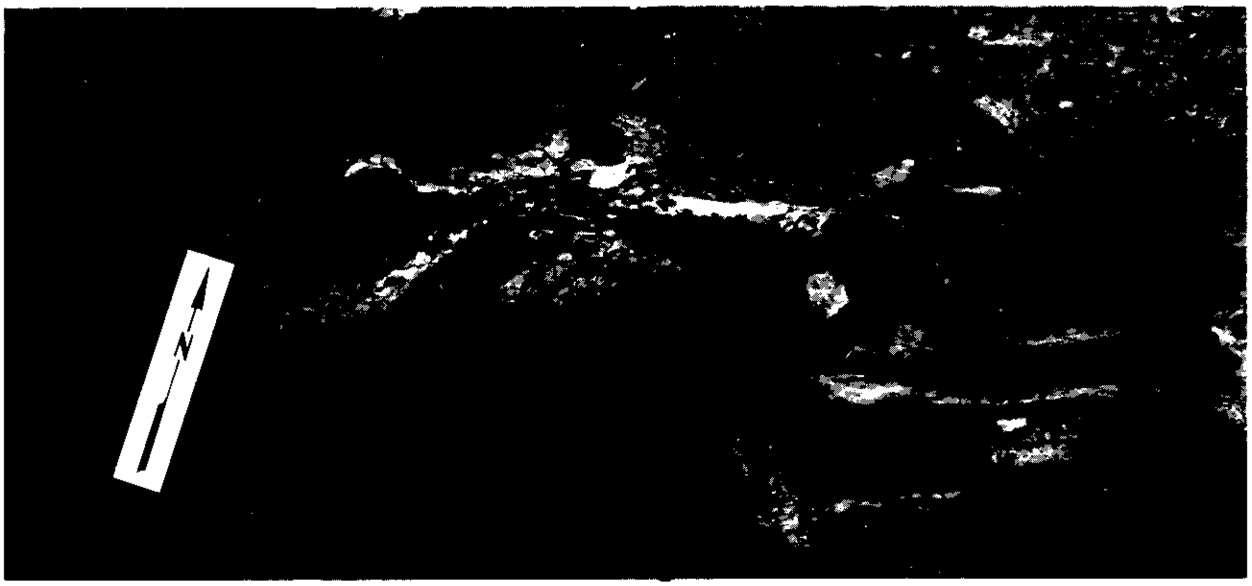

Figure 12kk. GOES VISSR (visible) image for 8 April 1977.

Figure 12ll. NOM VHRR (visible) image for 11 March 1977.

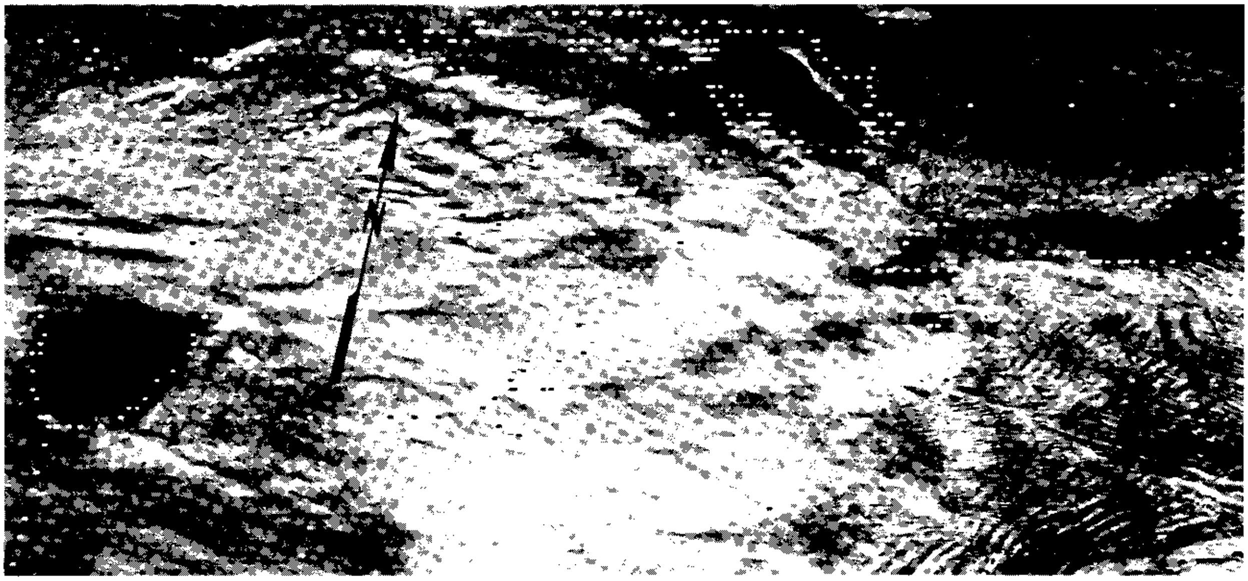

Figure 12mm. GOES VISSR (visible) image for 27 December 1977.

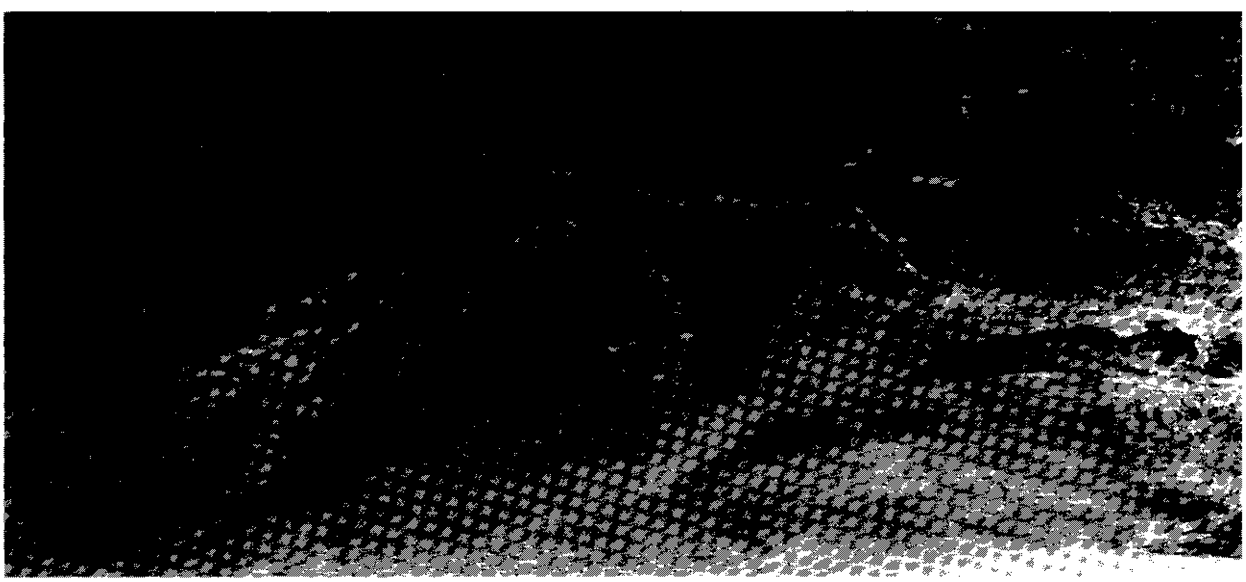

Figure 12nn. GOES VISSR (visible) image for 9 January 1977.

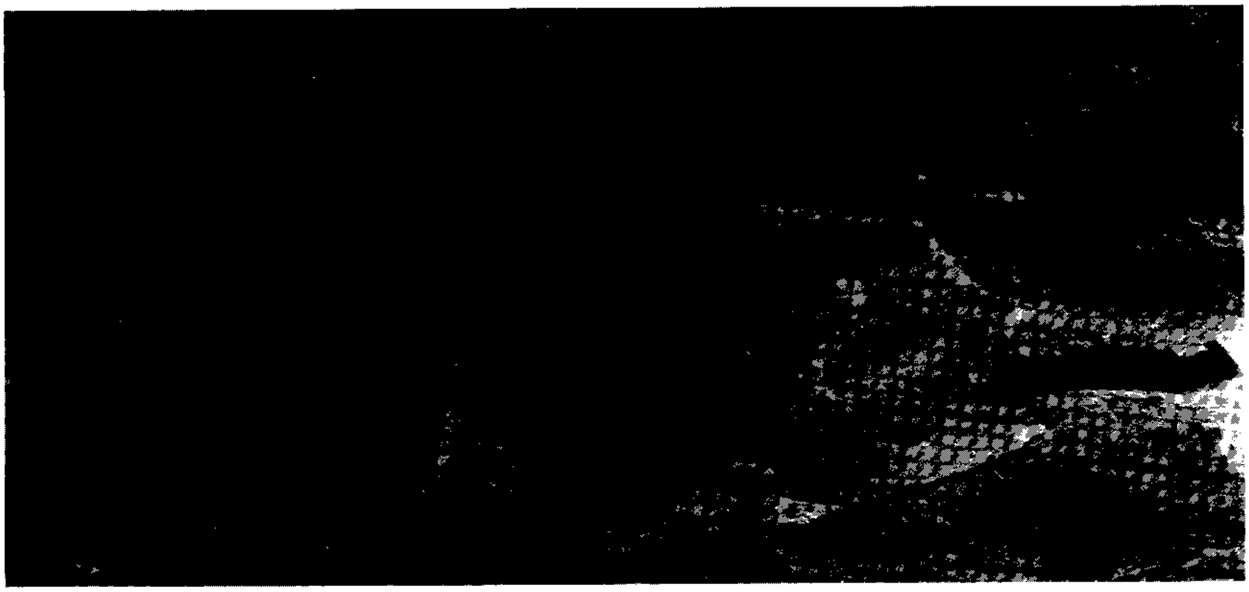

Figure 1200. GOES VISSR (visible) image for 7 February 1977.

