Oscillatory dynamics do not mask linear trends in the timing of ice breakup for Northern Hemisphere lakes from 1855-2004

Sapna Sharma[1*] and John J. Magnuson[2]

[1]Department of Biology, York University, 4700 Keele Street, Toronto, Ontario, Canada

[2]Center for Limnology, University of Wisconsin-Madison, Madison, Wisconsin, USA

[*]Corresponding author: sharma11@yorku.ca; Phone: (416) 736-2100

Short title: Lake ice: oscillatory dynamics vs. linear trends

Abstract

Our analyses partition the relative influence of progressive climate change and large-scale climate drivers that can be associated with the Quasi-Biennial Oscillation (QBO), El Niño Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), solar sunspot cycle, and multi-decadal oscillations on lake ice breakup dates. Oscillatory dynamics explain 26% of the total variance in the time series compared with 15% for linear trends, leaving 60% unexplained and likely attributable, in part, to local weather. Significant oscillatory dynamics include frequencies in 2-3 year periods (9.4% of the total variance), 3-6 year periods (8.2%), 10-12 year periods (1.6%) and various multidecadal periods (0.4-1.3%). All thirteen study lakes, although widely scattered in the Northern Hemisphere, had similar oscillatory dynamics and linear trends, emphasizing that global processes influence lake ice breakup locally. We illustrate that while quasi-periodic dynamics associated with large-scale climate drivers are important, they do not mask the clear evidence for progressive climate change.

Introduction

Lake ice seasonality is a sensitive indicator of climate change (Kuusisto 1987; Robertson et al. 1992; Magnuson et al. 2000; Weyhenmeyer et al. 2011; Benson et al. 2012; Sharma et al. 2013). Long-term lake ice records are useful because they are easy to visualize, simple to measure without instruments or models, and integrate many aspects of climate (Magnuson et al. 2000). Temporal patterns in lake ice breakup dates are related to: i) linear changes in lake ice breakup dates attributed to global climate change and ii) oscillations corresponding to various large-scale climatic drivers. However, the relative importance of each has not been previously quantified.

Ice records of Northern Hemisphere lakes have shifted towards later freezing, earlier breakup, and shorter ice cover over the past 150 years (Kuusisto 1987; Robertson et al. 1992; Magnuson et al. 2000; Weyhenmeyer et al. 2011; Benson et al. 2012; Sharma et al. 2013), and they reveal oscillations corresponding to large-scale climate drivers (Livingstone 2000; Robertson et al. 2000; Magnuson et al. 2004; Bonsal et al. 2006; Ghanbari et al. 2009; Bai et al. 2012; Mudelsee 2012; Benson et al. 2012; Sharma et al. 2013). Independently, large-scale climate drivers have been found to be associated with lake ice breakup dates in the Northern Hemisphere, include the Quasi-Biennial Oscillation (QBO), El Niño Southern Oscillation (ENSO), Solar Sunspot Cycle, Pacific Decadal Oscillation (PDO), and North Atlantic Oscillation (NAO) (Livingstone 2000; Robertson et al. 2000; Magnuson et al. 2004; Bonsal et al. 2006; Ghanbari et al. 2009; Bai et al. 2012; Benson et al. 2012; Mudelsee 2012; Sharma et al. 2013). For example, in previous studies of lake ice dynamics, ENSO appears to be related to ice breakup dates such that El Niňo events corresponded to later ice breakup (Anderson et al. 1996; Livingstone 2000; Robertson et al. 2000; Bonsal et al. 2006) and lower ice cover (Bai et al. 2012). Solar activity has been linked to indicators of global climate (Eddy 1976) and lake ice breakup (Sharma et al. 2013). Lakes across the Northern Hemisphere have been associated with the NAO (Livingstone 2000; George et al. 2004; Magnuson et al. 2004; George 2007; Ghanbari et al. 2009; Karetnikov and Naumenko 2011). NAO may influence ice breakup dates through its effects on winter air temperature (Bleckner et al. 2007), snowfall (Ghanbari et al. 2009), and alteration in strengths of southerly and westerly winds (Bai et al. 2012).

Lake ice records since the 1850s have provided evidence of progressive climate change and various large-scale climate drivers, but previously each of these potential influences has been assessed independently of each other (Livingstone 2000; Magnuson et al. 2000; Weyhenmeyer et al. 2011; Benson et al. 2012). Thus, the relative influence of linear trends and oscillatory dynamics for lake ice breakup remains unclear. Here, we analyze ice breakup records for a 150-year period for 13 lakes in the Northern Hemisphere to determine the relative influence of linear trends and oscillatory dynamics associated with progressive climate change and large-scale climate drivers in widely scattered geographic areas.

Methods

Data Acquisition

Lake ice breakup date records for a 150-year period (1854/5 to 2003/4) were obtained for 13 lakes located in Northcentral North America, Northeastern North America, Switzerland, and Finland (Figs. 1-3). More specifically, we acquired data for three lakes in the northern mid-west region in the USA, 6 lakes in the northeastern region of the USA, including one lake in the Appalachian Mountains (Moosehead Lake), one lake in Switzerland, and three lakes in Finland. Data are available from the National Snow and Ice Data Center which is limited to the Northern Hemisphere (Benson and Magnuson 2012). Our dataset was limited to lake ice breakup, North America and Europe and the 150-year record (1855-2004) owing to the limited availability of data. All lakes with more than 5% missing data in the time-series analyses were excluded; 8 of the 13 lakes had no missing data, four had one missing value, and one had seven. The average ice breakup date was used for years when ice breakup date was missing such that when the time series was detrended, the residuals of the missing years would be 0 for subsequent analysis in an effort to minimize the influence of missing data. Ten of the 13 lakes froze every year over the time series. The other three did not freeze in one year over the 150-year ice record. If the lake did not freeze, we used the earliest observed ice breakup date for that lake (Benson et al. 2012).

