



Lake Superior summer water temperatures are increasing more rapidly than regional air temperatures: A positive ice-albedo feedback

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[1] Lake Superior summer (July–September) surface water temperatures have increased approximately 2.5°C over the interval 1979–2006, equivalent to a rate of $(11 \pm 6) \times 10^{-20^{\circ}\text{C yr}^{-1}}$, significantly in excess of regional atmospheric warming. This discrepancy is caused by declining winter ice cover, which is causing the onset of the positively stratified season to occur earlier at a rate of roughly a half day per year. An earlier start of the stratified season significantly increases the period over which the lake warms during the summer months, leading to a stronger trend in mean summer temperatures than would be expected from changes in summer air temperature alone.

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1. Introduction

[2] Much of the focus on global warming has concentrated on surface air temperature and ocean temperatures [Hansen *et al.*, 2006; Intergovernmental Panel on Climate Change (IPCC), 2001]. While some modeling studies have considered the response of large lakes to climate change [Croley, 1990; McCormick, 1990] little is known from direct observation about how these complex systems respond to climate change. Long term trends have been studied in some tropical lakes [O'Reilly *et al.*, 2003; Verburg *et al.*, 2003; Vollmer *et al.*, 2005], which have weak annual thermal cycles and respond roughly proportionately to changes in atmospheric temperature. In contrast, mid-latitude lakes occupy a distinct thermal regime, characterized by one or more isothermal mixing events annually (due to the density maximum for freshwater at 3.98°C), and the formation of ice to varying degrees, depending on regional winter air temperatures and the depth of the lake [Assel *et al.*, 2003]. Ice plays a distinct role in an ocean-atmosphere or lake-atmosphere heat balance, as it significantly increases the surface albedo, reducing the ability of the water body to absorb shortwave radiation. Changes in ice concentration have been hypothesized as a significant positive climate feedback [IPCC, 2001; Ingram *et al.*, 1989] and the date of ice-out has been studied in lakes as an indicator of climate change [Anderson *et al.*, 1996; Palecki and Barry, 1986;

Robertson *et al.*, 1992; Schindler *et al.*, 1990]. The oceanic systems in which ice albedo effects operate are complex enough to make meaningful direct measurements of this feedback very difficult. Compared to high-latitude oceans, large lakes provide a simpler system for study, where these effects may be easier to quantify. In addition, as the ice in these lakes is completely “reset” each year, they provide multiple independent examples of the role of ice in these systems, so that interannual variability provides a better view of the relationship between ice cover and lake response, independent of long-term warming.

[3] Here we present evidence that Lake Superior (and the other Northern Great Lakes, Huron and Michigan) summer surface water temperature is increasing more rapidly than regional air temperature. This results from a progressively earlier start of the summer stratified season, in response to a significant decline in average winter ice cover. Given a longer summer stratified season, surface waters can be heated to higher temperatures than that expected from the increase in air temperature alone.

2. Data

[4] The National Oceanic and Atmospheric Administration's National Data Buoy Center (NDBC, available at <http://www.ndbc.noaa.gov/>) maintains three surface buoys in Western, Central, and Eastern Lake Superior (Figure 1; NDBC 45006, 45001, and 45004, respectively) from April through November (the buoys are removed from the lake from December–April to avoid ice cover). These make hourly measurements of near-surface water and air temperature as well as wind velocity and have been in operation since 1981, 1979, and 1980, respectively. In addition, the NDBC maintains several Coastal Marine Automated Network (CMAN) stations around the periphery of the lake and on islands within the lake (ROAM4, PILM4, DISW3, and STDM4) which have collected hourly air temperature and wind velocity data since about 1980 (ROAM4 also records surface water temperature). CMAN stations typically have higher meteorological measurement heights than open water buoys (from 15 m to 35 m above lake level for these stations), and all wind speeds have been adjusted to 5 m using a power-law scaling [Hsu *et al.*, 1994]. Open water NDBC buoys in Lakes Huron, Michigan, and Erie (NDBC 45002 and 45007 in Michigan, 45003 and 45008 in Huron, and 45005 in Erie) have been collecting similar data since about 1980. Lake Ontario will be omitted from this analysis since NOAA-NDBC data is only available from 2002 to the present.

