Environment Canada / Environnement Canada
Atmospheric Environment Service / Service de l'environnement atmosphérique

5th International Meeting on Statistical Climatology

22-26 June 1992
Toronto, Canada

Canada

CLIMATIC CHANGES NEAR THE GREAT LAKES INFERRED FROM 141 YEAR ICE RECORDS

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ABSTRACT. *Freeze-up and break-up dates and duration of ice cover for lakes and rivers represent an integration of weather conditions prior to the specified event(s). Changes in mean ice conditions may be used as quantitative indicators of climatic changes if long homogenous ice records are accompanied by sufficiently homogenous air temperature records to calibrate the changes in mean ice cover in terms of climatic variables. Historical ice records dating back to 1855 are available for Lake Mendota, WI (located on the southwestern side of Lake Michigan) and back to 1851 for Grand Traverse Bay, MI (located on the northeastern side of Lake Michigan). Changes in the mean ice cover of these two systems were used to describe changes in fall, winter, and spring air temperatures in the area near the Great Lakes during the past 141 years.*

INTRODUCTION. Many indicators have been used to detect and quantify historical climatic changes. The most obvious of these indicators is the weather records themselves. However, observational biases (for example, changes in observation time, measurement technique, and station location) have often caused apparent historical climatic changes (Schaal and Dale, 1977; Karl and Williams, 1987). In regions where historical weather records are very limited, other indicators have been used to detect and quantify past climatic changes or to verify or discredit the changes found in the limited weather records. One such indicator is the ice records of rivers and lakes. Annual dates of freeze-up or break-up are dependent on daily and often hourly air temperature and wind conditions; however, changes in the mean conditions (freeze-up, break-up, or total days of ice cover (ice duration)) represent changes in the local climate, primarily air temperature (McFadden, 1965; Palecki and Barry, 1986; Robertson, et al., 1992). Freeze-up and break-up events can occur over several days or weeks in some systems; therefore, these records are not free of observer biases. However, in some systems, freeze-up and break-up occur very quickly and can usually be resolved to within one or two days. Ice records for systems with rapid transition periods should have minimal observational biases and make good potential climatic-change indicators.

Changes in mean ice conditions can be used not only to detect climatic changes, but also to quantify these changes, provided the changes in ice cover can be calibrated in terms of climatic variables. Robertson, et al. (1992) used the ice records for Lake Mendota, WI, from 1855 to 1991, and the weather records for that area, for the period 1884 to 1991, to calibrate changes in mean freeze-up and break-up dates in terms of changes in air temperature. The changes in mean ice cover were then used to describe climatic changes occurring in southern Wisconsin during the ice cover record. Ice records from 1851 to 1991 are also available for Grand Traverse Bay, MI, located on the northeastern shore of Lake Michigan.

In this paper we will: 1) identify and quantify changes in air temperature near Grand Traverse Bay over the past 141 years, 2) compare and contrast climatic changes inferred for Grand Traverse Bay with those estimated for Lake Mendota, and 3) discuss changes in air temperature occurring throughout the Great Lakes region over the past 141 years.

STUDY SITES. Lake Mendota is a eutrophic lake located in the city of Madison in south-central Wisconsin (43°40' N, 89°24' W). The lake has a surface area of 39.4 km^2, a mean depth of 12.4 m, a maximum fetch of 9.8 km, and strongly stratifies during the summer. Uninterrupted annual ice records are available for Lake Mendota from 1855 to 1991. The exact criteria used to define freeze-up and break-up on Lake Mendota has not been defined; however, in general, these are rapid transitional events and can usually be described to within one or two days (Bryson and Bunge, 1956). Lake Mendota has formed a complete ice cover every year since ice records have been collected. Continuous daily weather data for Madison are available from 1869 to present. Inhomogeneities in the air temperature records associated with observer biases were removed by Robertson (1989) from 1884 to 1989. Air temperature data prior to 1884 contain several incorrectable observational biases and were therefore not used. All air temperature and ice records were obtained from the Wisconsin State Climatologist's Office.

