Prediction of Lake Levels on Lakes Michigan-Huron and Erie

Baird Report III

March 10, 2020 | 12676.101.R1.RevC

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Prediction of Lake Levels on Lakes Michigan-Huron and Erie

Baird Report III

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12676.101.R1.RevC

Revision	Date	Status	Comments	Prepared	Reviewed	Approved
Rev #	Select date	Status	Click to enter text	Initials	Initials	Initials
1	9/18/2017	RevB	Final Report	QL	RN	RN
2	3/3/2020	RevC	Revised Report	QL	RN	RN

Abstract

An analysis of the historic water level fluctuations between 1850 and 2016 was completed for Lake Erie and Lake Michigan-Huron, based on historical records, to determine the major harmonic constituents with periods less than about 60 years. These data were supplemented with paleo lake levels derived from beach ridge records and reconstructed lake levels from tree-ring chronologies. Harmonic analysis of these data reveals four major quasi-periodic cycles, including 160-year and 11-year quasi-periodic cycles driven by sunspots, the 30-year quasi-periodic precipitation cycles, and the 4-year quasi-periodic cycles linked to North Atlantic Oscillation (NAO) and El Niño Southern Oscillation (ENSO), and an annual cycle. Major drivers of these cycles appear to be sunspot activity and the NAO. We used the four major quasi-periodic cycles to develop a predictive model for Lake Erie and Lake Michigan-Huron that was calibrated with the measured lake levels between 1850 and 2016. The prediction errors were also evaluated with forecasting time and indicate that the model has capability to predict lake levels in decadal time frames. The findings have important implications to activities influenced by lake level, including consumptive use of water, recreational use, navigation, hydro-power generation, and environmental restoration. The findings also have wider application to sectors associated with the climate of the Great Lakes basin including agriculture and flood risk management. Finally, the technique presented may provide a method of monitoring and differentiating human-induced climate change.

Index Words. Great Lakes; Lake Level; Quasi-Periodic Cycle; Prediction; Sunspot Number; NAO

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1. Introduction

Fluctuations in the levels of the North American Great Lakes are predominantly controlled by a balance between precipitation and evaporation over the 764,600 km^2 Great Lakes Basin. The Great Lakes function as a unique integrator of temporal changes in the climate over a vast region. Lake levels are also modulated by flows through the interconnecting channels of the five main lakes and through a variety of direct human influences such as channel deepening for navigation, diversions and direct controls on flows. These human factors are relatively well defined for each lake (IJC 1987 and 2000).

Modern and continuous monthly lake level records date back to 1865 and there are intermittent periods of measurements back to 1819 (Tait 1983, Quinn and Sellinger 1990). The water levels fluctuate from record highs to record lows in a range of 1 to 2 m, depending on the lake. The lake levels in Lake Michigan-Huron were reconstructed from tree-ring chronologies back to 1600 (Quinn and Sellinger 2006). Paleo lake level data, derived from beach ridges and shoreline positions, extend back several thousand years (Baedke and Thompson 2000). Both the modern and paleo records suggest “quasi-periodic” fluctuations (see Figure 1.1), with two main periods of approximately 33 and 160 years (Thompson and Baedke 1995 and 1997).

Suggestions of links between levels of large lakes and sunspot activity have been reported by others and are more than a century old (Dawson 1874, Dixey 1924, Yousef *et al.* 2000). Figure 1.2 shows a time series comparison between the fluctuations of the modern water levels on Lake Erie and the annual sunspot number. A link between flows of the Nile River and NAO periodicity has been proposed by Kondrashov *et al.* (2005). Links between lake level variability and synoptic climate phenomena have been studied by Polderman and Pryor (2004) and Changnon (2004).

Changes in water levels play an important role in human activities and in coastal processes and near-shore ecosystems, including development and maintenance of beaches, dunes, and wetlands (Wilcox *et al* 2007). Low lake levels have a significant economic impact on the commercial navigation in the Great Lakes – St. Lawrence River System (Millerd 2005). The predictability of lake levels has great significance and is beneficial to many sectors of water resource usage on the Great Lakes.

A few investigators have attempted to find the periodic cycles and to develop the forecasting models for the future water level prediction in the Great Lakes. Liu (1970) applied a spectral analytic technique to investigate the annual fluctuation of water levels in the Great Lakes. He found the existence of longer-term 8-year and 27-year periodic water level cycles; however, no attempt was made to determine the amplitude or phase relationships of these cycles for lake level prediction. Cohn and Robison (1976) performed spectral analysis of the monthly average lake levels and found prominent cycles with periods of approximately 1, 11, 22, and 36 years. The magnitudes and phases of these cycles were determined from measured data and predictions of Great Lakes levels were made out to the year 2010. These predictions did not compare well for the high lake levels that occurred in 1997 and the low lake levels in 2001. The reason for these poor predictions may be due to the model excluding the low frequency cycles which were found in the paleo and reconstructed data (Baedke and Thompson 2000, Quinn and Sellinger 2006). As will be shown, these low frequency cycles are important with respect to lake level prediction.

Decooke and Megerian (1961 and 1967) and Crowley (1987) proposed operational forecast models of lake stages for a forecast horizon of less than 6 months as the model was based on the apparent assumption that the natural driving force for lake level change is random precipitation. Walton (1989) utilized a recent geophysical digital signal processing algorithm, the Maximum Entropy Method, to forecast Great Lake monthly average water levels in an attempt to separate monthly average water level signal content from random noise in the time series. This has been shown to provide a forecast horizon well beyond one year in the case of the lower Great Lakes. These forecasting models are limited to relatively short-term forecasts with prediction errors expected to increase in larger forecast horizons.

The fluctuation of water level on the Great Lakes is primarily driven by precipitation and temperature which are, in turn, potentially linked to the change in numbers of sunspots. The "quasi-periodic" fluctuation of lake levels is revealed by both the modern measured data and the paleo ridge data. These cycles can be numerically described by a group of single cycles of similar frequency, similar to wave group theory. Based on this theory, the authors developed a model to predict lake levels for Lake Erie in 2005. The frequency of cycles and the harmonic parameters of the cycles were determined by using the measured monthly-average lake levels from 1865 to 2004. The comparison of measured lake levels with the predicted water levels after the prediction is shown in Figure 1.3. The model predicted the lake levels well from 2005 to 2015. But there is significant diversion from the measured lake level after 2015 and this likely resulted from errors in the phases of some cycles. In this paper, the approach has been updated and improved by using longer term data to develop long-term (decadal) predictions of lake level fluctuation as driven by natural climate processes. As Lake Superior and Lake Ontario are regulated, the fluctuation of levels on these lakes does not well represent the effect of natural processes. Therefore, this study focused on Lake Michigan-Huron (MH) and Lake Erie, which are unregulated.

This report was revised by updating the harmonic parameters, which were determined by using measured lake levels up to September of 2019.

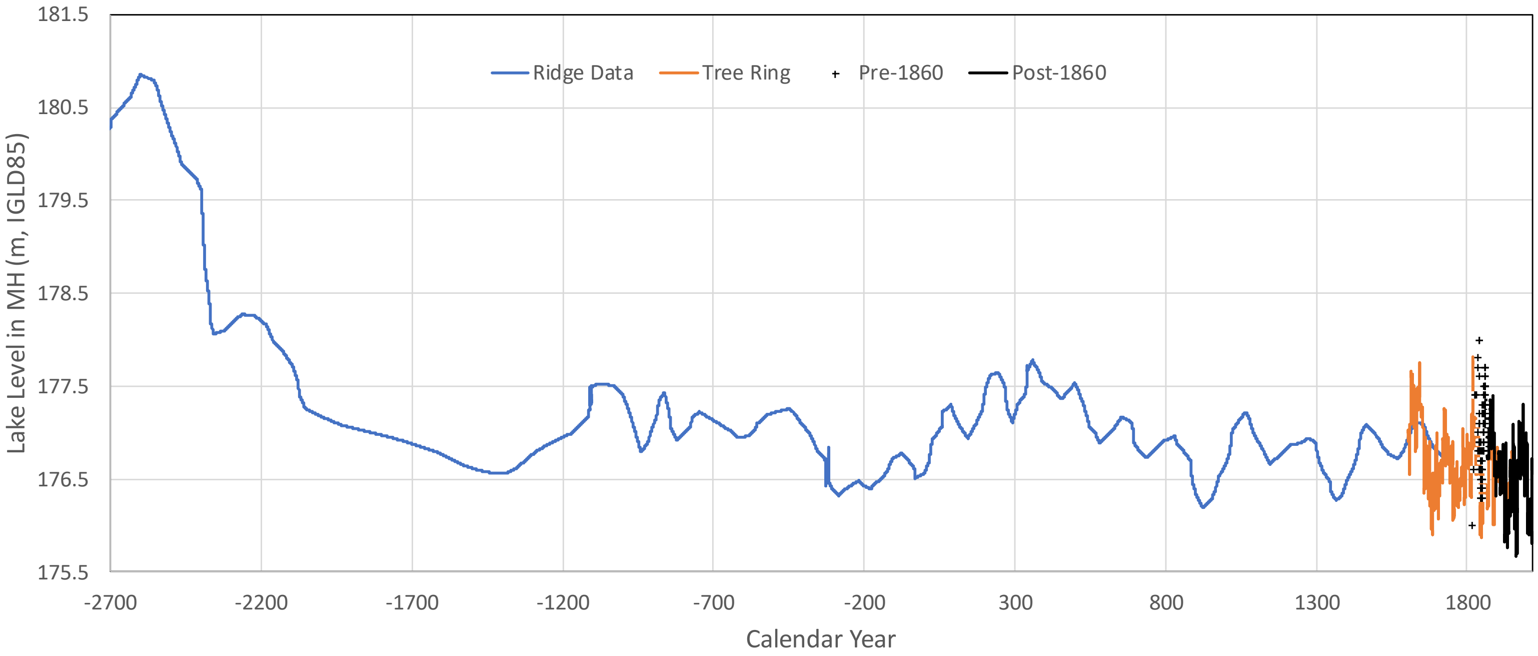

Figure 1.1: Lake levels in Lake Michigan-Huron for four data sources, including measured monthly-averaged lake levels (1865-2016), intermittent period of measurement back to 1819, reconstructed lake level from tree-ring chronologies (1600-1961), and the paleo lake level data derived from beach ridges and shoreline positions (2700 BC – 1700).
The data reveals the periodicity of the lake level.

