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Key Points:

- Lake Michigan has been in an altered thermal regime since the late 1990s
- The 2013–2014 winter may return Lake Michigan to pre-1998 thermal conditions
- Hydrological impacts of the 2013–2014 cold winter remain unclear

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Impacts of extreme 2013–2014 winter conditions on Lake Michigan's fall heat content, surface temperature, and evaporation

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Abstract Since the late 1990s, the Laurentian Great Lakes have experienced persistent low water levels and above average over-lake evaporation rates. During the winter of 2013–2014, the lakes endured the most persistent, lowest temperatures and highest ice cover in recent history, fostering speculation that over-lake evaporation rates might decrease and that water levels might rise. To address this speculation, we examined interseasonal relationships in Lake Michigan's thermal regime. We find pronounced relationships between winter conditions and subsequent fall heat content, modest relationships with fall surface temperature, but essentially no correlation with fall evaporation rates. Our findings suggest that the extreme winter conditions of 2013–2014 may have induced a shift in Lake Michigan's thermal regime and that this shift coincides with a recent (and ongoing) rise in Great Lakes water levels. If the shift persists, it could (assuming precipitation rates remain relatively constant) represent a return to thermal and hydrologic conditions not observed on Lake Michigan in over 15 years.

1. Introduction

Between December 2013 and April 2014, much of North America experienced an extremely cold winter [*NOAA National Climatic Data Center*, 2014]. On the North American Laurentian Great Lakes (the largest lake system on Earth), the harsh winter conditions led to very low surface water temperatures and exceptionally broad and persistent areal ice cover [*Clites et al.*, 2014]. On Lakes Superior, Michigan, and Huron, the first, third, and fourth largest lakes on Earth by surface area [*Gronewold et al.*, 2013], measurements of maximum ice extent and late spring ice cover either exceeded or were extremely close to those dating back to 1972 [*Wang et al.*, 2012]. These conditions were unexpected because the Great Lakes have experienced high surface water temperatures [*Austin and Colman*, 2007; *Van Cleave et al.*, 2014] and below average ice cover since the late 1990s, including record low ice cover in early 2012 [*Bai et al.*, 2015]. The beginning of this warm period coincided with the strong 1997–1998 El Niño [*Chandra et al.*, 1998; *Assel*, 1998; *McPhaden*, 1999] and also marked the beginning of an altered hydrologic regime on the Great Lakes characterized by high over-lake evaporation rates [*Assel et al.*, 2004; *Gronewold et al.*, 2013] that propagated into persistent below average water levels including record lows set on Lake Superior in 2007 and on Lakes Michigan and Huron in 2012 and 2013 [*Gronewold and Stow*, 2014].

The contrast between the extreme 2013–2014 winter conditions and those of the preceding 15 year period raises the question of whether the Great Lakes might return to a thermal and hydrologic regime similar to that which preceded the 1997–1998 El Niño [*Clites et al.*, 2014], a period characterized by lower water temperatures, more extensive ice cover, and higher water levels. Recent seasonal surface water temperatures (Figure 1) reflect both the relatively cold conditions on Lake Michigan during the early months of 2014 as well as the tendency for surface temperatures to converge in the fall, regardless of temperatures earlier in the year. This convergence suggests that Lake Michigan may have a poor "memory" of prior winter surface temperatures. If the lake's memory of winter temperatures is indeed poor, we would also expect minimal correlation with other successive thermal conditions, including fall heat content and fall evaporation rates. We recognize,

