

Extreme events, trends, and variability in Northern Hemisphere lake-ice phenology (1855–2005)

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Abstract Often extreme events, more than changes in mean conditions, have the greatest impact on the environment and human well-being. Here we examine changes in the occurrence of extremes in the timing of the annual formation and disappearance of lake ice in the Northern Hemisphere. Both changes in the mean condition and in variability around

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the mean condition can alter the probability of extreme events. Using long-term ice phenology data covering two periods 1855–6 to 2004–5 and 1905–6 to 2004–5 for a total of 75 lakes, we examined patterns in long-term trends and variability in the context of understanding the occurrence of extreme events. We also examined patterns in trends for a 30-year subset (1975–6 to 2004–5) of the 100-year data set. Trends for ice variables in the recent 30-year period were steeper than those in the 100- and 150-year periods, and trends in the 150-year period were steeper than in the 100-year period. Ranges of rates of change (days per decade) among time periods based on linear regression were 0.3–1.6 later for freeze, 0.5–1.9 earlier for breakup, and 0.7–4.3 shorter for duration. Mostly, standard deviation did not change, or it decreased in the 150-year and 100-year periods. During the recent 50-year period, standard deviation calculated in 10-year windows increased for all ice measures. For the 150-year and 100-year periods changes in the mean ice dates rather than changes in variability most strongly influenced the significant increases in the frequency of extreme lake ice events associated with warmer conditions and decreases in the frequency of extreme events associated with cooler conditions.

1 Introduction

Extreme events such as unusually powerful storms, intense rain, prolonged drought, and high air temperatures have captured attention in this time of global climate change (Changnon 2007; Trenberth et al. 2007; Easterling et al. 2000; Kunkel et al. 1999). Often extreme events, more than changes in mean conditions, have the greatest impact on the environment and human well-being. Here we examine changes in the occurrence of extremes in the timing of the annual formation and disappearance of lake ice in the Northern Hemisphere. At mid to high latitudes this timing provides measures of seasonality (phenology): the dates of freeze and breakup and the resulting duration of ice cover. Historical records are available for some lakes starting in the 1850s or earlier, even before weather measurements at those sites, and for numerous lakes since 1900. While lake ice phenologies can serve as a proxy for air temperature data, the dynamics of lake ice cover are interesting scientifically and have ecological consequences for lake ecosystems. These ecological consequences are known to span physical, chemical, and biological responses such as effects on lake level from increased evaporation (Magnuson et al. 1997) and reduction of anoxia in shallow lakes that can alter fish community composition (Lodge 1993; Magnuson et al. 1997). Changes in lake ice phenology affect people living near or using the lake for a variety of recreational and economic purposes (Kling et al. 2003).

Studies examining lake ice phenology trends have been expanding from analyses of individual lakes, to multiple regions and to global scales. Such studies have revealed patterns of later freeze, earlier breakup, or shorter duration of ice cover for a few selected lakes (Kuusisto 1987; Schindler et al. 1990; Robertson et al. 1992; Likens 2000; Livingstone 2000) and for compilations with larger numbers of lakes and/or rivers mainly in northern Europe and North America (Magnuson et al. 2000; Futter 2003; Duguay et al. 2006; Korhonen 2006). As more lakes and rivers were analyzed, spatial patterns in trends

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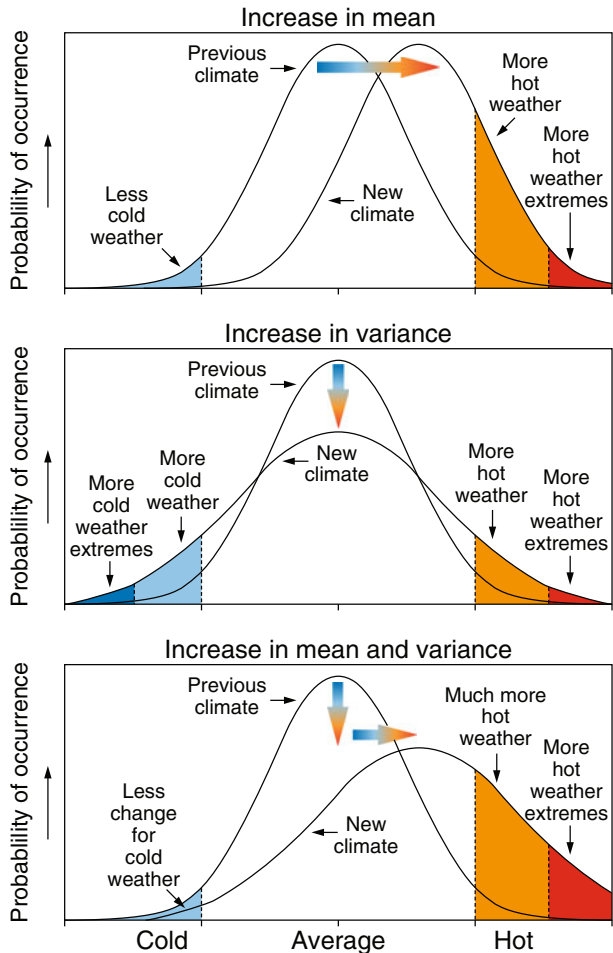
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were noted across the Laurentian Great Lakes Region (Magnuson et al. 2004; Jensen et al. 2007), Canada (Duguay et al. 2006), and Sweden (Weyhenmeyer et al. 2005). All of these analyses focused on spatial and temporal patterns in mean ice phenology dates or ice duration. Our analysis is the first to consider patterns in the inter-annual variability of lake ice phenology data, quantified as standard deviation over various temporal extents and grains. It is based on an expansion and update (through winter 2004–5) of the data on lake ice phenology around the Northern Hemisphere presented in Magnuson et al. (2000).

Although numerous studies have documented long-term changes in mean freeze and breakup dates and ice duration, less is known about changes in variability within the Northern Hemisphere (analyzed by Kratz et al. (2000) from 1951 to 1990 and by Weyhenmeyer et al. (2011) from 1961 to 1990). Little is known about changes in the occurrence of extreme lake ice dates. Hendricks Franssen and Scherrer (2008) found the freezing frequency of lakes on the Swiss Plateau has declined over the period 1901–2006.

Changes both in the mean condition and in variability around the mean condition can alter the probability of extreme events (Fig. 1). For example, a trend toward earlier ice breakup increases the probability of extremely early breakup events and decreases the

Fig. 1 Diagram of changes in the frequency of extreme events if the mean increases (top), the variance increases (middle), or both increase (bottom). Modified from Figure 2.32 in the Intergovernmental Panel on Climate Change, Working Group I report (2001)



probability of extremely late breakup events. Similarly, if the variability of ice breakup dates increases, the probabilities of both extremely early and extremely late events may increase owing to the change in variability alone. Extreme events in the context of lake ice dynamics include, for example, extremely late freeze, extremely early breakup, and, for lakes that usually freeze, years of no ice cover.

An area of active investigation is the assessment of whether climate change is leading to an increase in climatic variability at various time scales (Michaels et al. 1998; Scherrer et al. 2005; Peel and McMahon 2006; Trenberth et al. 2007). Changes in variance may be indicative of changes in system resiliency and stability (Epstein and McCarthy 2004; Carpenter and Brock 2006). Thus, in addition to characterizing long-term trends in ice dynamics, the investigation of trends or patterns in the variability can be informative about ecosystem properties.

Ice phenology records for lakes around the Northern Hemisphere display complex variation composed of long-term trends and interannual and interdecadal variation (Livingstone et al. 2010) as well as spatial autocorrelation at scales of 10s to 100s of km (Magnuson et al. 2005). Here we examine patterns in long-term trends and interannual variability in the context of understanding the occurrence of extreme events.

The questions we address are:

How do trends in ice phenology differ among recent 150-, 100-, and 30-year periods?

How does the variation in lake ice freeze and breakup dates and duration compare with the Northern Hemisphere seasonal land air temperatures?

Has the interannual variability in ice phenology increased over the last 100 and 150 years in Northern Hemisphere lakes?

Have extreme events in ice phenology and ice duration increased?

Are changes in extreme lake-ice events explained better by changes in the mean ice dates, by changes in variability around the mean ice dates, or both?