Data Analyses

Spatial patterns

K-means cluster analysis was used to partition the lakes into groups that were most similar to one another in the timing of ice break-up over the 150-year period. K-means cluster analysis minimizes the within-group sum of square errors such that the objects within a K group are more similar to one another than to objects in any other K group (Legendre and Legendre 2012). The calinski criterion was used to determine the number of significant K groups (clusters) within the dataset (Calinski and Harabasz 1974). Following group assignment, we performed a Mann-Whitney U Test to identify whether the mean date of lake ice break-up over the 150 years differed significantly between the two groups.

Rates of change

Linear regression models of ice break-up dates over time were generated. The slopes of the linear regression models were identified as the linear rates of change in ice break-up dates for lakes over the 150-year record (1855-2004), and each 50-year period (1855-1904; 1905-1955; 1955-2004). Mann-Whitney tests were used to identify whether the significant K-means groups differed significantly. In addition, a Mann-Whitney test was used to identify whether the variance explained by linear trends differed significantly between the significant K-means groups.

Temporal Oscillations

Moran Eigenvector Maps (MEM) identified oscillatory dynamics in ice breakup time series using the residuals generated from the linear regression model. We used a Mann-Whitney test to identify whether the variance explained by oscillatory dynamics differed significantly between the significant K-means groups. Moran Eigenvector Maps quantify spatial structure and can be extended to quantify temporal structure (Sharma et al. 2013). The MEM approach is preferred to classical time series analyses in our study because it generates a series of sine waves with decreasing periods that are orthogonal to one another and can be used as independent variables in a subsequent analysis, such as linear regression. This allows us to quantify the variation explained by each cycle and quantify its contribution to ice breakup dates. Details of the MEM analyses follow. First, a linear regression is performed on the response variable over time. If the linear regression is significant, the response variable is detrended to remove the linear trend in the response data. A linear trend is an indication of temporal structure acting at a longer interval than the extent of observations. Second, MEM eigenfunctions are constructed on the residuals of the linear regression by computing the Euclidean distance among the sampling times, which here were years. A Principal Coordinates Analysis (PCoA) is conducted on the modified Euclidean distance matrix and generates eigenfunctions representing the temporal structure in the dataset. A forward selection procedure with 1000 permutations was used because the number of MEM variables produced was large. Only significant MEM variables are used as predictor variables representing temporal structure in the response data (Borcard and Legendre 2002). The MEM approach elucidates oscillations in the time-series data that occur with different periods. The first MEM-variables represent the broad temporal oscillations, and subsequent MEM variables represent oscillations with decreasing periods (Borcard and Legendre 2002; Sharma et al. 2013). We provide a visual example of the results from the analyses for ice breakup in Lake Mendota between 1855 and 2004 (Fig. 4).

Linear trends and oscillatory dynamics

We attributed the linear changes in lake ice break-up dates to progressive climate change. We did not ascribe oscillations acting at inter-annual or inter-decadal scales to specific named large-scale climatic drivers as frequency bands are not specific to individual large-scale climatic drivers. The Quasi-Biennial Oscillation (QBO) which represents equatorial zonal winds is believed to have a period between 1.5 and 3 years (Salby and Callaghan 2000; Tangang 2001). The El Niño Southern Oscillation Index (ENSO) considers the variation in surface water temperatures of the tropical eastern Pacific Ocean and the variation in pressure of the air surface in the tropical western Pacific Ocean and is hypothesized to have a period of 3-7 years, with an average of 4 years (MacMynowski and Tziperman 2008). Yiou et al. found that the average period of ENSO was 4.7 years from 1943-1961 and 3.25 years from 1963-1980 (Yiou et al. 2000). The solar sunspot cycle reflects the amount of solar-magnetic activity on the sun. The average length of the sunspot cycle has been identified as approximately 11 years (Christensen and Lassen 1991; Lee et al. 1995; Salby and Callaghan 2000), although there is variation in cycle length between 9 and 12 years (Lee et al. 1995), particularly in the latter half of the 20th century (Christensen and Lassen 1991). The North Atlantic Oscillation (NAO) has significant peaks at inter-annual and inter-decadal periods (Hurrell and van Loon 1997; Higuchi et al. 1999). For example, the NAO index has significant spectral peaks at 2-3 years, 6-10 years, 20 years, and 60 years (Hurrell and van Loon 1997; Higuchi et al. 1999). In addition, Huang et al. (1998) analyzed the spectral relationship between the NAO and ENSO and found significant coherence at 2-4 year and 5-6 year periods (Huang et al. 1998). Further, we did not ascribe oscillations acting at multi-decadal scales to a specific named large-scale climatic driver, such as the Pacific Decadal Oscillation, and Atlantic Multidecadal Oscillation. Even with 150-year time series, few repetitions of possible multi-decadal oscillations occur and estimation of these period lengths are quite uncertain.

We calculated the percentage of all lakes that had significant oscillations as determined by the Moran Eigenvector Maps corresponding to inter-annual and inter-decadal cycle lengths.

We were unable to directly include the time-series of the indices of the large-scale climate drivers in our analyses because most of those time-series do not go as far back as the ice records (1855).