Grand Traverse Bay, located on the northeast side of Lake Michigan (45°46'N, 85°37'W), is 51.5 km long and 16.1 km wide. The head of Grand Traverse Bay is divided into the east and west arms by a narrow peninsula extending 27.3 km northward. The west arm of the bay from the south shore to Marion Island, a distance about 9.6 km out in the bay, has a mean depth of about 46 m and an area of about 53.8 km^2. Freeze-up in this area is defined as the date that a solid ice cover forms out to Marion Island. Break-up is the date the ice breaks-up or moves out of this area. For both Lake Mendota and the western arm of Grand Traverse Bay, ice duration is the number of days with complete ice cover. In the case of multiple occurrences of freeze-up or break-up, the first freeze-up and last break-up are used in this analysis. In 25 of the 141 winters, a solid ice cover did not form out to Marion Island; ice duration during these winters was set to zero and the freeze-up and break-up dates were set to March 8. This date is the mid-point of the median dates of freeze-up and break-up for the five winters with the shortest ice duration. There were eight winters with missing data for freeze-up and four winters with missing dates for break-up; these years were not used in our analysis. Dates of freeze-up and break-up for the west arm of Grand Traverse Bay from 1851 to 1973 were obtained from Snider (1974), and for winters 1974 to 1991 from the Chamber of Commerce, Traverse City, Michigan (personal communication). Air temperature records at Traverse City, Michigan were used for analysis of Grand Traverse Bay ice records. Only air temperature data after 1950 were used in this analysis because of inhomogeneities in the earlier record.

CHANGES IN MEAN ICE COVER. Changes in mean freeze-up, break-up, and total ice duration were determined by smoothing the original time series using a ten-year moving average and by plotting cumulative z-scores (a z-score is the standardized value calculated for each observation by subtracting the overall average and dividing by the standard deviation of the data). The ten-year moving averages for each ice-cover parameter are shown in Figure 1. A ten-year moving average was chosen because each ice cover parameter had significant periodicity between seven and ten years (found using Fourier spectral analysis). The smoothed time series for both Lake Mendota and Grand Traverse Bay demonstrate that mean freeze-up has become later, mean break-up has become earlier, and total ice duration has become shorter. These changes did not appear to be monotonic, but rather occurred as short term, rather abrupt, changes. These more abrupt changes can be more clearly seen in the cumulative z-score plots (Figure 2). The largest change occurs around 1888 when the cumulative z-score curve abruptly change slope. Prior to 1889, average freeze-up was earlier (from 1851 for Grand Traverse Bay and from 1856 for Lake Mendota), and average break-up was later (from 1865 for Grand Traverse Bay and from 1856 for Lake Mendota) (Table 1). These changes were found to be statistically significant at the 95% confidence level using a student's t-test. Taken together these changes suggest the fall, winter, and spring climate was significantly cooler prior to 1889. Unfortunately, the length of this cooler, earlier period is difficult to quantify from the present data. The data for Lake Mendota supported no earlier date to this period. The earlier (break-up) dates prior to 1865 for Grand Traverse Bay suggest warmer average late-winter and early- spring temperature (from 1851 to 1864) than the average from 1865 to 1888 (Table 1).

Since 1888, mean ice conditions for Lake Mendota were relatively stationary until after approximately 1979, when mean break-up became significantly earlier and ice duration has become significantly shorter (statistically significant at the 95% confidence level using a student's t-test). Since 1888, ice cover for Grand Traverse Bay has experienced two recent periods with earlier break-up and shorter ice durations: the late 1940's - early 1950's and the period since 1979. These changes also suggest the recent period was characterized by higher late winter and spring air temperatures. Very little change in average freeze-up dates was observed at either site, suggesting little change in fall and early-winter air temperatures. Based on these changes in ice cover, we divided the freeze-up date time series of both Grand Traverse Bay and Lake Mendota into two periods: prior to 1889 and from 1889 to present. The break-up date and ice duration time series were divided into three periods for each area: prior to 1889 (both systems), from 1889 to 1939 (Grand Traverse Bay) and from 1889 to 1979 (Lake Mendota), and from 1940 to 1991 (Grand Traverse Bay) and from 1980 to 1991 (Lake Mendota) (Table 1).

