Connecting climate variability to the water levels of Lakes Michigan and Huron

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Abstract

The water levels of Lakes Michigan and Huron have been monitored since 1865, and numerous attempts have since been made to connect their variations to potentially predictable large-scale climate modes. In the present study, the levels are analyzed after outflow-related damping effects were removed, increasing the transparency of the lake-level fluctuations and potential climate connections. This filtering exposes a large oscillation which is connected to the Atlantic Multidecadal Oscillation (AMO), and a ~27-yr periodicity that is likely resulting from the intermodulation of two near-decadal cycles originating in the North Atlantic region. While the lake-level fluctuations prior to 1980 were predominately driven by changes in precipitation, it is now found that for the first time in our years of record, evaporation has begun to significantly contribute to lake-level changes. Summertime evaporation rates have more than doubled since 1980 as a result of increasing water-surface temperatures, which are significantly correlated with decreasing wintertime ice cover.

Fig. 1. Laurentian Great Lakes; Lakes Michigan and Huron are highlighted. Original image obtained from: Visible Earth (http://visibleearth.nasa.gov/).

Introduction

The water levels of Lakes Michigan and Huron have been of interest for many years due to the large impacts that their changes have on surrounding communities. These impacts range from increased shoreline erosion when the levels are higher than normal, to inflated shipping costs when the levels are too low for cargo ships to carry typical-sized loads. When lake-level extremes are not foreseen, the negative impacts are inevitable, as proper preparation is oftentimes not possible. Connections to potentially-predicable climate modes can lead to improved lake-level forecasting ability, which would result in better preparation and decreased negative effects from these lake-level extremes.

The importance of linking interannual lake-level fluctuations to climate is now becoming more urgent due to anticipated changing precipitation and temperature trends resulting from global climate change. The unpredictable historic lake-level extremes have already proven problematic, and future uncertain trends will likely only amplify these issues.

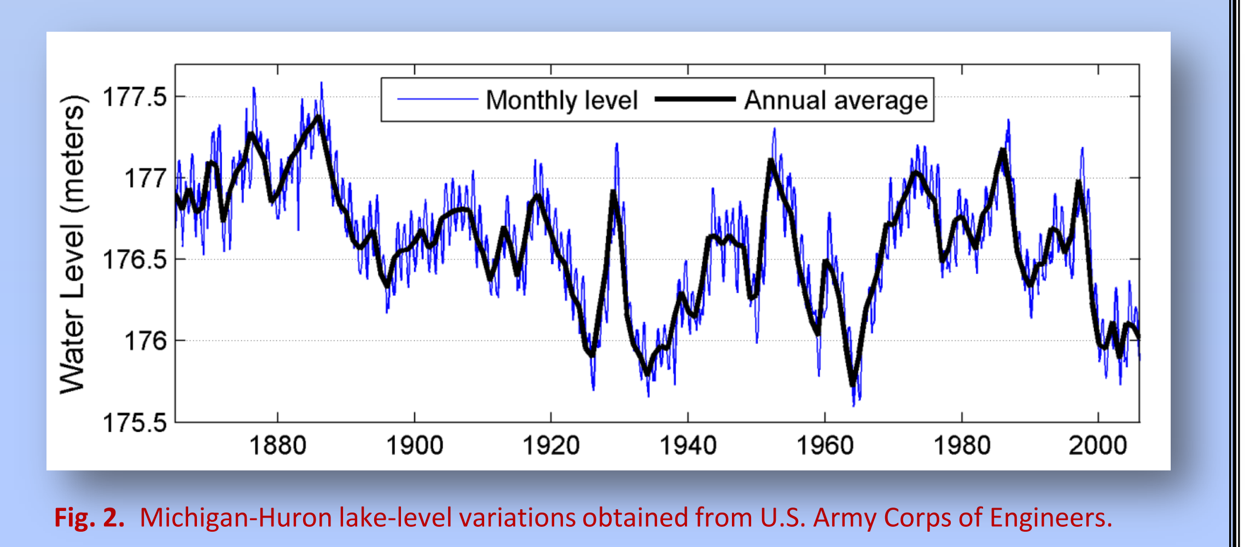

Fig. 2. Michigan-Huron lake-level variations obtained from U.S. Army Corps of Engineers.