2 Methods

2.1 Ice-phenology data

Ice phenology records for a total of 75 lakes were analyzed (map Fig. 2; Table S1 in the online Supplement). These records have been deposited with and are available from the National Snow and Ice Data Center (<http://nsidc.org/data/g01377.html>). Lakes were grouped into four regions (Fig. 2): North central North America, Northeastern North America, Europe (Nordic countries plus Switzerland), and Asia. Three time periods were analyzed: a 150-year period (winter of 1855–6 to winter of 2004–5), a 100-year period (winter of 1905–6 to winter of 2004–5), and a 30-year period (winter of 1975–6 to winter of 2004–5). For the 150-year period, 9 lakes had freeze data, 17 lakes had breakup data, and 8 lakes had duration data. For the 100-year period, 40 lakes had freeze data, 71 lakes had breakup data, and 33 lakes had duration data. For the 30-year period, 38 lakes had freeze data, 66 had breakup data, and 32 lakes had duration data. Lakes with more than 10% missing data were excluded from the analysis. The 30-year data set was the subset of the 100-year data set where lakes had no more than 10% missing years in the 30-year period. For the 9 data sets (3 ice parameters for 3 time periods) the mean percent missing ranged from 2% to 4.7%. The ice phenology data set and analyses extend the Magnuson et al. (2000) paper in multiple ways: more recent years, more lakes, updates and corrections to some data, and systematic control of the time window of analysis.

Some lakes did not freeze in some winters. For analyses such as regression, we chose to quantify the no-freeze years for a lake by using the latest observed freeze date (for freeze

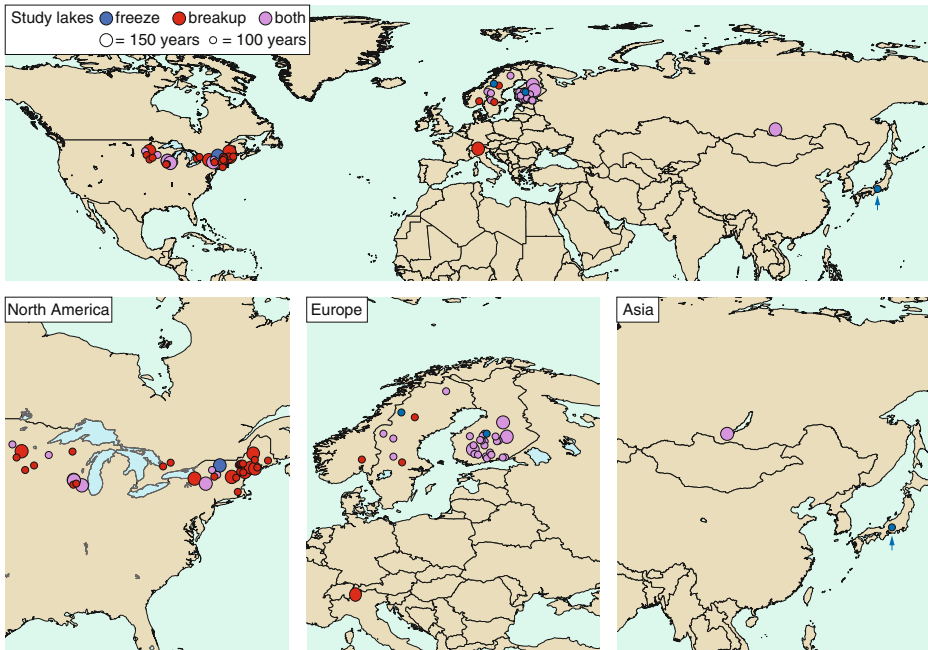


Fig. 2 Map showing the locations of the lakes included in the analysis. Information on the locations and names of the lakes is given in Table S1 in the online Supplement

date) or the earliest observed breakup date (for breakup date). Only eight of the 75 lakes had no-freeze years. Removing the no-freeze years from the analysis would clearly bias the results; using the most extreme observed date is conservative (no-freeze years are clearly more extreme than the latest freeze or earliest breakup and thus rates of change are underestimated) though somewhat arbitrary. Other authors have used a variety of methods to deal with no-freeze years in analyses that depend on the kind of data available (Assel and Robertson 1995; Magnuson et al. 2000; Jensen et al. 2007).

2.2 Northern Hemisphere air temperature

The Northern Hemisphere monthly air temperature anomalies (1855–2005), relative to the 1961–1990 mean, were generated by the Climatic Research Unit at the University of East Anglia in conjunction with the Hadley Centre of the UK Met Office (<http://www.cru.uea.ac.uk/cru/data/temperature/> Brohan et al. 2006; Jones et al. 1999). We used the variance-adjusted land air temperature anomalies (CRUTEM3v) to calculate seasonal means (DJF, MAM, SON) for the years 1855–6 to 2004–5.

2.3 Analysis methods

2.3.1 Analysis of trends

Temporal trends for ice freeze dates, ice breakup dates, and ice duration were calculated using least-squares linear regression and the non-parametric Theil-Sen method (Theil 1950; Sen 1968;

calculated with an Excel program SK-THEIL developed by J. Fölster, Swedish University of Agricultural Sciences, Uppsala, Sweden and J. Seibert, University of Zurich, Switzerland).

A one-way t-test and a Wilcoxon sign-rank test were performed on trends for all lakes for the 150-, 100-, and 30-year data to test whether the trends for the group of lakes were significantly different from zero. Two-way tests, t and Wilcoxon sign-rank, were performed to compare trends among the 150-, 100-, and 30-year periods (calculated both as least-square and Theil-Sen estimates). This analysis used matched pairs and thus was constrained to lakes with a trend estimate for each time period being compared. For each of the three periods, the rate of change of freeze was compared to the rate of change of breakup using paired tests, t and Wilcoxon sign-rank.

Marginally significant p-values should be considered in the context of spatial autocorrelation, which can result in underestimated confidence intervals and has been found to be present (i.e., $r^2 > 0.2$) in breakup time series for pairs of lakes separated by up to 400 km in the north–south direction and 900 km in the east–west direction (Magnuson et al. 2005). An analysis which eliminated spatial autocorrelation was done that was based on a composite time series for each ice variable by time period combination. The composite was calculated as the mean anomaly over lakes. Linear least-square and Theil-Sen slopes were computed for each of the composite time series.

To investigate the long-term relationship between ice phenology and Northern Hemisphere land air temperature in the 150-year data, we calculated a mean anomaly time series for each ice phenology variable, by first calculating an anomaly time series for each lake and then averaging the anomalies over lakes. Ice duration mean anomalies were regressed against the mean of the fall, winter, and spring air temperature anomalies; freeze date mean anomalies were regressed against the fall air temperature anomalies; breakup date mean anomalies were regressed against the spring air temperature anomalies.

2.3.2 Analysis of variability

We used two approaches to examine whether measures of variability changed over time. The first was to calculate the standard deviation for each lake's ice variables for fixed 10-year windows. This analysis was done on the 150-year and on the 100-year data sets. For each ice variable, analysis of covariance (SAS v8, GLM procedure) was used to test whether the lakes, as a group, had significant trends in standard deviation, separately for the 150- and 100-year periods. We also estimated the trends in standard deviation (based on the fixed 10-year windows) for individual lakes.

The second approach compared the variability between 50-year windows. Using the 100-year data set, 1905–1954 was compared to 1955–2004. Standard deviation and skewness were compared between the two periods for all lakes and for each major region (North central North America, Northeastern North America, Europe, and Asia). The 95% confidence interval about the regional mean was computed to test for significant differences in both standard deviation and skewness between the periods, except for Asia where the number of lakes was less than or equal to two. The standard deviations of the three sequential 50-year data sets contained within the 150-year data set were compared pairwise using a two-tailed t-test.

2.3.3 Analysis of extreme events

Three categories of extreme events were identified for each lake: 50-year events, 25-year events, and 10-year events, defined as occurring once every 50, 25, and 10 years,

respectively. For example, during the 150-year period, the three latest freeze dates were chosen as the 50-year extreme events for late freeze and the three earliest freeze dates were chosen as the 50-year extreme events for early freeze. An example of 25-year events for Lake Mendota is given in Fig. 3. Ties were included in the selection of extremes, which in some cases resulted in more than the expected number of extreme events. Logistic regression (SAS 9.1.3, LOGISTIC procedure) was used to look for trends in the frequency of extreme events. These trends are expressed in terms of the odds ratio $([p/(1-p)]^2)$ where p is the probability of an extreme event), which represents the change in the odds from one year to the next. For example, an odds ratio of 1.15 represents a 15% increase in the odds per year.

The most extreme event for a lake that typically freezes is when the lake does not freeze completely at all. We examined the proportion of lakes in each year that did not freeze and used logistic regression to test for a temporal trend in the frequency of no-freeze years.

