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A century of temperature variability in Lake Superior

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Abstract

A 100-yr-long time series of water temperature measured just downstream of Lake Superior is used to produce proxy time series of open-lake temperature. This analysis suggests that open-water Lake Superior summer temperatures have increased by roughly 3.5°C over the last century, most of that warming occurring in the last three decades. Correspondingly, the length of the positively stratified season has increased from 145 d to 170 d. The observed amount of warming is greater than the observed change in regional temperature over the same time period by roughly a factor of two. The discrepancy can be understood in the context of reduced winter ice cover, and implies that spatially and temporally averaged ice cover in Lake Superior has decreased from 23% to 12% over the last century.

Global average air temperatures have recently warmed beyond their natural limits in historic atmospheric records (IPCC 2007). However, the expected response of temperature of oceans and other water bodies is less clear. Water temperatures of large natural systems may respond to the atmospheric warming trend in unexpected ways, due to nonlinearities, geographic variability, and feedback mechanisms. Unlike air temperature records, such as the Goddard Institute for Space Science (GISS) database (Hansen et al. 1999), reliable century-scale records of measured water temperature are exceedingly rare (Nixon et al. 2004); long, continuous records in lakes more so.

Some analyses of lake-water temperature trends over nearly a century have been performed in the hypolimnetic waters of tropical lakes such as Lake Tanganyika (O'Reilly et al. 2003; Verburg et al. 2003) and Lake Malawi (Vollmer et al. 2005). Due to the absence of strong seasonal variation in surface heat flux and a lack of seasonal overturn, the deep water of these lakes respond gradually, and roughly proportionally, to changes in climate, and can be reliably analyzed using relatively temporally sparse data. In contrast, mid-latitude lakes with large inter-annual and annual variability compared to the magnitude of a long-term trend (for instance, the Laurentian Great Lakes), require dense temporal coverage in order to extract a statistically significant trend. These sorts of long time series are especially important in large lakes, since it has been shown (Austin and Colman 2007) that the thermal response of a complex system like a large, seasonally ice-covered lake can significantly exceed the rate of temperature change experienced by the regional atmospheric climate. This can be explained in terms of a coincident reduction of winter ice cover, which in turns leads to earlier spring overturn and a longer warming season.

One example of such a time series of daily water temperature has been collected in the St. Mary's River, just downstream of Lake Superior, at a pair of locations near Sault Ste. Marie (McCormick 1996) from 1906 to the present. These data (through 1992) were previously discussed (McCormick and Fahnenstiel 1999) along with several other long time series collected at power plants and municipal water supplies from around the Great Lakes. Their analysis revealed an increase in annual mean temperature on the order of 0.006°C yr^{-1} over the time period 1906–1992, and a lengthening of the positively stratified season from roughly 192 d to 206 d over the same time period. While this time series is, to our knowledge, as long as any measured (as opposed to a paleolimnological time series of temperature proxies) in any lake, it is not clear how representative it is of open-lake conditions due to its location.

The work presented here is both an update and an extension of the previous work on the Sault Ste. Marie (SSM) time series. McCormick and Fahnenstiel (1999) considered this time series among others but, at the time, only had access to data through 1992. As we show, noteworthy change has occurred in the subsequent 15 yr. Extending their analysis, we use this downstream, coastal temperature data to infer changes in open waters of Lake Superior. We show that while temperature at SSM does not accurately reflect the absolute surface temperature in Lake Superior (it is significantly warmer at SSM than the open lake), it is highly correlated with open-lake temperatures and can serve as an effective proxy for interannual variability in the lake. Using this proxy instead of the raw coastal temperature results in significantly different results when studying the timings of summer and autumn overturns in the open lake. While such a proxy is not perfect, it does still provide insight into long-term trends in open-lake conditions. The estimated open-lake stratified season is significantly shorter than previously reported, and the rate of increase in the length of the stratified season is greater than

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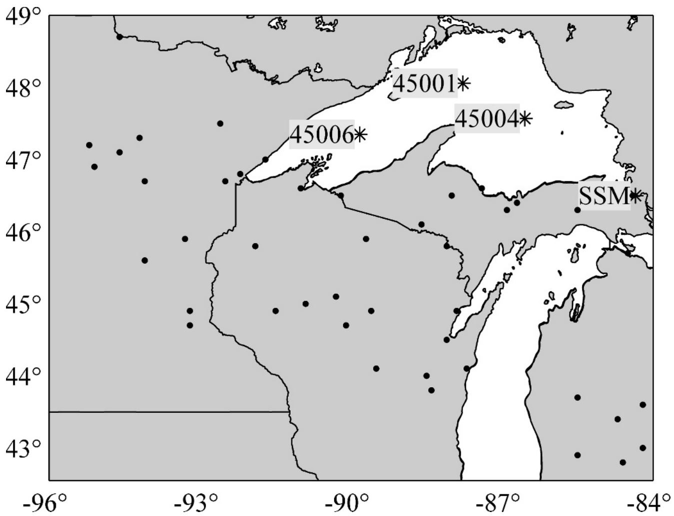