Visualization of the influence of short-term variability on the patterns of change

We used running means to visualize the influence of short-term variability on the patterns of change in ice breakup for the residuals of the mean ice breakup date for lakes across the Northern Hemisphere. First, we calculated a composite mean ice breakup date for all of the 13 lakes for each year. We calculated the average of the composite means across all years for the 150-year time series (grand average). We then calculated the residuals for each year by subtracting the grand average from the composite mean for a particular year to generate a 150-year time series of the residuals of ice breakup date. Second, we used running means at intervals of 2, 7 and 12-years to successively remove the high frequency oscillations and variation. This analysis removes both the influences of these large-scale climatic drivers and any other sources of variation associated with weather and random noise at those frequencies. Unlike our statistical analysis where we initially detrended the data, here we did not first remove the linear trend in order to visualize the linear trend in the absence of high frequency variation. All data analyses were performed in the R-language environment.

Results

Spatial patterns

Lakes were assigned to two groups based on a K-means cluster analysis and similarities in temporal patterns of ice breakup (Fig. 1). The lake ice in the “early” group of lakes broke up in April (mean: day 101, range: day 90-112) and the “late” group broke up in May (mean: 134, range: 128-145). Except for one high altitude lake, lakes in the continental USA were in the "early" group. The "late" group comprised lakes in Europe and the higher altitude lake in the USA. On average, ice breakup in the "early" group was 33 days earlier than in the "late" group ($p=0.001$; Mann-Whitney U Test). "Early" lakes were located 12.2 degrees farther south, on average, than "late" lakes. In addition, "early" lakes were on average 314 m lower in altitude than "late" lakes (Early: 162 m vs. Late: 476 m).

Rates of change

All 13 lakes exhibited a significant negative linear trend towards earlier breakup as well as significant oscillatory dynamics at a number of frequencies (all linear trends and oscillatory dynamics presented were significant at $p < 0.05$). The linear trends explained on average 15% (4.9-26.5%) of the variance in lake ice breakup dates (Table 1). In the recent 50 years between 1955 and 2004, lake ice of the "early" group broke up at rates of 3 days per decade earlier or twice as fast as lakes in the "late" group ($p=0.0007$). However, the rates of change of lake ice breakup over the entire 150-year ice record did not differ significantly between the two groups ($p=0.12$), between 1904 and 1953 ($p = 0.38$) and between 1855 and 1903 ($p=0.12$).

Temporal oscillations

Model selection of MEM eigenfunctions identified significant oscillations at $p<0.05$ of 2-12, 15, 20, 29, 50, and 67 years over the 150-year ice record in the 13 lakes across the Northern Hemisphere. There was variation in the proportion of lakes with significant oscillations of specific periods between the lakes in the "early" and "late" groups (Table 1). For example, a larger proportion of "early" lakes had significant periods of 2-3, 11, and 29 year oscillations relative to "late" ice break-up lakes. Conversely, a higher proportion of lakes with "late" ice break-up had significant periods of 3-10, 15, 50 and 67 years relative to lakes with "early" ice break-up (Table 1).

Linear trends and oscillatory dynamics

Each lake exhibited a statistically significant linear trend in lake ice, break-up dates (Table 1). On average, the linear trend explained 14.8% of the variation in all lake ice break-up dates. Oscillations explained 25.7% of the variation in ice break-up dates on average. Models developed including both trends and oscillations for each of the lakes explained 26.8 – 53.1% of the variation (Table 1).

Oscillations at higher frequencies explained more of the variance than those at lower frequencies. The 2-3 year oscillations were evident ($p<0.05$) in all lakes; overall they explained 9.4% of the variance in ice breakup dates. All but one lake exhibited ($p<0.05$) 3-6 year oscillations; overall they explained 8.2% of the variance. All of the lakes in the "late" group had a significant association with cycles between 7 and 10 years that explained 1.1% of the variance on average. Sixty percent of the lakes had an association with 10-12 year oscillations and lake ice breakup ($p<0.05$) but explained little variance (on average 1.6%). Overall, multi-decadal oscillations, with periods of 20, 29, 50, and 67 years, explained an average of 3.6% of the total variance in ice breakup. Individual multidecadal oscillation explained little variation in lake ice break-up dates (0.4 – 1.3% of variation on average; Table 1). Oscillatory dynamics in total explained significantly more variance for "late" lakes (31.3%) than for "early" lakes (22.2%, Mann-Whitney U Test; $p = 0.004$).

Visualization of the influence of short-term variability on the patterns of change

We illustrate the importance of climate change on lake ice breakup, in addition to large-scale climate drivers and local weather (Fig. 5). The variation from the high-frequency climate drivers and weather can obscure the linear trend attributable to the influence of climate change. The proportion of variation explained by the linear trend in the original annual time series (30%)

increases to 78% for the 12-year running mean. Applying progressively longer running means clearly shows how successive removal of higher frequency variation reveals the existence and importance of the long-term linear trend (Fig. 5). We highlight the influence of progressive climate change, large-scale climate drivers, and local weather on lake ice breakup. Moderately long time series are essential to infer progressive climate change in the presence of large amounts of variation related to inter-annual and decadal climate drivers and local weather (Magnuson 2002; Sharma et al. 2013). Analyses or examination of short time series can mistakenly ascribe portions of an oscillatory dynamics to a change in any long-term trend.

Discussion

Our study is the first to quantify the relative influence of linear trends that could be associated with progressive climate change versus the oscillatory dynamics that could be associated with large-scale climate drivers on lake ice breakup across the Northern Hemisphere. The response of each of these lakes to similar drivers indicates the global influence of climate change and the large-scale climate drivers. Our findings that lake ice breakup is occurring earlier across the Northern Hemisphere is not new and is consistent with a warming climate (Kuusisto 1987; Robertson et al. 1992; Magnuson et al. 2000; Weyhenmeyer et al. 2011; Benson et al. 2012; Sharma et al. 2013). The rates at which these changes are occurring are higher in recent decades because the rate of air temperature increases has been higher and the onset of spring has been earlier (IPCC 2007; Benson et al. 2012). In addition at more southern latitudes, air temperatures tend to warm to 0° C earlier in the spring, the thinner ice does not require as much warming to melt, and the sensitivity to incident solar radiation and solar elevation is higher at the time of ice breakup (Weyhenmeyer et al. 2004; Weyhenmeyer et al. 2011; Benson et al. 2012; Shuter et al. 2013).