Figure 12pp. GOES VISSR (visible) image for 21 February 1977.

Figure 12qq. GOES VISSR (visible) image for 1 March 1977.

Figure 12rr. GOES VISSR (visible) image for 2 March 1977.

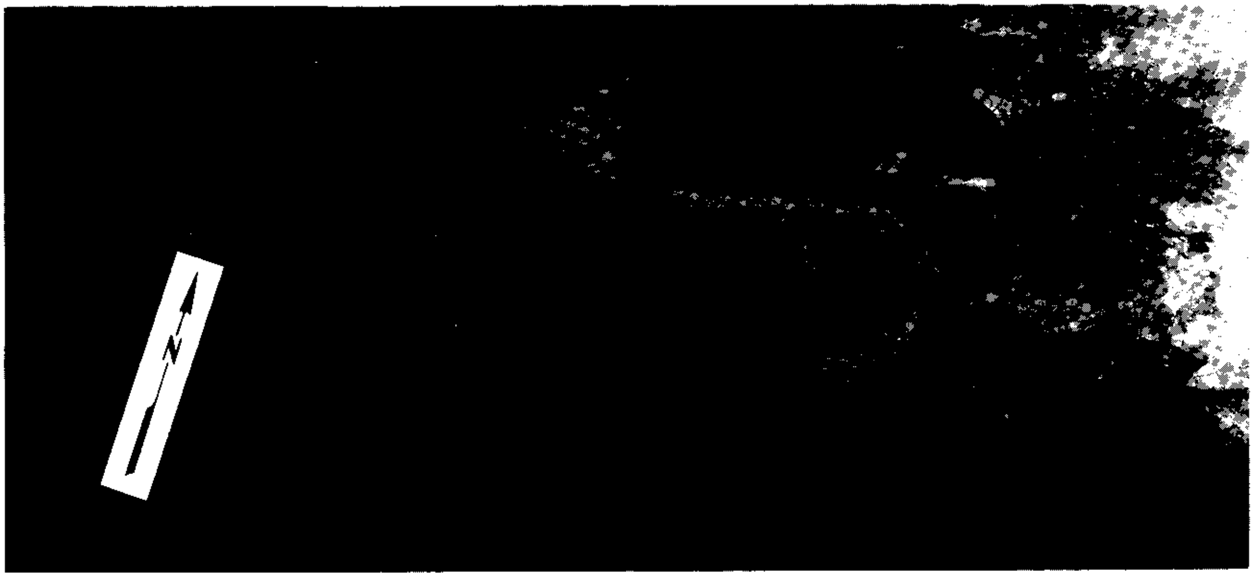

Figure 12ss. GOES VISSR (visible) image for 8 March 1977.

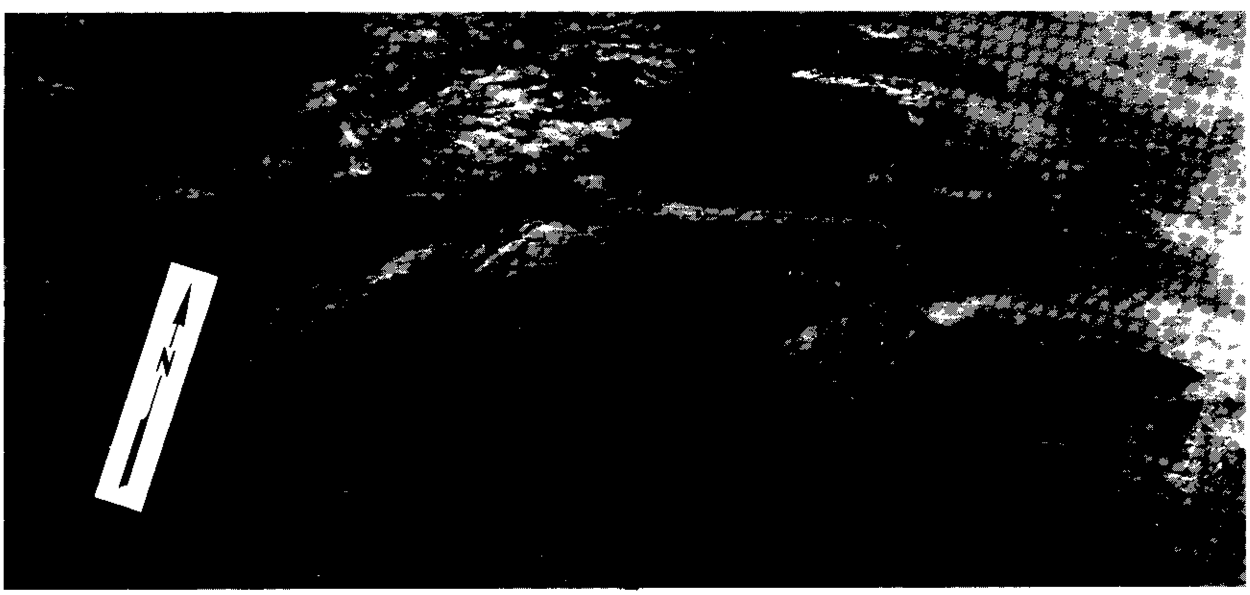

Figure 12tt. GOES VISSR (visible) image for 9 March 1977.

Figure 12uu. GOES VISSR(visible) image for 19 March 1977.

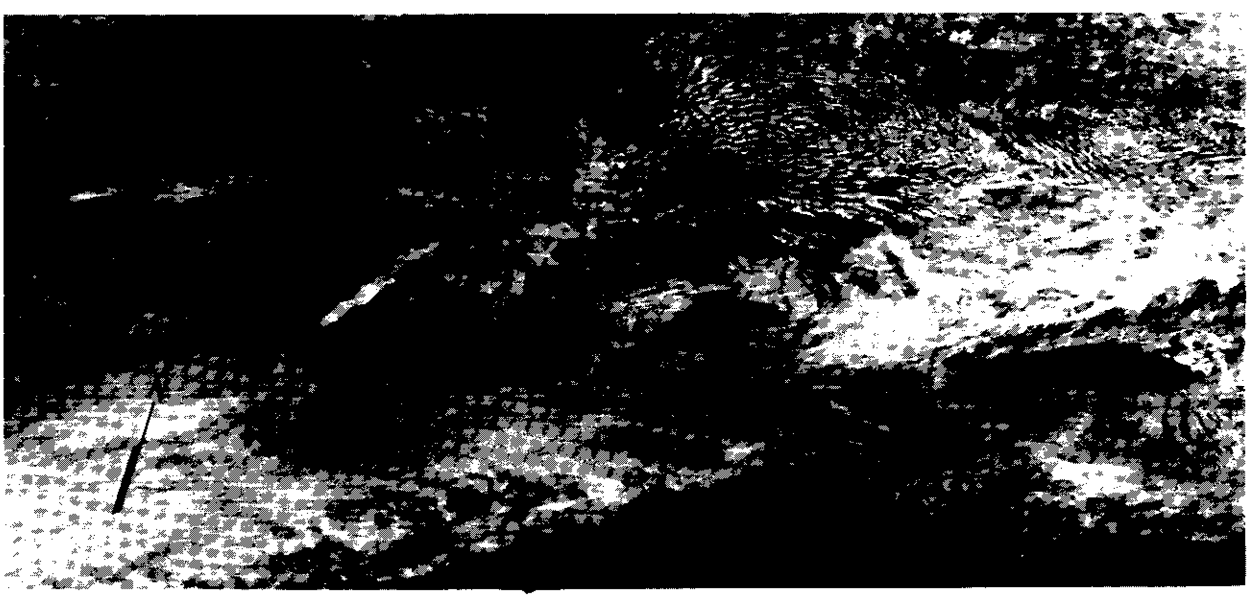

Figure 12vv. GOES VISSR(visible) image for 21 March 1977.

Figure 12ww. GOES VISSR (visible) image for 24 March 1977.