Fig. 1. Map of Lake Superior indicating locations of SSM and NOAA stations. Small markers on land indicate locations of GISS air temperature stations used in deriving mean air temperature.

previously reported. Moreover, the seasonally averaged temperatures measured at the eastern buoy are highly correlated with those measured at the central and western buoys, suggesting that the data is a reasonable proxy for the rest of the lake. More speculatively, we will use the relationship between open-lake temperature and ice cover presented by Austin and Colman (2007) to infer long-term changes in ice cover.

Methods

We will consider two primary time series: a record from the Army Corps of Engineers St. Mary Falls Canal Hydropower Plant at Sault Ste. Marie (hereafter SSM) and records from the open-water Eastern Lake Superior National Data Buoy Center (NDBC) buoy (45004), which will be used as a standard against which to compare the longer coastal time series (Fig. 1). Average summer temperatures at the eastern buoy are highly correlated with the central (45001; $r^2 = 0.89$) and western (45006; $r^2 = 0.69$) buoy, so it serves as representative of whole-lake conditions, at least with respect to interannual variability. The buoy data overlap with the SSM time series from 1980 to the present. Because the data from these buoys has been previously considered (Austin and Colman 2007) the eastern buoy will be used primarily to determine the relationship of the SSM time series to open-lake conditions.

Daily water temperatures have been recorded from 1906 just upstream of the Soo Locks in the St. Marys River, which drains Lake Superior into the rest of the Great Lakes (Fig. 1). The data is a combination of two records, one from 1906 to 1963 and another, taken 1.7 km away, from 1964 to the present (McCormick and Fahnenstiel 1999). The sensors, in both cases, were located at roughly 6-m depth. From satellite imagery, there does not appear to be any major construction upstream of these sites which would impose a bias on these data. This data is available through the Great Lakes Environmental Research Laboratory (McCormick 1996) from 1906 to 1992 and is considered at length in McCormick and Fahnenstiel (1999). The remaining data (1993–Jun 2006) was transcribed from logbook entries. Data in 1994 and 1996 are sparse, but otherwise the dataset is complete. Temperatures are often not recorded during December–February period, when water temperatures typically drop below freezing. Geographically, the origin of the St. Marys River is in Whitefish Bay, a large, relatively shallow bay in the southeast corner of Lake Superior.

The NDBC buoys are the most reliable sources of information with regards to traceable sensor calibration and data documentation, and are the focus of previous work (Austin and Colman 2007); all data is available in the public domain (www.ndbc.noaa.gov). There are three NDBC buoys on Lake Superior (Fig. 1): 45006 in the western basin, 45001 in the center of the lake, and 45004 in the eastern basin of the lake. These buoys started recording data in June 1981, May 1979, and April 1980, respectively, with an average record length to present of 27 yr. All time series used in this analysis end in December 2005. The buoys record water temperature hourly at a depth of 1 m with a reported accuracy of 1°C and resolution of 0.1°C. With few exceptions, buoys are deployed in March or April, before the start of the positively stratified season (i.e., surface-water temperature >3.98°C), and pulled out in October or November, before the onset of ice, and also typically before the beginning of the negatively stratified season (the exception to this was the winter of 1990–1991, when the eastern buoy was not recovered, providing a single year with information about the overturn date). This precludes any direct analysis from these datasets of trends in stratified season length.

Results

The time period over which the time series can be most appropriately compared is May–October, the period during which the National Oceanic and Atmospheric Administration (NOAA) buoys are typically deployed. We will use the NOAA surface-water temperature data from the eastern buoy as a standard against which to measure the usefulness of the SSM time series as an indicator of variability in the open lake, acknowledging that both SSM is separated from the Eastern NDBC buoy by roughly 100 km, and that the water which reaches the SSM site has likely undergone significant warming as it passed through Whitefish Bay.

