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A Computer Tutorial and Animation of the Normal Ice Cycle of the Laurentian Great Lakes of North America for 1960-1979

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A COMPUTER TUTORIAL AND ANIMATION OF THE NORMAL ICE CYCLE OF THE LAURBNTIAN GREAT LAKES OF NORTH AMERICA FOR 1960.1979

R.A. Assel and J.M. Ratkos

ABSTRACT. An interactive, menu-driven computer tutorial was developed to provide an overview of the annual Great Lakes ice cycle. The tutorial includes an animation to aid in visualizing the seasonal progression and the spatial patterns of ice cover for the base period 1960-1979. The computer algorithm was developed from data contained in the NOAA Great *Lakes* Ice *Atlas*. This material is presented as a government technical memorandum to make the tutorial available to the public at large for educational purposes. A computer diskette needed to load and run the tutorial (on a Macintosh Plus with at least 2 megabytes of memory) is included as an appendix. Background information on the ice cover data and methods used to create the tutorial is followed by a description of the spatial and seasonal ice cover distribution patterns as related to lake bathymetry.

1. INTRODUCTION

This memorandum contains an interactive, menu-driven computer tutorial on the contemporary ice cover climatology (winters 1960 to 1979) of the Great Lakes of North America (Assel and Ratkos, 1991). Place names mentioned in the tutorial arc given in Figure 1. The information presented is primarily descriptive and is intended to be used as an educational tool. The computer tutorial contains two text modules: (1) background information on ice cover data sources and analysis methodology, and (2) an overview of the annual ice cycle (fall cooling, ice formation, ice thickness, maximal ice coverage, ice loss, ice as a hazard) and one animation module of ice cycles of individual Great Lakes. A single page of text annotates the ice animation of each lake. That text is a brief discussion of lake physiography and a very general description of the spatial and seasonal trends in ice cover in terms of lake bathymetric characteristics, air temperatures, and dominant wind directions. These data am given in hard copy as Appendix A and in floppy diskette copy as Appendix B. Methods used to create the animation and procedures and the hardware needed to load and run the tutorial are discussed below. Ancillary data not included in the tutorial but useful in interpreting the seasonal progression and spatial patterns of ice cover are also given below and include maps of lake bathymetry and graphs of average ice cover for discrete depth ranges versus time. The reference section includes literature not cited in the text for those readers who may wish to obtain additional educational and technical information on the Great Lakes ice cover.

2. THE ICE COVER ANIMATION

The ice cover animation portrays the progression of the daily spatial distribution of five ranges of ice concentration for each Great Lake from December 1 to May 7 (see Appendix A, Lake Superior, for an example of the ice cover concentration legend). Ice concentration is the percentage of a unit of surface area covered by ice. The daily ice charts are calculated from the normal seasonal distribution of ice cover for nine half-month periods (December 16-31 to April 16-30) given in the NOAA Great Lakes *Ice Atlas* (Assel et al., 1983): they really represent the transition from the normal ice cover distribution pattern from

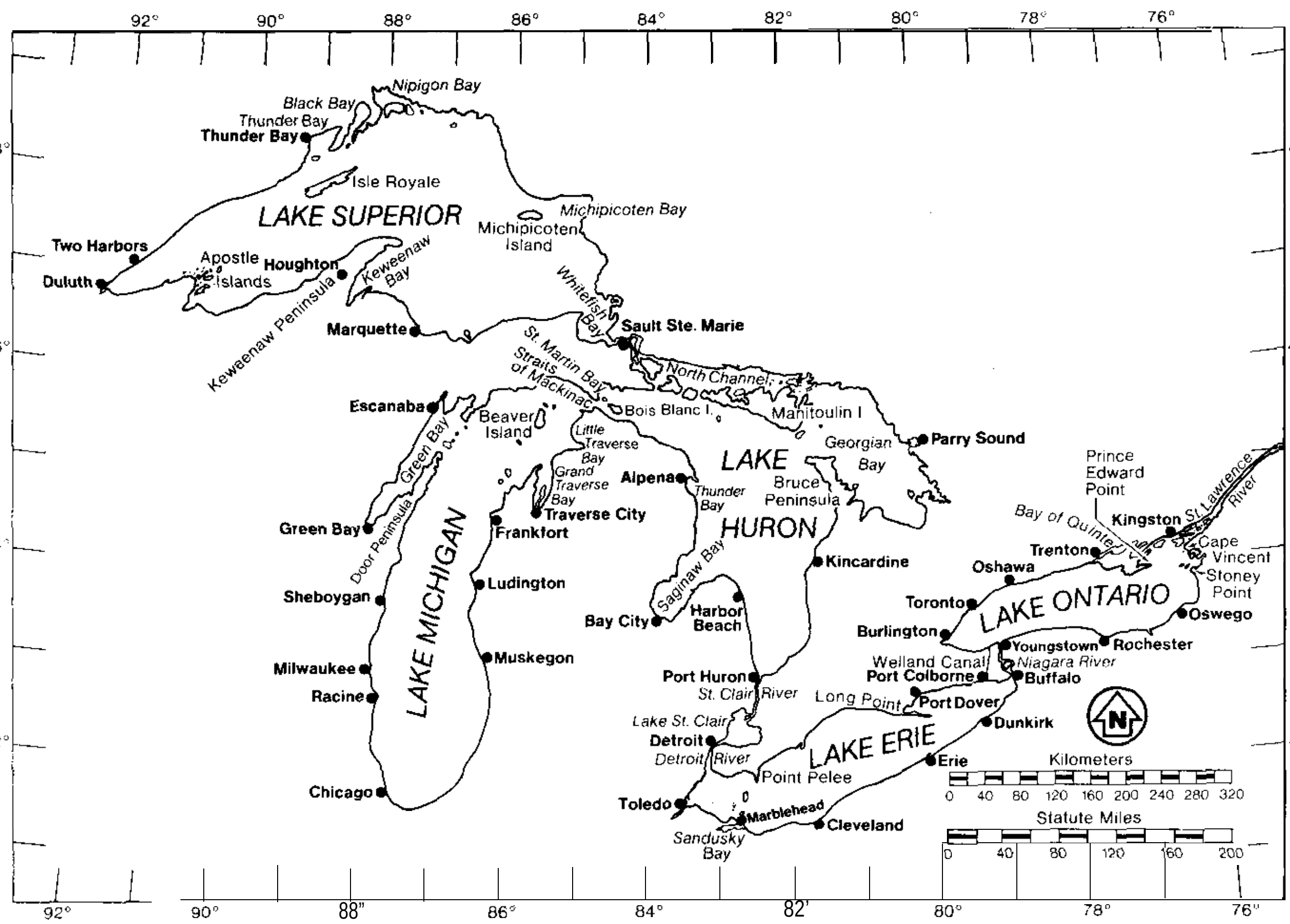

Figure 1.--Place Names.

one half-month period to the next as approximated by a linear interpolation of the normal ice concentration between midpoint dates of the nine half-month periods (see Appendix A, Background Information). It should be. cautioned that the daily time series of ice charts produced using this method may not be representative of the true daily normal ice cover distribution pattern for a given date in the winter season or for a given area in the Great Lakes. Nevertheless it is a useful way to visualize an approximation to the normal seasonal progression of ice cover on the Great Lakes. The lakes were assumed to be free of ice on December 1. Ice formation between December I and December 22 and ice loss between April 23 and May 7 were arbitrarily simulated as nonlinear functions of time and initial ice concentration.

We made 157 daily lake image interpolations for each of the five Great Lakes. Each lake image screen display had to be captured, individually clipped, and imported into a multimedia package, VideoWorks II (MacroMind, 1987), through the use of a paint program, SuperPaint (Silicon Beach Software, 1988). The final individual lake images were combined into a cellular animation, along with ancillary information, including a legend, map scale, and calendar. The Lake Michigan image had to be divided into a northern half and southern half because the large north-to-south extent of that lake (see Appendix A, Lake Michigan) made it difficult to display the entire lake image as a unit, A disadvantage of the current method of producing this type. of animation is, that because each image had to be manually clipped and imported into the multimedia package, it is very labor intensive.

The animations created by VideoWorks were run through a MacroMind utility called an accelerator which converts VideoWorks files to a mom constant running file. This ensures that each frame is displayed the same amount of time, allowing smoother, mom consistent results. The accelerator file is incorporated into a HyperCard stack. The HyperCard stack was used to make the final product a menu-driven package. You can select a topic by simply moving the mouse to direct the on-screen cursor to one of the menu items (see Appendix A, Menu).

3. LOADING AND RUNNING THE TUTORIAL

To load and run the tutorial from the floppy diskette given as Appendix B, you need a Macintosh Plus computer with a hard disk drive. The program requires about 2 megabytes of random access memory on the hard disk. A basic understanding of how to load diskettes and move files from diskette to the hard disk drive is assumed. The procedure for loading and running the tutorial is given as Table 1. Hard copy of the tutorial for all screen images except for the actual animations are given as Appendix A.

4. LAKE DEPTH AND ICE COVER PATTERNS

Lake depth (bathymetric) patterns for each Great Lake are portrayed in Figures 2a-2e. Comparing the seasonal pattern of ice formation given in the ice animation in Appendix B with these figures will help you gain an appreciation for the depth dependence of the spatial pattern of ice cover formation on the Great Lakes, The general pattern of depth dependence is noted in the text screen that comes before each animation.

To quantify the depth dependence of ice formation, the spatial average ice concentration for six discrete depth intervals was calculated for each normal ice chart in the NOAA *Great Lakes Ice Atlas* (Assel et al., 1983). Results are displayed in Figures 3a-3e. In general the duration of ice cover and the amount of ice per unit area (ice concentration) decrease with increasing depth for a given lake. This would be expected because the deeper areas of a lake with greater heat storage and greater wind fetch are generally the last to form ice in winter and the first to lose ice in the spring.