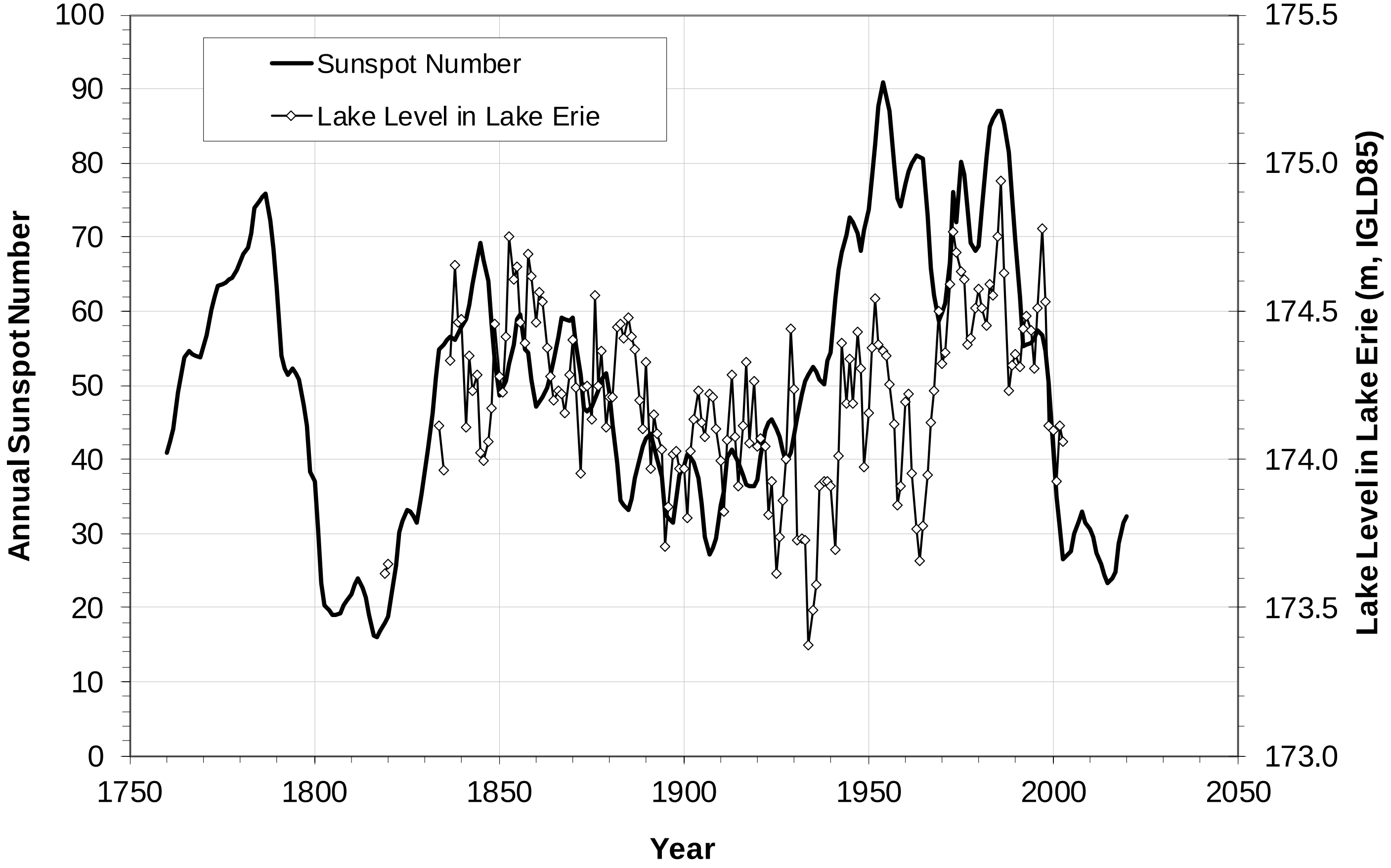

Figure 1.2: Correlation between annual sunspot number and lake level in Lake Erie.
Black line, the annual sunspot number; line with diamond dot, lake level measured at the Cleveland station in Lake Erie. The lake level is high as the annual sunspot number is high.

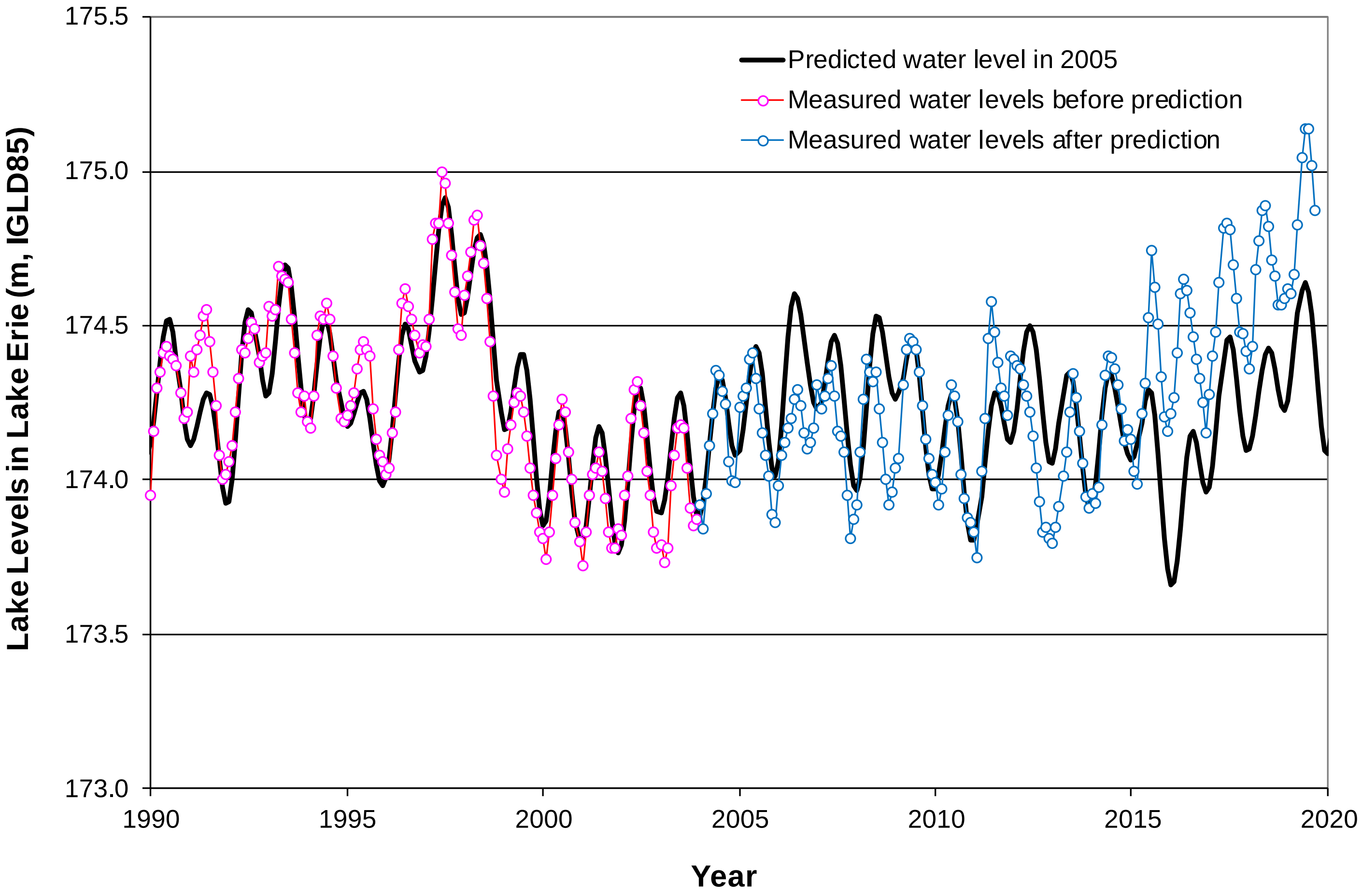

Figure 1.3: Comparison of measured lake levels with the water levels predicted in 2005 by the authors using an earlier version of their method. The model was developed in 2005 and was used to predict the lake levels after 2005. The results show that the model predicted the lake levels in Lake Erie relatively well from 2005 to 2015, but there is significant diversion after 2016.

2. Methods

2.1 Data

Modern and continuous monthly lake level records dating back to 1860 (see Figure 1.1) were obtained from the National Oceanic and Atmospheric Administration's (NOAA) National Ocean Services database (NOAA tide and current data base, 2017). The monthly lake levels were downloaded for the gage at Harbor Beach in Lake Huron and for the gage at Cleveland in Lake Erie. These two stations are the most representative of average lake levels since they are located mid-lake and are less influenced by seasonal winds from a dominant direction. The downloaded water level data were verified by NOAA (NOAA tide and current data base, 2017). All modern water levels are referred to International Great Lakes Datum 1985 (IGLD85).

There are intermittent periods of measurements back to 1815 at the other available gages on both Lake Michigan-Huron and Lake Erie. Quinn and Sellinger (1990) published the intermittent lake levels in Lake Michigan-Huron from 1815 to 1859, which were converted from the measured lake level at Milwaukee, Wisconsin and adjusted due to differential isostatic rebound. Tait (1983) listed the lake levels measured at three gages (Buffalo, Cleveland, and Pt. Colborne) in Lake Erie, which were converted to International Great Lake Datum 1955 (IGLD55). All of these lake levels were converted to IGLD85 for this study.

Quinn and Sellinger (2006) used a dendrochronolgy of annual precipitation and air temperature from tree-ring chronologies at six Great Lakes locations to reconstruct lake levels in Lake Michigan for the period 1600-1961. The reconstructed water levels matched well with the multiple year average lake levels from 1910 to 1960 but had a significant offset when compared to the measured water levels from 1850 to 1900 (see Figure 2.1). These data suggested a return interval of 150 – 190 years for extreme lake levels in Lake Michigan-Huron.

Paleo lake level data, derived from beach ridges and shoreline positions, extend back several thousand years (Baedke and Thompson 2000). Both the modern and paleo records suggest "quasi-periodic" fluctuations, with two main periods of approximately 33 years (32 +/- 6.6 years) and 160 years (120 – 200 years), as shown in Figure 1.1.

2.2 Finding Cycles

The measured lake level data depict so-called "quasi-periodic" cycles, as suggested by others (Thompson and Baedke 1995 and 1997, Baedke and Thompson 2000, Polderman and Pryor 2004). "Quasi-periodic" cycles can be described by the superposition of different periodic cycles with periods that are very close. Therefore, "quasi-periodic" fluctuations of lake levels on the Great Lakes can be described by a number of cosine functions once any non-periodic trend is filtered out.

A harmonic analysis of the historic fluctuations on available lake level data was completed to find the major cycles which are important to the lake level fluctuations and to determine the characteristic parameters of major harmonic constituents; that is, frequency, magnitude, and phase. The mathematical equation used to find these characteristic parameters is:

$$z = z_0 + \alpha \cdot (t - t_0) + \sum_{k=1}^{N} a_k \cos(\omega_k t + \phi_k) \tag{1}$$

where z is the lake level (in meters), t is time (in calendar years), z_0 is the mean lake level (in metres) which is determined from monthly lake level records (see appendix). The variables of the last two terms of Equation (1) are described below.

The second term of Equation (1) describes the linear trend of the lake levels over the period of record. The trend term was introduced to account for the non-periodic change of lake levels caused by historical human activities or by the influence of glacial isostatic adjustment on lake levels. For example, the outlet of Lake Erie is rising at 6 to 9 cm/century (The Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data 2001) and this results in an equivalent rise in the mean level of this lake. The trend term also accounts for periodic changes of the lake levels linked to the climate change cycles with very long periods (over 500 years) that cannot be determined as the existing lake level record is too short. Cycles with a very long period which cannot be determined with the available data can be approximately represented as a linear trend in the short term. The slope coefficient (α) and initial time (t_0) were determined by using regression analysis of the lake level record (see appendix).

The third term in Equation (1) represents the periodic cycles expressed by a series of cosine functions. Each cosine function represents a harmonic in lake level cycles. The subscript *k* represents the *k*-th cycle and *N* is the total number of cycles. Each cycle contains three unknown constants that must be determined from the lake level records: amplitude (*a*), frequency ($\omega = 2\pi/T$, where *T* is the period), and the initial phase (ϕ).

Harmonic analysis is based on three assumptions that must apply over the full length of the lake level record (Katznelson, 2004): 1) the average value of all sample data must be zero; 2) the average value of any product $\cos(\omega_i t) \bullet \cos(\omega_j t)$, $\cos(\omega_i t) \bullet \sin(\omega_j t)$, $\sin(\omega_i t) \bullet \cos(\omega_j t)$, and $\sin(\omega_i t) \bullet \sin(\omega_j t)$ where $i \neq j$ must be zero; and 3) the average of $\cos^2(\omega_i t)$ or $\sin^2(\omega_i t)$ is equal to ½ (see more detailed explanation in appendix). Therefore, the amplitude and initial phase for a cycle are determined by the following expressions:

$$a_k = 2\sqrt{A_k^2 + B_k^2} \qquad (2)$$

$$\phi_k = \arctan(-B_k / A_k)$$

where

$$A_k = \frac{1}{M}\sum_{i=1}^{M} z_i' \cdot \cos(\omega_k t_i)\,,\ B_k = \frac{1}{M}\sum_{i=1}^{M} z_i' \cdot \sin(\omega_k t_i)\,,\ \text{and}\ z' = z - z_0 - \alpha(t - t_0) \qquad (3)$$

Using Equations (2) and (3), the amplitude (a_k) and the initial phase (ϕ_k) can be calculated if the frequency (ω_k) is known.

