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Computer Visualization of Long-Term Average Great Lakes Temperatures and Ice Cover

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ABSTRACT. *The Great Lakes Environmental Research Laboratory (GLERL) developed data sets of daily long-term averages over the annual cycle for surface water temperature, ice cover concentration, and derived lake-averaged vertical temperature profiles for each of the Laurentian Great Lakes. The two-dimensional data sets have a spatial resolution of approximately 2.5 km and are geo-referenced with latitude and longitude. A lake bathymetry data set was also produced for the same grid. The objective of assembling these particular data sets was to develop a computer tool to visualize and explore spatial and particularly temporal relationships between long-term averages of temperature (surface and lake-averaged vertical profile), ice cover, and bathymetry on a given lake and between lakes. Here, we briefly describe the data sets, summarize data sources and algorithms used to develop these data sets, and discuss the limitations of these data. We also briefly summarize the capabilities of the interactive menu-driven system to manipulate and display the daily long-term average temperatures and ice cover.*

INDEX WORDS: *Computer animation, Great Lakes, temperature, ice, climatology.*

INTRODUCTION

Water temperature and ice cover are two important climatic variables, between the lakes and the atmosphere, affecting physical and biological processes in the Great Lakes. While daily surface temperature and ice cover patterns are strongly influenced by meteorology, weekly or monthly temperatures are very stable from year to year; this suggests interest in long-term average temperature and ice cover data bases. Advances in remote-sensing technology over the past 30 years enabled better climatologic descriptions of water temperature (Irbe 1992) and ice cover (Assel *et al.* 1983), than were previously possible. However, one limitation of a written presentation of climatological time series is that maps and charts do not convey, or enable the user to easily visualize, the seasonal spatial dynamics and interactions between these climatic variables and lake limnokinetics and bathymetry.

In a recent study (Schneider *et al.* 1993), we used available digital climatic information on water temperatures and ice cover to develop long-term average data sets of daily spatial patterns of these data throughout the annual cycle. These long-term averages were calculated for each day of the year, for each point in a grid defining the spatial domain of the surface of each Great Lake. These data sets are an incidental by-product of the main objective of our study: to provide a research tool for visually exploring and examining the 2-dimensional spatial and temporal characteristics of the daily long-term average surface temperature, ice cover, and lake-averaged vertical temperature profile for the Great Lakes.

The purposes of this paper are: 1) to briefly describe: a) the sources of data used to establish the data sets, b) the methods used to construct the data sets, and c) the limitations associated with the source data and the constructed data sets of daily long-term averages; 2) to briefly highlight the computer animation interface capabilities for exploring

TABLE 3. Total number of images available for each month for 1966–1993.

Lake	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Superior	18	24	59	50	78	105	113	132	85	57	35	16	772
Michigan	31	35	49	36	64	96	98	107	75	44	31	38	704
Huron	27	23	56	69	97	129	118	134	93	55	46	33	880
Erie	29	37	69	81	81	124	111	141	111	78	42	57	544
St. Clair	12	20	25	35	45	79	67	89	75	35	23	39	961
Ontario	44	63	92	83	93	122	125	127	123	86	54	62	1,074

are corrected by GLERL with an automatic correction algorithm (Schwab *et al.* 1992).

The satellite images are also processed at GLERL to derive cloud-free water surface temperature data. The data are tested for cloud cover and cloud contamination in an automatic cloud-testing procedure: 1) cloud-free lake surface temperatures for each lake are extracted from the original satellite images; 2) if at least 33% of the lake surface tested cloud free, these data are used in further image processing steps; 3) small cloud-contaminated areas are filled by using an inverse-squared-distance weighting of cloud-free pixels within seven pixels from the cloud-contaminated grid point. The results of these automatic processing steps are visually checked, and corrections are performed manually.

To combine the AES surface temperature measurements with the GLERL AVHRR satellite-derived temperatures, we extrapolated the surface temperatures for each observed day with more than 33% observed grid points to the 2.56-km grid by again using an inverse-squared-distance weighting. The long-term ice cover data set was also adapted to this grid in a similar manner.

AES data accuracy

A comparison of 452 satellite-based temperature measurements with buoy measurements at 1-m depth yielded higher temperatures for the satellite data, with an average difference of 0.3°C, and a standard deviation of differences of 0.9°C (Irbe 1992). Fifty-one intercomparisons for airborne measurements with submerged thermistors and ship buckets revealed an average 0.0°C difference and a standard deviation of differences of 0.6°C (Irbe 1992). Given that radiometric temperature measurements take place within the viscous boundary layer and that conventional measurements are taken within the turbulent mixed zone below this boundary layer, this difference is negligible from a climatological viewpoint.

