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A 420-Year Perspective on Winter Lake Erie Levels

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Key Points:

- Western North American tree-ring records are used to reconstruct changes in Lake Erie winter water levels for the past 420 years
- One of the highest lake levels in the past 420 years occurred in 2020, which is the highest value in the observational record. The lowest levels occurred during the 1930s Dust Bowl
- Correlation of lake levels with the Pacific Decadal Oscillation and the Atlantic Multidecadal Oscillation reveal a shift from a strong North Pacific signal to one in the North Atlantic around 1960

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Here, we present a 420-year-long winter lake level reconstruction for Lake Erie based primarily on temperature-sensitive tree-ring chronologies from Alaska, Oregon, and California. This well-verified model explains more than 51% of the variance in winter lake levels over a 131-year calibration period (1860–1990) and shows strong decadal fluctuations related to changes in sea surface temperatures in the North Pacific and the North Atlantic, which alternate in terms of their relative influence. Decadal variability is superimposed on a persistent secular lake level rise that began in the mid-1900s coinciding with a growing influence of the Atlantic sector. In the context of the last 420 years, the instrumental period experienced extreme lake levels, with the lowest over the entire record during the Dustbowl and the highest in 2020. Fluctuations in Lake Erie water levels are primarily determined by climate, and their variability greatly impacts the region's infrastructure and ecosystems.

Plain Language Summary Tree rings are annually resolved records of past climate. Here, we use 49 tree-ring records from Western North America to reconstruct Lake Erie winter water levels back to CE 1600. The record shows that the lowest and one of the highest stands of the lake have occurred over the past 100 years with the lows recorded during the American Dustbowl years in the 1930s and the high in 2020. The analyses of this extended record can help to better anticipate future lake level changes in a warmer climate, which greatly affect infrastructure and ecosystems along Erie's shorelines.

1. Introduction

The international waters of the Laurentian Great Lakes collectively hold 20% of the Earth's unfrozen freshwater and have almost 7,300 km of coastline (Gronewold et al., 2013, 2019; NOAA, 2021). They provide drinking water for over 30 million people and generate more than $3 trillion in gross domestic product annually (NOAA, 2021).

Intra-annual variations of approximately 0.5 m in water levels of the Great Lakes are of greater magnitude than rising sea levels experienced in coastal regions over the past century (Gronewold et al., 2013). Water levels rise in the spring, reach their peak in the summer, and then decline to a minimum in the late summer or early fall (Croley et al., 1998; Gronewold et al., 2016). Over the past two decades, levels have ranged from extreme lows in the early 2010s to a record high in some lakes in 2020 (Gronewold et al., 2021; Figure S1 in Supporting Information S1). In addition, record-setting rates of rise between January of 2013 and December 2014 occurred during the transitions to extreme levels in Lakes Superior and Michigan-Huron (Gronewold et al., 2016). Variations in the water levels of the Great Lakes are important for the surrounding economies and communities with high water levels leading to erosion and flooding and low stands to increased costs incurred from dredging of harbors and reduced shipping (ELPC, 2019; NOAA, 2021).

It is well accepted that climate-driven changes to the Great Lakes hydrologic budgets were the primary cause of past changes in water levels (Gronewold & Rood, 2019; Gronewold et al., 2021). However, we do not know how these lake level fluctuations have responded to internal climate variability in the ocean-atmospheric system or to external forcings (Adams et al., 2003; Rind et al., 2004). One way to extend the observational record is by developing proxy reconstructions on decadal to century timescales using tree-ring-based reconstructions of annual lake levels (Quinn & Sellinger, 2006; Wiles et al., 2009).