3 Results

3.1 Trends for 150-, 100-, and 30-year periods

When all lakes are considered together, the mean trends in measures of lake ice phenology were consistently in the direction of later freezes, earlier breakups, and shorter durations in each of the three time periods (Table 1). For the 150-year period, absolute rates of change (mean least-square slopes) ranged from 0.9 to 1.7 days per decade, for the 100-year period from 0.3 to 0.7 days per decade, and for the most recent 30 years from 1.6 to 4.3 days per decade. Least-square slopes were statistically significant for each combination of ice measure and time period ($p=0.04$ to $p<0.0001$). Theil-Sen slopes averaged 13% less than least-square slopes and were statistically significant in 7 of the 9 combinations of ice measures and time period ($p=0.14$ to $p<0.0001$). In most cases, differences in the median slopes tracked patterns of the mean least-square and Theil-Sen slopes but the median slopes averaged 7% less than the least-square slopes. Any marginally significant p -values should be considered in the context of spatial autocorrelation, which can result in underestimated confidence intervals. A less powerful test that eliminated spatial autocorrelation showed significant trends for 5 of the 9 ice variable by time period combinations (Table 1 composite

Fig. 3 Ice-cover durations and extremes for the winters of 1855–6 through 2004–5 for Lake Mendota, Wisconsin. The linear trend, r^2 , and the 25-year extremes (6 years out of 150 years) for long and for short ice durations are provided. Seven designations for extreme short durations result because there are 2 years with the same duration tied for inclusion as extremes

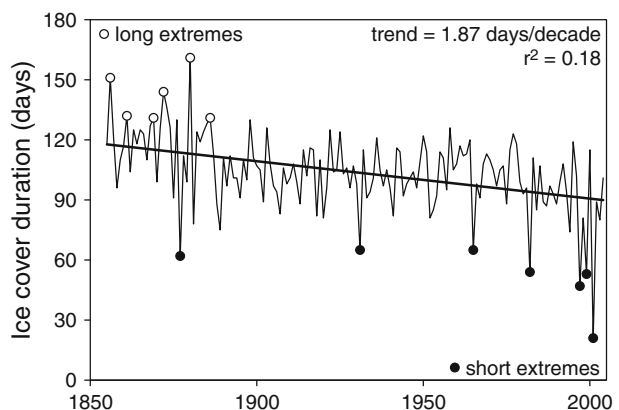


Table 1 Trends in days/decade in freeze date, breakup date, and ice cover duration for all lake-ice sites in the Northern Hemisphere for 150-year (1855–6 to 2004–5), 100-year (1905–6 to 2004–5), and 30-year (1975–6 to 2004–5) data sets using least square and Theil-Sen slopes (mean and median). Mean and median slopes (p in parenthesis), direction of change, and the number of lakes (N) are given. One-way significant differences from zero slope were tested with one-way t - and Wilcoxon sign-rank tests. If significance differed between the two tests, we present the lower significance of the two. The composite (one for each ice variable and time period combination) represents the time series generated from the mean anomalies across lakes. For the composite, least-squares regression and Theil-Sen slopes were calculated

Variable	Statistics	150 years days/decade	100 years days/decade	30 years days/decade
Freeze	SLOPES			
	least square			
	mean	1.08 ($p=0.002$)	0.27 ($p=0.04$)	1.59 ($p=0.003$)
	median	0.88	0.14	1.35
	Theil-Sen			
	mean	1.01 ($p=0.002$)	0.21 ($p=0.07$)	0.66 ($p=0.14$)
	median	0.80	0.00	0.00
	N	9	40	38
	composite			
	least square	1.07 ($p<0.0001$)	0.29 ($p=0.33$)	1.61 ($p=0.38$)
	Theil-Sen	1.10 ($p<0.0001$)	0.25 ($p=0.47$)	1.51 ($p=0.56$)
direction	later	later	later	
Breakup	SLOPES			
	least square			
	mean	-0.89 ($p<0.0001$)	-0.52 ($p<0.0001$)	-1.87 ($p<0.0001$)
	median	-0.88	-0.45	-1.93
	Theil-Sen			
	mean	-0.88 ($p<0.0001$)	-0.50 ($p<0.0001$)	-1.86 ($p<0.0001$)
	median	-0.86	-0.46	-2.09
	N	17	71	66
	composite			
	least square	-0.88 ($p<0.0001$)	-0.54 ($p=0.006$)	-1.84 ($p=0.07$)
	Theil-Sen	-0.85 ($p<0.0001$)	-0.58 ($p=0.003$)	-1.61 ($p=0.16$)
direction	earlier	earlier	earlier	
Duration	SLOPES			
	least square			
	mean	-1.74 ($p=0.004$)	-0.68 ($p<0.0001$)	-4.34 ($p<0.0001$)
	median	-1.69	-0.69	-3.74
	Theil-Sen			
	mean	-1.64 ($p=0.004$)	-0.62 ($p<0.0001$)	-3.46 ($p<0.0001$)
	median	-1.61	-0.46	-2.82
	N	8	33	32
	composite			
	least square	-1.74 ($p<0.0001$)	-0.74 ($p=0.06$)	-4.36 ($p=0.05$)
	Theil-Sen	-1.67 ($p<0.0001$)	-0.80 ($p=0.05$)	-5.31 ($p=0.04$)
direction	shorter	shorter	shorter	

results). Lack of significance may be due to either the removal of spatial autocorrelation or the use of a less powerful test. Jensen et al. (2007) found little evidence of spatial autocorrelation in freeze dates.

Generally consistent differences in rates of change existed between time periods (Table 1). The overall pattern of differences in trends between time periods was that trends in the 30-year period were steeper than those in the 100- and 150-year periods, and trends in the 150-year period were steeper than in the 100-year period. Seven of nine differences between the linear least-square trends were statistically significant (Table S2 in the online Supplement) at $p < 0.05$ ($p = 0.10$ to $p < 0.0001$); six of the nine differences between the Theil-Sen slopes were significant (Table S2 in the online Supplement) at $p \leq 0.05$ ($p = 0.34$ to $p < 0.0001$).

Overall, breakup dates changed more rapidly than freeze dates (Table 2). The one exception was that freeze changed more rapidly than breakup dates during the 30-year period for North American lakes ($n = 8$, $p = 0.007$). All differences for the 150-year period were small and statistically insignificant but sample sizes for the analysis were also small ($n = 3$ to 8). Changes in duration (Table 1) were more rapid than changes in freeze or breakup dates because changes in duration incorporate changes in both freeze and breakup. The steepest slopes for duration were during the most recent 30 years (4.3 days per decade for linear least-square slopes and 3.5 days per decade for Theil-Sen slopes).

The 150-year time series of the mean anomalies of freeze date, breakup date, and ice duration showed significant linear trends with time (Fig. 4). For ice-cover duration, the linear trend in the mean anomalies was negative (toward shorter ice duration) and explained 31% of the variability. The linear trend in mean freeze date anomalies was positive (toward later freeze) and explained 28% of the variability. The linear trend in mean breakup date anomalies was negative (toward earlier breakup) and explained 27% of the variability. While these trends account for an important part of the variation and are statistically significant at $p < 0.0001$, about 70% of the variation in ice measure anomalies for lakes around the Northern Hemisphere is unexplained by the linear trends and constitutes variability around the regression. The lake ice variables show substantial interdecadal and interannual variability (Figs. 4 and 5).

Table 2 Breakup trends versus freeze trends for all lakes, North American lakes, or European lakes for 150-year (1855–6 to 2004–5), 100-year (1905–6 to 2004–5), and 30-year (1975–6 to 2004–5) time periods. Entries include the absolute difference (Δ) between mean slopes (freeze versus breakup) for matched pairs (same lake), the variable with the faster rate of change, the significance of the difference (p level from two-way matched pair tests: t and Wilcoxon sign-rank), and the sample size (N). When significances differed between the two tests, we present the lower significance of the two

Lakes	Statistics	150 years days/decade	100 years days/decade	30 years days/decade
All	Δ slope	0.08 ($p = 0.48$)	0.38 ($p = 0.003$)	1.11 ($p = 0.06$)
	faster rate	breakup	breakup	breakup
	N	8	36	36
North America	Δ slope	0.16 ($p = 0.29$)	0.04 ($p = 1.00$)	2.88 ($p = 0.007$)
	faster rate	breakup	breakup	freeze
	N	4	8	8
Europe	Δ slope	0.17 ($p = 0.25$)	0.55 ($p < 0.0001$)	2.29 ($p = 0.0002$)
	faster rate	breakup	breakup	breakup
	N	3	27	27

3.2 Relations between ice dates and air temperature in the 150-year data set

The trends in ice dates over time (Fig. 4) reflect the changes that were occurring in land air temperatures in the Northern Hemisphere (Fig. 5). The shared variance between mean anomalies of ice duration and the mean anomalies of Northern Hemisphere land temperatures (fall, winter, and spring mean) was 48%. This shared variance includes both trends and interannual variability because we chose not to detrend the time series. The 8 lakes with sufficient data for time series this long (150 years) were 3 lakes in Wisconsin, 1 lake in New York, 3 in Finland, and Lake Baikal in Siberia. Individual lakes shared 13 to 35% of the variance in the duration of their ice cover with the air temperature time series. For freeze date and breakup date the shared variances with land air temperatures were smaller than the shared variance of land air temperature with duration. The shared variance for freeze date with fall air temperatures was 36%. The shared variance for breakup with spring air temperatures was 37%.