We found significant associations with lake ice breakup and oscillations of 2-12, 15, 20, 29, 50, and 67 years. We cannot ascribe directly which large-scale climatic driver is associated to each significant period owing to interactions between large-scale climatic drivers and the overlapping spectral signals for various large-scale climatic drivers (e.g., Hurrell and van Loon 1997; Huang et al. 1998). However, there are large-scale climatic drivers that operate at the cycle lengths we found to be significant across the Northern Hemisphere. For example, each of our lakes had a significant correlation with the 2-3 year cycle which could be associated to the QBO which has a large-scale influence of equatorial zonal winds on lake ice breakup and appears to operate on cycles with periods of 1.5-3 years (Salby and Callaghan 2000; Tangang 2001). Only one earlier study has demonstrated a relationship between lake ice cover and the QBO in Lakes Superior and Erie (Assel 1990). Further, all but one lake exhibited a cycle with periods between 3-7 years which is consistent with ENSO (MacMynowski and Tziperman 2008). Previous studies have also shown an association between El Niño events with later ice breakup in North America (Anderson et al. 1996; Livingstone 2000; Robertson et al. 2000; Bonsal et al. 2006) and reduced ice coverage (Bai et al. 2012). The relative influence of El Niño events on lake ice breakup may differ depending upon latitude (Anderson et al. 1996). For example, lake ice in southern Wisconsin tended to melt in late March when there is a strong relationship between air temperatures and El Niño events. However, there did not appear to be a strong relationship between El Niño events and air temperature in April when lake ice in northern Wisconsin tended to breakup (Anderson et al. 1996).

The solar sunspot cycle length is 9-12 years (Lee et al. 1995) to which 60% of these study lakes had a correlation, although these cycle lengths explain little variance. Sharma et al. (2013) found a relationship between the solar sunspot cycle which correlates with the intensity of solar radiation, and ice breakup date for Lakes Mendota and Monona, Wisconsin (Sharma et al. 2013). At more northern latitudes, the timing of lake ice breakup for Canadian lakes showed increased sensitivity to incident solar radiation at the time air temperatures exceed 0°C in the spring (Shuter et al. 2013). The North Atlantic Oscillation Index has significant spectral peaks at 2-3 years, 6-10 years, 20 years, and 60 years (Hurrell and van Loon 1997; Higuchi et al. 1999) and has also been associated with lake ice breakup across the Northern Hemisphere in previous studies (Livingstone 2000; Magnuson et al. 2004; Ghanbari et al. 2009; Sharma et al. 2013). The ENSO and NAO have been shown to interact with one another (Huang et al. 1998). For example, in the Great Lakes, there tends to less ice cover during El Niño and positive NAO events and more ice cover in La Niña and negative NAO events (Bai et al. 2012). The lower frequency (longer period) oscillations did not explain relatively large percentages of variance (Livingstone 2000; Ghanbari et al. 2009), but can be higher for selectively shorter time periods (Livingstone 2000; Magnuson 2002).

The time series of lake ice breakup is influenced by at least three classes of interacting factors. First, lake ice breakup is influenced by a linear trend that is the product of long term, consistent climate change. We found that the linear trend explained on average 15% of the variance in lake ice breakup. Second, ice breakup is affected by oscillatory dynamics acting at inter-annual and inter-decadal scales (including large-scale distant climate drivers such as the QBO, ENSO, and the solar sunspot cycle) which collectively explained 26%. Together the linear trend and the large-scale drivers explained 41% of the variance (range among lakes: 26.8-53.1%; Table 1) in lake ice breakup dates. Third, local weather may explain the remaining variance. Approximately 60% of the variance was unexplained in this analysis, but can be, in part, explained by local weather (Sharma et al. 2013). Unfortunately we could not treat weather directly in this analysis because we did not have 150 years of local weather data for the 13 lakes. Fortunately local weather data was available for Lakes Mendota and Monona, Wisconsin over 100-years (Sharma et al. 2013). This allowed Sharma et al. (2013) to partition the variance associated with linear trends, large-scale climate drivers, and local weather when combined explained 59% of the variance (Sharma et al. 2013). In that analysis, local weather was represented by daily and winter air temperatures, precipitation, and snowfall and these variables together explained 28% of the total variance in ice breakup (Sharma et al. 2013). The shared contributions through interactions between weather and large-scale climate drivers contributed an additional 10% of the total variance (Sharma et al. 2013). Thus, local weather uniquely and in combination with large-scale climate drivers explained up to 38% of the total variance (Sharma et al. 2013).

Conclusions and Implications

Our findings in this study and earlier papers (Magnuson 2002; Sharma et al. 2013) can be applied to classic problems in science literacy and outreach with regards to climate change. We have used long-term lake ice records because they are easy to visualize, simple to measure without instruments or models, and they integrate many aspects of climate. We highlight the importance of using long-term records to illustrate the influence of a complex array of factors on ice breakup including climate change, large-scale climate drivers, and the vagaries of local weather for lakes spread across the Northern Hemisphere. We hope these results can help resolve two classic problems surrounding climate change research: i) the influence of progressive climate change and natural oscillations of large-scale climate drivers on lake ice breakup, and ii) using short-term records to infer progressive climate change when so much variation in ice breakup is caused by climate drivers acting at inter-annual and inter-decadal scales and local weather (Magnuson et al. 2000; Magnuson 2002).