GLERL data accuracy

Three procedures were used to process the GLERL AVHRR data set: SSTMAP (April 1990–June 1991), IMGMAP (June 1991–October 1992), and OCNMAP (since June 1992). The major distinctions between these algorithms are different atmospheric correction equations (Leshkevich *et al.* 1993). Only fully atmospherically corrected images of AVHRR-11 were used in this study. A comparison of buoy measurements at 0.5-m depth with AVHRR-11 SSTMAP temperature measurements yielded lower SSTMAP temperatures, mean offset 1.13°C for daytime images and 1.72°C for nighttime (Leshkevich *et al.* 1993). The different offset for daytime and nighttime images is likely due in part to different satellite computer processing algorithms. Using the IMGMAP procedure, the mean difference was –0.11°C for daytime images and –0.03°C for nighttime images. A comparison of temperatures, produced by OCNMAP and IMGMAP atmospheric correction equations with buoy measurements, revealed that OCNMAP-derived temperatures generally showed a lower bias than IMGMAP temperatures.

The lower satellite relative to buoy temperatures of Leshkevich *et al.* (1993) are the opposite of Irbe's (1992) finding (higher satellite relative to buoy temperatures). These opposing results indicate great care must be taken in making physical processes inferences from satellite observations of geophysical data. The differences in years of observations and the differences in evolving satellite computer processing algorithms are likely contributing factors to above noted opposing results.

Method to Produce the Daily Average Temperature Data Set

Due to spatially and temporally changing cloud cover, the surface temperature data set is not homogeneous. The typical long-term temperature at each grid point for each day of the year cannot be calculated as an arithmetic mean over all such days of all years, since each grid point and day has a different observational base. Especially in the late fall and winter, the high probability of cloud cover decreases the frequency of satellite-derived surface temperature images considerably (Table 3).

Following a method described by Irbe (1992), the long-term average lake surface temperature was derived using a regression method. A day number was assigned to each image according to its day of the year (Julian day). A linear least-squares regression of Julian day number and long-term average temperature for each grid point, was calculated from observations from 15 days before to 15 days after the day in question. An arbitrary minimum of five observations before the day of interest and five observations after were used and the time range was extended as necessary to satisfy this minimum. Five observations were found intuitively to be sufficient to avoid unacceptable small sample errors. This was sometimes the case in late fall and winter for North Channel, Green Bay, Grand Traverse Bay, Black Bay, and Nipigon Bay. For instance, to calculate the long-term average temperature for Julian day number 215 (3 August in a non-leap year), all images with Julian day numbers 200 (19 July) through 230 (18 August) were used for the linear regression analysis. The long-term average surface water temperatures are recorded to the nearest 0.1°C. Figure 1 shows example long-term average temperatures calculated for grid point number 4000 (43.83°N, 82.09°W) on Lake Huron; 772 observations were available for this grid point.

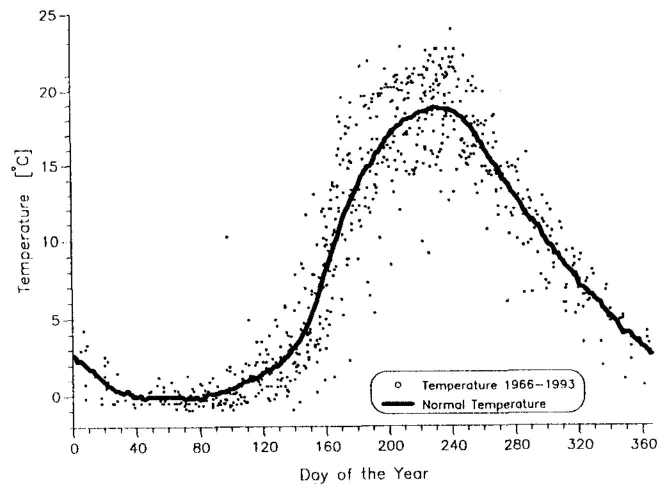

FIG. 1. ***Calculation of long-term average temperature at grid point 4000 (43.83°N, 82.09°W) on Lake Huron.***

COMBINING LONG-TERM AVERAGE ICE COVER AND TEMPERATURE DATA SETS

The two data sets, average ice cover and average surface temperature, are derived from different observational bases and with different techniques. They are inconsistent on location and timing of ice cover, especially during the freezing and melting period. Ice cover in the surface water temperature data set was indicated by water temperatures of zero or below zero. However, the locations of subzero-degree grids (ice covered) in the long-term average water temperature data set and ice covered grids in the long-term average ice cover data set did not match in all cases. In combining the two data sets for each day, grids that had any ice cover in the ice cover data base were assumed to be 0°C in the combined data set, and the long-term average temperature was lowered so that the lake area at or below 0°C matched the ice-covered area of the long-term average ice cover data set. The combined ice-temperature map was then smoothed using a 3 × 3 mean filter. This arbitrary filter was large enough to smooth discontinuities yet it was small enough to preserve much of the spatial detail. On an average over the ice-cover period, Lake Superior temperatures were decreased by 0.95°C, Lake Michigan by 1.38°C, Lake Huron by 1.06°C, Lake Erie/St.Clair by 1.48°C, and Lake Ontario by 1.15°C. The initially higher temperature versus ice cover maps is attributed to the (previously mentioned) fair-weather (cloud free) bias of the remotely-sensed surface water temperature data which likely resulted in an overestimate of the long-term average surface temperatures.