Historic lake-level and component data

For the present study, monthly average lake levels were obtained from the U.S. Army Corps of Engineers for January 1865 to January 2009. In addition, components that contribute to the lake-level fluctuations were obtained online from the Great Lakes Environmental Research Laboratory (GLERL), which are available for various spans of time in the form of total monthly linear units over the lake's surface. These components consist of the net basin supply (NBS) which is made up of the total annual over-lake precipitation P_y, runoff R_y, and evaporation E_y. Also included, are the total annual inflows I_y from Lake Superior and the outflows O_y into the lower Great Lakes. The resulting water balance equation is as follows:

$$L_{y+1} = L_y + P_y + R_y - E_y + I_y - O_y + \varepsilon_y$$

where L_y (Fig. 2 thick black line), is the beginning lake level in a given year as estimated by the January average level, and ε_y is the residual error resulting from additional negligible lake-level sources, and measurement uncertainties. Assuming no error bias, ε_y should largely cancel out over the entire time series, however, there exists a negative error trend about 0.0018 meters per year after 1960, which can likely be attributed to factors not pertinent to this study. To maintain a focus on climate-related fluctuations, the trend is removed from the lake-level time series after removing outflow effects as outlined below.

Outflow-removed lake level and climate connections

The outflow rates, which represent the combined total flow of the St. Clair River and the Chicago Diversion, are directly proportional to the levels of the Michigan-Huron system. Because of this strong dependence of outflow on the levels themselves, a natural damping of the lake - level variation occurs. Consequently, the fluctuations which might otherwise result from atmospheric variability are never fully realized, potentially concealing obvious connections. Therefore, it is useful to remove the outflow component from the historic levels, which is done by integrating the total monthly outflow O_y through time, and then subtracting the resulting curve out of the historic lake levels. The result is a lake-level time series which describes the behavior of the Michigan-Huron system if there were no outflow (Fig. 3, thick black line).

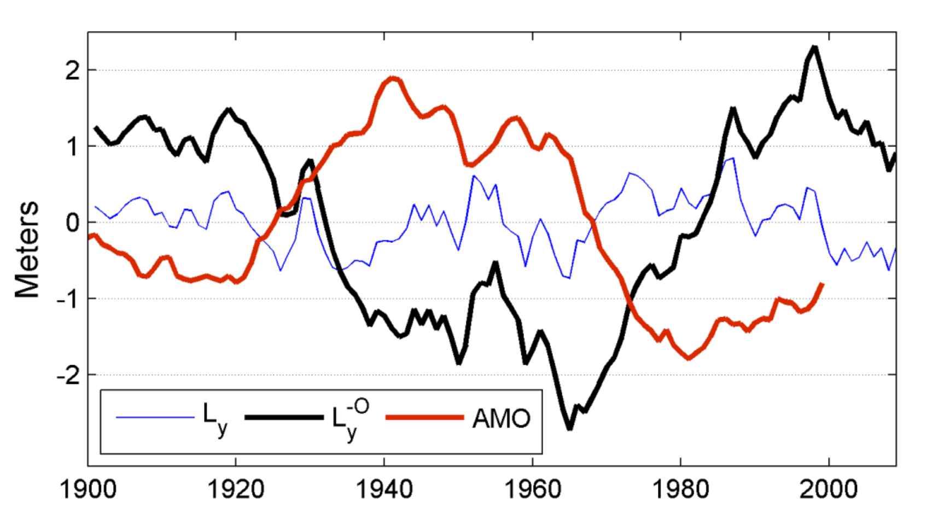

Fig. 3. Beginning-of-year Michigan-Huron lake-level anomaly (blue), outflow-removed and detrended lake-level anomaly (black), and AMO index (red).

Outflow level: $L_{y+1}^{O} = L_y^{O} - O_y$

Outflow-removed level: $L_y^{-O} = L_y - L_y^{O}$

The most striking feature of the new outflow-removed lake-level time series L_y^{-O} is an apparent low-frequency, large-amplitude, oscillation with a period of about 80 years. This pattern is significantly correlated with the AMO loading pattern (Fig. 3, thick red line) derived by Kravtsov and Spannagle [2008].

In addition to the multidecadal climate connection, there is also evidence that near-decadal climate signals are being transmitted to the water levels. Hanrahan et al. [2009] identified statistically significant 8 and 12-yr periodicities in the annually-averaged lake-level time series, which they believe to be connected to the North Atlantic region, where two similar modes have also been identified [Deser and Blackmon, 1993; Moron et al., 1998]. It was then speculated that a larger ~30-yr lake-level cycle [Thompson and Baedke, 1997] may result from the intermodulation of these two near-decadal cycles. The existence of this periodicity has now been confirmed by multi-taper method spectral analysis of the high-pass filtered, outflow-removed lake-level curve.

