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A regime shift in Lake Superior ice cover, evaporation, and water temperature following the warm El Niño winter of 1997–1998

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Abstract

Significant trends in Lake Superior water temperature and ice cover have been observed in recent decades, and these trends have typically been analyzed using standard linear regression techniques. Although the linear trends are statistically significant and contribute to an understanding of environmental change, a careful examination of the trends shows important nonlinearities. We identify a pronounced step change that occurred in Lake Superior following the warm El Niño winter of 1997–1998, resulting in a "regime shift" in summer evaporation rate, water temperature, and numerous metrics of winter ice cover. This statistically significant step change accounts for most of the long-term trends in ice cover, water temperature, and evaporation during the period 1973–2010, and it was preceded (and followed) by insignificant linear trends in nearly all of the metrics examined. The 1998 step change is associated with a decrease in winter ice duration of 39 d (a 34% decline), an increase of ~ 2–3°C in mean surface water temperature (July–September averages), and a 91% increase in July–August evaporation rates, reflecting an earlier start to the summer evaporation season. Maximum wintertime ice extent decreased by nearly a factor of two, from an average of 69% of the lake surface area (before 1997–1998) to 36% after the step change. This reassessment of long-term trends highlights the importance of nonlinear regime shifts such as the 1997–1998 break point—an event that may be related to a similar shift in the Pacific Decadal Oscillation that occurred around the same time. These pronounced changes in Lake Superior physical characteristics are likely to have important implications for the broader lake ecosystem.

Increases in lake surface temperature have been widely documented in recent years throughout North America (Anderson et al. 1996; McCormick and Fahnenstiel 1999; Schneider et al. 2009) as well as globally (Schneider and Hook 2010). This long-term warming is especially apparent for the Laurentian Great Lakes, where summer water temperatures are generally found to be increasing faster than the ambient air temperature, particularly for Lake Superior (Lenters 2004; Austin and Colman 2007). During roughly the same time period, changes in lake-ice regimes have occurred in deep, Arctic lakes (Mueller et al. 2009), and shallow thermokarst lakes with bedfast ice (Arp et al. 2012; Surdu et al. 2014). Significant reductions in ice duration have also been noted for numerous other lakes throughout the world (Magnuson et al. 2000; Duguay et al. 2006; Benson et al. 2012). Again, this is especially true for Lake Superior, which has experienced a 79% decrease in ice coverage over the past few decades (Assel et al. 2003; Wang et al. 2012).

It has been suggested, in fact, that reductions in Lake Superior ice cover are mechanistically related to the concomitant increases in summer water temperature (Van Cleave 2012), possibly through ice-albedo feedbacks and the timing and duration of the summer stratification period (Austin and Colman 2007). Additional connections between summer evaporation rates and changes in lake level are also likely, as evidenced by recent increases in summer evaporation and declines in water level that have been noted for Lake Michigan–Huron (Hanrahan et al. 2010) as well as smaller, inland lakes in the Great Lakes region (Mishra et al. 2010). Observations from the nascent Great Lakes evaporation network also show an earlier start to the Lake Superior evaporation season during warm summers following low-ice winters (Lenters et al. 2013).

Many of the previous studies noted above have used standard linear regression techniques to assess rates of change over a specified time period. This is often an appropriate method for lake systems that undergo relatively linear changes through time. However, while a linear regression can be statistically significant, it implies that year-to-year changes are monotonic, often masking the presence of step changes that occur along the way (Liu et al. 2013; North et al. 2013). The underlying mechanisms that are responsible for a step change, as opposed to gradual, linear trends, can also greatly affect interpretations of long-term data sets (Mueller et al. 2009; North et al. 2014). As we show in the current study, these considerations turn out to be extremely important for understanding recent decadal-scale changes in Lake Superior physical characteristics. More specifically, we find that the majority of the aforementioned long-term "trends" in each of Lake Superior's prominent trending variables (ice cover, water temperature, and evaporation) are associated with a pronounced, nonlinear "regime shift" that occurred around 1997–1998.

In the following sections, the data and methodology used to assess changes in a variety of physical lake variables are discussed, along with the mean seasonal variability in Lake Superior water temperature, ice cover, and evaporation. This is followed by a description of the step-change analysis

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that is used to detect the timing of the regime shift as well as an analysis of long-term trends and nonlinear step changes in each of these variables. Finally, we conclude by summarizing the overall results, examining potential large-scale mechanisms for the observed regime shift, and discussing the broader implications of the work.

Methods

Water temperature and evaporation—Hourly surface water temperature data were obtained from three National Oceanic and Atmospheric Administration (NOAA) National Data Buoy Center (NDBC) buoys located in the eastern (45004), central (45001), and western (45006) offshore regions of Lake Superior. These buoys are typically deployed by late April or early May (i.e., after ice-out) and removed from the lake by late October or early November (before ice onset). Data gaps are generally short, with the exception of the western buoy during 2007, for which no data are available. The buoys measure the bulk water temperature at a depth of 60–100 cm below the surface and have initial deployment years of 1979 (central), 1980 (eastern), and 1981 (western). For the purposes of this study, we examined the full period of record from 1979 to 2010 using an aggregation of the three NDBC buoys (described below).

Basic quality control checks were performed to identify any major outliers in the hourly water temperature data, and steps were taken to fill data gaps prior to calculating monthly averages. For example, linear interpolation was used to fill data gaps less than or equal to 6 h in length, with gaps of 7 h or longer left as "missing." The hourly values were then averaged to daily means, and days that were missing 7 or more hours of data (i.e., 25% or more) were left as missing. The daily mean data were then interpolated and averaged to monthly means through a similar process (i.e., applied only to months that had fewer than 8 d of missing data). Finally, any remaining missing data in the monthly means were filled through regressions with monthly mean data from the most representative adjacent buoy (for a given month and across all years), and all three buoys were then averaged together to create a monthly time series of "mean offshore" surface water temperature. A few remaining months during which all three buoys had missing data were filled with regressions against adjacent monthly means (e.g., June vs. July). The end result is a complete record of monthly offshore surface water temperature for the period May–October 1979–2010.