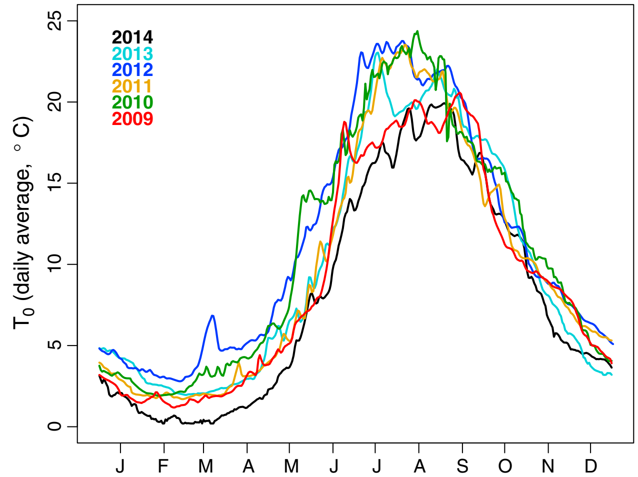

Figure 1. Lake Michigan daily lake-wide average surface water temperatures (T_0) from 2009 to 2014 from NOAA's Great Lakes Surface Environmental Analysis (GLSEA) (for details, see *Leshkevich et al.* [1996] and *Schwab et al.* [1999]).

however, that fall evaporation rates are affected by atmospheric variables, such as humidity, wind speed, and the stability of the planetary boundary layer, all of which can be difficult to predict at regional scales.

Here we investigate consequences of the 2013–2014 cold winter on Lake Michigan (the second largest of the Great Lakes by volume and the third largest by surface area) by analyzing historical (i.e., across many decades) interseasonal relationships between the lake's late winter and subsequent late fall thermal regimes. We expect these historical relationships to reflect the strength of the lake's memory of the previous winter's thermal conditions above and beyond those implied by interseasonal temperature relationships from the past few years alone (i.e., Figure 1). More importantly, we hope to determine if the extreme winter conditions of 2013–2014 might constitute a sufficient enough perturbation to return Lake Michigan to a thermal and hydrologic regime that more closely resembles the pre-1998 conditions that were characterized by lower heat content, lower surface water temperatures, and higher water levels. Finally, we expect our findings to set the stage for, and perhaps foreshadow results from, similar future investigations on the other Great Lakes.

2. Methods

We assess the strength of interseasonal relationships in Lake Michigan's thermal regime by comparing a suite of variables from different models and measurement-based data sets. We focus our analysis on Lake Michigan alone because it has at least as many in situ measurements of surface water temperature (and related conditions) as any other Great Lake and because an analysis of Lake Michigan sets the stage for a subsequent analysis of the entire Great Lakes system. We also focus on Lake Michigan because its recent record low water levels have (unlike conditions on Lakes Erie and Ontario, which have remained close to their long-term average levels) (for details, see *Gronewold et al.* [2013] and *Gronewold and Stow* [2014]) raised pressing questions about long-term water level variability and expected future hydrologic conditions that might lead to increasing or decreasing water levels.

To begin, we represent winter thermal conditions on Lake Michigan using estimates of total lake heat content Q_t (in kJ, with reference temperature 0°C), lake-wide average surface water temperature T_0 (in °C), and ice cover (expressed as a percentage of total lake surface area), each averaged from January to March of each calendar year from 1950 to 2013. We represent corresponding fall conditions from each calendar year using estimates of average Q_t and T_0, as well as cumulative evaporation E (in cm), from October to December. To improve understanding of factors that influence the transition between winter and (following) fall conditions, we also quantify average monthly incident short-wave radiation $S\downarrow$ (in W/m^2) from April to September.

We derive estimates for each of these variables using readily available models and measurement-based data sets. Specifically, we use daily estimates of lake-wide T_0, Q_t, E, and $S\downarrow$ from NOAA's one-dimensional large lake thermodynamics model (or LLTM) [*Croley*, 1989; *Croley and Assel*, 1994] for the entire period of record (1950 to 2014). We employ estimates of ice cover from 1973 to 2014 from the Great Lakes ice atlas (and extensions of the ice atlas project, as described in *Wang et al.* [2012]). Finally, we derive projected fall 2014 conditions from the NOAA Great Lakes Advanced Hydrologic Prediction System (or AHPS) (for further reading, see *Croley and Hartmann* [1987], *Croley and Lee* [1993], and *Gronewold et al.* [2011]) based on calculations made in late spring 2014.

