Limnol. Oceanogr., 40(1), 1995, 165–176

Changes in winter air temperatures near Lake Michigan, 1851–1993, as determined from regional lake-ice records

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Abstract

Records of freezeup and breakup dates for Grand Traverse Bay, Michigan, and Lake Mendota, Wisconsin, are among the longest ice records available near the Great Lakes, beginning in 1851 and 1855, respectively. The timing of freezeup and breakup results from an integration of meteorological conditions (primarily air temperature) that occur before these events. Changes in the average timing of these ice-events are translated into changes in air temperature by the use of empirical and process-driven models. The timing of freezeup and breakup at the two locations represents an integration of air temperatures over slightly different seasons (months). Records from both locations indicate that the early winter period before about 1890 was ~1.5°C cooler than the early winter period after that time; the mean temperature has, however, remained relatively constant since about 1890. Changes in breakup dates demonstrate a similar 1.0–1.5°C increase in late winter and early spring air temperatures about 1890. More recent average breakup dates at both locations have been earlier than during 1890–1940, indicating an additional warming of 1.2°C in March since about 1940 and a warming of 1.1°C in January–March since about 1980. Ice records at these sites will continue to provide an early indication of the anticipated climatic warming, not only because of the large response of ice cover to small changes in air temperature but also because these records integrate climatic conditions during the seasons (winter–spring) when most warming is forecast to occur. Future reductions in ice cover may strongly affect the winter ecology of the Great Lakes by reducing the stable environment required by various levels of the food chain.

General circulation models (GCMs) have forecast an increase in air temperatures (Hansen et al. 1984; Schlesinger and Zhao 1989), especially during winter in mid- to high latitudes, as a result of continually increasing concentrations of atmospheric CO_2 and other greenhouse gases (U.S. Dep. Energy 1991). These climatic changes are expected to profoundly affect the physical, chemical, and biological processes of most ecosystems (U.S. Environ. Protection Agency 1989; Intergov. Panel on Climate Change 1990). To determine how these climatic changes will affect ecosystems, scientists have put much effort into detecting and quantifying past climatic changes and determining how these changes have affected specific physical, chemical, and biological processes. Hansen and Lebedeff (1987) detected and quantified increases in average hemispheric and global air temperatures since the late 1800s by analyzing records from many meteorological stations. However, quantification of past climatic changes at specific locations has been difficult because of the lack of enough unbiased air-temperature records. Most long-term records of air temperature (if available) incorporate observational biases (such as recorded changes in air temperature resulting from changes in observational time or measurement techniques) that are commonly larger than the subtle climatic changes under investigation (Karl and Williams 1987). Therefore, it has been necessary to use other phenological data, such as ice-cover records (Tramoni et al. 1985; Palecki and Barry 1986; Magnuson 1990; Robertson et al. 1992) or tree-ring data (Fritts 1991) to detect and quantify past climatic changes.

Ice-cover records (freezeup and breakup dates and total duration of ice cover) represent an integration of local weather conditions, primarily air temperature (Tramoni et al. 1985; Palecki and Barry 1986; Robertson et al. 1992). The exact timing of freezeup or breakup in a given year depends on daily and shorter-than-daily weather conditions such as air temperature and windspeed. For many lakes and rivers, weather conditions that are marginally favorable for freezeup or breakup can extend over a long period of time, making the precise date difficult to identify and exposing the data record to observational biases. Ice formation and removal in rivers is often affected by runoff and river flow. In many lakes, however, freezeup and breakup occur rapidly, allowing the annual dates of freezeup and breakup to be identified precisely. Changes in the general timing or average date (or duration) of an event reflect changes in the regional climate.

Acknowledgments

This work was partially funded by the National Oceanic and Atmospheric Administration Office of Global Programs project entitled "Climate change and Great Lakes ecosystems: Retrospective analysis of water temperature, lake ice, and fish communities."

We thank J. Magnuson, K. Stewart, and J. Walker for their review of an earlier version of this paper.

Great Lakes Environmental Research Laboratory contribution 874.

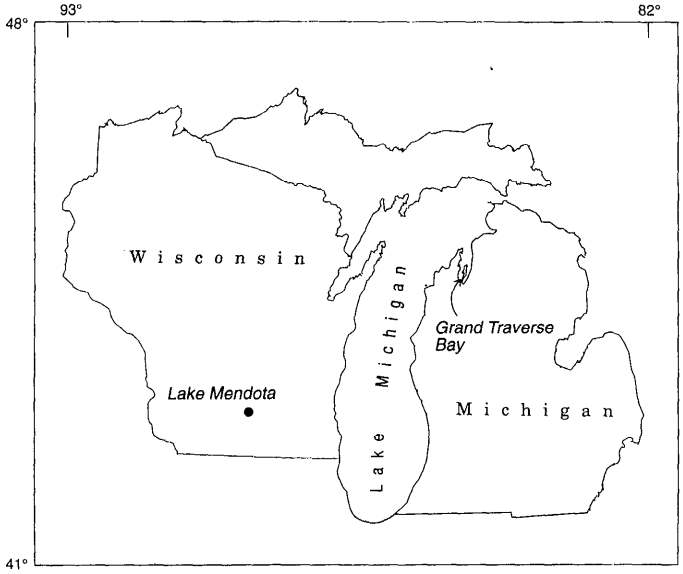

Fig. 1. Grand Traverse Bay is a large deep fjord along the northeast shore of Lake Michigan. Lake Mendota is a small shallow lake inland of the southwest shore of Lake Michigan.

In addition, if changes in the mean timing of these events can be calibrated in terms of specific meteorological variables, the changes in climatic conditions can be quantified. Therefore, ice records may be more accurate long-term indices of air temperature than air-temperature records themselves.

Woolard (1943) used ice records from inland lakes and rivers in Minnesota, Wisconsin, and Michigan (from the 1850s to 1941) to show that after the 1880s winters were shorter and springs were earlier than during the 1850s through the 1880s. More recently, Hanson et al. (1992) found a significant trend from 1955 to 1990 toward earlier loss of ice cover in the shore zone of the Great Lakes, indicative of increasing air temperatures in spring. Robertson et al. (1992) used ice records for Lake Mendota to quantify changes in air temperatures during 1855–1991 near Madison, Wisconsin. They found that air temperatures in fall and early winter increased by ~2°C during this period and that most of this increase occurred over a brief period around 1890. They also found that air temperatures in late winter and spring increased by ~2.5°C and that half the increase occurred about 1890 and the other half after 1979. The changes for Lake Mendota may reflect actual climatic changes in the midwest, which have also been indicated by trends in recent breakup dates of Canadian lakes (Schindler et al. 1990; Skinner 1993), or changes in local climatic conditions resulting from urban warming associated with industrial and population growth. However, if the changes were caused by urbanization, they would be expected to be more consistent and gradual.

