Recent changes in Great Lake hydrologic variability: an artifact of chance or a robust change?

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Abstract

Water levels in the Laurentian Great Lakes have fluctuated dramatically over recent decades. Since 2015, each of the lakes has reached a record high, often following a recent record or near-record low. These exceptional swings have motivated examinations of changes in lake level variability, particularly given the known climate change-driven intensification of the hydrologic cycle. Recent studies have presented evidence of rising lake level variability and changing water balance components (i.e., overlake precipitation, overlake evaporation, and basin runoff), however a full characterization of trends in variability is needed. Here, we build on previous analyses by quantitatively answering the question: are trends in hydrologic interannual variability over the Great Lakes over recent decades – both lake levels and individual hydrologic components – statistically robust, or simply the result of random chance? Using two non-parametric trend tests, we find that interannual variability of lake levels is significantly increasing in Lakes Superior, Michigan-Huron, and Erie, while decreasing in well-regulated Lake Ontario. We also find robust increasing variability in overlake precipitation, overlake evaporation, and basin runoff for the vast majority of lakes. These results suggest that critical work must follow to both attribute causes of detected trends and to determine if trends will continue increasing in the future with continued anthropogenic climate change.

1. Introduction

Recent extraordinary shifts in Great Lakes water levels have prompted questions about potential changes in year-over-year lake level variability. Changes in the variability of Great Lake levels, namely, how quickly lake levels fluctuate between higher and lower water levels, can have dramatic environmental and societal impacts. Examples include shifts in shoreline erosion patterns (Gronewold and Stow, 2014; Davidson-Arnott, 2016), shipping costs (Millerd, 2010; Lindeberg and Albercook, 2000; Wang et al., 2012), tourism and recreation (Wall, 1998; Hartmann, 1990), and risks to critical infrastructure like water resource management (de Loe and Kreutzwiser, 2000), hydropower (Meyer et al., 2017), and toxic waste facilities (Environmental Law and Policy Center, 2022). Researchers and the public alike have thus been captivated by the rapid transition of Great Lake levels between record low and high lake levels and the resultant impacts (e.g., Gronewold et al., 2021; Egan, 2021). This interest is further motivated by the observed and projected intensification of the hydrologic cycle due to anthropogenic climate change (IPCC, 2021; Seager, 2014). Within this context, Gronewold et al. (2021) presented evidence of rising lake level variability and described the situation caused by this hydrologic cycle intensification as a "continental-scale hydrological tug-of-war" between changing water balance components.

Lake levels of large lakes are dominated by three net basin supply (NBS) components: overlake precipitation, overlake evaporation, and basin runoff, where the collective balance of these three components largely determine Great Lakes levels ($\Delta_{\text{lake storage}} = p_{\text{overlake}} + r_{\text{basin}} - e_{\text{overlake}}$) (Gronewold et al., 2021). Note that we define runoff here as the amount of water entering the lake from all incoming river systems in a respective Great Lakes basin, excepting flow from any upstream lakes. These components are all expected to change with the amplification of anthropogenic climate change and trends in these components have already been well observed. For instance, Javed et al. (2019) find increasing evaporation, spatially mixed results on precipitation, and no change in runoff, over Lakes Michigan and Huron. Harp and Horton (2022) characterize an increase in wet day precipitation intensity of ˜5% over the U.S.-portion of the Great Lakes basin from 1951 to the present. Looking forward, Mailhot et al. (2019) found increases in net basin supply components with an intensifying annual cycle, but claimed "no long-term changes can be confidently estimated for lake levels." Kayastha et al. (2022) used a regionally downscaled model to project future Great Lake levels and found a rise in both water levels and net basin supply components, particularly overlake precipitation and runoff. The climate change-driven increase in Great Lake levels was similarly projected by Van De Weghe et al. (2022). These findings differ with earlier work by Hayhoe et al. (2010) which projected falling Great Lakes levels based on increasing evaporation rates with increasing regional temperatures. Examining individual hydrologic components, Wang et al. (2018) project a 16% increase in lake evaporation by the end of the 21st century in a high greenhouse gas emissions scenario (RCP8.5). However, despite examination of trends of lake levels, little attention has been given to statistically characterizing observed trends in variability for either Great Lakes levels or their net basin supply components. Here, we address this knowledge gap by providing a statistically rigorous assessment of changes in interannual variability over the past five decades.