Additional estimates of Q_t and T_0 are available, including those from NOAA's Great Lakes Coastal Forecasting System (or GLCFS) (for details, see *Schwab and Bedford* [1994] and *Beletsky and Schwab* [2001]), as well as

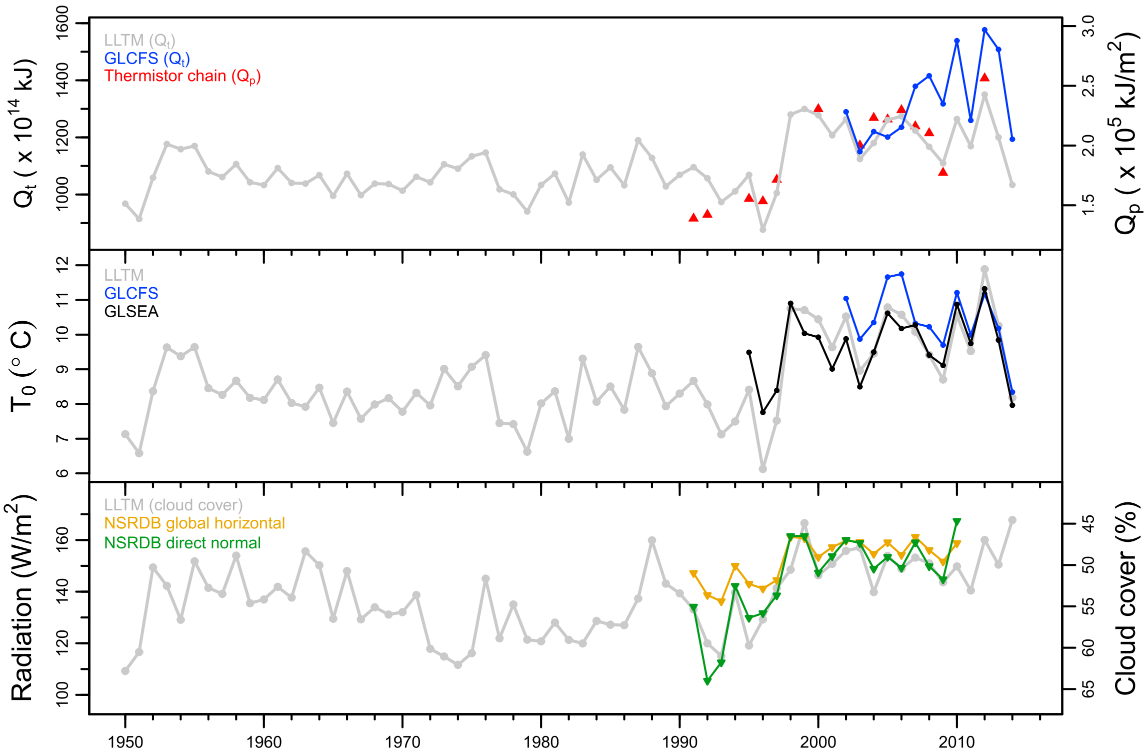

Figure 2. Comparison between alternative sources of Lake Michigan's historical heat content (including both lake-wide, Q_t, and thermistor chain-derived point estimates, Q_p), alternative sources of lake-wide surface water temperature (T_0), and alternative sources of solar radiation (including cloud cover estimates used to simulate S↓ in the LLTM). Points represent annual averages for each respective calendar year and are connected by lines for clarity (with the exception of the thermistor chain Q_p measurements, which are discontinuous over the period of record).

point estimates of heat content (Q_p) from a long-term thermistor chain in southern Lake Michigan [*Beletsky et al.*, 2006]. Lake-wide estimates of T_0 are also available from 1995 to 2014 from NOAA's Great Lakes Surface Environmental Analysis (GLSEA) (for details, see *Leshkevich et al.* [1996] and *Schwab et al.* [1999]). A visual comparison between these alternate data sources (Figure 2) indicates that the LLTM provides a relatively robust, long-term representation of Lake Michigan's thermal properties and that, for the periods where overlapping data are available, the various sources are consistent. In particular, we observe that through the late 1990s, both the LLTM and the thermistor chain reflect a significant increase in lake heat content, while in the following decade, estimates of heat content from all three potential sources (i.e., LLTM, GLCFS, and the thermistor chain) are relatively consistent.