In this paper, we examine the ice records for Lake Mendota, Wisconsin, and Grand Traverse Bay, Michigan, since the 1850s to demonstrate that the techniques used by Robertson et al. (1992) to detect and quantify past climatic changes from the ice records for Lake Mendota are transferable to other systems. We use the techniques of Robertson et al. for Grand Traverse Bay, compare and contrast the climatic changes inferred from each ice record to describe regional climatic changes near the Great Lakes, place ice records for 1981–1990 into historical perspective by comparing decadal information, discuss the implications of past and future climatic changes on the ice cover of lakes, and give examples of the potential effects of these changes on the ends of the food chain in the lake ecosystem.

Study sites, ice records, and air-temperature data

Lake Mendota (43°40′N, 89°24′W) (Fig. 1) has a surface area of 39.4 km^2, a mean depth of 12.4 m, and a maximum fetch of 9.8 km. Uninterrupted annual ice records for Lake Mendota from 1855 through spring 1993 were obtained from the Wisconsin State Climatologist. Although no exact identifications of freezeup and breakup were available from the published records (Robertson 1989), freezeup and breakup are generally rapid transitional events that can usually be determined to within 1 or 2 d (R. A. Bryson and W. W. Bunge, Jr. unpubl. rep.). Complete ice cover has formed on Lake Mendota every year since ice records have been collected. Madison air temperature records (obtained from the Wisconsin State Climatologist) were used in the development of ice models for the lake. Air temperature data for 1884–1989 were adjusted by Robertson (1989) to remove possible biases caused by changes in station location. This was done by quantifying changes in the monthly relationships (using monthly multiple regressions) with that of four nearby weather stations that had previously been adjusted by Karl and Williams (1987) to remove observational biases. Data collected before 1884 contain several uncorrectable observational biases that precluded our use of these earlier records.

The west arm of Grand Traverse Bay (45°46′N, 85°37′W) (Fig. 1) out to Marion Island (~9.6 km) has a mean depth of ~46 m, a maximum depth >100 m, and an area of ~53.8 km^2. Freezeup and breakup records for Grand Traverse Bay for winters 1851–1973 were abstracted from Snider (1974), and records for the winters 1974–1993 were obtained from the Traverse City Chamber of Commerce. Freezeup of the bay is defined as the date that a solid ice cover forms out to Marion Island. Breakup is defined as the date the ice disappears or moves out past the island. In the case of multiple occurrences of freezeup and breakup during a winter, the first freezeup and last breakup were used in this analysis. In 26 of the 142 winters, a solid ice cover did not form in the bay. The freezeup and breakup dates were set to 8 March, the average date between the freezeup and breakup dates for the five winters with the shortest ice durations: 1898 (11 d), 1944 (5 d), 1956 (4 d), 1957 (12 d), and 1973 (4 d). Freezeup dates were missing for eight winters and breakup dates were missing for four; these years were discarded from the analysis. Air temperature records at Traverse City were used to analyze Grand Traverse Bay ice records.

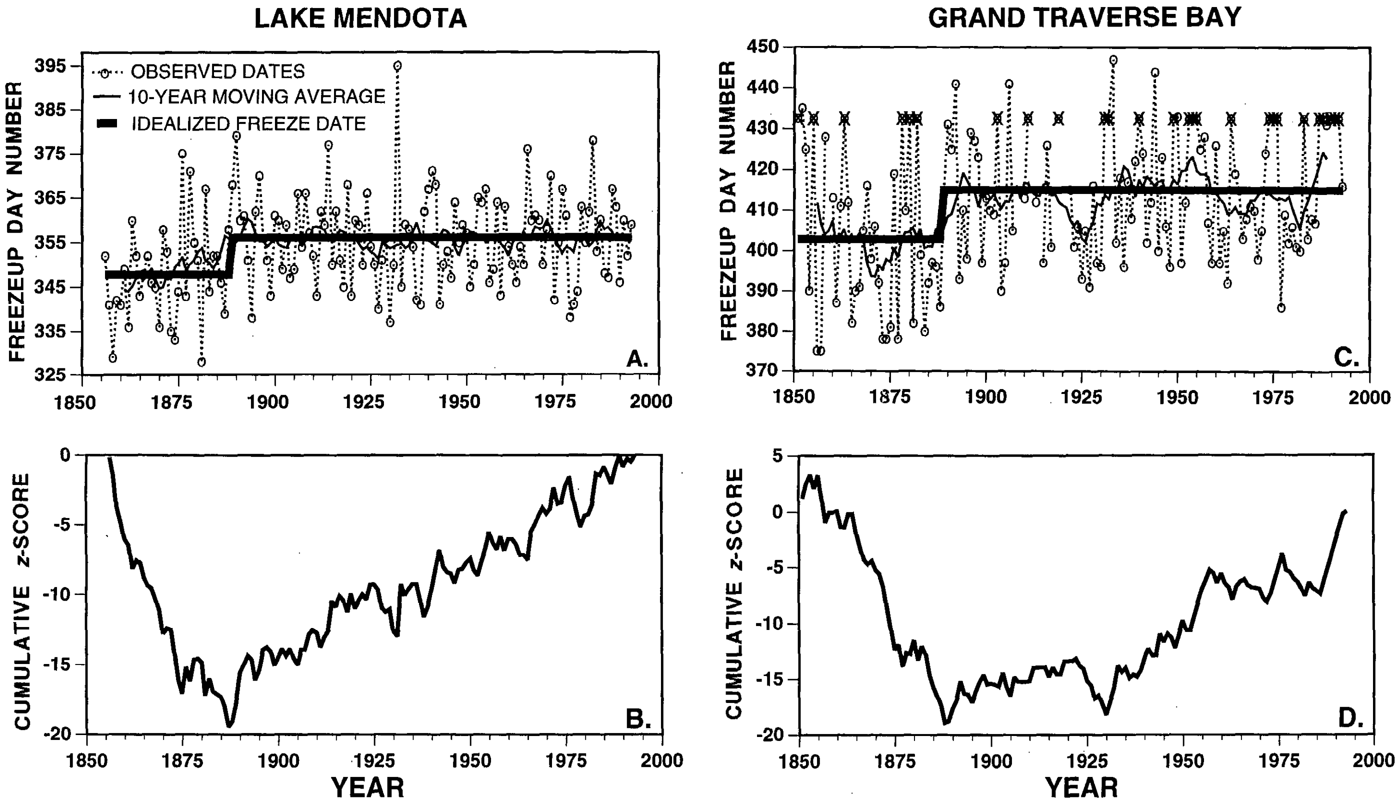

Fig. 2. Changes in the freezeup dates and cumulative z-scores. Freezeup day numbers are computed as days from 1 January of the year preceding breakup. Thus, 1 January of the year in which breakup occurs is day 366, 1 February of the year in which breakup occurs is day 397, and so on. The 10-yr moving average line is plotted in year 6. Years in which Grand Traverse Bay did not freeze over are identified by ×s on day 433.

Average monthly air temperatures for 1897–1977 were adjusted by Gaskill (1982) to remove site inhomogeneities by relating average seasonal temperature of a nearby weather station with a homogeneous record (through use of a temperature difference series) to the record for Traverse City. However, rather abrupt discontinuities still appeared in the monthly average data when the observational changes were documented. Therefore, only daily air-temperature data after 1950 were used to calibrate the ice model; this restriction limited both the calibration and model-evaluation periods used in the analyses. Consequently, long-term changes in air temperatures near Grand Traverse Bay for specific months before 1950 were only used for comparison with those from Madison.