Precipitation as a historic lake-level driver

Historically, precipitation-related fluxes have been the primary drivers of interannual lake-level fluctuations [Brinkmann, 2000; Hanrahan et al., 2009]. To determine whether this is also the case with the identified multidecadal lake-level oscillation, average basin precipitation and runoff totals are compared during the significant phases of the AMO index, which are concurrent with the most extreme outflow-removed lake levels of opposite sign. This analysis concludes that the average annual totals were about 18 cm higher during the negative phases of the AMO (1916 – 1924 and 1973 – 1991), than during the positive AMO years (1932 – 1967). A t-test was conducted to determine the probability of equal means during the different phases, which concludes that the null hypothesis can be rejected at the 0.01% level. Therefore, similar to interannual lake-level variations, interdecadal fluctuations have also primarily resulted from changes in precipitation.

Recent evaporative effects

While evaporation is a primary driver of seasonal cycles, its interannual variance has historically been relatively small and has therefore had little influence on interannual lake-level changes. Analysis of recent annual evaporation data, however, reveals a positive trend that began around 1980, which is now having a significant impact on the long-term water levels. This evolving relationship is clear when examining the time series of lake-level anomalies calculated by integrating the sum of the lake-level components, and removing the pre-1985 trendlines (Fig. 4). This detrending period was chosen because L_y^{-O} and evaporation-excluded levels L_y^{P+R+I} consistently match up until then, after which, the curves and their respective trendlines begin to diverge. Due to increasing precipitation, L_y^{P+R+I} shows a continued increase through the present time, but a separation of L_y^{-O} occurs in the late 1980s, as it responds to the changing behavior of evaporation L_y^{E}.

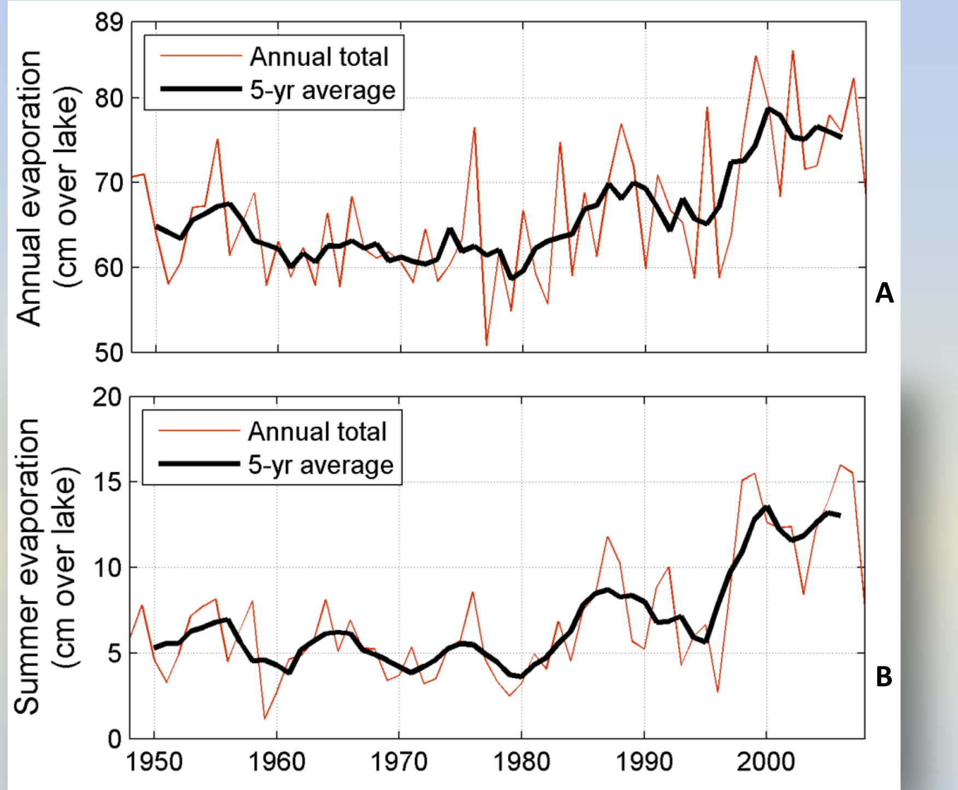

Fig. 5. Time series of annual (thin red) and 5-yr moving average (thick black) of total yearly (A) and summertime (B) evaporative losses.