To complete the harmonic analysis, the frequency of each harmonic constituent or cycle must be first determined. The harmonic analysis technique was initially applied to search for possible cycles by scanning periods from 0.5 year to 500 years with an interval of 0.01 year. In each trial, only one harmonic (i.e. N=1 in Equation (1)) with the given period or frequency was tested by using Equation (1). The amplitude and phase for each trial cycle was determined by using Equations (2) and (3). The predicted lake level was then calculated by using Equation (1) and the standard deviation of the prediction error, which is the difference between the predicted and measured lake levels, was also calculated. The cycles were determined or defined by examining the response of amplitudes and standard deviations as the frequency changed. The amplitude of the found cycles should be a maximum and the standard deviation should be a minimum if the cycle with the given period has a significant role in lake level fluctuations.

To verify the approach for finding cycles, the artificial data that were generated by using the three known cycles with periods of 30, 40 and 50 years and unit amplitudes were tested. The amplitude and standard deviation changes with period are shown in Figure 2.2. The largest amplitudes and smallest standard deviations were located exactly at the three known periods and therefore the three cycles were identified. In this way lake level cycles were identified.

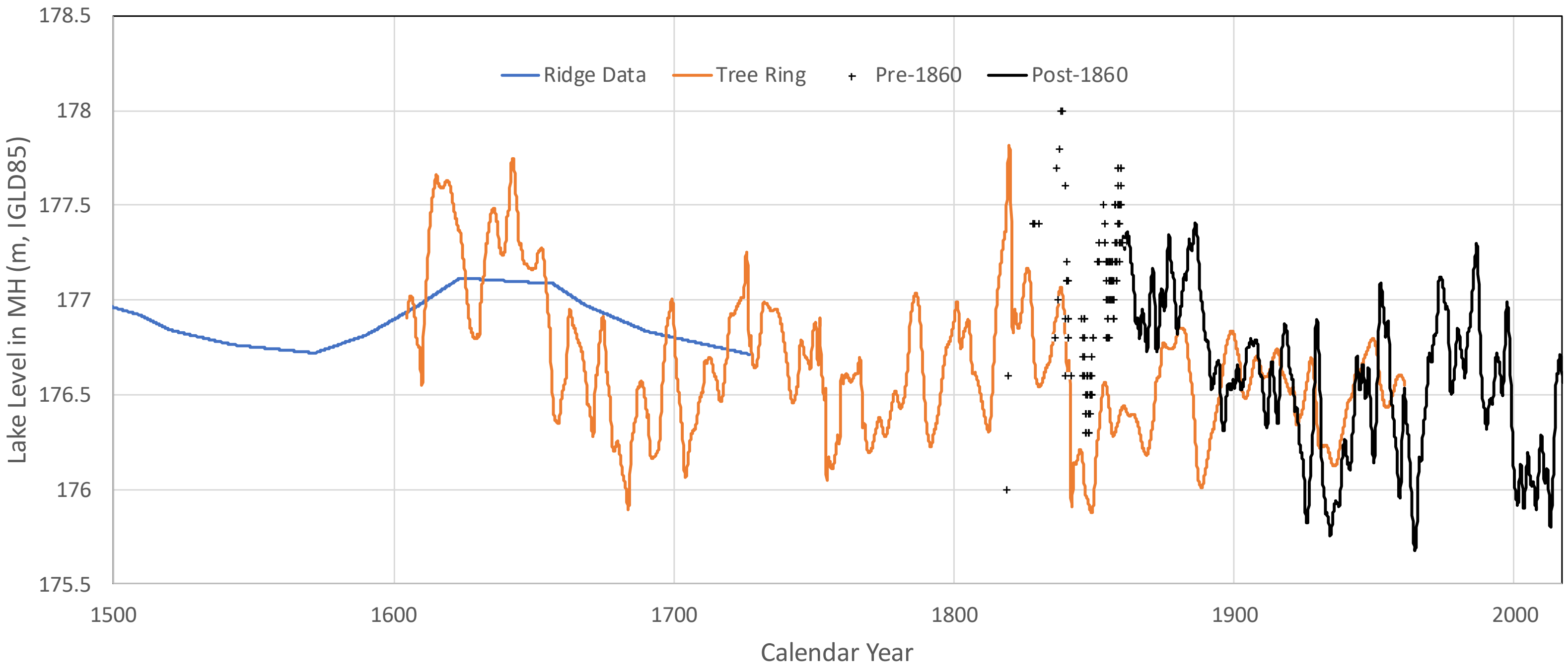

Figure 2.1: Comparison of lake levels in Lake Michigan-Huron from the different data sources.
The reconstructed water levels from tree ring data matched well with the multiple year average lake levels from 1910 to 1960 but had a significant offset when compared to the measured water levels from 1850 to 1900.

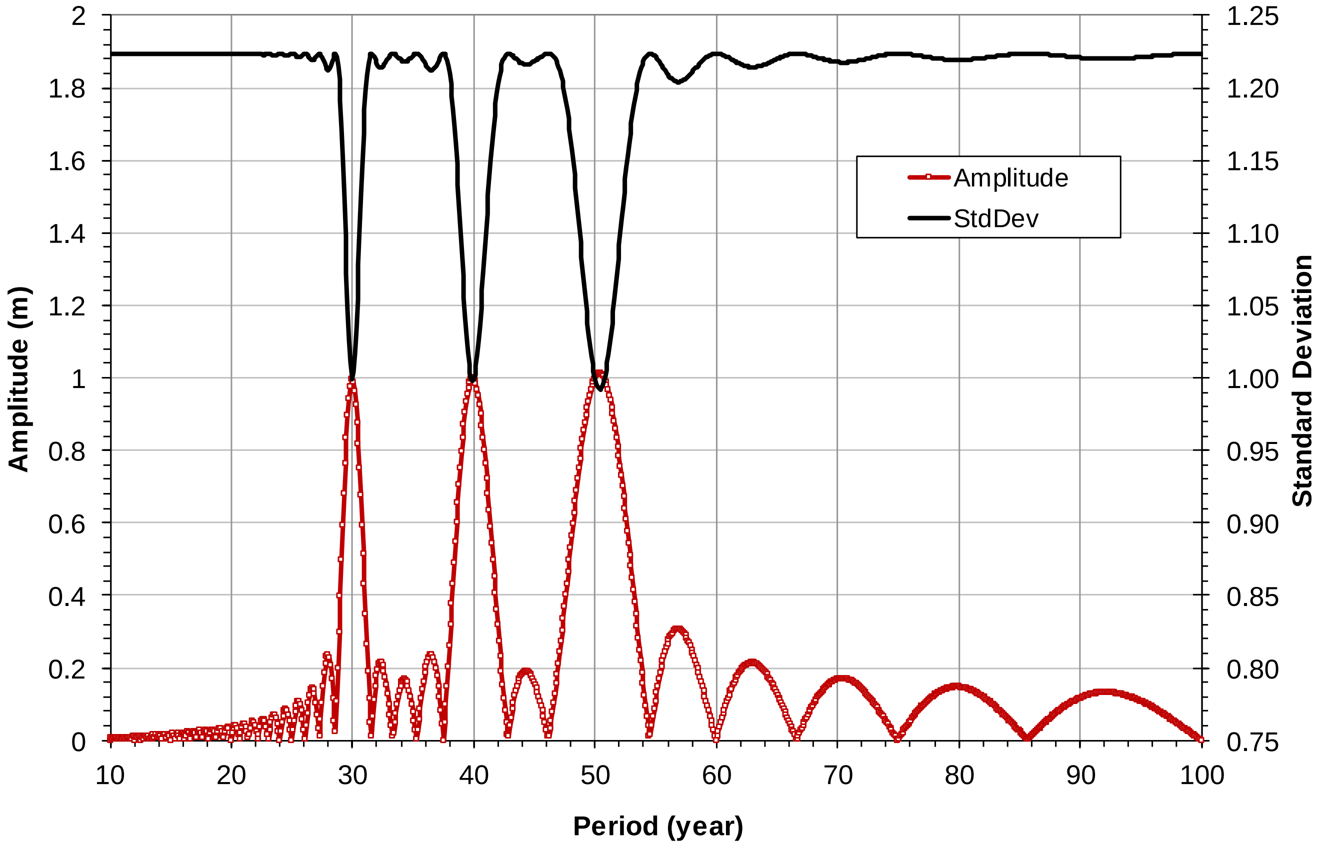

Figure 2.2: The variation of standard deviation (SD) and amplitude with period change using the data generated by the three known cycles (30 years, 40 years, and 50 years) for testing purposes.
Black line, the standard deviation of prediction error varied with period - the periods at the minima of standard deviations are the cycles found in the data; line with square dot, the amplitude variation with frequency- the frequencies at the maxima of amplitudes are the cycles found in data.

Using continuous monthly lake level data measured at the Cleveland gage on Lake Erie dating back to 1850, the analysis was completed to determine the major harmonic constituents with periods less than approximately 60 years. The recorded lake levels in Lake Erie are recognized to be the most representative of lake level fluctuation driven by the natural climates since the lake is not regulated and differential isostatic rebound at the outlet is small. This analysis was also completed for the paleo lake level records derived from Indiana Dunes beach ridges (Thompson and Baedke 1995 and 1997) and the reconstructed lake level data from tree-ring chronologies (Quinn and Sellinger 2006) to search for very low frequency cycles with periods from 60 to 500 years. Harmonic analyses of the NAO records (Hurrell and Van Loon 1997, Burns 2002, Ostermeier and Wallace 2003) from 1658 to 2001 and sunspot number data records (Gleissberg 1971, Siscoe 1978) from 1760 to 2005 were also examined to identify possible climate drivers for the cycles identified in the lake level data.

2.3 Determination of Amplitudes and Phases of the Identified Cycles

Using the major harmonic constituents found in the above analysis, the amplitudes and phases of these cycles (see Table 3.1) were then recalculated using Equation (1) for Lake Erie and Lake Michigan-Huron separately. Due to the geographical location of the two lake systems and regional variation of climate, the amplitude and phases of these identified cycles are expected to be different.

Without any data processing, the recorded lake level in Lake Erie was used to determine the magnitudes and phases of the identified cycles directly. The differential isostatic rebound in Lake Erie is 6-9 cm/century at the outlet (IJC 2000), which is small. The outlet at the Niagara River is recognized to be stable and no significant erosion of the river bed has been identified. The impact of human activities (such as water diversion) on Lake Erie is minimal. Therefore, the fluctuation of recorded lake levels in Lake Erie is directly representative of the natural variation of climate in the lower Great Lakes.

The recorded lake levels in Lake Michigan-Huron depict a decline since 1900, when compared to the trend of lake levels in Lake Erie. IJC (1987) identifies a permanent drop of lake level of about 41 cm (36 cm ~ 46 cm) caused by human activities, such as the Chicago diversion and the various Detroit/St. Clair River channel modifications through dredging. Recently, the erosion of the St. Clair River has been identified and this has contributed to an unrecoverable decline of lake level in Lake Michigan-Huron (Baird, 2005). These anthropogenic influences on lake level must be removed from the record of measured lake levels in order for the lake level fluctuation to represent natural climate variations. Therefore, the estimated permanent water level reductions caused by the human activities were added to the recorded lake levels as shown in Figure 2.3. The adjusted water levels were then used to determine the amplitudes and phases of the identified cycles by applying Equation (1). Note that the slope filter described by the second term in Equation (1) was also applied to account for the constant decline caused by the erosion in the St. Clair River bed.

