Chapter 2

Relationship between Water Levels in the North American Great Lakes and Climate Indices

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Additional information is available at the end of the chapter

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Abstract

The goal of this study is to look at how the interconnection of five North American Great Lakes affects the relationship between climate indices and mean annual and extreme daily water levels during the period from 1918 to 2012, and how human activity impacts the dependence between these two variables. Analysis of correlation revealed the existence of a negative correlation between water levels in Lakes Superior, Michigan–Huron and Erie, and the Atlantic Multidecadal Oscillation (AMO) climate index, although this correlation is not observed at the daily scale for Lake Superior. Water levels in Lake Ontario are negatively correlated with Pacific Decadal Oscillation (PDO). The temporal evolution of the dependence between water levels and climate indices is characterized by breaks interpreted to result from variations in the amount of precipitation probably linked with an AMO phase change in the Lakes Superior, Michigan–Huron, and Erie watersheds. In the case of Lake Ontario, such breaks in dependence are thought to be related to water level regulation in this lake resulting from the digging of the St. Lawrence Seaway.

Keywords: water levels, climate indices, correlation, copula, Great Lakes

1. Introduction

The North American Great Lakes system is one of the largest bodies of freshwater in the world. The system holds nearly 23,000 km^3 of water or about 20% of the World's freshwater reserves [1]. It is a rich and diverse aquatic ecosystem and continues to play a crucial role in the social and economic development of interior regions of the United States and Canada. For these reasons, the Great Lakes are the subject of numerous multidisciplinary studies. From a hydroclimate standpoint, most of these studies have focused primarily on the following four elements:

- the variability of hydroclimate variables (water levels, temperature, precipitation, evaporation, etc.) at different time scales (hourly, daily, seasonal, annual and secular) as it relates to natural and human factors [2–16, 17].
- the potential impacts of climate change on this variability, a topic of growing attention given the current climate warming [17–24, 25].
- the seasonal and interannual ice dynamics and its impacts on temperature and water levels in the Great Lakes [26–29, 30].
- the interaction of this water body with regional and/or global climate [31–33].

Few studies have attempted to determine which climate indices affect the interannual variability of water levels [2, 3, 12, 26, 29, 34], and most of these studies only focused on the relationship between climate indices and extreme water levels. To fill this gap, the first goal of the study is to analyze the relationship between climate indices and annual mean and daily extreme (maximum and minimum) water levels in five North American Great Lakes. Underlying this goal is the following hypothesis: because of their interconnected nature, water levels in the Great Lakes are correlated with each other and, as a result, are correlated with the same climate indices. In addition, given that some of the Great Lakes are affected to varying degrees by water level regulation [7, 35, 36], it might be expected that this regulation affects the dependence between water levels and climate indices over time. The second goal of this paper is therefore to analyze this change in dependence over time.

2. Methodology

2.1. Location and sources of data

Located almost entirely along the Canada–US border, the North American Great Lakes system comprises five large lakes (Superior, Michigan, Huron, Erie and Ontario) and a plethora of smaller ones (**Figure 1**). These large lakes vary in surface area from 82,367 km^2 (Superior) to 19,009 km^2 (Ontario), and in volume from 12,221 km^3 (Superior) to 458 km^3 (Erie Water residence time ranges from 191 (Superior) to 2.6 years (Erie).

Water level data were taken from the Environment Canada web site (http://www.waterlevels.gc.ca/C&A/network_means.html). It is important to note that from a hydraulic standpoint, Lakes Michigan and Huron form a single system (Michigan–Huron), and their water levels fluctuate in identical fashion. As a result, these fluctuations are measured at a single station, on Lake Michigan. For each lake, water level was correlated with the five climate indices which have been shown to affect climate in North America. These are: Atlantic Multidecadal Oscillation (AMO), Arctic Oscillation (AO), North Atlantic Oscillation (NAO),