Methods

Changes in ice cover—Year-to-year variations in freezeup and breakup dates were large for both locations (Fig. 2), making changes in general mean conditions hard to determine. Three techniques were used collectively to describe how mean ice cover changed during 1851–1993: 10-yr moving averages, cumulative z-scores, and autoregressive integrated moving averages (ARIMA). The 10-yr moving average, superimposed on the annual data (Fig. 2A,C), and a cumulative z-score plot (Fig. 2B,D) (graphical techniques) were used to qualitatively detect changes in mean conditions. The years in which Grand Traverse Bay did not freeze over were identified on the graph of the 10-yr moving average for comparison. A z-score is a standardized value calculated for each observation by subtracting the average of the entire data set and dividing the result by the standard deviation of the data. The 10-yr moving average and the z-score plot smoothed the data, making it easier to identify trends. With this information, ARIMA intervention analyses (Box and Tiao 1975) were then fitted only to the raw data of Lake Mendota to determine statistically the best description of the changes in mean conditions (i.e. abrupt changes or gradual trends). ARIMA analysis at Grand Traverse Bay was precluded because of the winters without freezeup and the winters of missing data. The specific years used to describe changes in the mean conditions of Lake Mendota were obtained by comparing t-ratios from consecutive yearly interventions. All changes in mean conditions reported here were significant at $\alpha = 0.05$ unless otherwise noted.

Calibration of mean freezeup and breakup dates—Before ice records can be used as quantitative climatic indicators, each ice parameter (for each location) must be calibrated in terms of specific meteorological parameters. In this study, we calibrated changes in each ice parameter only in terms of changes in air temperature; short-term wind effects were not examined. Two techniques were used to calibrate the ice records: fixed-period regression analysis (Palecki and Barry 1986; Tramoni et al. 1985) and dynamic sensible heat-transfer (SH) (variable time period) freezeup and breakup models (Bilello 1964; Robertson et al. 1992).

For the fixed-period regression analysis, the ice records were calibrated by regressing average air-temperature parameters with coinciding freezeup or breakup dates. This type of analysis requires extensive coincident ice and meteorological data. The fixed period most strongly related to each ice parameter was determined from the coefficients of determination (R^2) of various combinations of monthly and seasonal air temperatures regressed against freezeup and breakup dates (1948–1987 for Lake Mendota; even years, 1952–1990, for Grand Traverse Bay). For ease of comparison between models, all air temperatures in the graphs and in the equations are given as departures from the long-term average (1884–1990 for Lake Mendota; 1951–1990 for Grand Traverse Bay). The slopes of the regressions of air temperature on the ice-cover parameters indicate the change in ice-cover parameter per degree Celsius (°C) change in air temperature, whereas the slopes of the regressions of the ice-cover parameters on air temperature indicate the change in air temperature per day of change in ice-cover parameter. These slopes will not be the inverse of each other because R^2 is <1.0. The implications of the slopes are similar for the calibration of the dynamic models.

The second approach to simulate freezeup and (or) breakup dates used the dynamic SH freezeup and breakup models described by Robertson et al. (1992):

Freezeup model:

$$W_t - W_{t-1} = \alpha + K_F[A_{t-1} - W_{t-1}]$$
$$W_t = \alpha + K_F[A_{t-1}] + (1 - K_F)[W_{t-1}]. \quad (1)$$

W_t and W_{t-1} are the water temperatures on day t and day $t - 1$, A_{t-1} is the average air temperature from the previous day, and α and K_F are empirical constants. The model was used to estimate water temperatures for each year from 1 October until the day the water temperature became negative (predicted freezeup date). The initial value of W_{t-1} was 20°C.

Breakup model:

$$I_t - I_{t-1} = \beta + K_I[A_{t-1} - I_{t-1}]$$
$$I_t = \beta + K_I[A_{t-1}] + (1 - K_I)[I_{t-1}]. \quad (2)$$

I_t and I_{t-1} are the daily subfreezing head deficit on day t and day $t - 1$, and β and K_I are empirical constants. The model was used to estimate subfreezing heat deficits from the day the lake froze (or was predicted to freeze when simulating various climatic scenarios) until the day the subfreezing heat deficits change from a negative to a positive value. The initial value of I_{t-1} was an additional empirical constant, I_0. Values for α, β, I_0, K_F, and K_I were determined by the Nelder-Mead simplex procedure (O'Neill 1971), which iteratively minimizes the sum-of-square errors of the 40-yr reference period (1948–1987) for Lake Mendota and of a 20-yr reference period (even years, 1952–1990) for Grand Traverse Bay.

The calibrated dynamic ice models for each site were applied to nine temperature scenarios, and the average freezeup and breakup dates for each scenario were computed. The temperature scenarios were created by adding five increments of 1°C warming and three increments of 1°C cooling to the actual daily air temperatures for a 30-yr reference period (1948–1977 for Lake Mendota and 1951–1980 for Grand Traverse Bay). For years in which the model predicted that the location would not freeze, a date of 1 March was used for Lake Mendota (the latest predicted freezeup date) and of 8 March for Grand Traverse Bay (described earlier). Freezeup and breakup were then calibrated (defining the change in temperature for a 1-d change in freezeup or breakup date) by regressing the change in air temperature (−3° to +5°C) with coinciding average freezeup or breakup dates for each scenario.

Model evaluation—To determine how well the models worked and which model provided the most reliable results, we used each model to simulate freezeup and breakup for an independent period (that was not used in the calibration phase). We then compared root-mean-square (RMS) errors of each model simulation. A 50-yr period (1898–1947) was used for Lake Mendota, and a 20-yr period (odd years, 1951–1989) was used for Grand Traverse Bay.

Results

Changes in mean freezeup dates—The annual and smoothed freezeup dates are presented in Fig. 2A and C. The smoothed data show a trend toward later freezeup dates for both sites during the 142-yr record. The changes appear as short-term shifts rather than gradual changes. The abrupt shifts are clearly illustrated in the cumulative z-score plots (Fig. 2B and D). The largest shift (global minimum in curve) in both took place in 1888, at which point the general slopes of the cumulative z-score curves change sign. ARIMA interventions applied to the period around 1888 for Lake Mendota indicate that the best or idealized description of mean conditions consists of two periods of uniform mean conditions (from the beginning of each record to 1888 and from 1889 to 1993) separated in 1888 by abrupt changes of 8.30 d for Lake Mendota and 12.22 d for Grand Traverse Bay (Fig. 2A and C and Table 1). A possible trend before 1889 for Lake Mendota is statistically insignificant. No changes were observed in the long-term average freezeup date after 1888 at either site, although the frequency of winters when Grand Traverse Bay did not freeze increased after 1940 (Fig. 2C).