The relationship between the temperature observed at SSM site and in the eastern open lake (at NDBC 45004) is complex. Lake Superior has several geographic thermal regimes as described by (Bennett 1978), and SSM is downstream of Whitefish Bay, a broad shallow bay at the southeastern corner of the lake, which Bennett (1978) describes as a thermal regime distinct from the open lake. As an example, water temperature from the eastern buoy (45004) and SSM (Fig. 2) for 1980 (other years show similar trends) shows that SSM reaches 3.98°C considerably earlier than the open-lake location, and in general is considerably warmer than the open-lake location early in the season. Plotting daily average temperature for 1980–2005 from SSM and NDBC 45004 against each other

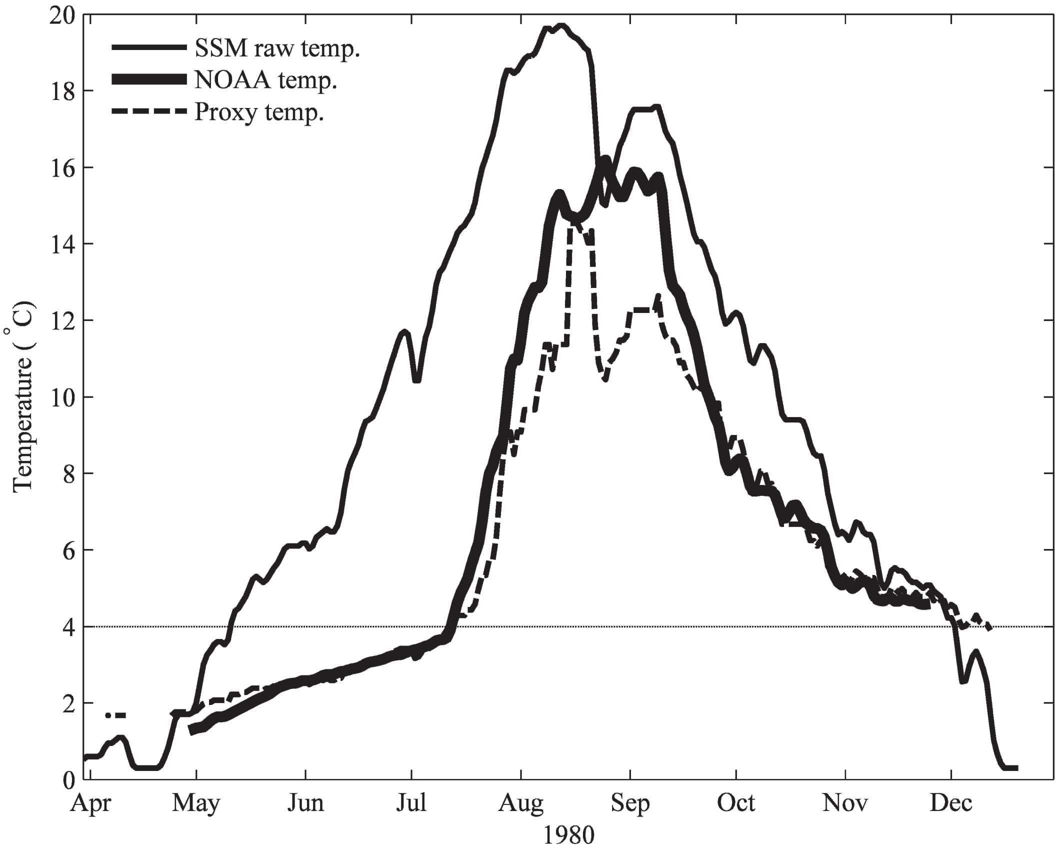

Fig. 2. Water temperature at 45004 (Eastern Lake; dashed curve), raw SSM data (solid curve), and SSM proxy for open lake (dotted curve) for 1980.

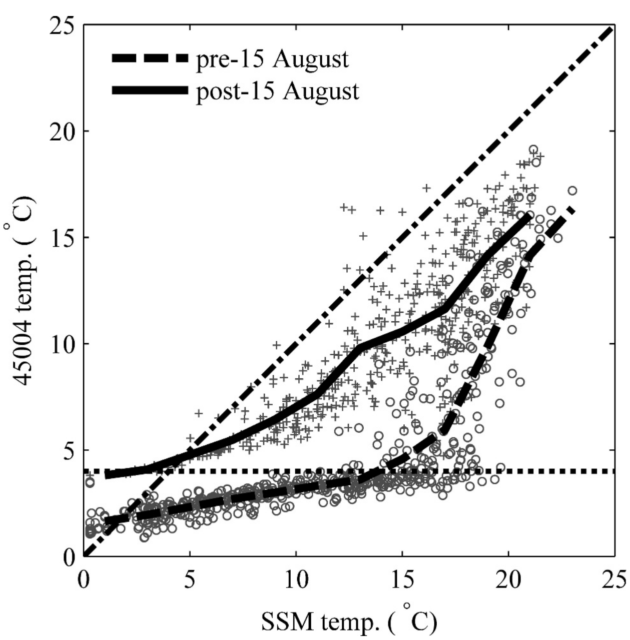

Fig. 3. Raw daily temperature data at SSM and NDBC 45004. Heavy curves are data binned into 2°C intervals for pre–15 August and post–15 August data. Dash-dotted line is the identity line.