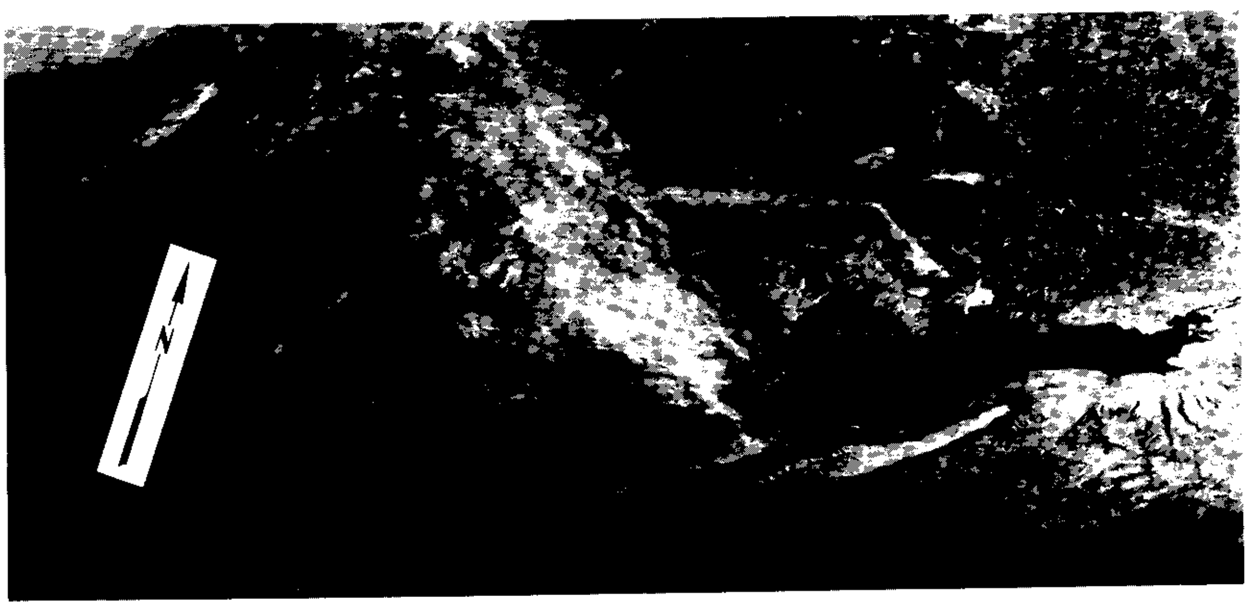

Figure 12xx. GOES VISSR (visible) image for 25 March 1977.

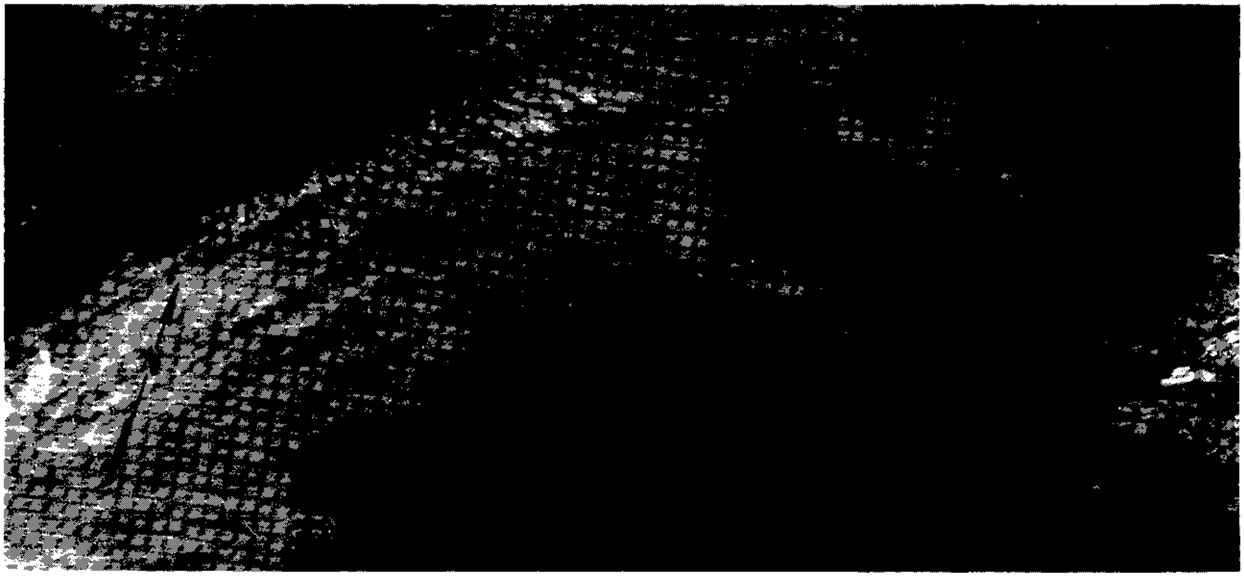

Figure 12yy. GOES VISSR (visible) image for 27 March 1977.

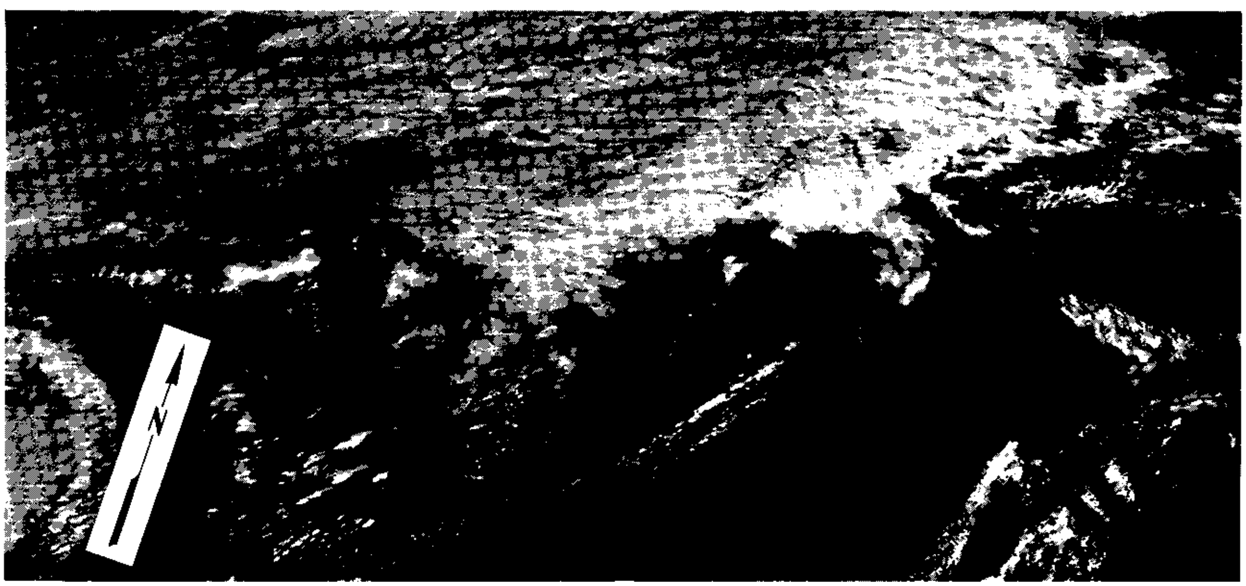

Figure 12zz. GOES VISSR (visible) image for 30 March 1977.

Figure 12aaa. GOES VISSR (visible) image for 9 April 1977.

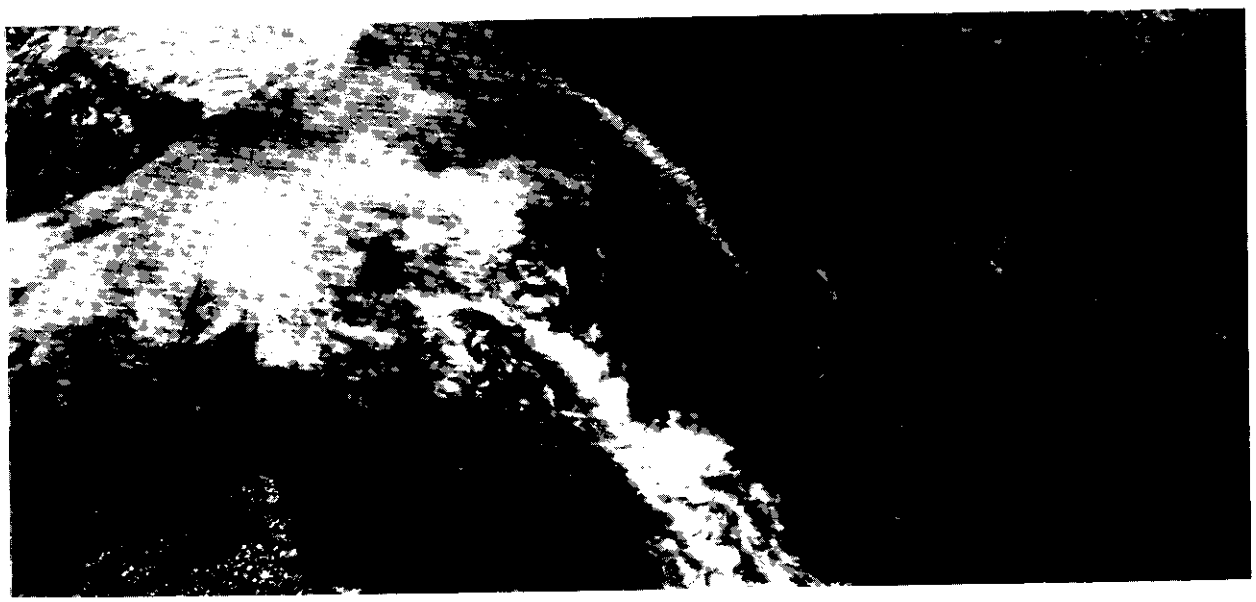

Figure 12bbb. GOES VISSR (visible) image for ii April 1977.

of the Great Lakes and gradually expanded east and south. The bulk of the ice was gone by 24 April. Areas of ice on that date included the southeastern shore of Lake Superior, Green Bay in Lake Michigan, the North Channel and the Georgian Bay in Lake Huron, and the Buffalo vicinity on eastern Lake Erie.