Changes in mean breakup dates—The annual and smoothed breakup dates are presented in Fig. 3. The

Table 1. Changes in average freezeup and breakup dates for Lake Mendota and Grand Traverse Bay and corresponding changes in air temperatures estimated by use of fixed-period regression (FP) and sensible-heat transfer (SH) models.

Years modeled	Avg date	Change in days	Change in temp. (°C) FP	Change in temp. (°C) SH
		Freezeup date		
Lake Mendota				
1856–1888	13.8 Dec			
1889–1993	22.1 Dec	+8.30	+1.16	+1.53*
Grand Traverse Bay				
1851–1888	6.8 Feb			
1889–1993	19.0 Feb	+12.22	+1.89	+1.45*
		Breakup date		
Lake Mendota				
1856–1888	11.0 Apr			
1889–1979	3.8 Apr	+7.26	+0.91	+1.12*
1980–1993	27.6 Mar	+7.20	+0.90	+1.11*
Grand Traverse Bay				
1851–1864	28.6 Mar			
1865–1888	14.0 Apr	−16.40	−1.34	−2.29*
1889–1939	2.7 Apr	+11.26	+0.92	+1.57*
1940–1993	25.4 Mar	+8.32	+0.68	+1.16*

* Best estimate for change in air temperature from the preceding period.

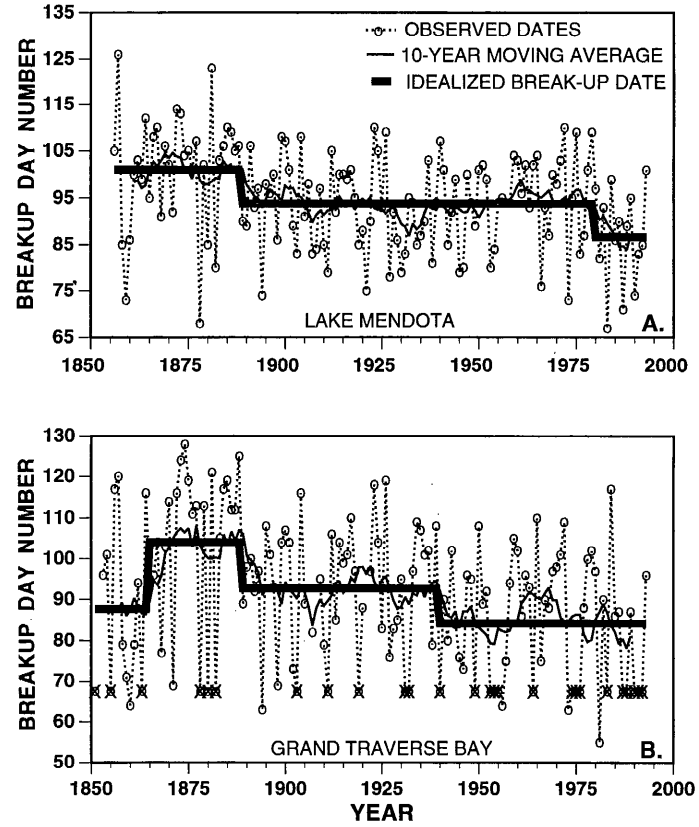

Fig. 3. Changes in breakup dates. Breakup day numbers are computed as days from 1 January. The 10-yr moving average line is plotted in year 6. Years in which Grand Traverse Bay did not freeze over are identified by ×s on day 67.

smoothed data portray a trend toward earlier breakup dates at both sites. The single largest change occurred about 1888. The mean post-1888 breakup date for Lake Mendota did not change again until about 1980, when it once more shifted to earlier dates. The smoothed data demonstrate several shifts in mean breakup date at Grand Traverse Bay: one shift toward later dates about 1865 and two shifts toward earlier dates around 1888 and 1940. ARIMA interventions applied around 1888 and 1980 for Lake Mendota indicate the best description of mean conditions for the lake consists of three periods of uniform mean conditions: from the beginning of record to 1888, 1889–1979, and 1980–1993 (Fig. 3A and Table 1). A possible trend after 1979 is statistically insignificant. The description of mean conditions used for Grand Traverse Bay consists of four periods of uniform mean conditions: the beginning of record to 1864, 1865–1888, 1889–1939, and 1940–1993 (Fig. 3B and Table 1).

Calibration of freezeup date—Fixed-period regression analyses and dynamic SH freezeup models were used to determine the changes in air temperature that would have been necessary to cause the changes in mean freezeup dates shown in Fig. 2. Average November–December (ND) air temperatures for Lake Mendota are most strongly correlated with annual freezeup dates (Fig. 4A). The slopes of the regressions of freezeup dates against air temperature indicate that a 1-d change in the average freezeup date equates to a 0.141°C change in average ND air temperature and that a 1°C change in average ND air temperature equates to a 4.00-d change in freezeup date (Table 2). Therefore, the 8.30-d change in average freezeup date around 1888 equates to a 1.16°C increase in ND air temperature (Table 1). The average January air temperatures for Grand Traverse Bay were most strongly correlated with annual freezeup dates (Fig. 4C). The slopes of the regressions indicate that a 1-d change in average freezeup date equates to a 0.155°C change in average January air temperature and that a 1°C change in average January air temperature equates to a 1.98-d change in freezeup date (Table 2). Therefore, the 12.22-d change in freezeup date equates to a 1.89°C increase in January air temperature (Table 1).

The calibrated SH freezeup models and average predicted freezeup dates for each of the nine climatic scenarios are shown in Fig. 4B and D. Changes in freezeup dates for Lake Mendota are linear throughout this 9°C temperature range; however, the magnitude of the change from the reference period for Grand Traverse Bay decreases with temperature increases of 2°C or more. This nonlinear response is caused by predictions that Grand Traverse Bay would remain ice-free with increasing regularity as air temperature increased; therefore, the freezeup date approached 8 March (the date used if no freezeup was predicted). With increases of 4 and 5°C, the bay