Tree rings are absolutely dated to the calendar year and are variously sensitive to precipitation, temperature, and large-scale ocean-atmosphere variability and teleconnections, which are the same climate-related inputs that drive changes in lake levels. Reconstruction efforts for the Great Lakes using tree rings have been underway since Brinkmann (1989) investigated opportunities for using teleconnection patterns in conjunction with local

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tree-ring data to reconstruct lake levels. He found that trees within the Great Lakes region, which correlate well with net basin supply (Brinkmann, 1987; combined over-lake precipitation, lake evaporation, and runoff into the lake) were insufficiently sensitive to reconstruct lake level fluctuations and thus suggested leveraging data from other areas that have strong climate teleconnections with the Great Lakes region. The use of existing tree-ring series from forests growing in the Great Lakes basins still do not appear to be robust enough for lake level reconstructions, although efforts are underway to improve this (Larson & Rawling, 2016; Matheus & Maxwell, 2018).

Progress has also been made using teleconnected tree ring sites. Quinn and Sellinger (2006) used tree ring estimates of precipitation and temperature from tree ring data compiled by Fritts (1991) in a multiple linear regression to extend Lake Michigan-Huron water levels back to 1602. They found that past changes in lake levels in the 1600s were greater than those of the observational record. Wiles et al. (2009) leveraged the Pacific North American (PNA) teleconnection pattern to develop a 265-year reconstruction of Lake Erie water levels using a principal component regression based on four Gulf of Alaska tree ring chronologies. They determined that high lake levels in the first decade of the 2000s were greater than previous centuries. The motivation for the present study is to generate a higher skilled and longer reconstruction of winter Lake Erie levels based on a growing database of tree-ring series. We specifically seek to place the historically unprecedented lake level high in 2020 into a longer-term context.

2. Materials and Methods

US and Canadian agencies have been measuring monthly lake levels continuously since 1860 (NOAA, 2021). These records have become some of the longest hydroclimate time series in North America. The monthly record during the interval between 1860 and 1917 for Lake Erie relied on a single water gauge in Cleveland (NOAA, 2021), after that time (1918-present) an international network of gauges is being used to measure lake levels (Figure S1 in Supporting Information S1; Gronewold et al., 2013). This monthly lake level series spans the late portion of the Little Ice Age (LIA; ∼1860–1880) and the entire post-industrial warming period. We use the entire record back to 1860 in our modeling, which allows us to assess how the lake level data from the 1860–1917 period that is based on the single station compare with the multi-station compilation post 1918. A remarkable feature of the Lake Erie winter (mean January–March; JFM) observational series is the historically unprecedented lows in the 1930s and the high in 2020 (Figure 1; Figure S1 in Supporting Information S1).

We focus on Lake Erie because its hydrologic budget is thought to be primarily driven by climate, and human influences have not greatly altered water levels there (Croley et al., 1998). As an illustration of the dominance of climate control, Assani et al. (2016) found that Lake Erie was the only Great Lake that responded sensitively to four historical precipitation shifts, which represented both increases and decreases in effective moisture for the region. Lake Erie is also purported to be the Great Lake that most closely tracks regional climate as evidenced by its lake levels having the highest shared variance among the other Great Lakes (Rodionov, 1994). This sensitivity is likely explained by a combination of its shallow water depth, its relative downstream position in the chain of lakes, and the relative lack of human control on its inlets and outlets.

To reconstruct Lake Erie levels, we use a network of ring-width and maximum latewood density series from Alaska and the west coast of the coterminous US (Zhao et al., 2019; Figure S2 and Table S1 in Supporting Information S1). Our use of this expanded, geographically diverse, Western North American data set was then used to reconstruct Lake Erie levels over the past several hundred years and the resulting reconstruction is examined in light of secular changes in climate and multidecadal shifts in the North Pacific and North Atlantic basins. Our efforts in 2009 (Wiles et al., 2009) were based on an entirely independent set of tree ring series not included in the present model results.

Tree-ring chronologies were all standardized using the signal-free (SF), age-dependent spline approach (Melvin & Briffa, 2008, 2014). This method reduces biases that can occur in detrending by extracting the common forcing signal within each tree-ring series (Buckley et al., 2018). We used several freeware programs developed at the Lamont-Doherty Earth Observatory Tree Ring Lab (https://www.ldeo.columbia.edu/tree-ring-laboratory/resources/software), such as program RCSig based on the ARSTAN program (Cook, 1985) for detrending tree-ring series within the signal-free framework and PCReg (principal component regression analysis), which was used for modeling and lake-level reconstruction.