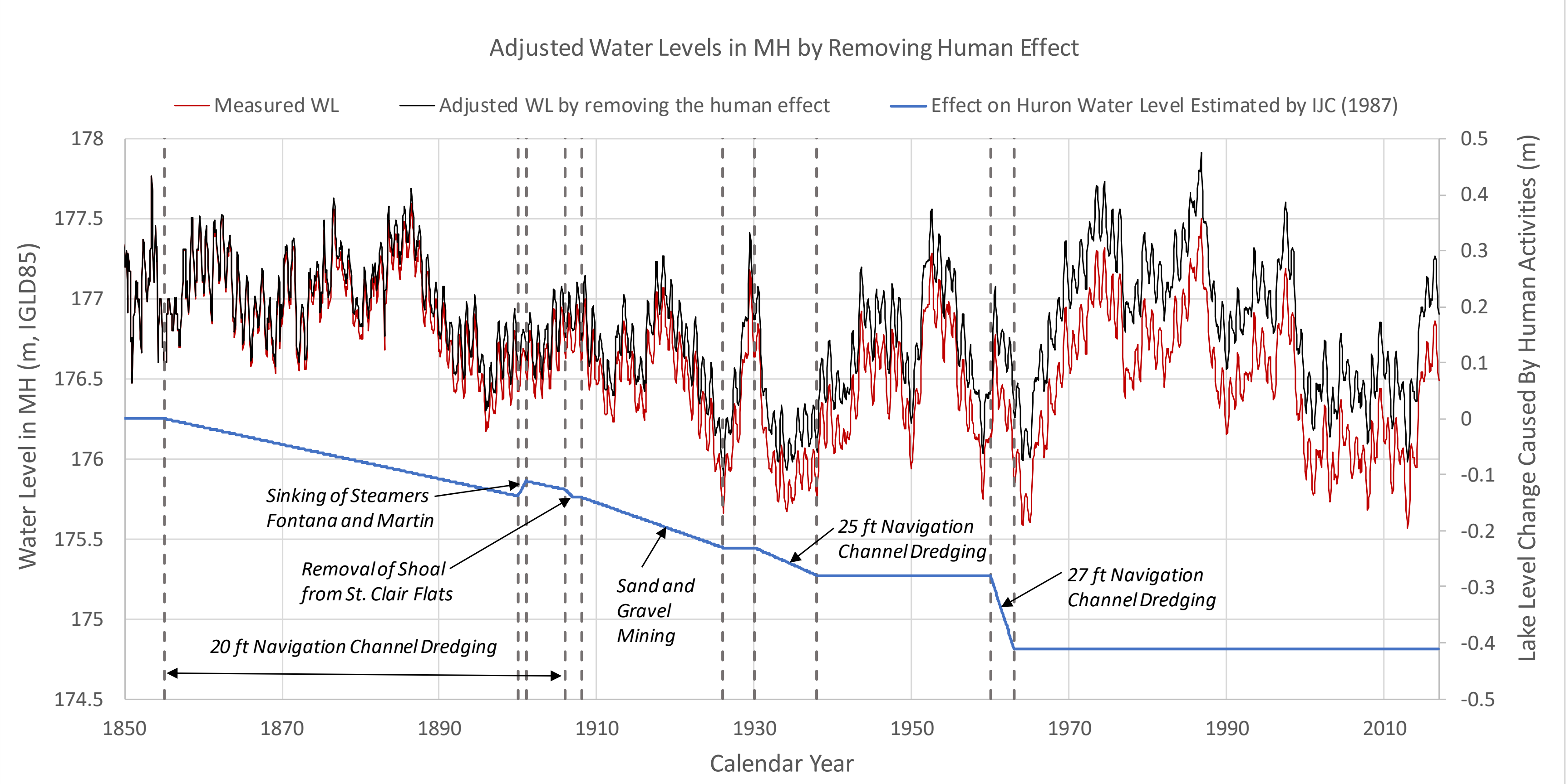

Figure 2.3: Adjustment of lake level data in Lake Michigan-Huron by removing the permanent lake level drops caused by human activities. Brown line, measured monthly-average lake level in Lake Michigan-Huron. Black line, lake level by removing the man-made lake level drop. Blue line, the permanent lake level drop or rise caused by human activities (IJC, 1987).

3. Results

There were 16 major cycles identified from the measured lake levels and the paleo lake level data (see Table 3.1). These major cycles are grouped into four quasi-periodic cycles: the 80-year sunspot quasi-periodic cycles; the 30-year precipitation quasi-periodic cycles; the 11-year sunspot quasi-period cycles, and the 4-year NAO and ENSO quasi-periodic cycles, plus the annual cycle. Of the sunspot cycles, it is generally accepted that the 11-year cycle is generally predictable with a period ranging from 10 to 14 years, but that longer cycles are less well understood, considered “quasi-periodic” and not reliably predictable (Usokin, 2017). Table 3.1 presents some of the “quasi-periodic” cycles that have been discussed previously in the literature, including the 33-year cycles determined from paleo lake levels (Thompson and Baedke 1995, Thompson and Baedke 1997). In these cases, the apparent “quasi-periodicity” is explained by a number of lake level cycles with similar periods (e.g. the 32 and 23-year cycles likely explain the quasi-periodic approximate 30-year cycle). The 11-year quasi-periodic cycle we found in the lake level data corresponds to the well-known 11-year sunspot cycle (Hathaway *et al.* 1994), which has also been implicated in fluctuations in the levels of Lake Victoria (Yousef *et al.* 2000), Lake Nyasa (Dixey 1924), and the Great Lakes of North America (Dawson 1874). The approximate 4-year cycle may be linked to the NAO and ENSO. The annual cycle of water level fluctuation on the Great Lakes, resulting from the earth’s orbit around the sun, is identified as the important cycle in terms of amplitude.

Table 3.1: Major Cycles Found in the Water Level Data for Lake Erie and Lake Michigan and Huron

Lakes	**Lake Erie**			**Lake MH**		
Mean Lake Level (m)	174.154			176.846		
Slope [a*(t-b)]	not included				-0.001	1935
Quasi-Period Cycles	**Period (year)**	**Amplitude (m)**	**Phase (deg)**	**Period (year)**	**Amplitude (m)**	**Phase (deg)**
80-year Sunspot Cycles	138.3	0.246	-154	115.7	0.252	-55
	59.2	0.091	-150	54.3	0.119	-162
	41.1	0.092	-107	34.4	0.199	108
30-year Precipitation Cycles	32.5	0.167	-10	27.3	0.069	-52
	22.9	0.133	-62	22.6	0.164	-113
	19.8	0.036	101	19.2	0.049	0
11-year Sunspot Cycles	14.4	0.062	43	14	0.097	43
	12.8	0.055	42	12.2	0.062	178
	11	0.096	-169	11.1	0.160	51
NAO Cycles	9.7	0.038	29	9.8	0.044	69
	8.3	0.045	-133	8.3	0.080	-114
	7.5	0.066	-111	7.8	0.079	169
	6.3	0.048	-117	7.5	0.060	-111
	5.5	0.032	-32	6.1	0.069	158
	5.3	0.039	14	5.8	0.058	168

Annual Cycle	1	0.191	-164	1	0.151	168

Some of the cycles we found are less well known. A 23-year cycle, which was found in the water level data for Lake Erie, significantly contributes to lake level fluctuations. This cycle matches a NAO index cycle and is likely related to the 22-year rainfall cycle found in many places (Yousef *et al.* 2000). Many cycles that we have found in the Great Lakes water level data were also observed in the Nile River levels (Kondrashov *et al.* 2005).

For the short-term variation of the lake levels, the 32-year, 23-year, 11-year, and annual cycles have the most important influence on the water level fluctuation of Lake Erie. These cycles appear to be due to the influence of NAO cycles, with the exception of the 11-year cycle which may result from the Schwabe sunspot cycle with the same period (Hathaway *et al.* 1994).

The selected cycles (see Table 3.1) were then used to predict the lake levels in the two lakes. We examined the ability of the harmonic lake level cycles to describe and predict lake level fluctuations for the 1850 to 2019 period using Equation (1) and the characteristic parameters listed in Table 3.1. Figure 3.1 and Figure 3.2 show a reasonable match between the calibrated predictions and the measured fluctuations of monthly average lake level for both Lake Erie and Lake Michigan-Huron, respectively. The correlation between the predicted lake levels and the measured lake levels for Lake Erie and Lake Michigan-Huron are shown in Figure 3.3 and Figure 3.4, respectively. The overall correlation between predictions and measurements from 1850 to 2019 is over 0.9, which indicates the prediction matches well to the measurements. The prediction errors are within a range of +/-0.27 m for Lake Erie and +/-0.30 m for Lake Michigan-Huron.

Provided that the cycles and trends that explain the fluctuations of Lake Erie and Lake Michigan-Huron for the last 166 years (and longer considering paleo data) continue, it is possible to predict future lake levels. In Figure 3.5 and Figure 3.6 we produce just such a prediction, extending several decades into the future, for Lake Erie and Lake Michigan-Huron, respectively. The figures also show the lower and upper limit of prediction errors with 95% confidence. If our analysis is correct and provided that climate change does not influence these cycles (which appear to be predominantly solar influenced), the lake levels in both lakes are entering a low and declining period that will persist until approximately 2035.

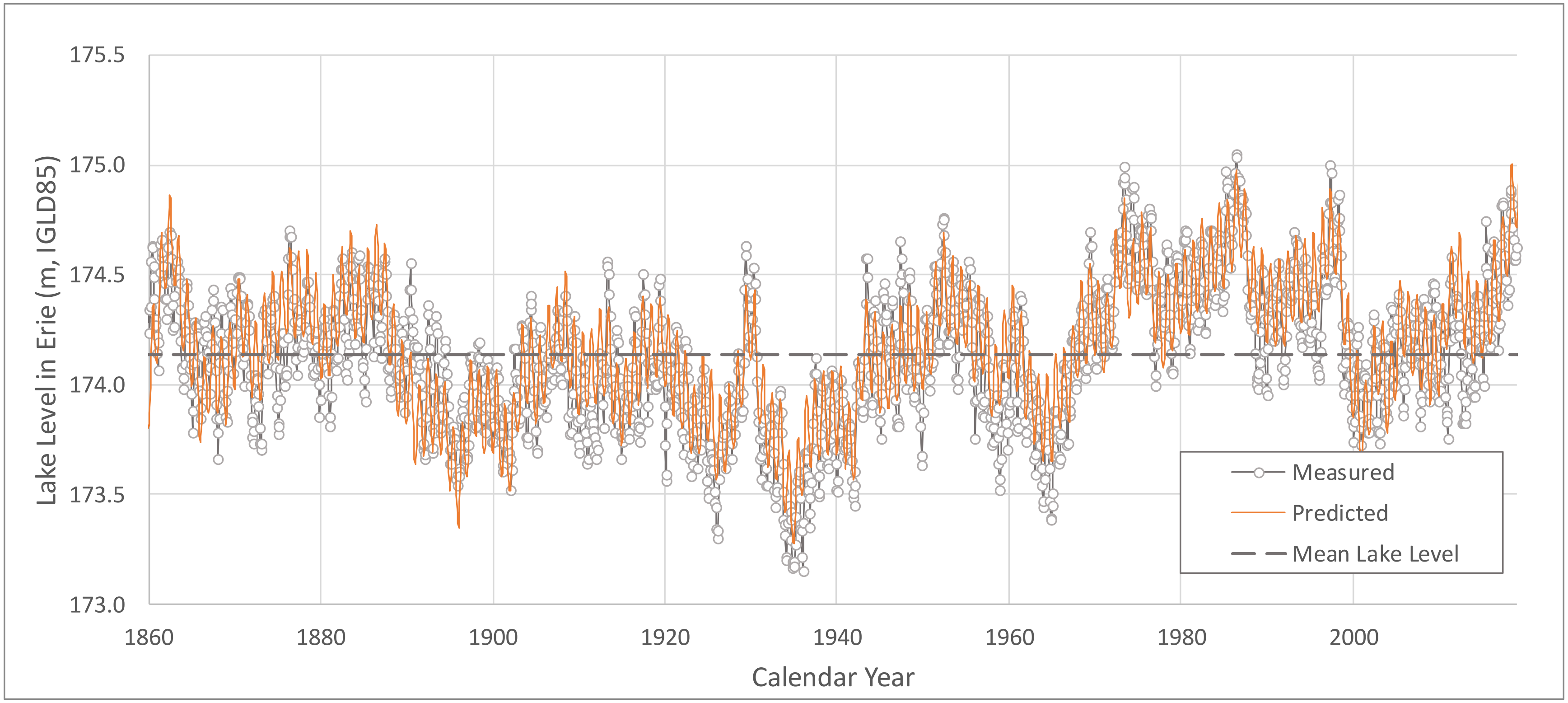

Figure 3.1: Comparison of predicted and measured monthly-averaged lake levels in Lake Erie for the calibration period (1850-2019). Solid line, the predicted monthly-averaged lake levels. Grey line with dot, measured monthly-average lake levels. Grey dash line, mean lake level.

