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Key Points:

- A climatically driven decadal oscillation dominates the regional water cycle
- The oscillation is governed by ($P - E$) and a stage-dependent runoff flux
- A recent change in oscillation may mark the onset of a new hydroclimatic regime

Supporting Information:

- Readme
- Relationship between total evaporation (May-November) and summer evaporation (June, July and August) for the in-lake evaporation pan.
- Spectral analysis (FFT) of the time-series for: annual water level (A), annual change in water level (B), annual precipitation minus evaporation (C), annual precipitation (D), annual evaporation (E), annual water level pre-1998 (F), annual water level post-1998 (G) in the NHLD. (data detrended; cs2Hann window; PSD SSA: power spectral density as sum squared amplitude) Horizontal lines indicate the 50% (yellow), 90% (green), 95% (blue) and 99% (red) significance levels (white noise model). (H) Detrended time-series for annual NHLD water level, post-1998 data only. We note that power spectra were also generated for the Lake Michigan-Huron, Lake Superior and the modelled NHLD water level time-series (cf. Figs. 2B and 3D). The results for all three annualized time-series indicated prominent but not statistically significant signals with a period of 12y to 13y. Further FFT results for Lake Michigan-Huron using monthly data from Fig. 2B indicated highly significant peaks (99.9%) that correspond to periods of 12.7y and 1y.
- Analysis of time lag and integration window effects (both in years) on the relationship between annual ΔS and annual (P-E) for the aggregated NHLD dataset.
- Time-series for water levels in 27 NHLD lakes over the time period 2008-2013. Data are the weekly grand mean ± standard deviation for a suite of 15 seepage lakes, 10 drainage lakes and 2 drained lakes. Source: Anne Kretchmann, North Lakeland Discovery Center, Manitowish Waters, WI (unpublished data).

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Decadal oscillation of lakes and aquifers in the upper Great Lakes region of North America: Hydroclimatic implications

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Abstract We report a unique hydrologic time series which indicates that water levels in lakes and aquifers across the upper Great Lakes region of North America have been dominated by a climatically driven, near-decadal oscillation for at least 70 years. The historical oscillation (~13 years) is remarkably consistent among small seepage lakes, groundwater tables, and the two largest Laurentian Great Lakes despite substantial differences in hydrology. Hydrologic analyses indicate that the oscillation has been governed primarily by changes in the net atmospheric flux of water ($P - E$) and stage-dependent outflow. The oscillation is hypothetically connected to large-scale atmospheric circulation patterns originating in the midlatitude North Pacific that support the flux of moisture into the region from the Gulf of Mexico. Recent data indicate an apparent change in the historical oscillation characterized by an ~12 years downward trend beginning in 1998. Record low water levels region wide may mark the onset of a new hydroclimatic regime.

1. Introduction

Hydrologic responses to contemporary climate change in North America are uncertain in part because instrumental records are generally short, sparse, and often confounded by direct human influence, such as dredging, diversion, impoundment, and withdrawal. Among the longest instrumental records are those for the Laurentian Great Lakes, which date back to the 1860s. Several studies have identified decadal to multidecadal oscillations in these records (or in geological proxies such as coastal ridges) that imply climatic forcing [*Cohn and Robinson*, 1976; *Thompson and Baedke*, 1997; *Polderman and Prior*, 2004; *Hanrahan et al.*, 2009]. In recent years, sharply declining water levels in the upper Great Lakes have focused attention on hydrologic drivers and their potential connection to large-scale climatic modes [*Assel et al.*, 2004; *Sellinger et al.*, 2008; *Hanrahan et al.*, 2010]. The recent declines have been attributed to multiple factors, including channel dredging and changes in precipitation and evaporation [cf. *Stow et al.*, 2008; *Hanrahan et al.*, 2010; *Egan*, 2013a]. The question of potential drivers has hydroclimatic, economic, social, and political dimensions [*Egan*, 2013b].

The complexity of water budgets for very large systems like the Laurentian Great Lakes complicates mechanistic investigation. In their simplest form, water budgets can be expressed as $S_t = S_{t-1} + (P - E + Q)$ where S is storage (water level or stage), t is time, P is precipitation, E is evaporation, and Q comprises all other inflows and outflows. For the upper Great Lakes, Q can be decomposed into at least five inflow terms (fluvial inflow, groundwater inflow, surface runoff, diversion in, and connecting channel inflow) and four outflow terms (fluvial outflow, groundwater outflow, diversion out, and consumptive use).