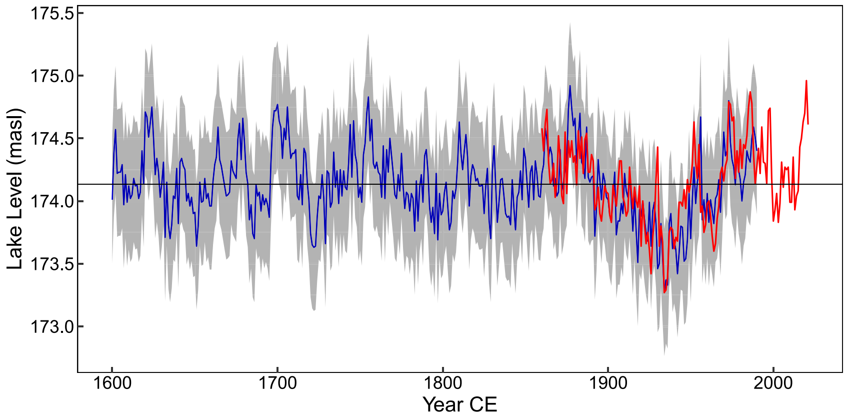

Figure 1. Reconstruction of Lake Erie water levels back to 1600 CE. Estimated lake levels are shown by the solid blue lines and observational lake levels for a 131-year period (1860–1990) are shown by the solid red line. The correlation between the reconstruction and the actual lake levels is 0.72 (n = 131 years). The gray shading indicates the 95% confidence interval derived from the root squared mean error (RSME). Forty-nine tree-ring records were included in this full reconstruction model. From those chronologies nine PCs were retained for the reconstruction using theEigenvalue-1 and maximum r-square criteria in PC regression, which explains 51% of the variance. For comparison, an alternative model with similar results, using the Eigenvalue-1, t-statistic >1 criteria yielded 7 PCs and accounted for 50% of the variance.

Once our reconstruction was completed, we then compared the lake-level reconstruction and observations with the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO) to assess the relative influence and linkages to lake levels with SSTs in these basins over time. The PDO and AMO are indices that capture interannual atmosphere-ocean decadal variability based on SST fields that span a portion of the North Pacific and North Atlantic, respectively. The PDO (1900–present) is defined as the leading EOF of SST anomalies in the North Pacific basin (poleward of 20°N; Mantua & Hare, 2002; Mantua et al., 1997). The phases of the PDO integrate internal variability of the North Pacific along with ENSO variability from lower latitudes (Newman et al., 2016). The AMO, spanning 1880 to present, is a large-scale mode of SST variability in the North Atlantic (25°–60°N, 7°–75°W; van Oldenborgh et al., 2009; based on HadlSST1 from NCDC). The secular rise in global SST's during the post-industrial period is removed from both the PDO and AMO time series.

2.1. How Are Western North American Tree Ring Records Linked to Lake Erie Levels?

We follow the recommendation of Brinkmann (1989) and past success using Alaskan tree-ring records (Wiles et al., 2009) to reconstruct Lake Erie levels. We use Alaskan tree-ring records along with other Western North American series as candidate predictor series to track large-scale circulation patterns in the Pacific sector that influence downwind hydroclimate in the Midwestern US, leveraging teleconnections across North America (Coleman & Rogers, 2003, 2007; Hanrahan et al., 2014; Rodionov, 1994; Rodionov & Assel, 2000; Rogers & Coleman, 2004). Rodionov (1994) identified a linkage between the climate of the North Pacific and the Great Lakes region based, in part, on an analysis of storm tracks (Rodionov, 1994; Whittaker & Horn, 1984). He examined two distinct modes of circulation linked to the PNA (Rodionov, 1994). This study and more recent studies (Bishop, Williams, Seager, et al., 2019; Lukens et al., 2018) provide a conceptual basis for linking temperature-sensitive trees in Alaska and the American West to Midwestern hydroclimate and ultimately Lake Erie levels.