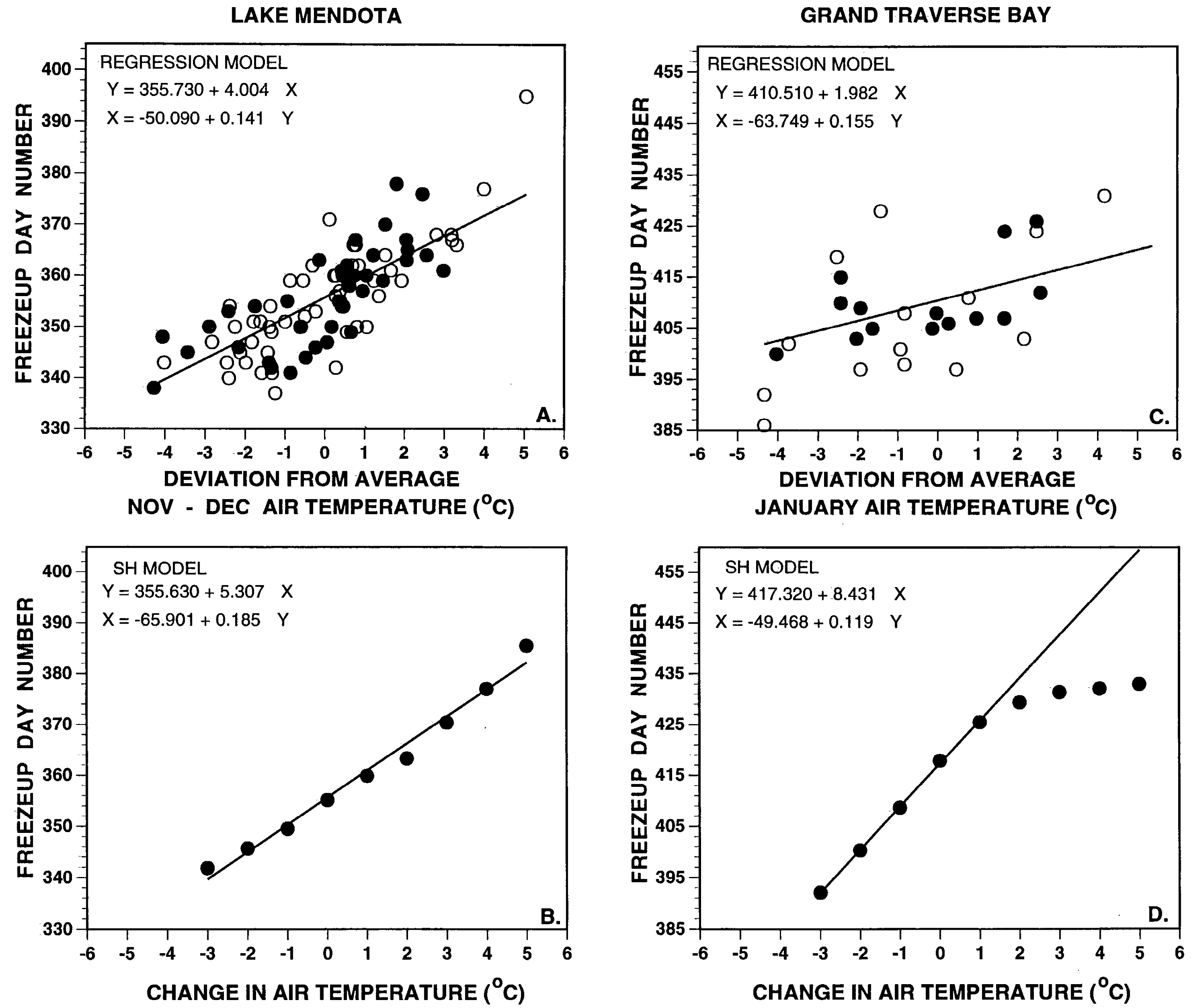

Fig. 4. Calibration of freezeup dates. Numbering convention for freezeup date as given in Fig. 2. All linear regression equations are shown on the graphs. Each line represents the freezeup date predicted from air temperature. A, C. Freezeup day number related to deviation from the long-term average November–December and January air temperatures. Years used in the regression—●; years used in error analysis—○. B, D. Sensible-heat transfer (SH) model for Lake Mendota (air temperature changes of −3, −2, −1, 0, 1, 2, 3, 4, and +5°C were used in this regression) and Grand Traverse Bay (air temperature changes of −3, −2, −1, 0, and +1°C were used in this regression). Air temperature changes from the 1948–1977 reference period for Lake Mendota and from the 1951–1980 reference period for Grand Traverse Bay—●.

should rarely freeze (2 and 0 yr out of 30, respectively). Lake Mendota has frozen every year on record and is predicted to freeze every year in the climatic scenarios until air temperature increases 4°C or more from the reference period. With increases of 4 and 5°C, Lake Mendota is predicted to remain ice-free 1 and 2 yr out of 30, respectively. The slopes of the regressions between average predicted freezeup date and air temperature indicate that a 1-d change in average freezeup equates to a 0.185°C change in fall and early winter air temperature and that a 1°C change in air temperature equates to a 5.31-d change in freezeup date (Table 2). Therefore, the 8.30-d change in average freezeup date around 1888 equates to a 1.53°C increase in fall and early winter air temperature (Table 1). Because of the nonlinearity of changes in predicted average freezeup date for Grand Traverse Bay, the only scenarios used in the final regression (calibration) were −3, −2, −1, 0, and +1°C. The slopes of these regressions suggest that a 1-d change in average freezeup date equates to a 0.119°C change in average air temperature and that a 1°C change in average air temperature equates to a 8.43-d change in freezeup date (Table 2). Therefore, the 12.22-d change in average freezeup date equates to a 1.45°C increase in fall and early winter air temperature (Table 1).

Calibration of breakup date—The same approach used to calibrate changes in freezeup date is used to determine the changes in air temperature needed to cause the observed change in mean breakup dates in Fig. 3. In this case, average January–March (JM) air temperatures are most strongly correlated to breakup dates for Lake Mendota, and average March air temperatures are most strongly correlated to breakup dates for Grand Traverse Bay (Fig. 5). For Lake Mendota, the slopes of the regressions indicate that a 1-d change in the average breakup date equates to a 0.126°C change in JM air temperature and that a 1°C change in JM temperature equates to a 3.91-d change in breakup date (Table 2). Therefore, the 7.26-d change around 1888 and the 7.20-d change around 1980 equate to increases of 0.91°C and 0.90°C in JM air temperature, respectively (Table 1). For Grand Traverse Bay, the slopes of the regressions indicate that a 1-d change in the average breakup date equates to a 0.082°C change in March air temperature and that a 1°C change in March temperature equates to a 2.76-d change in breakup date. Therefore, the 16.40-d change around 1865 equates to a 1.34°C decrease in March air temperature, and the 11.26-d change around 1888 and the 8.32-d change around 1940 equate to increases in March temperatures of 0.92°C and 0.68°C, respectively.

The slopes of the regressions for the SH breakup models indicate that a 1-d change in average breakup date equates to changes of 0.154 and 0.140°C in late winter and spring air temperatures for Lake Mendota and Grand Traverse Bay, respectively, and that a 1°C change in these air temperatures equates to a 6.40- and 7.08-d change in breakup dates for the lake and the bay, respectively (Table 2). Therefore, the 7.26-d change in breakup date around 1888 and the 7.20-d change around 1980 for Lake Mendota equate to increases in late winter and spring air temperatures of 1.12 and 1.11°C, respectively (Table 1). For Grand Traverse Bay, the 16.40-d change in breakup around 1865 equates to a decrease of 2.29°C in late winter and spring air temperatures, and the 11.26-d change around 1888 and the 8.32-d change around 1940 equate to increases of 1.57 and 1.16°C, respectively.