Table 1 .-- Installation of Great Lakes Ice Cover Tutorial

Step	Description
1.	Select "New Folder" under file.
2.	Name empty folder "Ice Animation."
3.	Insert and open Install disk.
4.	Double click "Install Ice Animation."
5.	Select "Ice Animation" folder.
6.	Double click Install (it takes 2 to 5 minutes to install).
7.	Select Quit.
8.	Remove install disk.
9.	Open "Ice Animation" folder.
10.	Find "Ice Cover" stack and double click to begin tutorial.

Note: To go through the HyperCard stack simply move the screen cursor to the proper icon on the screen (usually located in one of the cornets of the screen) and click on the mouse.

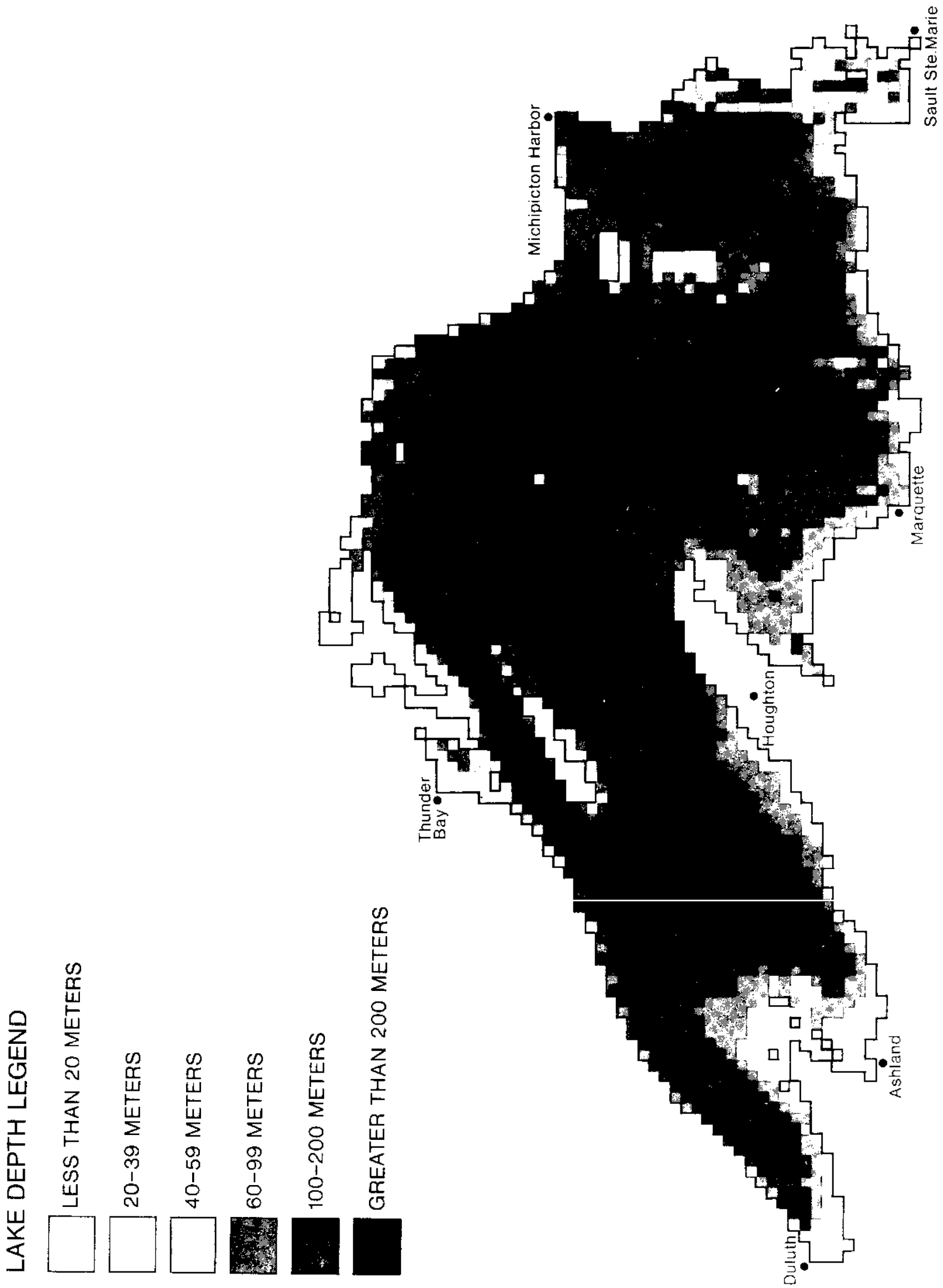

Figure 2a.--Lake Superior Bathymetry Chart.

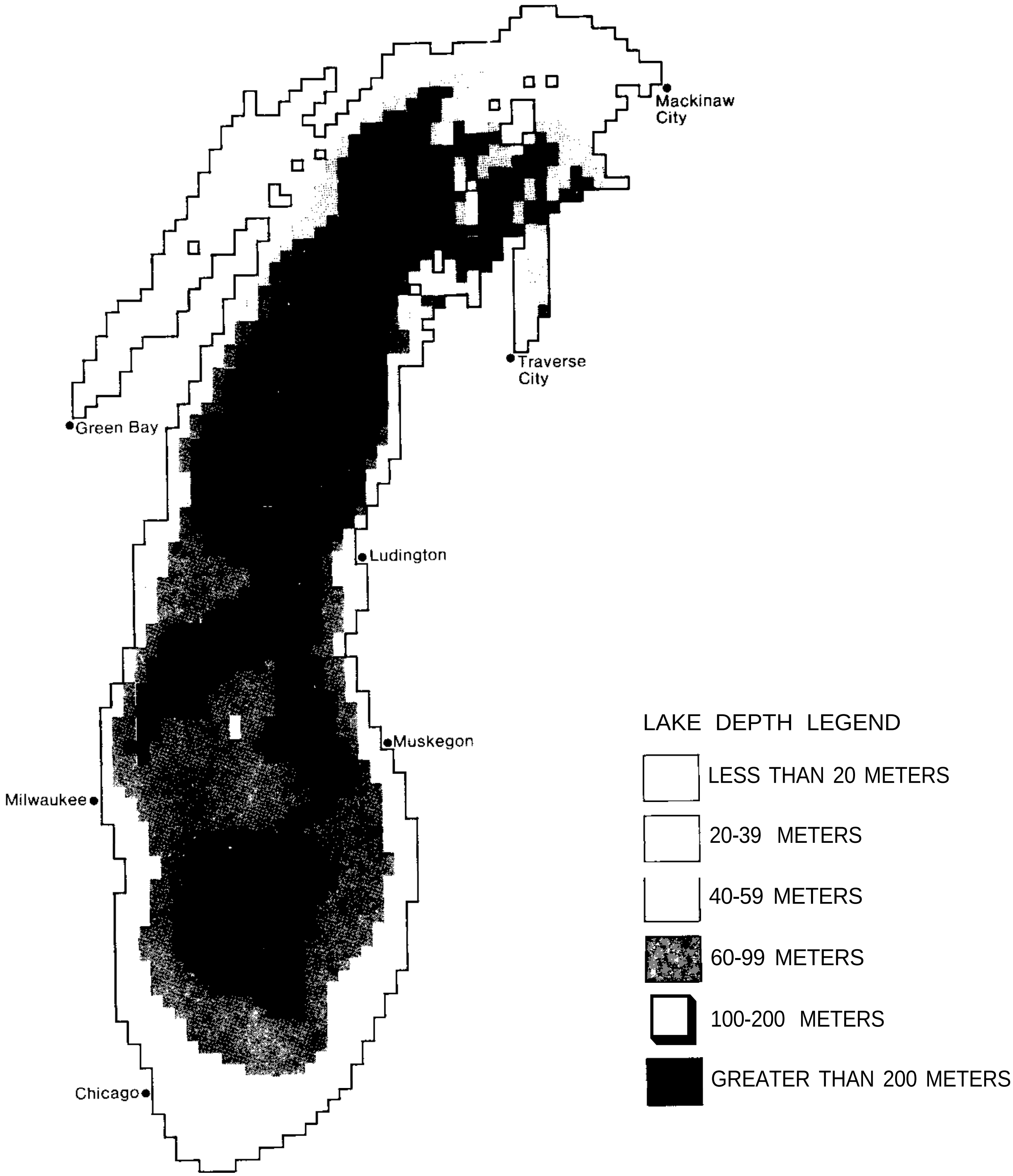

Figure 2b.--Lake Michigan Bathymetry Chart.