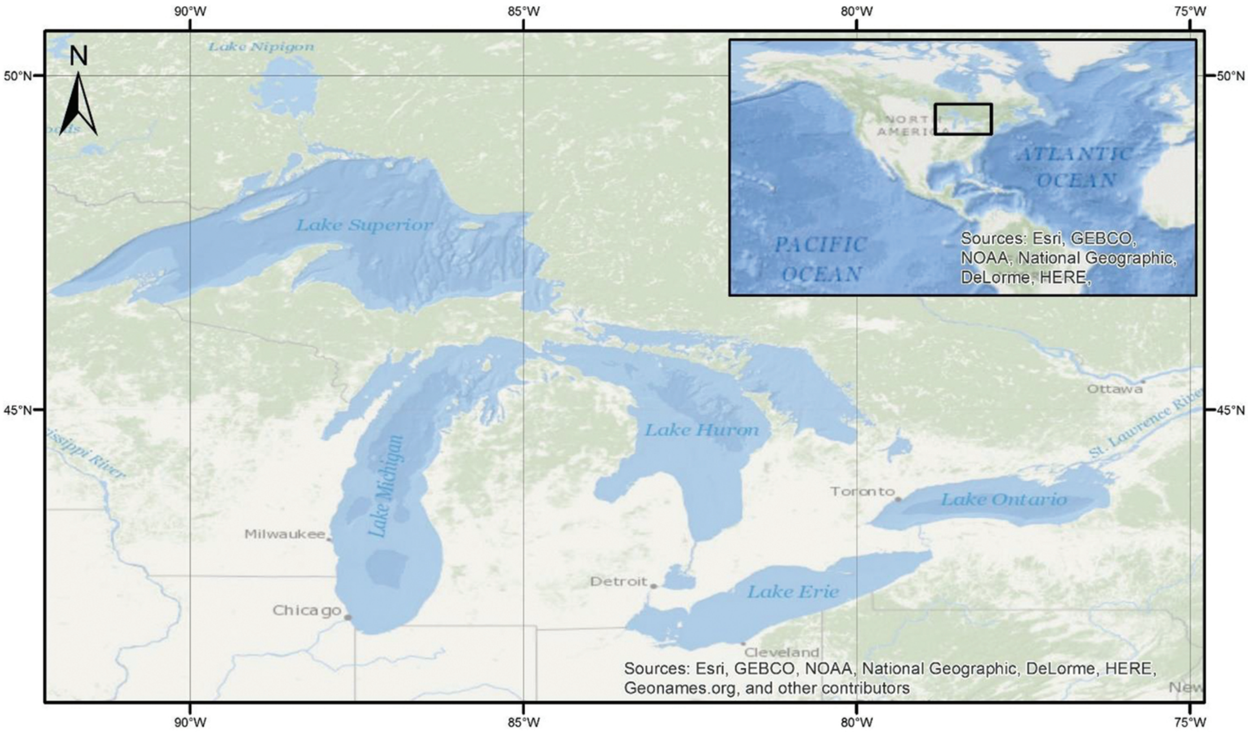

Figure 1. Location of the North American Great Lakes.

Pacific Decadal Oscillation (PDO), and Southern Oscillation Index (SOI). Climate indexes for the AMO and PDO were taken from the following website: http://www.cdc.noaa.gov/ClimateIndices/List, the NAO from http://www.cgd.ucar.edu/cas/jhurrell/indices.data.html, the AO from http://jisao.washington.edu/data/ao/, and the SOI from http://www.cgd.ucar.edu./cas/catalog/climind/soi.html. Data for these climate indices (NAO, AO and SOI) after 2006 were taken from the NOAA website: http://www.esrl.noaa.gov/psd/data/climateindices/list/. Data for all these indices since 1950 are available on the NOAA website: http://www.esrl.noaa.gov/psd/data/climateindices/list/.

For each of the five Great Lakes, the following series will be produced:

- A series of annual mean water levels (average of the 12 monthly values) for the period from 1918 to 2012.

- A series of annual daily maximum and minimum water levels consisting of the highest (maximum) and lowest (minimum) water level values measured each year from 1918 to 2012.

These series will be correlated with time series for five climate indices, including AMO, AO, NAO, PDO, and SOI. For each of these indices, the following three series will be produced:

- A series of annual means (average of the 12 monthly values) of the climate indices.

- A series of seasonal means in winter (average of monthly values of the 6 months from October to March) and in summer (average of monthly values of the 6 months from April to September).