Fig. 4 Trends for the 150 years from 1855–6 through 2004–5 in mean annual values of freeze day (*top*), breakup day (*middle*), and ice-cover duration (*bottom*), expressed as anomalies from the 150-year mean. Years with earlier than average freeze, later than average breakup, and longer than average duration are given as gray bars, and years with later than average freeze, earlier than average breakup, and shorter than average duration are black bars. The linear trend is provided as is the slope, p-value, r^2 , and the number of lakes for each ice measure. The year shown is the beginning year of the winter season

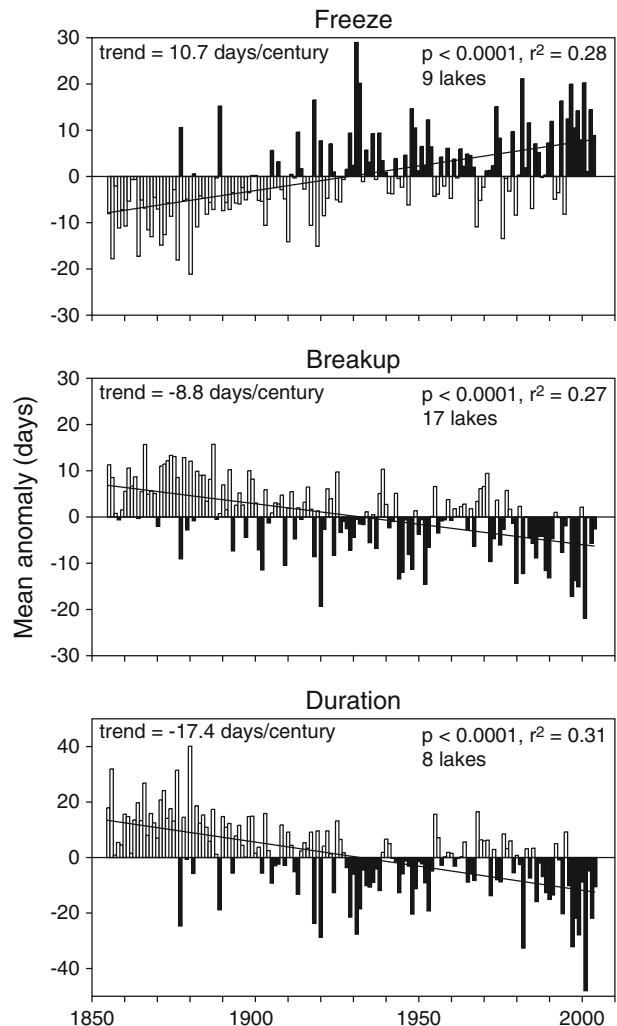
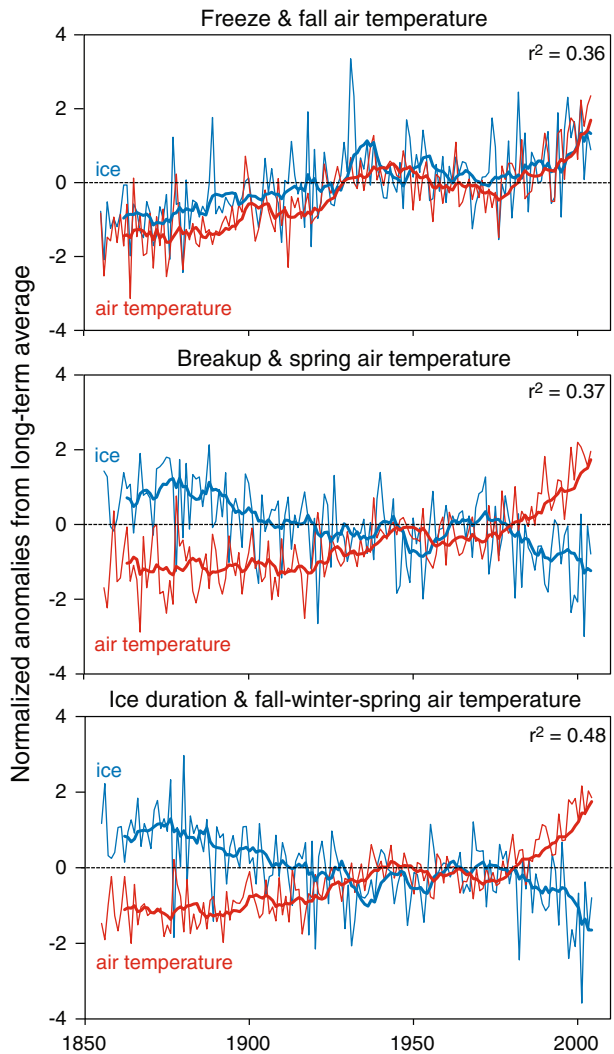


Fig. 5 Comparisons of anomaly time series for ice measures and land air temperatures for the Northern Hemisphere (http://www.cru.uea.ac.uk/cru/data/temperature/) from 1855–6 though 2004–5. All values are expressed as normalized anomalies (standard deviations of the measure being compared): top (freeze day and fall temperatures), middle (breakup day and spring temperatures), and bottom (ice duration and the average of fall, winter, and spring temperatures). Annual values are indicated by thin lines and 8-year running means by heavy lines; ice measures are blue and air temperatures are red. r^2 is presented for the linear relationship between the ice measures and the corresponding air temperatures



An examination of Fig. 5 reveals that not only are the 150-year trends in ice dates and Northern Hemisphere air temperatures related in the expected directions, but also individual high and low years frequently correspond between the ice and the air temperature series.

3.3 Differences among individual lakes and regions

Overall, the rates of change in ice dates for individual lakes (Fig. S1 in the online Supplement) were generally consistent with the patterns for the means of all lakes together (Table 1). However, linear least-square slopes differed in direction among lakes, and statistical significance for individual lakes often was absent. The greatest consistency was apparent for the 150-year period, where the directions of change of individual lakes were consistent with those of the means for all lakes. Each lake had later freeze ($n=9$), earlier

breakup ($n=17$), and shorter duration ($n=8$), and the linear least-square slopes were significant for each measure for each lake (two-way t-test, $p \leq 0.05$).

Mean slopes for regions with sufficient numbers of lakes had consistent patterns with the overall results for the Northern Hemisphere. Detailed results from this analysis are presented in Section 1 of the online Supplement.

3.4 Variability

Estimates of standard deviation, in the ten-year fixed windows mentioned earlier, were analyzed for the group of lakes as a whole (analysis of covariance) for each ice variable in the 150-year period and in the 100-year period (Table S3 in the online Supplement). Four of the six variable by time period cases had insignificant interactions between lake and the ten-year window. For these cases, two had significant trends ($p \leq 0.05$) in standard deviation after removing the interaction from the model: negative trends for both freeze over 100 years ($p=0.008$) and duration over 100 years ($p=0.002$). Only freeze for the 150 years and breakup for 100 years showed a significant difference among lakes when the differences were controlled for the covariate, ten-year windows; in these cases the interaction term (lake by “ten-year window” effect) was significant ($p=0.038$ and $p=0.0002$) indicating that temporal trends in variability differed among individual lakes.

Any marginally significant p-values should be considered in the context of spatial autocorrelation, which can result in underestimated confidence intervals. To eliminate the spatial autocorrelation, the trends were also calculated on anomalies averaged over lakes.

