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**Temporal Behavior of the Levels of Middle
and Upper Great Lakes Reveals Major Space
and Time Climate Differences
During 1861-2001**

by
Stanley A. Changnon and Jonathon Burroughs

December 2003



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Abstract

Levels of Lakes Superior, Michigan-Huron, and Erie were assessed to identify key temporal fluctuations in their averages and extreme values during the 1861-2001 period. Behavior of levels of Lakes Michigan-Huron and Superior since 1861 has included vastly different long-term distributions, differences in amount of variability over time, and differences in occurrence times of their record-high and low levels. Record high or low 15-year periods were present on one or more lakes in 64 years, and record events based on 25-year periods were present in 96 of 141 years, both representative of records during a much longer period than if the record events had occurred simultaneously on all lakes. These lake-level differences reflect significant differences in climate conditions between basins, and principally precipitation over time. There were two eras when levels of all lakes exhibited exceptional variability and extreme high and low levels, 1923-1938 and 1973-2001, reflecting considerable climatic instability over the entire Great Lakes basin.

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Introduction

Water levels of the Great Lakes remain one of the never-ending key issues in the Great Lakes basin. The levels are constantly changing, including the frequent setting of records for extreme levels and rates of change, and have been a subject of deep concern for more than 100 years (Changnon, 1990). Various stakeholders in the lakes over time have become more sensitive to lake-level fluctuations (Horvath et al., 1988). Record high lake levels in the mid-1980s led the United States and Canada to conduct a major water-levels reference study, considering possible ways to ameliorate the impacts of fluctuating water levels (Water Supply and Technology Board, 1989). Extensive damages from record-high levels and ensuing inundation of facilities and the erosion of shorelines and properties were estimated to range from \$62 million to \$72 million (1992 dollars) per year (Working Committee 2, 1993). During 1985-1987, private persons and the two governments spent \$102 million (1992 dollars) on shore protection facilities. Low water damages to recreational facilities were estimated at \$1.2 million.

During the 19th Century and early decades of the 20th Century, there was uncertainty over the importance of the various factors controlling the lake levels, a situation that led many to suspect that the diversion of lakewaters at Chicago during 1898-1930 was the major cause for the simultaneous lowering of Lakes Michigan, Huron, and Erie (Changnon and Changnon, 1996). Robert E. Horton, a famed hydrologist, issued the first adequate and widely accepted scientific analysis of the factors affecting lake-level fluctuations (Horton and Grunsky, 1927). That assessment was done to help resolve a multi-decadal legal controversy resulting from 1) a long decline in the level of Lake Michigan, and 2) the diversion of lakewaters at Chicago, seen by many as the cause of the decline (Changnon and Changnon, 1996). Horton and Grunsky's assessment made clear the singular role of climate as the major factor controlling lake levels at any given time, along with the amount of inflow from upstream lakes (another climate-controlled factor), and the amount and rate of outflow from the lakes. Scientific knowledge of climate behavior also was evolving, revealing that the climate of the Great Lakes basin included short-term (1- to 2-year) fluctuations, mid-term oscillations (2- to 25-year), and longer term (multi-decadal-century scale) trends (Day, 1926; Bruce and Rodgers, 1962).

In addition to long-term climate-driven fluctuations, there are three other types of lake-level fluctuations. Weather extremes cause short-term fluctuations that can last from a few hours to a few days (e.g., storm surges and seiches). A second type is the regular seasonal fluctuation reflecting the annual hydroclimatic cycle from summer's high levels to winter's low levels. The third type of fluctuations result from the artificial regulation of lake levels by control works at the outlets of Lakes Superior and Ontario. The slow crustal movement of the Earth' surface is upwards across the basin, and it also slowly lowers lake levels over time.

More than 40 million people reside in the basin. Urban development along U.S. shorelines accounts for 15 percent (Lake Superior) to 58 percent (Lake Erie) of the shoreline. Fluctuating water levels affect virtually every aspect of life in the Great Lakes basin either directly or indirectly (Horvath et al., 1988). Thus, those living around the lakes, and those using them for various purposes, including shipping, all have considerable economic and/or environmental interests in lake levels. The deep interest of this huge constituency has led to various efforts to try to control the lake levels. Water flow control works were built to help control the outflows from Lakes Superior and Ontario (U.S. COE, 2000). Alteration of connecting channels between Lakes Huron and Erie for navigation and other reasons has changed flows, and hence lake levels. Since the 1900s, there have been repeated efforts to limit the amount of water diverted from Lake Michigan at Chicago (Changnon and Changnon, 1996). During the 1940s, water was added to Lake Superior by diverting water flowing into the Hudson Bay basin into two Canadian rivers that empty into the lake.

Regardless of the settings of these human-made control works and drainage changes, climate is the primary determinant of lake levels. Thus, the lake levels are a “climate indicator,” reflecting both short- and long-term climatic conditions (Brinkmann, 1984). Groundwater inflow to the lakes reflects historic climatic conditions, whereas streamflow into the lakes is largely a result of the climate conditions of the past 3-24 months, primarily precipitation over the basin and evaporation from the lakes (Brunk, 1959). Evaporation rates reflect temperatures and air flow over the lakes, and represent 30 percent of the water lost from Lakes Michigan-Huron (U.S. COE, 1991).

Impacts of Water-Level Extremes

Major fluctuations in lake levels exert both adverse and beneficial impacts. Hence, concerns about lake levels fall into two classes: those interested in having high levels and those interested in or concerned about lower lake levels. In general, lake interests have learned to accommodate normal seasonal fluctuations, but problems come with climate-driven, multi-year and longer fluctuations. The primary physical impacts of water-level extremes are flooding, erosion, and environmental damages.

Those who favor high lake levels are shippers and ports, water-supply interests, and hydroelectric generators along connecting rivers. Shoreline damages result from flooding and erosion when levels are high, and concurrent major storms produce added damages as they lead to sudden high water levels on shores downwind of strong, persistent winds. Shoreline facilities, including lake-side residences and businesses, favor lower lake levels that minimize shoreline erosion and flooding (Changnon, 1987). However, extremely low levels expose submerged structures to air, which may result in deterioration, and often restrict access to harbors and piers, which affects shipping. Low lake levels have detrimental impacts on fish and wildlife, and either extremely high or low levels hurt recreational boating. The net result is a conflict of interests that no lake level can satisfy.

Extensive damages from high levels during 1985-1987 led to calls for increasing outflows at Chicago, which was opposed by downstream interests, who feared high water damages along the rivers (Changnon, 1987). Conversely, the 1988-1989 drought drastically reduced river flows in the Mississippi River basin, and drought-stricken interests sought added diversion of lake water at Chicago to sustain river levels, a situation resisted by lake interests (Changnon, 1989). These problems reflect the physical and political inability to manage lake levels that satisfy all interests.

Recent concerns over climate change resulting from global warming during the 21st Century have added fuel to the concerns over lake levels (Changnon and Glantz, 1996; Changnon, 1997; Quinn, 1999). Will a future change bring lower or higher lake levels? Recent shifts in lake levels have led to a major disaster-oriented assessment of the “record” declines in recent years that attributed them to climate change resulting from global warming (*National Geographic*, 2002). Numerous scientific studies have tried to estimate the effects of climate change on future lake levels (Quinn et al., 1997; Croley et al., 1998).

For these reasons, an assessment of the levels of the unregulated middle lakes (Lakes Michigan-Huron and Erie) and their source of inflow (Lake Superior) was pursued to examine both short-term and mid-term historic fluctuations and trends to ascertain when and where extremes occurred. Lake Ontario was not included because of long-term controls of its levels through inflows and outflows.

Factors Affecting Lake Levels

Lake levels are a result of several physical and anthropogenic factors, with climate being the dominant factor. The amount of precipitation over the lakes and their basins is the single most important factor, followed by the amount of evaporation, mainly a wind- and temperature-driven variable (U.S. COE, 2001). Study of 100-year records of lake levels and precipitation in the Lake Michigan-Huron basin found a correlation coefficient of +0.84 based on a one-year lag. Thus, precipitation explains 71 percent of the variability in the lake levels (Muller et al., 1965).

Table 1 shows how the water moves in and out the lakes under study. Lake Superior has little inflow (mainly from diversions), and Lakes Michigan-Huron receive 70 percent of their water from overlake precipitation and from land basin runoff, which is largely a precipitation-controlled variable. Most water in Lake Erie is a result of its amounts of inflow and outflow.

Because precipitation and evapotranspiration (ET) over the land areas of the lakes’ basins have a lag time before they affect the lake levels, all studies have found a one- to two-year in lag in the relationship between precipitation and lake levels (Great Lakes Commission, 1986). Groundwater affects lake levels but has a much greater lag, and it is not a major contributor. Seiches created by major storms also create short-term shifts in water levels over hours or days. Four important physical conditions that affect levels are not measured and must be estimated: 1) overlake precipitation, 2) overlake evaporation, 3) groundwater exchange, and 4) overland evapotranspiration (Bruce and Rodgers, 1962).

Humans have made changes in the lakes, particularly to the channels between them, and these also have affected lake levels. Channels between Lakes Huron and Erie were deepened during the 1930s and 1960s, leading to an estimated 37-centimeter lowering of Lakes Michigan-Huron over the past 70 years (Quinn, 1999). Flow through the channel between Lakes Superior

Table 1. Sources of Input and Output of Water from the Great Lakes (U.S. COE, 1991)

Lake	Inputs (%)			Outputs (%)	
	Inflow	Precipitation	Runoff	Evaporation	Outflow
Superior	5	55	40	40	60
Michigan-Huron	30	35	35	30	70
Erie	80	10	10	13	87

and Michigan-Huron has been controlled since 1921, with subsequent changes in controlled flows in 1946, and again in 1979. The outflow regulation established in the 1977 control plan seeks to bring the levels of Lakes Michigan-Huron and Superior to nearly the same relative position within their historic ranges of levels, and specifically to keep Lake Superior's levels between 603.2 feet and 599.6 feet (U.S. COE, 1997). The capability to regulate the outflows from Lake Superior does not mean that a major control of the lake levels is possible. The major factors (precipitation and evaporation) cannot be controlled. For example, recent lake-level fluctuations on Lakes Michigan and Erie, from near-record high levels in 1997 to the lowest levels in 35 years in 2000, revealed that the Lake Superior outflow control had only a minimal influence on lake levels (U.S. COE, 2002). In summary, the effect of the outflow regulations on lake levels is very small when compared to the role that nature plays.

Other anthropogenic actions have affected levels. Water has been diverted from Lake Michigan at Chicago since the 1870s, with a major increase in the amount diverted in 1898-1930 (Changnon and Changnon, 1996). This diversion is now regulated by a U.S. Supreme Court decree at 3200 cubic feet per second (cfs). Water also has been diverted into Lake Superior from the Hudson Bay basin at Long Lac (since 1941) and Ogoki, Canada (since 1943). The diversion at Chicago and the water inputs at Long Lac and Ogoki have only a minor effect on water levels, much less than the effects of climate factors on lake levels (U.S. COE, 2000). Regulation of Lake Superior has produced little bias in the levels of Lakes Michigan-Huron (Quinn and Sellinger, 1990).