To facilitate analysis, we focus instead on the historical water level fluctuations of small, relatively undisturbed systems with simpler hydrologic budgets that can be written as $S_t = S_{t-1} + (P - E + G_{\text{net}})$ where G_{net} (the net groundwater flux) is the only substantial component of Q. Compiling instrumental data from several sources, we report a unique 70 years time series comprising two small seepage lakes and two sets of groundwater monitoring stations that are within the upper Great Lakes region but outside the Great Lakes basin. We compare this time series to

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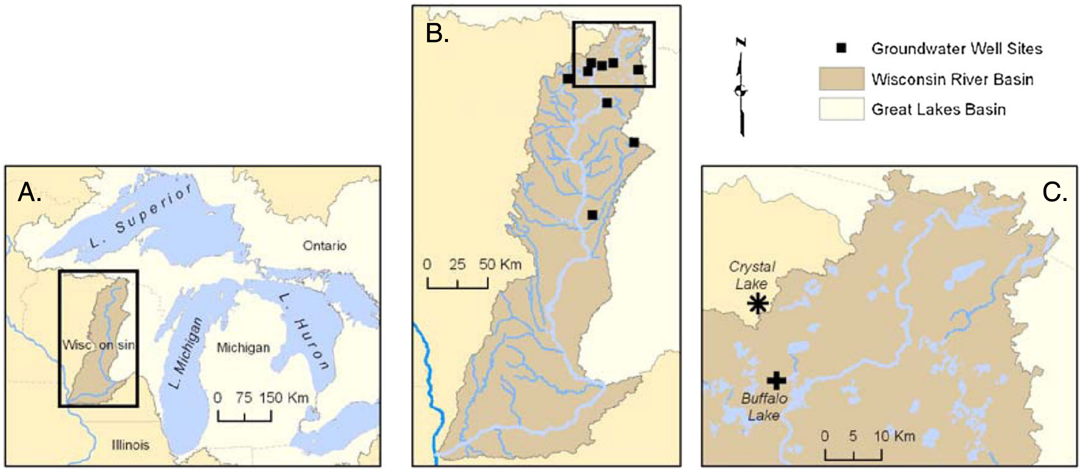

Figure 1. Map of the study area. (a) Laurentian Great Lakes region, showing upper Great Lakes basin (Lake Superior and Lake Michigan-Huron) and Wisconsin River drainage (flowing south to the Mississippi River). (b) Wisconsin River drainage, showing location of nine groundwater monitoring wells. (c) Location of Buffalo Lake (45°52′N, 89°33′W, area 56 ha, maximum depth 8 m) and Crystal Lake (46°0′N, 89°36′W, area 34 ha, maximum depth 20 m) within the NHLD.

analogous data for the two largest Laurentian Great Lakes over the time period 1942–2011. We use contemporaneous time series for precipitation and evaporation to investigate the importance of proximate hydrologic drivers. We then explore relations with global atmospheric variables using correlations with global geopotential height (GPH) at 500 hPa and sea level pressure (SLP). Our findings indicate that a climatically driven near-decadal oscillation has dominated water levels across the upper Great Lakes region for most of the past century, and they suggest that a change in the historical oscillation may have occurred during the past two decades.

2. Study Sites and Data

The region under study is shown in Figure 1. Lake Superior and Lake Michigan-Huron are the two largest freshwater lakes in the region (world), with a total catchment area of 5.8×10^5 km^2. Crystal Lake and Buffalo Lake are small seepage lakes ($<$60 ha) located adjacent to the Great Lakes Basin in the northern Chippewa River drainage and the upper Wisconsin River drainage, respectively (both of which flow southward to the Mississippi River) (Figures 1b and 1c). As seepage lakes, they have no inflowing or outflowing streams and receive negligible surface runoff from their small terrestrial catchments. Both lakes lie within the Northern Highland Lake District (NHLD) of Wisconsin, an area which contains thousands of poorly integrated lakes and wetlands situated in deep glacial tills (30–60 m) and outwash sands that were formed as the Wisconsonian glacial period ended roughly 10 kyr B.P. [*Magnuson et al.*, 2006].