2.2. Statistical analysis

2.2.1. Analysis of correlation

For statistical data analysis, we used the following programs: SAS Version 9.2 32 bits (correlation analysis and canonical correlation analysis), and Matlab Version R2013a (Lombard analysis). The statistical analysis was carried out in three steps. The first step consisted in deriving simple coefficients of correlation between water levels in five the Great Lakes in order to constrain the effect of their interconnected nature on the temporal variability of their water levels. As a second step, coefficients of correlation were derived between climate indices and water levels. These two approaches, however, cannot detect potential interactions between the five climate indices and the temporal variability of water levels. For this reason, canonical correlation analysis (CCA) [36] was used as a third step. This method allows the simultaneous analysis of correlation between two groups of variables.

If one wishes to calculate the relation between two groups, one of X variables (X1, X2,…, Xp) and the other of Y variables (Y1, Y2,…, Yq), one must calculate the canonical variables V (V1, V2,…,Vp) and (W1, W2,…, Wq), which are linear combinations of the X variables of the first group (in this case, the climatic indices) and the Y variables of the second group (in this case, the water levels of the five Great Lakes). Then, the canonical variables V and W are correlated between themselves, that is to say, V1 is correlated with W1, V2 to W2 and so on, in order to obtain the canonical correlation coefficients. After that, the canonical variables V and W are correlated with the variables X and Y, so as to obtain what are called structure coefficients. In fact, these coefficients measure the link (the correlation) between the canonical variables (V and W) and the original variables of groups X and Y. Thus, if X1 and X2 are correlated, for example, to V1, Y1 is correlated with W1. Y1 is therefore correlated with the original variables X1 and X2, since the canonical variables V1 and W1 are correlated. The main purpose of CCA is to maximize the correlations between the two groups of variables.

2.2.2. The copula method

To test the second hypothesis that underlies the study, the copula method will be applied to the series of water levels in the Great Lakes and the climate indices with which they are significantly correlated. This method is used to analyze the evolution over time of the dependence between two correlated variables by detecting significant breaks in Kendall's tau values. The timing of these breaks will be compared with the timing of construction of man-made structures carried out over time to regulate water levels in the Great Lakes. We described this method in some of our previous work [i.e., F*or example*, see 2].

The dependence in a random vector (X, Y) is contained in its corresponding copula function C. Specifically, the celebrated theorem of Sklar ensures that there exists a unique $C:[0, 1]^2 \rightarrow [0, 1]$ such that

$$P(X \le x, Y \le y) = C\{P(X \le x), P(Y \le y)\}. \quad (1)$$

Quessy et al. [37] developed a testing procedure to identify a change in the copula (*i.e.*, dependence structure) of a bivariate series $(X_1, Y_1), \ldots, (X_n, Y_n)$. The idea is based on Kendall's tau, which is a nonparametric measure of dependence. Let $\hat{T}_{1:T}$ be Kendall's tau measured for the first T observations and $\hat{T}_{T+1:n}$ be Kendall's tau for the remaining $n - T$ observations. The proposed test statistic is

$$M_n = \max_{1<T<n} \frac{T(n-t)}{n\sqrt{n}} \left| \hat{T}_{1:T} - \hat{T}_{T+1:n} \right| \quad (2)$$

that is, a maximum weighted difference between the Kendall's tau. Since M_n depends on the unknown distribution of the observations, the so-called multiplier re-sampling method is used for the computation of p-values. Specifically, for n sufficiently large (n > 50), this method yields independent copies $M_n^{(1)}, \ldots M_n^{(N)}$ of M_n. Then, a valid p-value for the test is given by the proportion of $M_n^{(i)}$'s larger than M_n. For more details [i.e., F*or example*, see 37]. Usually, one can expect that the series $X_1, \ldots, X_n$ and $Y_1, \ldots, Y_n$ are subject to changes in the mean and/or variance following, for example, the smooth-change model [38]. If such changes are detected, the series must be stabilized (to remove the shift of the mean and variance) in order to have (approximately) constant means and variances. Finally, a change in the degree of dependence between two series is statistically significant when $M_n > V_c$, where V_c is the critical value derived from observational data. As part of this study, the copula method was applied to standardized water level and climate index data after removing any break in mean values in the hydroclimate series.

3. Results

3.1. Simple linear correlation analysis

The values of coefficients of correlation derived between water levels in each of the five Great Lakes are shown in **Table 1**, in which it may be seen that those values increase with decreasing distance between lakes. Thus, the lowest coefficient of correlation values are between Lakes Superior and Ontario. However, coefficients of correlation between Lakes Superior and Michigan–Huron, which are adjacent to one another, are lower than those observed between the other three lakes, which are closer to one another.

