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Modeling Transitions in the Hydrologic and Thermal Regimes of Earth's Largest Lake System

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Background

Starting in the late 1990s, the seasonal hydrologic and thermal regimes of the North American Great Lakes (Earth's largest lake system) have been characterized by very high surface water temperatures, below-average ice cover, persistent low water levels and extremely high over-lake evaporation rates (Figure 1). However, the harsh winter conditions of 2013-2014 led to very low surface water temperatures (Figure 2) and an exceptionally broad and persistent areal extent of ice cover (Figure 3). The contrast between the extreme 2013-2014 winter conditions on the Great Lakes and the conditions from the preceding 15-year period raises compelling questions about the extent to which hydrometeorological conditions have changed in the Great Lakes region, how they might be expected to change in the future, and to what extent those changes are reflected in current regional research-oriented and operational forecasts.

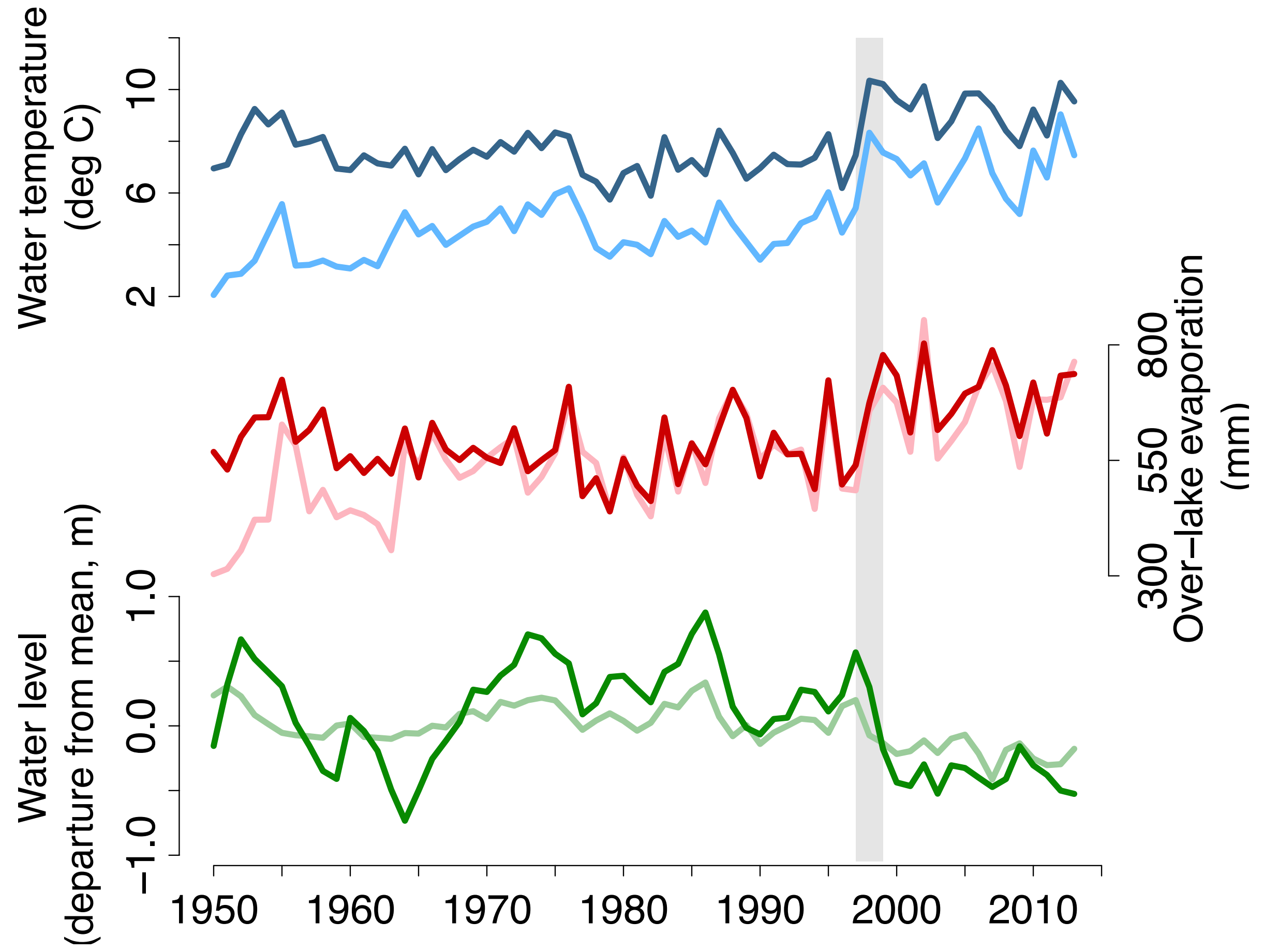

Figure 1. Time series of annual-average climate and hydrological variables for Lake Superior (dark colors) and Lake Michigan-Huron (light colors) reflecting long-term trends and abrupt shifts in surface water temperature (blue lines) and over-lake evaporation (red lines). These factors, combined with human intervention (including dredging of channels connecting the Great Lakes) contribute to recent record low water levels on both lake systems (green lines). Vertical gray band indicates approximate period of 1997-1998 El Niño. Adapted from Gronewold and Stow [2014].