This adjustment gave unrealistically large temperature changes between the last ice-free day and the first ice day, and between the last day with ice cover and the first ice-free day. Before the first ice day and after the last ice day, temperature offset values for the entire lake surface were applied to the temperature maps to smoothly build up and decay temperatures for the first and the last ice day, respectively, using an arbitrary rate of 0.2°C per day.

VERTICAL TEMPERATURE PROFILES

The patterns of lake surface temperature and ice cover depend mainly on energy fluxes at the water surface, heat storage, and lake dynamics. The latter processes include horizontal and vertical mixing.

The depth of vertical mixing, along with the heat stored in a lake, can be understood by looking at vertical temperature profiles. Although the three-dimensional temperature structure cannot be shown here, the long-term spatial-average daily temperature-depth profiles are very important to understand the lake surface temperature and its patterns. Lake wide mean daily temperature profiles have been calculated from GLERL's thermodynamic and heat storage model (Croley 1989, 1992; Croley and Assel 1994). These temperature profiles were designed to describe the mean lake wide heat storage in the lakes.

Vertical Temperature Model Description and Evaluation

As detailed in the above references, GLERL's thermodynamic and heat storage model uses areal-average daily air temperature, wind speed, humidity, precipitation, and cloud cover. Over-land data are adjusted for over-water or over-ice conditions. The surface energy balance is calculated from shortwave radiation and reflection, net long wave radiation, advection, and latent and sensible heat flux. Atmospheric stability effects on the bulk transfer coefficient are formulated and used with the aerodynamic equation for sensible and latent heat flux.

Energy conservation and superposition mixing are used to account for heat storage in the lake. The effects of past heat additions or losses are superimposed to determine temperatures at all depths. Each past addition or loss is parameterized by its age and allowed to mix throughout the volume accordingly. Mass and energy conservation are used to account for ice formation and icepack decay in the lake. These relations are solved simultaneously through iterative determination and use of water surface temperature and ice cover.

Turnovers (mixing of deep waters with surface waters as surface temperature passes through that at maximum density), which are a fundamental behavior of dimictic lakes, are well represented by GLERL's thermodynamic and heat storage model. Hysteresis between heat in storage and surface temperature, observed during the heating and cooling cycle on the lakes, is preserved. The model also correctly depicts lake-wide seasonal heating and cooling cycles, vertical temperature distributions, and other mixed-layer developments.

Comparisons show good agreement with actual data, including 23 years of daily aerial and satellite observations of water surface temperature on all lakes (root mean square error of 1.1–1.6°C and correlation greater than 0.97), 8 years of bathythermograph observations of depth-temperature profiles on Lake Superior, and 1 year of independently derived weekly or monthly surface flux estimates on Lake Superior, Erie and Ontario (two estimates). Water balance derivations for 1951–88 exhibited low annual residuals when using model evaporation estimate.

Processing Modeled Vertical Temperatures to Produce Daily Long-Term Averages

Since turnover day changes from year to year, simply averaging vertical temperature profiles for each day over a long period yields nonsense profiles when pre-turnover profiles are averaged with post-turnover profiles. To calculate long-term average vertical temperature profiles, we used the following processing technique. For each lake, we calculated the mean turnover days (spring and autumn turnover) from modeled daily lake wide temperature profiles for 1956 to 1985 (Table 4). We then averaged all temperature profiles with the same relative distance (time) from the two annual turnover days. We recorded the modeled long-term average vertical temperature profiles at each 1-m depth to the nearest 0.01°C (precision exceeds accuracy).

BATHYMETRIC DATA BASE

For each grid point we extracted the depth of the nearest datum in the bathymetry data base published by Schwab and Sellers (1980) and assigned it to the grid point. Both mean and maximum depths, displayed in the animation program, are calculated by extrapolating gridded data. Because of the extrapolation method and the land-water mask used, shallow inshore areas are under-represented. This leads to higher average depth values than reported elsewhere.

THE COMPUTER ANIMATION PROGRAM

We programmed the computer to display maps and graphs sequentially, to animate the temporal development of spatial patterns for a user. Since our objective was to produce an animation that would run smoothly and at a reasonable speed to portray the temporal changes typical of the annual cycle, refined spatial mapping representations of the two-dimensional data fields on the computer screen (of surface temperature and ice concentration) were sacrificed to achieve meaningful animations.