Table 1. Changes in average freeze-up (FZUP) and break-up (BKUP) dates (julian date) for Lake Mendota (LM) and Grand Traverse Bay (GTB), and the estimated changes in air temperature inferred from these changes using the sensible heat transfer model.

	Average FZUP	Days Later	Estimated Change(°C)
LM			
1856-1888	347.8		
1889-1991	356.1	8.3	1.19
GTB			
1851-1888	37.0		
1889-1991	48.9	11.9	1.42
	Average BKUP	**Days Earlier**	**Estimated Change(°C)**
LM			
1856-1888	101.0		
1889-1979	93.8	7.2	1.11
1980-1991	85.5	8.3	1.28
GTB			
1851-1864	87.1		
1865-1888	103.1	-16.0	-2.24
1889-1939	92.2	10.9	1.53
1940-1991	83.1	9.1	1.27

CALIBRATION OF ICE COVER RECORDS INTO CLIMATIC INDICES. Two types of models were used to relate changes in freeze-up and break-up dates with changes in air temperature: fixed period (Palecki and Barry, 1986) and sensible heat transfer (Robertson, et al., 1992). fixed period models are used to estimate the time period for which the average air temperature best correlates with either annual freeze-up or break-up dates. Annual freeze-up and break-up dates and coinciding average air temperatures of the one or two month period prior to the transition date have been found to be strongly correlated (Palecki and Barry, 1986). The slope of the regression line between transition dates and the average air temperature of a specific time interval yields an estimate of the response of that indicator per one day change in the average transition date. For Lake Mendota, the period from 1948 to 1987 was used in this analysis. For Grand Traverse Bay, the even years from 1952 to 1990 were used.

For Lake Mendota, the average November/December air temperatures were most strongly correlated with annual freeze-up dates and the average January through March air temperatures correlated best with break-up dates. The slope of the regressions suggests that a one day change in mean freeze-up and break-up dates represents a 0.143°C and 0.146°C change in November/December and January through March air temperatures, respectively. For Grand Traverse Bay, average January air temperatures were most strongly correlated with annual freeze-up dates and average March air temperatures with break-up dates. The slope of the regressions suggests that a one day change in mean freeze-up and break-up dates represents a 0.085°C change and 0.056°C change in January and March air temperatures, respectively.

The sensible heat transfer freeze-up model estimates annual freeze-up dates by estimating when the surface water temperature on day t (W_t) becomes 0°C. Changes in water temperature, starting at 20°C on 1 October, are estimated using a sensible heat transfer algorithm (Table 2). The sensible heat transfer break-up model estimates annual break-up dates by estimating when the sub-freezing heat deficit on day t (I_t) is depleted (i.e., I_t becomes greater than 0) (Robertson, et al., 1992). Changes in I_t are estimated from the day after freezing (Table 2). Coefficients in the sensible heat transfer models were estimated using a Nelder-Mead Simplex minimization technique (O'Neill, 1971) to best approximate the freeze-up and break-up dates. The calibration period for the sensible heat transfer models was from 1948 to 1987 for Lake Mendota and the even years from 1952 to 1990 for Grand Traverse Bay. Estimated effects of changes in mean air temperature were made by comparing estimated average freeze-up dates of a 30-year period from 1948 to 1977 for Lake Mendota and from 1951 to 1980 for Grand Traverse Bay, with average predicted dates obtained from the models after daily air temperatures for the 30 years were raised or lowered by specific whole degree changes in air temperature. Daily air temperatures for all 30 years were lowered by 1 to 3°C and raised by 1 to 5°C. The slope of the line between the average transition date for each climatic condition versus the specified air temperature change yields an estimate of the response of that indicator per one day change in transition date.