Scope

Record highs and sudden drops in lake levels have led to three questions: 1) how many years over time have one or more lakes had record, or near-record water levels, 2) have the annual rates of change in lake levels increased, and 3) is the climate changing? Answers to these questions were goals of the study. Inspection of the lake levels plotted over time suggests distinct periods with more or less variability in levels; therefore, the variability over time also was assessed.

The primary basis of assessment of lake levels involved comparisons between the values of the four lakes. Average levels and their degree of variability for 5-, 15-, and 25-year moving periods were evaluated. Periods of record and near-record high and low lake levels and extreme variability also were identified and compared. Short-term changes in lake levels for one, two and three years ahead also were determined. The summary section interprets the findings in light of the regional-spatial behavior of climate conditions.

Data and Analysis

Monthly measures of lake levels for Lakes Superior, Erie, and Michigan-Huron were available for a 141-year period (1861-2001). These data were used to calculate 5-, 15-, and 25-year moving averages and, in turn, to compute their standard deviations (SDs) at the ending year of each period. Annual mean levels (January-December) were used to compute the rate of change in levels between the average level of a given year and the average levels of the next one-, two-, and three-year periods. These rates of change were computed for the total period of record for each lake.

Selection of years when extremely high or extremely low levels of variability occurred on a given lake was based on identifying high periods (or low periods) that were temporally inde-

pendent without overlapping years. For example, the maximum 25-year SD value for Lakes Michigan-Huron occurred during 1950-1974, and another high, but slightly less variable period occurred during 1962-1986. Because these periods overlapped, the lesser one (1962-1986) was not used in the analysis to identify the top three 25-year periods of high variability on Lakes Michigan-Huron during 1861-2001. Mention of Lake Huron with Lake Michigan is hereafter deleted in most text because the two lakes are interconnected and the levels on Lake Michigan and Lake Huron are essentially the same.

Average Lake Levels

The 141-year temporal distributions of the levels for each lake, based on the 5-, 15-, and 25-year moving averages, serve as a meaningful baseline for assessing various temporal fluctuations. The 25-year averages of Lake Superior levels indicate a long-term slow rise in lake levels from 1861 until about 1950 (Figure 1), with no marked upward or downward trend thereafter. The 5-year mean distribution is much less suggestive of a major long-term upward trend in levels, showing major fluctuations throughout the 141-year period.

The three sets of average levels for Lake Michigan (Figure 2) all display a distinct U-shaped distribution for the 141-year period. However, the U-shape is less obvious in the 5-year distribution than in the 15- and 25-year distributions. Values for 15- and 25-year periods reached their all-time lows for periods ending during 1938-1948.

The 141-year distribution of levels of Lake Erie (Figure 3), based on the 25-year averages, has a distribution similar to that for Lake Michigan. The lowest values occurred during 1931-1945, in close agreement with the Lake Michigan distribution. However, the early period high values on Lake Erie were less than those in recent years, a notable difference from the distribution of the levels of Lake Michigan that peaked early. The Lake Erie levels' distribution, based on the 5-year values, makes the recent upward trend less obvious with numerous highs and lows over time.

The temporal distribution of the Lake Superior levels for 15-year periods (Figure 4a) is markedly different than those for the other two lakes. These differences in the average distributions for the three lakes reveal that the climatic conditions affecting Lake Superior's basin from 1861 until about 1950 were markedly different than those affecting the basins of Lakes Michigan and Erie. A study of precipitation over each lake's basin for 1870-1979 found that the major decrease in the level of Lake Michigan during 1870-1940 was either not present or very minor in the other lakes (Quinn and Croley, 1981). A climatological study of the spatial frequency of cyclones, which produce much of the precipitation in the Great Lakes basin, shows a sharp north-south gradient in frequencies across the basin (Angel, 1996). The Lake Superior basin averages 31-35 cyclones annually compared to 25-29 cyclones annually across southern Lake Michigan and Lake Erie (Changnon et al., 1995). Figure 4b provides the 25-year average curves for the three lakes. Comparison of these curves further illustrates the sizable differences between Lake Superior and the other two lakes until about 1970.

The upward trends of the levels of Lakes Michigan and Erie since about 1940 (Figure 4) reflect an upward trend in annual precipitation across their basins and most of the nation since 1935-1940 (Karl and Knight, 1998). The national pattern of the precipitation trends showed increases in the basins of Lakes Michigan and Erie, but no upward trend in the area of Lake Superior. This helps explain the lack of a comparable increase in levels of Lake Superior. These

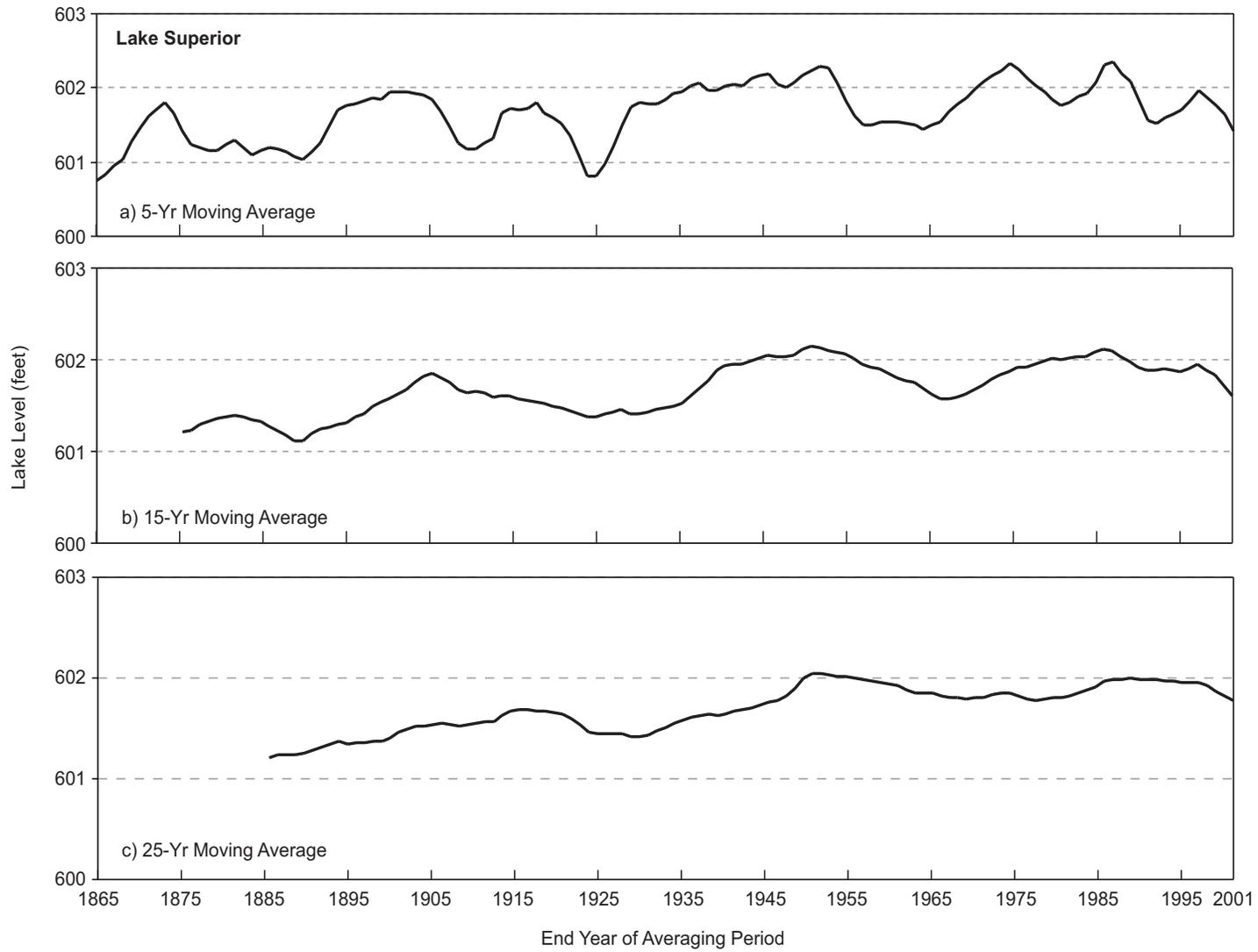


Figure 1. Curves based on 5-, 15-, and 25-year moving averages of the levels of Lake Superior.

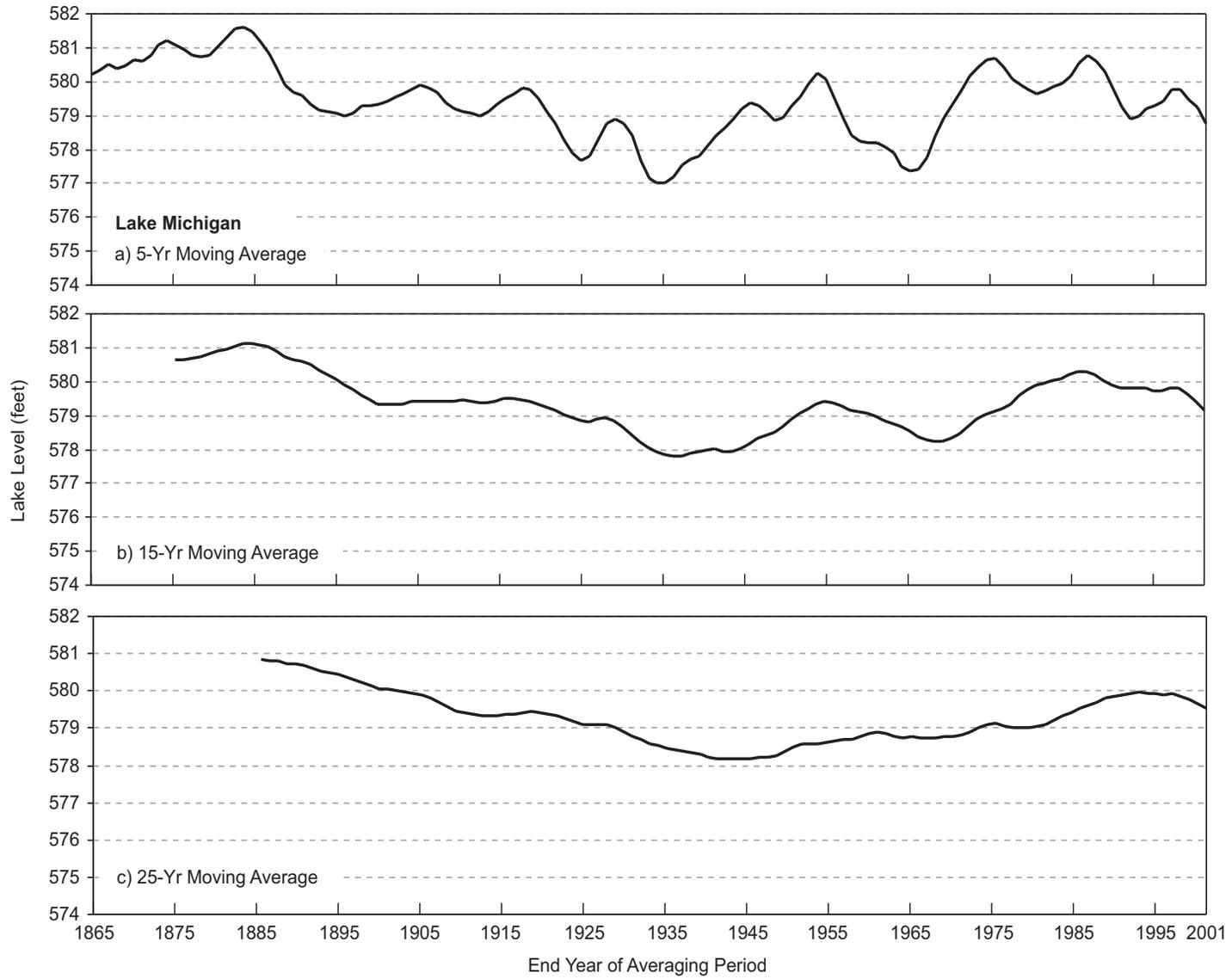


Figure 2. Curves based on 5-, 15-, and 25-year moving averages of the levels of Lake Michigan.