	Lake Superior	Lake Michigan	Lake Erie	Lake Ontario
Mean annual water level				
Lake Superior	1	0.6231	0.4059	0.3341
Lake Michigan		1	0.8613	0.7164
Lake Erie			1	0.8193
Lake Ontario				1
Annual maximum water level				
Lake Superior	1	0.5673	0.3783	0.3033
Lake Michigan		1	0.8442	0.7055
Lake Erie			1	0.8332
Lake Ontario				1
Annual minimum water level				
Lake Superior	1	0.6081	0.4110	0.2581
Lake Michigan		1	0.8261	0.6621
Lake Erie			1	0.7363
Lake Ontario				1

All coefficients of correlation are statistically significant at the 5% level.

Table 1. Correlation between water levels in the North American Great Lakes.

	Annual climatic indices				**Winter climatic indices**				**Summer climatic indices**			
	S	M–H	E	O	S	M–H	E	O	S	M–H	E	O
AMO	**−0.22**	**−0.42**	**−0.30**	−0.12	−0.19	**−0.42**	**−0.33**	−0.09	**−0.22**	**−0.38**	**−0.31**	−0.13
AO	−0.00	0.07	0.17	0.14	−0.01	0.07	0.15	0.12	0.01	0.02	0.08	0.10
NAO	0.07	0.05	−0.06	−0.04	0.07	0.16	0.18	0.08	0.02	−0.12	**−0.32**	−0.18
PDO	0.05	0.03	−0.01	**−0.22**	0.02	0.00	−0.06	**−0.28**	0.07	0.05	0.05	−0.16
SOI	−0.05	−0.09	−0.08	0.02	−0.06	−0.10	−0.07	0.05	−0.01	−0.04	−0.05	−0.02

Significant coefficient of correlation values at the 5% level are shown in bold.

Table 2. Coefficients of correlation calculated between the five climate indices and annual mean water levels (1918–2012).

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As far as the relationship between climate indices and annual mean water levels is concerned, **Table 2** and **Figure 2** shows that AMO is negatively correlated with water levels in Lakes Superior, Michigan–Huron, and Erie, with water levels in Lake Michigan–Huron showing better correlation with this climate index than water levels in the other two lakes. Annual mean water levels in Lake Ontario are negatively correlated with PDO (**Figure 3**), the same type of relationship being observed for both maximum (**Table 3**) and minimum (**Table 4**) daily water levels. Aside from PDO, daily extreme water levels in Lake Erie are also negatively correlated with the NAO summer indices. However, daily extreme (maximum and minimum) water levels in Lake Superior are not significantly correlated with any climate index.

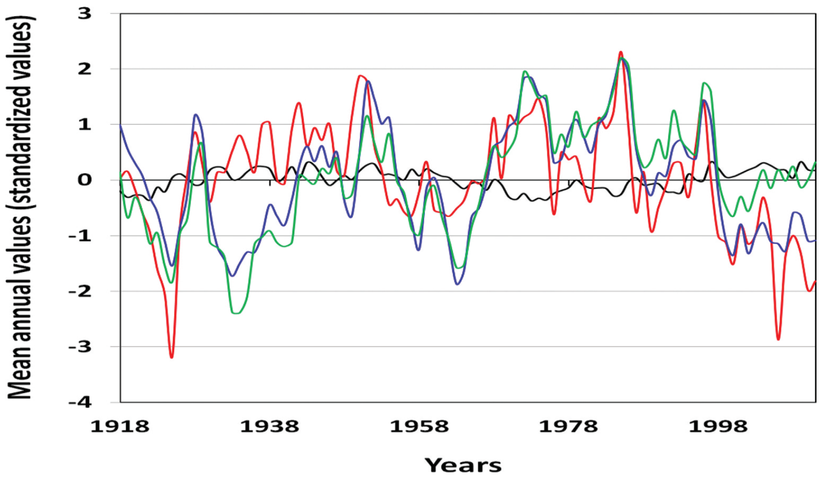

Figure 2. Comparison of the temporal variability of AMO mean annual indices (black curve) and mean annual water levels (standardized values) in Lakes Superior (red curve), Michigan–Huron (blue curve) and Erie (green curve) (1918–2012).