In addition to the in situ buoy records, estimates of lakewide mean surface water temperature and evaporation were obtained for 1973–2009 from the NOAA Great Lakes Environmental Research Laboratory (GLERL; Hunter and Croley 1993). Provisional estimates of 2010 surface water temperature and evaporation were also provided by GLERL (T. Hunter pers. comm.). This longer data set from 1973 to 2010 (intended to overlap with ice-cover data, described below) provides daily estimates of surface water temperature and evaporation rate using a one-dimensional (1-D) thermodynamic model (Croley 1989; Croley and Assel 1994) forced by meteorological observations (mostly nearshore but extrapolated and adjusted to provide over-lake estimates). The model output is available for the entire year, as opposed to the NDBC buoy data, which are available only during the ice-free season. Similar to the NDBC water temperature data, the GLERL model output was averaged from daily to monthly values to provide a complete record of monthly mean lakewide surface water temperature and evaporation rates.

For the purposes of the trend analysis and to be consistent with previous studies (Austin and Colman 2007), we also created 3-month summer-mean water temperatures using the months of July, August, and September (JAS) both for the buoy data and for the GLERL model output. We generally found very good agreement between the NDBC and GLERL data sets during the period of overlap (1979–2010) in terms of both the interannual variability and long-term trends. The NDBC JAS water temperatures tended to be $\sim 3^{\circ}\mathrm{C}$ cooler than the GLERL estimates on average. But this is to be expected given that the buoys are deployed well offshore, while the GLERL model represents a bulk estimate for the entire lake surface (i.e., including shallower, nearshore regions). Mean summer evaporation rates were calculated for the 2-month period July–August (JA) since these were the only 2 months in the GLERL model output that exhibited significant trends in lake evaporation during the study period (1973–2010). This is similar to Lenters (2004), who found significant upward trends in Lake Superior evaporation for the months of June, July, August, and October (for the period 1948–1999).

Ice cover and derived metrics—Ice-cover records for Lake Superior were obtained from the NOAA Great Lakes Ice Atlas for the period 1973–2002 (available from http://www.glerl.noaa.gov/data/ice/atlas), with supplementary data for 2003–2005 provided by Assel (2005). The data consist of composite ice charts and a blend of observations from various sources covering the Great Lakes region (such as ships, aircraft, satellites, and shore-based observations). Additional data for the period 2006–2010 were obtained from NOAA GLERL (A. Clites pers. comm.). The ice-cover records in each data set provide the fraction of the total lake surface area, f, that is covered by ice. The raw observations are available on a roughly biweekly basis from early December through late April or May and were linearly interpolated to obtain a daily time series for the entire 38-yr period (1973–2010). Fifteen-day running means were then calculated in order to provide a smooth, robust time series for examining various ice-cover characteristics (e.g., onset date, duration, and maximum extent).

The 15-d running mean fractional ice coverage, f_{15}, was used to derive a number of different ice metrics for this study. For example, we define the "ice-on" date to be the day on which f_{15} first reaches 0.05 (i.e., $\geq 5\%$ ice coverage). Similarly, "ice-off" is defined as the last day of ice coverage that is $\geq 5\%$, and "ice duration" is the length of time between ice-on and ice-off. The 5% threshold was chosen based on an examination of the distribution of first-ice values in the raw data set as well as the maximum f_{15} value reached during each of the 38 winters. Two years, for

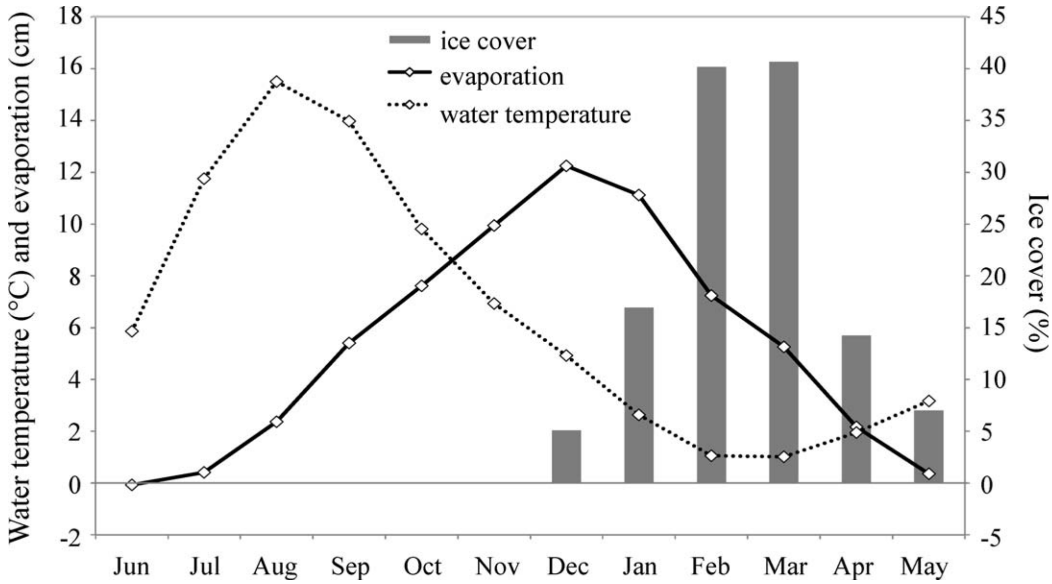

Fig. 1. Long-term monthly mean values of Lake Superior ice cover, evaporation, and water temperature for the period 1973–2010. Data obtained from NOAA GLERL. Monthly mean ice cover is calculated only for time periods that have at least 5% ice coverage.

example, reached a maximum f_{15} of only ~ 0.08 (1997–1998 and 2001–2002). For the occasional years in which f_{15} started or ended above 0.05 (because ice records for that year did not span the full winter season), linear extrapolation was used to identify the 5% ice-on or ice-off date. (This was required for 12 of the 38 ice-on dates and 7 of the 38 ice-off dates, but the average extrapolation length was only 7.7 d.) Although it is possible for ice coverage to rise and fall above the 5% threshold multiple times within a given winter, the 15-d smoothing process minimizes the likelihood of such events, causing it to occur only once during the entire 38-yr period (an 8-d interval during the winter of 1998–1999). Therefore, we ignore this one event and consider total ice duration to simply be the period between ice-on and ice-off.