Croley (1990) and Hanrahan et al. (2014) have noted that Erie levels are controlled primarily by precipitation driven, in part, by teleconnections and commensurate changes in circulation patterns primarily active during the winter months. Furthermore, the winter PNA phases (Leathers et al., 1991) have significant relationships with precipitation especially in the Ohio River Valley (Coleman & Rogers, 2003, 2007). These relationships exceed the strength of teleconnections associated with ENSO in the Midwest (Coleman & Rogers, 2003; LaValle et al., 2000; Rogers & Coleman, 2004). Like the PNA, the AMO and PDO also feature decadal variability that have been linked to lake levels (Doyle et al., 2021; Rodysill et al., 2018) and the Great Lakes hydroclimate (Lukens et al., 2018).

Others have leveraged Alaskan tree-ring series to reconstruct aspects of the PNA and related climate indices. Liu et al. (2017) and Trouet and Taylor (2010) used Alaskan tree-ring records along with other sites in North America to reconstruct the actual PNA. Additionally, Alaskan and Californian coastal tree-ring series have been used to reconstruct the PDO (Biondi et al., 2001; D'Arrigo et al., 2001; Gedalof & Smith, 2001; MacDonald & Case, 2005).

2.2. Lake Level Reconstruction

The average winter season (Figure 1; NOAA, 2021) was used to build a statistical tree-ring model using principal component regression. Here, we define winter based on the strongest correlations between monthly lake level records (mean of JFM) and the tree rings. January–March combines the strong variability of the winter season with the early rise of spring water levels that includes March, the most variable month. Out of the 200 tree-ring series that were screened for modeling, we retained 49 that both spanned the years 1600–1990 and were significantly correlated with the full 131-year record lake levels (1860–1990; p-value < 0.005). These are from Alaska (44 chronologies), Oregon (3), and California (2) and consist of ring-width (47) and latewood density (2) tree ring chronologies (Figure S2 and Table S1 in Supporting Information S1). Ring-width series have been shown to be temperature sensitive to a broad season of growth (i.e., January–September for the Gulf of Alaska series (Wiles et al., 2014)); the two maximum latewood density (MXD) series are generally more sensitive to summer temperatures.

3. Results

The 49 series were distilled into principal components used as predictors, which together explain 51.1% of variance in winter Lake Erie water levels for the full calibration period (Figure 1). To assess the fidelity of the regression model, we performed calibration and verification tests by initially calibrating a model with the early interval (1860–1925), which explains 51.9% and then the later portion (1926–1990) which explains 50.6% of the variance in mean JFM water levels (Table S1 in Supporting Information S1). We note that despite the early calibration interval being mostly based on the one (Cleveland, OH) lake level observational station (1860–1917), the modeling still performs well.

These models were further verified using the late and early halves of the observed data withheld from modeling, respectively. We calculated the non-first-differenced reduction of error (RE) and the more rigorous coefficient of error values (CE; Table S2 in Supporting Information S1; Cook & Kairiukstis, 1990; Cook et al., 1999) for the corresponding verification periods 1860–1925 and 1926–1990, respectively. Positive RE and CE values in each of these split-period verification tests indicate substantial model skill (Cook & Kairiukstis, 1990) indicating that the reconstruction performs better than the mean of the observed period. Analysis of the residual lake-level estimates using the Durbin-Watson statistic (Cook & Pederson, 2011) indicate no significant autocorrelation or linear trends in the residuals for any of the models. Taken together, these statistical tests suggest that our model has a high level of predictive skill over the 1860–1990 calibration interval. The final model reconstructs mean JFM Lake Erie water levels back to 1600 (Figure 1).