Figure 3. Curves based on 5-, 15-, and 25-year moving averages of the levels of Lake Erie.

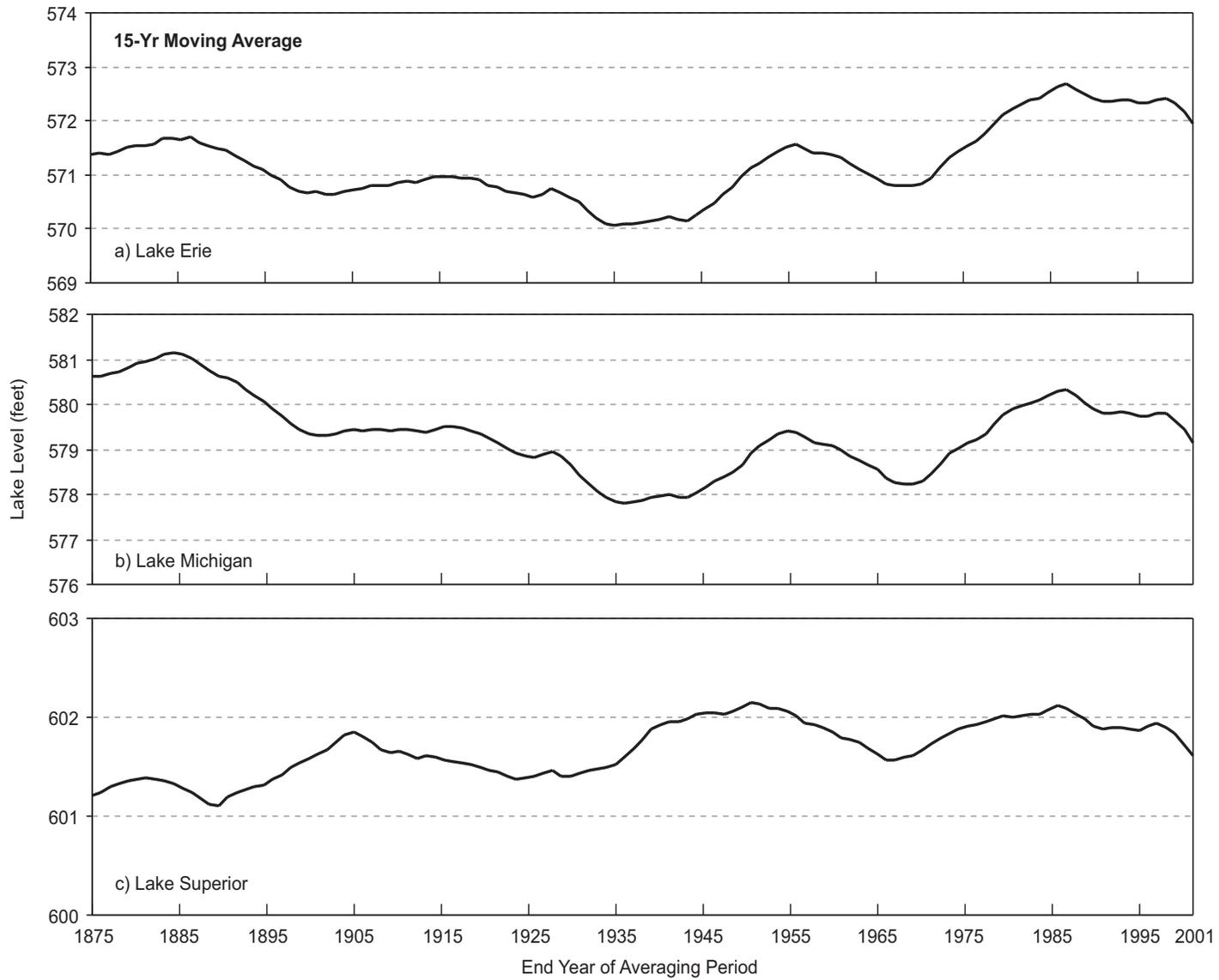


Figure 4. Moving average (AVG) levels based on 15-year and 25-year periods for Lakes Erie, Michigan, and Superior.



Figure 4. Concluded.

precipitation increases have led to marked increases in annual streamflows from 1948 to 1998 in Wisconsin, lower Michigan, and Ohio where rivers and streams feed Lakes Michigan and Erie (Lettenmaier et al., 1994). Their analysis of national temperature trends showed significant increases since 1948 in northern Wisconsin and Minnesota, including the basin of Lake Superior. This may be related to an increase in lake evaporation, another factor limiting any increase in Lake Superior's level. Lower Michigan and Ohio had significant temperature decreases in 1948-1998, a condition that likely would act to reduce evaporation over time and also lead to increased levels of Lakes Michigan and Erie. One analysis of the fluctuations in lake levels claimed a distinct basinwide change in climate around 1970 (Hartmann, 1988), whereas another assessment claimed the 1900-1986 period had two distinct precipitation basin patterns: below average mean of 30.77 inches in 1900-1940, and above average mean of 32.77 inches in 1941-1986 (Great Lakes Commission, 1986).

Record High and Low Levels

Noted temporal differences in the average levels of the three lakes are reflected in the times of occurrence of their highest and lowest levels. These extremes are presented for 5-, 15-, and 25-year intervals.

5-Year Periods

Table 2 indicates the ending years of the three highest and three lowest levels for 5-year periods attained on each lake during 1861-2001. The values show considerable temporal grouping of the high and low periods. For example, all three lakes had high levels in the early 1970s, and all were ranked as the second highest levels of the 141-year period. Levels of all three lakes peaked again during the early 1980s. However, four of the nine highest values were isolated in time and on a single lake. For example, only Lake Michigan had a high during 1883-1887, and only Lake Superior had a high during 1950-1954.

Timing of the low periods on Lakes Michigan and Erie were in close agreement, all ending in 1927, 1936-1937, and 1966. This reflects the strong impact of the outflow from Michi-

Table 2. Five-year Periods When Extremely High and Extremely Low Lake Levels Occurred on Lakes Michigan (M), Erie (E), and Superior (S), Including the Three Highest and Three Lowest Ranked Values, 1861-2001

<i>Ending year</i>	
<i>Highest three 5-year Values</i>	<i>Lowest three 5-year values</i>
1878 (M-2)	1869 (S-1)
1887 (M-1)	1893 (S-3)
1954 (S-3)	1926 (S-2)
1975 (S-2)	1927 (M-3, E-2)
1976 (E-2)	1936 (E-1)
1987 (S-1, M-3, E-1)	1937 (M-1)
1998 (E-3)	1966 (M-2, E-3)

Note: 1=most extreme, and 3=third most extreme.

gan to Erie (Table 1), as well as similar climate conditions (Brinkmann, 1983a). Two of the low levels on Lake Superior occurred during 1864-1893, much earlier than on the other two lakes. This outcome reveals that weather conditions capable of producing extremely dry conditions over relatively short periods, 5 years or less, often exhibit considerable spatial continuity across the basins of Lakes Erie and Michigan. These anomalous conditions seldom extend over the Lake Superior basin, and those over the Lake Superior basin often do not extend over Lake Michigan (Brinkmann, 1983b).

15-Year Periods

Table 3 indicates the years of occurrence of the first and second highest 15-year levels, and the first and second lowest levels for 15-year periods for the three lakes. The impact of the high and low 5-year levels (Table 2) is evident in the 15-year outcomes. Lakes Michigan and Erie both had low 15-year periods ending in 1937-1938 and in 1969, and both lakes had the lowest 5-year periods ending in 1936 and 1966 (Table 2).

Assessment of the years when the two highest and two lowest 15-year periods occurred during the 141-year study period reveals that only 48 years were not in a high or low period on one or more lakes. The longest period without an extreme was 1893-1922 (30 years). In contrast, 93 years of the 141 years (66 percent) either had one or more extreme high, or low, or both levels somewhere on the upper lakes.

Analysis based solely on the record highest and record lowest 15-year periods reveals no record event on one of the three lakes in 77 years during 1861-2001, and a record event on at least one of the three lakes in 64 years (45 percent of the total). If the three record highs and lows had all occurred at the same time, as in 1955-1969 for Lakes Michigan and Erie (Table 3), records would have occurred in only 30 of the 141 years, not in the 64 years with record extremes. In essence, several extreme lake levels were occurring quite independently such as a record low on one lake and no record on the other two lakes, leading to many more years than expected with record levels.

25-Year Periods

An analysis of the extreme lake levels based on values for the 25-year periods resulted in the periods shown in Table 4. During 1861-2001, there were 45 years without a record level, but a record high, low, or both occurred in 96 of the 141 years (69 percent) of the total. Had there been timing agreement of the three highest and three lowest periods on all three lakes, only 50

Table 3. Periods When the Two Highest Ranked Lake Levels and Two Lowest Ranked Lake Levels Occurred on Lakes Michigan (M), Erie (E), and Superior (S), Based on 15-year Periods

<i>Highest Levels</i>	<i>Lowest Levels</i>
1874-1888 (M-1)	1865-1879 (S-2)
1876-1890 (E-2)	1878-1892 (S-1)
1938-1952 (S-1)	1923-1937 (E-1)
1972-1986 (S-2)	1924-1938 (M-1)
1973-1987 (E-1, M-2)	1955-1969 (M-2, E-2)

Table 4. The 25-year Periods with Record Highest and Record Lowest Lake Levels on Lakes Michigan (M), Erie (E), and Superior (S)

<i>Years of highest value</i>	<i>Years of lowest value</i>
1865-1889 (M)	1865-1889 (S)
1928-1953 (S)	1918-1942 (E)
1963-1997 (E)	1921-1945 (M)

years would have experienced a record. The main temporal overlap in record periods was in the low periods on Lakes Michigan and Erie, and their lows during 1921-1942 overlapped the high on Lake Superior (1928-1945).

Summary

Record or near record high and low lake levels, based on 15- and 25-year periods, reveal considerable spatial difference frequently between the lakes (record highs on one lake at the same time as record lows on another lake). This reveals major spatial variations in precipitation and ET across the three basins during such multi-year periods. It also reveals that the influence of these interconnected lakes on their levels is not always large. Record levels (high or low) for 15-year periods were present in 52 percent of all years sampled and in 69 percent of the years with 25-year extremes. If the analysis of 15-year periods includes the two highest and two lowest independent periods on each lake during 1861-2001, these accounted for 66 percent of all years during that 141-year period.