Acknowledgments: Funding was provided by NSERC, York University, NSF, and the North Temperate Lakes LTER Program, University of Wisconsin-Madison. We thank Barbara Benson and the National Snow and Ice Center for providing data, William Feeny and Thomas Van Zuiden for figures, Steve Carpenter, Richard Lathrop, Brian Shuter, Richard Vogt, Norman Yan, Jake Vander Zanden, and two anonymous reviewers for comments on the manuscript.

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Table 1. Percentage of variance explained (R^2_{adj}) for each lake by linear trends and by each significant oscillation grouped into "Early" and "Late" breakup groups (Fig. 3A).

Lake	**Explained Variance (R^2_{adj})**			**Oscillations (years)**															
	Total	**Trend**	**Oscillations**	**2-3**	**3-4**	**4-5**	**5-6**	**6-7**	**7-8**	**8-9**	**9-10**	**10-11**	**11-12**	**15**	**20**	**29**	**50**	**67**
"Early"																			
Superior – Bayfield	46.8	26.5	20.3	13.3	0	4.5	0	0	0	0	0	1.9	0	0	0	1.9	0	0
Cobbosseecontee	45.5	16.7	28.8	13.7	0	0	0	0	0	0	0	0	5.9	0	2.3	3.2	0	0
Auburn	43	15.1	27.9	10.1	2.2	0	4.2	0	0	0	0	0	2.8	0	2.4	4.8	0	0
Monona	39.1	24.2	14.9	11	5.7	4.7	0	0	1.9	0	0	0	0	0	0	0	0	0
Damariscotta	37.8	14.6	23.2	16.4	0	0	5.8	0	0	0	0	0	2.7	0	0	2.5	0	0
Mendota	30.4	11.1	19.3	13.7	4.7	2.3	0	0	0	0	0	0	0	0	0	0	0	0
Otsego	27.9	6.3	21.6	9	4	1.6	0	0	2.8	0	0	0	2.8	0	2.	2.	0	0

				.											7	7		
Oneida	26.8	4.9	21.9	57.2	4.4	0	6.7	1.8	0	2.4	1.8	1.8	0	0	0	0	0	0
"Late"																		
Oulujarvi	53.1	11.8	41.3	6.9	0	2.8	3.3	0	3.7	0	0	1.7	0	0	0	0	0	0
Kallavesi	48.7	17.8	30.9	17.9	5.1	0	9	0	2.2	3.2	2.2	1.7	0	0	0	0	0	4.8
Nasijarvi	48.6	19.2	29.4	7.4	4.3	2.5	0	0	0	2	0	0	0	0	0	0	0	4.2
Murezzan	40.2	13.4	26.8	2.9	2	3.9	4.7	0	0	3.2	3.2	0	0	2	0	2.2	4.9	0
Moosehead	39.7	11.4	28.3	1.6	7.3	0	10	0	2.6	3.7	0	0	0	0	3.3	0	0	5.4
Mean: Early	37.2	14.9	22.2	10.6	2.6	1.6	2.1	0.2	0.6	0.3	0.2	0.5	1.8	0	0.9	1.9	0	0
Mean: Late	46.1	14.7	31.3	7.3	3.7	1.8	5.4	0	1.7	2.4	1.1	0.7	0	0.4	0.7	0.4	1	2.9
Mean: All	40.6	14.8	25.7	9.4	3.1	1.7	3.4	0.1	1	1.1	0.6	0.5	1.1	0.2	0.8	1.3	0.4	1.1

Figure legends.

Figure 1. Locations of our 13 study lakes and summary of spatial patterns**.** Two groups of lakes ("early" and "late" ice breakup) were identified. Grouping resulted from K-means analysis based on similar patterns in ice breakup for a 150-year lake ice record.

Figure 2. Mean, earliest, and latest ice breakup date for 13 lakes in the Northern Hemisphere (1855-2004).

Figure 3. Histogram of ice breakup dates of our 13 study lakes from 1855-2004.

Figure 4. Ice breakup dates over a 150-year time period (1855-2004) in Lake Mendota. A) The linear trend in ice breakup dates with the line representing the linear trend through the 150-year ice record, B) The residuals of ice breakup dates over time, C – F) Significant MEM variables that explain variance in ice breakup dates over the 150 year time series.

Figure 5. A) Residuals of lake ice break-up date over time averaged for 13 Northern Hemisphere lakes between 1855 and 2004; B) Residuals of lake ice breakup date over time using a running mean of 2 years; C) Residuals of lake ice breakup date over time using a running mean of 7 years; and D) Residuals of lake ice breakup date over time using a running mean of 12 years. The black line represents the linear trend in lake ice breakup dates over time.