Water levels experienced decadal fluctuations in the pre-industrial interval from the late 1600s to the late 1800s after which a gradual decline over the ensuing 50 years culminated in the low stands of the 1930s Dustbowl years. The lowest individual year is 1934, which is the lowest value in the reconstructed and the instrumental record (Figure 1). Since the 1930s, there has been a general secular rise in winter water levels that continues through the present (Figure 1). This rise is punctuated by intervals such as the notable decline to a relative low stand ca. 2000 (Figure 1).

The reconstruction also shows high water levels in ca. 1620, 1699, 1755, and 1810, with the latter three years coinciding with known volcanic events (Sigl et al., 2014). Whether the volcanic-derived climate changes impacted the trees alone through cooling and dimming effects or both the trees and the lake levels were affected through hydroclimatic change is unknown. Similarly, a high level in 1876 (a portion of the Global Famine of 1876–1878; Singh et al., 2018) is captured in our reconstruction; however, it is not evident in the observed record. This latter event coincides with a cooling in 1876 in the tropical Pacific followed by a record-breaking El Niño. It may be that intervals of strong equatorial influence associated with ENSO variability may influence the trees without affecting lake levels and thus individual years may result in a mismatch between the observed and our modeling

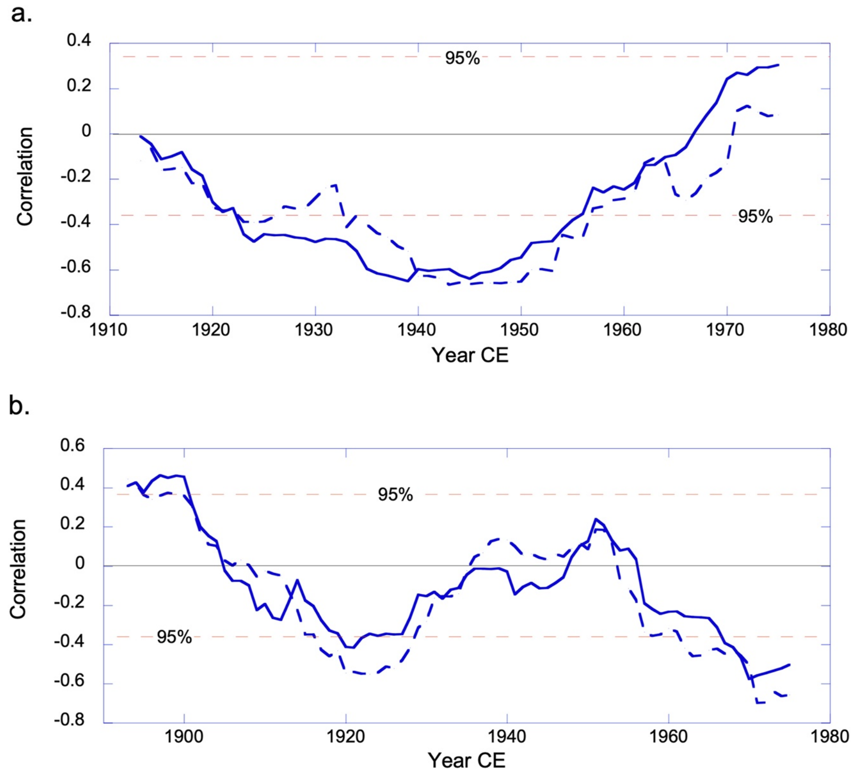

Figure 2. Pacific Decadal Oscillation (a) and Atlantic Multidecadal Oscillation (b) 31-year running correlations comparing the climate indices with the observed (solid lines) and the modeled (broken lines) winter Lake Erie levels. The labeled horizontal lines show the 95% significant levels.

results. Further discussion of possible forcing by volcanic events and ENSO and their roles in the modeling are beyond the scope of the present study.