(Fig. 3) shows that the relationship between the two is a strong function of season; in the spring (Fig. 3; circles) SSM warms quickly to roughly 14°C before the open-lake site reaches 3.98°C (Figs. 2, 3); after this, SSM warms more slowly, as the open lake stratifies and warms quickly. In mid-August, as the lake begins to cool, the relationship between the two locations changes. The open lake cools through 3.98°C slightly before the SSM site does (very little data exists in the open lake this late in the season). This typically occurs in late November to early December.

The relationship between these two time series suggests that the century-long time series at SSM could be used to develop a proxy time series for the open lake. As with any proxy method, an assumption is made in extending these results to the entire SSM time series that the relationship between SSM and the open lake does not change in any systematic way. The relationship between them demands a more complex algorithm than a simple linear regression.

We chose to break the data from each year into a warming phase and a cooling phase, as suggested by the hysteresis displayed in Fig. 3. Fifteen August was chosen to distinguish between the warming season and the cooling season because it minimizes the root mean-square error between the resulting proxy series and the measured data at the NDBC site. The discontinuity necessarily introduces error in August. Data from each season (pre–15 Aug and post–15 Aug) was binned separately into 2°C bins to develop a smoothed, monotonic relationship between the

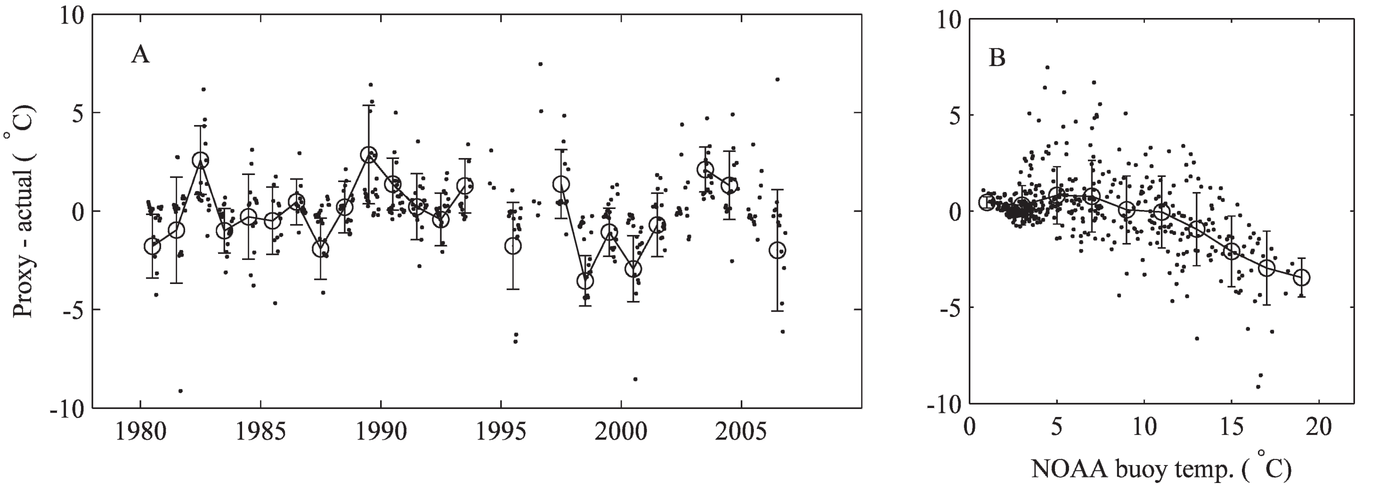

Fig. 4. Analysis of proxy bias. (A) annual mean average error, $T_{proxy} - T_{NOAA}$ buoy measurement (i.e., positive values are where the proxy overestimates the temperature). (B) error as a function of temperature at NOAA buoy.

two sites for the distinct seasons, which are shown in Fig. 3 as dashed and solid heavy curves. The binned data is then used to develop a proxy time series by linearly interpolating the raw SSM data. An example of such an interpolation for 1980 (Fig. 2; dashed line) shows that the proxy data from SSM captures the fundamental variability and timing of the open-lake data, but also has some deviations from the measured open-lake temperature, likely due in part to mesoscale variability.