3.2.3 The Ice Cycle on Lake Superior

Ice was first reported forming along the shore of Whitefish Bay on 8 November. By early December, Nipigon, Black, and Thunder Bays had also developed major ice covers (Fig. 11*a*). Significant ice developed around the lake shoreline by 2 January, from 2 to 4 weeks earlier than normal (Fig. 11*e*). The ice formation steadily progressed so that by 9 January the western end of the lake from Keweenaw Point to Duluth was primarily ice covered (Fig. 11*f*).

On 9 January fast ice formed along the entire northern shore of Lake Superior, responding to the bitter cold weather (Fig. 12*a*). Keweenaw Bay became covered by new ice and the entire western prong of the lake was ice covered from shore to shore. By 11 January westerly winds had moved the ice away from the Bayfield and Ashland, Wis., shoreline, opening north-south leads in the ice; the deeper portions of the lake continued to remain open water. Northwesterly winds on 11 and 12 January began to move the pack ice away from the northern shore in the vicinity of Nipigon Bay and out into the lake south of Isle Royale. However, directly south of Isle Royale, in the lee of the island, there was relatively little ice. The western third of the lake appeared to be completely ice covered. Thermal imagery on 13 January (Fig. 12*b*) showed a wide lead extending south from the Apostle Islands to the south shore. Other leads (east-west) could be seen in the Duluth area. The large mass of ice adjacent to the southern shore of the Keweenaw Peninsula had been moved offshore, but new ice quickly formed. The ice to the east of Isle Royale had broken into floes and was moving south and east. More than half the lake was covered by ice.

Ice formed in the eastern lake basin during the second half of January (Figs. llg-i). Around 16 January northerly winds caused a pileup of ice along the northwestern shore of the Keweenaw Peninsula. By 18 January, vast areas of the northern shore of the lake were blown free of ice (Fig. 12*d*). Only the area between Isle Royale and the mainland retained its ice. "Warmer" water from the lake bottom was upwelling along the shore and the ice pack moved to the center of the lake and toward the southern shore.

On 25 (Fig. 12*e*) and 27 January the Apostle Islands were again the scene of a large lead, as westerly winds broke up the ice, moved it out of bays, and caused ridging. By 1 February 1977 the entire northern shore, from Michipicoten Bay to Two Harbors, was ice free, except for ice around Isle Royale (Fig. 12*f*). Despite the record low temperatures, Lake Superior was now only about 25 percent ice covered.

In February the low temperatures and northwesterly winds persisted, causing rapid ice formation (Fig. 12*g*). Lake Superior was near maximum ice cover for the 1976-77 winter in early February and again in late February (Figs. 11*j-m*). The percent of lake surface covered by ice on both 6 and 27 February is estimated to be 83 percent. The ice cover in the mid-lake areas of the eastern and western basins was estimated to be primarily thin to medium ice, i.e., up to 30 cm in thickness, with ice near the shore areas as thick as 70 cm. These thickness values refer to natural ice growth on open lake areas and not to rafted or windblown ice, or to ice growth in harbors and sheltered portions of bays where ice thickness can exceed 70 cm. On 9 February the temperature at Duluth rose to 7°C, marking the first time it went above freezing since 18 December. On the 10th (Fig. 12*h*) large leads continued to persist. The ice far offshore was very fractured and less reflective and darker in appearance. By 13 February the winds had moved the ice 70 km off the northern shore, but Whitefish Bay was solid and ridged. On 22 February a long lead was observed along the southern shore and a second lead had developed from Cape Gargantua, south toward Whitefish Point (Fig. 12*i*). The ice formation period continued up to the second week in March, with changes in ice configuration as shown in Figures 11*j-o*. On 1 March the northern shore was ice free and a circular area of open water about 50 km in diameter was observed east of the Keweenaw Peninsula. A lead east of the Apostle Islands is seen in Figure 12*k* for 7 March. Also on 7 March the pack ice west of Keweenaw Point was well fractured and of low reflectance in the northern part, indicative of melting; the temperature reached 5°C at Duluth. Pack ice completely filled the eastern half of the lake and long curving leads were evident in the pack. On 8 March southwesterly winds of 10 mph opened a lead on the southern shore (Fig. 12*l*) and Duluth recorded its warmest day (13°C). The next day, 9 March, the lead along the southern shore, off Marquette, Mich., widened considerably. For the next few days easterly winds again moved the pack offshore, as by this time it was a detached mass of ice.

The decay period lasted approximately 6 weeks, from mid-March to the end of April. The pattern of ice-cover loss proceeded from north to south. Large areas of open water occurred lakeward of the northern shore and generally north of a line from the Apostle Islands to Marathon, Ont., by the end of the third week in March (Fig. 11*p*). On 21 March the lake was still more than half covered by ice, with the northern shore and outer Keweenaw Bay clear (Fig. 12*m*). The next day the ice was seen to be rotten, lacy, and melting throughout, with large floes detectable. At Duluth temperatures reached 7°C. On 25 March further separation of the large floes were seen in the western part of the lake (Fig. 12*n*). The mean monthly Duluth temperature for March was 4.4°C above normal.

The open-water areas in the western basin, west of Keweenaw Point, occurred along both the northern and southern shores in late March (Fig. 11*q*) and new ice formed along the northern shore in early April (Fig. 11*r*). By 3 April Michipicoten Bay was no longer ice bound and by 6 April only a few large floes were noted north of Grand Marais, Mich.

(Fig. 12*o*). Only about 20 percent of the lake retained ice (Fig. 12*p*) by 9 April. Patches of ice still persisted off the Apostle Islands and north of Grand Marais on 14 April (Fig. 12*q*). However, by the end of the second week of April the bulk of the ice was gone from the western basin (Fig. 11*s*).

The general pattern of ice loss the first half of April was by expansion of the open water area along the north shore with the main mass of ice left in the eastern basin located east of a line between Marathon, Ont., and Munising, Mich. (Fig. llt). This ice changed configuration during the following week and was reduced in extent. The only significant ice left in the lake in late April was located in bays and harbors (Fig. 11*u*). On 22 April the lake ice north of Isle Royale was gone (Fig. 12*r*). Three days later the bulk of the ice was gone from Whitefish Bay (Fig. 12s) and 1 day later, on the 26th, Thunder Bay and the Apostle Islands were virtually ice free as well. In late April only some vestiges of ice were still apparent in Duluth Harbor, Keweenaw Bay, east of Marquette, and in Black and Nipigon Bays.

3.2.4 The Ice Cycle on Lake Michigan

First reports of ice formation came from Green Bay during the second week in November. On 3 December ice was detected east of the Straits of Mackinac, in the Big Bay de Noc, in south Green Bay, and off Chicago. By 5 December an extensive ice cover had formed in the southern half and the northern extremities of Green Bay (Fig. 11*a*). The following week, 12 December, ice was forming along the entire length of Green Bay, along the northern shore of Lake Michigan, north of Green Bay, and in the Straits of Mackinac extending to Beaver Island. By the 13th most of Green Bay was ice covered (Fig. 12*t*). The ice off Chicago disappeared, but reappeared in the area on 21 December. Ice had also formed along the southern perimeter of the lake by late December, as shown in Figure 11*d*. On 30 December ice was seen forming off the entire western shore of the lake in response to subzero temperatures. Green Bay was iced in for the winter and ice was also forming on the eastern shore.

The ice configuration remained relatively stable through early January (Figs. 11*c*-*e*). The extent of the ice cover illustrated in Figure 11*d* is similar to that given by Rondy (1971) for normal winter early season ice cover for the period 25 January to 5 February. During January the ice cover increased in extent and concentration over the entire lake so that by the end of the month the lake north of a line from Little Bay de Noc to Grand Traverse Bay was almost 100-percent ice covered and ice concentrations of 40 to 90 percent extended lakeward from the shore south of this line (Fig. 11*i*). The ice-cover configuration at this time was greater than the maximum ice cover given by Rondy (1971) for a normal winter and it was occurring a month earlier.

By 7 January the Straits of Mackinac were solidly frozen out to Beaver Island and ice was forming in Grand Traverse Bay and all along the eastern shore. By 11 January ice had formed from shore out to 25 km off Chicago (Fig. 12*u*). Westerly winds continued to cause upwelling, chilling, and freezing along the western shore, constantly moving the newly formed ice offshore. By 21 January the ice was observed in the Michigan City, Ind.-Benton Harbor, Mich., area (Fig. 12*v*). On 27 January a wind-gathered ice accumulation of 15 km nestled along the eastern shore and more new ice had rapidly formed along the western shore (Fig. 12*w*). The cold and winds continued and on 7 February Lake Michigan was frozen from east to west, virtually entirely ice covered. The narrow lead extending all along the western shore and a few small areas of open water proved to be the only non-ice areas (Fig. 11*j* and 11*g*).