For Lake Mendota, the slopes of the regressions between average transition dates and air temperature changes suggest a one day change in transition date represents a 0.143°C change in fall and early winter air temperatures and a 0.154°C change in winter and spring air temperatures. With a 4 or 5°C change in air temperature, Lake Mendota would not freeze for the first time on record although this would still be a rare event (one year in approximately 30). For Grand Traverse Bay, increases in air temperature of more than 1°C resulted in a non-linear response in transition dates because more and more years were estimated to remain ice free, and therefore, the estimated transition dates approach March 8. With increases of 3°C or more, it will be a rare event for Grand Traverse Bay to meet the freeze-up criteria. Therefore, only temperature changes between -3°C and +1°C were used in the regressions. The slopes of the regressions between average transition dates and air temperature changes suggest a one day change in transition date represents a 0.119°C change in fall and early winter air temperatures and a 0.140°C change in winter and spring air temperatures.

To determine which model provides the best estimate of the changes in air temperature, both models were used to simulate the annual transition dates for an additional period and the percent reduction in the root mean square errors was compared (Table 2). A 50 year comparison period from 1898 to 1947 was used for Lake Mendota and a 20 year period, odd years from 1951 to 1991, was used for Grand Traverse Bay. It is important to note that the fixed period models were developed to estimate changes in air temperature from changes in ice cover; therefore, additional relationships were computed to estimate annual transition events from air temperatures. For both systems, the sensible heat transfer models were significantly better at estimating freeze-up and break-up dates (Table 2); therefore, changes in air temperature estimated from these results should be more accurate and are indicated in Table 1.

Table 2. Summary of the freeze-up (Fzup) and break-up (Bkup) models for Grand Traverse Bay (GTB) and Lake Mendota (LM). The ability of the fixed period (FP) and sensible heat transfer (SHT) models to estimate annual transition events is demonstrated using the percent reduction in the Root Mean Square Errors (%RRMSE) compared to that using the mean of the entire period. The exact periods are defined in the text.

	Freeze-up Model	%RRMSE
GTB		
FP	JTa=-10.89+0.09Fzup Date	
	Fzup Date=68.35+2.65JTa	24%
SHT	W_t=0.06+0.02A_{t-1}+0.98W_{t-1}	49%
LM		
FP	NDTa=-51.01+0.14Fzup Date	
	Fzup Date=355.84+4.28NDTa	41%
SHT	W_t=0.08+0.05A_{t-1}+0.95W_{t-1}	53%
	Initial W_{t-1}=20°C on 1 October;	
	Break-up Models	**%RRMSE**
GTB		
FP	MTa=2.91-0.06Bkup Date	
	Bkup Date=76.77-3.28MTa	23%
SHT	I_t=0.04+0.08A_{t-1}+0.92I_{t-1}	73%
	Initial I_{t-1}=-0.05 on Fzup Date	
LM		
FP	JMTa=13.66-0.15Bkup Date	
	Bkup Date=93.47-3.34JMTa	22%
SHT	I_t=0.04+0.04A_{t-1}+0.96I_{t-1}	43%
	Initial It-1=-0.044 on Fzup Date	

Ta = air temperature; ND = November,December;
J =January; JM = January, February, and March;
M = March;
W_{t-1} = water temperature on day t-1;
A_{t-1} = air temperature on day t-1;
I_{t-1} = subfreezing heat deficit stored in ice on day t-1.