[5] To characterize trends in regional terrestrial air temperature, 31 regional stations from the Goddard Institute for Space Studies (GISS) air temperature database (Surface

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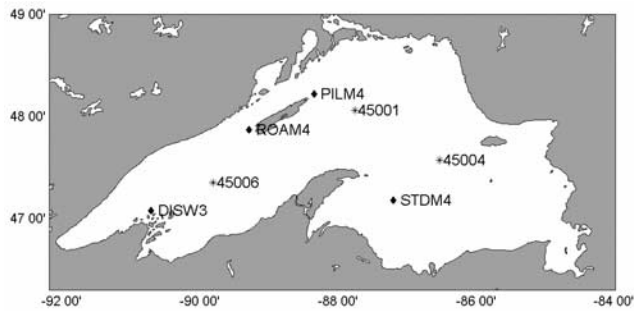


Figure 1. Map of Lake Superior, indicating locations of NOAA buoys (asterisk) and NOAA CMAN stations (diamond).

temperature station data, Goddard Institute for Space Studies, New York, available at <http://data.giss.nasa.gov/gistemp/>, 2006) within a 500 km radius of the center of Lake Superior have been averaged together. Stations were included if there was data available in at least 24 of the last 27 years. The trend in annually averaged air temperature from 1979 to 2005 for these stations is $(5.3 \pm 2.1) \times 10^{-2} \text{C yr}^{-1}$. The trend for the summer (defined here as July, August, and September) period is $(5.9 \pm 1.8) \times 10^{-2} \text{C yr}^{-1}$ (Figure 2a), consistent with literature values for the region [Hansen *et al.*, 2001, 2006]. Ice cover data (Figure 2b) are taken from NOAA data reports [Assel, 2003, 2005b]. For a given year, the metric used here represents spatially and temporally averaged ice cover percentage over the entire lake between 1 December of the previous year and 31 May. Ice cover has been declining at a rate of $(-0.42 \pm 0.20) \text{ %yr}^{-1}$ from 1979–2005.

3. Water Temperature Trends

[6] All three NOAA/NDBC buoys in Lake Superior show a rate of warming for the 1979–2006 period of about $(11 \pm 6) \times 10^{-2} \text{C yr}^{-1}$ (Figure 3 and Table 1). Air temperature trends (Figure 3 and Table 1) at the open water locations are similar to the water temperature trends, and are more a reflection of lake surface water temperature than terrestrial air temperature, as the rate is significantly higher than the terrestrially averaged rate. In addition, all sites show a general trend towards higher average wind speeds

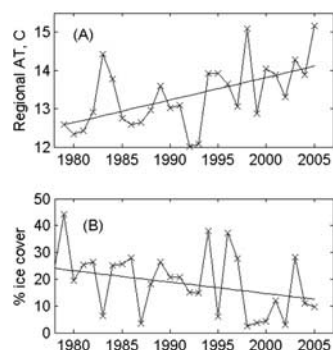


Figure 2. Regional air temperature and average ice cover: (a) mean July–September air temperatures from GISS sites (available at <http://data.giss.nasa.gov/gistemp/>) and (b) ice cover metric [Assel, 2003; 2005b], in percent.

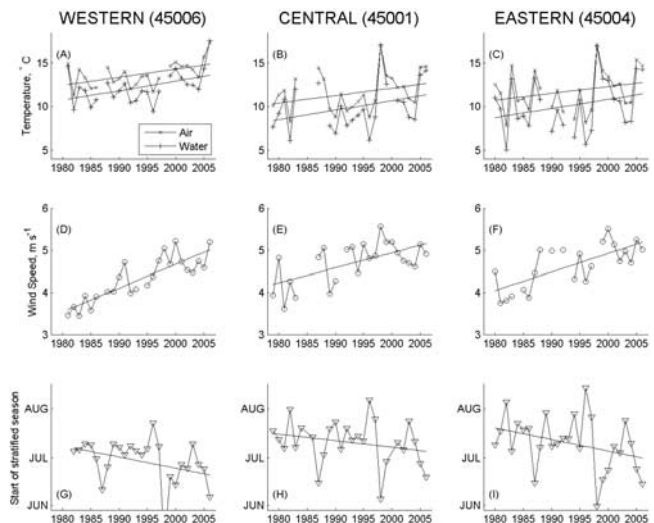


Figure 3. Buoy observation time series. (a–c) Summer (July–September) mean air temperatures (cross) and water temperatures (plus). (d–f) Summer mean wind speed. (g–i) Date of the start of summer stratified season (i.e., date on which water temperature reaches 3.98°C). Three Lake Superior buoys are shown: Western (Figures 3a, 3d, and 3g; 45006), Central (Figures 3b, 3e, and 3h; 45001), and Eastern (Figures 3c, 3f, and 3i; 45004).