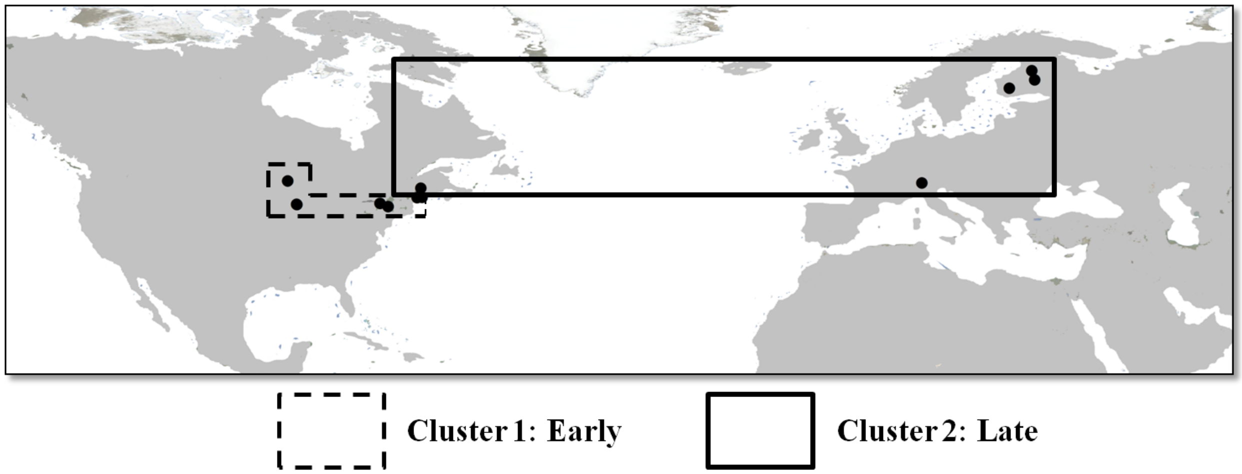
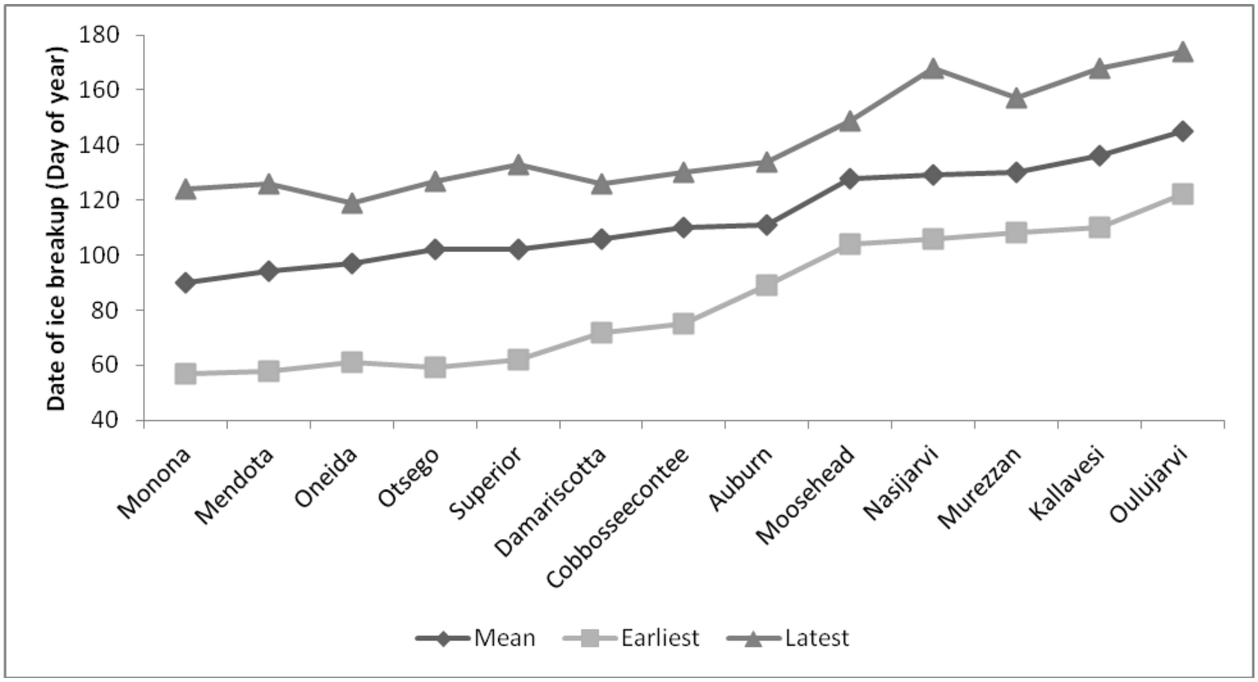


Fig. 1.



Date of ice breakup (Day of year)
180
160
140
120
100
80
60
40
Monona
Mendota
Oneida
Otsego
Superior
Damariscotta
Cobbosseecontee
Auburn
Moosehead
Nasijarvi
Murezzan
Kallavesi
Oulujarvi
Mean
Earliest
Latest