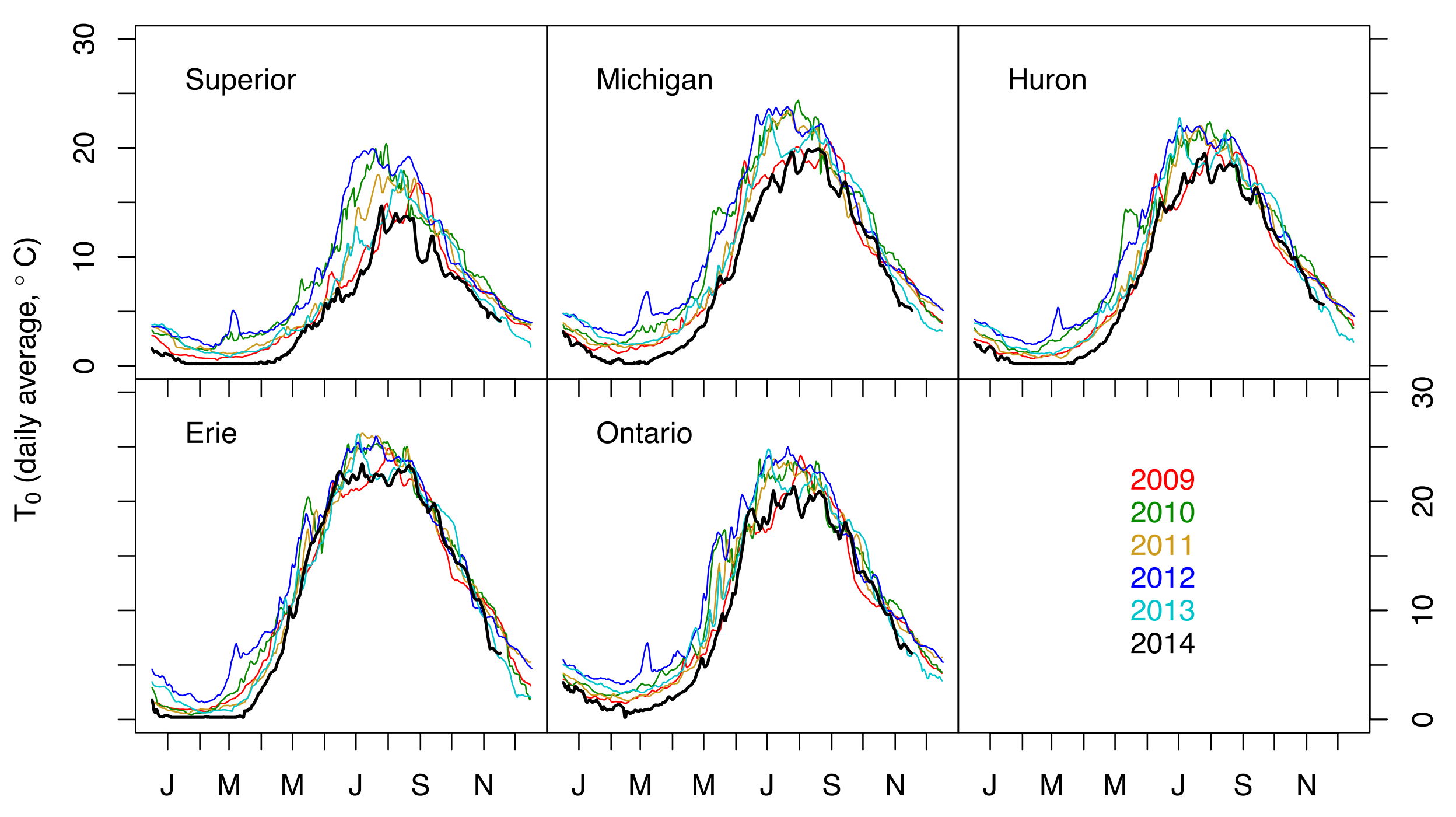

Figure 2. Lake Michigan daily lake-wide average surface water temperatures (T_0) from 2009 through November 2014 from NOAA's Great