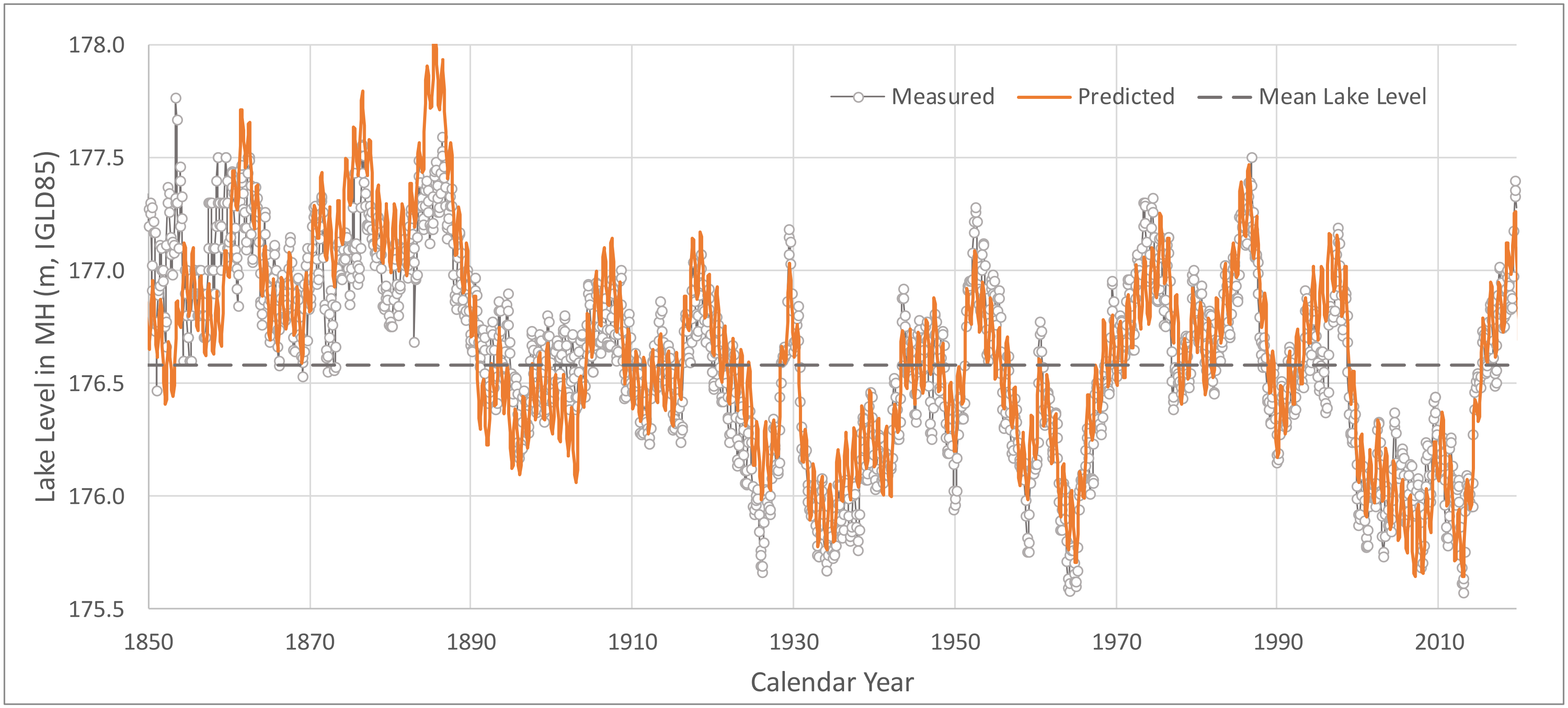

Figure 3.2: Comparison of predicted and measured monthly-averaged lake levels in Lake Michigan-Huron for the calibration period (1850-2019).
Solid line, the predicted monthly-averaged lake levels. Grey line with dot, measured monthly-average lake levels. Grey dash line, mean lake level.

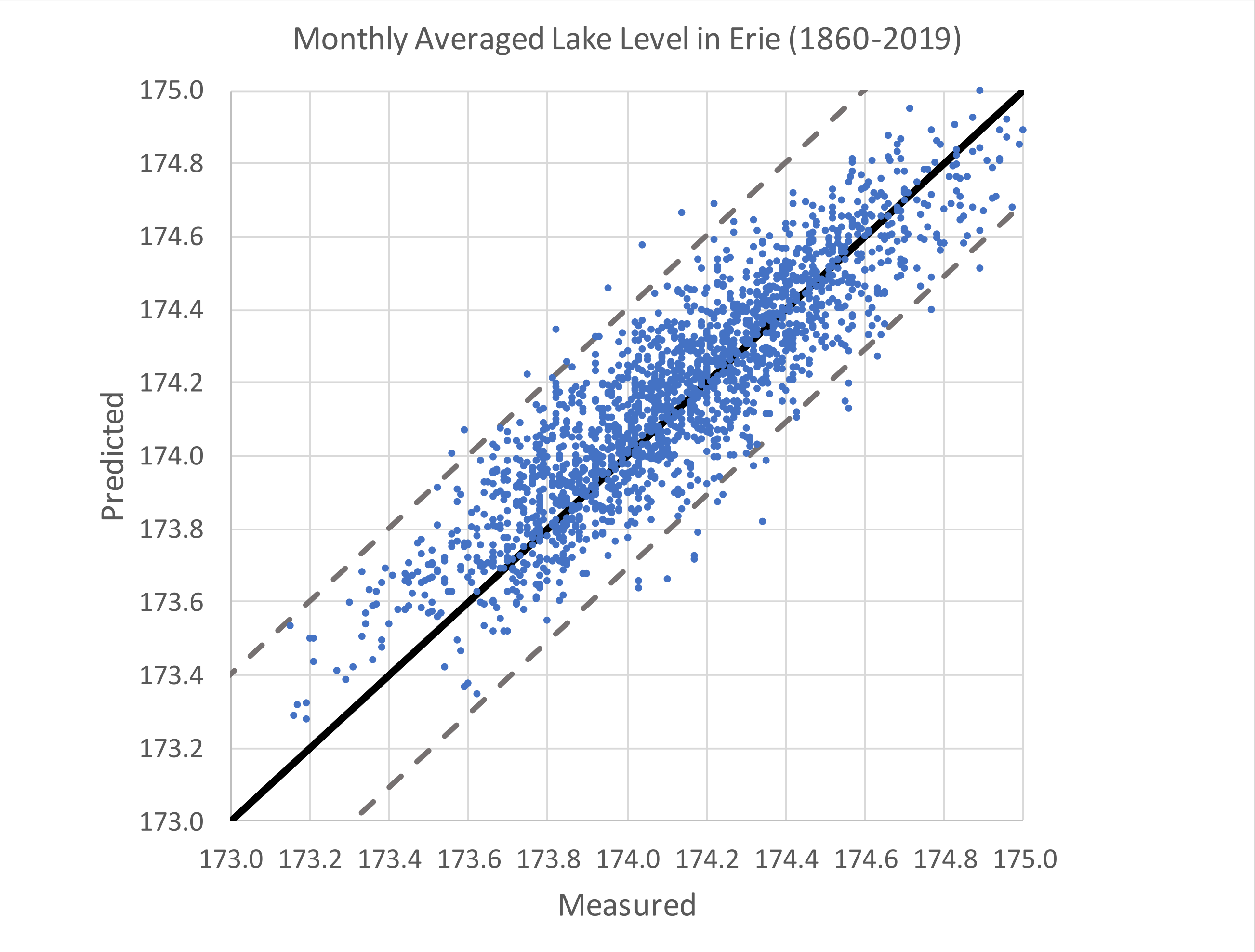

Figure 3.3: Correlation of measured and predicted monthly mean lake levels in Lake Erie.
Blue dot, the positive and negative correlation of prediction against the measurement. Back solid line, the line with no prediction error. Grey dash line, the lower and upper limit with 95% confidence.

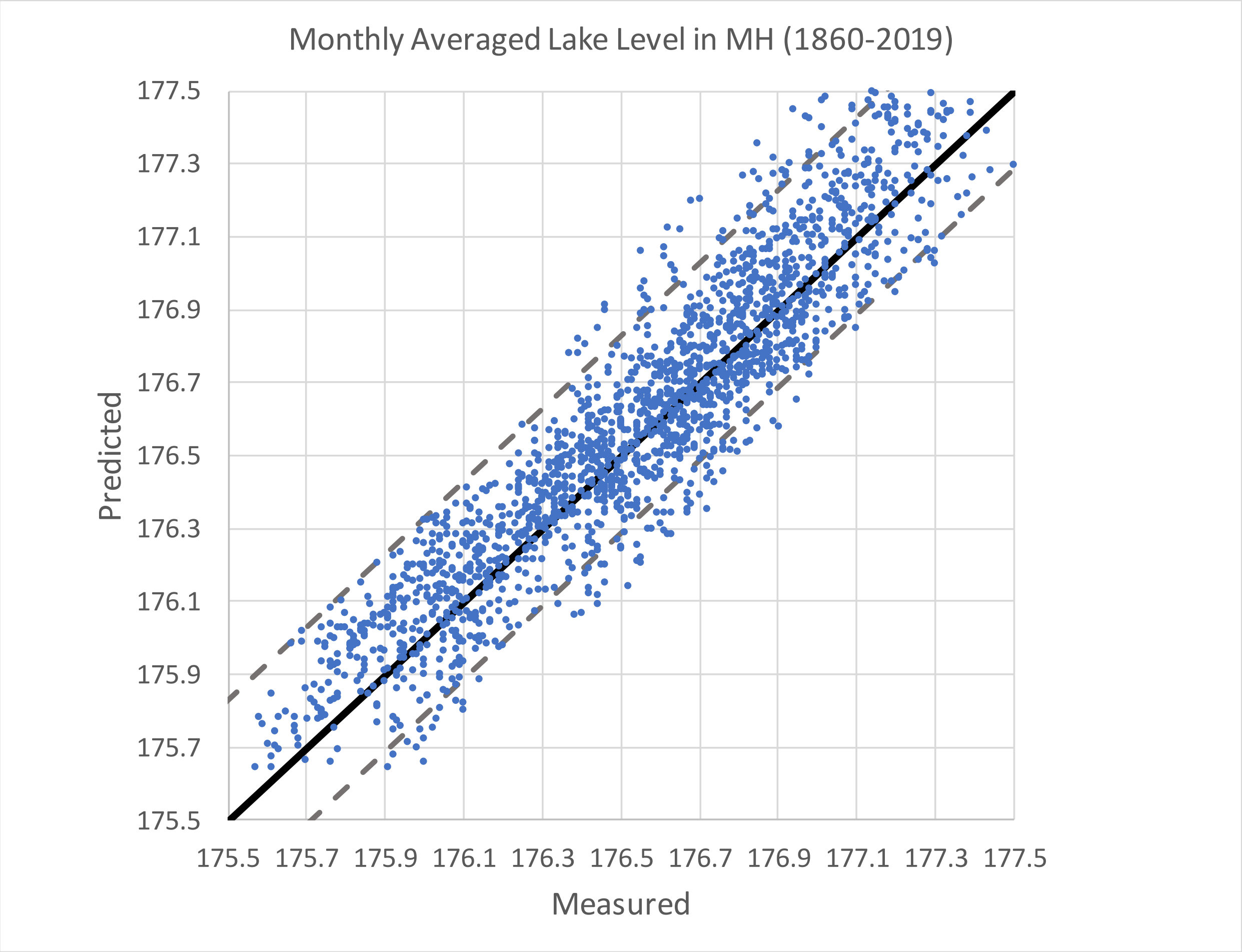

Figure 3.4: Correlation of measured and predicted monthly mean lake levels in Lake Michigan-Huron.
Blue dot, the positive and negative correlation of prediction against the measurement. Back solid line, the line with no prediction error. Grey dash line, the lower and upper limit with 95% confidence.