Fig. 2

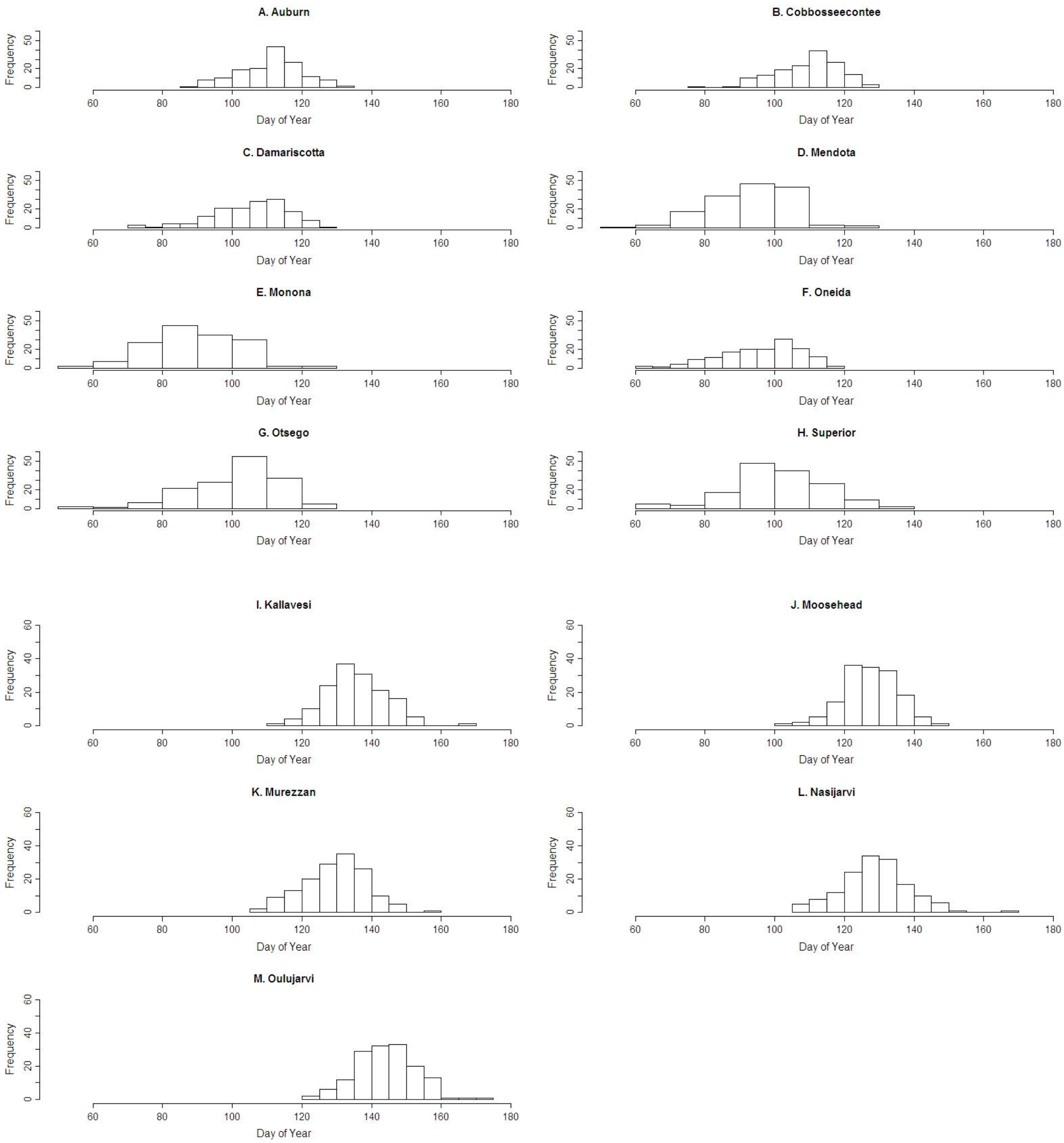
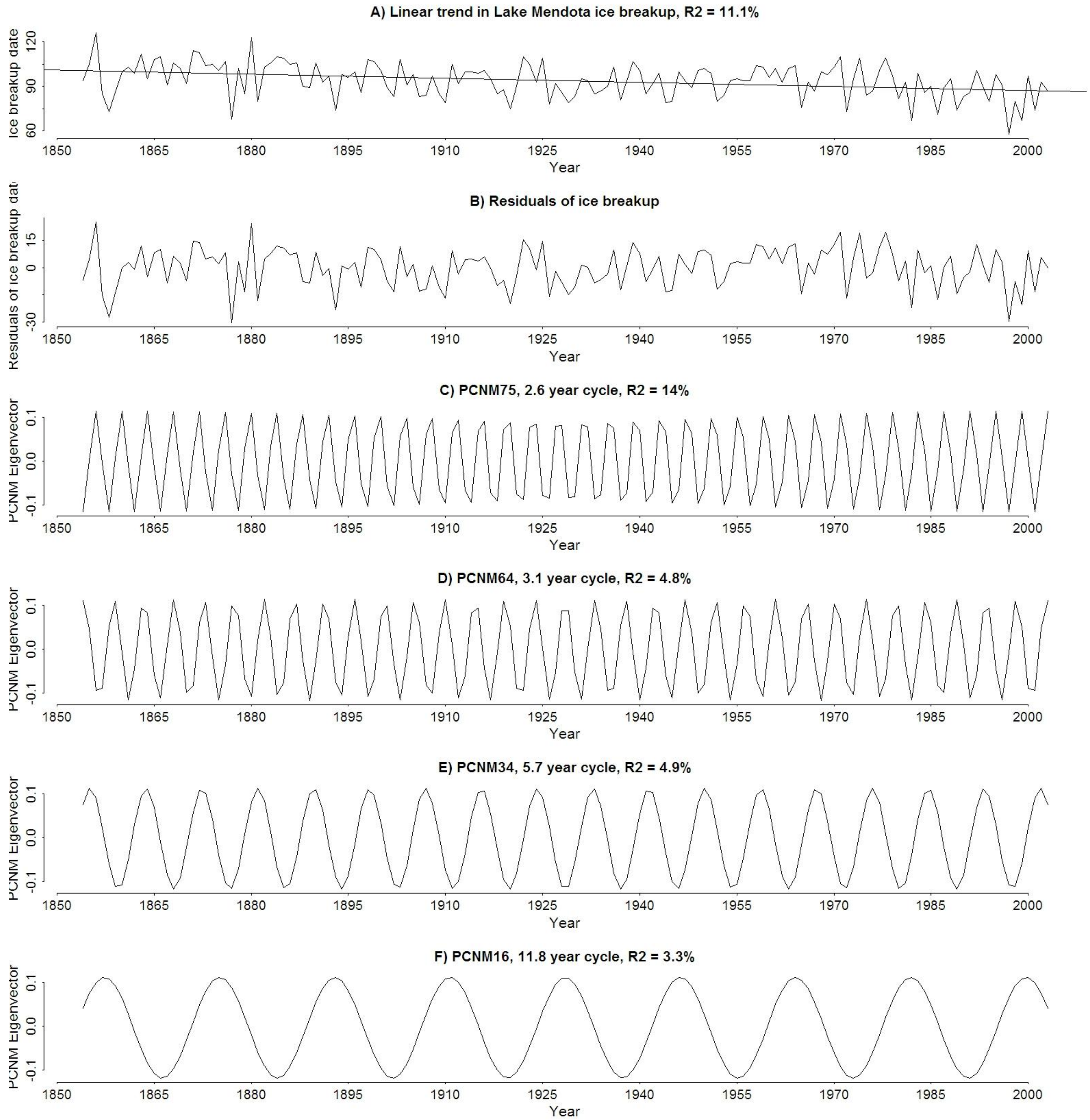