Point estimates of T_0 and E (among other variables) are also available from two NOAA National Data Buoy Center (NDBC) buoys on Lake Michigan [*Hamilton*, 1986; *Meindl and Hamilton*, 1992] and (along with estimates of $S\downarrow$) a recently installed offshore meteorological and flux measurement station on top of the White Shoal lighthouse in northern Lake Michigan (for descriptions of similar stations, see *Blanken et al.* [2000], *Spence et al.* [2011], *Blanken et al.* [2011], and *Spence et al.* [2013]). However, for our interseasonal variability analysis, we employ only the LLTM and the Great Lakes ice atlas as two data sources that are readily available on a lake-wide spatial scale for a relatively long (i.e., decades) period of record. It is informative to note that the NDBC buoys are used to verify the GLSEA temperature products and that the GLSEA temperature estimates are used as an observational basis for calibrating parameters of the LLTM.

Finally, additional sources of solar radiation data are available (i.e., in addition to the $S\downarrow$ values simulated by the LLTM), including estimates from the National Solar Radiation Data Base (for details, see *Maxwell* [1998]). Importantly, the National Solar Radiation Data Base (NSRDB) is divided into two time periods (1961 to 1990 and 1991 to 2010) and the first of these periods is known to have severe and unreconciled biases that significantly complicate analysis of long-term regional radiative forcings prior to 1990 (for details, see *Gueymard and Wilcox* [2011]). A visual comparison between global horizontal and direct normal average radiation from the NSRDB between 1991 and 2010, however, along with over-lake cloud cover estimates from the LLTM