To run the animation program, the following system resources are required: 1) IBM compatible PC, 2) 533 Kb accessible RAM, 3) VGA graphics

TABLE 4. Turnover dates from 1956 to 1985.

	Spring			Autumn		
Lake	Earliest	Mean	Latest	Earliest	Mean	Latest
Superior	16/06	02/07	22/07	09/12	21/12	04/01
Michigan	13/05	28/05	22/06	18/12	31/12	13/01
Huron	12/05	26/05	09/06	30/12	12/01	24/01
Georgian Bay	16/05	31/05	08/06	14/12	29/12	12/01
Erie	10/04	01/05	11/05	04/12	23/12	12/01
Ontario	04/05	30/05	19/06	22/12	11/01	27/01

adapter, 4) 14.5 Mb hard disk space, and 5) optionally, but highly recommended, a mouse. In addition, graphics font files supplied with Microsoft FORTRAN or Microsoft Windows are required to execute the program. Installation instructions are given by Schneider *et al.* (1993). The program is menu driven; the main menu (Table 5) lets one choose among five submenus by entering the appropriate number on the keyboard or by selecting the menu item with the mouse. Similar procedures are used for choosing from the submenus. Documentation of the data base, data processing, analysis methods, program usage, and commands is provided online and requires no further explanation. Data manipulation capabilities are provided through a button-bar menu on the left or bottom of the screen image for each of the animations. Image and data manipulation options which are described in detail elsewhere (Schneider *et al.* 1993) are given only in general terms here for the sake of brevity.

2-D Temperature and Ice Cover Animation

The two-dimensional (2-D) animation displays 2-D color-coded maps of long-term average surface temperature and ice cover in animated sequences, portraying their spatial pattern for each Great Lake throughout the annual cycle. The surface water temperature data are color-coded, and the ice cover data are gray-scale coded. For example, Lake Erie long-term average surface water temperature and ice cover for 5 March is given as Figure 2. Lake Erie on this date does not have any open-water areas, so no 2-D colored-coded water temperature patterns appear on this lake image (selected especially for display here in gray tones). The gray tones portray the spatial pattern of different ice cover concentrations; see the Ice-Cover [%] scale on the lower left of Figure 2. The water temperature scale, given to the right of the ice-cover scale in Figure 2, is a color spectrum on the actual computer animation but is reproduced here as gray scale. The 2-D animation screen can also be dumped to an ASCII file written as hexadecimal values in a (32Z2) FORTRAN format. Individual temperature and ice values at each lake grid point, as well as the latitude and longitude of that grid point, are displayed on the lower right portion of the screen image by moving the screen cursor to that grid point with the mouse or keyboard arrows. In addition, the lake-averaged surface temperature and its standard deviation for each day are displayed in the upper left of the screen; the month and day are displayed in the upper center, and the daily spatial maximum and minimum surface temperatures are displayed in the upper right.

Horizontal Temperature Profile Animation

The horizontal surface profile menu allows one to define a transect across any of the Great Lakes and then animate the long-term average surface temperature along this profile for each day of the annual cycle. The temperature, latitude, and longitude of any point on the line graph is displayed by pointing to it with the cursor. Figure 3 portrays an example of a horizontal profile of the long-term average temperature for 24 July on Lake Superior.

Vertical Lake-Averaged Temperature Profile Animation

The vertical profile menu allows animation of the modeled lake-averaged vertical temperature profile throughout the annual cycle for each Great Lake. One can display the animation for more than one Great Lake at a time so it is possible to compare temperature profiles of different lakes throughout the annual cycle. Figure 4 provides an example of this type of animation for the long-term average vertical temperature profile of 15 August for Lakes

TABLE 5. Main menu and submenu items.

MAIN MENU	2-D PATTERNS*
0) Return to Main Program	0) Quit
1) 2-D Pattern	1) Lake Superior
2) Horizontal Profile*	2) Lake Michigan
3) Vertical Profile	3) Lake Huron
4) Variable vs. Bathymetry*	4) Lake Erie
5) Documentation	5) Lake Ontario
VERTICAL PROFILE	DOCUMENTATION
0) Quit	1) Title Screen, Introduction, Data Base, and Data Processing
1) Lake Superior	2) 2-D Animation of Normal Temperature and Ice Cover
2) Lake Michigan	3) Animation of Horizontal Temperature Profiles
3) Lake Huron	4) Animation of Vertical Temperature Profiles
4) Lake Erie	5) Animation of Temperature/Ice-Bathymetry Relationship
5) Lake Ontario	
6) Georgian Bay	

*The submenus for the Horizontal Profile and the Variable vs. Bathymetry menu items are the same as the submenu items given for the 2-D PATTERNS submenu.

Huron, Michigan, and Superior. In the actual animation, each lake's graph appears in a different color. Temperature and depth for a given date can be displayed by placing the cursor at the desired point on the profile.