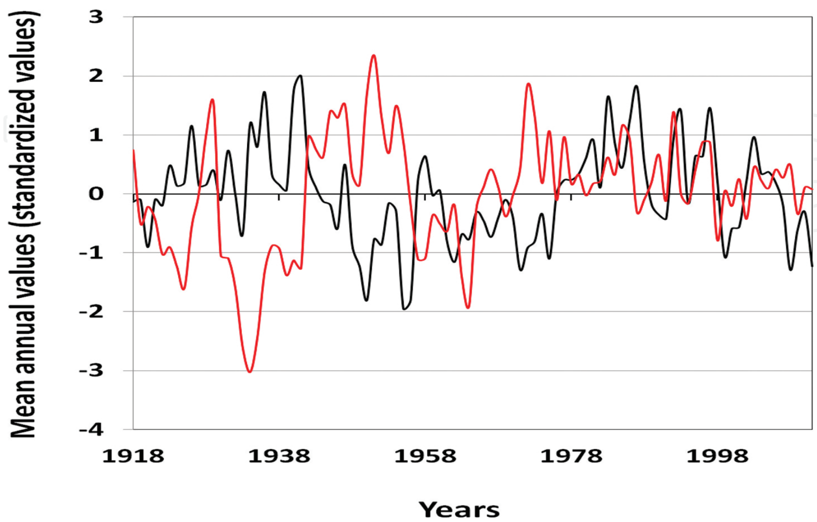

Figure 3. Comparison of the temporal variability of PDO mean annual indices (black curve) and mean annual water levels (standardized values) in Lake Ontario (red curve) (1918–2012).

	Annual climatic indices				**Winter climatic indices**				**Summer climatic indices**			
	S	M–H	E	O	S	M–H	E	O	S	M–H	E	O
AMO	−0.14	**−0.39**	**−0.23**	−0.10	−0.15	**−0.40**	**−0.27**	−0.12	0.04	0.08	0.10	0.14
AO	−0.09	0.09	0.12	0.08	−0.12	0.07	0.11	0.04	0.04	0.08	0.10	0.14
NAO	0.05	0.10	−0.03	0.01	0.04	0.19	0.20	0.13	0.03	−0.09	**−0.29**	−0.14
PDO	0.03	−0.01	−0.07	**−0.26**	0.02	−0.03	−0.11	**−0.29**	0.03	0.00	−0.02	**−0.21**
SOI	−0.15	−0.05	−0.02	−0.00	−0.11	**−0.34**	**−0.24**	−0.08	−0.10	−0.01	0.02	0.01

Significant coefficient of correlation values at the 5% level is shown in bold.

Table 3. Coefficients of correlation calculated between the five climate indices and maximum daily water levels (1918–2012).

	Annual climatic indices				**Winter climatic indices**				**Summer climatic indices**			
	S	M–H	E	O	S	M–H	E	O	S	M–H	E	O
AMO	−0.11	**−0.41**	**−0.31**	−0.12	−0.19	**−0.45**	**−0.35**	−0.10	−0.11	**−0.41**	**−0.31**	−0.12
AO	0.11	0.07	0.07	0.08	0.01	0.10	0.12	0.07	0.11	0.07	0.07	0.08
NAO	0.09	−0.06	−0.31	−0.20	0.09	0.20	0.14	0.08	0.09	−0.06	**−0.31**	−0.20
PDO	0.13	0.07	0.01	**−0.22**	0.12	0.04	−0.07	**−0.28**	0.13	0.07	0.01	**−0.22**
SOI	−0.07	−0.02	−0.01	−0.03	−0.12	−0.13	−0.11	−0.07	−0.07	−0.02	−0.01	−0.03

Significant coefficient of correlation values at the 5% level is shown in bold.

Table 4. Coefficients of correlation calculated between the five climate indices and minimum daily water levels (1918–2012).

3.2. Canonical analysis of correlation (CCA)

This analysis did not yield conclusive result. As an example, CCA results applied to annual mean water levels and annual mean climate indices are presented in **Tables 5** and **6**. From **Table 5**, it can be seen that the coefficient of canonical correlation between the first two axes is relatively low (0.633). CCA could not significantly maximize the coefficient of correlation values. Thus, the derived value of 0.633 is only slightly higher that the highest simple correlation coefficient of 0.425 (see **Table 2**). In addition, only the first two canonical axes are statistically significant at the 5% level. As far as coefficients of structure are concerned (**Table 6**), values of coefficients of structure related to water levels in the lakes are all lower than 0.600 on the first canonical axis. Thus, this axis shows little correlation with water levels in the lakes. The same is true for climate indices on the second canonical axis. As the last two

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canonical axes are not statistically significant, it is difficult to interpret their coefficients of structure.