Analysis of the 5-year periods with extremely high and low lake levels resulted in a somewhat different spatial perspective. There was considerable agreement between at least two lakes as to times when high or low levels occurred. This suggests much more regional uniformity in climate conditions controlling lake levels at shorter durations (5 years) than at longer durations (15 years or more).

The general disagreement in the timing of record high and low levels on Lakes Michigan and Superior is not surprising. The correlation coefficient between their annual basin precipitation amounts was only +0.62 for 1860-1989. This means that annual precipitation amounts on Lake Superior explained only 38 percent of the variations in annual precipitation over the Lake Michigan basin.

Assessment of 12-year wet and dry periods on the Lake Michigan and Superior basins, defined as periods having at least eight or more years with above or below average values, was used to define the occurrence of a given dry or wet condition on Lake Superior when one or the other existed on Lake Michigan. As shown in Table 5, when Lake Michigan experienced a dry period during 1854-1927, one also existed on Lake Superior in 44 percent of the years, but there was a wet period on Lake Superior in 13 percent of the dry years on Lake Michigan, and neither wet nor dry conditions in the Lake Superior basin in 43 percent of the years. A stronger relationship of dry conditions existed in the later period (1928-2000). When wet periods existed on Lake Michigan, Lake Superior had fewer wet periods than were found for joint dry periods. For example, when wet conditions occurred on Lake Michigan, only 34 percent of the years 1854-1927 were wet on Lake Superior, and 37 percent of the years 1928-2000. Both sets of relationships were slightly stronger in the second era, reflecting a temporal shift in regional climate conditions.

Table 5. Frequency of 12-year Wet and Dry Periods on Lake Superior When Either Condition Existed on Lake Michigan for Early and Late Eras

<i>Lake Michigan</i>	<i>Lake Superior</i>		
	<i>Wet period (%)</i>	<i>Wet period (%)</i>	<i>No wet or dry period (%)</i>
<i>Dry periods</i>			
1854-1927	44	13	43
1928-2000	64	6	30
<i>Wet periods</i>			
1854-1927	25	34	41
1928-2000	30	37	33

Variability of Lake Levels over Time

The SDs of lake levels were calculated for the moving averages of 5, 15, and 25 years. These SD values were used as a measure of the temporal variability in lake levels between 1861 and 2001.

The SD values on Lake Michigan for 5-year periods were the highest, and those of Lake Superior were the lowest throughout the 141-year period (Figure 5). The magnitude of the fluctuations in the SD values of Lake Superior did not shift during the 141-year period of study. The lack of an increase since the 1920s, as found on the other lakes, may reflect the regulation of Lake Superior's outflows beginning in 1921. Lake Erie's SD fluctuations from 1861 until the 1920s were different than those of Lake Michigan. Thereafter, the timing of the highs and lows in SD values on Lake Erie were similar to those on Lake Michigan, and levels of both lakes had greater variability after 1920. All three lakes experienced four major highs in their 5-year SD values, with the high during 1925-1933 exhibiting the greatest variability on Lake Superior. Lakes Michigan and Erie also had large values during 1925-1933, but their variability values peaked during 1986-2001.

The resulting periods of extreme variability in lake levels for 5-year periods are listed (Table 6). Levels on all three lakes exhibited extreme variability during the 1925-1934, when the nation's major droughts of the 1930s began. All three lakes also had high variability values for 5-year periods during 1996-2001. The other three periods of high variability occurred as time-isolated events on only one lake.

The SD values calculated for the 15-year moving averages on the three lakes from 1861 to 2001 (Figure 6) reveal several differences between lakes. First, the 141-year variability of levels of Lake Superior was notably less than those for Lakes Michigan-Huron and Erie. Regulation of Lake Superior's outflow to Lake Michigan began at a minor level in 1902, then was altered in 1921 to a control plan established in 1916, an endeavor not closely followed until 1941 when a new control plan was issued (U.S. COE, 1993). From 1941 to present, different regulations have been in place and closely followed, and a 1977 regulation plan sought to deal specifically with high lake levels. Comparison of the SD values for Lake Superior before 1921 and after 1941 does not suggest changes in the degree of variability over time, either before or after the different regulations were in place.

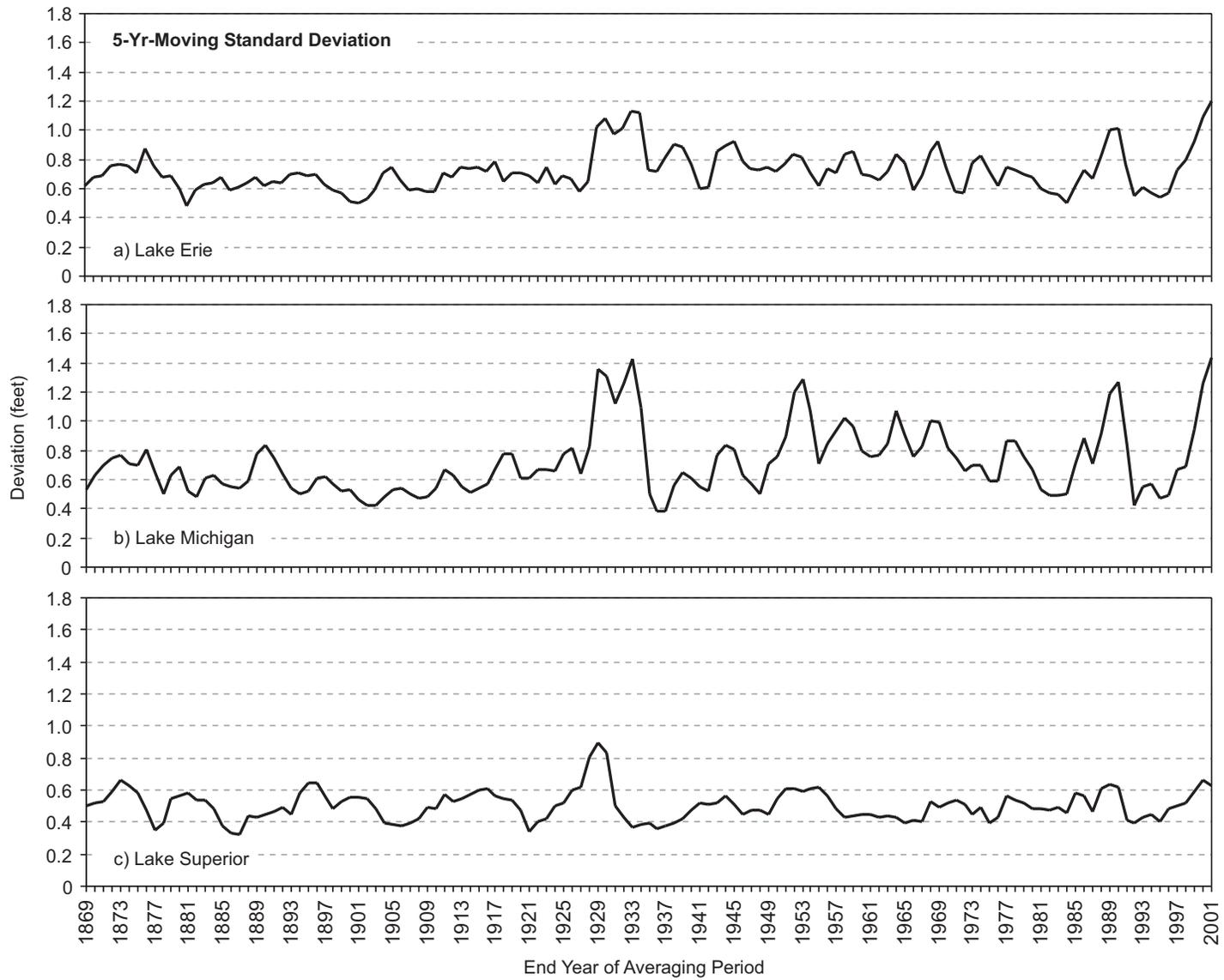


Figure 5. Variability of Standard Deviations in lake levels for 5-year periods on Lakes Erie, Michigan, and Superior.

Table 6. Three 5-year Periods with the Greatest Variability in Lake Levels for Lakes Superior, Michigan, and Erie

<i>Rank</i>	<i>Lake Superior</i>	<i>Lake Michigan</i>	<i>Lake Erie</i>
1	1925-1929	1997-2001	1997-2001
2	1996-2000	1929-1933	1930-1934
3	1869-1873	1949-1953	1986-1990

A second finding derived from Figure 6 is that the variability on Lake Erie and the values for Lake Michigan had a similar time distribution, but the Lake Erie SD values were mostly lower. Variability of levels of both lakes peaked in 1960-1975, whereas the peak SD value on Lake Superior was during 1925-1939.

The 15-year SD values for Lakes Michigan and Erie generally increased over time from 1861 to 1970, but thereafter became lower. The SD values of Lake Superior showed no upward trend and were essentially flat for 141 years. The major temporal differences in the variability values of Lakes Superior and Michigan are shown (Figure 7). Their magnitudes were similar during 1900-1920, but the magnitude and type of fluctuations differed in all other years before 1900 and after 1920.

Figure 8 presents the ranges in precipitation values, expressed as percent of average, for seven discrete 15-year periods on the basins of Lakes Superior and Michigan for 1898-2002 (Changnon, 2003). Values shown are based on the highest and lowest values from the numerous climate divisions in each basin. Comparison of the curves of the lakes reveals two important findings relevant to the SD values of the lakes' levels. First, differences in the two sets of curves illustrate that Lake Superior experienced much less spatial variability of precipitation in all but one of seven 15-year periods, thus agreeing with findings of lesser variability of levels exhibited on Figure 5. Second, the variability of precipitation amounts on the Lake Michigan basin began to increase after 1942 and exceeded precipitation variability on Lake Superior. Variability of precipitation on the Lake Superior basin decreased after the droughts of 1928-1942, and did not change much during the last three 15-year periods, as shown on Figure 8.

Comparison of the SD values based on the 25-year averages (Figure 9) shows Lake Michigan's values often were highest and Lake Superior's were lowest. Furthermore, the general long-term trends of the three lakes differ. The SD values for Lakes Michigan and Erie exhibit an upward trend from 1861 to 1988, whereas no upward or downward trend is seen in the 141-year SD values on Lake Superior. The distribution of 25-year variability values on Lakes Michigan and Superior are unlike those for 1861-2001. For example, Lake Superior had a peak in SD values during 1921-1947, a low variability period on Lake Michigan. Lake Michigan's all-time peak occurred during 1950-1974, whereas that on Lake Erie occurred during 1963-1987. The SD values for Lakes Michigan and Erie decreased rapidly after 1985.

The times when periods of high variability of lake levels occurred were assessed for each lake, and findings were intercompared for the three durations (5, 15, and 25 years). The three periods on each lake with the highest SD values were identified, and those selected had to be independent in time with no overlap in years.