Error analysis and best estimates for changes in air temperature—The fixed-period regression analysis and SH models provide different estimates of the translation of historical changes in ice cover to changes in air temperature. The difference between the two approaches was most extreme for the breakup dates for Grand Traverse Bay: results of the SH model indicate that the changes in ice cover represent changes in air temperature almost twice as large as those indicated by the regression approach. To determine which approach provides the most reliable estimates, we used both approaches to simulate freezeup and breakup dates for periods not used in the model calibration, basing the simulations on actual air temperatures. We then compared the RMS errors for both approaches (Table 2). The SH freezeup and breakup models seem to provide the most reliable estimates of changes in air temperature. The SH freezeup models reduced the RMS error by 53% for Lake Mendota and by 49% for Grand Traverse Bay, compared to reductions of 41 and 17% with the regression equations. Therefore, the best estimate of changes in mean freezeup date equates to an increase of ~1.5°C in fall and early winter air temperatures around 1888 for both sites. The SH breakup models reduced the RMS error by 43% for the lake and by 73% for the bay, compared to reductions of 22 and 23% with the regression equations. Thus, the best estimate of changes in mean breakup date equates to an increase of ~2.2–2.7°C in late winter and early spring air temperatures after about 1865. Two discrepancies are apparent in the breakup records. First, the early breakup dates at Grand Traverse Bay indicate a warmer period before 1865 that does not seem to have occurred at Lake Mendota. Second, the recent change in breakup date, indicative of warming, appears to have begun much earlier for the bay (1940) than for the lake (1980). We have no explanation for the

Table 2. Freezeup and breakup model calibration and error analysis (time periods used in the error analysis are described in the text).

Event modeled	Fixed-period regression	Sensible-heat transfer model
Lake Mendota—freezeup		
Change in days (°C)$^{-1}$	4.00	5.31
Change in °C d^{-1}	0.141	0.185
RMS error	6.37	4.99†
% reduction in RMS error*	40.50	53.40†
Grand Traverse Bay—freezeup		
Change in days (°C)$^{-1}$	1.98	8.43
Change in °C d^{-1}	0.155	0.119
RMS error	13.39	8.31†
% reduction in RMS error*	17.30	48.70†
Lake Mendota—breakup		
Change in days (°C)$^{-1}$	3.91	6.40
Change in °C d^{-1}	0.126	0.154
RMS error	7.44	5.43†
% reduction in RMS error*	21.80	42.70†
Grand Traverse Bay—breakup		
Change in days (°C)$^{-1}$	2.76	7.08
Change in °C d^{-1}	0.082	0.140
RMS error	13.68	4.74†
% reduction in RMS error*	22.80	73.30†

* Percent reduction in root mean square (RMS) errors by use of air-temperature models (as opposed to use of mean ice event date) to estimate freezeup or breakup date.

† Best model based on reduction of RMS errors.

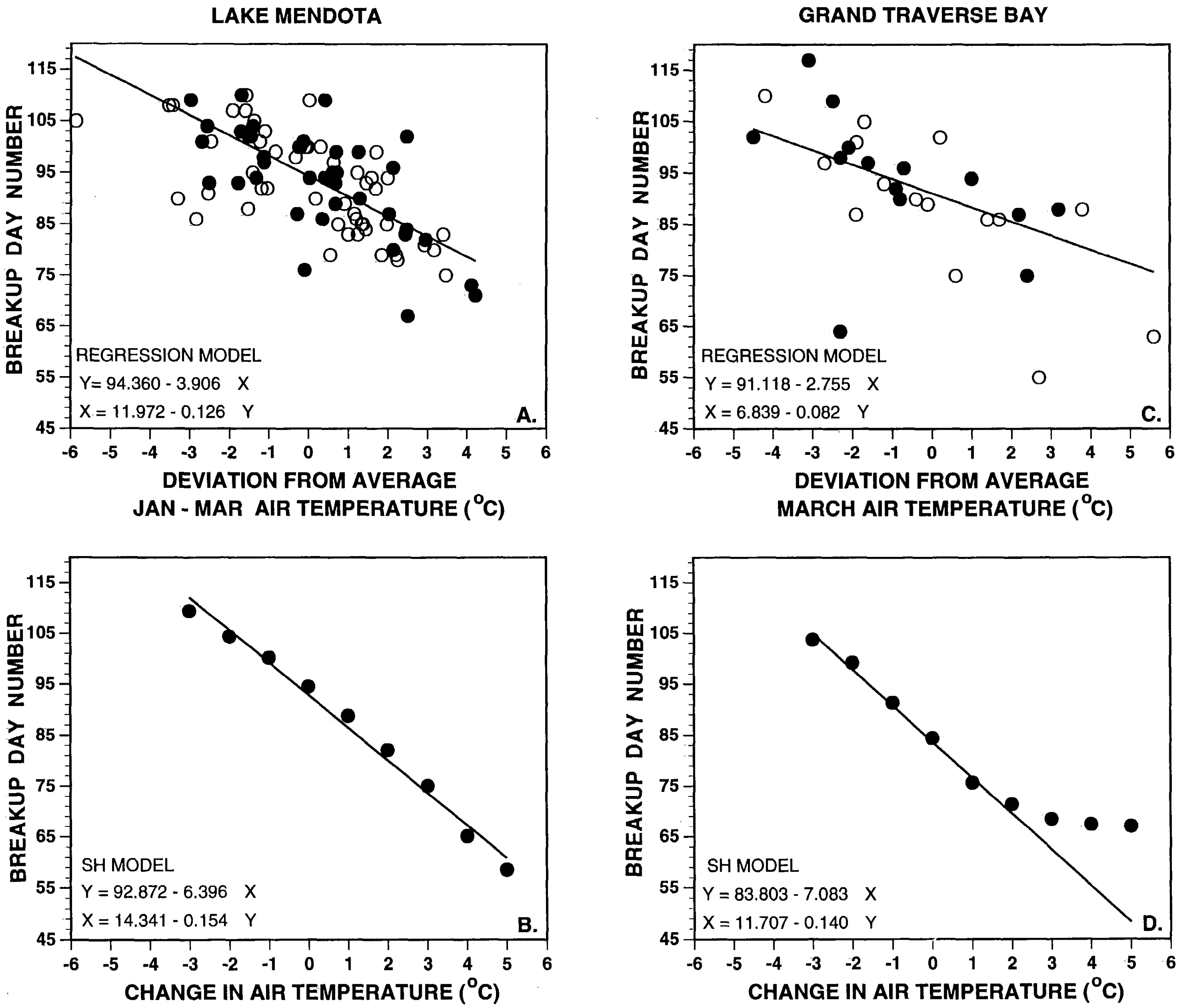

Fig. 5. Calibration of breakup dates. Numbering convention for breakup date as given in Fig. 3. All linear regression equations are shown on the graphs. Each line represents the breakup date predicted from air temperature. Symbols as in Fig. 4. A, C. Breakup day number as related to deviation from the long-term average January–March and March air temperatures. B, D. Sensible-heat transfer model for Lake Mendota (air temperature changes of −3, −2, −1, 0, 1, 2, 3, 4, and +5°C were used in this regression) and Grand Traverse Bay (air temperature changes of −3, −2, −1, 0, and +1°C were used in this regression).

difference in temperature trends before 1865; the difference since 1940 is discussed below.