Lakes Surface Environmental Analysis [Leshkevich et al., 1996].

Acknowledgements

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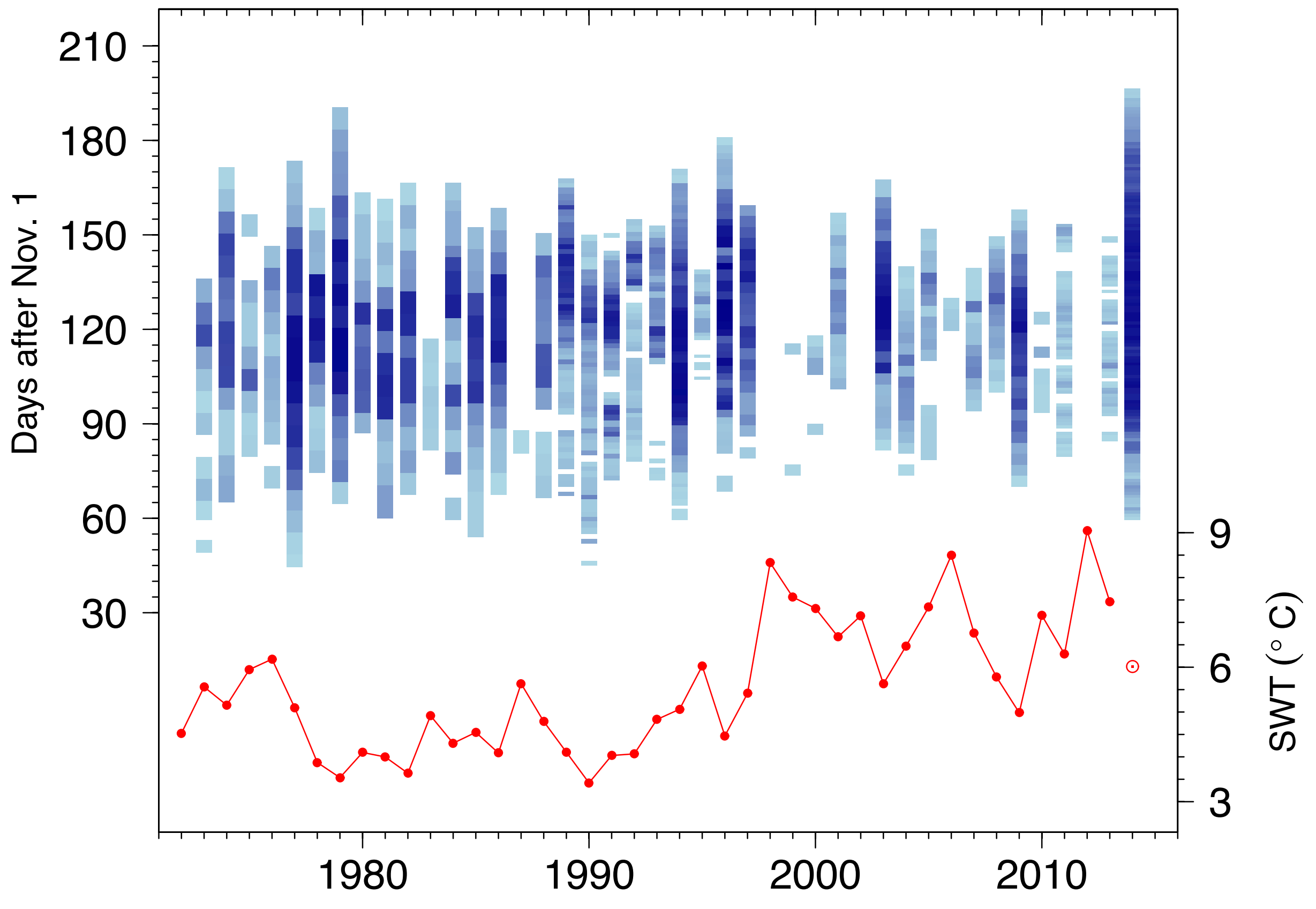