The three periods with the highest variability in lake levels for the 15-year and 25-year periods are shown (Figure 10). Four periods are shown for Lake Erie because the third and fourth

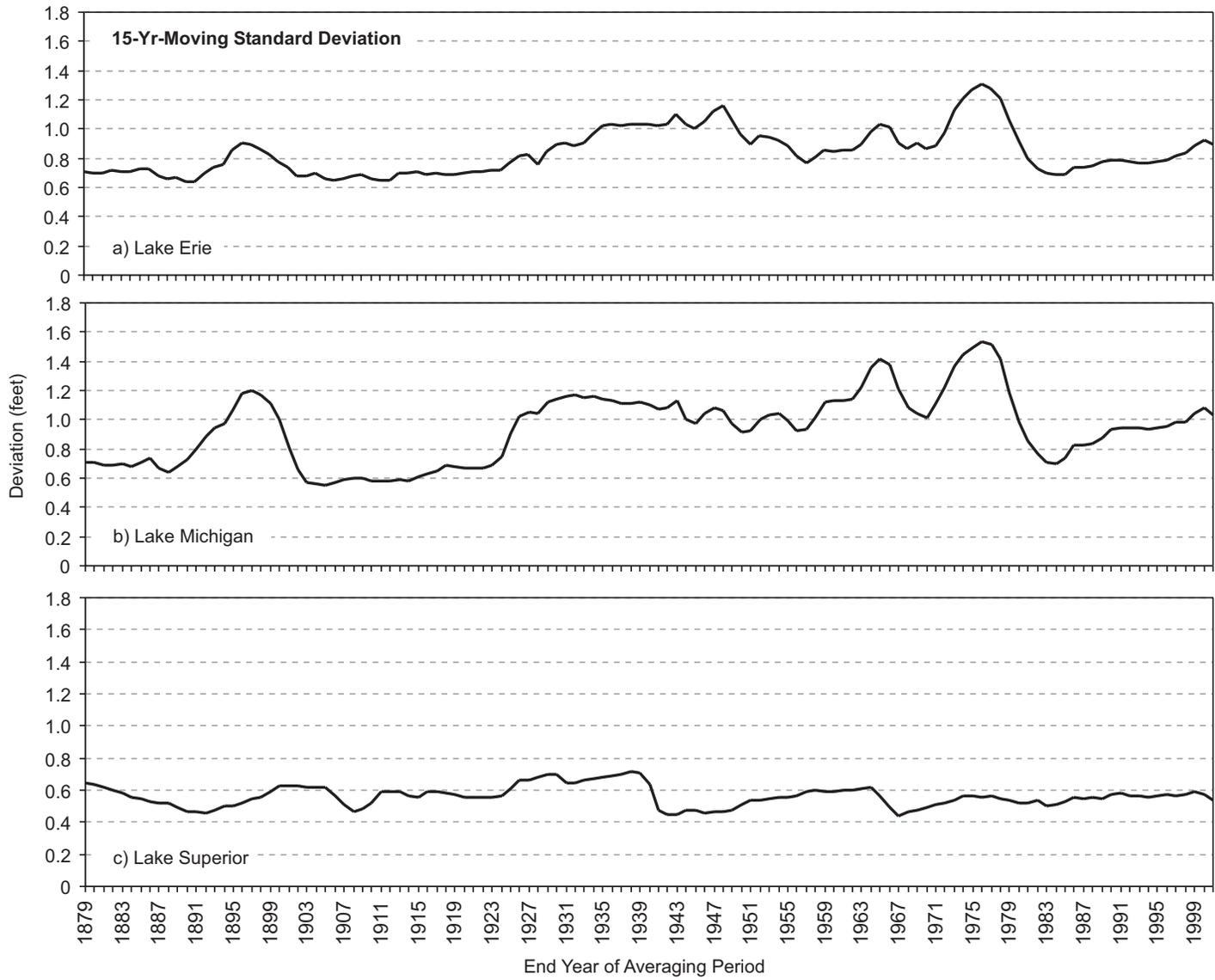


Figure 6. Variability of Standard Deviations in lake levels for 15-year on Lakes Erie, Michigan, and Superior.

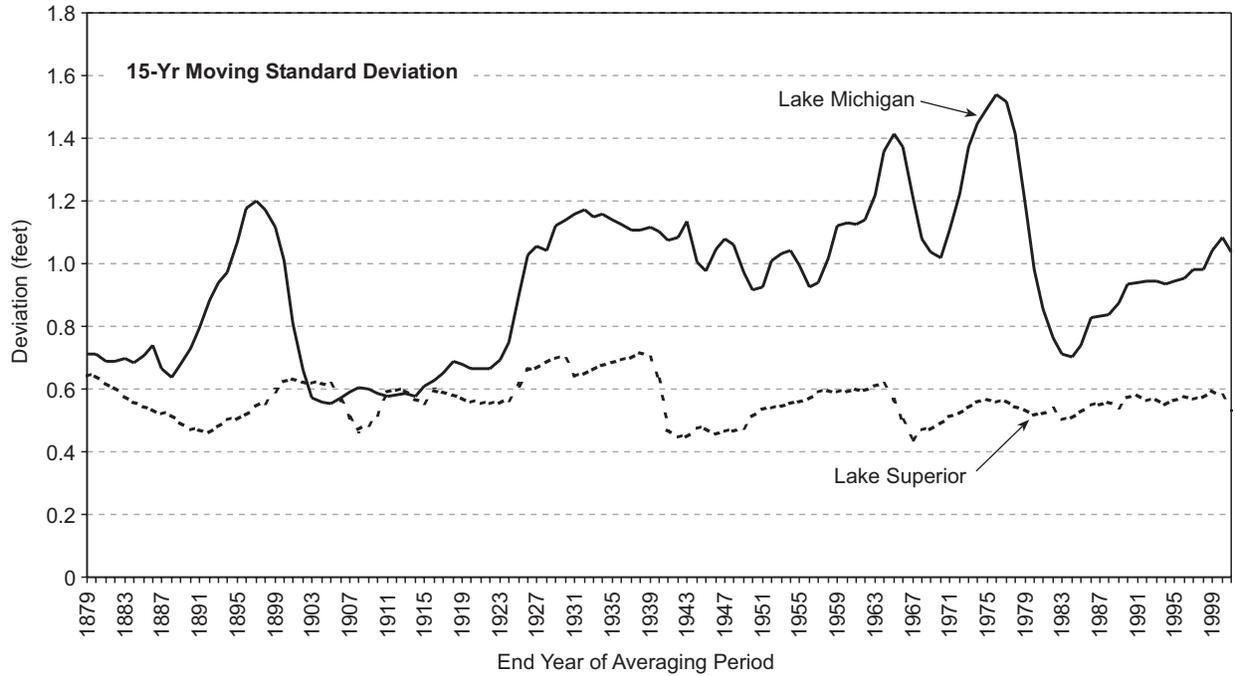


Figure 7. Comparison of Standard Deviation values for 15-year averages on Lake Michigan and Lake Superior, 1861-2001.

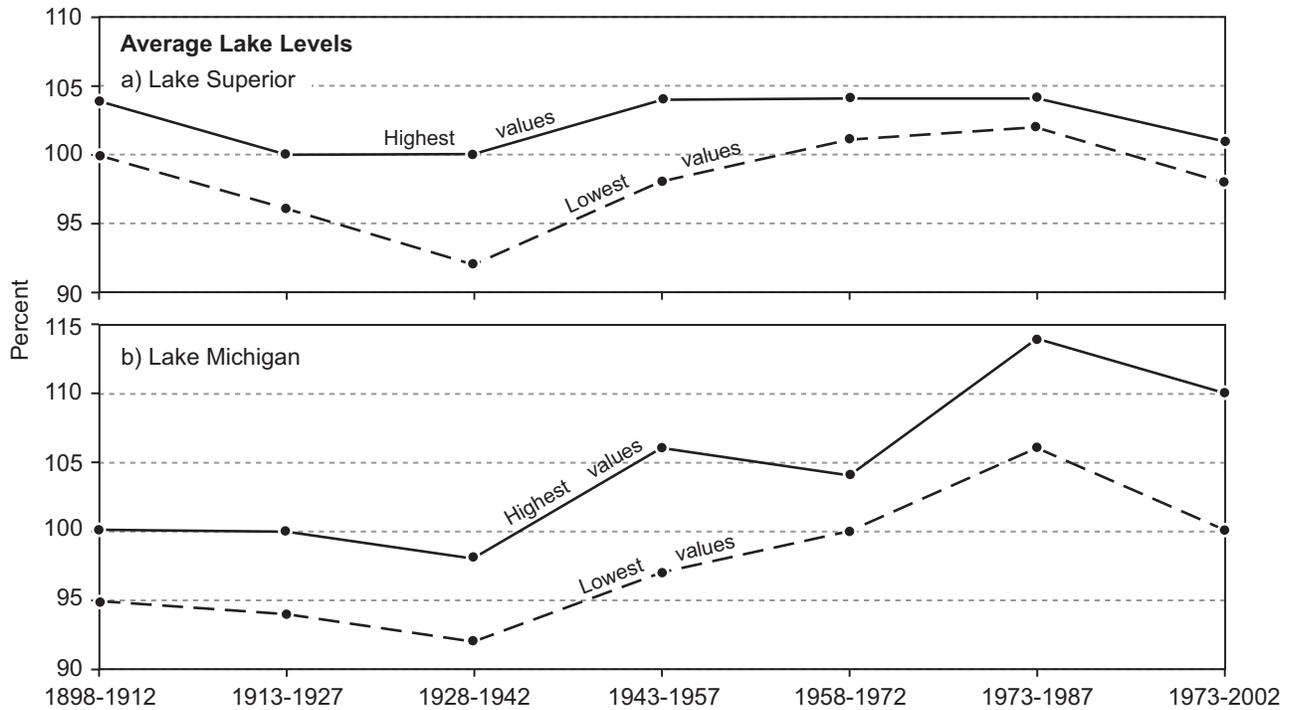


Figure 8. Range of precipitation values, expressed as a percent of average, in climate districts on the basins of Lakes Superior and Michigan for seven 15-year periods, 1898-2002.