Historical water levels of Buffalo Lake (arbitrary datum) and a set of nine groundwater monitoring wells distributed across the upper Wisconsin River basin were obtained from the Wisconsin Valley Improvement Company (WVIC) which manages flow in the Wisconsin River (Figure 1b). Weekly observations were made in Buffalo Lake from 1942 to 1989, and monthly observations were made in the wells from 1942 to 1995 (reported here as the ensemble mean anomaly for all nine wells). Historical water levels (1981–2012) of Crystal Lake and 10 adjacent groundwater monitoring wells were obtained from the North Temperate Lakes Long-Term Ecological Research (NTL-LTER) Program, Center for Limnology, University of Wisconsin-Madison (http://lter.limnology.wisc.edu/). The LTER protocol entailed biweekly readings of a referenced (mean annual sea level) staff gauge in the lake and manual measurements of water levels in the groundwater wells each month. Groundwater elevations for this well set are also reported as an ensemble mean. Monitoring wells were situated in shallow, unconfined aquifers within the deep glacial till and outwash sand.

Annual precipitation totals for the NHLD (1937–2011) were obtained from the WVIC as the monthly average of 10 to 12 weather stations in the upper Wisconsin River drainage extending northward from Wisconsin Rapids, WI, into Vilas and Oneida counties. Monthly evaporation totals for the approximate ice-free period (May–November, 1937–1993) were obtained from WVIC based on data from an in-lake evaporation pan. To accommodate missing *E* pan data for some months, annual evaporation totals were estimated from values for summer months using

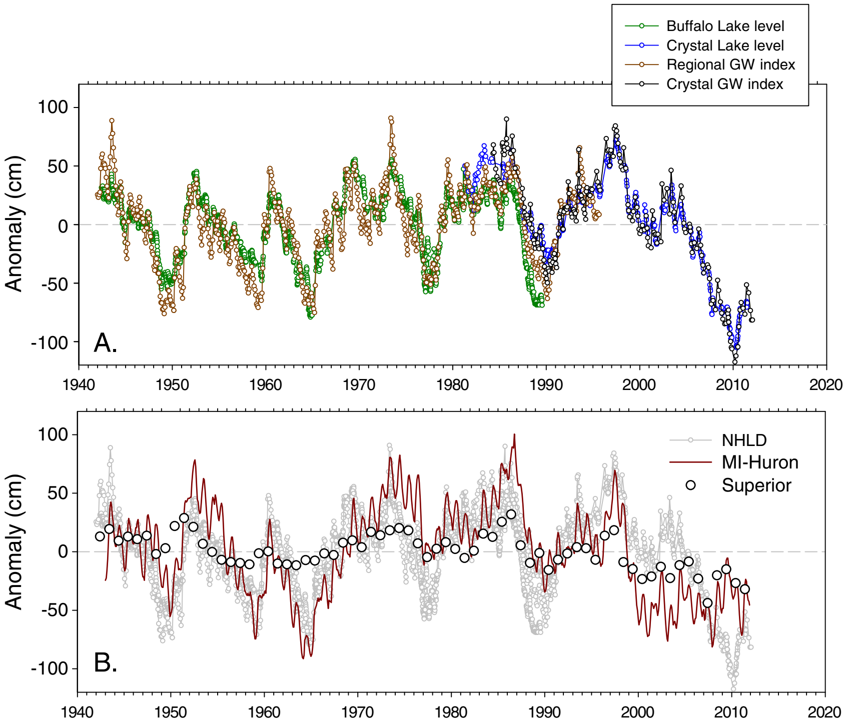

Figure 2. Near-decadal oscillation of regional water levels, 1942–2011. (a) Time series for Crystal Lake, Buffalo Lake, and the both sets of groundwater monitoring wells. (b) Time series for Lake Michigan-Huron (red line) and Lake Superior (circles) superimposed on the time series for the NHLD (grey).

the empirical relationship $E_{\text{May–Nov}} = 1.33 \cdot E_{\text{Jun–Aug}} + 8$ ($r^2 = 0.78$) which was derived for all years with complete records (Figure S1 in the supporting information). For the time period 1989–2011, annual evaporation totals for Crystal Lake were estimated using a Bowen ratio energy balance (BREB) method that uses a whole-lake energy budget to estimate evaporative fluxes (E) [*Lenters et al.*, 2005; *Read*, 2012]. For the BREB method, yearly simulations of E began on first day of open water (ice free) and ended on the last day of open water. To reconstruct a time series for evaporation during the approximate ice-free season for the period 1937–2011, we combined the WVIC data (1937–1993) with the BREB data (1994+). We note that during the brief period of overlap, mean estimates of E differed by ~16% between methods (paired $t = 2.78$, $p = 0.07$).