The proxy is not without bias; however, that bias is unavoidable, and can be characterized. The mean error (i.e., $T_{proxy} - T_{NOAA}$) for July–September temperatures as a function of year (Fig. 4A) shows no significant trend. However, the error as a function of observed temperature at the NOAA buoy (Fig. 4B) shows that as the buoy temperature gets higher, the proxy underestimates the buoy temperature. The average error can be as great as $-3°C$ for buoy temperatures above 18°C; however, a very small portion of the total dataset falls into this category (only 1% of the Jul–Sep data fell above 18°C; about 14% of the data is above 15°C). Because this bias is a function of the dependent variable, it cannot be corrected, since the NOAA

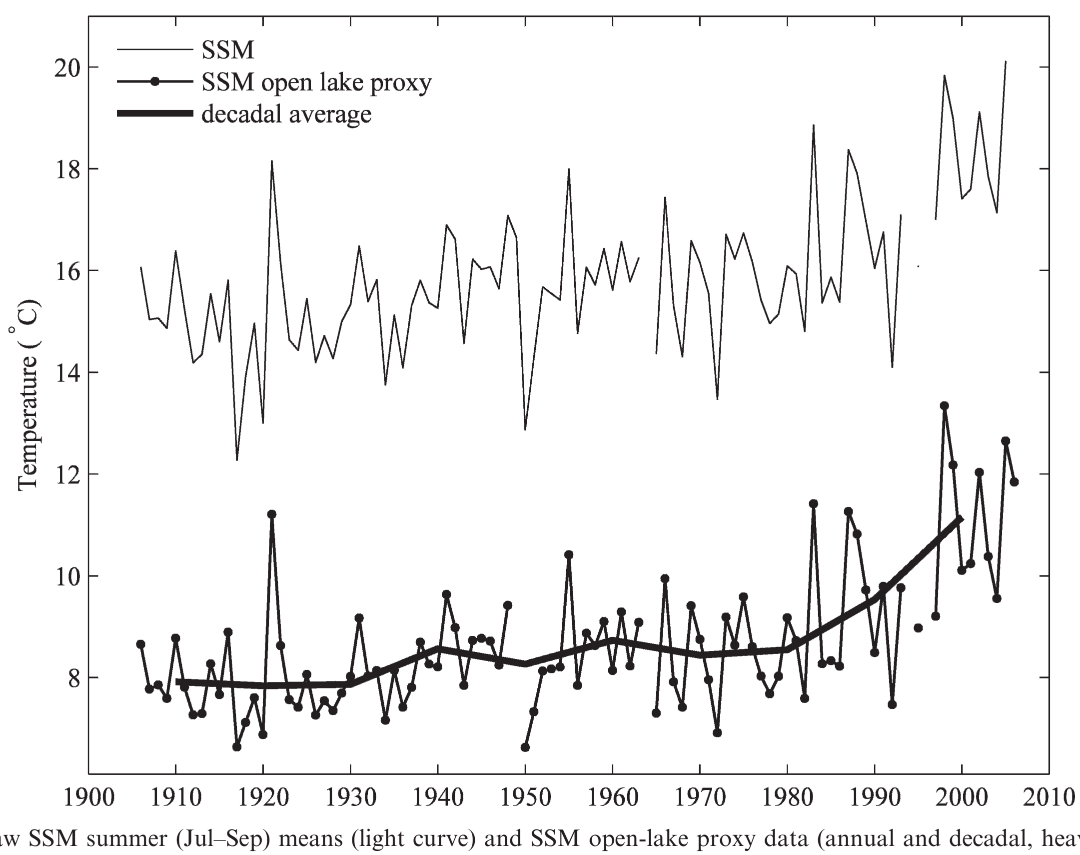

Fig. 5. Raw SSM summer (Jul–Sep) means (light curve) and SSM open-lake proxy data (annual and decadal, heavy curves).

Table 1. Rates of warming (10^{-2}°C yr^{-1}).

Location	Time span	Raw	Proxy
NOAA (western)	1980–2005	11±4	
NOAA (eastern)	1980–2005	10±7	
Sault Ste. Marie	1906–2005	2.7±0.4	2.7±0.4
	1980–2005	11±4	11±4
Regional air temperature	1906–2005	0.9±0.2	
	1980–2005	6.0±2	

data only goes back to 1980. This implies that the proxy may be underestimating the open-lake temperature during warm years. Most of the warm temperatures observed at SSM occur during the last two decades, and therefore underestimating temperatures during warm years will lead to an underestimate of the long-term trend. Because the SSM temperature is being treated as the independent variable, the proxy does not have a bias with respect to the SSM data (not shown).