Variable vs. Bathymetry Animation

The variable vs. bathymetry menu lets one investigate the dependency of surface temperature and ice cover on lake depth by calculating the spatial means for each 1-m depth step and displaying them in animated sequences for each day of the annual cycle; see Figure 5 for an example day. In order to provide versatility in the amount and type of detail given in the plots, the graphs can be smoothed by selecting one of three smoothing algorithms for the depth interval, over which spatial smoothing takes place: 1) averaging over classes, 2) averaging over depth steps, or 3) averaging over moving average of depth steps. A direct screen display of the spatially-averaged ice cover or surface temperature and depth for any point on the graph can be obtained by placing the cursor over the point. The program allows direct comparison of different lakes by displaying them simultaneously, as shown in Figure 5 for 5 January on Lakes Erie and Huron. The two curves with positive slopes, that is the curves that increase in value going from left to right, show the variation of the spatially averaged surface water temperature (for a given depth range) with depth, which increase with depth during winter because the deep areas cool more slowly than the shallow areas of a lake. Lake Erie's temperature curve is shorter because its maximum depth is smaller than Lake Huron's. The two curves with negative slop, that is the curves that decrease in value going from left to right, show the variation of spatially averaged ice cover with depth, which decreases with depth because ice cover forms first in the shallow areas of a lake and later in winter in the deeper more exposed areas of a lake. In the animation, each lake's graph appears in a different color.

DISCUSSION

Long-term average daily water temperature and ice cover data sets for the Great Lakes were developed and linked to a computer software interface to provide a capability to explore the temporal, bathymetric, and spatial relationships among these data sets in a way not possible by looking at maps in a climatological atlas. Actual temperature and ice cover patterns for a specific day, which are determined by the current meteorological and limnological situation are likely to be different from the long-term average patterns. Therefore, interpretations of the long-term average patterns for a specific location and time must be done only with great care as they could yield large errors. For example, the winter of 1982–83 was extremely mild, ice did not form in the mid lake areas of the Great Lakes as it usually does. Thus, using the long-term average ice cover to represent the 1982–83 ice cover would yield large errors for mid lake areas