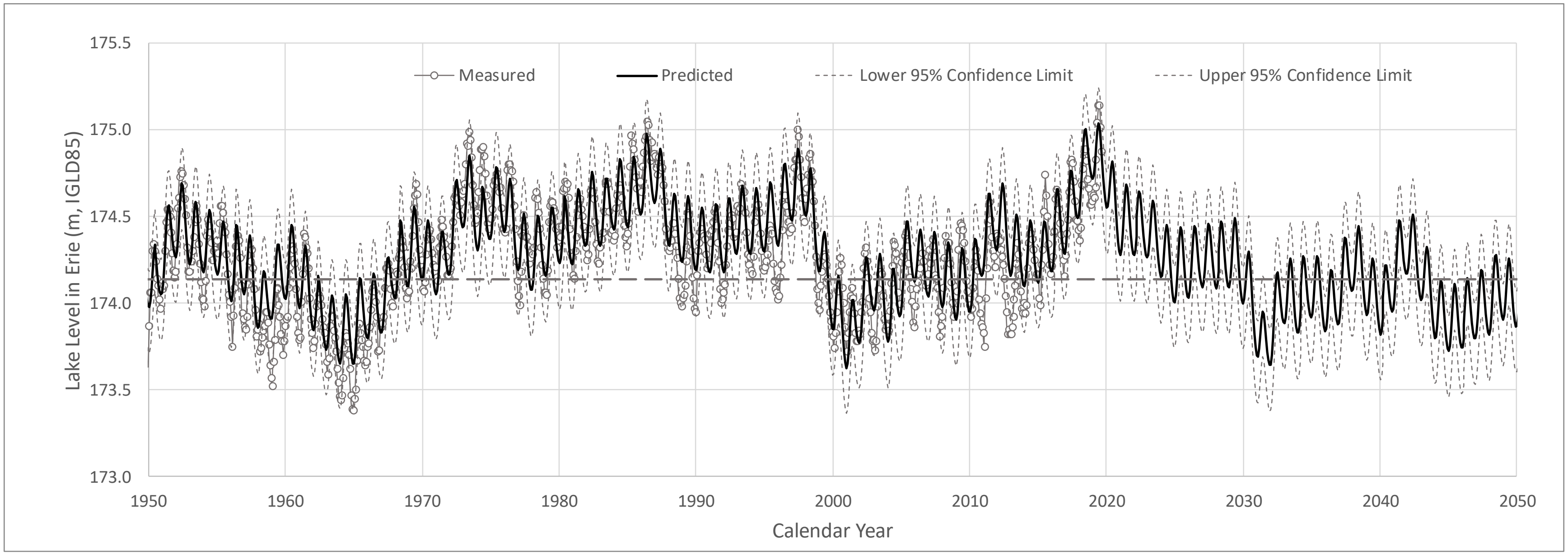

Figure 3.5: Predicted monthly mean lake levels in Lake Erie (1950-2050).
Solid line, the predicted monthly mean water level. Grey solid line with dot, measured monthly mean water level during calibration period (1950-2019). Grey dash line, lower and upper limit of prediction with 95% confidence. Grey dash thick line, mean lake level.

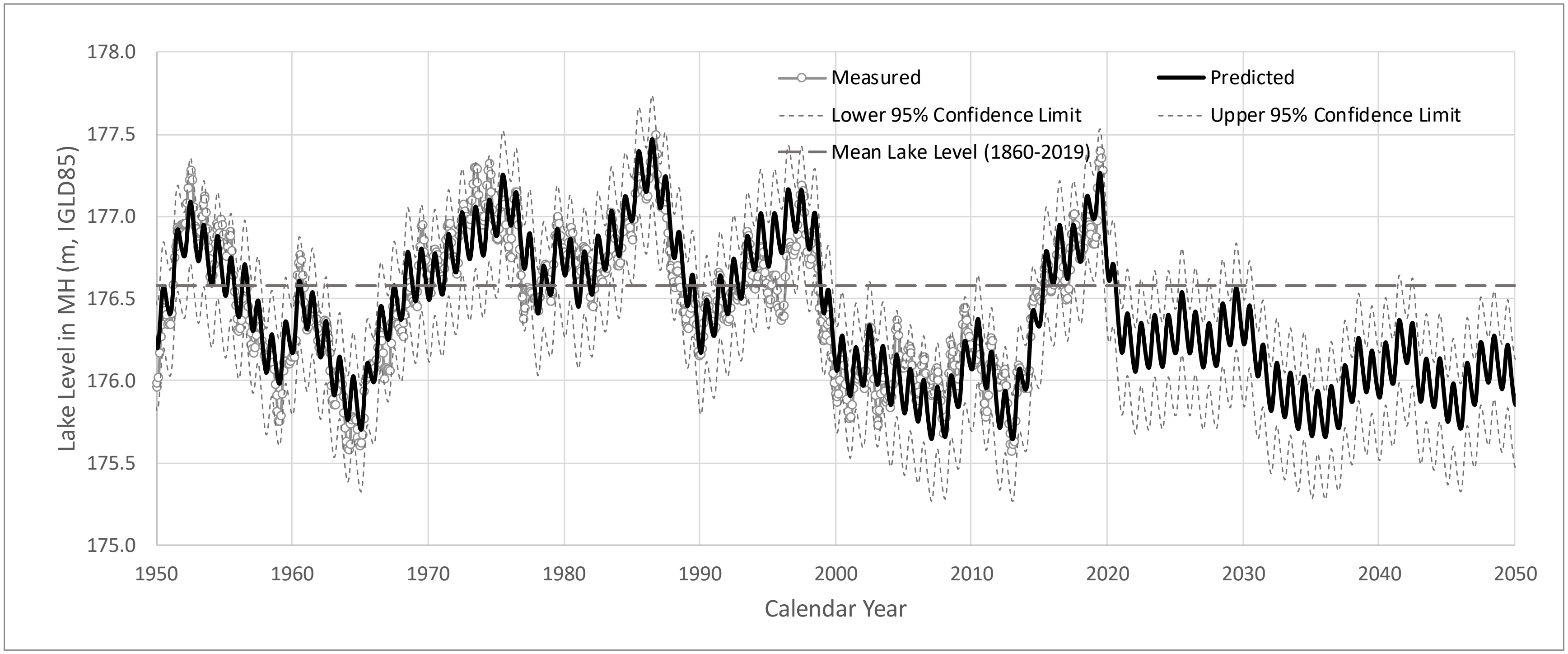

Figure 3.6: Predicted monthly mean lake levels in Lake Michigan-Huron (1950-2050).
Solid line, the predicted monthly mean water level. Grey solid line with dot, measured monthly mean water level during calibration period (1950-2019). Grey dash line, lower and upper limit of prediction with 95% confidence. Grey dash thick line, mean lake level.

4. Discussion

The ability to predict the fluctuation of the Great Lakes will greatly improve management and planning for navigation and dredging, commercial shipping and recreational boating, erosion and flooding, power generation and ecological restoration. The apparent link to climate drivers such as sunspot number and NAO index cycles suggests that climate trends, at least in terms of integrated influences on evaporation and precipitation, are predictable, and this has much wider implications to planning and management of many sectors unrelated to the lakes including the agriculture and insurance sectors.

To better understand how these climate drivers influence lake level fluctuation, Figure 4.1 to Figure 4.4 show the predicted water levels in Lake Michigan-Huron considering selected individual cycles. From these figures, the low lake level event that occurred in 1935 resulted from a combination of minima associated with the 160-year, 30-year, 11-year, and 4-year quasi-periodic cycles. The high lake level events that occurred in 1975 and in 1986 resulted from a combination of the 160-year quasi-periodic cycle peak with the peaks of other quasi-periodic cycles. Currently, the Great Lakes levels are entering a declining period of the 160-year quasi-periodic cycles, and are predicted to reach a minimum in approximately 2035. The recent high lake level appears to result from a combination of the peaks of 30-year precipitation cycles, the 11-year sunspot cycles, and the 4-year NAO and ENSO cycles. The lake level is expected to be low in the next decade.

It is important to understand the change in prediction errors with forecast horizon. Using the recorded lake levels from 1850 to 2016, the developed forecast model was run by changing the model training duration, in which the measured lake levels were used to determine the amplitudes and phases of the cycles, and the prediction horizon, in which the measured lake levels were used to evaluate the prediction errors. For example, with the forecast period of 10 years, the model was trained by using the measured lake levels from 1850 to 2006. The model was then used to predict the water level from 2007 to 2016 and the prediction error was calculated as the mean absolute error (MAE) and the root of mean square error (RMSE). The result is shown in Figure 4.5. Unlike an operational weather forecast model, the prediction error of this harmonic analysis approach does not increase significantly with forecast horizon.

The prediction was further checked to examine the patterns of lake level fluctuation in Lake Erie and Lake Michigan-Huron. Based on the recorded lake levels in both lakes from 1850 to 2016, the fluctuation of lake levels in Lake Michigan-Huron features the same patterns as the fluctuations in Lake Erie but the magnitude of the lake level variation in Lake Michigan-Huron is larger than in Lake Erie. This implies that the water levels in both lakes were driven by similar climates. Figure 4.6 shows similar patterns of forecast lake level fluctuation from 2019 to 2050 for the two lake systems.

With harmonic analysis, the maximum period of a cycle that can be detected depends on the length of recorded lake levels employed in the analysis. The lowest frequency for which amplitude and phase can be reliably determined from the available time series data for Michigan-Huron and Erie is about 160 years. Lower frequency or longer period cycles have been derived indirectly from approximate paleo cycle data. The magnitude and phase for cycles with frequencies larger than 160 years are less reliable. Therefore, this may result in some inaccuracy in terms of the timing of predicted lake level trends, and caution should be exercised when using the prediction results.