In addition to the 5% ice-on dates, 5% ice-off dates, and total ice duration, we also calculated the winter-mean fractional ice coverage for each year (based on the average of all f_{15} values from ice-on to ice-off). The maximum winter ice coverage (i.e., maximum f_{15} value) and the date on which it occurred were also determined for each year. The final ice metric that was calculated is something that we refer to as "ice fraction days" (IFD; similar, e.g., to the concept of freezing degree days). Here, IFD is simply defined as the cumulative fractional ice coverage from ice-on to ice-off (i.e., IFD = $\Sigma[f_{15} \times \Delta t]$, where Δt is 1 d and the summation interval is limited to the period of ice duration). Note that IFD is equal to the product of the mean fractional ice coverage and total ice duration and is, therefore, a useful integrative measure of overall winter severity. An IFD of 30 d, for example, would be equivalent to 30 d of 100% ice coverage (or 60 d of 50% coverage and so on). In total, seven different ice metrics for Lake Superior were examined in this study for the period 1973–2010 (i.e., ice-on date, ice-off date, winter-mean ice coverage, maximum winter ice coverage, date of maximum winter ice coverage, ice duration, and IFD).

Step-change and linear trend analyses—Given the length of the data records (38 yr for ice cover and 32 yr for NDBC water temperature), our analysis focuses on two time scales: decadal-scale variability within the period of record (e.g., step changes), and linear trends over the full time period. To identify decadal-scale step changes within the data sets, a 20-yr moving window (split into two 10-yr periods) was propagated through each time series, calculating means for both the first and the second 10-yr periods. A Mann–Whitney *U*-test was then used to calculate the probability that the difference between the two means was statistically significant. This technique, therefore, identifies decadal regime shifts that occur within 20-yr moving windows. Although longer averaging periods might be considered more desirable, our analysis is constrained by the limited observational period of the data sets. Thus, it was deemed that a two-decade moving window was suitable for the current study. For comparison purposes, we also calculated linear trends for each of the various time series using standard linear regression. The Mann–Kendall test was used to determine the level of statistical significance for the linear trends.

Results

Mean annual cycle (1973–2010)—On average, Lake Superior shows a regular, seasonal progression in monthly surface water temperature, evaporation, and ice cover (Fig. 1). Monthly mean water temperatures peak in August, followed by a rapid decline in autumn, as a result of increased latent and sensible heat fluxes (Blanken et al. 2011; Lenters et al. 2013; Spence et al. 2011). Monthly mean evaporation peaks in December, which also coincides with the average month of ice onset. Evaporation rates then begin to decline as water temperatures drop and ice cover increases (Fig. 1). Although maximum ice cover and minimum water temperatures usually occur in February and March, evaporation rates do not minimize until May or June due to significant lags between water temperature, air temperature, and associated vapor pressure gradients (Lenters 2004; Blanken et al. 2011; Lenters et al. 2013).

Step-change analysis—Results of the step-change analysis are shown in Table 1, which lists the decadal changes in water temperature, evaporation rate, and seven different ice metrics from 1973 to 2010 (i.e., 1983–2001 ±10 yr), along with the statistical significance. Note that decadal shifts for the NDBC buoy data are not shown prior to 1989 since the data set begins in 1979. JAS surface water temperature shows statistically significant step changes in 1997, 1998, 1999, and 2000 both for the NDBC buoy observations and for the GLERL model results (Table 1). A small step change is also evident in 1983 (for the GLERL data only) but with weaker statistical significance. The year 1998 shows the largest step change of all years, with summer water temperatures for the period 1998–2007 being roughly 2.5–3.2°C warmer than for the period 1988–1997, a difference that is significant well beyond the 99% level (Table 1).

Similar step changes were found for evaporation and ice cover, with both JA evaporation and winter IFD showing the largest decadal increase during 1998 (i.e., 1998–2007 compared to 1988–1997). For the purposes of this study, we refer to the winter "year" as being the latter portion of the winter season (e.g., 1998 refers to the winter of 1997–1998). Examination of five of the remaining six ice-cover metrics (ice-on, ice-off, duration, mean fractional ice coverage, and maximum [max] fractional ice coverage) shows that the largest decadal changes also occur during 1998, with all of the changes being statistically significant (Table 1). Only one ice metric (date of maximum ice extent) showed the largest significant step change to occur during a year other than 1998 (in this case, 1988). JA evaporation also shows evidence of a step change around 1983–1986 but only at the 95% significance level and with no correspondingly significant shift in IFD. It is striking, however, to note the strong inverse correlation (Table 1) between decadal changes in winter IFD and the following summer's JA evaporation (and JAS water temperature), suggesting that long-term changes in ice cover may be a useful predictor of summer conditions on the Great Lakes, similar to the results of Austin and Colman (2007).

Due to the prevalence, magnitude, and strong statistical significance of the 1998 step change throughout six of the seven ice-cover metrics, two independent summer water temperature estimates, and JA evaporation rates, we hereafter refer to this step change as the 1998 regime shift in Lake Superior. Weaker step changes, which are found in a few of the parameters (such as during 1983 and 1988), are not examined further in the present study but may merit additional consideration in future work. As such, we use 1998 as the break point to calculate mean values before and after the step change. So, for example, when examining linear trends in ice cover duration for the period 1973–2010, we also calculate mean values for 1973–1997 and 1998–2010 to illustrate the regime shift that occurred in 1998. Although we are now comparing two periods of differing length (i.e., 25 yr and 13 yr), it is important to note that the timing of the shift was identified using a consistent, decadal interval (Table 1). Furthermore, the differences in the means between the two varying time periods remain statistically significant in all of the cases that were examined (and at the 99% level).

Long-term trends—Figure 2 shows the winter values and long-term trends in Lake Superior fractional ice coverage (Fig. 2a) and IFD (Fig. 2b), calculated using both standard linear regression and the 1998 step-change analysis. Clearly, the lake has experienced a significant decline in ice cover over the past few decades, as has been noted in previous studies (Wang et al. 2012). This includes strong changes in ice-on dates, ice-off dates, and ice duration (Fig. 2a) as well as a decline in IFD of ~ 8 d per decade (Fig. 2b). There has also been a reduction in the frequency of years with high fractional ice coverage during the period 1973–2010 (e.g., years with maximum ice coverage of 40% or more; Fig. 2a). As would be expected from the step-change analysis, however, the trends illustrated in Fig. 2 are anything but linear. Rather, when the linear trends are split into two time periods (at the 1998 break point), the long-term trends largely disappear or even reverse (e.g., in the case of ice-off date and IFD). In fact, none of the pre- or post-1998 linear trends in ice cover are statistically significant at the 90% level except for winter-mean ice extent (not shown), which actually shows an *increase* in ice extent after 1998 (at a rate of ~ 11% per decade). Together with the step changes illustrated in Fig. 2, this demonstrates quite clearly that long-term changes in Lake Superior ice cover are not well represented by a simple, linear trend from 1973 to 2010. Rather, it is more appropriate to characterize the change as being associated with the 1998 regime shift. In comparing the mean values of the ice-cover metrics before and after 1998, we find that both the ice-on and ice-off dates have changed by almost three weeks (i.e., 19–20 d later and earlier, respectively), resulting in a 39-d reduction in ice duration (Fig. 2). Similarly, IFD experienced a nearly 60% decline—from 41 to 17 d—in conjunction with the 1998 regime shift (Fig. 2). This reflects not only a 34% drop in ice duration from 112 to 74 d but also a 44% reduction in mean ice fraction from 34% to 19% (both of which are significant at the 99% level). Maximum winter ice extent dropped by nearly a factor of two, from a mean value of 69% before 1998 to 36% after 1998.