Trends for the standard deviation in 10-year windows, expressed as anomalies and averaged over lakes, were not statistically significant for either the 150- or 100-year periods (Fig. 6). However, when comparable trends are fit for the last 5 decades, a consistent pattern of increasing standard deviation is demonstrated for freeze, breakup, and duration (Fig. 6) although the trend is statistically significant only for breakup in the 100-year period; the sample size ($n=5$) for the trends is small though. Analysis of covariance on the group of lakes as a whole for the last 5 decades (10-year windows) demonstrated significant increasing trends for standard deviation (Table S3 in the online Supplement) in lakes from the 150-year data set (freeze $p=0.009$, breakup $p=0.0001$, duration $p=0.001$) and from the 100-year data set (freeze $p < 0.0001$, breakup $p < 0.0001$, duration $p=0.0009$). None of the interaction terms was significant, and so these terms were removed from the model to estimate the trends.

Our second approach to characterizing changes in variability with time was to compare the standard deviation and skewness between the 50-year periods 1905–1954 and 1955–2004 for each lake. Standard deviation between the 50-year windows usually did not change or decreased for the 100-year data. For the mean over all lakes, standard deviation decreased significantly for freeze and breakup ($p \leq 0.05$) but the standard deviation of the duration was not significantly different between the two periods (Fig. 7).

In the following regional results, significance was based on the 95% confidence interval about the regional mean (Fig. 7). The most common result was for no significant change, followed by a decrease in variability. For freeze dates, only lakes in Europe had a significant change in standard deviation, toward less variability (Fig. 7 top). In contrast, breakup in Europe and North central North America had significant changes in standard deviation. However, the changes were in opposite directions with variability decreasing in Europe and increasing in North central North America (Fig. 7 middle). For duration Europe had a significant decrease in standard deviation while the other regions did not change (Fig. 7 bottom). Most of the comparisons of skewness (vertical axes Fig. 7) showed no

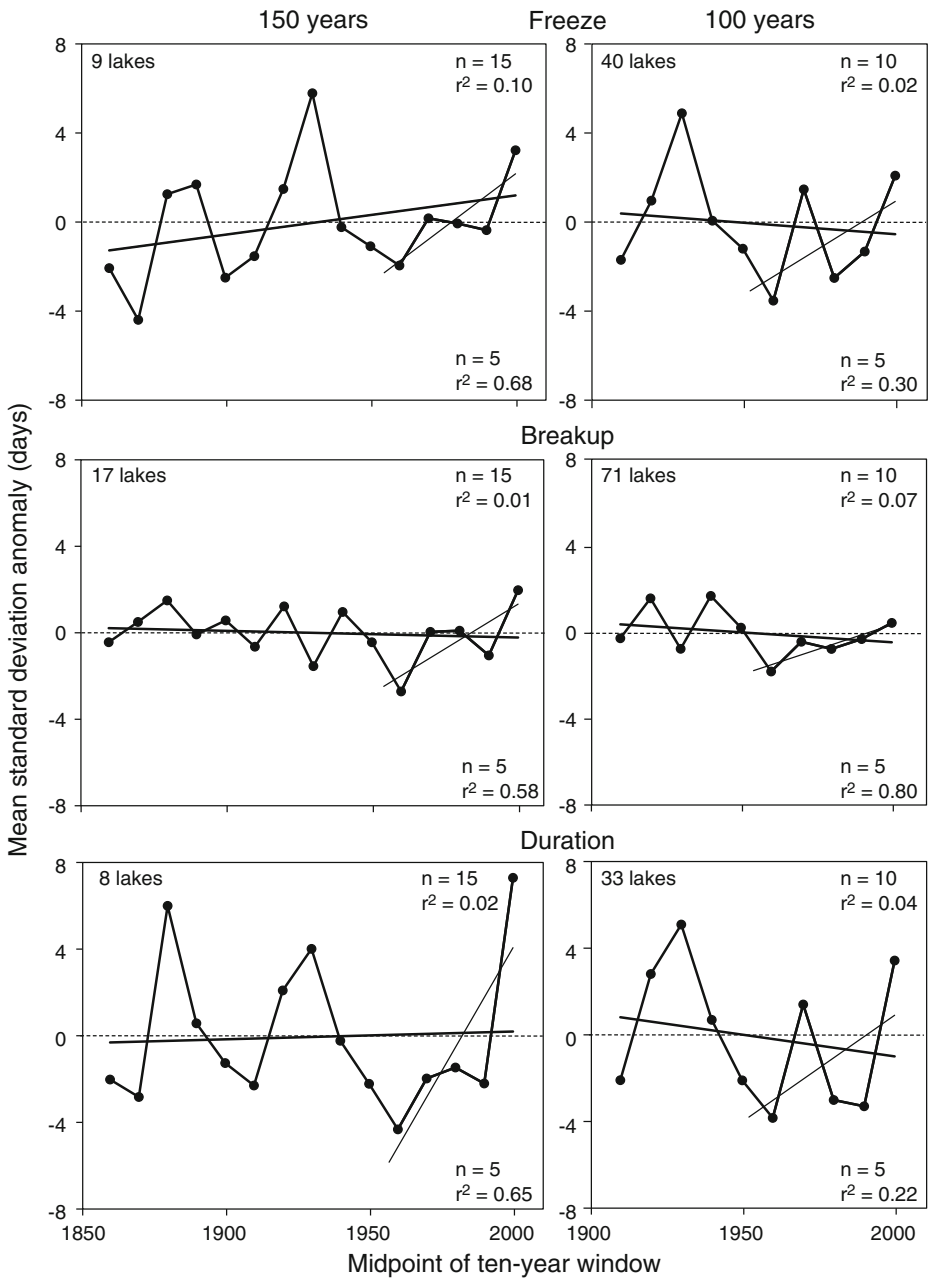
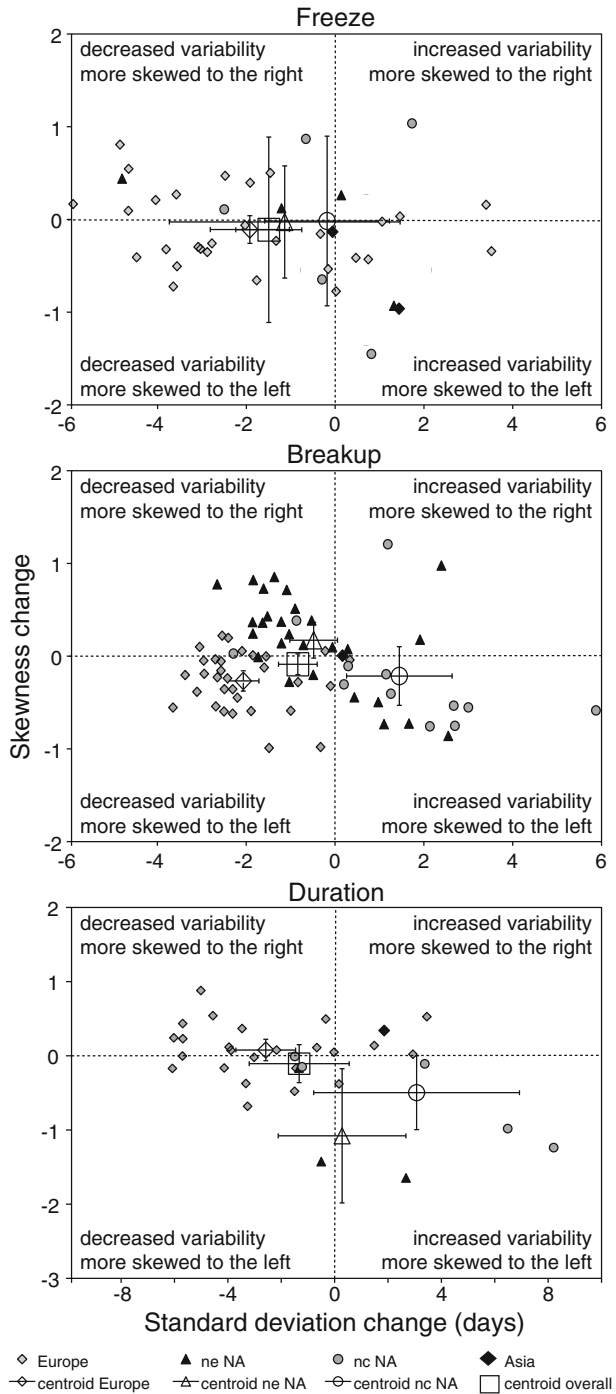