Our reconstruction does place the 2020 high stand into a long-term context (Figure 1). The 2020 high stand is not strictly unprecedented over the reconstruction interval, given the error in the model (Figure 1); however, 2020 does rank as one of the highest reconstructed and observed stands over the past 420 years. In addition to these annual extremes, the low frequency signal in the reconstruction was analyzed for the relative influence of the PDO and AMO. For the PDO index, the overall correlation for the full interval (1900–1990) with lake levels is not significant; however, a running correlation shows that the PDO correlates strongly with lake levels during an early period (1900–1960; $R = -0.45$; $p < 0.002$), switching from this relatively strong negative correlation to a weak positive relationship after this time (Figure 2a). The running correlation with the AMO also shows a non-stationary relationship, with a strong significant negative correlation of −0.52 ($p < 0.02$) after ~1960 (Figure 2b). These correlation series (Figure 2a, and 2b) suggest that after 1960, Lake Erie water levels underwent a shift from being strongly linked to Pacific-based processes to being primarily driven by ocean-atmosphere conditions in the Atlantic basin.

Spatial correlation patterns of SSTs with the observed and reconstructed lake level series records for the intervals of 1900–1959 and 1960–1990 (Figures 3a and 3b) are consistent with our time series comparisons and can help evaluate the model and provide further insights into changing relationships. For the PDO, the strongest correlations are in the early period for both the observed and reconstructed series which correlate most positively with the SSTs in the western Pacific mid-latitude region (Figure 3a). For the AMO, there is a strong increase in correlation after 1960 with negative correlations focused on the AMO region of the North Atlantic and becoming stronger with time (Figures 3c and 3d). These similar spatial correlation patterns for the observed and reconstructed lake level records provide additional confidence in our tree-ring based reconstruction, which is capturing the larger-scale climate patterns and the apparent shifting influence from the North Pacific to the North Atlantic SSTs as tracked by the PDO and AMO indices (Assani et al., 2015, 2016; Figures 2 and 3).