A. Auburn
B. Cobbosseecontee
C. Damariscotta
D. Mendota
E. Monona
F. Oneida
G. Otsego
H. Superior
I. Kallavesi
J. Moosehead
K. Murezzan
L. Nasijarvi
M. Oulujarvi
Frequency
Day of Year
60
80
100
120
140
160
180

Fig. 3



A) Linear trend in Lake Mendota ice breakup, R2 = 11.1%
Ice breakup date
Year
B) Residuals of ice breakup
Residuals of ice breakup date
Year
C) PCNM75, 2.6 year cycle, R2 = 14%
PCNM Eigenvector
Year
D) PCNM64, 3.1 year cycle, R2 = 4.8%
PCNM Eigenvector
Year
E) PCNM34, 5.7 year cycle, R2 = 4.9%
PCNM Eigenvector
Year
F) PCNM16, 11.8 year cycle, R2 = 3.3%
PCNM Eigenvector
Year

Fig. 4.

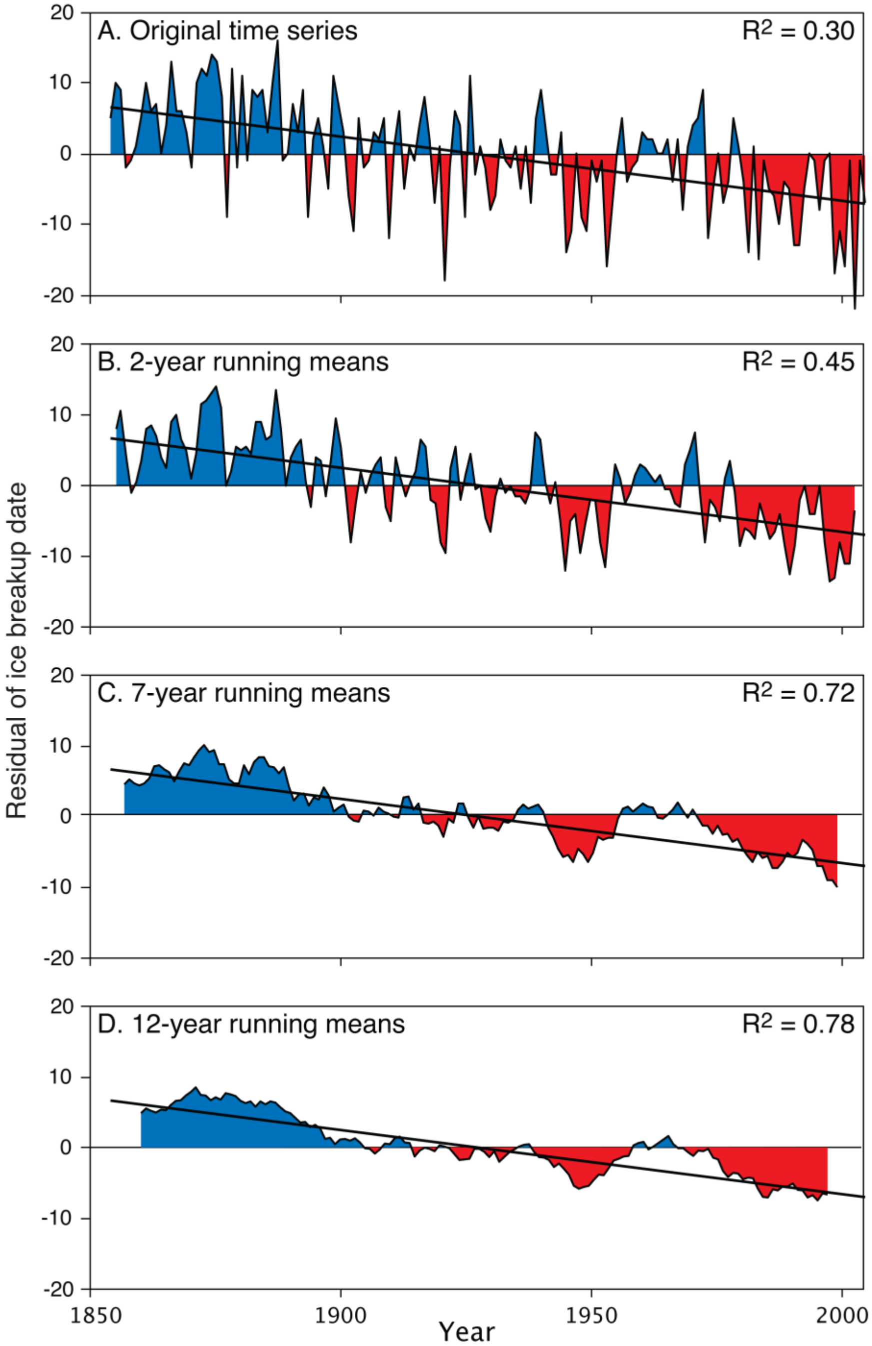

A. Original time series
R2 = 0.30
B. 2-year running means
R2 = 0.45
C. 7-year running means
R2 = 0.72
D. 12-year running means
R2 = 0.78
Residual of ice breakup date
Year
20
10
0
-10
-20
1850
1900
1950
2000

Fig. 5.