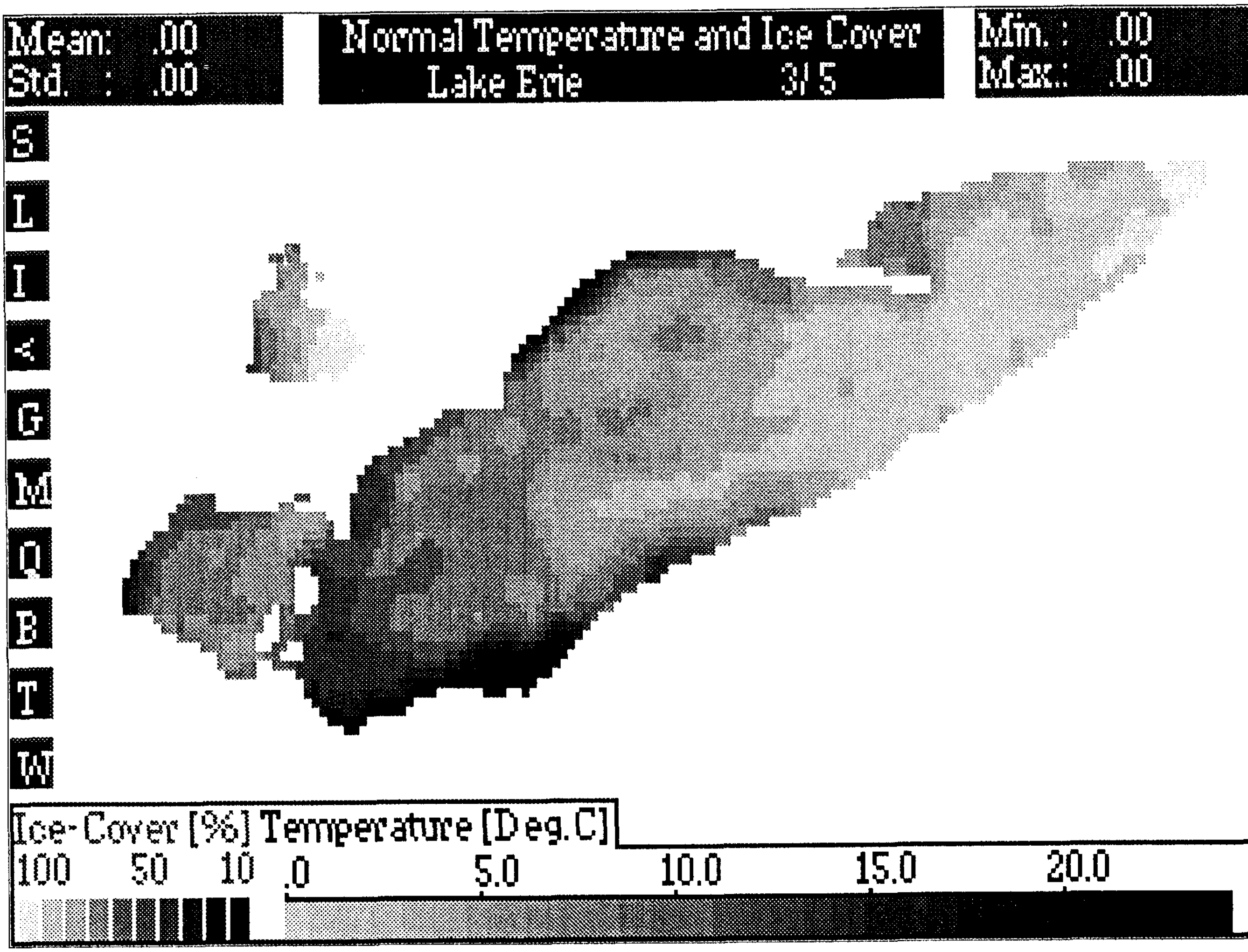

FIG. 2. Reproduction of computer screen image of the long-term average temperature and ice cover for Lake Erie for 5 March. The lake is covered with various concentrations of ice cover; the lightest gray tone represents the highest ice cover concentration and the darkest gray tone represent the lowest ice concentration. There are no ice-free areas in this image and, hence, no water temperatures displayed.

of the Great Lakes. In a similar manner, the formation of summer stratification for a given year could occur earlier or later than the long-term average and thus surface temperatures on a given date of a given year could be several degrees higher or lower than the long-term-average. The long-term average temperature and ice cover are derived with different observational bases and different methods. Thus, merging them into one data base resulted in discrepancies between surface temperature and ice cover at some locations making it necessary to smooth the data. The surface temperature measurements are based solely on remotely sensed data, limited to cloud-free weather. Thus, the long-term average surface temperature patterns are biased toward good weather. Although, under cloud-free skies, the surface temperature at night is usually lower due to increased long wave radiation, this effect is not likely to compensate for the warmer surface temperature during the day. The temperature decrease at night is limited by the fact that large energy losses at the surface lead to increasing convection. Thus, a larger water body participates first in the cooling process, then in the heating, limiting the temperature decrease at the water surface at night. The heating of the water leads (especially under calm wind conditions) to a strongly stratified upper water zone, where most of the incoming solar radiation is absorbed. The

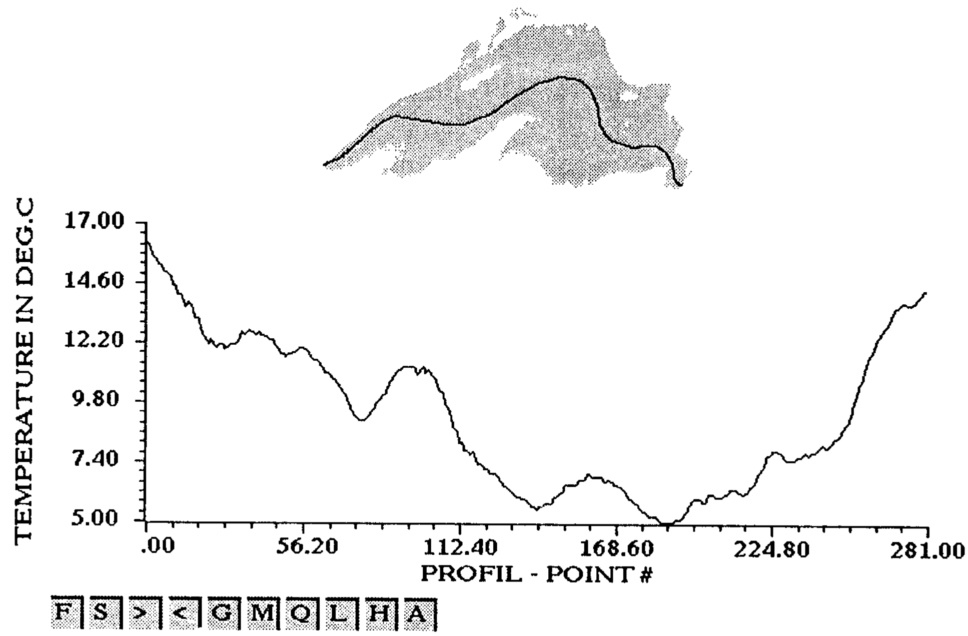

FIG. 3. ***Reproduction of computer screen image of horizontal surface temperature profile across Lake Superior for 23 July.***