The resulting mean summer water temperatures (Fig. 5; Jul–Sep average shown) shows significant warming over the last century, the majority of this warming occurring in the last three decades (Table 1). Decadal averages of the July–September means (Fig. 5) show that the rate of warming accelerates during the last 30 yr. While regression analysis of either the raw or proxy data yields a warming rate of 2.7×10^{-2}°C yr^{-1} (Table 1; corresponding to an increase of about 2.7°C over 100 yr), the actual difference in the decadal averages over the century is closer to 3.5°C, due to the recent rapid increase in temperature. Using data regarding summer water temperatures at the Eastern NOAA buoy and averaged ice cover (Assel 2005) in Lake Superior (Austin and Colman 2007; their fig. 4F), but using water temperature as the explanatory variable instead of ice cover, the increase in summer water temperature from 8°C to 11.5°C suggests a decrease in ice cover from about 23% to 12% over the last century, much of that change within the last quarter-century.

On a month-by-month basis, all months show warming over the last century (summer months at a greater rate). Warming is strongest in the summer (Fig. 6; light line) and weakest in the spring, but always positive. Performing the same analysis over just the 1980–2005 time period (Fig. 6; solid) results in significantly greater rates of change, but the same basic seasonal pattern, with the largest increases observed in the summer months of July–September. July–September rates of change for the 1980–2005 period are on the order of 0.1°C yr^{-1} (Table 1), again consistent with the results of Austin and Colman (2007).

The SSM data is the most useful data we have for determining long-term change in the length of the summer stratified season; it is the only time series that is both long and of a sufficiently high temporal resolution to accurately determine the date of spring and autumn overturn. There is significant spatial variability in the overturn date across the lake; for instance, the lake stratifies at the western buoy (45006) roughly 2 weeks earlier than at the eastern buoy (Austin and Colman 2007); and the development of the thermal bar implies that coastal regions stratify earlier than open-lake locations (Ullman et al. 1998). In addition, the

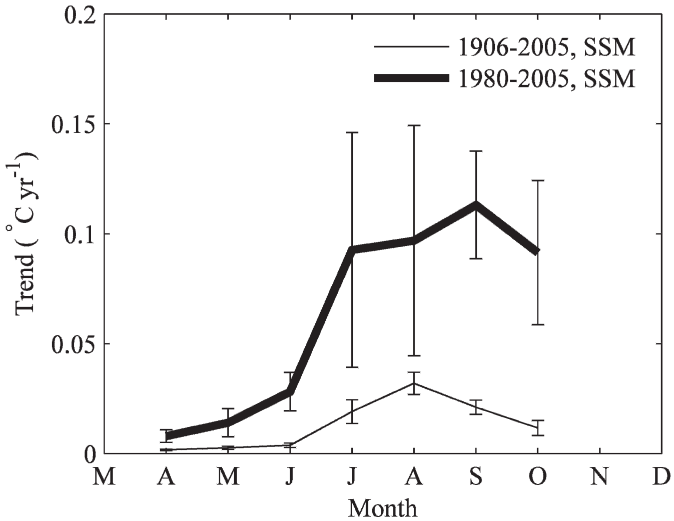

Fig. 6. Rates of warming as a function of month from the SSM site. Light line: 1906–2005. Heavy line: 1980–2005 (similar to the analysis of [Austin and Colman 2007]).

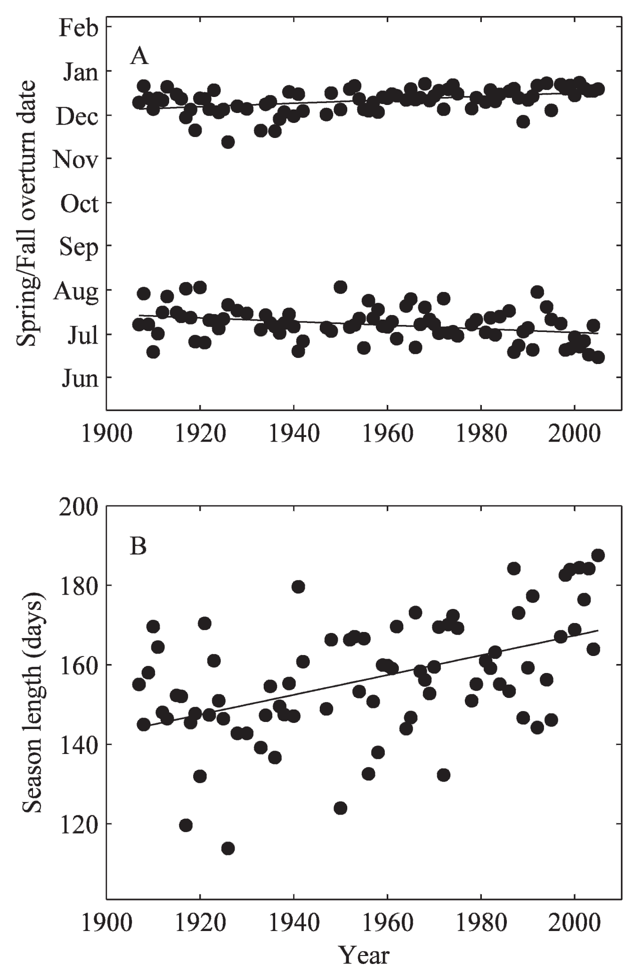

Fig. 7. (A) Start and end data of summer (positive) stratification using the SSM open-lake proxy. (B) length of stratified season, using SSM open-lake proxy.