Monthly water levels for Lake Superior and Lake Michigan-Huron (International Great Lakes Datum (IGLD) 1985) were obtained from the Watershed Hydrology Branch of the U.S. Army Corps of Engineers in Detroit, MI. Lake Superior elevations were based on a network of gauges in Duluth, MN; Marquette, MI; and Pt. Iroquois, Thunder Bay, and Michipicoten, Ontario. Lake Michigan-Huron elevations were based on a network of gauges in Harbor Beach, Mackinaw City, and Ludington, MI; Milwaukee, WI; and Tobermory and Thessalon, Ontario.

3. Water Level Oscillations

The time series of water level anomalies for Crystal Lake, Buffalo Lake, and NHLD groundwater tables is shown in Figure 2a. Visual inspection indicates strong coherence and suggests that a near-decadal oscillation has dominated water levels in the NHLD for at least seven decades. The amplitude of oscillation ranges approximately ±0.7 m, dwarfing the well-known annual cycle. To aggregate the NHLD data, we interpolated daily values for the time series in Figure 2a and we used the interpolated values for 1 January of each year to estimate annual water levels. Spectral analysis (fast Fourier transform) of the annualized water level data indicates a dominant periodicity of ~13 years (99% significance level, Figure S2a). Consistent with the findings of *Ault and St. George* [2010], spectral analysis did not indicate statistically significant oscillations for related variables, such as precipitation, evaporation, or the annual change in water level—except for a very low frequency signal in annual evaporation that reflects a gradual decreasing trend until 1970 and a gradual increase thereafter (Figures S2b–S2e).

The NHLD data are compared to analogous time series for Lake Michigan-Huron and Lake Superior in Figure 2b. The graphical comparison shows that the oscillation of Lake Michigan-Huron has been remarkably similar to the oscillation observed in the NHLD despite large differences in hydrology. Lake Superior has oscillated with a similar periodicity but with damped amplitude. The damping may be due to regulatory structures that control outflow through the Saint Mary's River within limits set by the International Lake Superior Board of Control. With this caveat, temporal coherence among these hydrologic systems indicates that the near-decadal oscillation is a general characteristic of the regional water cycle.

4. Hydrologic Mechanisms Underlying the Near-Decadal NHLD Oscillation

To investigate hydrologic mechanisms potentially driving the near-decadal water level oscillation, the NHLD water budget was expressed as $\Delta S = (P - E) + (G_{in} - G_{out})$ where ΔS is the change in stage (water level) over a specified time period and $(P - E)$ approximates the net atmospheric flux of water, all in L/T. The variability of P and E over annual time scales has been comparable for the time period 1937–2011 (means 79 and 51 cm yr^{-1}, coefficients of variation 12% and 15%, respectively). As expected for a humid region, P and E are negatively correlated (Figure 3a). The correlation implies a dual effect: increased P is associated with decreased E and the converse, thus amplifying the impact of dry and rainy years on water levels.

We estimated ΔS for the aggregated NHLD data over windows ranging from 1 to 4 years. These estimates were correlated with analogous values for $(P - E)$ over a series of yearly lags. The results indicated that a 1 year integration window with no lag in $(P - E)$ explained the most variance in observed ΔS (Figure S3). The best fit indicates that annual $(P - E)$ can account for 65% of the variability in ΔS from year to year (Figure 3b). The intercept implies a missing flux of -38 cm/yr (±3.7 cm, standard error (SE); $p < 0.001$), which hypothetically constitutes regional groundwater loss (G_{net}). The residuals were not correlated with time, but there was a correlation with stage, which suggests that the average groundwater flux (-38 cm/yr) was an underestimate when stage was high and an overestimate when stage was low.