These findings are consistent with those of Austin and Colman [2007] who found that Lake Superior's summertime water-surface temperatures are also increasing faster than regional air temperatures. They primarily attribute this discrepancy to decreasing wintertime ice cover, which is resulting in earlier annual stratification that subsequently leads to longer periods of radiative warming during the summer months. To determine whether this is also the cause of the increasing Michigan-Huron water-surface temperatures, ice cover data were obtained from the NOAA Great Lakes Ice Atlas [Assel, 2003, 2005]. They are available as daily spatial percentages of ice cover between December 1st and May 31st of each year, and are averaged further to obtain a single annual percentage for each winter between 1973 and 2005. This index represents the average percentage of lake ice for the entire Michigan-Huron system. There exists a strong negative correlation between these indices and succeeding summertime water-surface temperatures of $r^2 = 0.56$ ($p < 0.001$); the time evolutions of these variables are illustrated in Fig. 6. The recent periods of record-low wintertime ice cover are clearly concurrent with periods of record-high summertime water-surface temperatures, and increased summertime evaporative losses.

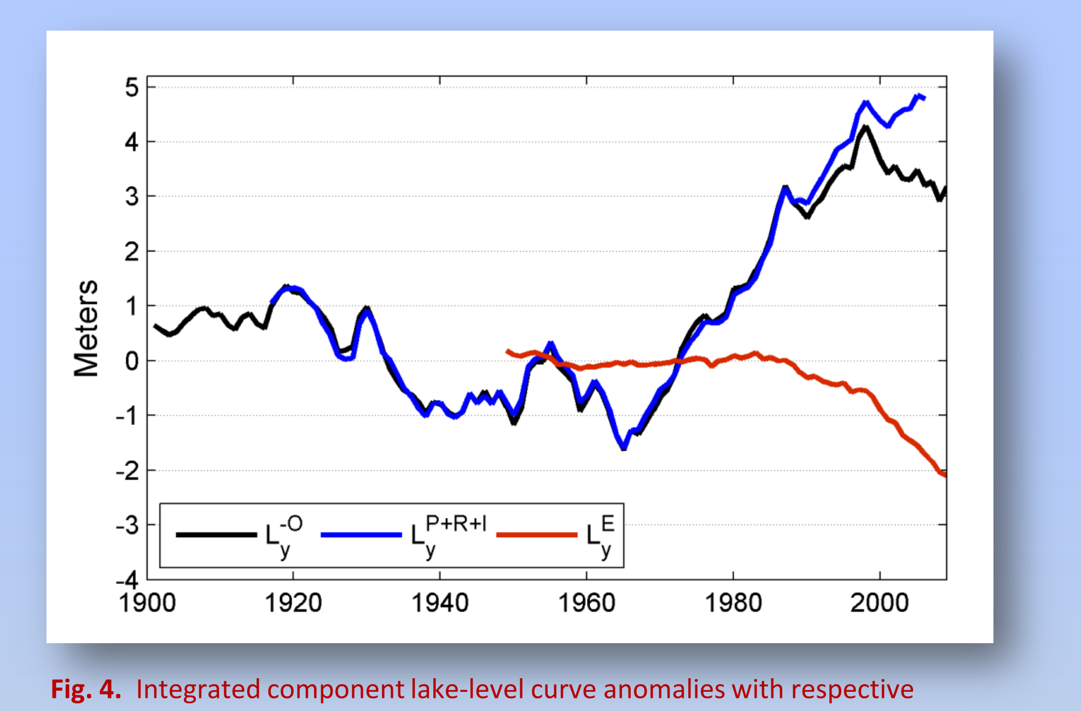

Fig. 4. Integrated component lake-level curve anomalies with respective pre-1985 trendlines removed. Evaporation-excluded curve (blue), outflow-removed curve (black), and evaporation curve (red).

Total annual evaporative losses have increased nearly 25% since 1980 [Fig. 5(A)], with the most drastic evaporative changes occurring during the summer months [Fig. 5(B)]. In order to further study the recently increasing summertime evaporation, an analysis of regional surface temperatures is also conducted. Monthly averaged water-surface and over-lake air temperatures were obtained online from GLERL, for 1948 – 2004. A recent warming trend is observed in the region's annual air temperatures, but the greatest temperature increase is occurring in the lakes themselves. The annually averaged water-surface temperatures have increased about 2°C between 1980 and 2004, and while all seasons have seen an increase in water temperatures over the last few decades, summertime temperature increases were the most significant with a jump of near 4°C as seen in Fig. 6 (thick black line). It follows that the differential heating rates between Lakes Michigan and Huron, and their overlying atmosphere, have resulted in record-high water loss through evaporation, primarily in the summer months.