2. Methods

To characterize changes in lake level variability, we analyzed lake level data compiled by the Great Lakes Coordinating Committee (Coordinating Committee on Great Lakes Basic Hydraulic Hydrologic Data, n.d.). Monthly mean lake level data are calculated by combining observations from a suite of gauges around the Great Lakes basin maintained by the U.S. National Oceanic and Atmospheric Administration (NOAA) and Canadian Hydrographic Service (CHS) (Fry et al., 2022). These data span from 1918 to the present. In addition to lake level data, our analysis uses Great Lakes monthly hydrologic data curated by the NOAA Great Lakes Environmental Research Laboratory (GLERL) for net basin supply variables: overlake precipitation, overlake evaporation, and runoff.

The NOAA-GLERL monthly hydrometeorological database (GLM-HMD) is the first dataset to assimilate hydrometeorological measurements across both the U.S. and Canadian portions of the Great Lakes basin dating back to the early and mid-1900s (Hunter et al., 2015). The GLM-HMD uses a Thiessen weighting approach to compute overlake precipitation from daily monitoring stations (Hunter et al., 2015), including stations up to 50 km from the lake basin depending on gauge density, though stations over the lake surface or on islands are sparse. It should also be noted that station availability expanded rapidly from the early 1900s before peaking from the late 1940s to the present (see fig. 2, Hunter et al., 2015) and GLM-HMD overlake precipitation calculations are thus available beginning in 1940. Overlake evaporation is computed by the Large Lake Thermodynamics Model (LLTM) as described in Croley (1989), and is available from 1950 to present. The LLTM is a 1-dimensional thermodynamics model that computes overlake evaporation by simulating the energy balance above the lake surface, vertically-summed heat storage through the lake columns, and aerodynamic evaporation (Fry et al., 2022). GLM-HMD estimates of runoff are calculated from streamflow measurements from the United States Geological Survey and Water Survey of Canada gauges based on subbasin area with extrapolations for unrepresented subbasin area and ungauged subbasins (Hunter et al., 2015). Fry et al. (2013) determine that this approach provides reliable estimates of total discharge to the lakes. In preparation to examine trends in interannual variability, we transformed monthly data to annual data by taking an annual mean (lake levels) or annual sum (precipitation, evaporation, runoff) on the component time series as appropriate. Finally, we note that we considered alternative data sources, notably output from the Large Lake Statistical Water Balance Model (L2SWBM) (Gronewold et al., 2020), and a comparison of annual values from GLM-HMD and L2SWBM produced correlations of at least 0.97 for all lake-component combinations.

Here, we define interannual variability as the standard deviation in a time series over a 13-year moving window. We select a 13-year window width for two reasons. First, this width is longer than the cycles of known 8- and 12-year modes of lake level variability (Hanrahan et al., 2014; Cheng et al., 2021). Interannual lake level fluctuations are driven both by modes of climate variability at various periodicities, with notable periodicities of 8, 12, and 30 years (Hanrahan et al., 2014; Cheng et al., 2021), as well as by long-term trends in net basin supply components. Relevant modes of climate variability include the Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO), North Atlantic Oscillation (NAO), El Nino-Southern Oscillation (ENSO), and the Pacific-North American Oscillation (PNA) (Wang et al., 2018; Ghanbari and Bravo, 2008). Second, we examined the dependence of trends through a sensitivity analysis using window widths ranging from 5 to 25 years. This revealed a consistency in trends in interannual variability for window widths greater than 12 years despite inconsistencies in trends across shorter window widths. We focus our analysis on the period from 1970 to the present. While this truncates the length of data available for time series analysis, this is a period of increasing influence of anthropogenic climate change. Notably, there is evidence of an emerging intensification of the hydrologic cycle early in this five-decade span or just prior to it (IPCC, 2021), an intensification which is expected to continue (Seager et al., 2014). However, we include the full extent of available data in Figure 1 to provide historical context for recent trends.