Given the results from Figure 3b and the dependence of the NHLD groundwater flux on stage, we used a recursive model to estimate the aggregate stage for a given year (t) as $S_t = S_{t-1} + m(P_t - E_t) - G_t$, where P_t and E_t are yearly total precipitation and evaporation and G_t is a stage-dependent groundwater flux term, given by $G_t = (b \cdot S_{t-1} - c)$. The constants "$m$," "$b$," and "$c$" were derived from the fit in Figure 3b, where "m" and "c" are the slope and intercept of the original fit and "b" is the slope of the residuals fit to stage. The initial stage (S_{1942}) and the stage dependence coefficient (b) were optimized to minimize the mean square error (MSE) between the modeled and observed stages (bounding possible values for b within its 95% confidence window). For the aggregated NHLD data, the model was able to explain 70% of the variability in annual ΔS over the time period 1943−2010 (Figure 3c). The time series for modeled stage (S) tracked the observed time series reasonably well ($r^2 = 0.62$, Figure 3d), confirming the importance of $(P - E)$ as a governing factor and the importance of a stage-dependent groundwater flux as a contributing factor.

5. Connection With Large-Scale Atmospheric Circulation Patterns

The similar near-decadal oscillation of NHLD and Great Lakes' water levels suggests that a common governing mechanism(s) has operated across the region despite large differences in the hydrology of individual systems. Since connections to large-scale climate modes have been suggested by *Ghanbari and Bravo* [2008], *Hanrahan* [2010], and *Hanrahan et al.* [2009, 2010] for the upper Great Lakes, we investigated the correlation between monthly changes in NHLD water levels and 500 hPa geopotential height and sea level pressure from the National Centers for Environmental Prediction-National Center for Atmospheric Research reanalysis data set for the 63 year period of 1948–2010. Because warm-season precipitation dominates the annual cycle in this region (data not shown), our correlation analysis focuses on monthly changes in stage between April and September, where each month has an associated change in stage (e.g., the April 1948 change in stage is the difference in stage between 1 May 1948 and 1 April 1948). The seasonal cycle was removed from all time series prior to correlating. This included removing the seasonal cycle from the change in stage time series and from the 500 hPa geopotential height and sea level pressure fields at each grid cell separately.

The correlation map between monthly change in stage and 500 hPa geopotential heights indicates that warm-season changes in stage are associated with a large-scale atmospheric wave train that extends from the central North Pacific, across central North America, and over western North Atlantic (Figure 4a). This wave train anomaly