Analysis of the long-term trends in summer water temperature and evaporation rate (Fig. 3) shows results similar to those already discussed for ice cover. Namely, the JAS surface water temperature (both NDBC and GLERL) and JA evaporation show significant, linear increases when looking at the common time period 1979–2010 (Fig. 3a). However, these trends largely disappear when the 1998 break point is applied (Fig. 3b). In fact, in one example, the linear trend after 1998 is actually significantly downward (−1.1°C per decade for the GLERL JAS water temperature; $p = 0.1$), indicating that Lake Superior actually *cooled* following the 1998 warm year. This is corroborated by the NDBC buoy data, which show an even higher rate of

Table 1. Change in decadal means (second half minus first half) within a 20-yr moving window for Lake Superior JAS water temperature, JA evaporation, and seven different ice cover metrics. Years refer to the start of the second 10 year period (and the latter portion of the winter season, in the case of the ice metrics). Single (double) asterisks denote statistical significance at the 95% (99%) level, with bold numbers denoting the year with the largest step change. Buoy = water temperature data from the three Lake Superior buoys.

	Change in JAS water temperature		Change in JA evaporation	Change in ice metrics						
Year	Buoy (°C)	GLERL (°C)	GLERL (cm)	IFD (d)	5% ice-on (d)	5% ice-off (d)	Duration (d)	Mean ƒ15 (%)	Max ƒ15 (%)	Date of max ƒ15 (d)
1983		+1.56*	+1.49*	−11.6	−2.9	−12.5*	−9.6	−7.4	−9.6	+2.5
1984		+1.24	+1.29*	−8.4	−4.6	−11.8*	−7.2	−4.6	−1.4	+7.7
1985		+0.91	+1.34*	−5.3	−4.0	−11.1	−7.1	−2.2	−1.1	+2.6
1986		+0.93	+1.20*	−11.7	+0.8	−11.7	−12.5	−7.1	−10.1	+1.9
1987		+0.66	+0.93	−12.9	+3.6	−9.0	−12.6	−8.4	−13.8	+4.2
1988		−0.23	−0.05	−0.7	−1.0	+3.4	+4.4	−0.5	+1.3	**+12.5***
1989	−0.42	−0.52	−0.26	−2.7	+0.8	+0.2	−0.6	−2.5	−1.6	+11.9
1990	+0.03	−0.62	−0.26	−3.6	+1.9	−1.5	−3.4	−3.9	−7.0	+7.4
1991	+0.69	+0.04	−0.05	−7.1	+8.4*	−4.6	−13.0	−5.2	−11.8	+5.1
1992	+0.87	+0.04	−0.12	−7.8	+6.4	−3.5	−9.9	−7.0	−15.7	+2.9
1993	+0.95	+0.11	−0.14	−8.2	+18.0**	−3.0	−21.0	−6.4	−18.7	+1.4
1994	+1.32	+0.30	−0.01	−7.4	+19.3**	−2.8	−22.1	−5.5	−19.4	−0.5
1995	+1.43	+0.61	+0.22	−14.9	+19.6**	−6.3	−25.9	−10.8	−26.0	+2.2
1996	+1.60	+0.76	+0.54	−10.4	+16.2*	−4.6	−20.8	−7.4	−18.8	+2.5
1997	+2.62*	+1.80*	+1.62	−18.4	+19.2*	−13.8	−33.0*	−12.1	−27.8	+1.5
1998	**+3.23****	**+2.55****	**+2.51****	**−26.6****	**+21.9****	**−23.8***	**−45.7****	**−17.3****	**−39.2****	−8.0
1999	+2.11**	+2.22**	+2.11**	−21.7*	+20.2**	−13.1	−33.3*	−13.3	−29.4	−2.6
2000	+1.39*	+1.78*	+1.65*	−12.8	+17.2*	−6.6	−23.8	−6.7	−15.3	−0.2
2001	+1.05	+1.43	+1.27	−9.6	+13.6	−2.0	−15.6	−5.0	−11.2	2.0