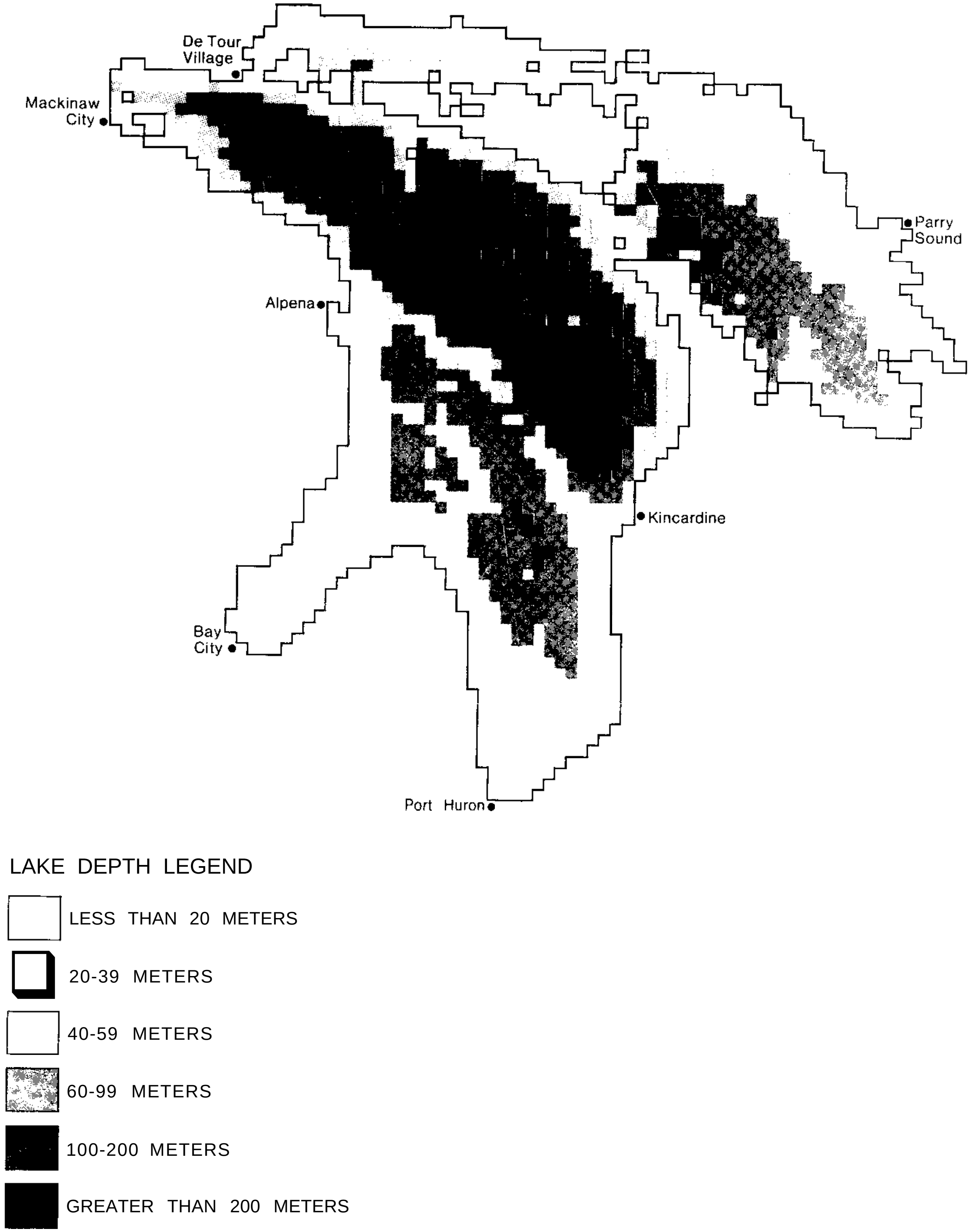

Figure 2c.--Lake Huron Bathymetry Chart.

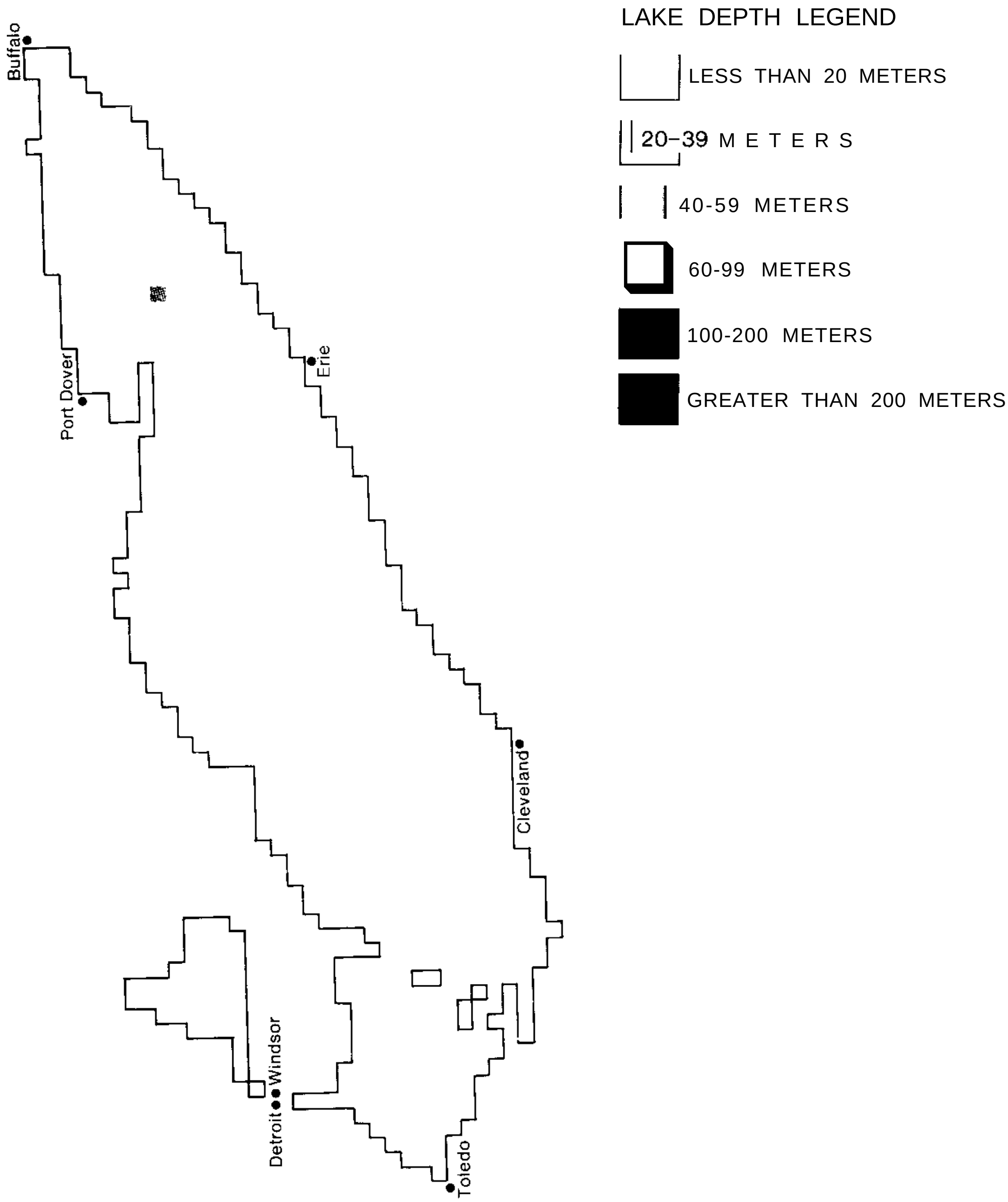

Figure 2d.--Lake Erie Bathymetry Chart.

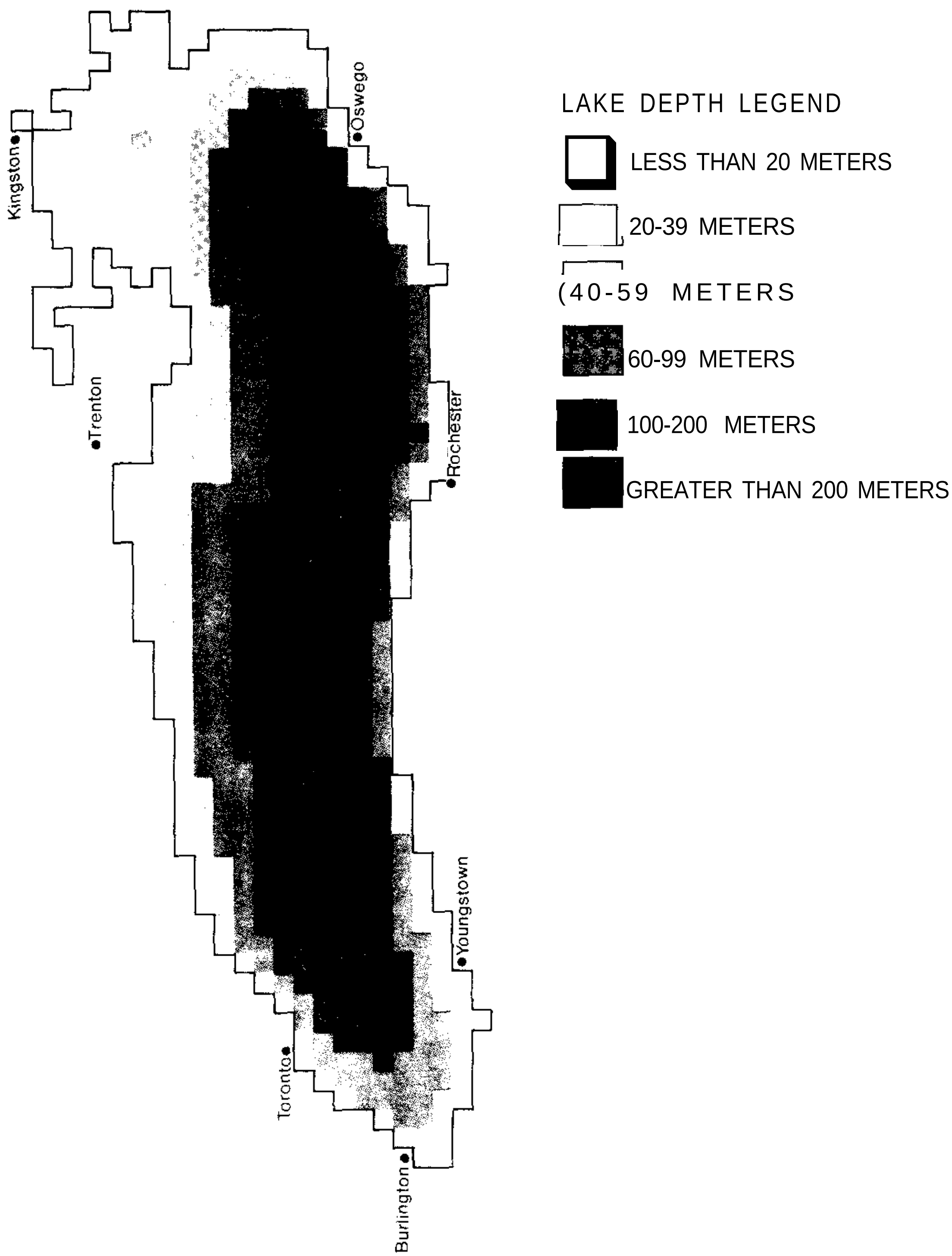

Figure 2e.--Lake Ontario Bathymetry Chart.