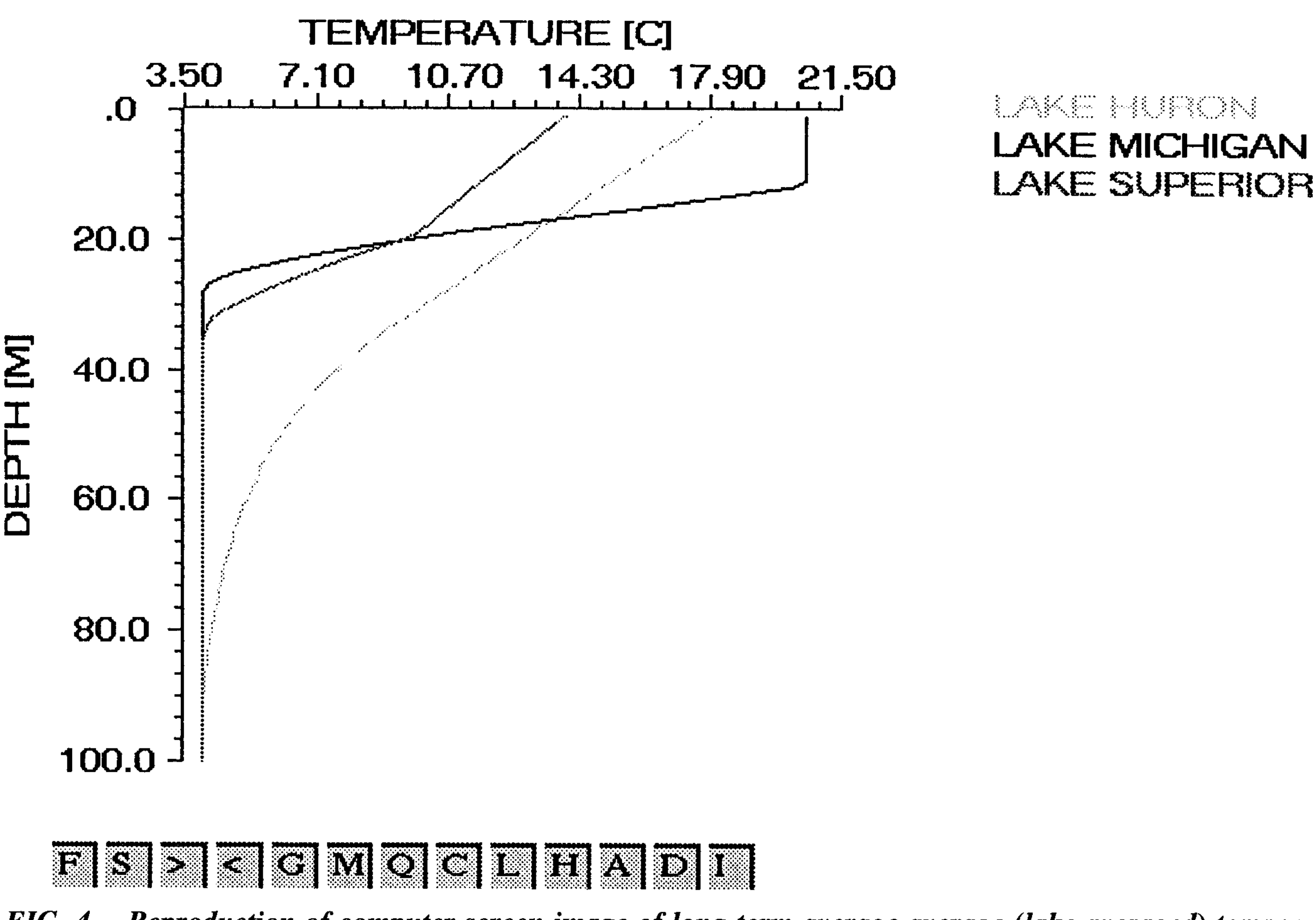

FIG. 4. ***Reproduction of computer screen image of long-term average average (lake averaged) temperature profile (modelled) for 15 August for Lakes Huron, Michigan, and Superior.***