Figure 3. Areal extent of daily ice cover (blue columns) and average annual lake-wide surface water temperature (SWT; red line) on Lake Superior from 1972 to 2014. Each column corresponds to the 'ice season' for given calendar year. The darkest shades of blue across all columns indicate ice cover near 100%, while the lightest shades of blue indicate ice cover near 10%. Ice cover and SWT data are from the NOAA Great Lakes ice atlas project [Assel, 2005; Wang et al., 2012] and the NOAA Lake Thermodynamics Model [Croley II and Assel, 1994], respectively. Figure adapted from Clites et al. [2014].

Analysis

We investigated potential consequences of the 2013-2014 cold winter on Lake Michigan (the second largest of the Great Lakes by volume, and third largest by surface area) by analyzing historical inter-seasonal relationships between the lake's late winter and subsequent late fall thermal regimes. We represent winter thermal conditions using estimates of total lake heat content Q_t (in kJ x 10^{14}), 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 through 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 through 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 through September.

We employed daily estimates of lake-wide Q_t, T_0, and $S\downarrow$ from NOAA's one-dimensional large lake thermodynamics model [Croley II and Assel, 1994] for the entire period of record (1950 to 2013). We also employ daily estimates of T_0 and ice cover from the LLTM, but only for the periods 1950 through 1994 (for T_0) and 1950 through 1972 (for ice cover). We employ estimates of T_0 from 1995 through 2014 from NOAA's Great Lakes Surface Environmental Analysis [Leshkevich et al., 1996], and 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 conditions for fall 2014 from the NOAA Great Lakes Advanced Hydrologic Prediction System [Croley II and Lee, 1993; Gronewold et al., 2011] based on calculations made on April 1, 2014. See Figures 4 and 5 for comparison between, and locations of, alternative data series.