Fig. 6 Changes in the standard deviation over successive 10-year periods for freeze (top), breakup (middle), and ice duration (bottom) in the 150-year period (left) and the 100-year period (right). Standard deviations are plotted as the mean standard deviation anomalies. For each panel the linear trend line is provided for the entire period and for the most recent 50 years, as is the number of lakes, r^2 , and the number of decades (n)

significant difference between periods. There were two exceptions: skewness for breakup in Europe (Fig. 7 middle) and duration in Northeast North America (Fig. 7 bottom) differed

Fig. 7 Differences in standard deviation and skewness between two 50-year periods (1955–6 to 2004–5 minus 1905–6 to 1954–5) for lakes in the 100-year data set in each of the four regions (Europe, Northeastern North America, North central North America, and Asia). The mean and 95% confidence interval are presented for freeze (*top*), breakup (*middle*), and ice duration (*bottom*). We did not calculate a centroid for Asia because only two lakes were available for freeze and only one lake for breakup and duration. The number of lakes in the 100-year data set are 40 (freeze), 71 (breakup), and 33 (duration). Methods are described in Section 2.3.2



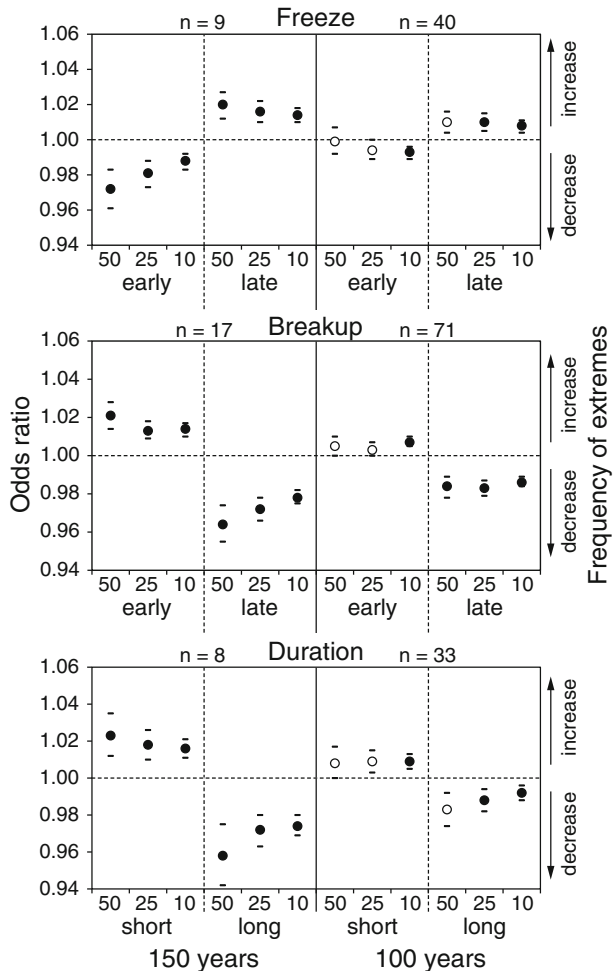
significantly between periods, with the probability distribution of the more recent period being more skewed toward the left.

Standard deviation in 50-year windows usually did not change for the 150-year data. Comparison of the three 50-year periods showed a significant increase in standard deviation between the first two 50-year windows for freeze. The other two comparisons for freeze were not significant nor were any of the six comparisons for breakup and duration ($p \leq 0.05$).

3.5 Extreme events

The frequencies of extremely late freeze, early breakup, and short duration increased for all ice measures for 50-year, 25-year, and 10-year extremes. For the 150-year period, all logistic regression trends for extreme events were highly significant (Fig. 8 left, $p < 0.0001$). In this period, the frequency of extreme events (50-year, 25-year, and 10-year extremes) decreased for early freeze, late breakup, and longer duration, while it increased for late freeze, early breakup, and shorter duration of ice cover. Trends in the frequency of extreme events were not as consistently and strongly significant in the 100-year period (Fig. 8 right),

Fig. 8 The odds ratio for the variable “year” from logistic regressions of extreme events: freeze (top), breakup (middle), and ice duration (bottom). Values above the horizontal line at 1.00 indicate an increase in the frequency of an extreme event occurring through time while values below the line indicate a decrease. Filled circles represent values significant at $p < 0.0001$. Also shown are 95% confidence intervals and sample sizes (n =number of lakes). Extreme events analyzed were 50-year, 25-year, and 10-year extremes. Methods are described in Section 2.3.3



except for a decreasing frequency of late breakup. However, the direction of trends in extreme events was similar between the 100-year and 150-year data sets. Over the 150-year period, the frequency of the extreme 50-year events changed more rapidly than 25-year events, which in turn changed more rapidly than 10-year events. The decline in frequency of extreme events associated with cold winters was more rapid than the increase in frequency of extreme events associated with warm winters over the 150-year period. That is, the odds ratios for early freeze, late breakup, and long duration were farther from 1.0 than the odds ratios for late freeze, early breakup, and short durations (Fig. 8).

The logistic regression of extreme events for the four regions appeared consistent with the overall results, with the frequency of extreme events changing largely in parallel with the Northern Hemisphere results, but with fewer statistically significant odds ratios. More detailed results on the regional analysis are given in Section 1 of the online Supplement.

The most extreme winter event for lakes that typically freeze occurs when the lake does not freeze over completely. The proportion of lakes without complete ice cover increased from the winters of 1905–6 through 2004–5 (Fig. 9; binary logistic regression $p < 0.001$). This result is consistent with the odds analyses above. The four lakes that had the highest number of no-freeze years ranged in number of missing years from 2 to 10 and as a group covered the time period well. Hence, the increasing frequency of no-ice years is not an artifact of missing data. Prior to the winter of 1905–6 none of the lakes in

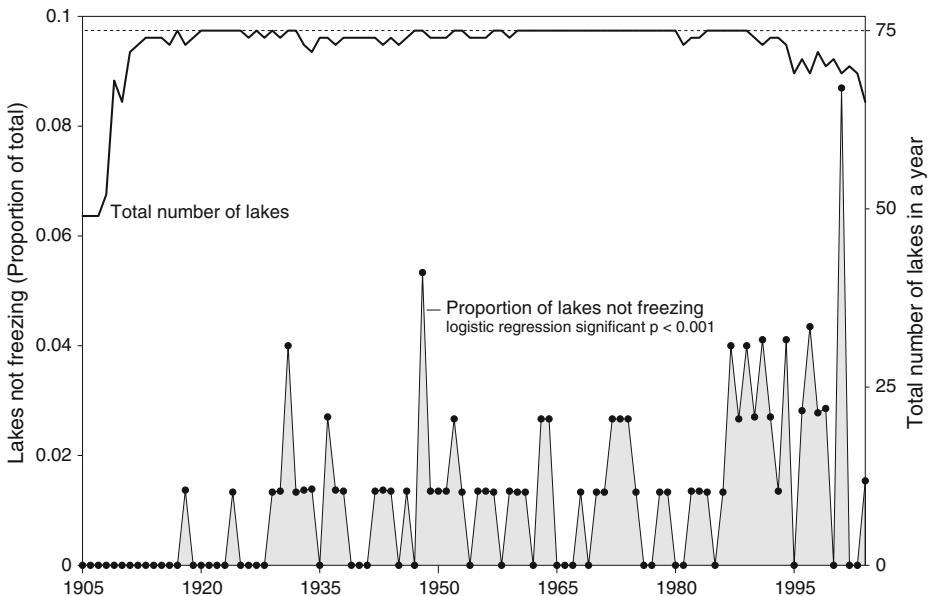


Fig. 9 The proportion of sampled lakes around the Northern Hemisphere that did not freeze over completely for winters from 1905–6 through 2004–5. The number of lakes available in each year is indicated. Lakes which had some years in which they did not freeze (where the number in parentheses indicates the number of no-freeze years) were Lakes Geneva (2), Otsego (1), Sebago (10), George (1), Oneida (1), Champlain (28), Mjosa Kisa-Kapp (25), and Suwa (21). See Table S1 in the online Supplement for location information on these lakes. Prior to the winter of 1904–5 none of the lakes in the 150-year data set were known to experience a winter without complete ice cover during the years from 1855–6 through 1904–5. Methods are described in Section 2.3.3

the 150-year data set were known to experience a winter without complete ice cover during the period 1855–6 through 1905–6.