CLIMATE CHANGES OVER THE PAST 141 YEARS. Ice records from Lake Mendota and Grand Traverse Bay suggest fall, winter, and spring air temperatures in the Great Lakes region have changed over the past 141 years. Around 1890, a rather abrupt change in ice cover occurred in both systems: freeze-up dates became later, break-up dates became earlier, and total ice duration became shorter. Results from the sensible heat transfer model suggests these changes were caused by a regional increase in air temperature of 1.1 to 1.5°C (Table 1). Additional recent changes in mean break-up dates suggest winter and early spring air temperatures have further increased about 1.3°C; however, freeze-up dates have demonstrated little change, suggesting little change in fall air temperatures. Based on this study, the recent warming has only occurred over the past 10 to 15 years for the southwest region (Lake Mendota); however, the recent warming appears to have started in the 1940's in the northeast region (Grand Traverse Bay). Further studies are being conducted to examine the differences occurring between these sites.

ACKNOWLEDGEMENTS. GLERL Cont. No. 801

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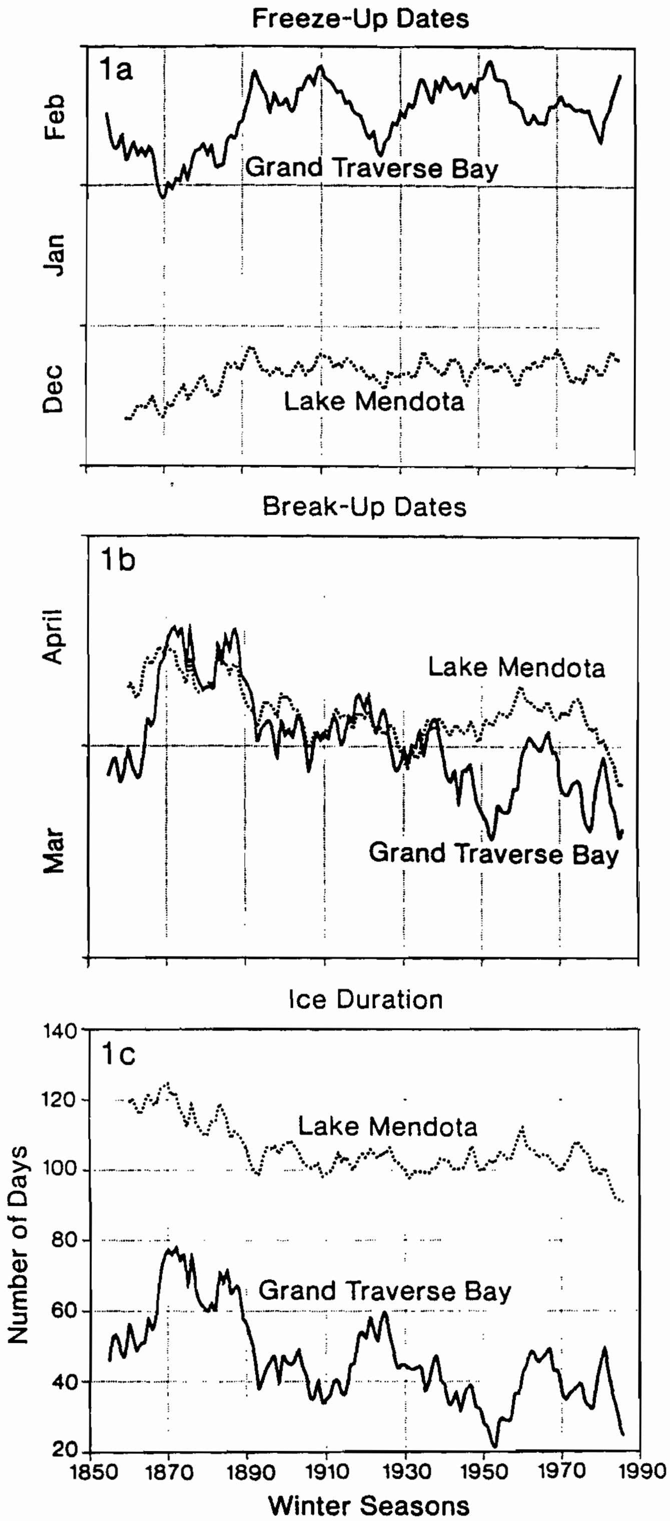

Figure 1. Decadal Running Average (1851–1991) Plotted on Year 5 of (1a) Freeze-Up, (1b) Break-Up, (1c) Ice Duration.