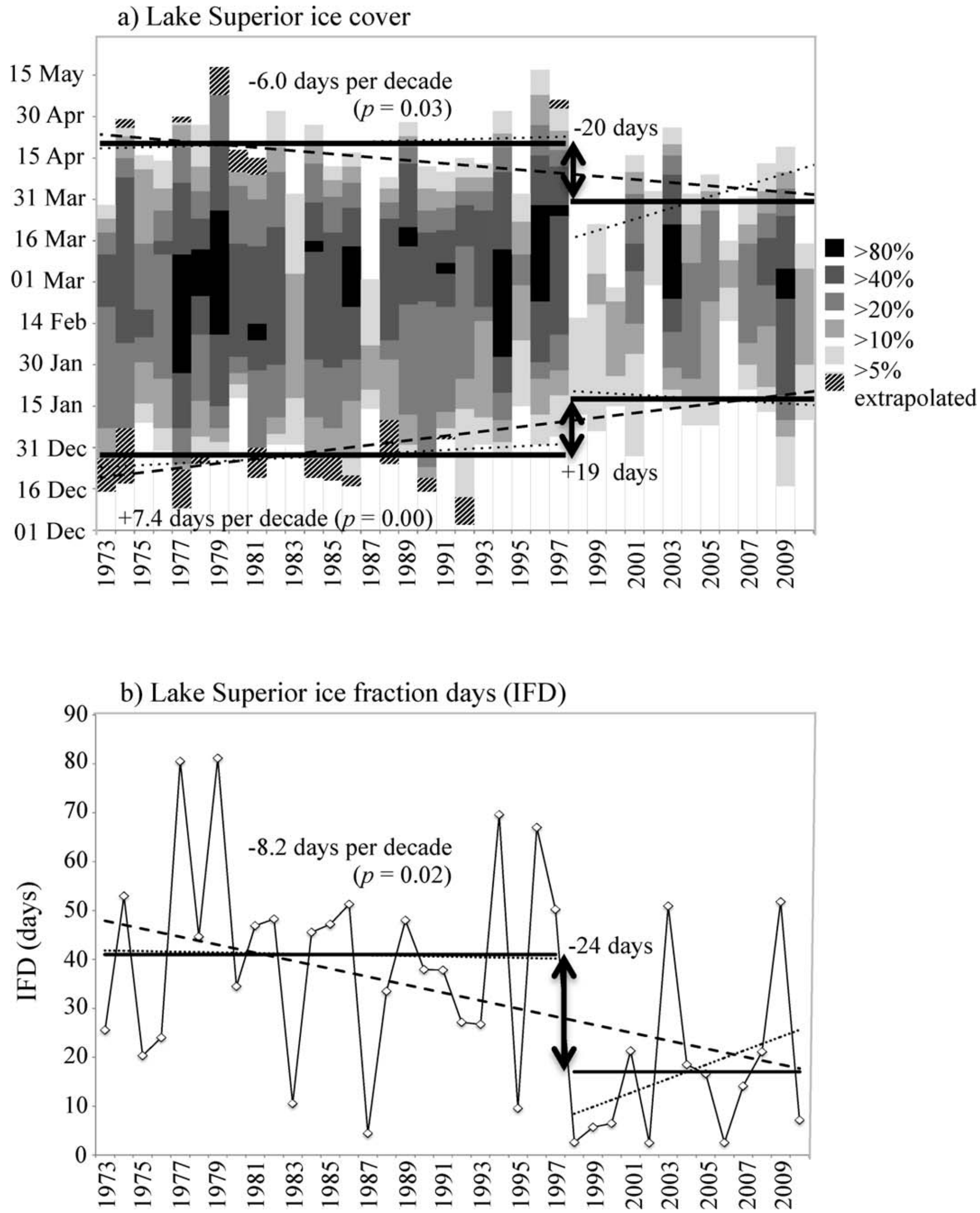

Fig. 2. (a) Lake Superior fractional ice coverage (in %) from 1973 to 2010. Also shown are the overall linear trends in 5% ice-on and ice-off dates (dashed lines), split linear trends for the years 1973–1997 and 1998–2010 (dotted lines), and long-term means for 1973–1997 and 1998–2010 (solid black lines). (b) As in (a), but for ice IFD. None of the split linear trends in either panel are statistically significant.

cooling ($-1.5°C$ per decade), although the statistical significance is weaker due to greater interannual variability. Similarly, JA evaporation shows a downward but insignificant trend after 1998. Given these observations (and the results of the step-change analysis in Table 1), the average JAS water temperature and JA evaporation rates were calculated for the pre- and post-1998 periods to assess the magnitude of the regime shift (Fig. 3c). The results show a significant warming of summer water temperatures by $\sim 2°C$ (GLERL) to 2.7°C (NDBC) following the 1998 event as well as a 91% increase in total JA evaporation (2.2–4.2 cm). All three step changes in Fig. 3c are statistically significant at the 99% level. Although July and August are typically times of the year when Lake Superior evaporation rates are quite low, the near doubling of JA evaporation rates is important, as it reflects an earlier start to the evaporation season, presumably in response to the warmer summer water temperatures (Lenters et al. 2013).

Discussion

The results of Fig. 1 clearly illustrate the strong seasonal connections among Lake Superior water temperature, evaporation, and ice cover, as evidenced by the 3- to 4-

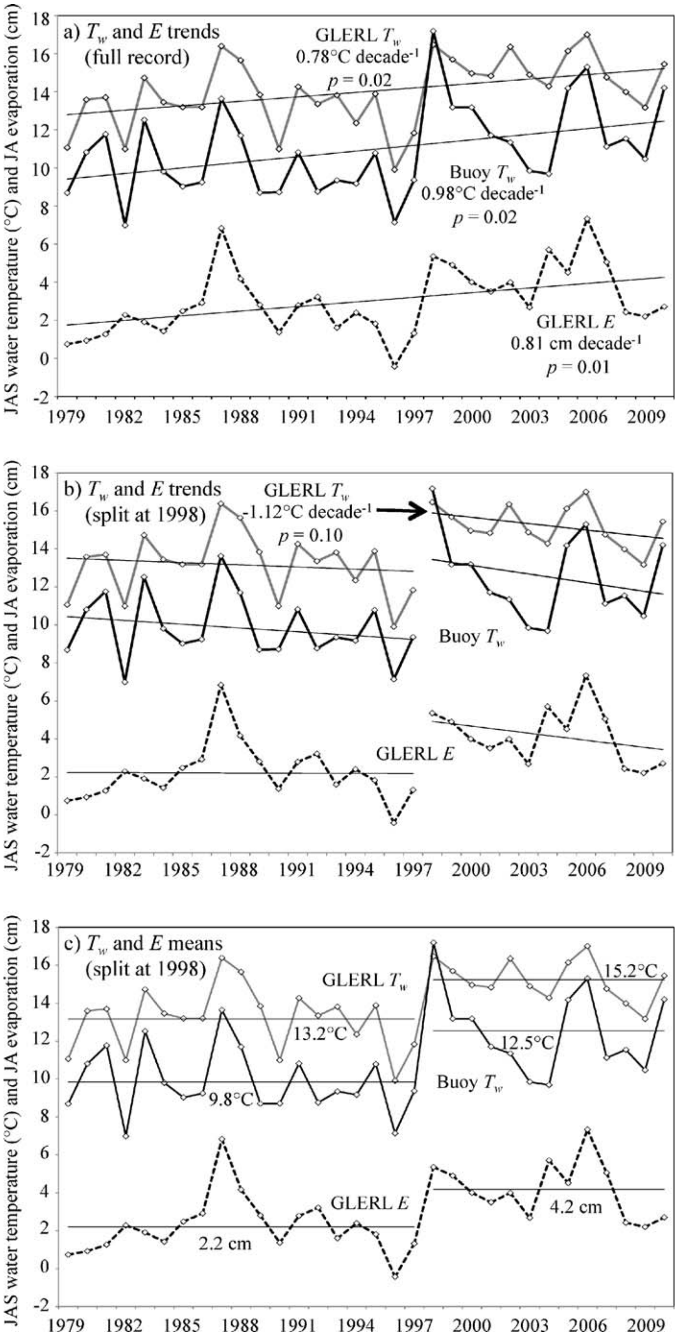

Fig. 3. Lake Superior JAS surface water temperature (T_w) and JA total evaporation (E) for the period 1979–2010. Also shown are the (a) overall linear trends, (b) split linear trends for the years 1979–1997 and 1998–2010, and (c) long-term means for 1979–1997 and 1998–2010. Trend values and step changes are only shown for instances that are statistically significant. Buoy = Lake Superior water temperature data from buoys.