During February there were large changes in ice cover as much of the ice that formed in the mid-lake area and along the southwestern shore was transported by wind and currents or melted by upwelling of warmer water (Fig. Ilk-m). On 8 February, with a strong northerly wind at Chicago, a long lead paralleling the shore developed from Chicago to Benton Harbor. On 9 and 10 February the southwestern winds cleared the western quarter of the lake (Fig. 12*h*). Chicago became ice free. On 14-17 February northerly winds drove the ice away from portions of the northern shore and broke up the large ice pack along the eastern shore (Fig. 12*x*). On 23 February the ice was severely brecciated by north-eastern winds and breakup had begun in earnest.

During the breakup period, ice-cover loss progressed from the southern end of the lake (Figs. 11*o*-*r*) to the open lake area of the northern portion, north of a line from Green Bay to Grand Traverse Bay (Figs. 11*p*-*s*). The last ice cover to dissipate was in the Straits of Mackinac out to Beaver Island and in Green Bay (Figs. 11*r*-*u*).

During the first few days of March, northerly currents began to carry the loose pack ice away from the western edge of the pack and toward Chicago in spite of southerly winds (Fig. 12*j*), but later, westerly winds pushed the mobile ice again to the east with a prominent ridge line showing up at the ice pack's leading edge. Next the pack "as forced northward along the eastern shore by southwesterly winds, and the northwestern edge of the ice began to bulge toward the Door Peninsula. But the warming of March was not to be denied. By 16 March only a third of the lake was covered by ice (Fig. 12*y*). By 19 March the pack was badly brecciated and broken, and only the Straits of Mackinac had solid ice, shore to shore. The Green Bay ice cover was beginning to thaw and by 22 March Grand Traverse Bay and areas in the straits were also thawing (Fig. 122). Open water was seen in Green Bay on 24 March and by 29 March the pack was largely sastrugi.

On 9 April Grand Traverse and Green Bay ice was breaking into floes (Fig. 12*p*). A lead through the Straits of Mackinac could be seen. Two days later, on 11 April, Green Bay Harbor was ice free, but the bay itself still contained numerous large floes, despite 16°C temperatures.

The long thin ice field off Washington Island lasted until about 25 April (Fig. 129). The last Lake Michigan ice was observed in Green Bay in late April.

Ice was estimated to cover 90 percent and 84 percent of Lake Michigan on 6 and 20 February, respectively. The extent of the ice cover makes the 1976-77 ice cycle comparable to and perhaps more severe than the 1962-63 ice cycle. Rondy (1971) classified the 1962-63 winter as severe for Lake Michigan.

3.2.5 The Ice Cycle on Lake Huron

The first observed ice cover on Lake Huron formed in Saginaw Bay during the first week in December (Fig. 11*a*). By the end of the next week, ice formation was taking place along the entire perimeter of the lake, and the Straits of Mackinac to Bois Blanc Island were frozen over, as was Saginaw Bay (Fig. 11*b*). In general, ice cover increased in December and January (Figs. 11*c*-*i*) and reached its maximum areal coverage in February (Figs. 11*j*-*l*). The early season ice cover, i.e., that in December and January, was more extensive than normal (Rondy, 1971).

By 15 December Saginaw Bay was frozen from north to south, and ice was noted in the North Channel of Georgian Bay (Fig. 12t). By 30 December Georgian Bay was half covered by ice and fast ice was on almost every shore of the lake. By 7 January the lake was producing ice all along the southwest shore from Cheboygan to Port Huron (Fig. 12*bb*). By 9 January the North Channel was frozen solid and the north half of Georgian Bay was ice bound. The southern basin was rapidly clogging with ice (Fig. 12*a*). On the 11th northwesterly winds blew the ice to the eastern shore and away from Alpena (Fig. 12*u*). The westerlies continued, and by 13 January the southern basin was completely ice covered (Fig. 12b). By the 19th of January Georgian Bay was ice covered except for the leads along the western edge (i.e., the eastern side of Manitoulin Island). On 27 January the lake was about 90 percent ice covered. From 27 January to 22 February (27 days) Lake Huron remained nearly 90-percent ice covered. On 9 February southwesterly winds pushed the ice away from the western shore, opening a large lead in outer Saginaw Bay (Fig. 12*cc*). The next day five leads, primarily oriented northeast-southwest, were formed in the southern basin in response to southeastern winds (Fig. 12*dd*). The Port Huron area appeared to be open from Port Sanilac, Mich., to Port Huron, while fast ice was evident along the Canadian shore. Portions of the St. Clair River appeared to be ice free. By 15 February the western shore from the outer portion of Saginaw Bay to Alpena was virtually ice free. The ice was then against the Bruce Peninsula and arcuate ridges and fractures paralleled the coastline (Fig. 12*ee*). The Georgian Bay ice had pulled away from the north shore with leads and cracks producing large floes. A large concentration of ice collected from Cheboygan, Mich., to North Point, but the lake mouth of Manitoulin Island was rather free of ice except for a single floe, about 15 km^2, west of Great Duck Island. On 17 February the lowest temperatures of the month occurred and the lake was nearly VO-percent ice covered (Fig. 12*x*). Subsequently, on 20 February the north winds returned and forced the ice southward, causing a jagged lead to open from Manitoulin Island to a point about 25 km west of Southampton, Ont. By 22 February the winds had changed from north to south to northeast and only a small area north of Pointe Aux Barques was free of ice (Fig. 12*i*).

By 28 February several days of westerly winds had reduced the ice cover along western shores of the lake except for inner Saginaw Bay (Fig. 12*ff*). The first of March marked the clear beginning of the breakup process (Fig. 12j). During the breakup period ice was first lost along the southwestern shore from Port Huron to Alpena, Mich., es cluding Saginaw Bay (Figs. 11*m-o*). Westerly winds and high temperatures freed much of the western shore except for the Mackinac Island area by 8 March (Fig. 12*b*). On 11 March a lead extended through the pack ice from a point 25 km east of Great Duck Island to a point on the Canadian shore 10 km south of Southampton in response to easterly winds, but this was closed by 14 March. By 17 March warm weather and northwesterly winds concentrated the ice against the Canadian shore, and in Georgian Bay the western half of the Bay was ice free except for some large floes (Fig. 12*gg*). On 19 March the brecciated ice pack was no longer tied to the shore. Even the ice in Saginaw Bay was adrift. Georgian Bay ice was detached, but shelf ice still clung to the eastern shore of the bay. The lake area between Alpena, Bois Blanc Island, and the North Channel became ice free the third week in March (Fig. 11*p*). Pack ice moved south on 24 March, moving inshore some 10 km south of Southampton. Only a thin band of floating ice barred entrance to Georgian Bay (Fig. 12*hh*). Saginaw Bay was almost clear of ice as was the entrance of Georgian Bay on *25* March. The main mass of ice in Lake Huron appeared to be composed of melting floes along the eastern shore on the 29th (Fig. 12*ii*). The breakup pattern the last few days of March and into early April, in general, was characterized by open-water areas that appeared along the northwestern and southwestern shores. These open-water areas merged to free the entire western shore and moved eastward (Figs. 11*q-r*). On 3 April the U.S. portion of the lake was ice free and the eastern shore still contained the main mass of pack ice left in the lake (Fig. 12*jj*). On 8 April the Straits of Mackinac appeared to be open, but not ice free (Fig. 12*kk*). An ice floe about 50 km in diameter was concentrated against the Bruce Peninsula. A patch of open water appeared in the North Channel at Meldrum Bay. By 25 April Georgian Bay and the North Channel were ice free (Fig. 12s). The ice in Lake Huron was last observed on 26 April. The next day the temperature reached 26°C at Alpena.

3.2.6 The Ice Cycle on Lake St. Clair

Lake St. Clair had an extensive ice cover by the end of the first week in December (Fig. 11*a* and 12*aa*). On 15 December the ice was blown toward the Canadian (eastern) side by southwesterly winds and open water extended all along the U.S. side. This condition persisted through 18 December. The lake was completely frozen over by 2 January. The lake stayed like a frozen tundra for almost 60 days. On 10 February a small open area was detected at the head of the Detroit River (Fig. 12*h*). By 19 February the open area had enlarged. Daytime temperatures were well above freezing. The open area slowly increased in size and on 1 March a patch of open water was seen adjacent to the northern channel of the St. Clair River at the northern end of the lake (Fig. 12j). On 8 March the reflectance of the lake ice was noticeably less, a sign of melting (Fig. 122). On 11 March Anchor Bay near New Baltimore, Mich., was ice free. By 16 March the ice pack had receded to the eastern shore and covered about a third of the lake (Fig. 12*y*). By 19 March only a few isolated fragments of ice remained. The lake lost its ice cover on 20 March (Fig. 11*f*).