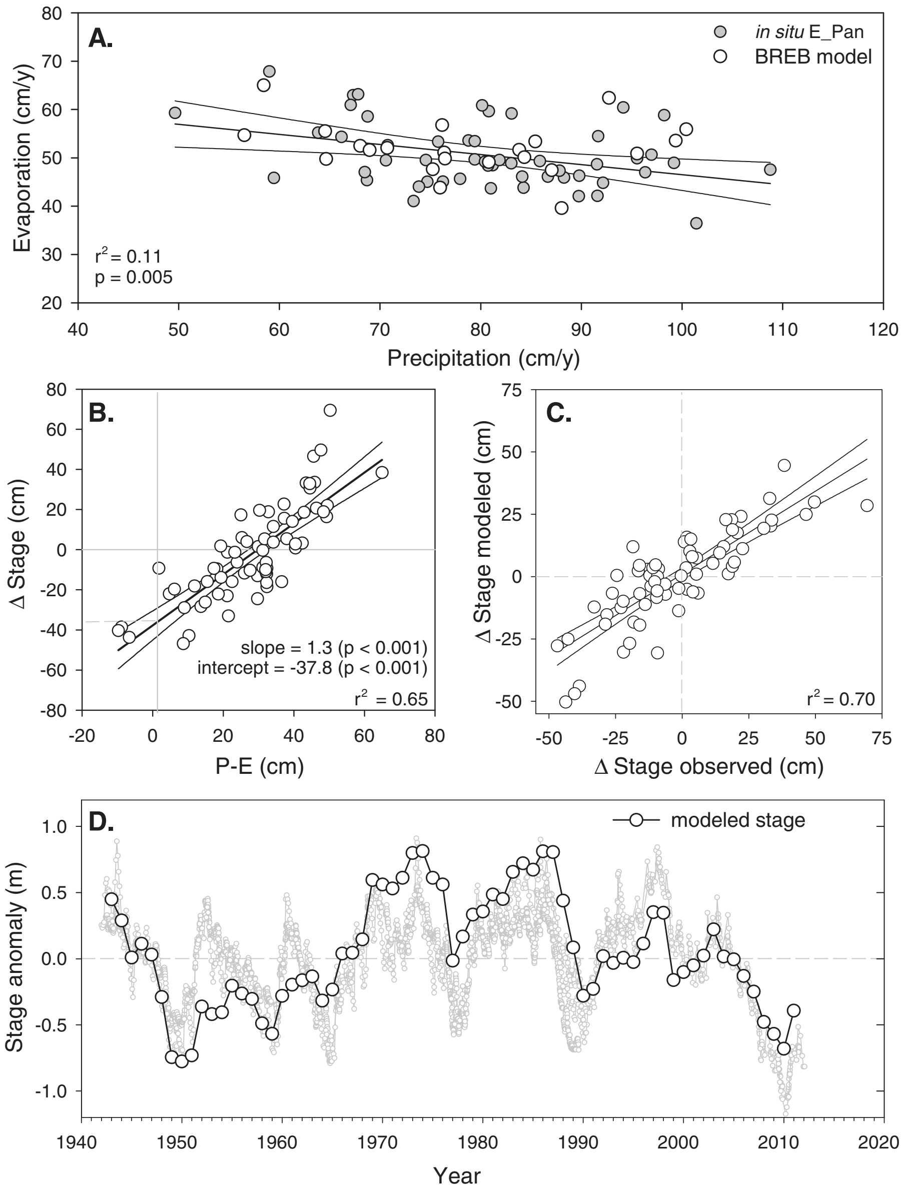

Figure 3. Relationship between NHLD water levels, precipitation, and evaporation, 1942–2010. (a) Negative relationship between P and E, (b) regression of annual $(P - E)$ on the annual change in stage (ΔS) using aggregated water levels, (c) comparison of observed ΔS to the predicted ΔS, based on recursive model with a stage-dependent groundwater flux (see section 4), and (d) time series for observed and modeled water levels.

pattern resembles the circumglobal teleconnection (CGT) pattern that propagates along the westerly waveguide [*Branstator*, 2002; *Ding and Wang*, 2005]. This is similar to the findings from *Small et al*. [2010], which suggest that the CGT influences regional hydrology across the United States and Canada during fall months. We surmise that the CGT enables upstream conditions, such as those over the North Pacific, to influence climate and climate variability across North America. We present the correlation map between monthly change in stage and sea level pressure to illustrate the relationship with atmospheric conditions near the surface (Figure 4b). Correlations in Figure 4b show that positive changes in lake stage are associated with a high-pressure anomaly near the Gulf of Alaska and near the southeast coast of the United States, along with a low-pressure anomaly near the central United States. The inferred flow regime based on the sea level pressure correlation map suggests that positive changes in lake stage are correlated with south-southwesterly winds into the Great Lakes region, possibly originating over the Gulf of Mexico. South-southwesterly surface winds from the Gulf of Mexico are often associated with warm temperatures and increased atmospheric moisture content,