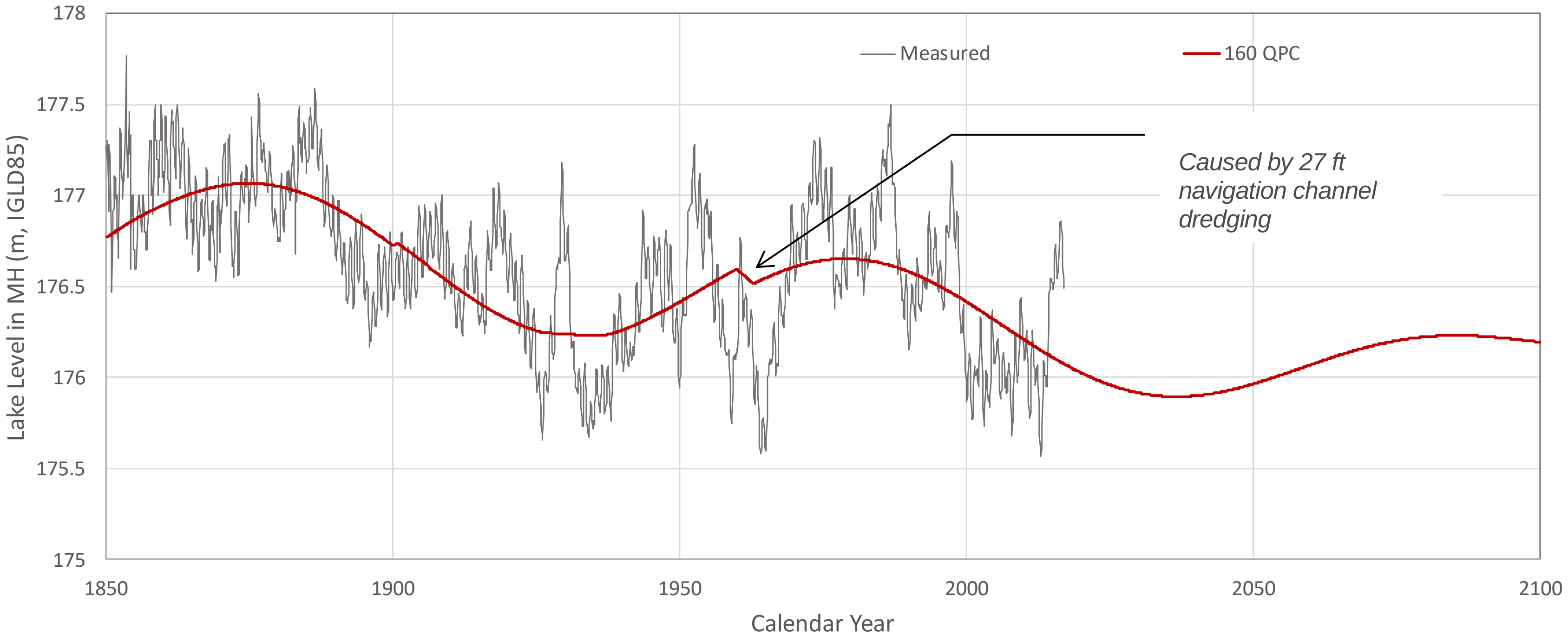

Figure 4.1: Comparison of measured annually-averaged lake level in Lake Michigan-Huron with lake levels predicted by using the 160-year quasi-periodic cycles.
Black thin line, measured lake level. Red line, predicted lake level with portion of cycles.

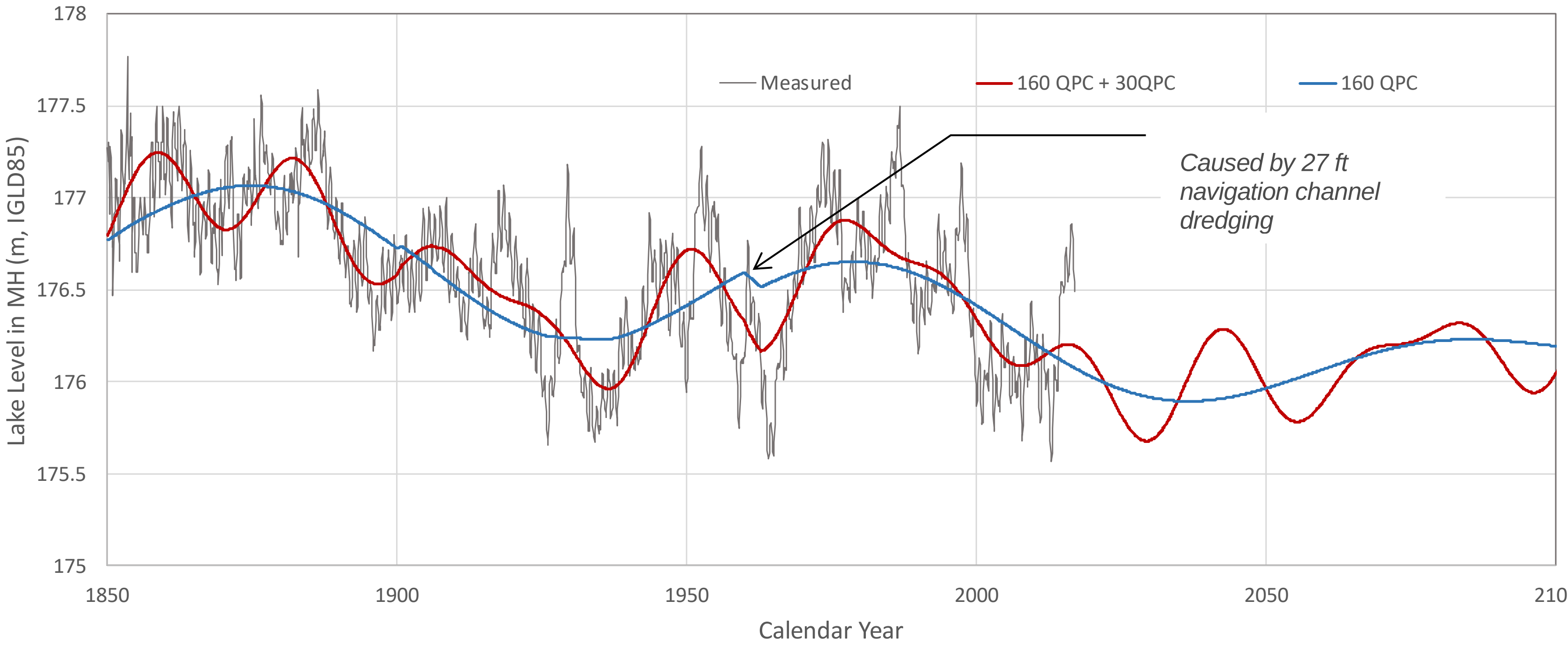

Figure 4.2: Comparison of measured annually-averaged lake level in Lake Michigan-Huron with lake levels predicted by using the 160-year quasi-periodic cycles and the 30-year quasi-periodic cycles.
Black thin line, measured lake level. Red and blue lines, predicted lake level with portion of cycles.

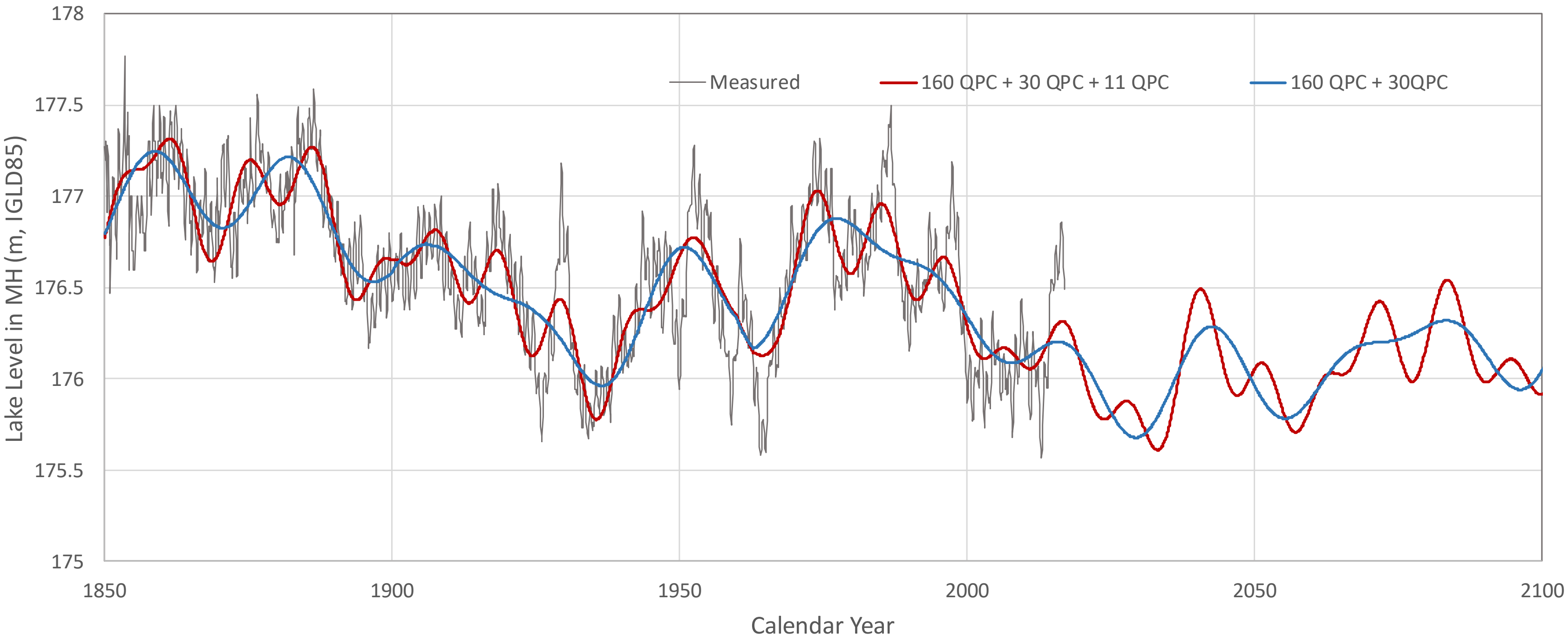

Figure 4.3: Comparison of measured annually-averaged lake level in Lake Michigan-Huron with lake levels predicted by using the 160-year quasi-periodic cycles, the 30-year quasi-periodic cycles, and the 11-year quasi-periodic cycles.
Black thin line, measured lake level. Red and blue line, predicted lake level with portion of cycles.

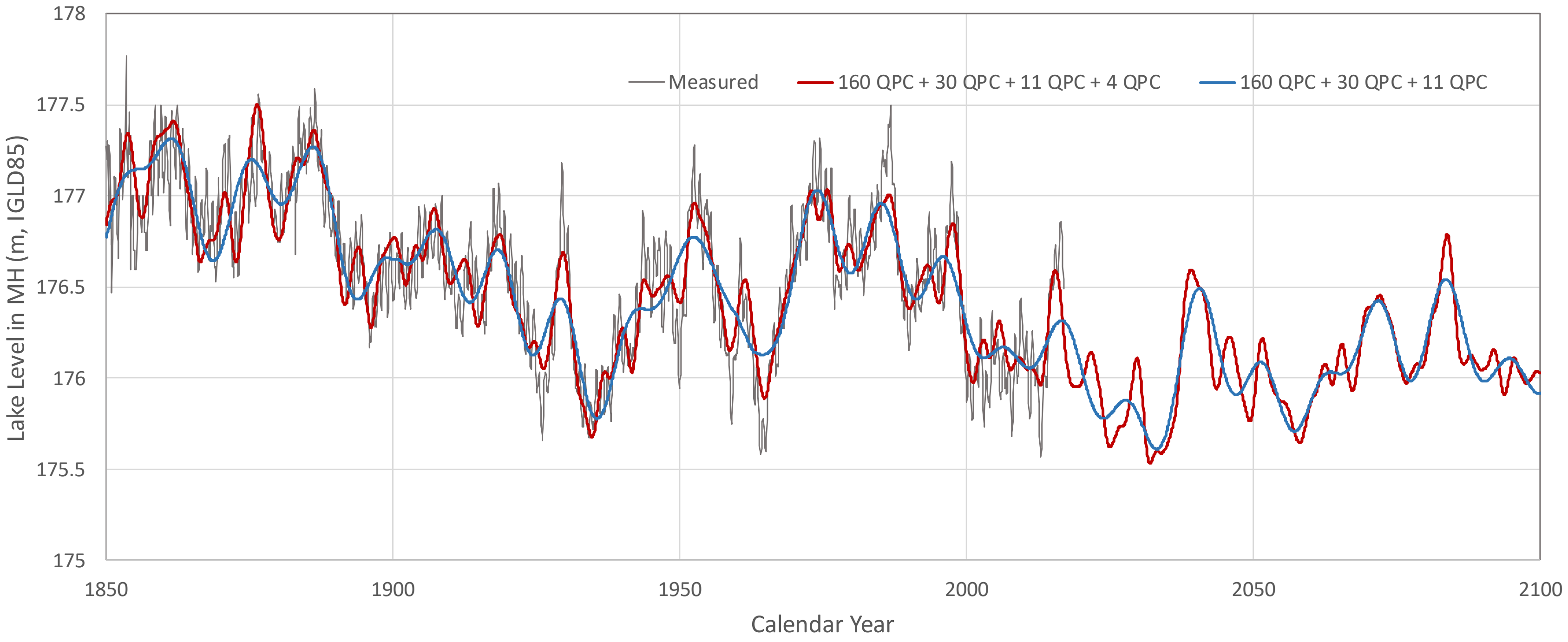

Figure 4.4: Comparison of measured annually-averaged lake level in Lake Michigan-Huron with lake levels predicted by using the 160-year quasi-periodic cycles, the 30-year quasi-periodic cycles, the 11-year quasi-periodic cycles, and the 4-year quasi-periodic cycles. Black thin line, measured lake level. Red and blue line, predicted lake level with portion of cycles.