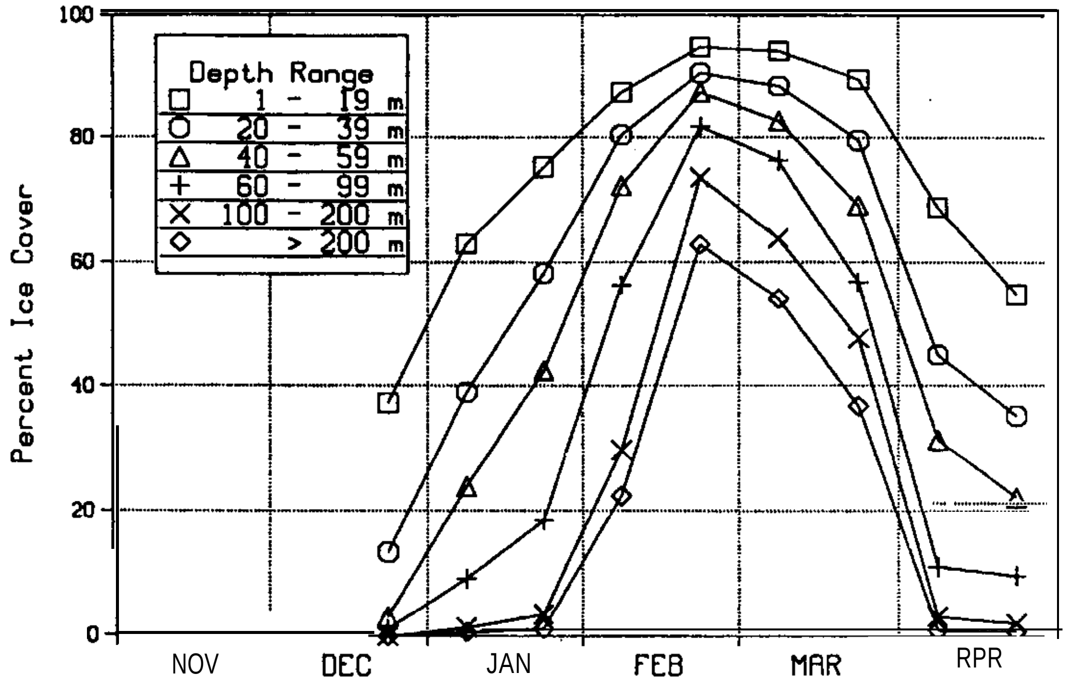

Figure 3a.--Lake Superior Ice Cover - Water Depth Graph

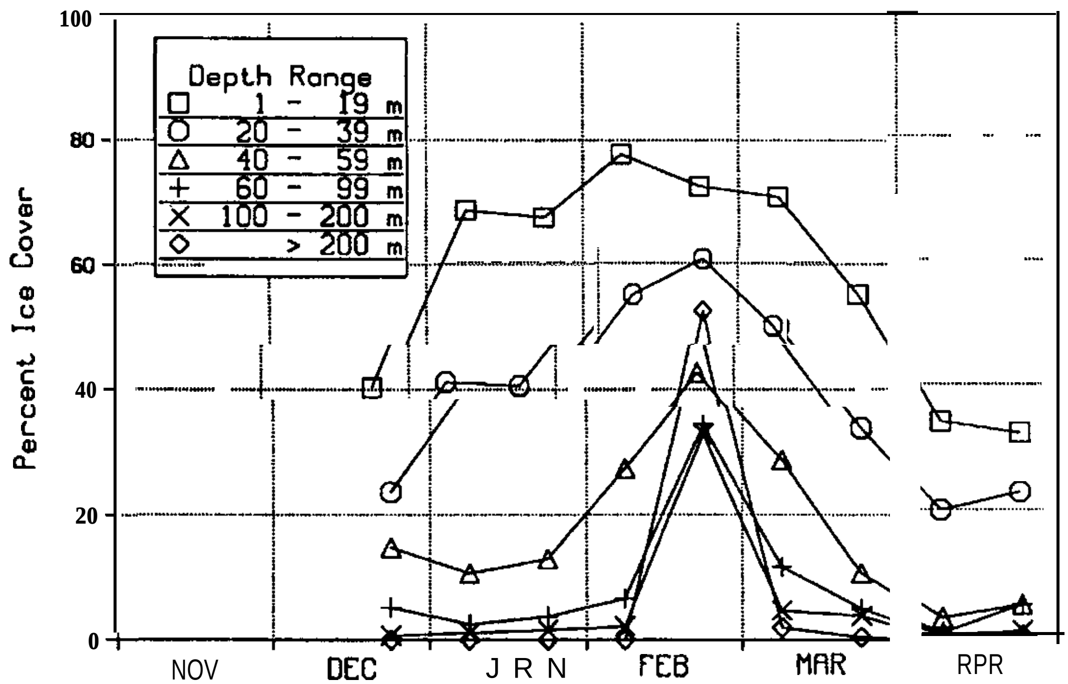

Figure 3b.--Lake Michigan Ice Cover-Water Depth Graph

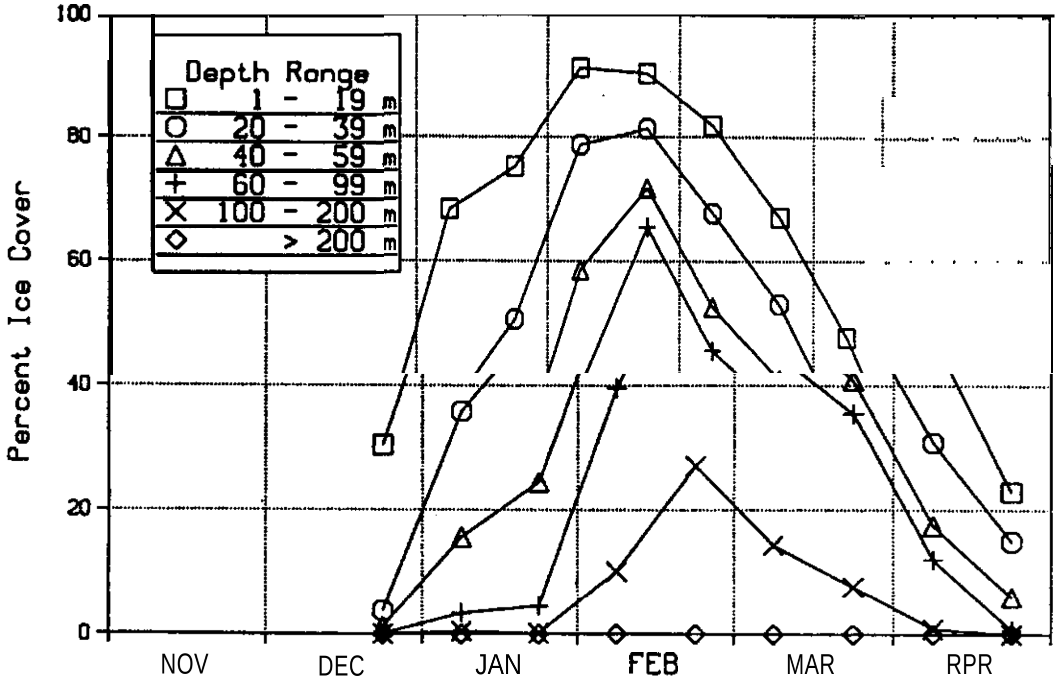

Figure 3c.--Lake Huron Ice Cover - Water Depth Graph

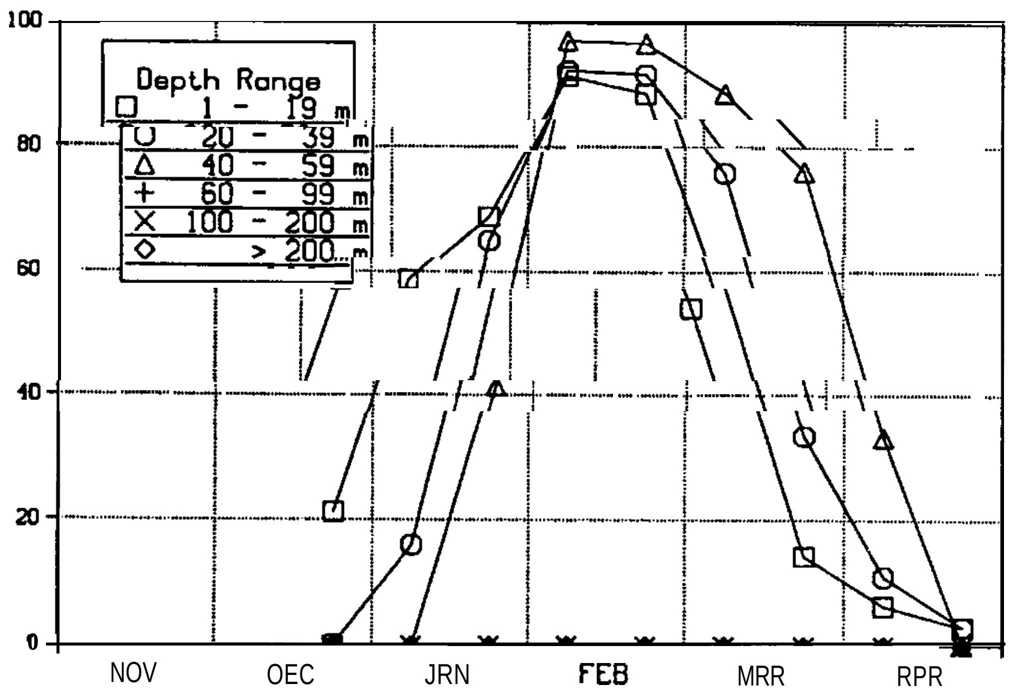

Figure 3d.--Lake Erie Ice Cover - Water Depth Graph

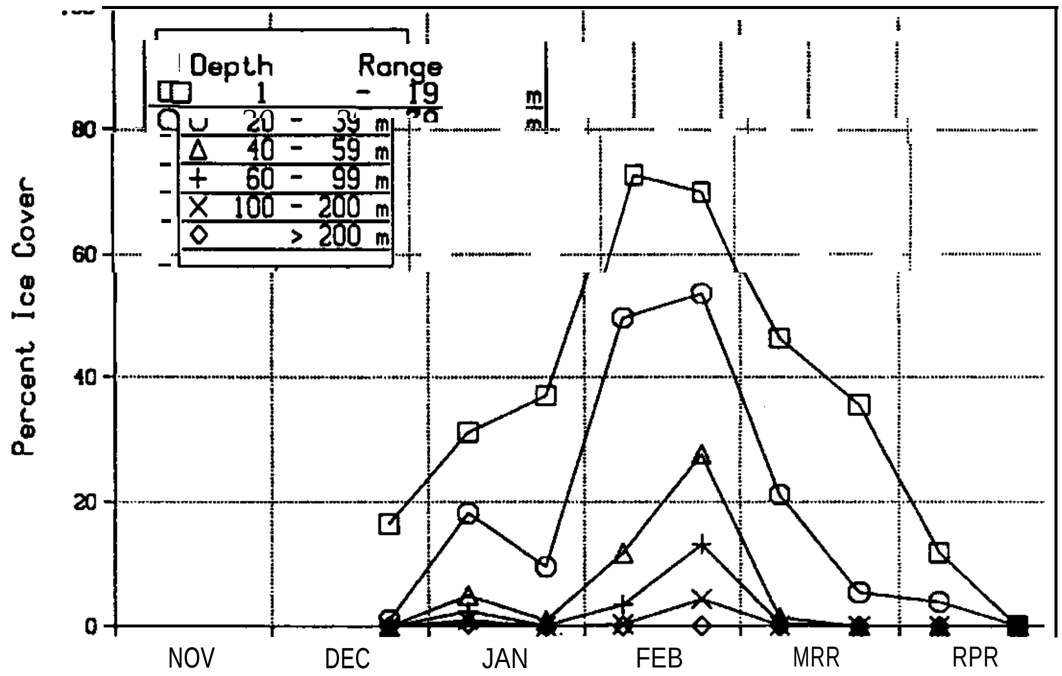

Figure 3e.--Lake Ontario Ice Cover - Water Depth Graph

Lakes Michigan and Erie ate exceptions to this pattern On Lake Michigan (Figure 3b), ice concentration over the deepest area (greater than 200 meters) exceeds ice. concentration over depths between 40 and 200 meters during the second half of February. This may be due to the low percentage of total surface area of the lake for which depths exceed 200 meters (Table 2 and Figure 2b) and the lower air temperatures that occur at this latitude (approximately 44°N) relative to the southern portion of the other depth ranges, which am located approximately 2° of latitude farther south.

On Lake Erie (Figure 3d), the ice concentration-depth relationship is reversed in March and April; that is, ice concentrations am higher with increasing depths. This apparent anomaly is explained by the fact that Lake Erie's depth increases going from west to east and its ice cover loss in March and April is also from west to east (due to the prevailing westerly winds), so that the average ice concentration over the deeper areas of the lake increases during the ice loss period.

5. CONCLUDING REMARKS

An interactive, menu-driven computer tutorial of the normal Great Lakes ice cycle for the base period 1960-1979 was produced using data from the NOAA Great *Lakes* Ice *Atlas* (Assel et al., 1983). This memorandum makes the tutorial available for educational purposes to the public at large. This material can