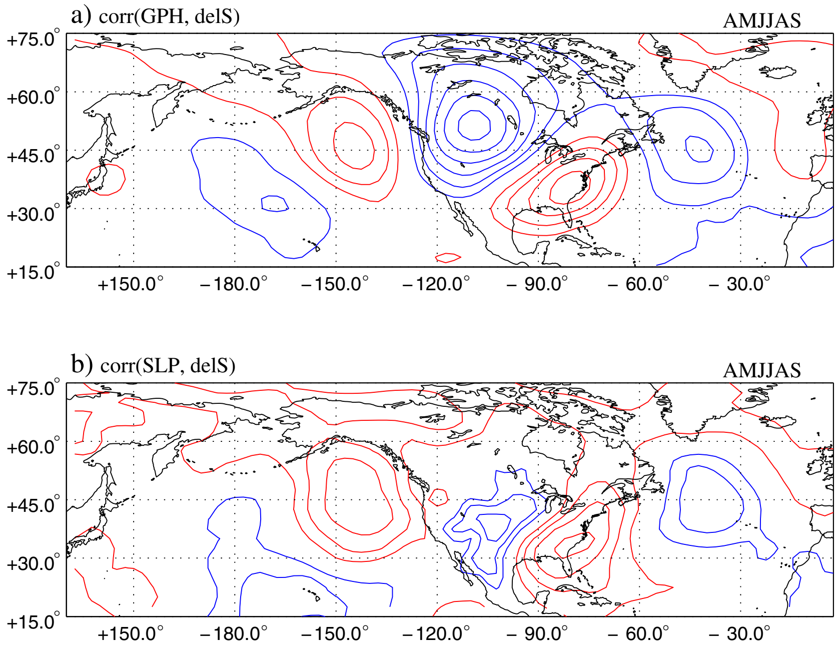

Figure 4. One-point correlation maps between monthly NHLD change in stage (delS) and (a) 500 hPa geopotential height (GPH) and (b) sea level pressure (SLP) during each month between April and September from 1948 to 2010. Red (blue) contours indicate positive (negative) correlation values. The contour interval is 0.05. The zero line is omitted. Values above/below ±0.11 are significant at the 99% contour interval based on Student's *t* test.

which may reduce stability in the region and also act to suppress surface evaporation. It should be noted that the correlation analysis presented in Figure 4 does not explicitly isolate the mechanism for the 13 year oscillation in NHLD and upper Great Lakes' water levels. Instead, the analysis provides a potential explanation of large-scale atmospheric circulations that influence warm-season hydrology across the upper Great Lakes region.

6. Potential Hydroclimatic Implications

The strong coherence among small NHLD lakes, groundwater, and the two largest Laurentian Great Lakes is surprising, but it is consistent with reports for other lakes in the region over shorter time spans [*Magnuson et al*., 2006; *Stow et al*., 2008; *White et al*., 2008]. A common oscillation among dissimilar systems seems to imply a common governing factor, and our data suggest that the common factor is ($P - E$). Until recently, evaporation has been considered a negligible factor in the near-decadal oscillation of the upper Great Lakes due to its relative constancy over most of the historical record [*Hanrahan et al*., 2009]. Recent correlations between a longer ice-free period, increased water temperature, and increased evaporation suggest a stronger influence of E on water budgets across the region [*Magnuson et al*., 2000; *Austin and Colman*, 2007; *Desai et al*., 2009; *Hanrahan et al*., 2010; *Mishra et al*., 2011].

During the past decade, unusually low water levels have been observed in both the NHLD and the upper Great Lakes. Following a peak in 1998, NHLD water levels have trended downward for roughly 12 years—reaching a record low elevation in 2010 (Figure 2a). Similarly, the water level of Lake Michigan-Huron recently dropped at a rate not seen since the 1930s megadrought [*Assel et al*., 2004; *Sellinger et al*., 2008]. Both Lake Superior and Lake Michigan-Huron have been consistently below average level for the longest sustained period in their historical records [*International Lake Superior Board of Control*, 2012], and in January 2013, Lake Michigan-Huron reached an all-time low water level (U.S. Army Corps of Engineers, unpublished data, 2013).

To assess an apparent change in the historical oscillation, spectral analysis was applied to the pre-1998 and post-1998 segments of the NHLD time series after trends were removed (Figures S2f and S2g). The results indicate a near-decadal oscillation in both detrended segments (13 years and 11 years, respectively), but the major spectral peak for the post-1998 segment is not statistically significant due to its relatively short length. Although speculative, this result suggests that a downward trend was superimposed on the historical oscillation beginning around 1998. The data also suggest that the amplitude of oscillation (if real) has decreased (Figure S2h). Ancillary data for a suite of 27 small NHLD lakes are consistent with this latter finding. Over the 5 year time period spanning 2008–2013, the 27 lake time series has been dominated by low-amplitude (±0.30 cm) seasonal and interannual fluctuations around a lower mean water level (Figure S4). Similarly low-amplitude fluctuations have characterized the time series for Lake Michigan-Huron during recent years (Figure 2b).

At least three future hydroclimatic scenarios seem possible for this midcontinental region: (1) the historical water cycle may resume in a few years, with the time period 1990–2012 as an aberration in the historical record; (2) the recently altered cycle may propagate through future time as an amplified oscillation around the historical mean water level; or (3) a step change (or series of step changes) to new mean water levels may occur. Because of the magnitude of past oscillations, it remains challenging to predict which scenario is most likely [*Meehl et al*., 2009]. However, as future climatic conditions evolve over time, small isolated lakes and water tables may prove to be useful sentinels of hydrologic change.

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