To calculate the time dependence of lake levels and NBS components, we use two non-parametric measures: the Kendall rank correlation coefficient and the Trend-Free Pre-Whitened Mann-Kendall trend test. We selected these tests due to the appropriateness of their application on time series with high levels of auto-correlation; this restriction ruled out more traditional linear regression techniques (e.g., the Ordinary Least Squares and conventional Mann-Kendall trend tests) whose statistical assumptions are not satisfied by the time series under analysis. The Kendall rank correlation coefficient is a rank-based test that determines if two variables are related regardless of distributions. The Trend-Free Pre-Whitened Mann-Kendall trend test is a modified version of the conventional Mann-Kendall trend test designed to overcome inaccuracies in analysis due to autocorrelation (Yue et al., 2002); both the modified and conventional Mann-Kendall trend tests are valid independent of the distribution of the underlying data. For ease of reading, we will refer to the Trend-Free Pre-Whitened Mann-Kendall trend test simply as the Mann-Kendall trend test throughout this study. In summary, to assess the robustness in trends of interannual variability, we apply a Mann-Kendall trend test to the 13-year moving window of standard deviation across lake levels and NBS components over the past fifty years.

3. Results and Discussion

We identify robust, statistically significant increasing trends in the year-over-year variability of lake levels in three of the four Great Lakes from 1970 to the present (Figure 1; Superior, $p < 0.001$; Michigan-Huron, $p < 0.001$; Erie, $p < 0.05$) with conflicting statistical significance results for Lake Ontario ($p > 0.05$ with Kendall rank correlation, $p < 0.05$ with Mann-Kendall trend test). While the long-term increases in lake level variability for Lakes Superior, Michigan-Huron, and Erie may be attributable to the non-stationarity of environmental conditions, it should be noted that the long-term decrease in Lake Ontario variability is attributable to human implemented controls, as Lake Ontario has been regulated since ˜1960 (Wilcox et al., 2007). Lake Superior has also been subject to a level of human control since the early 20th century, though to a lesser extent, with evolving regulation that "attempts to maintain natural variability" (Clites and Quinn, 2003). Beginning in 1973, regulations mandated that the levels of Lake Superior be maintained in a manner that considers the impacts of regulation on the rest of the Great Lakes system. This is a factor to be considered when examining recent trends in lake level variability for both Lake Superior, as well as the rest of the Great Lakes. In spite of this change, all four lake basins have attained relative maxima in interannual variability over the past decade. Lake Superior set its all-time maximum in variability, while the remaining lakes endured high water marks in variability not seen since around 1970.