Canonical roots	R	F	p-values
CC1	0.6330	3.81	<0.0001
CC2	0.4211	2.11	0.0171
CC3	0.2832	1.24	0.2872
CC4	0.0156	0.9997	0.9894

R = canonical coefficient of correlation.

Table 5. Canonical correlation analysis statistics.

Variables	W1	W2	W3	W4	V1	V2	V3	V4
Lake Superior	−0.370	0.003	0.258	0.893				
Lake Michigan–Huron	−0.587	0.263	0.725	0.245				
Lake Erie	−0.293	0.682	0.655	0.142				
Lake Ontario	0.133	0.346	0.914	0.164				
AMO					0.750	−0.195	−0.606	−0.033
AO					0.070	0.471	0.238	0.837
NAO					−0.195	−0.418	0.105	0.879
PDO					−0.470	0.200	−0.829	0.204
SOI					0.257	−0.157	0.093	−0.058

Table 6. Correlation between the annual mean water levels and canonical roots (W), and correlation between climatic indices and canonical roots (V).

3.3. Analysis of the dependence between water levels and climate indices using copulas

It is important to point out that the copula method was only applied for climate indices that are significantly correlated with water levels. Results obtained using this method are presented in **Table 7**, from which it may be seen that the dependence between the two climate indices (AMO and PDO) and water levels in the five Great Lakes, aside from annual mean water levels in Lake Ontario, shows a sharp break (**Figures 4–6**). In other words, the relationship between the two variables changed significantly over time.

As far as the timing of this change in dependence is concerned, **Table 7** shows that it is nearly synchronous for Lakes Michigan–Huron and Erie, having occurred in the late 1960s and early 1970s. In Lake Ontario, these breaks occurred in the late 1950s. Finally, for Lake Superior, the break in mean water levels took place during the first half of the 1950s. In all cases, the value of Kendall's tau decreases after the break.

Lakes	Indices	M_n	V_c	p-value	Year
Mean annual water levels					
Lake Superior	AMO	1.0614	0.9389	0.020	1954
Lake Michigan	AMO	1.2809	0.8337	0.001	1966
Lake Erie	AMO	1.3728	0.8204	0.000	1968
Lake Ontario	PDO	0.857	0.904	0.075	1960
Annual daily maximum water levels					
Lake Superior	–	–	–	–	–
Lake Michigan	AMO	0.9715	0.8972	0.0270	1968
Lake Erie	AMO	1.1435	0.9293	0.010	1972
Lake Ontario	PDO	0.994	0.8865	0.023	1959
Annual daily minimum water levels					
Lake Superior	–	–	–	–	–
Lake Michigan	AMO	1.1311	0.8636	0.000	1968
Lake Erie	AMO	1.3756	0.9205	0.000	1968
Lake Ontario	PDO	1.1311	0.9040	0.000	1959

p-values < 0.05 are statistically significant at the 5% level.
* Year of break in dependence.

Table 7. Analysis of the relationship between climate indices and water levels using copulas.

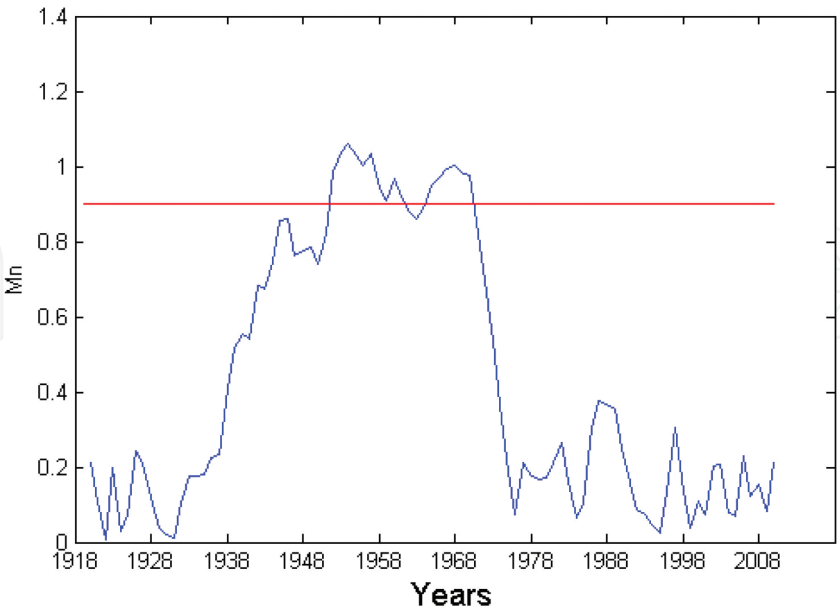

Figure 4. Interannual variability of M_n values of mean water levels. The red line represents the maximum value of V_c. Lake Superior.