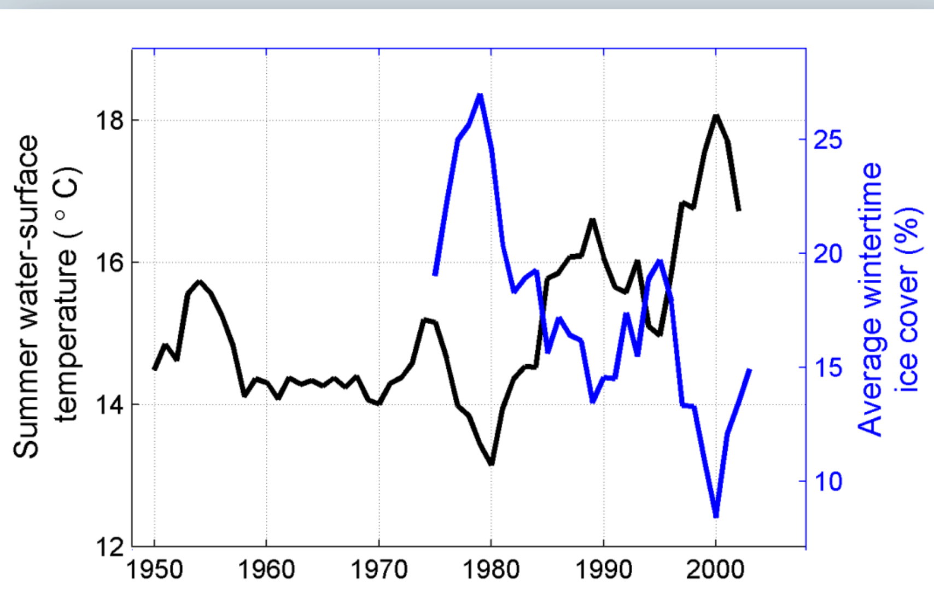

Fig. 6. 5-yr moving averages of summer water-surface temperatures (black), and average wintertime ice cover (blue).

Summary and discussion

In this study, the Michigan-Huron water levels are analyzed after damping effects from the system's outflow are removed, and the negative error trend in the lake-level time series, is accounted for. This analysis reveals a significant negative correlation between the filtered levels and the AMO index. The apparent connection of the lake levels to the AMO is further supported by previous studies that have found the AMO to have had a strong inverse effect on long-term precipitation patterns over much of the United States, including over the Michigan-Huron basin [Enfield et al., 2001; McCabe et al., 2004]. In addition to the multidecadal modes, ~8 and 12-yr precipitation periodicities have also been connected to processes in the North Atlantic region [Fye et al. 2006, Small and Islam 2006, Jutla et al. 2006]. These periodicities are consistent with lake-level cycles identified by Hanrahan et al. [2009], who speculated that their interaction might result in a ~30-yr lake-level periodicity [Thompson and Baedke, 1997]; we have now established the existence of this lake-level cycle.

It was recently determined that long-term lake-level fluctuations were primarily resulting from changes in precipitation [Brinkmann, 2000; Hanrahan et al., 2009], and since the pre-1980 interannual variation of evaporation was relatively small, it had little effect on long-term lake-level variations. Over the last few decades however, evaporation rates have begun to increase, resulting in near record-low lake levels, despite continued above-average precipitation. Most of the increasing evaporative losses are occurring in the summer months due to rapidly increasing summertime water-surface temperatures relative to the overlying air, which is likely a consequence of decreasing annual ice cover. Reduced spring ice cover results in the redirecting of energy, which would have otherwise been used during melting, increasing the amount of total radiation that is absorbed by the water during the summer months. There exist significant correlations between average wintertime ice cover and summer water-surface temperatures, for both Lake Michigan-Huron and Lake Superior. This period of increased evaporation which began around 1980, is consistent with the timing of the recent onset of rapid global warming.

In terms of both natural climate variability and anthropogenic forcing, more work needs to be done to gain a better understanding of how the lakes respond to atmospheric changes. The drastic differences between long-term heating rates of the lakes and their overlying air need to be examined further, and the long-term effects of decreasing wintertime ice cover should be estimated in order to improve our understanding of the lake-level decreases. Also, because it is possible that the lake levels will at some point, again closely follow changes in precipitation, a clearer understanding of underlying North Atlantic forcing is needed to help further detangle the identified overlapping periodicities.

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