Discussion

Contemporary ice records as viewed from a historical perspective—The ice-cover characteristics of the 1980s are of particular interest because of growing concern about global warming. To evaluate the severity of recent winter ice cover with respect to the 142-yr base period, we calculated decadal averages for total ice duration. The shortest decadal averages were 1981–1990 (Lake Mendota, 91.3 d; Grand Traverse Bay, 26.7 d). The decades with the longest average ice durations were 1861–1970 for Lake Mendota (121.2 d) and 1881–1990 for Grand Traverse Bay (71.3 d). Therefore, the ice cover of the 1980s, as a decadal group, had the shortest duration of any of the past 13 decades, indicating that the 1980s decade had the mildest winters.

Another indication of the mildness of recent winters is

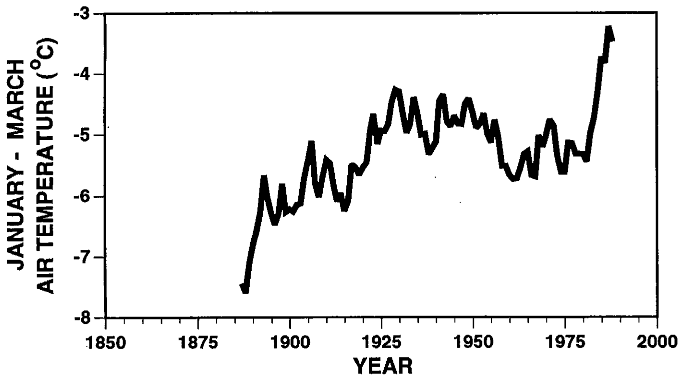

Fig. 6. Change in air temperature associated with changes in breakup date for Lake Mendota. The 10-yr moving average January–March air temperature for Madison is plotted in year 6.

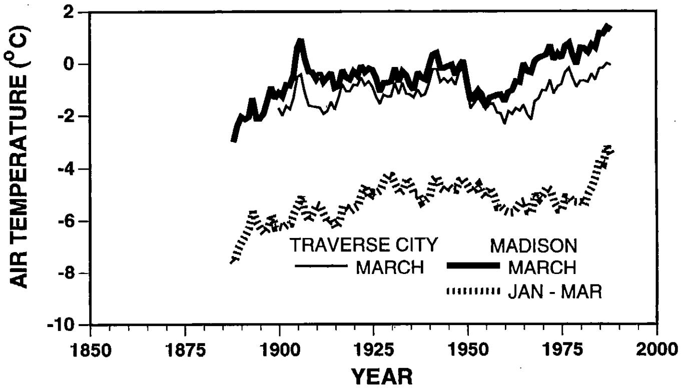

Fig. 7. Change in air temperature associated with changes in breakup date for Grand Traverse Bay. The 10-yr moving average air temperatures for Traverse City and Madison are plotted in year 6.

that during the 10-yr period from 1983 through 1992, Grand Traverse Bay did not freeze in 6 of the 10 winters (the bay did freeze, however, during winter 1993). The next highest frequency of winters without complete freezing was 4 yr out of 10, which occurred twice (1949–1958 and 1974–1983). Thus, the winters of 1983–1992 are without parallel during the 142-yr of record for Grand Traverse Bay. The 10-yr moving average for breakup dates at Lake Mendota was also the earliest on record during 1983–1992, providing additional evidence of the regional scope of unique recent winter mildness.

Freezeup date integration periods—Results from the fixed-period regression models indicate that the freezeup dates for Lake Mendota and Grand Traverse Bay integrate weather conditions over different time periods but are most affected by air temperatures 1 or 2 months before freezing. Freezeup dates for the lake are most highly correlated with average ND air temperatures, whereas those for the bay are most highly correlated with average January air temperatures (Fig. 4). Stewart and Haugen (1990) found that freezeup dates for lakes depended primarily on air temperatures and mean lake depth, a relationship supported by the differences in the integration periods found in our study. Grand Traverse Bay is located along the east shore of Lake Michigan, so it has a climate moderated by the effects of Lake Michigan and therefore has warmer fall and early winter air temperatures than Lake Mendota. The higher air temperatures at Grand Traverse Bay, in combination with its greater depth (and associated larger thermal capacity) and potential for episodic mixing with Lake Michigan, result in the bay freezing 6–8 weeks later than Lake Mendota (Fig. 2). Therefore, Grand Traverse Bay integrates air temperatures over a later period. The lack of a significant change in the average freezeup date for Lake Mendota after 1889 indicates that the average ND air temperature has not changed significantly since about 1889. However, the increasing frequency of incomplete freezing of the bay, beginning in the 1930s, indicates an increase in January air temperatures.

Breakup date integration periods—The date of breakup depends on the thickness of the ice formed and on the duration, frequency, and magnitude of the net energy gain by the lake in late winter and spring. Thus, breakup date is affected by weather conditions from the date of freeze up, which influences ice thickness, to the date of breakup. These two sites freezeup at different times (usually mid-December for Lake Mendota and late February for Grand Traverse Bay), but both sites break up at about the same time (late March). Therefore, breakup dates for the lake are affected by and reflect the integration of weather conditions from December through March, whereas breakup dates for the bay are affected by and are representative of the integration of weather conditions during February and March. These integration periods are also found in the regression analyses, where the breakup dates for Lake Mendota are most highly correlated to JM air temperatures and breakup dates for Grand Traverse Bay are most highly correlated to March air temperatures (Fig. 5).

Changes in the breakup dates for Grand Traverse Bay and Lake Mendota from 1865 to about 1940 were very similar; however, after around 1940, mean breakup dates for the bay became earlier, whereas those for the lake did not change until about 1980 (Fig. 3). The later breakup dates for Grand Traverse Bay were caused primarily by an increased frequency of winters during which the bay did not freeze (Fig. 3); the average date of breakup for the years during which it did freeze remained about the same.

The difference in the timing of the transition to earlier breakup dates between Grand Traverse Bay and Lake Mendota can be explained partly by differences in the timing of the changes in air temperature for the two integration periods. The change to earlier breakup dates for Lake Mendota around 1980 coincided with abrupt changes in the average JM air temperatures (Fig. 6). The 10-yr moving-average JM air temperatures for Lake Mendota reached the warmest on record in 1992, which coincided with the earliest moving-average breakup date. Average breakup date for Grand Traverse Bay gradually became earlier beginning about 1940. Air temperature records for the bay before 1950 included several observational biases and abrupt changes in the smoothed air-temperature record that precluded use for long-term analyses before that year. Therefore, air-temperature records for Lake Mendota were examined and compared with air temperatures and breakup dates for Grand Traverse Bay (Fig. 7). Changes in March air temperatures for both sites were similar; however, those for Lake Mendota do not show the abrupt changes observed for Grand Traverse Bay during times when observational biases were expected. Changes in the 10-yr moving-average March air temperatures for the lake coincide fairly well with the observed changes in the breakup dates for the bay. The earlier breakup dates after the 1940s occurred at the same time as a more gradual increase in the observed March air temperature. Thus, the discrepancy in the timing of the recent warming (beginning around the 1940s as opposed to around 1980), as indicated by the ice records, seems to be the result of an increase in March air temperature beginning throughout the region in the 1940s, although JM air temperatures collectively began to exhibit an increase only after about 1980. This result indicates that ice records for individual lakes represent more than an indicator of the entire winter climatic conditions; they may also indicate changes in specific seasons.