3.6 Relationship between extreme events and changes in mean and variability

Changes in the mean ice measures over 150- and 100-year periods had strong and statistically significant influences on the frequency of extreme events, and there is some evidence that decreases in variability were associated with smaller changes in the frequency of extreme events (Fig. 10). The steeper the trends (days per decade) in ice measures, the greater were the changes in the odds of an extreme event. For example, changes toward shorter duration resulted in an increase in frequency (odds ratio >1.0) of extremely short ice cover events, but at the same time resulted in a decrease in the frequency (odds ratio <1.0) of extremely long ice cover events. In contrast, relationships between changes in variability and the odds ratio for extreme ice dates (freeze, breakup, and ice cover duration) were less apparent (Fig. 10). A comparison of odds ratio means among the three categories of variability change (decrease, no change, and increase) using a Student’s t-test showed odds ratios in the “decreased” category were significantly closer to 1 than those in the “no change” category for odds ratios <1; for odds ratios >1, odds ratios in the “decreased” category were again significantly closer to 1 than those in the “no change” and “increase” categories. In other words, extreme events were less likely if variability decreased. Standard deviation change categories for Fig. 10 were based on analysis of covariance for ten-year windows (Table S3 in the online Supplement) supplemented by trend directions from Fig. 6 when the interaction between lake and “ten-year window” was significant. Four of the twelve combinations of ice measure, record length, and event type (early or short, late or long) had no significant change in standard deviation from early to late in the time series. Of the other eight, six decreased in variability and two increased. Four of these where variability changed would have influenced the frequency of extreme events in the opposite

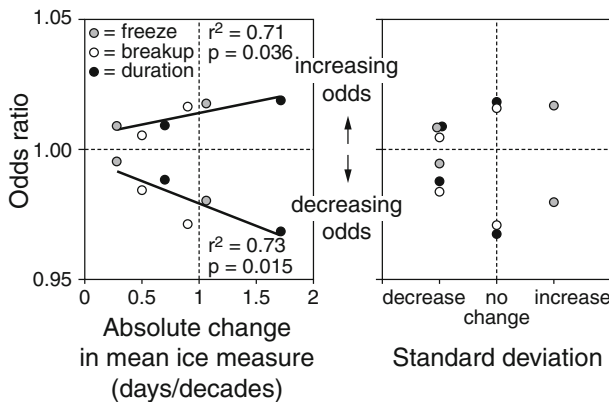


Fig. 10 Changes in mean odds (mean of 50-, 25-, and 10-year events) for the 150-year and 100-year data on ice measures (freeze, breakup, and duration) plotted in relation to changes in mean slopes (*left*) and changes in standard deviation (*right*). Each circle represents the mean odds ratio of one of the extreme event types (e.g., extremely long duration) for either the 150- or 100-year data. Lines in the left graph represent best-fit linear regressions of the odds ratio versus the change in the mean for extreme events (late freeze, early breakup, and short duration) for increasing odds (*top*) and extreme events (early freeze, late breakup, and long duration) for decreasing odds (*bottom*). Categories for standard deviation change were based on analysis with 10-year windows

direction to the change in mean ice dates. The other four where variability changed would have changed the frequency of extreme events in the same direction as the change in mean ice dates.

4 Discussion and conclusions

4.1 Trends in ice phenology and relation to air temperature

The overall trends in Northern Hemisphere lakes toward later freeze, earlier breakup, and shorter duration (Table 1, Fig. 4) are consistent with changes found by others (Livingstone 1997, 1999; Magnuson et al. 2000; Hodgkins et al. 2002; Weyhenmeyer et al. 2005; Duguay et al. 2006; Korhonen 2006; Livingstone et al. 2010). The mean trends in measures of lake ice phenology were consistently in the direction of later freezes, earlier breakups, and shorter durations in each of the three time periods (Table 1) although some trends were not significant based on Theil-Sen slopes or a less powerful test that eliminated spatial autocorrelation. Trends in the 30-year period were steeper than those in the 100- and 150-year periods, and trends in the 150-year period were steeper than in the 100-year period (Table 1; Table S2 in the online Supplement), demonstrating that the rates of change were not uniform over the 150 years. Thus the maximum rates of change were observed in the recent 30-year period: freeze 1.6 days per decade later, breakup 1.9 days per decade earlier, duration 4.3 days per decade shorter. Note that the discrepancy between calendar dates and the astronomical (orbital) equinoxes generates a trend in the vernal equinox of about 0.08 days per decade (Sagarin 2001). However, the rates of change in the ice freeze and breakup dates are considerably greater.

In our analyses, mean seasonal temperatures (Fig. 5) shared variability with freeze ($r^2=0.36$) and breakup ($r^2=0.37$) dates and ice duration ($r^2=0.48$). Changes in ice dates have been related by many authors to changes in air temperature, especially for certain months of the year, often allowing ice dates to be modeled from air temperature or vice versa (Palecki and Barry 1986; Wynne and Lillesand 1993; Assel and Robertson 1995; Ruosteenoja 1986; Vavrus et al. 1996; Gao and Stefan 1999; Adrian and Hintze 2000; Livingstone 1997, 1999; Williams et al. 2004; Holopainen et al. 2009; Livingstone and Adrian 2009).

Our observation that breakup date has usually been changing more rapidly than freeze date over 150, 100, and 30 years (Table 2) is consistent with the temperature sensitivity observed in lake-ice process models (Vavrus et al. 1996; Gao and Stefan 2004). In the Vavrus et al. (1996) model, breakup date changed 5.6 days per 1°C change in air temperature while freeze date sensitivity was lower, 3.9 days per 1°C change in air temperature. In Gao and Stefan's (2004) sensitivity analyses, a 5°C increase in air temperature delayed freeze date by 15 days but advanced breakup date by 22 days. Freeze date is also more dependent on lake-specific characteristics; for example, the freeze date depends on the lake heat budget which is affected by lake volume. While the sensitivity of breakup and freeze dates was based on linearized analyses, the relationship between annual mean air temperature and ice phenology is non-linear as described in the following paragraph.

The recent 30-year period, during which Northern Hemisphere air temperatures rose dramatically (Hansen et al. 2006), experienced more rapid changes in ice phenology than either the 100-year or 150-year periods. This pattern of rapid change in recent years already has been shown for specific regions such as the Laurentian Great Lakes region (Jensen et al. 2007) and Sweden (Weyhenmeyer et al. 2005). Our analysis is the first Northern-

Hemisphere-wide analysis of ice phenology to document more rapid change in recent years. The increased pace of ice loss is apparently the result of two processes. First, the rate of increase in air temperature has become faster in recent years (Hansen et al. 2006). Second, as air temperatures rise, lake and river ice becomes progressively more vulnerable; a 1°C increase in air temperature has a greater effect on ice duration in warmer regions as a result of the non-linear relationship between mean annual air temperature and the period of time that air temperatures are below zero (Weyhenmeyer et al. 2004, 2011; Livingstone and Adrian 2009). The magnitude and significance of trends over the recent 30 years may be influenced, in part, by multi-decadal oscillations of large-scale climate drivers. Lake-ice variables and air temperature show multidecadal low and high values in the last 150 years (Figs. 4 and 5); potential mechanisms behind the multidecadal variability are discussed in the next section.

4.2 Changes in variability

We had expected to find that increasing variability in ice phenology and duration was occurring and would contribute to the increases in the frequency of extremes associated with warm events. Analyses of lake-ice dates around the Northern Hemisphere by both Kratz et al. (2000) and Weyhenmeyer et al. (2011) had found increases in variability over 40- and 30-year periods ending in 1990. We observed similar increases in decadal variability over the last 50 years of our analyses that ended in the winter of 2004–5 (Fig. 6). This increasing variability was not consistent with the patterns over the 150- and 100-year periods (Figs. 6 and 7). Recent increases in variability do not appear to reach new high levels, but rather to return to levels of variability more common in the early 1900s and the late 1800s. However, for two of the six standard deviation time series, the standard deviation in the most recent ten-year window is greater than any earlier ten-year window. One is reminded of the value of observing patterns in the long term (Magnuson 1990) and that results are often scale-dependent. In our analyses the extent of the record and the grain of the analyses have a strong influence on the final result. We expect that both the warming that has occurred and the influences of large-scale climate drivers are important to trends and patterns of variability, as they are for trends and patterns in the ice variables themselves. This paper does not address the relative importance of climate warming due to greenhouse gases, large-scale drivers of interdecadal oscillations, or changes in solar radiation.