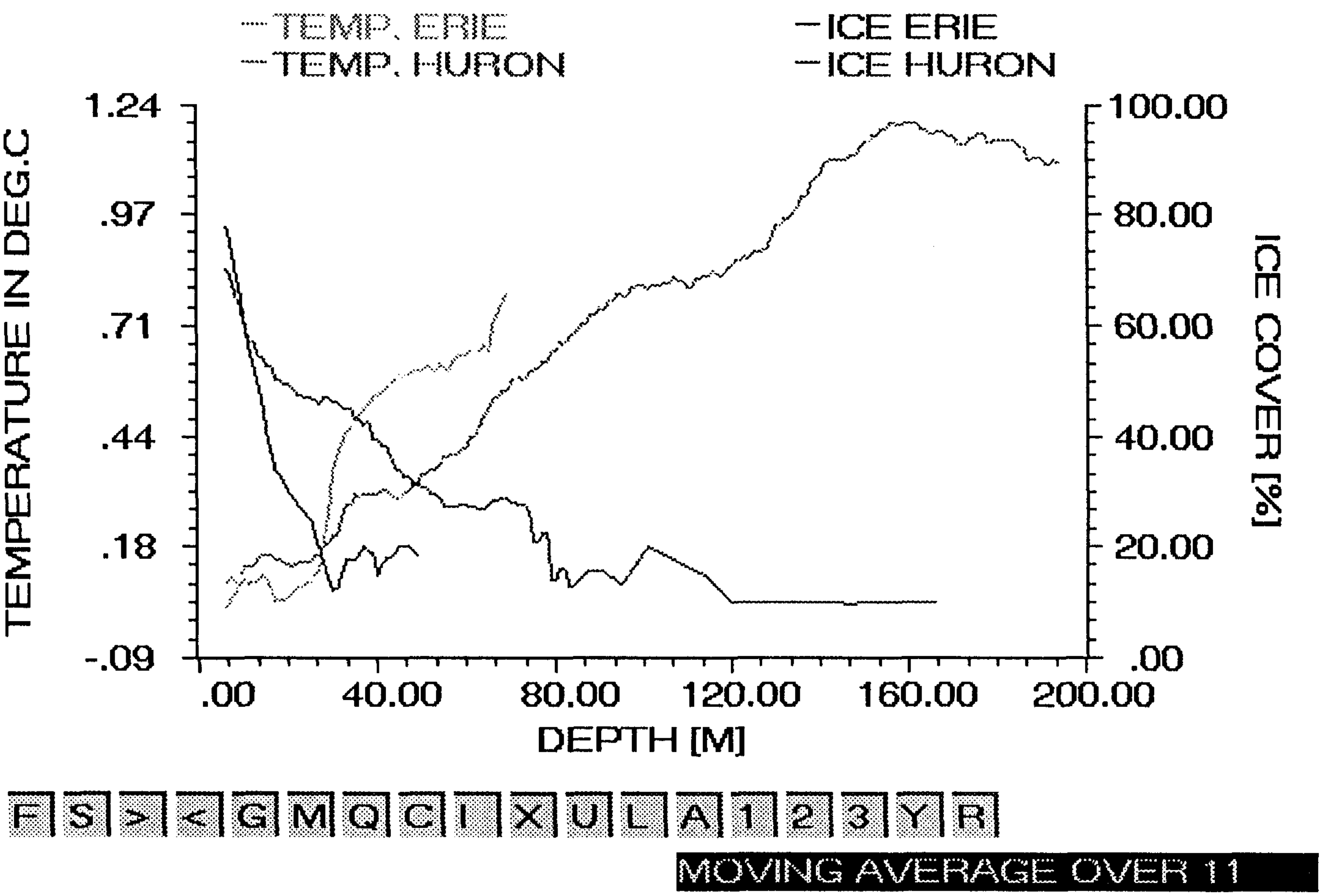

FIG. 5. Reproduction of computer screen image of long-term average temperature and ice cover vs. lake bathymetry for Lakes Erie and Huron for 5 January.

stronger the shortwave radiation is and the smaller the vertical mixing is, the higher is the surface temperature. Another problem with the measuring technique of surface temperature is that cloud-free conditions are frequently associated with specific wind situations. The likelihood of cloud-free skies is higher with northwesterly winds than with southern and southeasterly winds, which often bring humid air to the Great Lakes region. This wind bias probably has an effect on the temperature patterns. However, since westerly winds prevail in the Great Lakes region, and since this wind direction often allows remote surface temperature measurements, the effect of wind bias on the temperature patterns is most likely small. Given these caveats, the long-term average temperature and ice cover are useful to describe the general seasonal spatial patterns and their relation to lake bathymetry over an annual cycle. These general patterns have modeling applications as exemplified in a recent study in which these data were used in 2-D simulations of the surface energy budget throughout the annual cycle for all of the Great Lakes (Schneider and Croley 1994). There, long-term average ice cover and water temperature patterns were adjusted for specific dates in a simulation by using a lumped evaporation and lake heat storage model (Croley 1989, 1992) and a lake-averaged ice cover model (Croley and Assel 1994). Results were used in conjunction with a 2-D surface energy budget model to calculate the long-term (30-year) averages of evaporation, heat storage, ice cover, and surface energy fluxes for each Great Lake.

DATA AVAILABILITY

While the software interface we developed to animate the water temperature and ice cover data sets performs admirably, it does not allow extraction of the data. Therefore, we developed simple software to extract these data directly into ASCII files for those who wish to use the data in other ways. The computer animation program and the software to save the data bases, including the ice cover, surface water temperature, vertical temperature profile, lake bathymetry, and latitude and longitude grid data bases, are available by writing to us or via electronic mail (INTERNET) over anonymous ftp (FTP.GLERL.NOAA.GOV in the animation subdirectory). Please remember the caveats on data limitations and biases noted above.

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