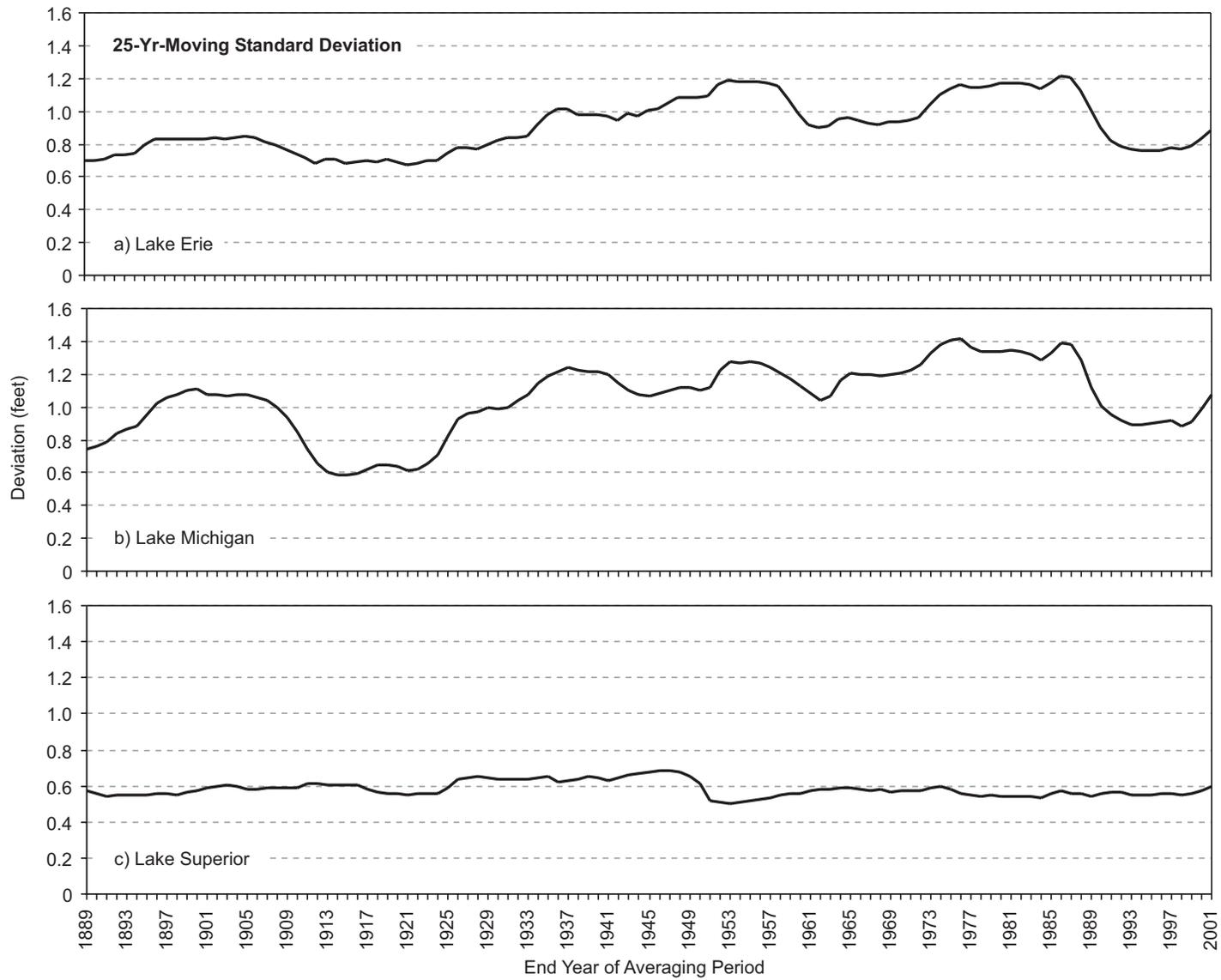


Figure 9. Variability of Standard Deviations in lake levels for 25-year periods on Lakes Erie, Michigan, and Superior.

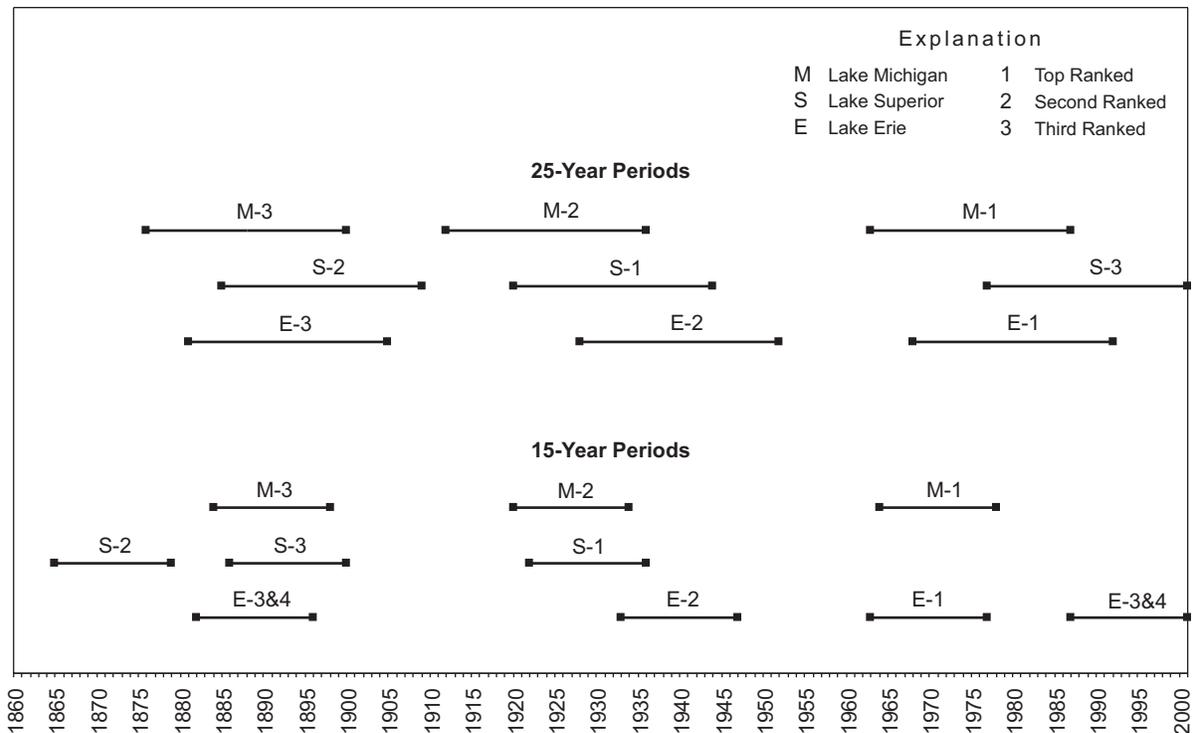


Figure 10. Three periods with the greatest variability in lake levels during 1861-2001 for Lakes Michigan-Huron, Erie, and Superior.

ranked periods had essentially equal values. The top variability for 25-year periods shows that all three lakes were experiencing high variability during 1884-1900, 1928-1937, and 1972-1987. The ranks of the 15-year period values displayed in Figure 10 show little temporal agreement. For example, each of the three lakes had highly variable 15-year periods ending during 1931-1936, but their ranks were #1 on Lake Superior, #2 on Lake Erie, and #3 on Lake Michigan. Inspection of the 25-year variability periods reveals Lakes Michigan and Erie experienced their greatest variability during the late 1960s to mid-1980s, but Lake Superior's variability in this same period was ranked only third highest.

Major Level Changes during One- to Three-Year Periods

The average annual levels on each lake were compared with the averages occurring during the following year, two years, and three years. The intent was to assess the major short-term shifts, up and down, in lake levels. Relatively rapid major changes in levels often create major adjustment problems for many lake activities (Horvath et al., 1988).

One-Year Changes

Shifts in levels between individual years on Lake Michigan are shown (Figure 11). The 1930-1931 shift was a decrease to 1.75 feet below average, the greatest one-year decrease during 1861-2001. Inspection of Figure 11 also shows other large singular one-year increases and decreases; in general, the changes since about 1930 have been greater than those in prior years, 1861-1930.

The top four rated single year increases and decreases during 1861-2001 for the three lakes are listed (Table 7). Assessment of the years of occurrence shows several periods of decreases extended across all three lakes, including 1987-1988 and 1998-1999, with Lakes Michigan and Erie experiencing a major drop (below average) in 1931. None of the years of major one-year increases were found on all three lakes, although an increase in 1929 occurred on two lakes and another in 1996-1997 on two lakes. These results reveal that when extremely dry conditions of one- to two-year durations occurred, they extended over more of the basin than did extremely wet conditions. Very few years of decreases occurred before 1930 (only in 1917 on Lake Superior), and 6 of the 12 major top four decreases occurred during 1987-1999. The years when increases occurred showed a greater temporal distribution from 1876 to 1997. The decreases for a given rank on Lake Superior were approximately 35 to 50 percent less than decreases on Lake Michigan.

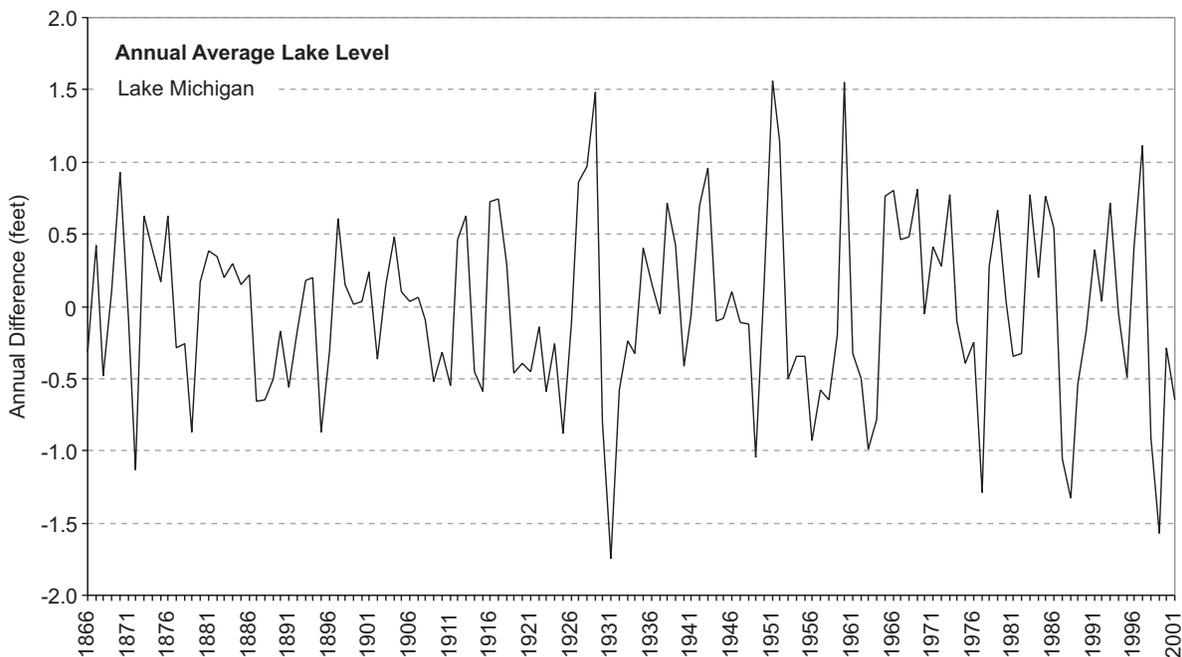


Figure 11. Magnitude of changes in lake levels between consecutive years on Lake Michigan, 1865-2001. Values are in feet above or below the long-term average.