be applied in different ways and at any educational level. For example, it can be presented simply as a visual aid to gain a primary understanding of the seasonal ice cover characteristics of the Great Lakes, It can be used in science classes at the elementary and secondary school levels. It also has application in college courses to familiarize students with the Great Lakes ice cover characteristics and as a point of departure for studies of ice cover, lake physiography, and climatology.

Table 2. Percentage of Total Lake Surface Area Over Discrete Depth Ranges.

Depth Range (m)	Superior	Michigan	Huron	Erie	Ontario
1-19	3.5	14.4	20.9	53.4	13.0
20-39	5.6	14.6	17.6	41.6	14.1
40-59	5.6	9.4	18.3	4.6	8.9
60-99	11.9	25.3	25.8	<1.	19.5
100-200	49.9	30.5	17.1	--	40.7
>200	23.5	5.5	--	--	2.9

The Information presented here has been simplified to facilitate understanding by nontechnical users: it should be used to gain only a general overview of the normal ice cover and even then only of the *normal* ice cover of the 1960s and 1970s. The normal ice cover of that base period may differ significantly from ice *cover* in future decades (Assel, 1991). and it is quite likely this base period ice cover has differed from the normal Great Lakes ice cover of earlier decades of this century (Assel, 1990). Therefore one must be careful not to make generalizations from this tutorial about Great Lakes ice cover for other decades or even for specific winters and locations In the Great Lakes for the decades of the base period. The references and bibliographic citations are a good place to start for those readers interested in obtaining additional information on Great Lakes ice cover.

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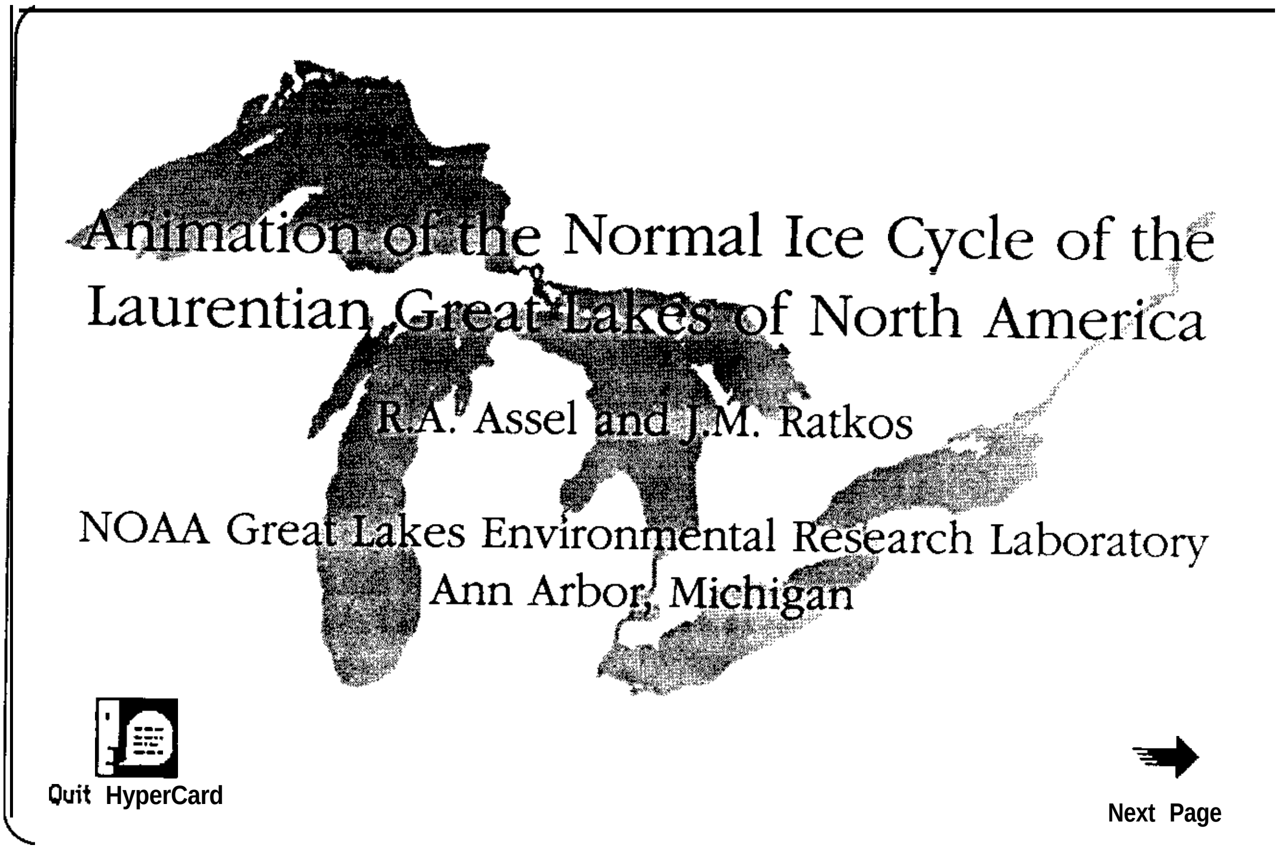
*These references are not cited in the text but are cited in the tutorial given in the appendices,