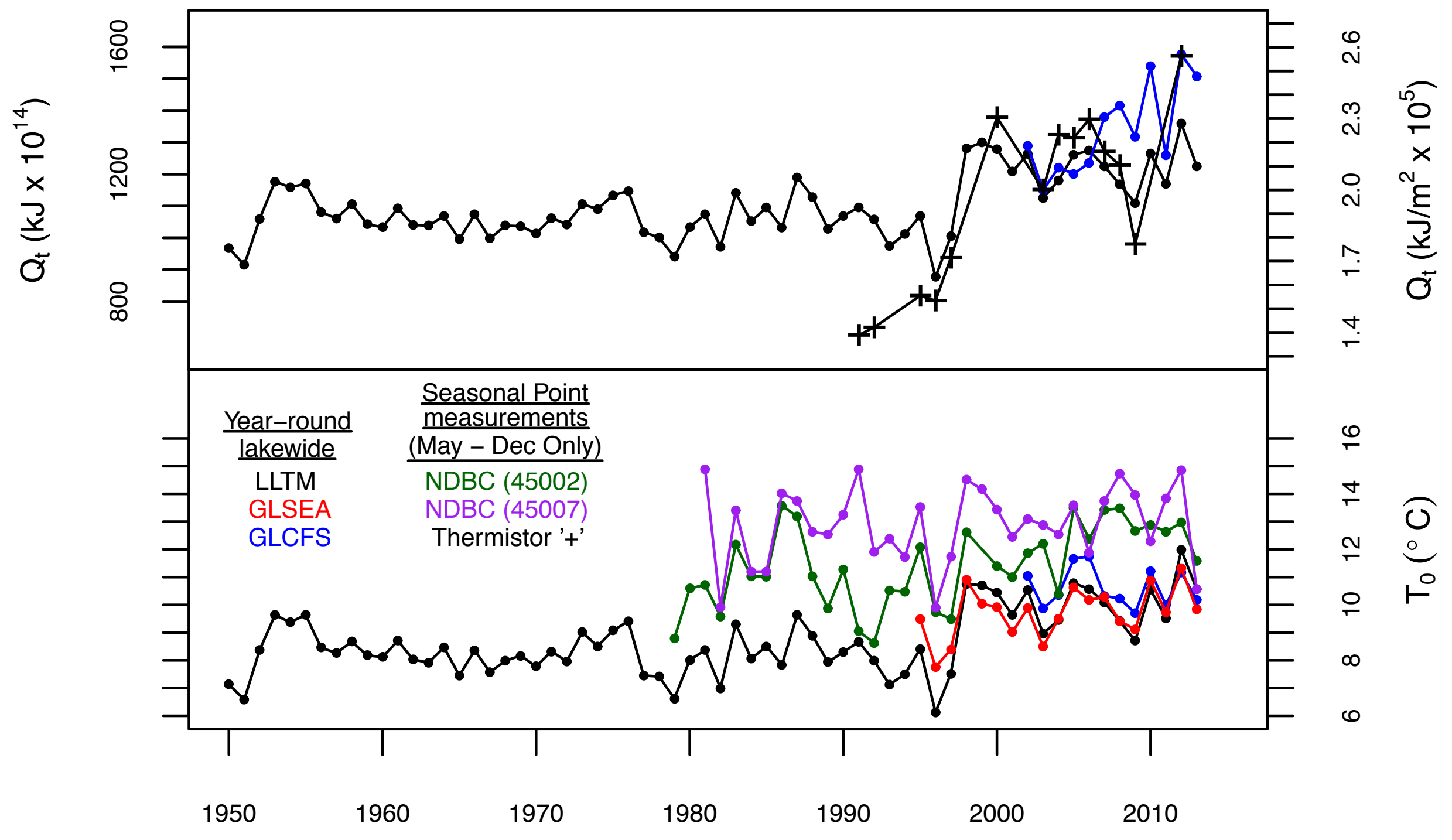


Figure 4. Time series of alternative measurements of Lake Michigan's heat content (top panel) and surface water temperature (bottom panel).