3.2.7 The Ice Cycle on Lake Erie

As on other Great Lakes, the ice-cover formation period started about a month earlier than normal on Lake Erie. By 5 December the western end of the lake had a 70- to VO-percent ice cover (Fig. 11*a*). An infrared nighttime NOAA-5 image from 8 December clearly revealed extensive ice floes covering more than half of Lake Erie's western basin. The ice was thin and mobile (Fig. 12*aa*). On 15 December a large mass of ice was detected between Point Pelee and Point aux Pins in the central basin. By 21 December the ice in the western basin and the western part of the central basin was forming at a rapid rate. By 26 December (Fig. 11*d*) the ice cover extended from Toledo, Ohio, on the western end of the lake to Buffalo on the eastern end, with the exception of open water lakeward of an area from Buffalo to Long Point. The following week, 2 January, much of this open-water area also formed ice and the western basin was totally ice covered (Fig. 11*e*). On 9 January the central basin was virtually ice covered as was the entire lake on 11 January (Figs. 12*u* and 12*bb*). Lake Erie remained nearly frozen for 44 days. From time to time the northwesterly winds would move the ice off the northern shore and force the ice to compact, but as the ice moved offshore, upwelling warmer water would be brought to the surface and frozen. Westerly winds constantly broke loose the ice in the Pelee Island area and moved it to the east. On the satellite images it is not possible to identify the western basin as a water body as it had the thermal and visible characteristics of a land mass. The eastern end of the lake, the deepest area, was also impossible to identify as water.

The ice cover is estimated to have reached maximum areal extent (in excess of 99 percent) during the first week in February (Fig. 11*j*). Areal coverage remained relatively unchanged through the next week, beginning on 13 February (Fig. Ilk), but the last half of the month brought some minor decrease in ice concentration as the ice formation period came to an end (Figs. 112-m).

On 10 February several very small patches of open water appeared on the Ohio shoreline in the vicinity of Sandusky, Lorain, and Cleveland. On 16 February the ever-present north-south lead in the Pelee Island area opened and new ice was produced. Breakup probably began about 24 February, and by 26 February it was well underway. The high temperature for Toledo for the month, 16°C, had been reached the previous day.

The first of March saw a typical early thaw pattern for Lake Erie ice (Fig. 12*j*). The western portion of the central basin began clearing from west to east owing to westerly winds. A large open-water area formed between Point Pelee and a point east of Cleveland the first week in March. Monroe and Toledo Harbors showed their first open-water areas, too. But the remainder of the lake was from 70- to 100-percent ice covered (Fig. 11*m*). A lead 40-km long developed along the shore east of Pointe aux Pins. Cleveland Harbor was opened on 2 March and Sandusky was opened on 10 March. The eastward moving ice was clearing faster along the southern shore. The ice in the western basin, as usual, was melting on a separate ice pack. By 16 March it was located just west of Point Pelee (Fig. 12*y*). Northwest winds pushed the pack away from the northern shore and open water, 10-20 km wide, extended from the Welland Canal to the Detroit River. The brecciated and fragmented nature of the main pack was now evident. By the third week of March the open water had expanded to encompass most of the shore area of the western end of the lake. Thin ice or open water also extended along the northern shore (Fig. 11*p*). The western basin was ice free on 24 March (Fig. 12*hh*). The last week in March the main mass of ice left in the lake was located along the southeastern shore between Cleveland and Buffalo (Fig. 11*q*). By 29 March the pack, floating offshore except at Buffalo, was rotten and lacy and had low reflectance (Fig. 12*ii*).

By 10 April (Fig. 11*s*) Lake Erie was ice free with the exception of the Buffalo area. Ice extended from Dunkirk, N.Y., to Buffalo along the shore out to 5-10 km and a "plug" at Buffalo formed for the second straight year. The "plug" melted about 29 April 1977, and ice was last reported in Buffalo on 30 April. There were at least 141 days when ice was present in Lake Erie.

3.2.8 The Ice Cycle on Lake Ontario

Ice formation in the open lake began in early January (Fig. 11*e*), although ice was reported forming in bays and harbors in early December. Ice first formed in the shallow northeastern section of the lake, proceeding westward and along the northern and eastern shores (Figs. 11*f*-*j*). The first ice noted in satellite imagery on 27 December was in the northeastern part of the lake near its outlet into the St. Lawrence River (Fig. 12*mm*). By 9 January ice was well formed in the Sacketts Harbor-Amherst Island area and along the eastern shore (Fig. 12*mm*).

The lake was estimated to have its greatest areal ice coverage in early February, when 38 percent of its surface was ice covered. There were significant changes in ice configuration during February and early March (Figs. Ilk-m) and total areal coverage was estimated to be 20 percent the end of the first week in March.

On 7 February it appeared that the entire eastern third of the lake was ice covered and that ice was forming all along the northern shore and at the western end, but some clouds were present, making the interpretation somewhat uncertain (Fig. 1200). The fifteenth of February had ice extending 10-20 km offshore of Canada (Fig. 12ee). The eastern end of the lake from about Fair Haven, N.Y., east had heavy ice concentrations. On 21 February ice was concentrated from just east of Rochester, N.Y., to the southeastern shore of the lake, with the edge of the ice pack extending to the northeast (Fig. 12*ff*).

By 1 March a large pack of ice was concentrated east of a line from Fair Haven to the Bay of Quinte, and the edge of the windblown pack was oriented north-south (Fig. 12*qq*). A good clear image was obtained on 2 March and fast ice was noted from Cobourg, Ont., to the Bay of Quinte, where it merged with the main pack (Fig. 12*rr*). On 8 March, as a result of prior southwesterly winds, the ice pack's lake edge was oriented southeast-northwest from Oswego, N.Y., to Wellington, Ont. (Fig. 12*ss*). Sodus Bay and Irondequoit Bay were still ice covered. On 9 March a large open-water area developed in the vicinity of Amherst Island at the entrance to the St. Lawrence River (Fig. 12tt). Notable decreases in the main mass of ice, located in the northeastern section of the lake, occurred between 13 and 20 March (Figs. 110-p). The ice melted in place until 18 March; then, on 19 March it was observed that the ice pack was disintegrating and migrating westward toward the center of the lake (Fig. 12*uu*). By 21 March the winds again were consolidating the pack in the northeastern section (Fig. 12*vv*). From 24 through 27 March northwesterly winds pushed the now very mobile pack into the southeastern corner of the lake, thus clearing the entrance to the St. Lawrence entrance of ice (Figs. 12*ww-yy*, 12*ii*). On 29 and 30 March the ice pack seemed to expand as it moved back north, but this effect was undoubtedly owing to a mobile pack spreading out with reduced concentration of ice as a result of southerly winds (Fig. 1222).

On 3 April the pack was concentrated in the northeastern area again, from Kingston, Ont., to a point midway along the eastern shore (Fig. 12*jj*). It diminished greatly in size from 8 April (Fig. 12*kk*) to 9 April (Fig. 12*aaa*) and was again spread southward by the northwesterly winds. The melting ice was observed on 17 April (Fig. 12*bbb*) and was completely gone by 24 April (Fig. 11*u*).

3.3 Comparisons with Previous Winters

By making comparisons of normal ice-cover configuration and dates given by Rondy (1971) for four periods in the winter, early winter, midwinter, maximum ice cover, and early decay, the 1976-77 winter can be put in perspective relative to normal conditions. Table 5 shows the dates 1976-77 ice cover was similar to normal ice configuration in the four winter periods. From this table it can be seen that ice-cover configuration similar to normal early winter, mid-winter, and maximum ice cover occurred on the average of 4 to 5 weeks earlier than normal during the 1976-77 winter. In addition, while the early decay period was near normal on Lakes Superior, Michigan, and Huron, it was approximately 2 weeks later than normal on Lakes Erie and Ontario.

A second comparison of the 1976-77 winter is made in Table 6, which shows 1976-77 percent maximum ice extent and those given by Rodgers (1976a) and Leshkevich (1976, 1977) for the Great Lakes during the past 14 winters. From Table 6, it can be seen that 1976-77 maximum ice extent was only exceeded by four winters for Lake Superior, no winters for Lake Michigan, one winter for Lake Huron, and one winter for Lake Ontario. No comparisons are made for Lakes Erie and St. Clair as they freeze over most winters. Table 6 also contains the mean and standard deviation of maximum ice extent for the past 15 winters on the Great Lakes. Defining as normal the mean plus or minus one standard deviation, the 1976-77 winter can be classified as having above normal maximum ice extent for Lakes Michigan, Huron, and Ontario and normal ice extent for Lakes Superior and Erie.

Summarizing, the 1976-77 ice cover occurred earlier than usual and was more extensive than usual for the early winter, mid-winter, and maximum ice extent winter periods. Ice cover on the entire Great Lakes in 1976-77 was more severe in many respects than any year during the past one and one-half decades for which well-documented records exist. The ice decay period came near the normal date of occurrence on the northern portion of the Great Lakes, but was later on Lakes Erie and Ontario.

4. CONCLUDING REMARKS

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4.1 Effects on Lakes Commerce

During the winter of 1976-77 waterborne commerce on the Great Lakes was severely hampered by the abnormally large amount of ice cover and the long duration of the cover. Commerce continued throughout the season, but the iron ore trade from the lakehead into southern Lake Michigan and Lake Erie was suspended for almost 2 months during mid-winter--the first such break in traffic in 3 years. Direct icebreaking assists by the U.S. Coast Guard were up nearly 55 percent over the "previous season.