month lags within the mean annual cycle. As has also been noted by Van Cleave (2012) and Spence et al. (2013), increases in evaporation contribute both to the decline in water temperature and to the onset of ice cover. Similarly, both reductions in evaporative cooling in spring and higher amounts of solar radiation play important roles in the rapid warming of surface water temperatures from April to August. Besides the seasonal cycle presented in Fig. 1, it should also be noted that Lake Superior exhibits strong interannual variability in temperature, evaporation, and ice cover. Summer (JAS) water temperatures, for example, can range from 7°C to 17°C on a year-to-year basis (Fig. 3). Similarly, ice duration ranges from weeks to months, sometimes lasting from December to May (Fig. 2), while in other years exceeding the 5% threshold for only a few weeks.

The step-change analysis presented in this study has uncovered two statistically distinct hydroclimatic regimes for Lake Superior, defined not only by ice cover characteristics but also by summer water temperature and evaporation rate. Namely, the lake experienced a pronounced change during the winter of 1997–1998, when ice cover reached (at that time) record-low values of winter-mean and winter-maximum ice fraction, IFD, and ice duration (Fig. 2) as well as a record-early ice-off date. This was followed by record-warm JAS water temperatures (Fig. 3) and near-record JA evaporation rates (surpassed only by 1987). There is some weak evidence that the lake "recovered" slightly from the anomalous 1997–1998 event, showing later ice-off dates and greater winter-mean ice extent in subsequent years (Fig. 2a) as well as increased IFD (Fig. 2b), cooler JAS water temperatures (Fig. 3b), and reduced JA evaporation (Fig. 3b). Most of these recovery trends are not, however, statistically significant, suggesting that the 1997–1998 regime shift was largely sustained through the summer of 2010.

Although our analysis has not yet been extended to the present, it is worth noting that the Great Lakes experienced one of its lowest ice-covered winters in 2011–2012, followed by an extremely warm summer. Two years later, however, the region experienced a severe winter in 2013–2014 that, by some metrics, eclipsed even the winter of 1978–1979. Thus, the Great Lakes system continues to exhibit high variability, illustrating the necessity for maintaining a long-term perspective when evaluating long-term change. Variability notwithstanding, however, the Lake Superior regime shift identified in 1998 is not an isolated occurrence. Rather, a similar transition to warmer conditions in the late 1990s was noted by Mueller et al. (2009) for high Arctic lakes, with a corresponding shift to a reduced lake-ice regime. Furthermore, an even larger study of 75 Northern Hemisphere lakes (Benson et al. 2012) also showed a pronounced drop in lake ice duration in the late 1990s, suggesting that the regime shift identified here may reflect a broader geographic pattern, similar to what was noted in European lakes in response to the late-1980s climate regime shift (North et al. 2014).

It is notable that the 1998 step change in Lake Superior ice cover, water temperature, and evaporation occurred around the same time as an anomalous climatic event (i.e., the warm El Niño winter of 1997–1998). Although this does not imply that the entire, prolonged regime shift is causally linked to a single El Niño event, it did encourage an analysis of a number of teleconnection indices to assess their potential role. While the El Niño–Southern Oscillation (ENSO) pattern has a strong effect on winter air

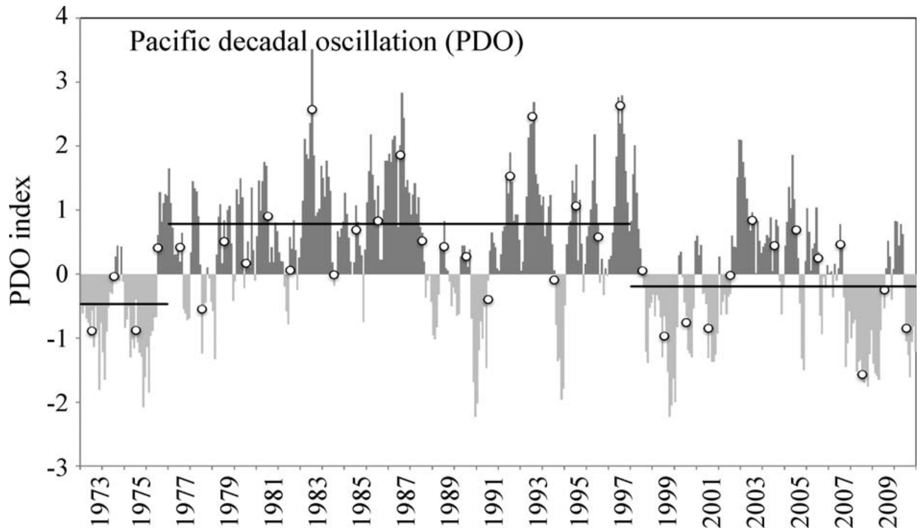

Fig. 4. Monthly PDO index for the period 1973–2010 (shaded gray). Dots indicate the summer PDO index (PDOs) for each year, with step changes occurring in 1977 and 1998. Solid black lines indicate long-term mean values of the PDOs for the periods 1944–1976, 1977–1997, and 1998–2010.

temperatures and ice severity in the Great Lakes region (Assel 1998; Rodionov and Assel 2003), long-term variations in the Nino 3.4 index over the past few decades (not shown) do not readily explain the regime shift seen in 1997–1998. In fact, in recent years within the 1973–2010 period, the negative phase of ENSO (i.e., La Niña) has dominated, which, by itself, would not be consistent with the warmer winters experienced over Lake Superior since 1997–1998. Similarly, we examined the Arctic Oscillation (AO) during the same period of study and found it to be split almost equally between cold and warm phases, suggesting that the AO is also not directly associated with the regime shift.