Table 7. The Four Greatest Increases and Decreases (feet) in Lake Levels between Single Years, Measured in Feet from Average Lake Levels and Year of Occurrence, 1861-2001

<i>Lake Michigan</i>		<i>Lake Superior</i>		<i>Lake Erie</i>	
<i>Decreases</i>	<i>Increases</i>	<i>Decreases</i>	<i>Increases</i>	<i>Decreases</i>	<i>Increases</i>
1.75 (1931)	1.56 (1951)	0.90 (1998)	1.25 (1927)	1.85 (1931)	1.39 (1876)
1.57 (1999)	1.55 (1960)	0.87 (1987)	1.01 (1916)	1.51 (1999)	1.20 (1943)
1.33 (1988)	1.48 (1929)	0.61 (1917)	0.68 (1894)	1.33 (1988)	1.16 (1929)
1.29 (1977)	1.15 (1952)	0.57 (1940)	0.68 (1996)	1.13 (1934)	1.15 (1997)

Two-Year Changes

Changes in lake levels from the annual average in a given year (annual average) and the average level of the ensuing two years were assessed. Changes for Lake Michigan (Figure 12) reveal the biggest upward shift from 1950 to 1951-1952, a difference of 1.35 feet, and the greatest decrease was from 1929 to 1930-1931, the start of the 1930s droughts.

Assessment of the four greatest increases and four greatest decreases for the ensuing two-year periods on all three lakes revealed only two of the 12 major changes occurred before 1910. Both were on Lake Superior: a major decrease from 1892 to 1893-1894, and an increase from 1877 to 1878-1879. As with the one-year shifts, the major decreases showed more widespread multi-lake agreement than did the increases. Two recent decreases occurred on all three lakes, from 1986 to 1987-1988 and from 1997 to 1998-1999, the first or second greatest decreases on all three lakes during 1861-2001. The most sizable increases in levels occurred during 1926-1927 and 1927-1928 on Lake Superior, and from 1927 to 1928-1929 on Lakes Michigan and Erie, revealing an expected one-year lag downstream. These peaks on Lakes Michigan and Erie were followed by high-ranked decreases from 1929 to 1930-1931.

Three-Year Changes

Changes in lake levels from the annual average in a given year and the average level of the ensuing three years also were assessed. The 1861-2001 annual changes on Lake Michigan (Figure 13) reveal an overall increase in the magnitude and frequency of extreme changes after the mid-1920s. The peak three-year increase was 1.11 feet above the average level from 1926 to 1927-1929, and the greatest decrease occurred from 1929 to 1930-1932 (Table 8).

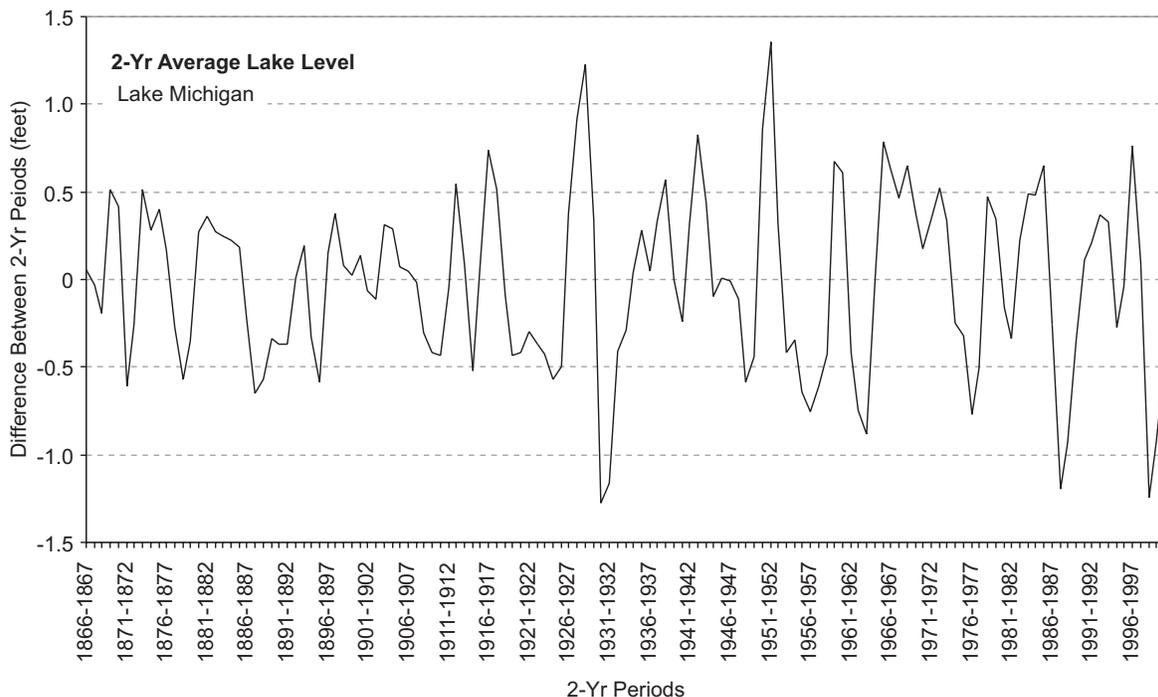


Figure 12. Magnitude of changes in lake levels between one year and the average of the next two years on Lake Michigan, 1865-2001. Values are in feet above or below the long-term average.

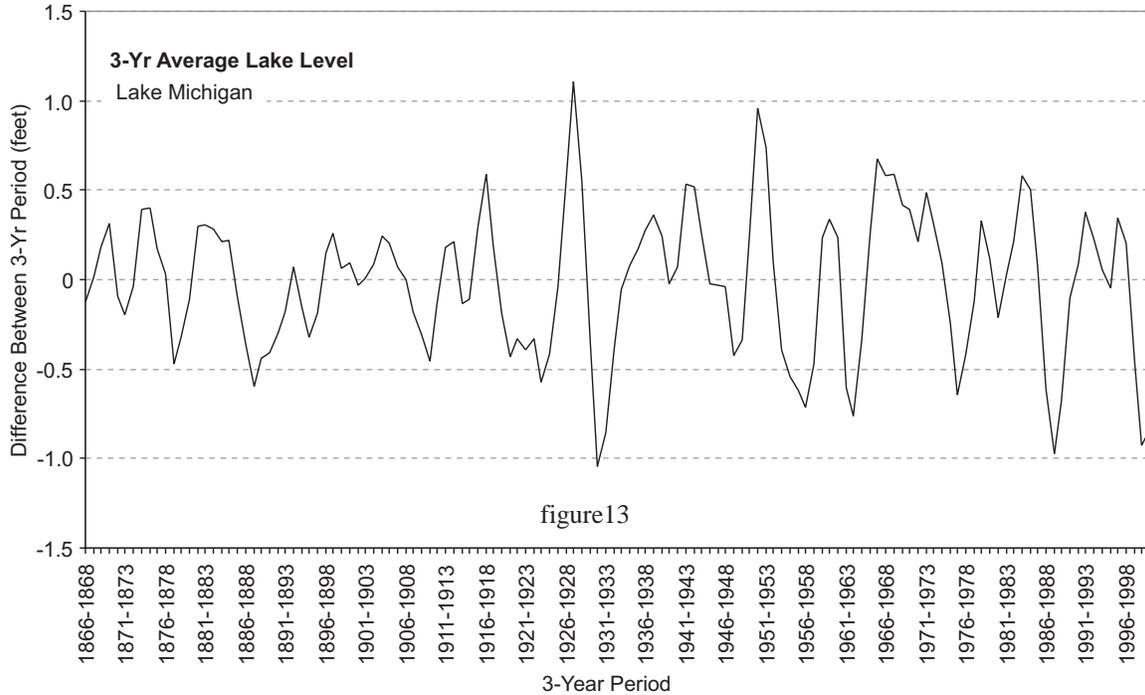


Figure 13. Magnitude of changes in lake levels between one year and the average of the next three years on Lake Michigan, 1865-2001. Values are in feet above or below the long-term average.

Table 8. The Five Greatest Increases and Decreases (feet) in Lake Levels between Single Years and the Average Level of the Ensuing Three Years, Measured in Feet, and Years of Occurrence, 1861-2001

<i>Lake Michigan</i>		<i>Lake Superior</i>		<i>Lake Erie</i>	
<i>Decreases</i>	<i>Increases</i>	<i>Decreases</i>	<i>Increases</i>	<i>Decreases</i>	<i>Increases</i>
1.04 (1930-32)	1.11(1927-29)	0.46(1998-00)	0.61(1927-29)	0.78(1998-00)	0.77(1927-29)
0.98 (1987-89)	0.96(1950-52)	0.38(1986-88)	0.48(1926-28)	0.72(1987-89)	0.57(1950-52)
0.92 (1998-00)	0.74(1951-53)	0.36(1987-89)	0.36(1892-94)	0.70(1999-01)	0.56(1966-68)
0.86 (1931-33)	0.68(1965-67)	0.34(1877-79)	0.35(1893-95)	0.66(1931-33)	0.55(1971-73)
0.84 (1999-01)	0.59(1967-69)	0.32(1952-54)	0.34(1949-51)	0.63(1930-32)	0.54(1967-69)

Figure 14 presents the three-year level changes for Lake Superior. Comparison of the temporal distribution for Lake Superior with that for Lake Michigan (Figure 13) reveals some major differences. The pre-1930 years on Lake Superior had changes comparable in magnitude and frequency to those in the post-1930 period, whereas changes on Lake Michigan increased after the mid-1920s. The results do not suggest that regulated outflows from Lake Superior had any major influence over time on the magnitude of the major three-year shifts in lake levels. The magnitudes of the two lakes' values show lesser changes on Lake Superior. For example, Lake Michigan had a decrease of 0.92 feet from 1997 to 1998-2000, double the 0.46-foot drop on Lake Superior (Table 8). Comparison of the shapes of the two curves reveals several other

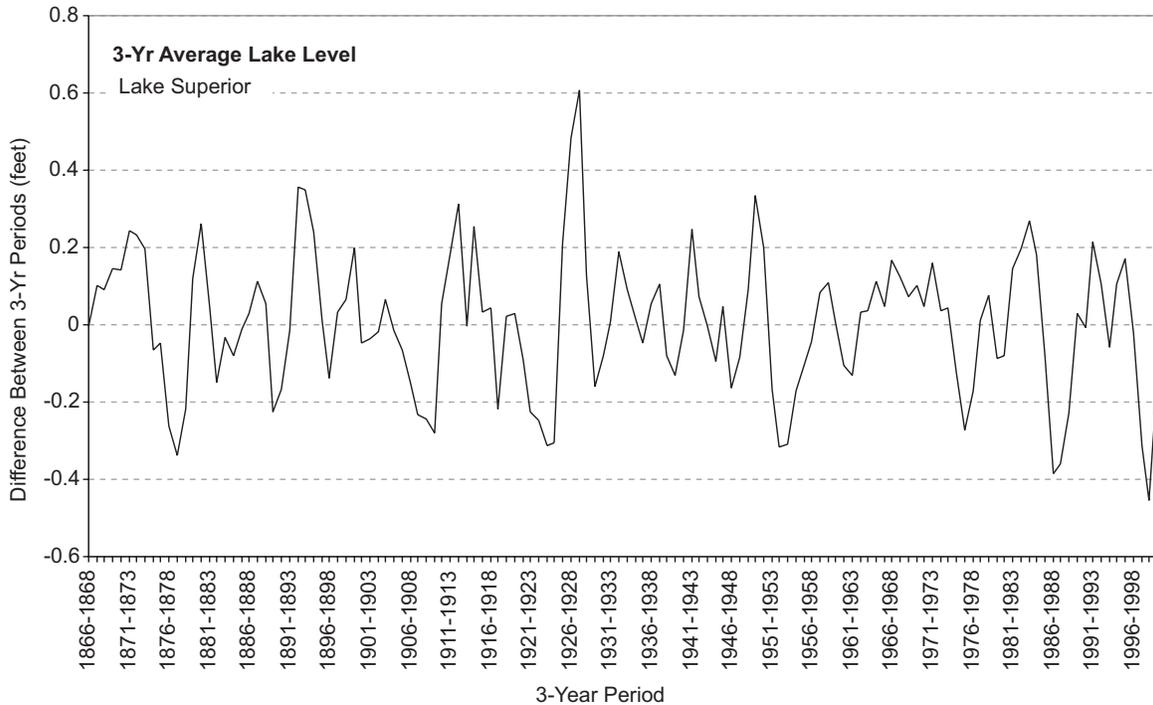


Figure 14. Magnitude of changes in lake levels between one year and the average of the next three years on Lake Superior, 1865-2001. Values are in feet above or below the long-term average.

dissimilarities, such as a peak change in Lake Michigan levels in the mid-1960s with only a minor peak on Lake Superior.

