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ANIMATION OF THE NORMAL ICE CYCLE OF THE LAURENTIAN GREAT LAKES OF NORTH AMERICA

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1. INTRODUCTION

This paper describes an interactive menu-driven computer tutorial on the contemporary ice cover climatology of the Great Lakes of North America. Because the information presented is primarily descriptive in nature, the potential application of this program is not limited to the scientific or research audience. The program contains two text modules and one graphics module (Table 1). The first text module contains background information on ice cover data and analysis, and the second text module contains a generalized description of the annual Great Lakes ice cycle. The graphics module contains an animation of the normal seasonal progression of advance and retreat of the ice cover over each Great Lake. The graphics module is also annotated with text describing the characteristics of ice cover for each Great Lake portrayed by the animation. The program is structured in such a way that the user can go back and forth between topics in a given module, or the user can go from one of the modules to another.

2. BACKGROUND

2.1 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. Ice concentrations on ice charts were digitized in 10 percent increments from 0 to 100 percent coverage. Ice concentration is the percentage of the total surface area covered by ice. 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. Results are summarized as a Great Lakes ice atlas (Assel et al., 1983) depicting the normal (median) and composited extremes of ice cover for each Great Lake for the 1960-1979 base period.

Table 1. INTERACTIVE MENU-DRIVEN COMPUTER PROGRAM THE NORMAL ICE CYCLE OF THE GREAT LAKES OF NORTH AMERICA

MENU ITEMS AND TOPICS

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

2.2 Production of Animation.

The animation portrays the spatial distribution of the ice cover for each Great Lake 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 (Table 2). The lakes were assumed to be ice free on December 1. Ice formation between December 1 and December 22 and ice loss between April 23 and May 7 was arbitrarily simulated as non-linear functions of time and initial ice concentration as given in Table 2.

Table 2. Interpolation Periods and Associated Equations for the Animation and the Half-month Periods Given for the Nine NOAA Ice Atlas Ice Chart Plates

Ice Atlas Plate No./Period	Interpolation Period Start	End	EQ No.
	Dec 1	Dec 22	EQ(1)
1. Dec 16-31	→Dec 23	Jan 7	EQ(2)
2. Jan 1-15	→Jan 8	Jan 22	EQ(2)
3. Jan 16-31	→Jan 23	Feb 7	EQ(2)
4. Feb 1-14	→Feb 8	Feb 21	EQ(2)
5. Feb 15-28	→Feb 22	Mar 7	EQ(2)
6. Mar 1-15	→Mar 8	Mar 22	EQ(2)
7. Mar 16-31	→Mar 23	Apr 7	EQ(2)
8. Apr 1-15	→Apr 8	Apr 22	EQ(2)
9. Apr 16-30			
	Apr 23	May 7	EQ(3)

EQ(1) $i(t) = i(p1) \times t^3/\text{Days}$

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

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

t = any day in a given interpolation period.

di = difference in ice concentration between consecutive ice atlas plates for a given grid cell.

$i(t_1)$ = ice concentration at start of period, from ice atlas, for a given grid cell.

Days = the number of days in a given period.

$i(p1)$ = ice concentration for ice atlas plate 1 for a given grid cell.

$i(p9)$ = ice concentration for ice atlas plate 9 for a given grid cell.

$i(t)$ = interpolated ice concentration for day t and a given grid cell.

One-hundred-and-fifty-seven lake image interpolations were made for each of the five Great Lakes. These data were transferred to an Apple Macintosh SE computer, 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 a multi-media package, VideoWorks II, (MacroMind, 1987) through the use of a paint program, SuperPaint 2.0 (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. A disadvantage of the current method to produce this type of animation is that each screen lake image had to be manually clipped and imported into the multi-media package making the production of this animation very labor intensive.

The animations created by VideoWorks were run through a MacroMind utility called Accelerator which converts VideoWorks files to a compressed file format. This insures that each frame is displayed the same amount of time, allowing smoother, more consistent results. The accelerator file is incorporated into a HyperCard stack.

A HyperCard stack was used to make the final product a menu-driven package. Selection of a topic is made by simply moving the mouse to direct the on-screen cursor to select one of the main menu items given in Table 1. Once this is done, HyperCard prompts the user to choose a topic under the main menu item. After display of the topic, the user is prompted to: (1) choose another topic under that menu item, or (2) choose another main menu item or (3) end the program.

3. OVERVIEW OF THE ANNUAL GREAT LAKES ICE CYCLE

3.1 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.

3.2 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).

3.3 Ice Thickness.

Vertical ice accretion occurs as a result of heat transfer from the ice-water interface through the ice to the atmosphere. As ice sheets thicken, 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).

3.4 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 low maximum ice cover on Lake Ontario is due to 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).

3.5 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.

3.6 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). 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).

4. ANIMATION OF GREAT LAKES ICE CYCLE

Animations helps the viewer visualize the temporal and spatial progression of ice cover over Great Lakes. The animation for each Great Lake is annotated with a text summarizing the normal spatial sequence of ice formation and loss along with other pertinent information.

4.1 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 1-14. 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 1-15. Only shore ice remains the second half of April.

4.2 Lake Michigan:

surface area 57,750, volume 4,920 km^3, 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.

4.3 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.

4.4 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.

4.5 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.

5. SUMMARY AND CONCLUSIONS

An interactive menu-driven computer program of the normal Great Lakes ice cycle was produced using data from a digital ice concentration data base (Assel, 1983), a Macintosh SE computer, and associated software. The menu allows the user to go back and forth between menu topics to gain insight into the dynamics of the spatial and temporal characteristics of the normal Great Lakes ice cycle. However, because the ice cover climatology of the 1990s may differ from the contemporary ice cover climatology given here (Assel, 1989), and because the information presented here is simplified to facilitate understanding by nontechnical users, it is recommended that it only be used to gain an overview of the Great Lakes ice cover climatology. The citations given in this paper are a good place to start for those interested in more information on Great Lakes ice cover.

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