Warm phases of the Pacific Decadal Oscillation (PDO; Mantua and Hare 2002), in the absence of strong El Niño events, are coincident with more northerly flow over North America and, therefore, colder temperatures and greater ice cover over the Great Lakes (Rodionov and Assel 2003). The PDO has also been found to be temporally coherent with Lake Superior water levels, air temperature, and evaporation on interdecadal time scales (Ghanbari and Bravo 2008). Furthermore, a study of Lake Mendota (Wisconsin), located southwest of Lake Superior, found the PDO to be temporally coherent with both ice duration and ice-off dates on interannual and interdecadal time scales (Ghanbari et al. 2009). Beginning in 1977, a warm phase of the PDO began, coinciding with a significant, upward shift in the PDO index (Fig. 4). This warm phase persisted until 1998, when the PDO went through a strong, downward shift, which, aside from 2003 and 2004, was largely sustained. This suggests that the 1998 regime shift in Lake Superior may be at least partly related to an observed transition to a negative phase of the PDO. It should be noted that Bonsal et al. (2006) found *positive* phases of the PDO to be associated with shorter ice duration in Canadian lakes rather than negative phases. This response, however, was confined largely to western portions of Canada rather than the vicinity of Lake Superior.

On applying the same step-change procedure (described earlier) to the PDO index, we found significant, decadal-scale changes in the annual PDO as well as the PDO summer index (PDOs) and winter index (PDOw). Significant upward shifts in all three indices were identified around 1977 and 1926 (which was also a record-low year for Lake Superior water levels), while significant downward shifts were found in 1944 (during a period of relatively high water levels). The PDOs also underwent a significant, downward step-change in 1998, as shown by the solid, horizontal line in Fig. 4, while the PDOw did not. The annual PDO index also shifted downward in 1998, but the change was significant at only the 85% level. Thus, it can generally be concluded that the PDO warm phase (associated with colder Great Lakes winters) dominated from 1977 to 1997, while the cold-phase PDO (warmer Great Lakes winters) dominated from 1998 on. Although the ice cover and NDBC buoy observations used in this study are too short to assess potential decadal changes around 1977, it is noteworthy that the winters of 1976–1977 and 1978–1979 were two of the most severe winters on record in terms of ice cover (Fig. 2). Summer water temperatures in 1979 were also below normal (Fig. 3).

The potential connections identified here between the PDO and the 1997–1998 Lake Superior regime shift do not provide an exhaustive explanation for the observed step change. It is not clear, for example, why a downward shift in the PDO summer index around 1998 (but not the PDOw) might be associated with decreased wintertime ice coverage. Lake Superior is a large, deep lake, and there is strong potential for intrinsic thermal "memory" in the system due to the large heat capacity and delayed response to atmospheric forcing (Blanken et al. 2011; Spence et al. 2013). Warm summer water temperatures, for example, could lead to a delayed ice onset in the winter, similar to how winter ice cover has been proposed to affect spring stratification and summer water temperature (Austin and Colman 2007). This strong interplay among ice cover, water temperature, and evaporation should continue to be investigated as a potential contributing explanation for the 1997–1998 regime shift within the Lake Superior system, including its prolonged but weak "recovery." On the other hand, there are a multitude of other external climatic factors that could also be examined, including changes in air temperature, cloud cover, humidity, and wind speed, all of which affect water temperature, evaporation, and ice cover to varying degrees. Finally, additional research is needed to examine the ecological implications of the observed step changes in Lake Superior ice cover and water temperature, as previous studies have shown climate regime shifts to have important effects on lake mixing regimes and nutrient dynamics (North et al. 2014).

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References

ANDERSON, W. L., D. M. ROBERTSON, AND J. J. MAGNUSON. 1996. Evidence of recent warming and El Niño-related variations in ice breakup of Wisconsin lakes. Limnol. Oceanogr. **41:** 815–821, doi:10.4319/lo.1996.41.5.0815

ARP, C. D., B. M. JONES, Z. LU, AND M. S. WHITMAN. 2012. Shifting balance of thermokarst lake ice regimes across the Arctic Coastal Plain of northern Alaska. Geophys. Res. Lett. **39:** L16503, doi:10.1029/2012GL052518

ASSEL, R. A. 1998. The 1997 ENSO event and implication for North American Laurentian Great Lakes winter severity and ice cover. Geophys. Res. Lett. **25:** 1031–1033, doi:10.1029/98GL00720

———. 2005. Great Lakes ice cover climatology update: Winters 2003, 2004, and 2005. NOAA Technical Memorandum GLERL-135. NOAA, Great Lakes Environmental Research Laboratory, Available from http://www.glerl.noaa.gov/ftp/publications/tech_reports/glerl-135/tm-135.pdf

———, K. CRONK, AND D. NORTON. 2003. Recent trends in Laurentian Great Lakes ice cover. Clim. Change **57:** 185–204, doi:10.1023/A:1022140604052

AUSTIN, J. A., AND S. M. COLMAN. 2007. Lake Superior summer water temperatures are increasing more rapidly than regional air temperatures: A positive ice-albedo feedback. Geophys. Res. Lett. **34:** L06604, doi:10.1029/2006GL029021

BENSON, B. J., AND OTHERS. 2012. Extreme events, trends, and variability in Northern Hemisphere lake-ice phenology (1855–2005). Clim. Change **112:** 299–323, doi:10.1007/s10584-011-0212-8

BLANKEN, P. D., C. SPENCE, N. HEDSTROM, AND J. D. LENTERS. 2011. Evaporation from Lake Superior: 1. Physical controls and processes. J. Great Lakes Res. **37:** 707–716, doi:10.1016/j.jglr.2011.08.009

BONSAL, B. R., T. D. PROWSE, C. R. DUGUAY, AND M. P. LACROIX. 2006. Impacts of large-scale teleconnections on freshwater-ice break/freeze-up dates over Canada. J. Hydrol. **330:** 340–353, doi:10.1016/j.jhydrol.2006.03.022

CROLEY, T. E., II. 1989. Verifiable evaporation modeling on the Laurentian Great Lakes. Water Resour. Res. **25:** 781–792, doi:10.1029/WR025i005p00781