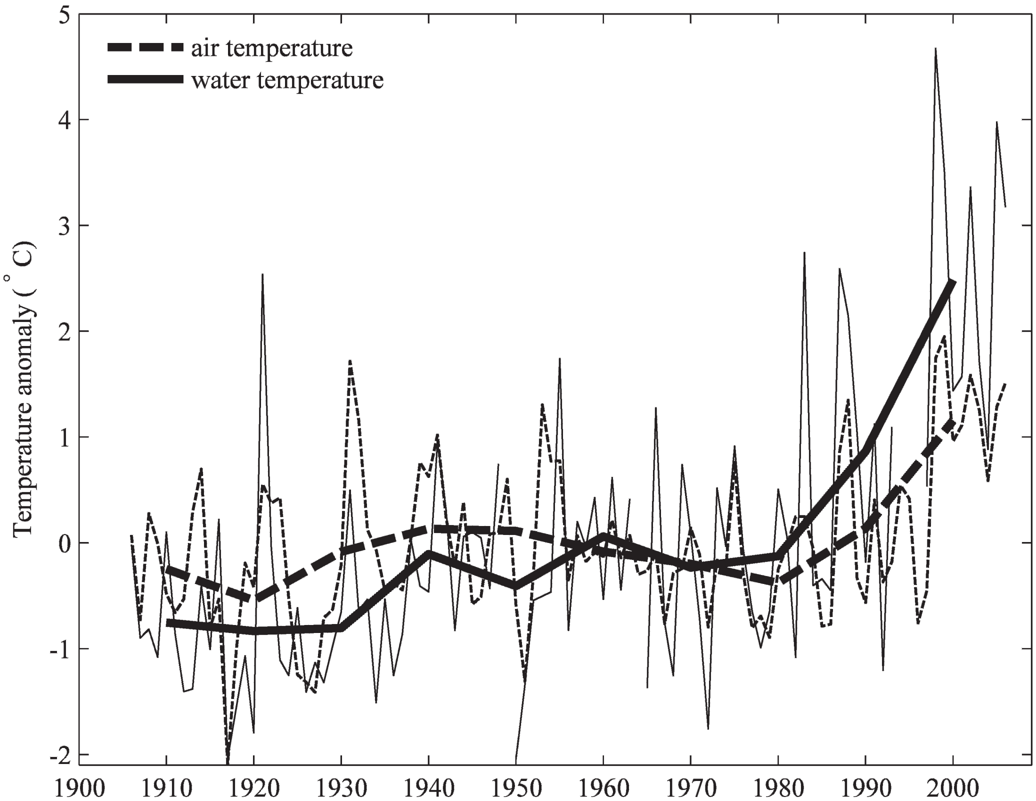

Fig. 8. Summer mean water-temperature anomaly from SSM open-lake proxy (solid curve) and air temperature anomaly from regional GISS stations (dashed curve). Light lines are annual data, heavy lines are decadal averages.

significant offset between SSM temperatures and those at the nearest NDBC buoy requires a careful choice of the appropriate criteria for determining the onset of the stratified season in the open lake. We will use the proxy time series described earlier to determine the length of the season; this is roughly equivalent to using 14°C at SSM as the criterion for the start of the open-lake stratified season (Fig. 3A), and 2°C at SSM as the criterion for the end of the stratified season. Using the raw SSM data to determine the length of the season results in a significant overestimate of the length of the open-lake stratified season.

Using the open-lake proxy time series, the start of the positively stratified season in eastern Lake Superior has been getting earlier at a rate of 13 d per century, the end of the season has been getting later at a rate of 12 d per century (Fig. 7A), which implies an increase in the length of season on the order of 25 d over the last century (Fig. 7B). The length of the season has increased from roughly 145 d to 170 d, an increase of about 17%. These are more rapid rates of change than had been previously reported by McCormick and Fahnenstiel (1999), who found the season starting 6 d earlier, ending 11 d later, and hence becoming 17 d longer per century. The difference in the reported rates is due both to the extended dataset used (1906–2005, instead of 1906–1992) and the use of different criteria for overturn. The modern absolute length of the season estimated here is shorter than previously reported (170 d instead of 208 d) because of the use of the open-lake proxy time series as opposed to the raw SSM data. It should be noted that very little measured open-water data exists for times as late as the winter overturn, so the specific date of the winter overturn or the absolute length of season are not as well-constrained as the date of the onset of stratification. From direct observation (Austin and Colman 2007), the date of onset in the western arm of the lake is earlier than in the eastern arm, but is getting earlier at roughly the same rate, about one-half day per year over the last 27 yr. Data on the end of the season from the NOAA buoys is sparse, and hence the length of the season in the western basin is unavailable.