Regional climatic changes—In general, changes in air temperatures near Traverse City as determined from changes in the ice cover for Grand Traverse Bay were similar to those near Madison as determined from changes in the ice cover for Lake Mendota. This similarity indicates that the entire region near Lake Michigan has warmed by ~1.5°C in November–January and by ~2.7°C in February–March since about 1865. Changes in ice cover at Grand Traverse Bay were larger than at Lake Mendota, but these changes equated to similar changes in air temperatures. Most of the change in November–January air temperatures occurred abruptly about 1890; since that time, these temperatures have remained relatively stable. Late winter and early spring air temperatures increased similarly, by ~1.5°C, around 1890. However, late winter and spring air temperatures increased an additional 1.1–1.2°C after 1890. JM air temperatures, analyzed collectively, remained relatively stable from 1890 to 1980 and then increased abruptly by 1.1°C. The increase in March air temperature has been more gradual, ~1.2°C since the late 1940s.

Ice records as alternatives to air-temperature records for detecting and quantifying climatic changes—The most obvious indicators of climatic changes are the weather records themselves; however, observational biases incorporated in the records commonly produce data that seem to show climatic changes or obscure the actual changes. The changes introduced by observational biases can be significantly larger than the more subtle climatic changes that may actually be taking place. This was the case with the air-temperature records for Grand Traverse Bay. These records indicated changes in mean conditions before 1950 (even after adjustments were made), but these changes were artifacts of known observational changes. The large response of freezeup and breakup (5–8 d each) of these sites to a 1°C change in air temperature has enabled us to infer changes in air temperature since the 1850s which could not be detected or quantified by means of conventional air-temperature records. If scientists continue to monitor ice records at these sites, they will be able to detect and quantify future changes in air temperature without reference to weather records, which may be obscured by future observational changes. Ice records should be useful for detecting the future global warming that has been forecast to be most extreme at high latitudes, especially during winter and early spring—the periods these ice records integrate. Changes in the ice as recorded at both sites indicate that warming may have already begun near the Great Lakes.

Effects of changes in ice cover on the winter ecology and economics of Lake Michigan—How changes in the presence, absence, or amount of ice cover affect the winter ecology of the Great Lakes is not well known because of the small number of observations; thus, our understanding of the physical, chemical, and biological processes in the lakes during winter is incomplete. Changes in the mean dates of freezeup and breakup or in the percentage of winters in which freezing is incomplete may have positive or negative effects on the abundance or even the survival of some species. Several studies of Grand Traverse Bay and northern Lake Michigan that have examined the effects of ice cover and changes in ice conditions on both ends of the food chain in the Great Lakes are described below.

Ice cover can provide a stable environment that enables increased production at the lower end of the food chain if sufficient solar radiation is available. Bolsenga and Vanderploeg (1992) found that if the ice was not snow covered, the amount of photosynthetically active radiation reaching the top of the water column beneath clear ice in Grand Traverse Bay was ~45% of that at the air–ice interface. This 45% is still sufficient for algal production. Stewart and Brockett (1984) made a similar study of 10 frozen Adirondack lakes. Vanderploeg et al. (1992) found that during the period of winter ice cover on Grand Traverse Bay (again with snow-free ice), a winter–spring phytoplankton bloom developed in the upper 40 m, resulting in a 4–7-fold increase in feeding rate of adult *Diaptomus* spp. and a correspondingly enhanced reproductive output.

Ice cover has also been shown to affect higher levels of the food chain. In general, early and extensive ice cover over whitefish spawning grounds and abundant spring food supply were important factors producing strong year-classes. Freeberg et al. (1990) showed that overwinter egg mortality of whitefish in the spawning grounds of the east arm of Grand Traverse Bay was higher during winter 1983—a winter when the area did not freeze—than in 1984—a winter when the area did freeze. During winter 1984, ice-covered spawning grounds during the egg-incubation period protected the eggs against mortality induced by wind and wave action.

Brown et al. (1993) found that extensive early winter ice cover was an important parameter in regression models describing whitefish recruitment in northern Green Bay and the north shore of Lake Michigan near Port Inland, Michigan. Taylor et al. (1987) compared historical trends of Lake Michigan whitefish yields during 1900–1982 with corresponding winter air temperatures near Lake Michigan. They found that around 1930, after several cold winters in the 1920s, Lake Michigan whitefish yields increased, whereas during the next 30 yr (1931–1960), when winter temperatures were warmer (Assel 1980), whitefish yields decreased, except in 1947. The high yield in 1947 was attributed to the cold winter of 1943, which produced a large year-class. The strength of the 1943 year-class is important because it provides evidence that a single abnormal winter (in this case a winter of longer than normal ice cover) can cause a temporary reversal from a long-term trend in fish yields. As stated earlier, our analysis indicates an increase in the number of years in which Grand Traverse Bay did not freeze during the late 1940s and 1950. Taylor et al. (1987) also found that the cold winters of the late 1970s and early 1980s were associated with increases in whitefish yields in the early 1980s. Given this relation and assuming that other factors affecting the life cycle of whitefish in northern Lake Michigan have not changed, one would expect that the high frequency of winters during which Grand Traverse Bay did not freeze in the 1980s and early 1990s has increased the potential for a decline of whitefish yield. If so, projected decreases in duration and extent of ice cover (Assel 1991) and projected increases in water temperature (McCormick 1990) under various GCM greenhouse warming scenarios lend credence to predictions of longer term decreases in whitefish populations and possible changes in the fishery species composition (Meisner et al. 1987; Magnuson and Hill 1990), both of which could have significant economic effects on the Great Lakes commercial and sports fishing industries.

Conclusions

Ice records from Grand Traverse Bay and Lake Mendota indicate that fall, winter, and spring air temperatures near Lake Michigan increased from 1851 to 1993. Differences in the timing of changes in air temperature for discrete periods were observable because of differences in the integration periods of the two sites. However, the similarity in results at these two sites—on opposite sides of Lake Michigan ~320 km apart—indicates that these changes in air temperature are indicative of regional climatic changes. Whether this trend will continue is uncertain; however, continued monitoring and analysis of ice records will provide an early indicator (possibly better than the weather records themselves) of the anticipated greenhouse warming because of the large response of ice cover to small changes in air temperature and because these records integrate climatic conditions during the period (winter–spring) when most warming is forecast to occur. Changes in amount and frequency of winter ice cover are also important because of their relevance to winter lake ecology, the Great Lakes fishery, and the regional economy.

If the current trend toward milder winter and spring temperatures continues, climatic implications for Great Lakes ice cover include increasingly infrequent complete freezing for embayments in the Great Lakes, winters without freezeup for Lake Mendota, and later mean freezeup dates and earlier mean breakup dates for inland lakes.

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Submitted: 7 February 1994
Accepted: 6 June 1994
Amended: 17 November 1994