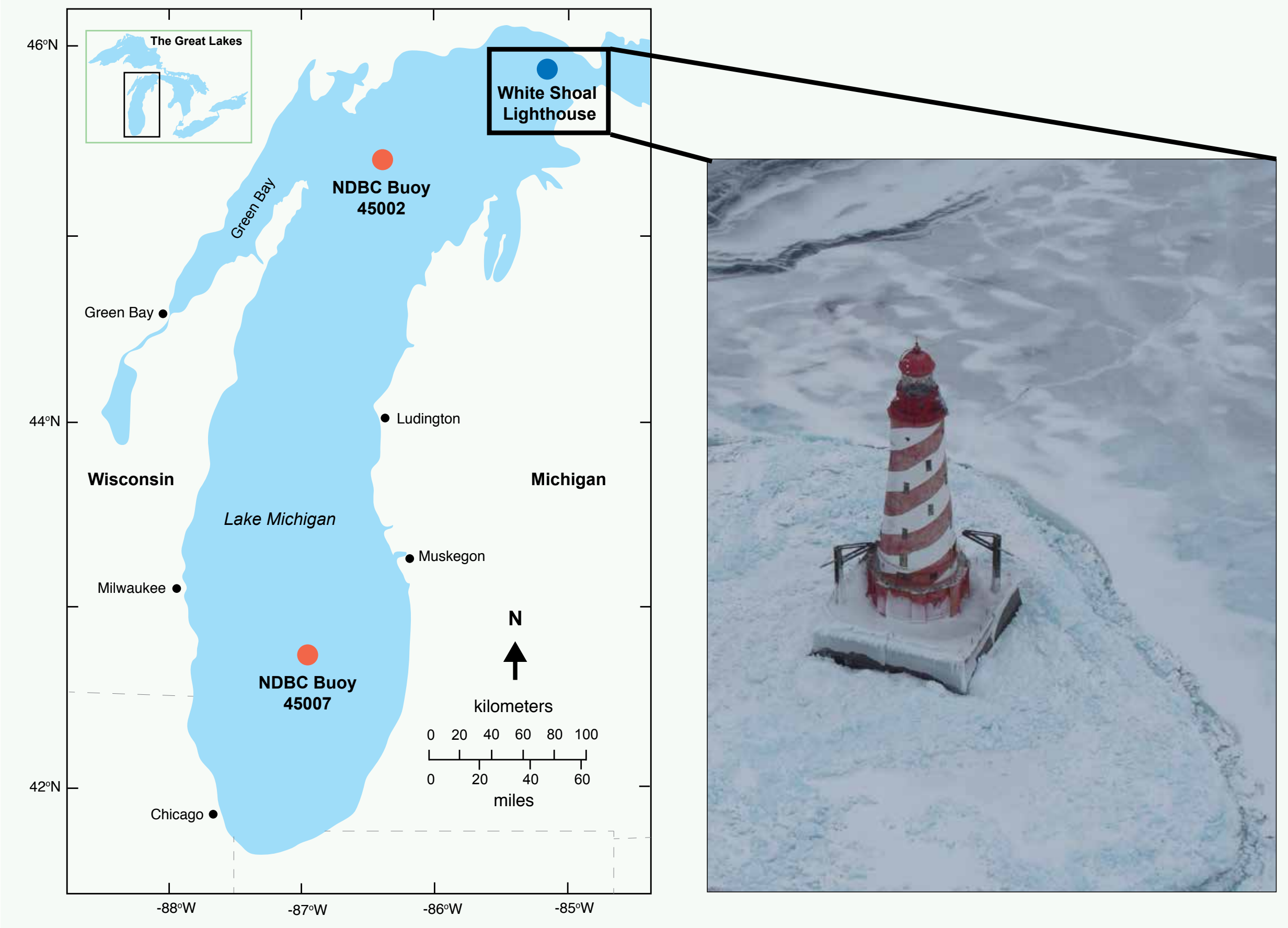


Figure 5. Map of Lake Michigan identifying NDBC buoys 45002 and 45007, and the White Shoal lighthouse (which currently houses a new eddy-covariance station). Aerial photo of White Shoal light in northern Lake Michigan. January 13, 2014. Credit: D. Moehl and Great Lakes Air.

Results

Prior to 1995 (Figure 6a), Lake Michigan was in a relatively 'cool' regime, with winter Q_t ranging between roughly 540 and 720 kJ x 10^{14}, and fall Q_t ranging between roughly 1200 and 1500 kJ x 10^{14}. The period from 1995 through 2001 (Figure 6a) 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 and 900 kJ x 10^{14}, and fall Q_t ranging between roughly 1450 and 1600 kJ x 10^{14}. These two periods are also distinguished by changes in summer $S\downarrow$ (proportional to diameter of dots in Figure 6); 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.