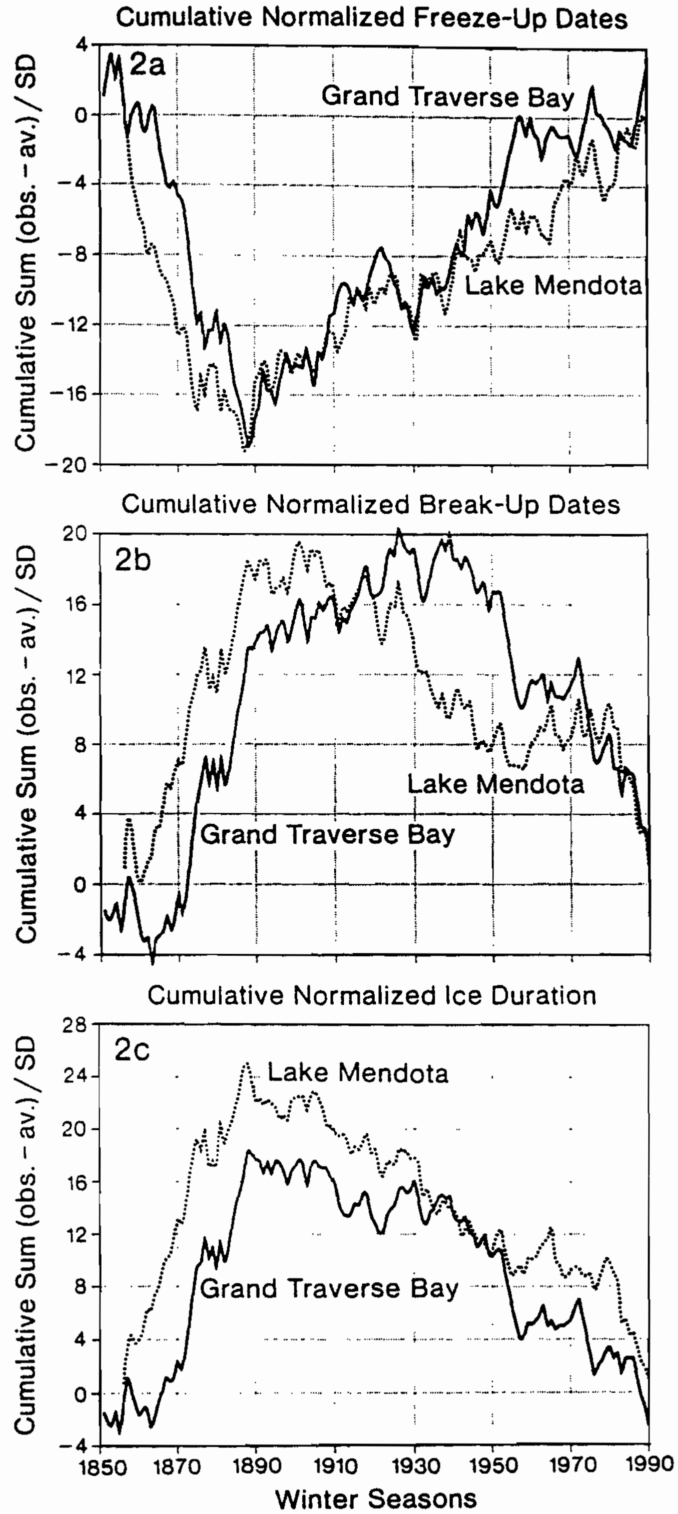

Figure 2. Cumulative Z-Score of Winters (1851–1991) of (2a) Freeze-Up, (2b) Break-Up, and (2c) Ice Duration.