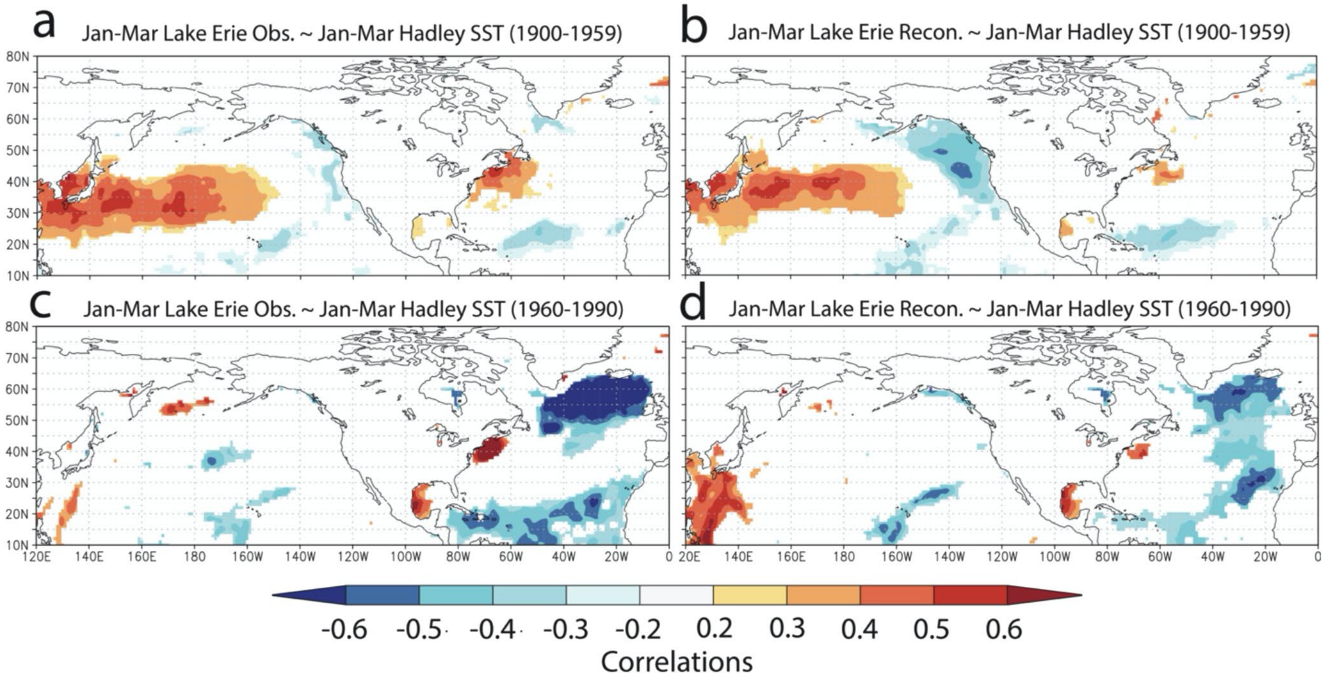

Figure 3. Observed (a, c) and modeled (b, d) lake levels correlated with sea surface temperatures for the interval 1900–1959 (a, b) and 1960–1990 (c, d). Note how the correlation patterns for the Pacific Decadal Oscillation (a, b) and the Atlantic Multidecadal Oscillation (c, d) are spatially similar for the observed and modeled series.

4. Discussion and Conclusions

This interval encompasses a portion of the LIA as well as the recent period of contemporary warming and provides insights into the past winter water levels of Lake Erie. This new reconstruction extends previous efforts (Wiles et al., 2009) back more than 100 years. The record high in 2020 in the observational record is one of the highest values over the last 420 years, consistent with the recent increase in precipitation in the region (ELPC, 2019). Additionally, the 1934 value is among the very lowest (Figure 1) corresponding with the driest year across North America over the entire past millennium (Cook et al., 1999, 2014). Inferred high winter lake levels (1699, 1755, and 1810) correspond with some known volcanic events during the LIA; however, the linkage among these higher water levels, cooling temperatures, and changes in hydroclimate as the result of volcanism is unclear. We do note that explosive volcanic events of the last millennium significantly impacted hydroclimate variability in Europe and elsewhere (Anchukaitis et al., 2010; Rao et al., 2017).

In addition to more direct climate linkages, the most extreme years during the observation period (1934 and 2020) coincide with major changes in land use and water management across the Lake Erie basin. The conversion of wetlands and forests to agricultural lands (~1850 CE) has occurred over vast regions of northwestern Ohio, including in the >4,000 km^2 Great Black Swamp (Reutter, 2019) in the Maumee River watershed, which is the largest tributary contributing to Lake Erie (Mitsch, 2017) outside of the main Detroit River inlet. The loss of wetlands in the Maumee basin has been implicated in detrimental water quality, including major toxic algae blooms (ELPC, 2019). Furthermore, the loss of water storage in wetlands that surround the basin may be a contributing factor to more extreme low- and high water levels due to loss of storage capacity buffering runoff to the Lake Erie basin. Additional investigation is needed to account for the extremes recorded in the post-settlement period and the possible role of changing land use in these fluctuations.

Since the 1930s, there has been a general secular rise in Lake Erie winter water levels with a superimposed decadal variability that is alternatively linked to change in SST patterns in the North Pacific and North Atlantic (Figure 2). Our model captures variability in both the Atlantic and Pacific basins as approximated by climate indices and suggests that an earlier period (pre-1960) is dominated by cyclogenesis in the western Pacific, shifting to the Atlantic and Gulf of Mexico storm tracks after about 1960 (Figure 3). Watras et al. (2013) also linked large-scale atmospheric circulation patterns with the hydroclimate of Midwestern North America, detecting an overall rise in water tables as well as Great Lake levels with a decadal variability consistent with North Pacific

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climate and increased moisture flux from the Gulf of Mexico. During 1900–1960, when we found the PDO was more strongly correlated with lake levels, there was a tendency toward lower levels perhaps because of the prevalence of storm tracks and air masses depleted in moisture tracking across the continent (Figure S2 in Supporting Information S1). This observation is plausible in that more positive modes of the PDO are linked to lower lake levels, and the PDO influences circulation in the Northern Hemisphere as the PNA teleconnection pattern shifts the positioning of the polar jet stream (Mantua & Hare, 2002). The two series (PDO and PNA) are positively correlated with one another for the winter/spring ($r = 0.74$ for JFM; $n = 71$ years), thus during the positive phase of the PDO, the PNA will also be in its positive phase favoring lower lake levels in the Erie basin (Ghanbari & Bravo, 2008).