Interannual and interdecadal variability in lake-ice dates have many sources that operate at local to global scales. For Lake Mendota (Fig. 3), only 18% of the variability in ice duration in the 150-year period is associated with the long-term trend towards shorter duration; the remainder, 82%, is associated with interannual, interdecadal, and multi-decadal variability. Time series of lake ice measures have statistical correlations with large-scale climate drivers such as the El Niño Southern Oscillation (ENSO) (Anderson et al. 1996; Livingstone 2000; Robertson et al. 2000; Magnuson et al. 2004; Bonsal et al. 2006), the North Atlantic Oscillation (NAO) (Livingstone 1999, 2000; Magnuson et al. 2004), the Pacific Decadal Oscillation (PDO) (Magnuson et al. 2004; Bonsal et al. 2006), the Pacific North American Pattern (PNA) (Benson et al. 2000; Bonsal et al. 2006), the Western Pacific Pattern (WP) (Benson et al. 2000), the North Pacific index (NP) (Magnuson et al. 2004), and the Arctic Oscillation (AO) (Bonsal et al. 2006). Again for Lake Mendota (Namdar Ghanbari et al. 2009), variability in ice duration as expressed through time series coherence in the frequency domain was related to annual measures of local weather (air temperatures and snow) and large-scale climate drivers (SOI, NAO, PDO, NP). Lakes in different regions

differ in their relation to the large-scale climate drivers (Livingstone 2000; Magnuson et al. 2004; Bonsal et al. 2006).

Some interannual variability in ice measures can be quite local in apparent origin (Gao and Stefan 1999, 2004; Magnuson et al. 2004, 2006; Livingstone et al. 2010). At time scales of days and weeks, ice freeze and breakup dates can be associated with movement of the jet stream and the occurrence of weather fronts and storms. A freeze event can be delayed by a windy period or nocturnal cloud cover that insulates against heat loss. For breakup, similar rather local conditions can accelerate breakup (a week of warm sunny weather) or delay it (a week of cloudy cold weather).

Individual lakes showed different patterns of changes in standard deviation over time (Fig. S2 in the online Supplement), with some showing increases, some decreases, some no change, and some a more complex pattern. The lack of a consistent pattern across lakes and regions might help explain cases where the trend for variability over all lakes was not significant. A collection of lakes exhibiting increasing changes, decreasing changes, complex changes, or no change, when taken together reveal the absence of a consistent pattern of variability change at aggregated scales.

The trends in ice dates and variability were not entirely consistent among or within regions. For example, the patterns of extreme events and trends in ice phenology were generally consistent across most regions (i.e. Asia, North central North America, Northeast North America, and northern Europe) yet in northern Europe a number of lakes had trends towards early freeze date during the 100-year and 30-year periods (Fig. S1 in the online Supplement). This departure from the overall patterns points to a complex set of interactions among variables such as global air temperature patterns, regional climate oscillations, and lake size and morphometry.

4.3 Extreme events

There has been much discussion of the potential for increases in the frequency and magnitude of climate events such as storms, hurricanes, and droughts, as well as some evidence that this is already happening (see review in Trenberth et al. 2007). Our analyses of lake ice time series reveal significant increases in the frequency of extreme events (Figs. 3 and 8) associated with warmer conditions and decreases in the frequency of extreme events associated with cooler conditions. These warmer extremes include later freeze, earlier breakup, and shorter ice cover duration as well as an increase in the proportion of lakes that do not freeze completely during the winter (Fig. 9). The frequency of extreme ice events associated with very cold winters—i.e., extremely early freeze, extremely late breakup, and an extremely long duration of ice cover—is declining (Fig. 8). Extreme events are not only noticed by the media and the public, they also often have severe environmental and human consequences (Katz and Brown 1992). In the case of lakes, the first winter when a lake is largely ice-free will not only make the local news, it will have social and economic consequences for those who enjoy winter pastimes or depend on the winter economy (Kling et al. 2003; Jensen 2008).

Direct effects of decreasing lake ice duration include physical, chemical, biological, and human-use changes (Magnuson et al. 1997). If ice cover does not occur, deeper lakes that typically mixed twice a year (in spring and fall) now only mix once per year, in the cool season. Reductions in ice cover result in greater rates of water loss to the atmosphere because evaporation from the open water is greater than sublimation from ice. The winter reduction in dissolved oxygen content is less as ice cover becomes shorter, and in shallow lakes the development of anoxic conditions and winterkill of fishes can be eliminated (Fang

and Stefan 2009). Predacious fishes that are not adapted to anoxic conditions can then become established (Tonn and Magnuson 1982; Magnuson et al. 1989); subsequently, the communities of small fishes characteristic of winterkill lakes are lost (Lodge 1993; Magnuson et al. 1997). In deeper Scandinavian lakes that do not experience winterkill, loss of ice cover favors brown trout over arctic char (Helland et al. 2011). Lake metabolism is altered, and products of metabolism like carbon dioxide do not accumulate in winter when the lake is largely ice-free. Photosynthesis continues later in fall and starts sooner in spring because without ice cover, snow cover cannot block sunlight. Winter dependent zooplankton species decline. Activities such as skating, ice fishing, ice boating, skiing, and winter ice festivals are reduced and become less safe (Kling et al. 2003).

4.4 Effects of changes in mean and variability on the frequency of extremes

We investigated the numerical explanations of the increasing odds of extreme ice dates in the context of whether the explanatory factor is a change in the mean condition (about which variation occurs) or whether the variability itself is increasing. The dichotomy is illustrated well in the third assessment report of the Intergovernmental Panel on Climate Change (2001) and reproduced here in modified form as Fig. 1. The question of the relative importance of changes in mean and changes in variability remains largely unresolved, but constitutes a useful area of analysis. For example, if the extremes result entirely from a change in the mean condition, then developing scenarios for future extremes is simpler than developing scenarios where the variability changes or both the mean and variability change. Ballester et al. (2009) illustrate this topic in their analyses of heat waves in central Europe. Their empirical analyses found that the change in baseline or mean condition was the salient explanation for increasing heat waves and that changes in variability were uninformative.

The various kinds of extreme events are generated from a diverse array of climatic processes, and there is no reason to assume that extremes other than those of lake ice phenology, such as rain events and hot days, would have the same numerical causes. In fact one would expect that the role of mean condition and variability would differ among the kinds of events and perhaps even the location of interest. Extremes in lake ice phenology are not unique as they represent only one aspect of a broad group of extreme, climate-related events such as unusually hot weather (Meehl and Tebaldi 2004), heavy rains and flooding (Easterling et al. 2000), and catastrophic winter storms (Changnon 2007). Changes in the frequency of occurrence of such extreme events are under discussion as to their likelihood of being consequences of our changing climate (Kunkel et al. 1999; Easterling et al. 2000).

The lake ice data provide an opportunity to explore the possible roles of changes in mean condition and changes in variability in explaining the changes in odds that so clearly are demonstrated (Fig. 8) for freeze and breakup dates and ice duration around the Northern Hemisphere. While significant trends in freeze date (later), breakup date (earlier), and ice duration (shorter) were observed during the 150- and 100-year periods across the lakes as a group, there was little evidence that variability increased during those periods. Out of all the analyses for variability, only a single increasing trend was significant. Otherwise, there was either no trend in variability or the variability was decreasing. When the expected influence of the change in the mean and the change in variability were in opposite directions (refer to Fig. 1 and a hypothetical example: a decrease in variability would reduce the likelihood of a hot extreme event while the increase in the mean would increase the likelihood), the influence of the change in the mean prevailed in determining the direction of changing

odds. The alternate case occurs when the expected influence of the change in the mean and the change in the variability would have reinforced each other (refer to Fig. 1 and a hypothetical example: an increase in variability would increase the likelihood of a hot extreme event as would an increase in the mean). In this case, the mean deviation of the odds ratios from 1 did not differ significantly ($p \leq 0.05$) from the mean deviation when the mean and variability differed in their direction of influence on the odds ratios.

Based on the above discussion, the strongest influence on the changing odds of extreme lake-ice dates resulted from the changes in the mean ice dates rather than changes in variability. This result makes clear that an increase in the frequency of occurrence of extreme events does not necessarily imply an increase in variability. Nevertheless, differences among regions and among individual lakes do occur (Fig. S2 in the online Supplement), so that the general conclusion that any changes in variability are overwhelmed by changes in mean conditions might not hold for some lakes.

As the climate continues to warm beyond temperatures seen in recent millennia (Intergovernmental Panel on Climate Change 2007), and as a change in the mean ice condition seems likely in a warmer climate (Gao and Stefan 2004), extreme events in ice phenology are likely to become more frequent. While the global impact of climate warming on lake ice phenology is becoming increasingly clear and better understood, understanding the reasons for regional and temporal differences in the patterns of change of lake ice phenology and their relationship to large-scale climatic forcing remain less well understood.

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