(Figure 3 and Table 1), with increases at the open-water buoy sites on the order of $0.05 \text{ ms}^{-1}\text{yr}^{-1}$, significant compared to mean summer wind speeds of $4\text{--}6 \text{ ms}^{-1}$. The increase in wind speeds may be caused by destabilization of the atmospheric boundary layer due to a decreased air density gradient (since the surface air temperature is becoming progressively warmer), which allows momentum to be more efficiently transferred to the surface from winds aloft. The weaker trends at the CMAN sites may be due either to their coastal location, so that they measure winds coming off the land as often as they measure winds off the lake, or may be due to their measurement height, in that they are not as deep within the atmospheric boundary layer. Increases in wind speed should lead to deeper mixed-layer depths, while increased stratification (resulting from higher surface temperatures) should stabilize the surface layer. Simple scalings of mixed layer depth [Pollard *et al.*, 1973] suggest that the observed increase in wind speed is likely considerably more important than the increase in the strength of stratification; hence mixed layer depths are likely to be increasing. The actual mixed layer depths would be sensitive to the time-dependent nature of surface forcing, and modeling studies using time-dependent wind forcing and surface heating would need to be conducted to quantify the trend in mixed-layer depth. This implies that the amount of heat being absorbed and released annually by the lake is growing at a rate even greater than that suggested by the increase in surface water temperature increase alone. Unfortunately, no data exists to document trends in mixed layer depth in Lake Superior.

[7] The rates of change in water temperature, air temperature, and wind speed do not appear to be confined to Lake Superior. Analyses of similar records from Lakes Michigan and Huron from the period 1979–2006 show similar surface

Table 1. Statistics for July–September Mean Trends From 1979–2006^a

Name	Location	d(WT)/dt, 10 ⁻² °C/yr	d(SSS)/dt, days/year	d(AT)/dt, 10 ⁻² °C/yr	d(WS)/dt, 10 ⁻² ms ⁻¹ /yr
45006	Western Superior	11.0 ± 4.4	-0.71 ± 0.42	9.4 ± 3.3	5.6 ± 0.7
45001	Central Superior	11.0 ± 6.6	-0.42 ± 0.33	8.6 ± 5.3	3.6 ± 1.0
45004	Eastern Superior	10.4 ± 7.3	-0.73 ± 0.40	7.8 ± 5.8	4.4 ± 0.9
DISW3	Western Superior	–	–	7.1 ± 3.0	0.1 ± 0.5
ROAM4	Western Superior	16.0 ± 10.4	–	13.5 ± 4.0	0.8 ± 0.8
PILM4	Western Superior	–	–	10.8 ± 4.1	2.2 ± 0.5
STD4	Central Superior	–	–	13.7 ± 4.4	2.6 ± 1.1
45002	Northern Michigan	7.8 ± 3.6	-0.58 ± 0.82	7.4 ± 2.9	4.4 ± 0.7
45007	Southern Michigan	5.1 ± 3.4	-1.42 ± 0.55	3.8 ± 2.9	3.0 ± 0.7
45003	Northern Huron	9.8 ± 4.5	-0.89 ± 0.35	7.6 ± 3.6	4.3 ± 0.9
45008	Southern Huron	7.4 ± 3.8	-0.40 ± 0.29	5.7 ± 3.1	4.6 ± 0.9
45005	Western Erie	1.0 ± 1.9	– ^b	1.1 ± 2.0	4.9 ± 1.3

^aWT, water temperature; AT, air temperature; WS, wind speed; SSS, start of stratified season, yeardays.

^bInsufficient data.

water temperature and air temperature increases, as well as increases in wind speed (Table 1). Lake Erie, however, does not display a significant trend in mean summer water temperature.

[8] To first order, the equilibrium surface water temperature should respond proportionally to changes in surface air temperature. The surface waters never reach this equilibrium, as the response time for the surface layer, especially prior to the spring transition, is long compared to the rate of change of surface forcing. The rate at which the lake approaches equilibrium will be a function of wind speed and the depth over which the heat is being distributed. As it appears that lake surface temperatures are increasing significantly faster than regional air temperatures, we hypothesize that the difference is a result in a shift towards an earlier onset of the summer stratified season. This in turn is due to a trend towards milder winters. Milder winters result in less ice cover, more absorbed shortwave radiation, and a quicker recovery to summer stratification.