Although our work here does not directly reveal the precise climate dynamics that force these lake level changes, relevant observations and inferences can be made including the shift to a stronger relationship with the AMO since about 1960. For example, the 1960 change seen in our analysis has also been noted by shifts in global atmospheric circulation (Baines & Folland, 2007), the polar jet (Trouet et al., 2018) and the AMO (McCabe et al., 2004) at this time. Modeling results of Zhang and Delworth (2007) show an AMO switch from a positive to a negative phase around 1965, which was then followed 12 years later by the 1976–1977 regime shift in the Pacific, thus potentially connecting the Atlantic and Pacific basins. Assani et al. (2016) determined that Lake Erie levels are significantly (0.05 level) negatively correlated with the AMO for the 1918–2012 interval. During the AMO's positive phase, the northern Atlantic Ocean experiences warmer temperatures and the Midwest is likely to experience below-average rainfalls (Knight et al., 2006; Trenberth et al., 2019). Thus, positive (negative) phases of the AMO lead to lower (higher) water levels. Also associated with changes in the Atlantic basin, Bishop, Williams, Seager, et al. (2019) and Bishop, Williams, and Seager (2019) identified a growing intensity of frontal storms that have contributed to the strong wetting of the American Southeast. After 1960, wetter air masses originating in the Gulf of Mexico (Bishop, Williams, Seager, et al., 2019; Bishop, Williams, & Seager, 2019; Rodionov, 1994; Watras et al., 2013) have been increasingly tracking toward the northeast in North America. This tendency is associated with a stronger North Atlantic subtropical high (Bishop, Williams, & Seager, 2019) especially during the fall months. An increase in the Gulf-derived storm intensity during the fall dry season can drive lakes to higher levels and appears also to be a driver in the pluvial conditions in the Midwest (Kunkel et al., 2013).

We recognize that using teleconnections to link Western North American tree growth to Midwest hydroclimate as done here can be problematic. McGregor (2017) points out that climate mechanisms that seek to better explain such linkages should be investigated and that teleconnections are statistical constructs of complex large-scale ocean-atmosphere phenomena. Since the dynamics of the climate system are constantly in flux, it is unreasonable to assume that these relationships have been or will be stable in time. Indeed, by extending the modern-day record well into the past, we can begin to test if teleconnection linkages to Lake Erie water level are likely to persist as warming proceeds.

Despite these caveats, we have provided an additional perspective, placing the highs and lows of a major lake into a longer-term context. The high levels of Lake Erie over the past few years and the remarkable increase in stormwater in the Great Lakes region (Gronewold et al., 2021; Hayhoe et al., 2007) are having a transformative impact on the Great Lake communities. There is great interest in better understanding and anticipating the future of the Great Lake water levels as precipitation continues to increase over the region (Wuebbles et al., 2019) and water level rises along with increased wave activity that results in increased coastal erosion and loss of infrastructure (Huang et al., 2021).

Data Availability Statement

The lake level reconstruction in Figure 1 and tree-ring records are available at the Paleoclimatology database maintained by the National Centers for Environmental Information (NCEI) (https://www.ncei.noaa.gov/access/paleo-search/study/37099). The winter monthly lake observational level data shown in Figure 1 and Figure S1 in Supporting Information S1 can be found at the archives of the Great Lakes Environmental Research Laboratory (https://www.glerl.noaa.gov/data/dashboard/data/).

Acknowledgments

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