APPENDIX A

SCREEN IMAGES OF THE COMPUTER TUTORIAL

APPENDIX A - Table of Contents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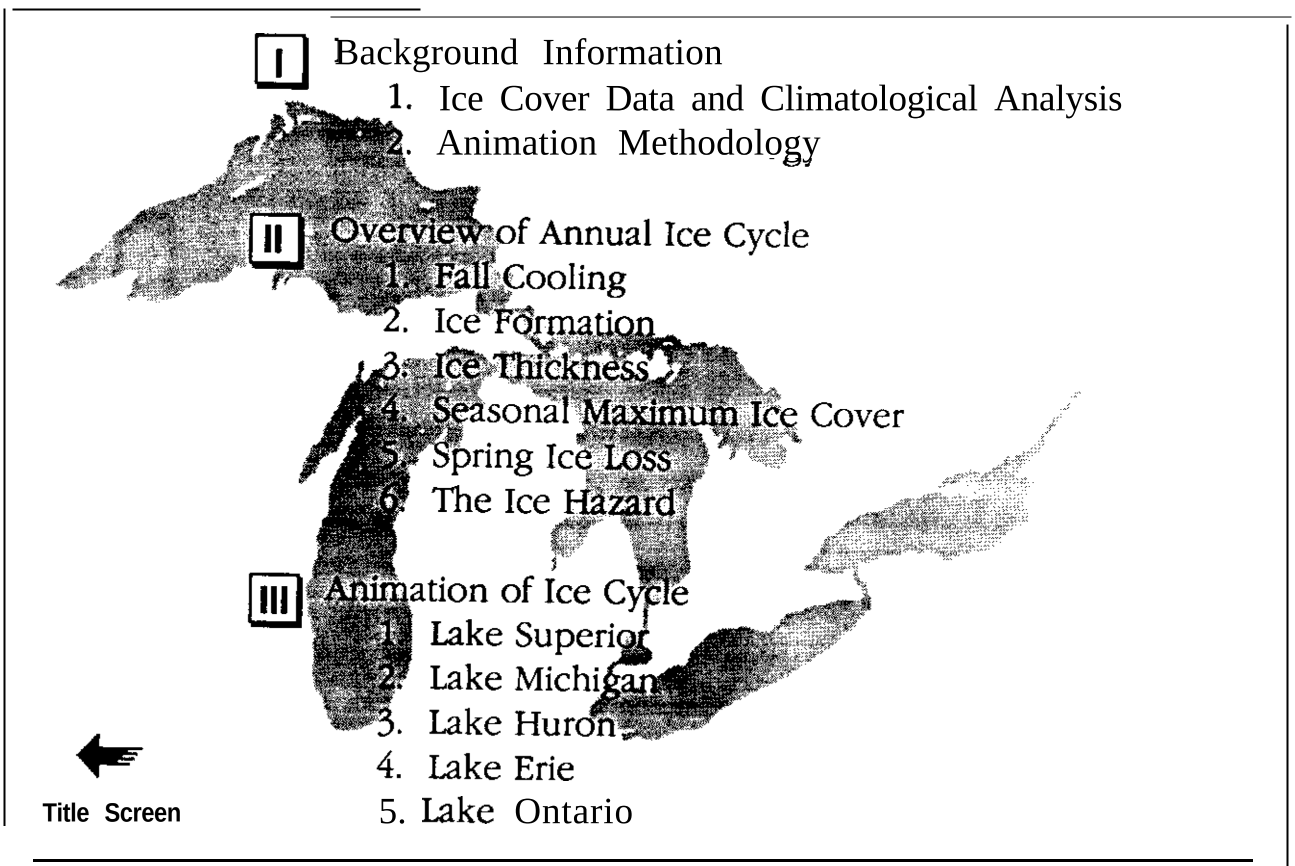
I Background Information
1. Ice Cover Data and Climatological Analysis
2. Animation Methodology
II Overview of Annual Ice Cycle
1. Fall Cooling
2. Ice Formation
3. Ice Thickness
4. Seasonal Maximum Ice Cover
5. Spring Ice Loss
6. The Ice Hazard
III Animation of Ice Cycle
1. Lake Superior
2. Lake Michigan
3. Lake Huron
4. Lake Erie
5. Lake Ontario
Title Screen

Background Information

1. Ice Cover Data and Climatological Analysis

In the late 1970s and the early 1980s over 2800 Great Lakes ice charts dating from 1960 to 1979 were digitized and computerized. Spatially and temporally heterogeneous ice concentration observations were converted to geographically fixed 5 x 5 km grid cells composing the surface area of each Great Lake. Each grid cell was analyzed for the median, maximum and minimum ice concentration over the 20 years of record for each of nine half month periods from December 16-31 to April 16-30. Ice concentration is the percentage of the total surface area covered by ice. Ice concentrations were digitized in ten percent increments from zero to 100 percent coverage. Results are summarized as a Great Lakes ice atlas (Assel et al., 1983) depicting the normal (median) and cornposited extremes of ice cover for each Great Lakes for the 1960-1979 period.

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Background Information

2. Animation Methodology

The animation portrays the spatial distribution of the ice cover for each Great Lakes from December 1 to May 7. The normal daily progression of the ice cover over the winter season was defined primarily by a linear interpolation of the median ice concentration at each grid cell between midpoint dates of the nine half month periods given in the NOAA Great Lakes Ice Atlas, as shown in the table on the next page. The Great Lakes were assumed to be ice free on December 1. Ice formation between December 1 dnd December 22 and ice loss between April 23 and May 7 were arbitrarily simulated as nonlinear functions of time and initial ice concentration as given in the table on the next page.

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Background Information

2. Animation Methodology (Cont.)

The resulting 157 lake image files were transferred to an Apple Macintosh SE and a PASCAL program was used to display the lake images and assign one of five graphic patterns for each of the ice concentrations. Each of the screen displays had to be captured, individually clipped and imported into the multi-media package, VideoWorks II, (MacroMind, Inc., 1987) through the use of a paint program, SuperPaint 2.0 (Silicon Beach Software, 1988).

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interpolation method	Ice Atlas	Intemolation periods: dates for interpolation	# of days
equation1 }		Dec 1 - Dec 22	21
equation 2	Dec 11-15		
	Jan 16-31	Dec 23 - Jan 7	16
	Jan 1-14	Jan 8 - Jan 22	15
		Jan 23 - Feb 7	16
	Feb	8 - Feb 21	14
	Feb 15-28	Feb Feb 22 - Mar 7	16
	Mar 1-15		
	Mar 16-31	Mar 8 - Mar 22	15
		Mar 23 - Apr 7	16
	Apr 1-15		
	Apr 16-30	Apr 8 - Apr 22	15
equation3 }		Apr 23 - May 7	15

equation 1: $i(t) = i(p1) \times t^3 / Days^3$

equation 2: $i(t) = i(t_1) + \{[di / Days] \times t\}$

equation 3: $i(t) = i(p9) \times \{[1/t] - [1/15]\}$

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Where:

$i(t_1)$ = ice concentration at start of period, from ice atlas

t = any day in a given interpolation period

Days = the number of days in a given period.

di = difference in ice concentration between consecutive ice atlas plates

$i(p1)$ = ice concentration for ice atlas plate 1 (December 16-31)

$i(p9)$ = ice concentration for ice atlas plate 9 (April 16-30)

$i(t)$ = interpolated ice concentration for day t.

Overview of Annual Ice Cycle

1. Fall Cooling

The Great Lakes become thermally stratified in summer. During fall, stratification is lost as the entire water mass cools to the temperature of maximum density near 4°C (Derecki, 1976). Subsequent cooling results in the formation of less dense surface water, winter restratification, and ice formation.

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Overview of Annual Ice Cycle

2. Ice Formation

Ice assumes a wide variety of shapes, sizes, and composition, depending upon the weather (snowfall, calm or windy [still vs. turbulent water]) at the time of its formation and weather conditions after its formation (Rondy, 1976). The majority of the ice formed in the Great Lakes is not fixed to shore and is mobile due to the action of winds, waves, and currents. Ice cover forms in bays and harbors of the Great Lakes in December; the deeper bays and perimeter of the Great Lakes usually form ice during January; Lake Erie because of its shallow depth also forms midlake ice cover in January; midlake areas of the other Great Lakes usually form extensive ice cover in February (Assel et al., 1983).

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Overview of Annual Ice Cycle

3. Ice Thickness

Vertical ice accretion occurs as a result of heat transfer from the ice-water interface through the ice to the atmosphere. As an ice sheet thickens, its own mass retards further growth by its insulating effect. The upper limit of thermodynamic ice growth is approximately 100 cm for Great Lakes bay and harbor sites (Bolsenga et al., 1988). Local factors at each site such as air temperature, water depth, winds, and snowfall affect spatial and annual variations of maximum ice thickness (Bolsenga, 1987). Ice thickness in excess of 1 meter occurs when winds cause portions of an ice cover to override or submerge under the remaining ice cover. The resulting ice is called rafted, ridged, or jammed ice, depending upon the amount and extent of ice rubble formed. The U.S. Coast Guard has reported rafted ice on the order of 8 meters thick in the Great Lakes (U.S. Coast Guard, 1977).

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Overview of Annual Ice Cycle

4. Seasonal Maximum Ice Cover

Seasonal maximum ice coverage occurs in February and early March. Even during this period some areas of open water remain on the Great Lakes except during brief episodes of low air temperatures and calm conditions; normal maximum ice cover expressed as a percent of total lake surface area is 90% for Erie, 75% for Superior, 68% for Huron, 45% for Michigan, and only 24% for Ontario. The small seasonal maximum ice over Lake Ontario is due to the combination of its large heat storage capacity (mean depth of 86 m) and its relatively mild winter temperatures (-4.4°C for Ontario compared to -9.8” C for Lake Superior). Seasonal maximum ice extent averaged for the Great Lakes has varied from virtually 100% in 1979 to less than 25% in 1983 (Assel et al., 1985).

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Overview of Annual Ice Cycle

5. Spring Ice Loss

In spring, above-freezing air temperature and solar radiation cause melting of ice; solar radiation penetrating the ice and absorbed within the ice reduces the structural strength of the ice due to preferential melting at ice crystal boundaries. The weakened ice cover can then be easily broken by winds and wave action and melted or transported to eastern lake shores (Rondy, 1976). Areas of open water and low ice concentration expand from the deeper, more exposed midlake areas toward the perimeter and eastern shores of the Great Lakes in March. By mid-April, ice left in the lakes is usually located in the shore zone.

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Overview of Annual Ice Cycle

6. The Ice Hazard

Lake vessels cannot transit heavily rafted, ridged, or jammed ice fields without the assistance of higher powered Coast Guard ships because the commercial ships are relatively low powered vessels with blunt bows. Areas of the Great Lakes where Coast Guard ice breaking assistance is sometimes required in spring include the connecting channels of the Great Lakes (Derecki and Quinn, 1986), the east and west ends of Lake Superior, the Straits of Mackinaw, Green Bay, eastern Lake Erie, and other bays and harbor entrances that become clogged with ice (U.S. Coast Guard, 1977). Besides being a hazard to navigation in the open lake, ice in the connecting channels and ice in the shore zone of the Great Lakes can cause property damage and operational problems for hydroelectric power plants (International Niagara Working Committee, 1983).