———, AND R. A. ASSEL. 1994. A one-dimensional ice thermodynamics model for the Laurentian Great Lakes. Water Resour. Res. **30:** 625–639, doi:10.1029/93WR03415

DUGUAY, C. R., T. D. PROWSE, B. R. BONSAL, R. D. BROWN, M. P. LACROIX, AND P. MENARD. 2006. Recent trends in Canadian lake ice cover. Hydrol. Process. **20:** 781–801, doi:10.1002/hyp.6131

GHANBARI, R. N., AND H. R. BRAVO. 2008. Coherence between atmospheric teleconnections, Great Lakes water levels, and regional climate. Adv. Water Resour. **31:** 1284–1298, doi:10.1016/j.advwatres.2008.05.002

———, ———, J. J. MAGNUSON, W. G. HYZER, AND B. J. BENSON. 2009. Coherence between lake ice cover, local climate, and teleconnections (Lake Mendota, Wisconsin). J. Hydrol. **374:** 282–293, doi:10.1016/j.jhydrol.2009.06.024

HANRAHAN, J. L., S. V. KRAVTSOV, AND P. J. ROEBBER. 2010. Connecting past and present climate variability to the water levels of Lakes Michigan and Huron. Geophys. Res. Lett. **37:** L01701, doi:10.1029/2009GL041707

HUNTER, T. S., AND T. E. CROLEY, II. 1993. Great Lakes monthly hydrologic data. NOAA Data Report ERL GLERL, National Technical Information Service, Available from http://www.glerl.noaa.gov/data/arc/hydro/mnth-hydro.html.

LENTERS, J. D. 2004. Trends in the Lake Superior water budget since 1948: A weakening seasonal cycle. J. Great Lakes Res. **30:** 20–40, doi:10.1016/S0380-1330(04)70375-5

———, J. B. ANDERTON, P. D. BLANKEN, C. SPENCE, AND A. E. SUYKER. 2013. Assessing the impacts of climate variability and change on Great Lakes evaporation, p. 1–11. *In* D. Brown, D. Bidwell, and L. Briley [eds.], 2011 project reports. Great Lakes Integrated Sciences and Assessments Center, Available from http://glisaclimate.org/media/GLISA_Lake_Evaporation.pdf

LIU, Y. B., G. P. WU, AND X. S. ZHAO. 2013. Recent declines in China's largest freshwater lake: Trend or regime shift? Environ. Res. Lett. **8:** 014010, doi:10.1088/1748-9326/8/1/014010

MAGNUSON, J. J., AND OTHERS. 2000. Historical trends in lake and river ice cover in the Northern Hemisphere. Science **289:** 1743–1746, doi:10.1126/science.289.5485.1743

MANTUA, N., AND S. HARE. 2002. The Pacific Decadal Oscillation. J. Oceanogr. **58:** 35–44. , doi:10.1023/A:1015820616384

MCCORMICK, M. J., AND G. L. FAHNENSTIEL. 1999. Recent climatic trends in nearshore water temperatures in the St. Lawrence Great Lakes. Limnol. Oceanogr. **44:** 530–540, doi:10.4319/lo.1999.44.3.0530

MISHRA, V., K. A. CHERKAUER, AND L. C. BOWLING. 2010. Changing thermal dynamics of lakes in the Great Lakes region: Role of ice cover feedbacks. Glob. Planet. Change **75:** 3–4.

MUELLER, D. R., P. VAN HOVE, D. ANTONIADES, M. O. JEFFRIES, AND W. F. VINCENT. 2009. High Arctic lakes as sentinel ecosystems: Cascading regime shifts in climate, ice cover, and mixing. Limnol. Oceanogr. **54:** 2371–2385, doi:10.4319/lo.2009.54.6_part_2.2371

North, R. P., D. M. Livingstone, R. E. Hari, O. Koster, P. Niederhauser, and R. Kipfer. 2013. The physical impact of the late 1980s climate regime shift on Swiss rivers and lakes. Inland Waters **3:** 341–350, doi:10.5268/IW-3.3.560

———, R. L. North, D. M. Livingstone, O. Koster, and R. Kipfer. 2014. Long-term changes in hypoxia and soluble reactive phosphorus in the hypolimnion of a large temperate lake: Consequences of a climate regime shift. Glob. Change Biol. **20:** 811–823, doi:10.1111/gcb.12371

Rodionov, S., and R. A. Assel. 2003. Winter severity in the Great Lakes: A tale of two oscillations. Clim. Res. **24:** 19–31, doi:10.3354/cr024019

Schneider, P., and S. Hook. 2010. Space observations of inland water bodies show rapid surface warming since 1985. Geophys. Res. Lett. **37:** L22405, doi:10.1029/2010GL045059

———, ———, R. G. Radocinski, G. K. Corlett, G. C. Hulley, S. G. Schladow, and T. E. Steissberg. 2009. Satellite observations indicate rapid warming trend for lakes in California and Nevada. Geophys. Res. Lett. **36:** L22402, doi:10.1029/2009GL040846

Spence, C., P. D. Blanken, N. Hedstrom, V. Fortin, and H. Wilson. 2011. Evaporation from Lake Superior: 2. Spatial distribution and variability. J. Great Lakes Res. **37:** 717–724, doi:10.1016/j.jglr.2011.08.013

———, ———, J. D. Lenters, and N. Hedstrom. 2013. The importance of spring and autumn atmospheric conditions for the evaporation regime of Lake Superior. J. Hydrometeorol. **14:** 1647–1658, doi:10.1175/JHM-D-12-0170.1

Surdu, C. M., C. R. Duguay, L. C. Brown, and D. F. Prieto. 2014. Response of ice cover on shallow lakes of the North Slope of Alaska to contemporary climate conditions (1950–2011): Radar remote-sensing and numerical modeling data analysis. Cryosphere **8:** 167–180, doi:10.5194/tc-8-167-2014

Van Cleave, K. 2012. Interactions among evaporation, ice cover, and water temperature on Lake Superior: Decadal, interannual, and seasonal variability. Dissertations and Theses in Natural Resources, Available from http://digitalcommons.unl.edu/natresdiss/52

Wang, J., X. Bai, H. Hu, A. Clites, M. Colton, and B. Lofgren. 2012. Temporal and spatial variability of Great Lakes ice cover, 1973–2010. J. Clim. **25:** 1318–1329, doi:10.1175/2011JCLI4066.1

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