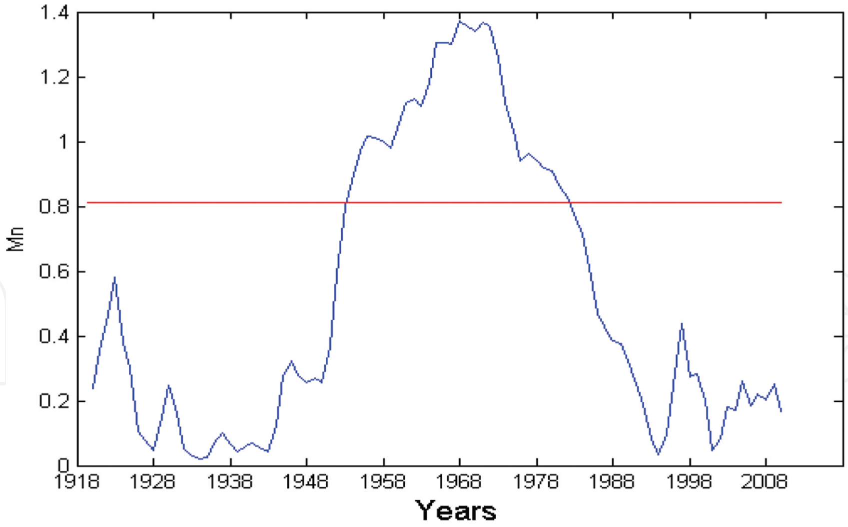

Figure 5. Interannual variability of M_n values of mean water levels. The red line represents the maximum value of V_c. Lakes Michigan–Huron.

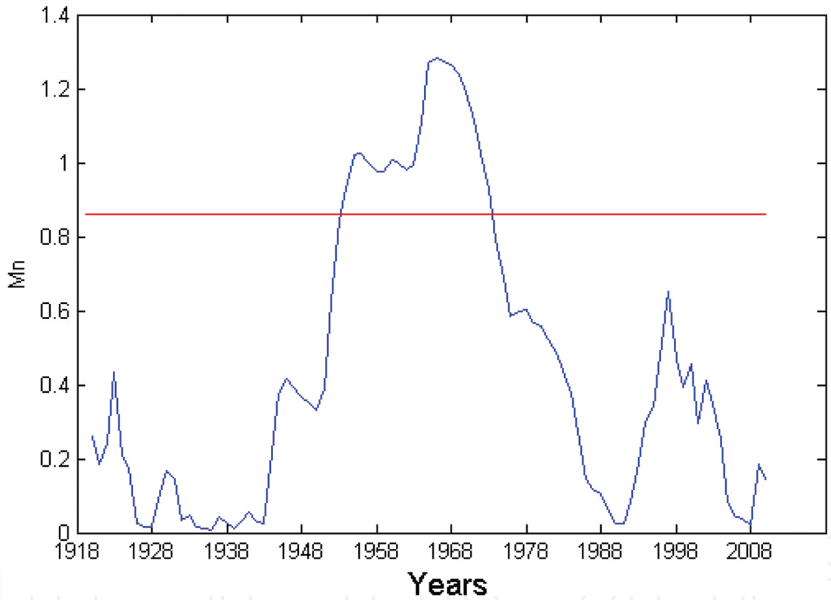

Figure 6. Interannual variability of M_n values of mean water levels. The red line represents the maximum value of V_c. Lake Erie.