Table 5. Comparison of Dates When Ice Cover for 1976-77 Was Similar in Configuration to Normal Ice Cover for Early Winter, Mid-Winter, Maximum Ice Extent, and Early Decay Winter Periods.

Location	Early Winter Normal	Early Winter 1976-77	Early Winter Deviation 1976-77 (days)	Mid-Winter Normal	Mid-Winter 1976-77	Mid-Winter Deviation 1976-77 (days)
Lake Superior	20-30 Jan.	2 Jan.	+18	25 Feb.-S Mar.	9 Jan.	+47
Lake Michigan	25 Jan.-5 Feb.	26 Dec.	+30	20-28 Feb.	9 Jan.	+42
Lake Huron	25 Jan.-5 Feb.	12 Dec.	+44	25 Feb.-5 Mar.	16 Jan.	+40
Lake Erie	15-25 Jan.	5 Dec.	+41	1-10 Feb.	9 Jan.	+23
Lake Ontario	25 Jan.-5 Feb.	9 Jan.	+16	15-25 Feb.	16 Jan.	+30
Mean			+30	Mean		+36

Location	Maximum Ice Extent Normal	Maximum Ice Extent 1976-77	Maximum Ice Extent Deviation 1976-77 (days)	Early Decay Normal	Early Decay 1976-77	Early Decay Deviation 1976-77 (days)
Lake Superior	25 Mar.-5 Apr.	23 Jan.	+61	l-10 Apr.	17 Apr.	-7
Lake Michigan	15-25 Mar.	16 Jan.	+58	20-30 Mar.	3 Apr.	+4
Lake Huron	20-30 Mar.	30 Jan.	+49	25 Mar.-5 Apr.	27 Mar.	0
Lake Erie	20-28 Feb.	6 Feb.	+14	25 Feb.-5 Mar.	20 Mar.	-15
Lake Ontario	10-20 Mar.	27 Feb.	+10	15-25 Mar.	10 Apr.	-16
Mean			+38	Mean		-7

Table 6. Comparison of Maximum Percent Ice Extent on the Great Lakes: 1976-77 and Previous Winters

Winter	Superior, %		Michigan, %		Huron, %		Erie, %	Ontario, %	
1962-63	95		80[a]	+[b]	97		98	51	
1963-64	31	+	13	+	32	+	91	12	+
1964-65	90		40	+	60	+	NA[c]	10	+
1965-66	60	+	15	+	29	+	NA	15	+
1966-67	88		46	+	80	+	90	12	+
1967-68	90		30	+	50	+	98	10	+
1968-69	40	+	15	+	50	+	80	10	+
1969-70	80	+	30	+	50	+	95	17	+
1970-71	48	+	27	+	45	+	92	10	+
1971-72	95		45	+	70	+	95	20	+
1972-73	55	+	20	+	60	+	95	20	+
1973-74	70	+	20	+	65	+	95	25	+
1974-75	30	+	25	+	45	+	80	16	+
1975-76	40	+	20	+	50	+	95	20	+
1976-77	83		90		89		100	38	
Total +'s		9		14		13	NA		13
Mean ice extent	65		34		58		93	19	
Standard deviation	25		23		19		6		12

[a]As given by Rondy (1971).

[b]+ is 1976-77 winter had more extensive ice cover.

[c]NA is not available.

With the addition of another 1000-ft vessel to the iron ore trade during the season, tonnage was up over 2 million tons from the previous year. By the end of 1976, demands were much lower and the natural ore season ended in Duluth on 24 October. Some ships laid up shortly afterward. Other ore ships transported grain cargoes during November.

The generally frigid autumn resulted in ice in some navigation channels in late November in northern lake ports. By early December the ice was widespread in many shallow waters and the Coast Guard reported that damage to navigation aids was the worst in 30 years. The NWS predicted the worst ice year on the Great Lakes in over 5 years in a forecast issued in late November. Only days later the ice began to take its toll. A Norwegian ship, *Kings Star,* drifted helplessly in Lake Erie on 1 December. Numerous vessels were pushed out of dredged channels by the ice and 20 ships had gone aground by the year's end. The worst incident was the grounding of the *Cliff's Victory*. She went hard aground near Johnson Point in the lower St. Marys River on 9 December, blocking the two-way channel. While part of her cargo was off-loaded and tugs pulled her free, 70 ships went to anchor waiting to transit the river. At least one of those delayed was a foreign flag ship racing to pick up in Duluth a cargo bound for Europe before the closing of the St. Lawrence Seaway system on 18 December.

The U.S. Coast Guard cutter *Bramble* provided the first direct icebreaking assist of the season when she helped the *E. M. Ford* and the Merchant Vessel (M/V) *Nicolet* into Saginaw Bay on 3 December. The next day the Canadian *Meaford* was helped in the St. Marys River by the *Naugatuck*. Several vessels were assisted in northern Green Bay by the *Arundel*. The polar icebreaker *Westwind* (Fig. 13) moved from her homeport of Milwaukee, Wis., to Duluth. She chalked up several assists by mid-December.

The closing of the St. Lawrence Seaway was delayed for several days as exceptionally severe ice conditions hampered efforts to get the last few foreign vessels through the river. Water temperatures on 8 December were the lowest for that date since the seaway opened in 1959. Shipping was halted from 12 to 14 December to permit a stable ice cover to form and thus reduce the likelihood of damage to hydroelectric facilities. The Liberian freighter *Attica* and the Canadian Seaway *Queen* were the last ships through the locks; this was on 19 December. Similar ice problems plagued the Welland Canal. On 3 January the Canadian *Black Bay* was the last ship to travel through the canal. The *Tarantau* started a voyage through the canal, but became stuck and stayed near lock 7 for the winter.

There was little relief in the unrelenting cold in December, and the Coast Guard had logged 238 icebreaking assists by New Year's Eve. Preventative icebreaking was also being performed by vessels not deployed to remove seasonal aids to navigation. Vessel traffic ended on Lake Erie with the exception of the "coal shovel" run between Toledo and Detroit.

Figure 13. U.S. Coast Guard icebreaker Westwind. *(Photograph courtesy of the U.S. Coast Guard Air Station, Detroit, Mich.)*

As an extremely cold January favored steady ice growth throughout the Lakes, icebreaking continued at record levels. Over 150 vessels were assisted in the first half of the month owing to some of the worst conditions of the season. The Canadian Coast Guard cutter *Griffon* attempted to escort the M/V *Canadian Mariner* across Lake Erie, but was turned back near Long Point. On 11 January the tanker Amoco *Indiana* went aground in ice near Grand Traverse Bay in Lake Michigan. There was concern that the ice might cause an oil pollution incident, but the vessel was refloated the next day with minimum pollution.

On 17 January the Winter Navigation Board, composed of government agencies assigned to demonstrate and study the feasibility of winter navigation on the Great Lakes and St. Lawrence Seaway, announced that bad weather and ice conditions in Lake Superior and the St. Marys River were forcing them to close the area to vessel traffic. The last American vessels cleared the locks on 23 January, ending 34 months of continuous operation at Sault Ste. Marie. Ironically, the same severe weather that promoted the suspension of winter navigation in western Lake Superior necessitated shipping into Thunder Bay, Ont., to avert potential fuel shortages. The Canadian ships *Doan Transport, Hudson Transport,* and *Imperial St. Clair* transported fuels and supplies to Thunder Bay and Sault Ste. Marie, Ont., on several trips in late January and early February.

On 20 January, strong pressure on the moorings of the Little Rapids Cut ice boom on the St. Marys River broke the structure. Some ice moved from Soo Harbor into the cut, but the Sugar Island Ferry continued to operate. Four commercial vessels were delayed 2 days while repairs were made. Another 80 boats were assisted during the last half of January.

February was a landmark month on the Great Lakes. For the first time since 1963 all of the lakes with the exception of Lake Ontario were nearly 100-percent ice covered. Fifteen ships continued to sail during the first week of the month, but icebreaking assists were nearly constant. One of the Coast Guard's two major lake icebreakers, the *Mackinaw,* was damaged on 3 February. While working in the St. Marys River, her port propeller shaft was bent and one blade was sheared off. Trips into Lake Superior continued, but the Canadian tankers were able to move at only 1.6 km per hour (1 mile per hour) at times in the l-m thick ice. The round trip from Sarnia, Ont., to Thunder Bay took about 2 weeks.

The weather alternated between cold and mild periods in February. The milder weather during the last week of the month was sufficient to loosen river ice in the lower lakes. It took the Km, the *Arundel*, the *Bramble,* and finally the *Westwind* to break the tough ice near Fairport Harbor in Lake Erie. Meanwhile, on Lake Michigan the sustained westerly winds had "windrowed" the ice so badly that carferry operations out of Muskegon, Mich., and Frankfort, Mich., were halted on 17 February. The *City of Midland* lost one of her prop blades outside of Ludington, Mich. Direct icebreaking assists numbered just under 100 for the month.

The milder weather in early March eased ice conditions throughout the Lakes. The trend was encouraging enough for iron ore haulers to schedule a resumption of traffic to western Lake Superior. On 15 March U.S. Steel's *Anderson*, *Callaway*, *Clarke*, and Munson left Milwaukee for Two Harbors, Minn. On 17 March the *Callaway* was the first to transit the American locks at the Soo. The date was the earliest on record for the opening of the "spring" season. On Lake Erie the season opened 20 March with the arrival of 6000 tons of cement on the *S. T. Crapo*. Most shipping companies delayed outfitting their ships until later in April. Thirty ships were operating at the end of the month.