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Overview of Annual Ice Cycle

6. The Ice Hazard (Cont.)

Frazil ice, unconsolidated ice crystals formed in super-cooled water, can clog water intakes. River ice jams reduce river flow rates causing loss of hydroelectric generating capacity and damage property by flooding and ice rafting on docks and buildings in the immediate area. Ice can also cause damage to docks and other shore installations along the shores of the Great Lakes proper. Any movement of the ice cover either horizontally or vertically causes piers frozen in the ice to be distorted or destroyed (Wortley, 1985).

Animation of the Ice Cycle

Lake Superior

surface area 82,100 km^2, volume 12,230 km^3, mean depth 148 m, length 563 km, breadth 257 km. Mean monthly air temperature is below freezing in November. Ice forms along the lake perimeter in December and January. Ice forms in the west basin building out from the shallow, southern shore, the west part of the Keweenaw Peninsula, and along the northern lake shore from January 16-31 to February l-14. Ice forms last in the deep, eastern lake basin in February and March. Monthly air temperatures are above freezing in April. Ice is lost over the entire lake from March 16-31 to April l-15. Only shore ice remains the second half of April.

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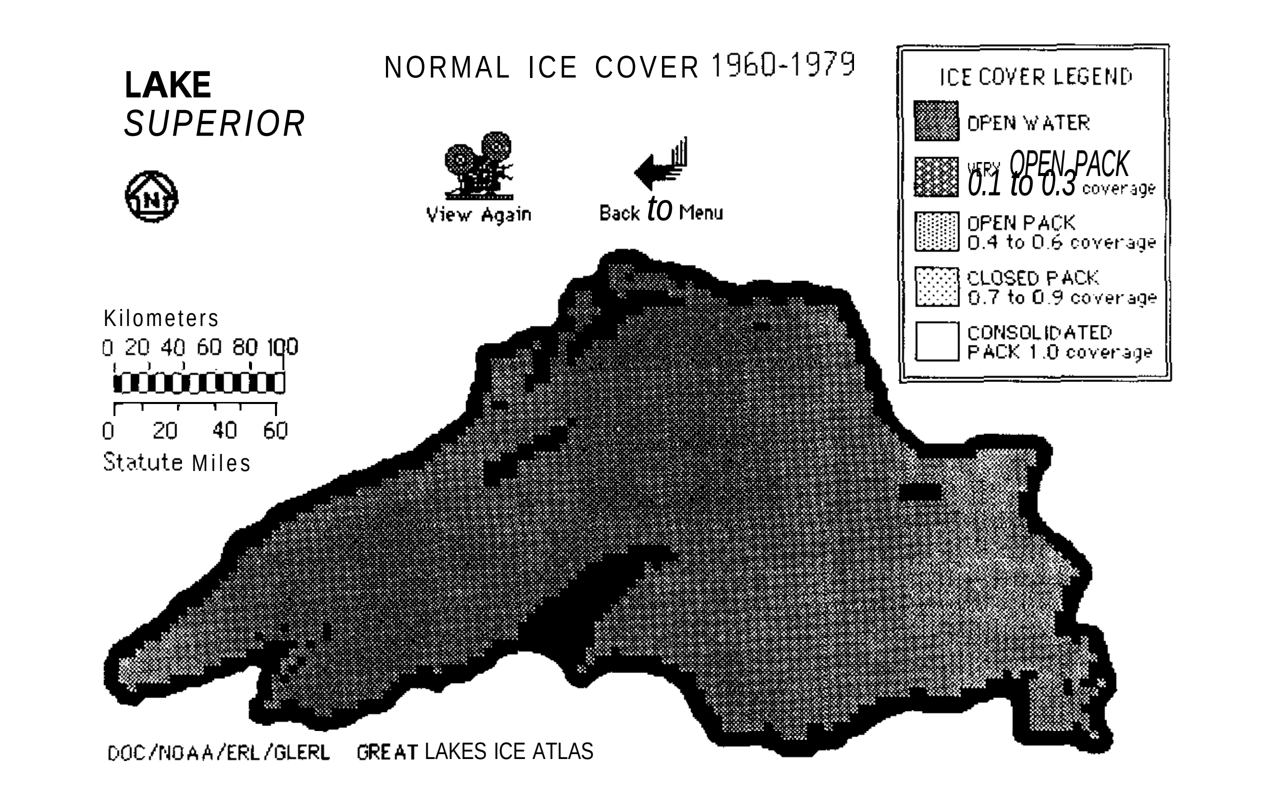
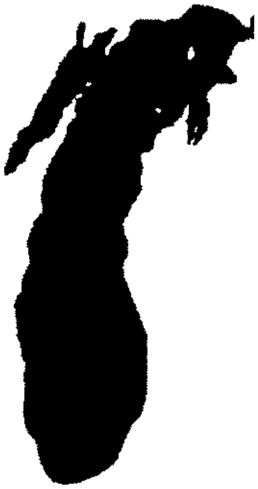
View Entire Animation



Animation of the Ice Cycle

Lake Michigan



surface area 57,750 km², volume 4,920 km³, mean depth 85 m, length 494 km, breadth 190 km. Because of the large north to south extent of this lake, mean monthly air temperature is below freezing in November at the northern end of this lake and at the southern end in December. Ice forms along the lake perimeter, in Green Bay, and the shallow, north portion of the lake to Beaver Island starting in December. Ice forms in the midlake areas south of Beaver Island to Milwaukee, Wisconsin in the second half of February The midlake area south of Milwaukee normally remains relatively ice free. Most of the midlake ice south of Beaver Island is lost during the first half of March. Ice north of Beaver Island and in Green Bay dissipates gradually over the next 6 weeks.

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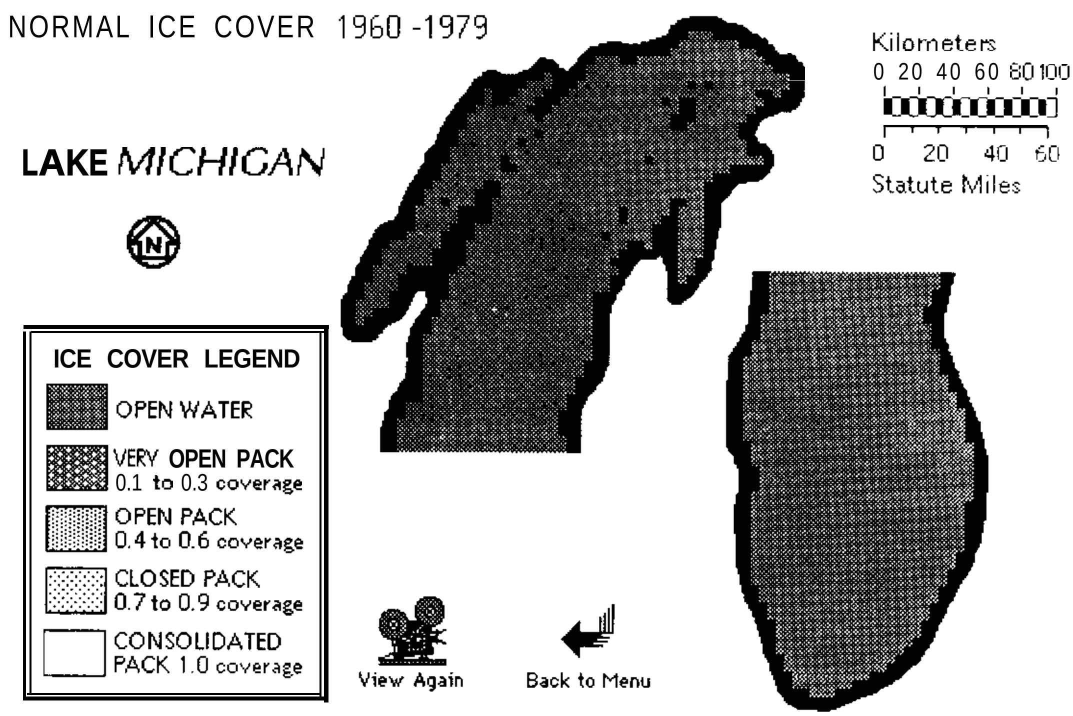
View Entire Animation



Animation of the Ice Cycle

Lake Huron

surface area 59,500 km^2, volume 3,537 km^3, mean depth 59 m, length 331 km, breadth 294 km. Ice formation is restricted to the shallow embayments along the lake perimeter in December and January. Ice gradually builds out to the deeper lake areas in January and February so that only the midlake area between Kincardine, Ontario, and Alpena, Michigan remains free of ice by the end of February. This area of open water gradually increases in March, The only areas of extensive ice by mid-April are the large embayments along the northern shore, the Straits of Mackinaw, and the southeast shore. The ice in these areas gradually dissipates over the next 2 to 4 weeks.