4. Discussion and conclusion

The five North American Great Lakes comprise the largest freshwater aquatic ecosystem in the world. One of the characteristic features of these water bodies is their interconnected nature. Simple correlation analysis revealed that the effect of this interconnection on the temporal variability of water levels is strongly influenced by the distance between any two lakes. As this distance increases, the influence of the upstream lake on the temporal variability of water levels in the downstream lake decreases significantly. Thus, the weakest correlation between water levels is derived between Lakes Superior and Ontario; the two lakes located the furthest apart. In contrast, the strongest correlations are observed between adjacent lakes. This diminishing influence of interconnection with distance between lakes may in part be due to the dominant influence of local climate conditions in the watershed of each of the Great Lakes on the temporal variability of water levels [3].

The interconnected nature of the five lakes leads to the postulate that the interannual variability of their water levels may be correlated with the same climate indices. Analysis of the correlation between these water levels and five climate indices revealed a negative correlation between AMO and water levels in Lakes Superior, Michigan–Huron, and Erie, on one hand, and a negative correlation between PDO and water levels in Lake Ontario, on the other hand. It is worth specifying, however, that for Lake Superior, this correlation is only observed at the annual scale. While this result cannot be used to conclude that the interconnected nature of the lakes influences the relationship between climate indices and water levels, it does suggest a possible influence of the effects of water level regulation on this relationship. The two least regulated of the five lakes (Michigan–Huron and Erie) are correlated with the same climate indices at all time scales. Although Lake Superior is adjacent to Lake Michigan–Huron, its water levels are not correlated with AMO at all scale. And as far as Lake Ontario is concerned, despite its proximity to Lake Erie, its water levels are correlated to a different climate index, namely PDO.

The influence of AMO on the temporal variability of hydroclimate variables has been highlighted for many regions of North America [39–43, 44]. The sign of this correlation changes from region to region. For instance, in the Pacific Northwest and Northeastern regions of the United States, as well as in Florida, this correlation is positive, whereas in the continental region and the Mississippi River and Great Lakes watersheds, this correlation is negative [41]. Thus, during a positive phase of AMO, water levels in the Great Lakes tend to increase due to an increase in precipitation likely resulting from enhanced cyclonic activity in winter. In contrast, the influence of PDO on the temporal variability of hydroclimate variables has mainly been detected in the western part of the North American continent [45–49, 50]. In the Great Lakes watershed, a negative correlation between PDO and amount of snow has been brought to light [51, 52, 53], with the negative phase of this index being associated with an increase in amount of snow and, as a result, in water levels in Lake Ontario.

Over the years, the Great Lakes were affected to varying degree by human activity, including diversion within watersheds; dredging of natural channels connecting the lakes; and regulation of water levels [8, 54, 55]. It is therefore reasonable to expect that these different human impacts may have affected the dependence between climate indices and water levels in the lakes. Application of the copula method revealed breaks in this dependence at different scales. For water levels in Lakes Michigan–Huron and Erie, the three waterbodies least affected by human activity, breaks in this dependence occurred in the late 1960s and early 1970s. The only plausible factor that could account for these breaks is changing climate conditions in the watersheds of these three Great Lakes. Between 1970 and 1990, precipitations increased

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significantly in the Great Lakes watershed [e.g., *For example*, see 2], coinciding with a change in phase for AMO, from positive to negative after 1970 [41]. As far as Lake Ontario is concerned, the breaks in dependence occurred in the late 1950s and may therefore be related to water level regulation in this lake as a result of the digging of the Great Lakes-St. Lawrence Seaway System. Finally, for Lake Superior, the break in dependence occurred in 1954, which is not related to any significant development project. However, from a hydrological and climate standpoint, Assani et al. [2] observed an increase in the frequency of relatively low water levels during the 1950s and 1960s, reflecting a trend of decreasing precipitation in the watershed.

In conclusion, the influence of the interconnected nature of the Great Lakes on the temporal variability of their water levels decreases with increasing distance between individual lakes, likely as a result of the effect of local climate conditions on this variability. At the annual scale, however, water levels in four of the five Great Lakes are negatively correlated with AMO, and only water levels in Lake Ontario, the most downstream of the lakes, are correlated with PDO. For the first four lakes, the break in dependence between water levels and climate indices was affected by changes in climate conditions in their watersheds, whereas for Lake Ontario, water level regulation in its watershed affected this break. This study shows that the influence of local climate conditions and human activity in the watersheds of the Great Lakes strongly dampen the effects of interconnection on the temporal variability of water levels in the lakes. As a result, hydroclimate changes affecting one lake do not necessarily propagate to other lakes located downstream.

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