4. The Role of Ice

[9] While ice-out dates for rivers and lakes are an important phenological indicator of climate change in small lakes and have been becoming progressively earlier [Anderson *et al.*, 1996; Magnuson *et al.*, 2000; Robertson *et al.*, 1992; Schindler *et al.*, 1990], another important metric for assessing long-term change in the thermal regime of large lakes is the date of the onset of summer stratification. In large lakes, the summer thermocline is typically relatively shallow compared to the winter thermocline [Bennett, 1973], and the rate of surface warming after the onset of positive stratification is significantly greater than before. Therefore, the mean summer temperature is sensitive to the date at which the lake surface reaches 3.98°C. Over the last 27 years, the date at which summer stratification starts has been occurring increasingly earlier in the year at all three buoys, at a rate of roughly a half day per year; i.e. nearly two weeks earlier now than 27 years ago (Figures 3g–3i and Table 1). This is a significantly greater than the rate previously reported [McCormick and Fahnenstiel, 1999], in a study using data spanning 1906 to 1992. A trend towards earlier summer stratification is also present in Lakes Michigan and Huron. Lake Erie's transition typically occurs in mid-April, significantly earlier than that of the northern Great Lakes. Because of the buoy deployment schedule, not

enough data is available to reliably determine trends in the onset of summer stratification in Erie.

[10] Fractional ice coverage in Lake Superior has been decreasing over the last several decades [Assel *et al.*, 2003] (Figure 2b), and on northern hemisphere lakes and rivers in general [Magnuson *et al.*, 2000]. The percentage of ice cover formed in any particular year is sensitive to small changes in atmospheric forcing. The presence of ice dramatically changes the dynamics of thermal exchange, primarily by increasing the albedo, thereby reducing absorption of incoming shortwave radiation [IPCC, 2001; Ingram *et al.*, 1989]. In the case of large northern lakes, the date of the start of the stratified season is a strong function of the ice coverage from the previous winter. The whole-lake ice average is a useful metric here because it is related to the total amount of shortwave radiation that is reflected back from the lake surface, and hence related to the area-averaged deficit of heat received by the lake during a winter/spring season.

[11] There is a clear relationship between the whole-lake fractional ice cover in a given season and the subsequent onset of summer stratification at all three buoys (Figures 4a–4c) and hence mean summer temperature (Figures 4d–4f), with a majority of the interannual variability in summer temperatures explained by variability in the previous winter's ice cover ($r^2 = 0.36, 0.47,$ and 0.71 at the Western, Central, and Eastern buoy, respectively). Similarly, summer water temperatures are positively correlated (slopes of $0.70 \pm 0.4, 1.4 \pm 0.6,$ and 1.5 ± 0.7) with the summer regional air temperature (Figure 2a) but at lower levels of significance ($r^2 = 0.14, 0.23,$ and $0.18,$ respectively). This suggests that while summer water temperature has an order 1 dependence on regional air temperature, interannual variability air temperature does not explain much of the observed variability in summer water temperature. Ice cover and regional summer air temperature are poorly correlated ($r^2 = 0.07$), so that they contribute independently to the variability in summer water temperature. The significant outlier (i.e., early start to the summer season and high summer temperatures) at all locations is 1998, when an exceptionally warm winter caused in part by a major el Niño event [Assel *et al.*, 2000] resulted in a nearly ice-free winter and anomalously high summer water temperatures. While the regional ice cover in Lake Superior is variable, exchange between basins appears to effectively average out the effect that ice cover has on lake temperatures. Preliminary box-modeling (not presented