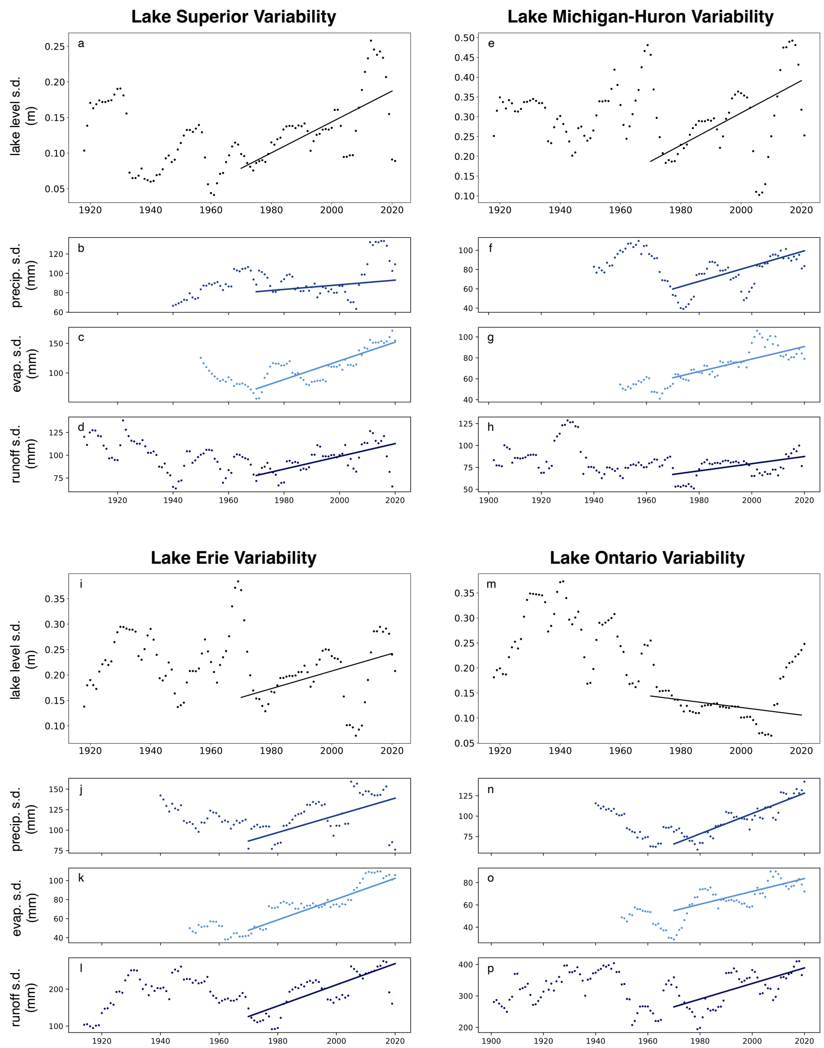

Figure 1: *Figure 1* : Interannual variability in hydrologic components of the Laurentian Great Lakes. a) Interannual variability of Lake Superior lake levels calculated as the standard deviation over a 13-year moving window (m; black scatter). The trend in interannual variability from 1970 to 2020 as determined by a Trend-Free Pre-Whitened Mann-Kendall trend test is also shown (black line). b) Same as a but for lake surface area-averaged interannual variability of precipitation (mm; medium blue). c) Same as b but for evaporation (mm; light blue). d) Same as b but for runoff (mm; dark blue) from 1970-2019. e-h) Same as a-d but for Lake Michigan-Huron. i-l) Same as a-d but for Lake Erie. m-p) Same as a-d but for Lake Ontario.

In addition to analyzing lake level variability, we also examine trends in the variability of precipitation, evaporation, and basin runoff, the three dominant components of net basin supply (Figure 1). Interannual variability of overlake precipitation is increasing for all four basins for both the Mann-Kendall trend test and the Kendall-Tau test ($p < 0.001$), except for one increasing, though non-significant result for Lake Superior using the Kendall-Tau test ($p > 0.05$). Similarly, the interannual variability of runoff is increasing for all four basins for both tests ($p < 0.001$) with the exception of runoff into Michigan-Huron, which is significantly increasing when using the Kendall-Tau test ($p < 0.01$) and increasing, though non-significantly, using the Mann-Kendall trend test ($p > 0.05$). The interannual variability of evaporation is rising universally across all basins for both statistical tests ($p < 0.001$). Placing these trends within the greater context of the GLM-HMD time series, precipitation variability peaked over the past decade for Lakes Superior, Erie, and Ontario, and reached values not seen since around 1960 for Lake Michigan-Huron. The variability of evaporation has risen steadily for all lakes throughout the entire time series from 1950 onward. Variability for Lake Michigan-Huron peaked in the 2000s, again the only lake not to see a variability maximum in the 2010s. All lake basins endured variability maxima in runoff in the past decade at levels not seen since the 1940s or earlier. Thus, we note statistically significant trends that coincide with component maxima largely not observed over the past six decades.

4. Conclusions

This study assesses trends of year-over-year variability in both observed Laurentian Great Lake levels and net basin supply components. Our analysis found definitive statistical evidence of robustly increasing interannual variability in both the levels of individual Great Lakes – outside of well-regulated Lake Ontario – as well as in the individual hydrologic components of lake levels across all basins. These rises in variability coincide with a period of observed intensification of the hydrologic cycle due to anthropogenic-driven changes in climate (IPCC, 2021). Other potential factors contributing to the trends we observe here include changes in precipitation caused by evolving aerosol concentrations, changes in land use and urbanization, shifts in historical measurement availability and accuracy, and, in the case of lake level variability, changes in water level management and regulation (REF). Regardless of cause, our characterization of trends in interannual variability necessitates future work to determine if these increasing trends in hydrologic variability will persist in future climate states, as well as how this shift in the physical climate system will impact society and the environment.

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Figure Captions

Figure 1 : Interannual variability in hydrologic components of the Laurentian Great Lakes. a) Interannual variability of Lake Superior lake levels calculated as the standard deviation over a 13-year moving window (m; black scatter). The trend in interannual variability from 1970 to 2020 as determined by a Trend-Free Pre-Whitened Mann-Kendall trend test is also shown (black line). b) Same as a but for lake surface area-averaged interannual variability of precipitation (mm; medium blue). c) Same as b but for evaporation (mm; light blue). d) Same as b but for runoff (mm; dark blue) from 1970-2019. e-h) Same as a-d but for Lake Michigan-Huron. i-l) Same as a-d but for Lake Erie. k-n) Same as a-d but for Lake Ontario.