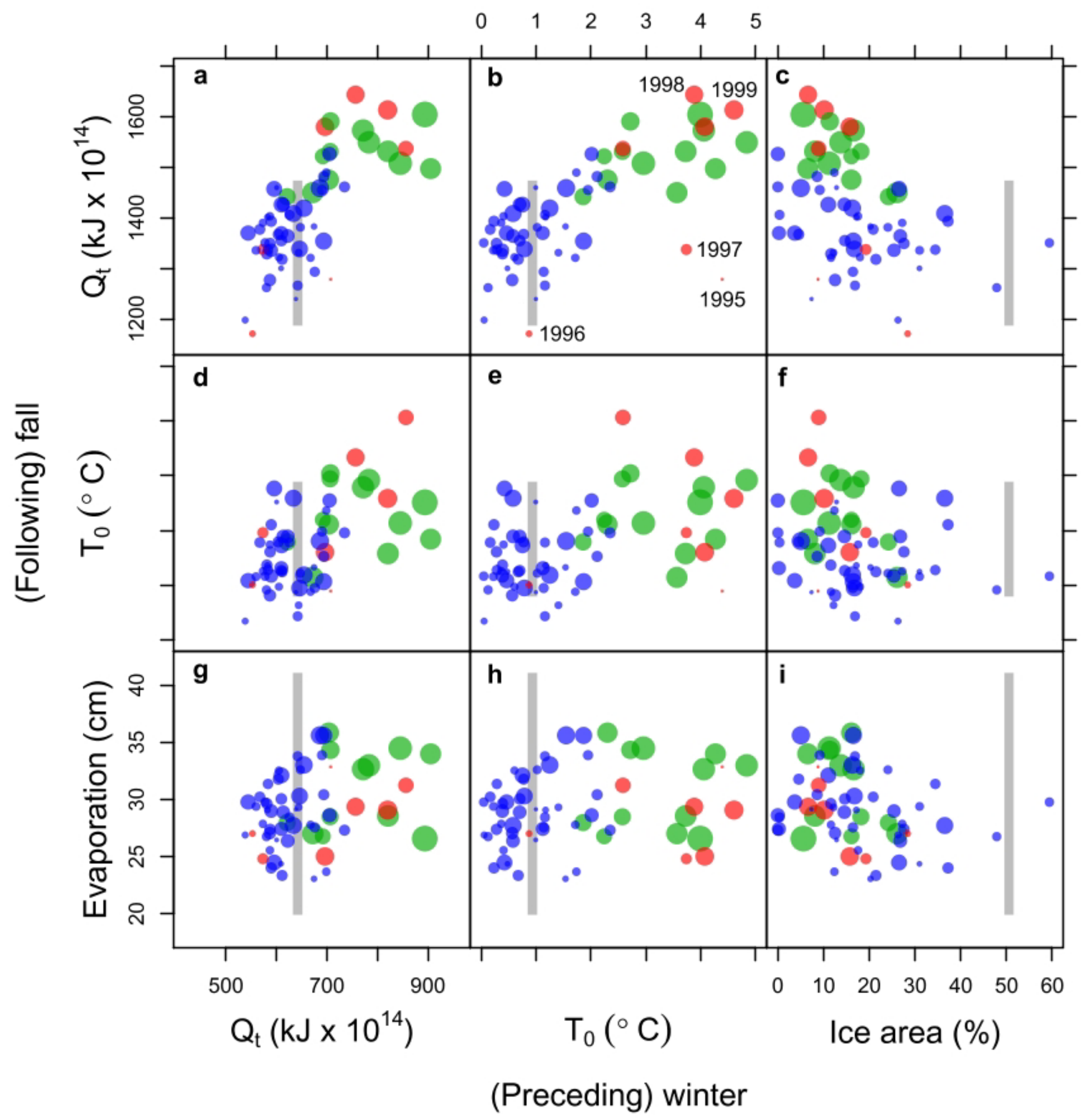
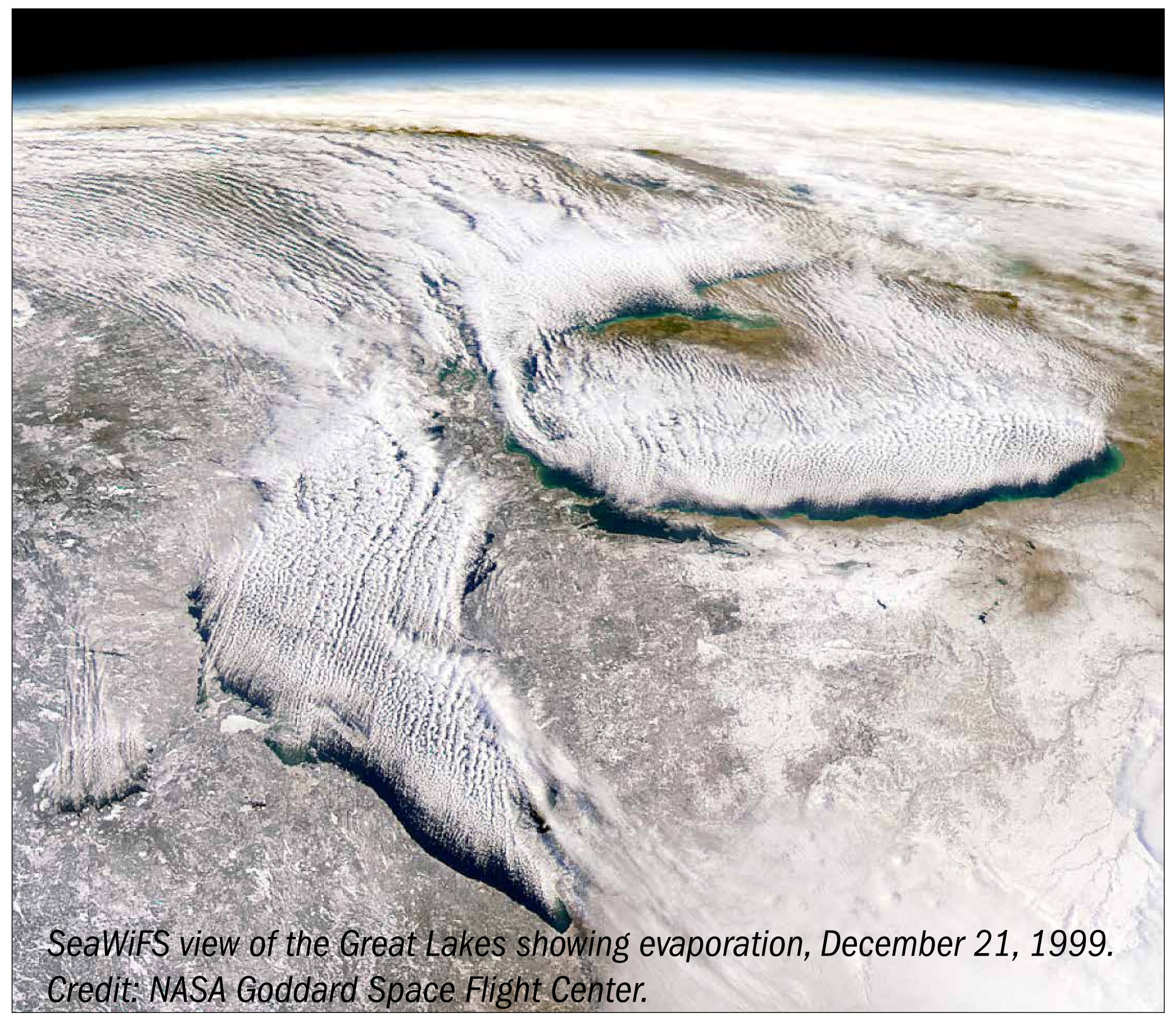


Figure 6. Relationships between winter and (following) fall thermal regimes on Lake Michigan from 1950 to 1994 (blue dots), 1995 through 2001 (red dots), and 2002 to 2013 (green dots). For clarity (and to coincide with results in section 3), years 1995 through 1999 are identified in panel b. Winter (observed) 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.

In contrast to inter-seasonal 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 6d-i). 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 [Spence et al., 2013].

Projections from AHPS-LLTM made in early April 2014 (Figure 6) 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 in the 2013-2014 winter alone will necessarily lead to noticeably lower fall evaporation rates (Figures 6g-i).



SeaWiFS view of the Great Lakes showing evaporation, December 21, 1999. Credit: NASA Goddard Space Flight Center.

Conclusions and Next Steps

We have found compelling evidence that one of Earth's largest lakes has been 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 found that it may have been sustained through a transition to above-average summer solar input [see Austin and Allen, 2011, for a related discussion].

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. The immediate fall hydrologic response to extreme winter conditions such as those experienced in 2014 remains unclear, as additional factors such as summer and fall meteorology play an important role in evaporation and water level dynamics.

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