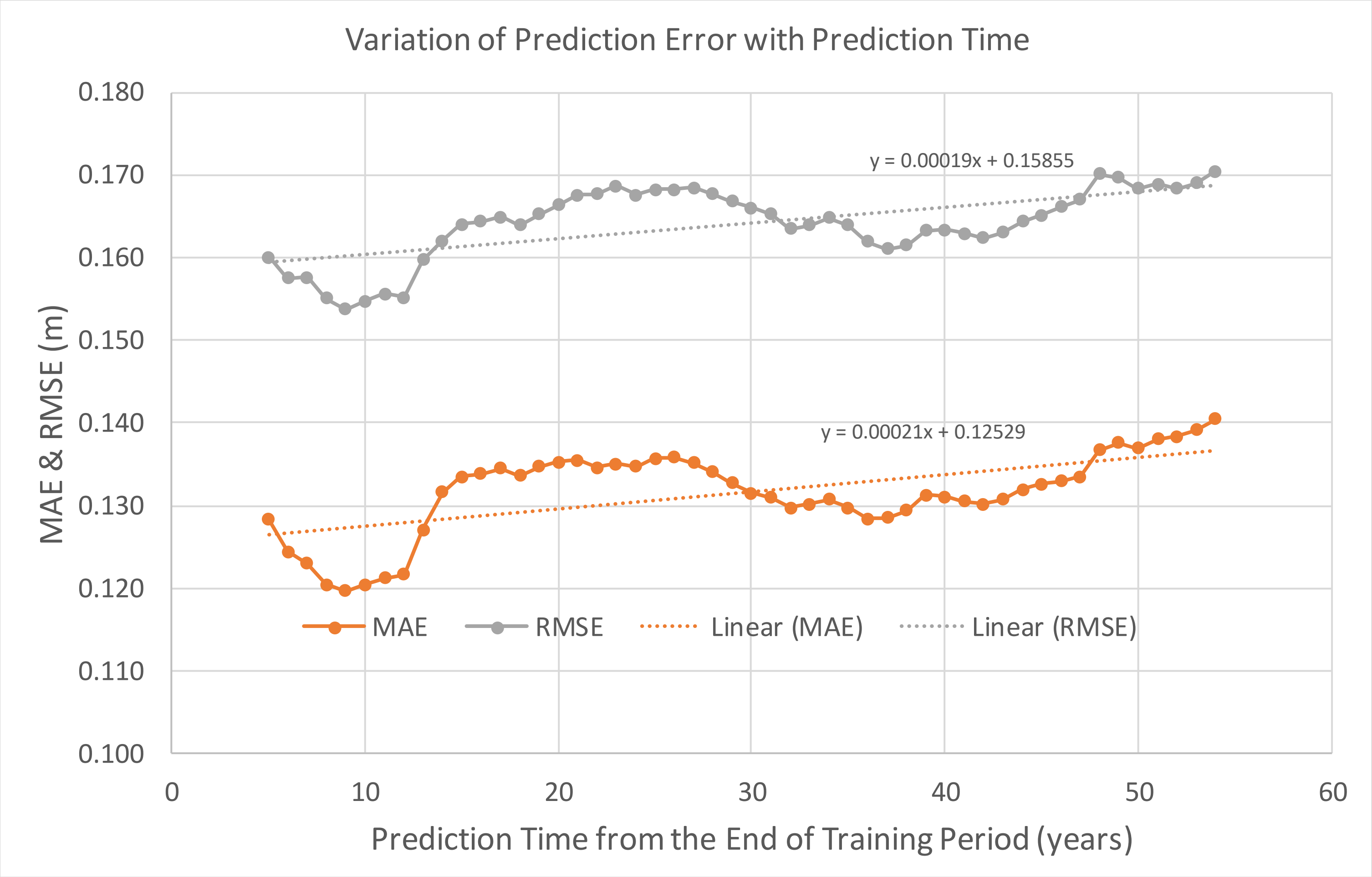

Figure 4.5: Variation of prediction errors with forecasting time.
Grey line with dot, the root of mean square error (RMSE). Orange line with dot, mean absolute error (MAE).

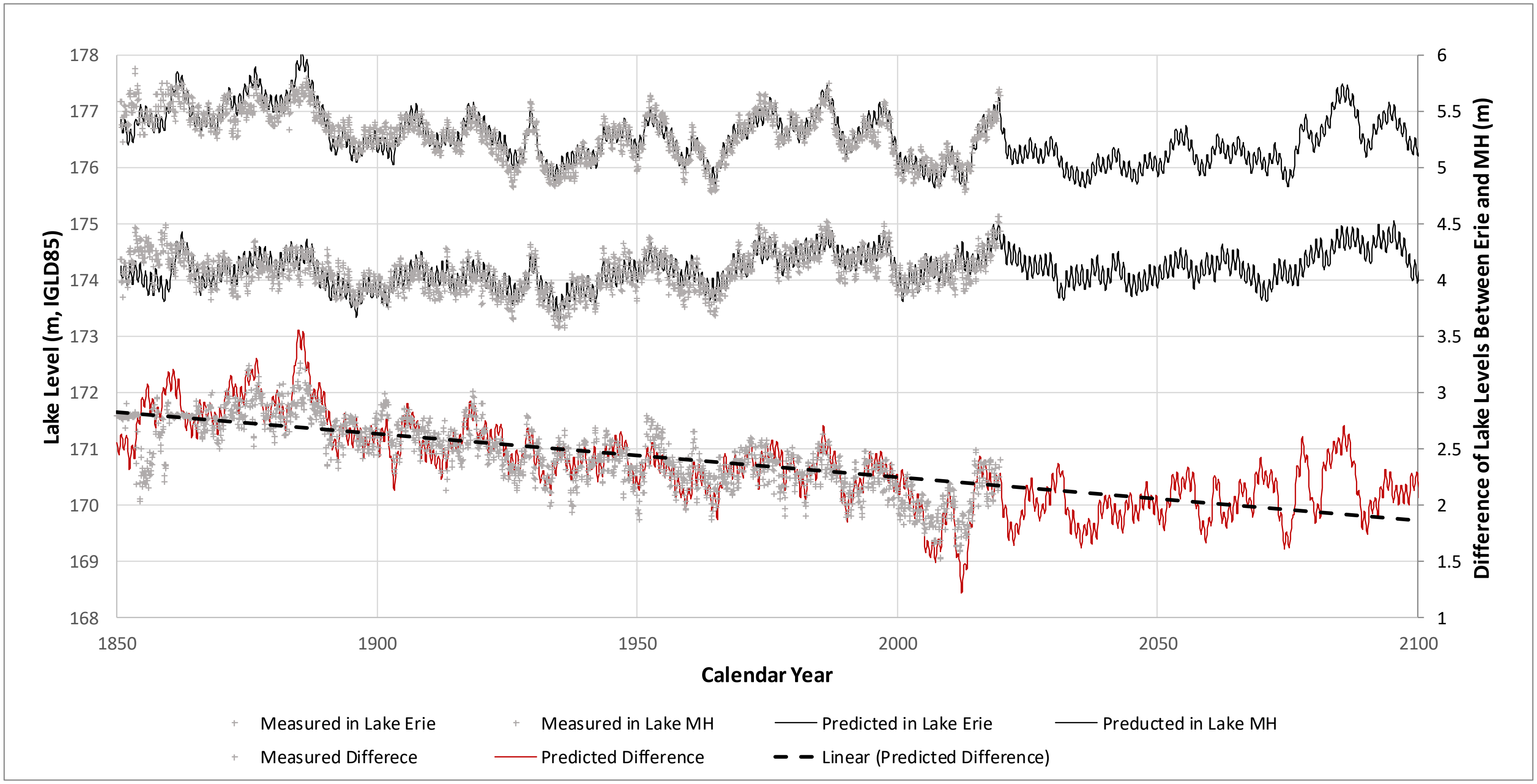

Figure 4.6: Comparison of lake level fluctuation patterns in Lake Erie and Lake Michigan-Huron.
Black lines, predicted lake levels. Grey plus (+) symbols, measured lake levels. Brown line, the difference of predicted lake levels between Lake Michigan-Huron and Lake Erie. Grey plus (+) symbols, the difference of measured lake levels between Lake Michigan-Huron and Lake Erie.

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Acknowledgements. The authors wish to acknowledge the fund provided by Georgian Bay Great Lakes Foundation and the review provided by Dr. Doug Scott.

Author Contributions. Dr. Lu was responsible for the harmonic analysis. Dr. Nairn and Dr. Lu pursued and developed the concept that harmonic constituents can describe and be used to predict lake level fluctuations, and that these may be linked to sunspot number and NAO cycles.

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Appendix A

Methods to Filter the Slope

The mean lake level (z_0) in Equation (1) is determined by using the monthly lake level records, i.e.

$$z_0 = \frac{1}{M}\sum_{i=1}^{M} z_i \tag{4}$$

where M is total lake level records, and z_i is the measured lake level.

The slope coefficient (α) and initial time (t_0) in Equation (1) were determined by using regression analysis, i.e.

$$\begin{aligned} \alpha &= \frac{\sum_{i=1}^{M} z_i \bullet \sum_{i=1}^{M} t_i - M\sum_{i=1}^{M}\left(z_i \cdot t_i\right)}{\left(\sum_{i=1}^{M} t_i\right)^2 - M\sum_{i=1}^{M} t_i^2} \\ t_0 &= \frac{1}{M}\left(\sum_{i=1}^{M} z_i - \alpha\sum_{i=1}^{M} t_i\right) \end{aligned} \tag{5}$$

where t_i is time at the i-th lake level record in Calendar year.

Three facts on which the harmonic analysis is based are: 1) the average value of all sample data must be zero. In the long run, the average value of any function of the form sin(ωt) or cos(ωt) must be zero. This is clear from looking at the graphs of these functions, i.e. each positive contribution to the average is exactly cancelled by a negative one. 2) The average value of any product $\cos(\omega_i t) \bullet \cos(\omega_j t)$, $\cos(\omega_i t) \bullet \sin(\omega_j t)$, $\sin(\omega_i t) \bullet \cos(\omega_j t)$, and $\sin(\omega_i t) \bullet \sin(\omega_j t)$ where $i \neq j$ must be zero. The reason is that in the long run the times when the two functions are out of phase (so the product is negative) will cancel the contributions from the times they are in phase. 3) The average of $\cos^2(\omega_i t)$ or $\sin^2(\omega_i t)$ is equal to ½ if the averages are taken over longer and longer time intervals. First of all, in each case the two factors are always in phase, in fact equal, so their product is always either the square of a positive number or the square of a negative number, or zero, but in any case, never negative, so there can be no cancellation. Since the graphs of the sine function and the cosine function are so similar, we can expect that in the long run sine-squared and cosine-squared would have the same average. On the other hand, the basic trigonometric identity $\cos^2(\omega_i t) + \sin^2(\omega_i t) = 1$, which holds everywhere must hold for the averages as well. Since the two averages are equal, and add up to one, they must each equal 1/2.