Austin and Colman (2007) showed that the rate of warming in northern Great Lakes was significantly greater than the regional rate of atmospheric warming, and that the discrepancy could be explained in terms of an increasingly earlier beginning of the stratified season, which was in turn due to decreasing ice cover. Ice acts as a barrier to spring warming by significantly increasing the mean albedo of the lake. While useful ice data is only available since the early 1970s (Assel 2003) for Lake Superior, analyses of a large number of lakes and rivers (Magnuson et al. 2000; Jensen et al. 2007) have shown a significant phenological trend towards later freezing and earlier ice breakup in smaller lakes in the region and around the world.

However, atmospheric temperature records do exist for the last century and we can compare them to the SSM synthetic open-lake time series. The GISS database contains a significant number of stations with sufficient data coverage over the period 1906–2005. Specifically, of 73 stations found within a 500-km radius of Lake Superior, 47 of these (Fig. 1) have enough monthly average data to provide at least 85

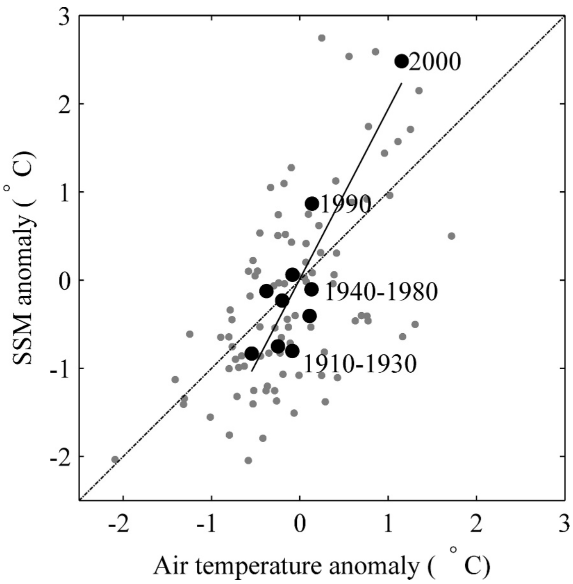

Fig. 9. SSM open-lake-water temperature anomaly as a function of regional GISS air temperature anomaly. Light points are individual years; heavy points are decadal averages.

annual averages over the last 100 yr (1906–2005; annual averages are taken as October of the previous year through September of the current year). These stations have a significant spatial distribution bias to the south of Lake Superior. So that annual mean values would be meaningful, missing data were filled in by linear regression between stations with high correlations for measured annual averages. The GISS station closest to Sault Ste. Marie (No. 727430000) does not show a trend significantly different than that for the rest of the basin. The annual mean air temperature data (Fig. 8; dashed line) shows a trend similar to that seen in the SSM data, with much of the warming taking place since about 1980. Decadal averaging of the data (Fig. 7; heavy dashed line) demonstrates this clearly, and shows warming on the order of roughly 1.5°C over the last 100 yr, most of that occurring since 1980. Comparing the two time series (Fig. 9) show that the SSM synthetic open-water temperature proxy is an amplified version of the regional air temperature, as found in Austin and Colman (2007). The air temperature trends are a half to a third of those observed with either the SSM proxy data or the NOAA data (Table 1). A fit of decadal averages (Fig. 9) shows the magnitude of the long-term trend in open-lake summer temperature estimated using SSM is twice that of annual mean air temperature, again consistent with Austin and Colman (2007). These decadal averages also show three distinct eras: a pre-1940 era, a plateau from the 1940s through the 1980s, and then rapidly warming climate and lake in the 1990s and 2000s.

A century-long time series of measured water temperature near Lake Superior shows behavior similar to those described for shorter, more recent time series by Austin and Colman (2007). Specifically, the observed trend in water temperature anomaly at the longer and more reliable of the two time series is roughly twice that observed in regional air temperature. Further, a careful extrapolation of this data to the open lake suggests that the summer-stratified season has increased in length from roughly 145 d to 170 d over the last century, an increase of about 17%. The change in the timing of the season suggests that average ice cover has fallen from roughly 23% to 12% over the last century, most of that change within the last 30 yr. More broadly, the documented changes in Lake Superior serve as a good example of the complex response of large natural systems to global climate change.

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