Inspection of the major three-year shifts on all three lakes (Table 8) reveals that three time periods had major shifts on all lakes. Major decreases occurred on all three lakes during 1930-1933, 1986-1989, and 1998-2001. Major increases occurred on all three lakes during 1926-1929, 1949-1953, and 1965-1969. The major feature on all three lakes was the big swing from top-ranked increases in the late 1920s immediately followed by large decreases in the early 1930s.

Summary and Conclusions

Levels of the Great Lakes remain a never-ending major issue. The upward and downward fluctuations, and the frequent occurrence of extreme levels and rates of change, have been a subject of deep concern, particularly during the past 30 years. These fluctuations largely reflect shifting climate conditions over time since climate is the major factor controlling lake levels. This assessment of the levels of four middle and upper lakes (Superior, Michigan-Huron, and Erie) examined short-term and long-term fluctuations and trends since 1860 to ascertain when and where extremes occurred and how the variability of levels shifted over time.

Those concerned over lake levels fall into two classes: those interested in having high levels and those interested in having lower lake levels. Those favoring high levels are shippers and ports, water-supply interests, and hydroelectric generators along connecting rivers. Those satisfied with low levels include shoreline residents, certain recreational interests, and industries that fear shoreline erosion and flooding.

High, damaging levels have led to calls for increasing outflows at Chicago, but this has been resisted by downstream interests, who fear high water damages along the rivers. Conversely, droughts in the Mississippi River basin have led drought-stricken interests to seek added diversion from the lakes to sustain river levels, a situation resisted by lake interests. These contrasts further reveal the problems of shifting lake levels. Recent concerns over climate change resulting from global warming during the 21st Century have added a new concern over lake levels: will a future change bring lower or higher levels?

The 141-year average lake level curves for 5-year and longer periods showed a U-shaped temporal distribution for Lake Michigan, being highest early (19th Century). The distribution for Lake Erie was also U-shaped, but the highest values came in recent years (1970-2001). The distribution for Lake Superior was very different, with a gradual increase over time until about 1950 and a flat trend thereafter.

The differing fluctuations in the levels of these upper lake systems was the primary factor for the frequent occurrence of record high or low lake levels on one or more lakes. Depending on the level criteria being examined, record-high or low levels were being set on one or more lakes nearly half the time over the 141-year period. "Records are set to be broken" is an old adage that appears appropriate for the levels of the Great Lakes. Assessment of extremes in lake levels, high or low, shows that record extremes for 15-year periods were occurring on one or more lakes during 52 percent of the years since 1860, and 25-year records (high, low, or both) prevailed during 71 percent of all 141 years. Certain periods, including 1875-1905, 1920-1950, and 1970-1990, had considerably more year-to-year variability in lake levels, a condition reflecting greater climate instabilities in the Great Lakes basin. Recent high levels on the lakes were records for Lakes Michigan and Erie, but not for Lake Superior.

Major short-term, one- to three-year, changes in lake levels revealed sizable differences between occurrences on the three lakes. Major differences also exist in the timing of record shifts between one-, two- and three-year long changes.

The variability in the levels of Lakes Michigan and Erie was less during 1861-1930 than during the 1931-2001 when it increased over time. This reflects a shift in the regional climate (Brinkmann, 1983a). The magnitude of the variability in the level of Lake Superior did not change during the 141-year period, but a climate assessment of wet and dry periods of Lakes Michigan and Superior showed more agreement after 1928 than in 1854-1927. There were two periods when the levels of all three lakes exhibited great variability, 1925-1936 and 1972-1987, illustrating highly variable, unstable atmospheric conditions. Both periods had a mix of exceptionally wet and dry years.

Anthropogenic changes in the channels between lakes partially affect a climatological interpretation of the historical fluctuations in lake levels. Alterations in the control of outflows from Lake Superior to Lake Michigan also conceivably could alter record levels, the degree of variability in levels, and rates of level changes from one year to another. However, inspection of the long-term behavior of the levels of Lake Superior does not suggest a detectable signal relating to the outflow changes. Temporal distributions of extremely high and low levels, and the variability of levels of Lake Superior do not appear to reflect any changes in the controlled outflow since 1921. Effects of controlled outflows on Lake Michigan levels is not evident either. For example, after the shift to strict controls of outflows in 1941, Lake Michigan levels, as measured for 5-, 15-, and 25-year periods, did not show a post-1941 perturbation in levels. Furthermore, 1941 was followed by ever-increasing levels (but not reaching the high levels of the

19th Century) and a period of extreme variability. It is reported that the series of changes in the channels between Lakes Michigan-Huron and Erie during 1910-1965 lowered the average level of Lake Michigan by 1.2 feet, but detection of this effect in the average curve for this era and following years is not possible.

Climate conditions producing most major low lake levels extended across all the lakes, whereas those producing high lake levels frequently did not extend over all four lakes. This reveals that the climate conditions producing sharp decreases (lower precipitation and higher evaporation) were more widespread than those in exceptionally wet periods. Inspection of the long-term behavior of the levels of the three lakes, including their averages and extremes, reveals that conditions on Lakes Superior and Michigan often did not agree. The trends of their averages are totally different, as are the times of most of their extremes and variability shifts. Fluctuations and variability of levels of Lake Superior were less than those of Lake Michigan, reflecting less climate variability in the north (Brinkmann, 1983a). Collectively, the results show that major climate differences often exist between the Lake Superior basin and the Lake Michigan-Huron basin.

The behavior of the levels of Lakes Michigan and Erie was generally similar, reflecting similar climate conditions plus the effects of the outflows from Lakes Michigan to Erie. The temporal variability of the levels of Lake Erie was generally less than that of Lake Michigan throughout the 141 years assessed.

What did these comparisons of averages, extremes, and variability of levels of the four lakes reveal about the climate conditions of their basins over the past 141 years? Recall, of course, that two of the critically important conditions affecting lake levels go unmeasured, overlake precipitation and evaporation, and their impact on levels is best revealed in how the levels behave. Comparisons of the levels of the lakes revealed two important findings about the past climate conditions that control lake levels.

First is the strong evidence of two major periods of change in the climate that significantly affected levels of all four lakes. One period occurred during 1923-1938:

- The variability of the levels of all lakes was exceptionally high during these 16 years.
- The levels reached lows in 1923-1926, rose rapidly (1927-1929), fell rapidly (1930-1932), and reached record lowest levels in the 1930s.
- After this period, the levels of Lakes Michigan, Huron, and Erie increased (but not that of Lake Superior).
- After this period the variability of Lakes Michigan, Huron, and Erie was much greater than in prior years (but not that of Lake Superior).

The second period of instability occurred during 1973-2001:

- The variability of levels on all four lakes (Michigan, Huron, Erie, and Superior) was exceptionally large in 1973-1987 and 1996-2001, but it did not match values during 1923-1938.
- All four lakes had record or near record highs twice during 1973-1987, with 1982-1987 being the highest period on all lakes.
- Lake levels oscillated, descending rapidly twice: during 1987-1989 and 1998-2001 (greatest fall during the 141-year period).

Other studies have noted there had been some form of climate change on the basin during the 141-year period. One such change was reported to have occurred around 1970 (Hartmann, 1988), and the Great Lakes Commission (1986) noted a change in annual precipitation around 1940. Another study that compared precipitation on the basins of Lakes Superior and Michigan-Huron concluded that a major change had occurred during the late 1920s (Changnon et al., 1990). These various observations had identified one of the two periods of change noted herein.

The second important climate-related finding is the clear evidence of major spatial differences in the climates of the basins of the lakes. Climate conditions controlling lake levels on Lakes Michigan-Huron are quite different than those controlling levels of Lake Superior:

- Their average height distributions for 1861-2001 are totally different.
- Times of most of their near record highs and lows differ, particularly for the high levels, although agreement was reached in the two exceptional climate periods (1923-1938 and 1973-2001).
- The variability of levels on Lakes Michigan-Huron (for all durations) is much higher than that for Lake Superior, with the variability of Lake Michigan levels increasing steadily after 1936, but not the Lake Superior levels.

Others have noted these differences in the behavior of the lake levels and hence climate conditions. Brinkmann (1983b) found a distinct climate difference between the two basins, and another study found major temporal disagreements in the incidence of 12-year wet and dry periods (Changnon et al., 1990). The correlation coefficient between the precipitation of the two lakes is only +0.62. Angel (1996) found differences in the temporal distribution of rain-producing cyclones with trends upward over time on Lakes Michigan-Huron and Erie, but no upward or downward trends in cyclone frequency over the Lake Superior basin.

Due to the large influence of the outflow from Lakes Michigan-Huron on the levels of Lake Erie, a good interaction is expected, and many aspects of the levels of Lakes Michigan-Huron and Erie were alike. This included their average long-term distributions (flat, then increasing after 1935), their joint increases in variability of levels after 1935, and in the times of occurrence of their record high and low levels. However, the levels of the two lakes disagreed in three ways. The highest levels on Lakes Michigan-Huron were in 1860-1890, but the highest levels on Lake Erie came during 1970-2000. Furthermore, the high variability of levels and the highest levels attained for 25-year moving average periods did not correspond.

Examination of the extremes and fluctuations in the lake levels for 5-year periods showed more agreement among the lakes than found in their levels for 15- and 25-year periods. This reveals that climate conditions affecting the lake levels, precipitation and evaporation, are more frequently similar across all four basins for short-term periods, such as 5 years, but the conditions differ much more when sampled over 15-year or longer periods.

The 1925-1937 period of great variability and record-low lake levels was followed by a shift in the climate on three lakes (Michigan-Huron and Erie). This has been noted to have been an ever wetter period (Karl and Knight, 1998) and a cooler period (Lettenmaier et al., 1994) over their basins, conditions conducive to increased lake levels. On Lake Superior's basin the temporal precipitation increase did not occur and temperatures rose over the last four decades, conditions that would not result in lake-level increases as occurred on the other lakes. A key question is: what type of climate will follow the unstable conditions of 1973-2001?

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