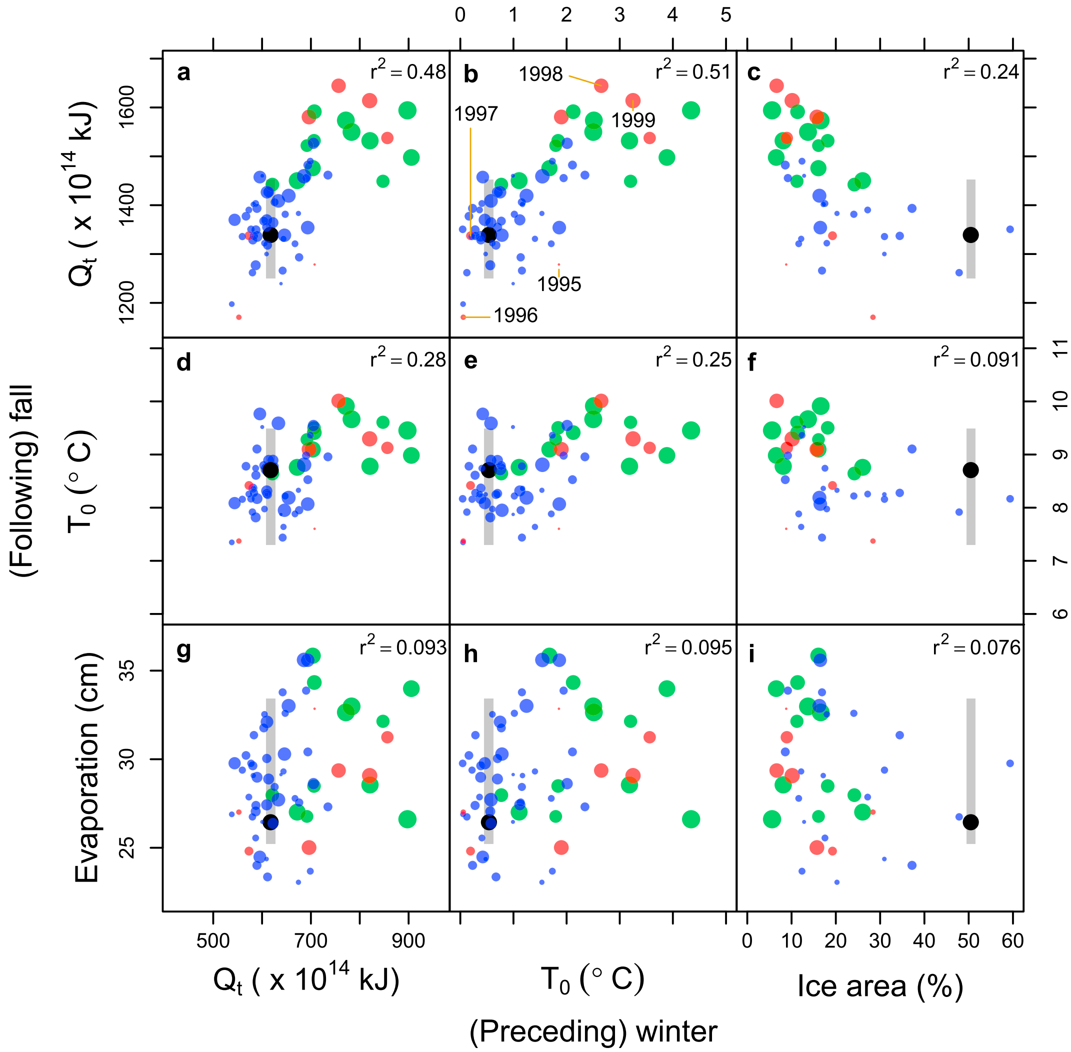

Figure 3. (a–i) Relationships between winter and (following) fall thermal conditions on Lake Michigan from 1950 to 1994 (blue dots), 1995 to 2001 (red dots), and 2002 to 2013 (green dots). Values for 2014 are represented by black dots. For clarity (and to coincide with results in section 3) years 1995 through 1999 are labeled in Figure 3b. Winter (observed) and fall (projected) conditions for 2014 are represented, respectively, by the horizontal position and the vertical bounds (defined by 95% prediction intervals from NOAA-AHPS, as described in *Gronewold et al.* [2011]) of the grey boxes in each panel. Dot areas are proportional to summer $S\downarrow$.

(Figure 2, bottom), suggest not only significant changes in solar forcings throughout the middle to late 1990s but also that the LLTM simulations employed in our interseasonal analysis reflect those changes (for further discussion of regional cloud cover data and its relationship to $S\downarrow$ simulations in the LLTM, see *Croley* [1992] and *Free and Sun* [2013]).

3. Results

Of the three metrics we used to represent Lake Michigan's fall thermal state (i.e., Q_t, T_0, and E), we find fall Q_t to be most closely related to conditions from the preceding winter (Figures 3a–3c). More specifically, we find that fall Q_t is strongly correlated with both winter Q_t ($r^2 = 0.48$) and winter T_0 ($r^2 = 0.51$) and moderately (negatively) correlated with winter ice cover ($r^2 = 0.24$). The lake's strong interseasonal memory of heat content from the previous winter, however, is overshadowed by a clear distinction between two historical thermal regimes.

Our results indicate that prior to 1995 (Figure 3a), Lake Michigan was in a relatively "cool" regime, with winter Q_t ranging between roughly 540×10^{14} and 720×10^{14} kJ and fall Q_t ranging between roughly 1200×10^{14} and 1500×10^{14} kJ. Posterior 95% credible intervals for the Q_t mean calculated using the `normpostsim` function in R [*Ihaka and Gentleman*, 1996] were, for pre-1995 winters and pre-1995 falls, [607×10^{14}, 635×10^{14}] and [1345×10^{14}, 1389×10^{14}], respectively (all in kJ). The period from 1995 to 2001 (Figure 3a) represents a transition (spanning a very broad range of Q_t) to a second regime beginning in 2002 with winter Q_t ranging between roughly 620×10^{14} and 900×10^{14} kJ and fall Q_t ranging between roughly 1450×10^{14} and 1600×10^{14} kJ (for a related perspective on recent changes in ocean heat content, see *Gregg and Newlin* [2014]). Posterior 95% credible intervals for the mean Q_t for each of these periods were found to be [702×10^{14}, 818×10^{14}] (post-2002 winter) and [1482×10^{14}, 1552×10^{14}] (post-2002 fall), providing very strong evidence of a significant difference in Q_t between the two time periods.