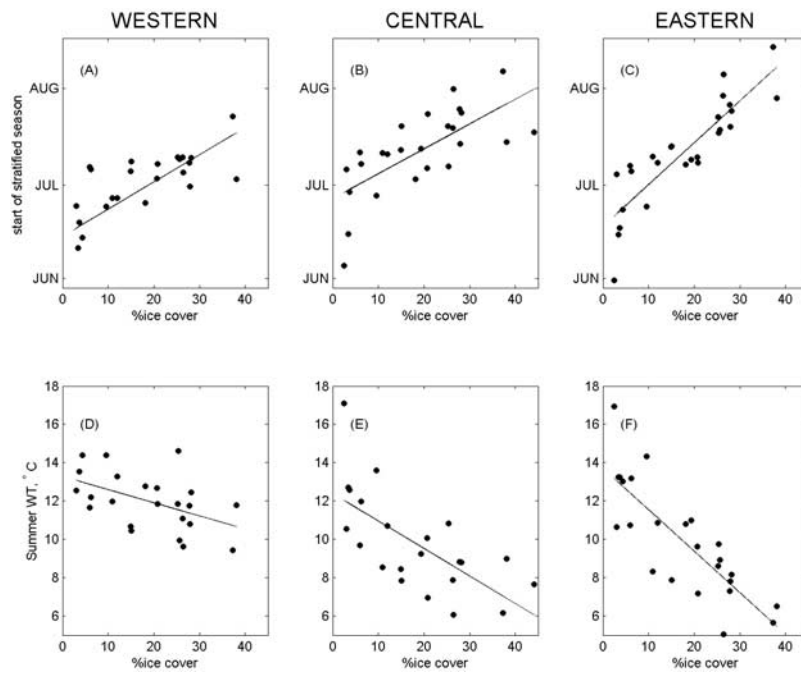


Figure 4. (a–c) Relationship between the date of the start of stratified season and the previous winter’s ice cover. (d–f) Relationship between summer mean water temperature and the previous winter’s ice cover.

here) suggests that changes in ice cover, not just in the amount of heat lost each season, is essential to the anomalous rise in summer temperatures.

[12] The observed increase in summer water temperatures is therefore hypothesized to be a combination of reduced ice cover leading to a progressively earlier start of the stratified season and higher summer air temperatures with which the lake is equilibrating. The relative contribution of these two effects to the total increase in summer temperature can be quantified by writing the rate of change of summer water temperature in terms of the rate of change of regional summer air temperature (Figure 2a) and the rate of change of ice cover (Figure 2b):

$$\frac{d(WT)}{dt} \approx \frac{\partial(WT)}{\partial(AT)} \frac{\partial(AT)}{\partial t} + \frac{\partial(WT)}{\partial(ICE)} \frac{\partial(ICE)}{\partial t}$$

[13] The rate of decline of ice cover, $(-0.42 \pm 0.20)\% \text{ yr}^{-1}$, combined with the dependence of summer temperatures on the ice coverage (which, averaged over the three stations in Superior, is $(-15 \pm 3) \times 10^{-2} \text{ °C}/\%$), yields a warming rate of $(6.3 \pm 4.3) \times 10^{-2} \text{ °C yr}^{-1}$ due solely to decreasing ice cover. Added to the regional rate of increase of air temperature $((5.9 \pm 1.7) \times 10^{-2} \text{ °C yr}^{-1})$, this produces an estimate consistent with the observed mean rate of warming of $(11 \pm 6) \times 10^{-2} \text{ °C yr}^{-1}$.

[14] The one long time series available in Lake Erie stands as an exception to this analysis. Because of its relatively low latitude, it is also the earliest to be ice-free [Assel, 2005a]. In addition, the single NDBC buoy in Erie is in very shallow water (12m) (available at <http://www.ndbc.noaa.gov/>). Other studies of water temperature trends in Lake Erie [Burns et al., 2005; Jones et al., 2001] have shown warming rates consistent with regional atmospheric warming. It appears that a combination of the earlier

end of ice cover, coupled with the relatively rapid lake-atmosphere equilibration time due to the shallowness of the buoy location, dampen the effect of the winter ice cover on summer temperatures.

5. Discussion

[15] Currently, the upper Great Lakes all form ice to a certain extent each year, significantly delaying the onset of summer stratification. The decline of this ice cover over the last several decades is contributing significantly to the rate of increase of summer water temperatures. Longer stratified seasons and warmer summer water temperatures are likely to have a significant impact on the ecology of the upper Great Lakes at all trophic levels [Brooks and Zastrow, 2002; Hill and Magnuson, 1990; Jones et al., 2006; Lehman, 2002; Magnuson et al., 1997]. At the current rate of decline of ice cover, Lake Superior will be ice-free in a typical winter in about three decades. At that time, the date of onset of the positively stratified season will change more slowly, in response only to the increased winter heat content, and the rate of increase of summer water temperatures will slow accordingly. The thermal structure of large lakes is a complex function of the applied meteorological forcing, and the simple approach we take here certainly does not capture all of the dynamics. To better understand the thermal response of large lakes and the role that ice plays in them, numerical models which incorporate surface flux dynamics, horizontal exchange, and ice will need to be developed.

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