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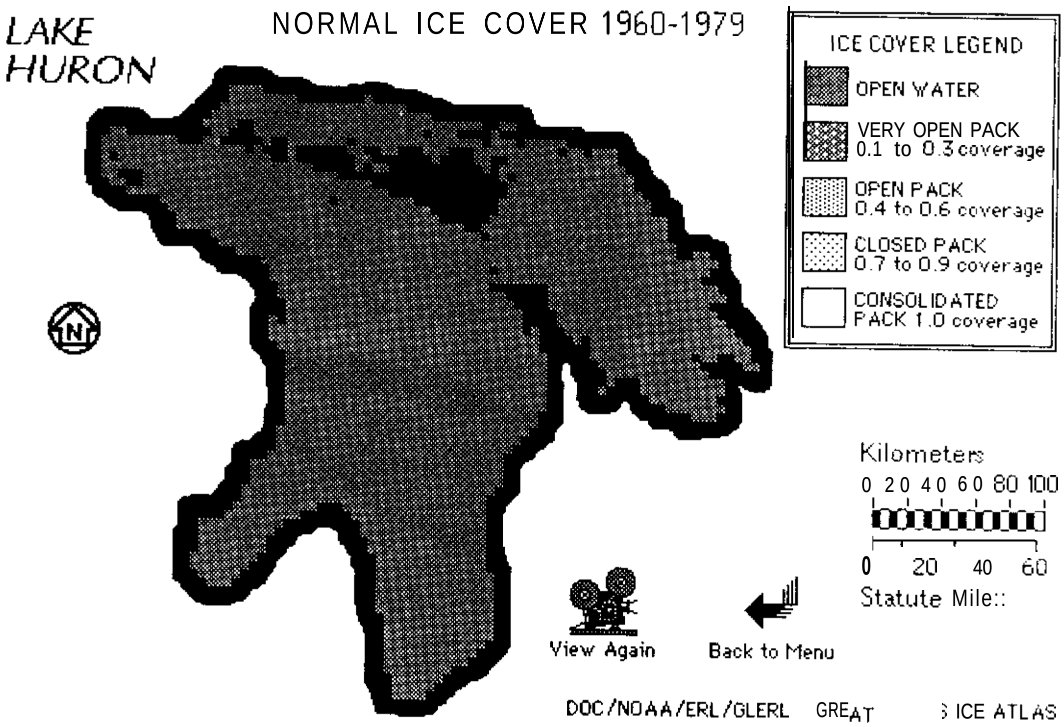
View Entire Animation



Animation of the Ice Cycle

Lake Erie

surface area 25,657 km^2, volume 483 km^3, mean depth 19 m, length 388 km, breadth 92 km. The progression of ice formation is from the shallow, west lake basin (mean depth 9 m) in mid December to the deep, east lake basin (mean depth 27 m) during the second half of January. By the end of January the lake is approaching its maximal ice cover. Lake Erie remains near its maximal ice cover during February. The ice loss pattern is from west basin to east basin, reflecting the orientation of the lake's axis approximately parallel to the prevailing westerly wind direction. The ice concentration in the first half of March decreases in the western lake basin. By the end of March the western third of the lake is ice free. By the end of April the only extensive ice left in the lake is located in the east end of the lake near Buffalo, NY.

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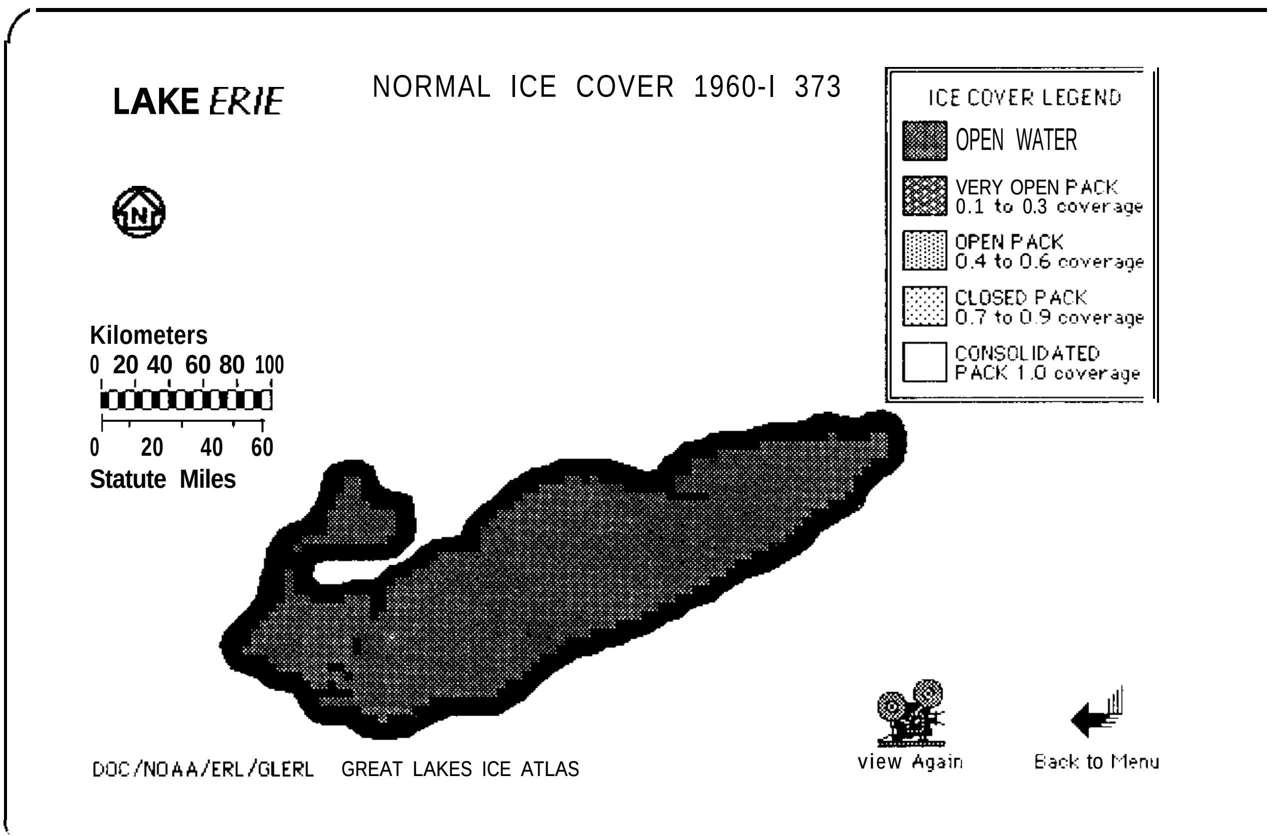

Animation of the Ice Cycle

Lake Ontario

surface area 19,000 km^2, volume 1,634 km^3, mean depth 86 m, length 311 km, breadth 85 km. The combination of relatively mild winter air temperatures and large mean lake depth, results in ice formation being restricted to the shallow areas along the lake shore all winter. Extensive shore ice forms first along the shallow embayments along the northeast shore in January and along the entire lake perimeter in February. With the exception of the northeast embayments, ice dissipates from the lake perimeter during the first half of March. The ice in these embayments gradually dissipates over the next 4 to 6 weeks as well, leaving the lake ice free by the end of April.

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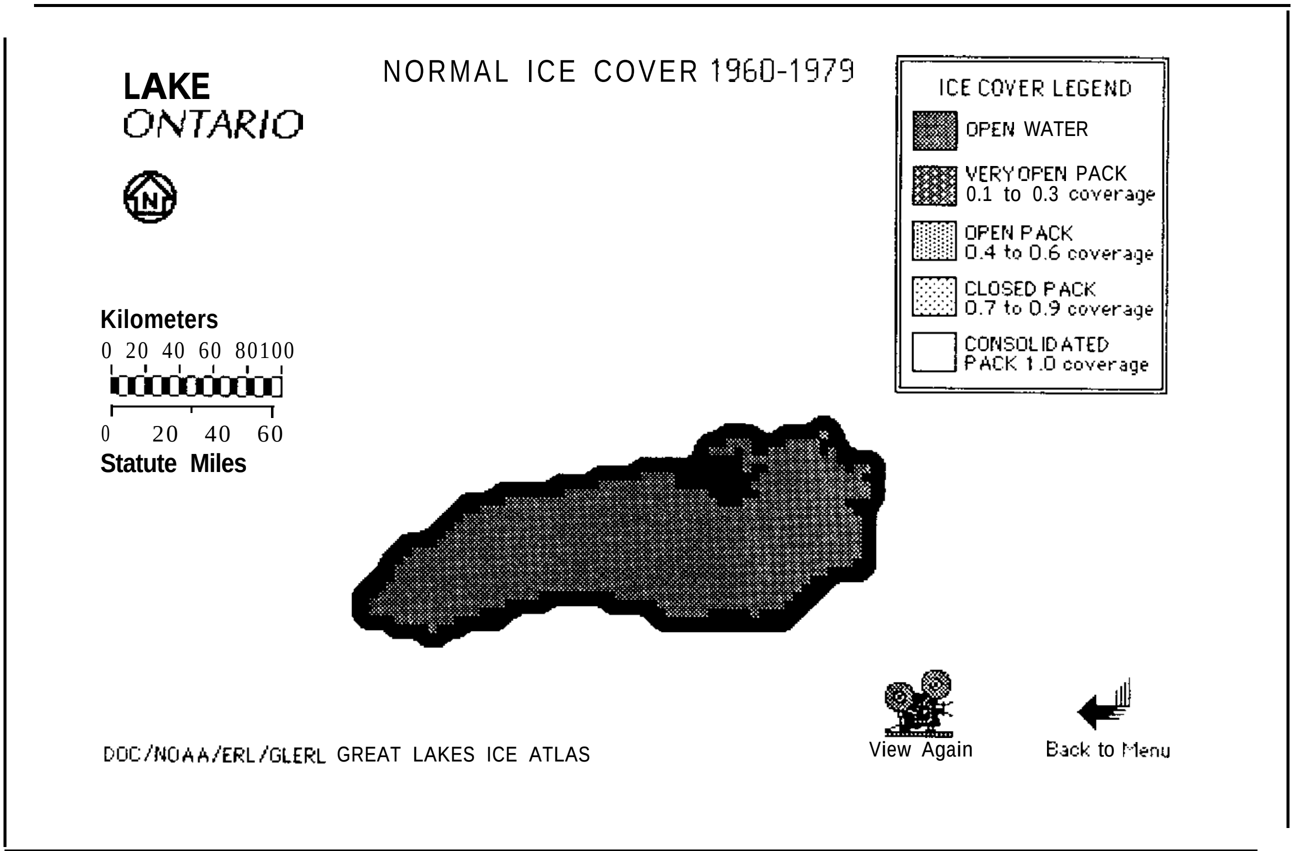

APPENDIX B

DISKETTE OF THE TUTORIAL.