The late 1990s transition in Lake Michigan's thermal regime is also evident through a shift in the relationship between fall Q_t and winter T_0 (Figure 3b). These findings provide strong evidence that while the transition in Lake Michigan's thermal regime in the late 1990s may have been triggered by abrupt increases in air and water temperatures associated with a strong coincident El Niño, it was likely sustained, if not reinforced, by persistent above average solar forcings (Figure 2) (for further discussion, see *Wild et al.* [2005] and *Free and Sun* [2013]). We find these two periods are also distinguished by changes in summer $S\downarrow$ (proportional to area of dots in Figure 3); from 1950 to 1996, $S\downarrow$ ranged between roughly 180 and 235 W/m^2, while from 1997 to 2013, it ranged between roughly 225 and 255 W/m^2.

In contrast to interseasonal relationships between fall Q_t, winter Q_t, and winter T_0, we find that fall T_0 and fall over-lake evaporation rates are relatively independent of conditions from the previous winter (Figures 3d–3i). We also find that this independence is relatively consistent across our period of record. These relationships underscore the importance of factors beyond T_0 and ice cover alone that drive fall evaporation on the Great Lakes including wind speed, dew point temperature, and cloud cover [*Croley*, 1992; *Spence et al.*, 2013].

Projections from AHPS-LLTM made in late spring of 2014 (Figure 3) reinforce empirical evidence from the historical record suggesting strong propagation of winter Q_t and T_0 into Q_t in the following fall. Both the historical record and the process models (i.e., AHPS-LLTM) employed in our study, however, provide very little evidence that extreme cold conditions alone (such as those experienced in the winters of 2013–2014 and 2014–2015) necessarily lead to noticeably lower fall evaporation rates and surface water temperatures (Figures 3g–3i).

4. Summary and Conclusions

We have found compelling evidence that one of Earth's largest lakes was in an altered thermal regime for the past 15 years, marking a shift in thermal conditions that were relatively consistent before the late 1990s (and dating back to at least 1950). While the most recent thermal regime appears to have been triggered by events related to the strong 1997–1998 El Niño, we have also found that it may have been sustained by above average solar inputs [*Austin and Allen*, 2011; *Foster and Heidinger*, 2014].

Hence, in the absence of some disruptive mechanism for thermal change, it appears that Lake Michigan's thermal conditions can be either classified as cool (similar to pre-1998 regime) or warm (similar to the 2002 to 2013 regime) and that during each of these periods seasonal (both fall and winter) Q_t and winter T_0 fall into limited ranges with moderate memory between winter conditions (particularly winter Q_t and T_0) and the subsequent fall Q_t. Interestingly, we find that relationships are stronger between winter Q_t and fall Q_t, and between winter T_0 and fall Q_t, in the pre-1998 period ($r^2 = 0.21$ and 0.24, respectively) than in the post-2002 period ($r^2 = 0.10$ and 0.20, respectively).

However, following the severe winter of 2013–2014, Lake Michigan Q_t dropped significantly to more closely resemble conditions of the thermal regime that ended in the late 1990s. Given the strong relationship between winter thermal conditions and fall Q_t, the recent abrupt change in Lake Michigan's winter Q_t may signify a return to the cooler thermal regime or at least a strong deviation in the trends derived from empirical evidence and model projections. We do not find strong evidence that extreme low T_0 or high ice cover in early 2014 would preclude lower evaporation rates in the fall of 2014. In other words, projecting fall hydrologic response to extreme winter conditions is complicated by summer and fall meteorological conditions that play an important role in evaporation and water level dynamics. Nonetheless, by the end of 2014, water levels on the Lake Michigan-Huron and Lake Superior systems had finished a 2 year record setting water level surge [*Gronewold et al.*, 2015].

Overall, Lake Michigan's strong interseasonal memory of heat content does not make seasonal predictions of ice cover, evaporation, or T_0 any easier, as evidenced by the interannual variability of T_0 and the influence of summer atmospheric conditions. Yet the insight gained from this analysis and further monitoring of the lake conditions, including continuation of offshore monitoring protocols proposed and implemented by (among others) *Edson et al.* [1998], *Laird and Kristovich* [2002], and *Spence et al.* [2013], can help further define the range of expected energy and water fluxes given the thermal and hydrologic regime of Lake Michigan.

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