As April began, emphasis on icebreaking in the lower lakes shifted from western Lake Erie and the St. Clair region to the eastern end of Lake Erie. The Canadian cutter *McLeod* Rogers arrived in Port Colborne, Ont., for the opening of the Welland Canal on 4 April. The *Ojibwa* was enroute to Buffalo for ice operations on 6 April when she sustained steering damage and became beset 11 miles west of the city. The St. Lawrence Seaway opened on schedule 4 April when the Norwegian vessel *Thorshope* entered the St. Lambert Lock. On the Detroit River the *J. W. Wescott II* began mail delivery for the season on 14 April.

Ice on the upper lakes continued to diminish throughout the month. Coast Guard icebreaking operations "Taconite" on Lake Superior and the Straits of Mackinac and "Oil Can" on Lake Michigan were terminated on 25 April. The ice boom in the St. Marys River was removed 3 days later. As shipping activity increased, so did icebreaking and 63 direct assists were recorded during the month.

At the beginning of May, ice could still be found in the northern bays, in eastern Lakes Superior and Huron, and especially in the Black Rock Canal near Buffalo. The last icebreaking assist of the season was made by the *Kaw* in the Buffalo area when she assisted the *Turecamo*. The Ice Navigation Center in Cleveland ended its operations for the season on 6 May and the "Open Buffalo" operation ended on 12 May as the last few pieces of drift ice finally melted.

4.2 Air-Lake (Water) Interaction

There is a flux of heat, moisture, and momentum between air and water. It is of interest to note the effect of the heavy ice cover of the winter of 1976-77 on these fluxes. Figures 5*a-b* and 4*a-c* to 10*a-b* all show relatively high air temperatures over and along the lee shores of the Lakes. The temperature gradient across a lake in the downwind direction on each of these charts is a function of the conductive heat transfer from water to air. The heat thus transferred is a combination of sensible and latent, including the latent heat of fusion for water. In the absence of ice, this transfer takes place at the air-water interface. When an ice sheet is present, additional freezing usually takes place at its lower surface. So either sensible heat from the water or latent heat from new freezing must be transferred to the air through the ice. The rate of conduction depends on the nature of the ice, its thickness, and the temperature difference between water and air. water temperature in the Great Lakes is very near 0°C during all but the early part of the winter. Thus, the water-air temperature difference is primarily a function of air temperature.

Thermal conductivity of ice and snow varies with their density. Solid ice (lake ice or "blue" ice) has a density of 0.9 g/cm^3 and a thermal conductivity of about 0.0054 $cal/cm^2/sec/°C$. New fallen snow has a density of about 0.1 g/cm^3 and a thermal conductivity of 0.00007 $cal/cm^2/sec/°C$. Closely packed snow, snow ice, slush, and "white" ice have intermediate values. The precipitation pattern discussed in Section 2.1 led to a preponderance of blue ice during the winter of 1976-77 and a relatively small amount of snow cover and white ice. Thus, one would expect that the thermal conductivity of the ice cover was greater than normal.

Both the nature of the ice and the below normal air temperatures during the winter of 1976-77 would have increased heat flow into the atmosphere; greater ice coverage and thickness would have decreased it.

Figures 4*c*, 8, and 9*c* show that the air temperature anomalies expressed as standard deviations were the same over land as over water. For this to be true, all the factors inhibiting or enhancing heat transfer must total approximately zero. We conclude that the amount of heat transferred from water to air varies linearly with the temperature difference between water and air, and is almost independent of the existence or thickness of ice cover.

Moisture is also transferred from lake to atmosphere. The rate of evaporation depends on the temperature of both water and air, the relative humidity, and the rate of removal of the moistened air from contact with the evaporating surface.

The low temperature of water and air restricts the amount of water that can be evaporated, but this is only true in a relative sense. While the absolute humidity of cold air must necessarily be low, the relative humidity can quickly approach 100 percent whenever a water surface much warmer than the air is encountered.

Horizontal wind flow is rather ineffective in evaporating moisture from large bodies of water. When air movement is laminar, most of the water is exposed only to air that has already become saturated. Vertical air currents, however, carry the moisture up away from the water surface and allow the entire area of the lake to be an effective evaporating surface. Vertical air currents arise from air mass instability. An air mass becomes more unstable whenever it is heated from below. Colder air is more strongly heated than warmer air over water of a nearly constant temperature. Thus, in a colder winter more moisture per unit area of open water will be introduced into the atmosphere.

Counteracting this greater evaporation per unit area is the decrease in exposed area as the ice cover increases. There is no direct way to determine whether the increase of evaporation due to greater instability was greater than the decrease due to increasing ice cover. Recourse can be made to sunshine statistics. Much of the moisture evaporated from the Great Lakes in winter forms into stratocumulus clouds, whose persistence is a characteristic feature of the local climate. Data for Detroit are used to compare the percent of possible sunshine during the winter of 1976-1977 to normal percentages (Table 7)

Table 7. Percentage of Possible Sunshine at Detroit, Mich.

Month and Year	Normal %	Actual %
Dec. 1976	28	49
Jan. 1977	38	49
Feb. 1977	46	46
Mar. 1977	49	59

Of the 4 months of ice cover 3 had more sunshine than normal; February had the normal amount. We conclude that ice cover inhibited evaporation more than cold air mass instability enhanced it. The lighter-than-normal precipitation alluded to above is further support for this conclusion. It should be noted, on the other hand, that a general lack of cyclonic activity contributed somewhat to the greater amount of sunshine.

Ice cover also prevents the conversion of wind energy into waves. This should add an increment to wind velocity over the region. All observers described the winter as quite windy, but the various influences which brought about this wind cannot be separated.

The extremely heavy snow that fell in narrow bands on some of the lee shores requires explanation. It was obviously "lake snow": there were no large scale weather disturbances in the area. Communities only a few miles away received little or no precipitation during these events. Classically lake snow has been attributed to instability showers dropping moisture picked up from the upwind lake. Some attention has been given to convergence in the wind flow as an enhancing factor. This convergence my arise from funneling or rising terrain features or from differences in frictional wind retardation over land and over water. Available moisture during the winter of 1976-77 "as demonstrably less than normal. Some of the heaviest snows were on the downwind ends of almost completely ice-covered lakes. Instability "as probably greater than normal, though it is hard to determine by how much at a particular time and place. Convergence in the wind flow was considerably greater than normal, and it "as concentrated in precisely the areas that got heavy snow. Convergence may play a larger role than "as previously suspected in the production of heavy snow bursts on the lee shores of the Great Lakes.

4.3 Hydrology

It is indeed fortunate that the satellite and SLAR aircraft coverage of the Great Lakes "as initiated prior to the Great Winter of 1976-77. The use of remote-sensing data from these valuable research tools has permitted a thorough and unprecedented series of ice observations to be made on the Great Lakes during the worst ice season certainly in more than 40 years and probably in the past 100 years.

Satellites have allowed us to see the effectiveness of the wind in concentrating ice; the cooling of the upwelling water as the Lakes become ice-producing "machines"; the effect of the stored heat on Lake Ontario, which produced the least ice; the new transparent ice transformed into older ice by movement, currents, and snow cover; the zones of weakness; and the patterns of breakup of certain parts of the ice.

The study of ice on the Great Lakes has been advanced from an art to a science by the remote sensors routinely providing half-hourly observations from geostationary satellites. The science of ice forecasting has been enormously advanced by these new observations. Although this paper is largely descriptive and attempts to do little more than document the intensity of a memorable ice year, it will be a source of basic data for generations to come. Studies of lake ice and climatic fluctuations cannot afford to overlook this record.

With improved quantitative data on area1 extent of ice and improved thermal data on both ice and water, one may confidently predict a number of studies on heat balance, heat exchange and storage capacity of the Lakes, effects of wind stress on lake ice, relation of freezing degree-days to ice formation, the relation of wind direction to local area icing conditions, etc.

The amount of ice in each of the five Great Lakes and Lake St. Clair is a complex function of temperature, wind, precipitation, shape of the lake, total water mass in the lake, and surface area of the lake. Each lake is unique in its response to the dynamic meteorological and hydrological events and the thermodynamic properties of the water mass. While the Lakes do react similarly at times, e.g., the first freeze, they react quite differently at other times. The effect of ice on the climate, commerce, transportation, and energy consumption of the inhabitants in the Great Lakes Basin is significant, and improved forecasting of ice conditions, which should result from satellite and aircraft remote sensing, will facilitate and improve transportation and commerce during ice seasons to come.

One of the popular new tools in lake hydrology is the use of computer models to study almost all phases of hydrology from pollutant dispersion to three-dimensional thermodynamic response to thermal loading. In this present era of increased environmental awareness, it is important that these models be as accurate as possible. Timely satellite observations allow hydrologists to verify their models. The combination of these two new approaches, modelling and satellite observations, can be a very powerful tool in man's continuing quest for an improving environment.

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