J. Great Lakes Res. 28(3):451–465
Internat. Assoc. Great Lakes Res., 2002

Secular Changes in Great Lakes Water Level Seasonal Cycles

Frank H. Quinn

Great Lakes Environmental Research Laboratory
National Oceanic and Atmospheric Administration
2205 Commonwealth Avenue
Ann Arbor, Michigan 48105

ABSTRACT. *The three primary scales of Great Lakes water level fluctuations are interannual, seasonal, and episodic. Of these three, the seasonal water level fluctuations have received relatively little attention. The Great Lakes water levels have a well defined seasonal cycle driven primarily by snowmelt in the spring and summer and lake evaporation in the fall and winter. The present average seasonal cycle ranges from 26 cm on Lake Superior to 38 cm on Lake Ontario. Great Lakes monthly water levels from 1860 to 2000 were used to assess changes in the seasonal cycle of each of the Great Lakes and Lake St. Clair over the past 140 years. Changes are found on all of the lakes during the period of record. They usually resulted in a decrease in seasonal range and a time shift in the months of seasonal maximum and minimum. The effects of lake regulation were found to be negligible in the case of Lake Superior and significant for Lake Ontario. The major changes on Lakes St. Clair and Erie are likely a result of changes in the connecting channels ice retardation rather than changes in seasonal hydrometeorology. Seasonal cycle regimes are delineated for each of the lakes and possible rationale for the changes discussed.*

INDEX WORDS: *Great Lakes, water levels, seasonal cycles, lake regulation.*

INTRODUCTION

The Great Lakes water levels have been fluctuating in the current general hydraulic regime since the Nippissing Flood, about 3,500 years ago. Of this long-term time series there are about 180 years of measurements to define and assess water level fluctuations. Lake level fluctuations are categorized into three primary time scales: interannual variability (2 m), seasonal cycles (20 to 40 cm), and episodic events such as storms and ice jams (50 cm to 3 m), and a secondary scale, the tidal scale, which is of limited interest due to the very small tidal range (1 to 5 cm). The inter-annual variability results from longer term changes in precipitation and air temperatures and is responsible for the record high and low monthly mean lake levels. The well developed seasonal cycle is primarily driven by seasonal changes in the water supply components, precipitation, tributary runoff, and lake evaporation. Changes in connecting channel ice retardation and jams, and lake regulation can also have significant impacts. Episodic lake level changes are due primarily to storm surges on the lakes and ice jams in the connecting channels. This study focuses on secular changes in the seasonal cycle of the individual Great Lakes and Lake St. Clair over the past 140 years. The seasonal cycle is important at the present time for assessing relative changes in the environment due to natural or anthropogenic effects, as well as assessing socio-economic impacts, commercial navigation, recreational boating, and hydropower, due to lake regulation.

The Great Lakes system, shown in Figure 1, encompasses the five Great Lakes, Lake St. Clair, and the St. Marys, St. Clair, Detroit, Niagara, and St. Lawrence rivers. The basin has a total land area of 534,000 km^2 with a water surface of 247,000 km^2. Two lakes, Superior and Ontario, are regulated by controlling their outflows according to approved regulation plans under the auspices of the International Joint Commission. The construction of the St. Lawrence Seaway began in the mid-1950s with the regulation of Lake Ontario following in 1959. The Lake Superior outlet has been modified since the late 1880s and the lake has been regulated since the early 1920s. Lake regulation has the potential to modify seasonal water level fluctuations as well as the interannual variability. In addition to regulation,

*Corresponding author. E-mail: fquinn@earthlink.net

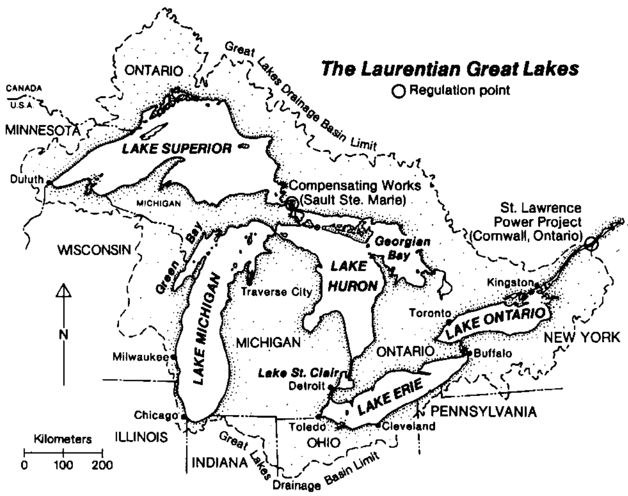

FIG. 1. Great Lakes basin.

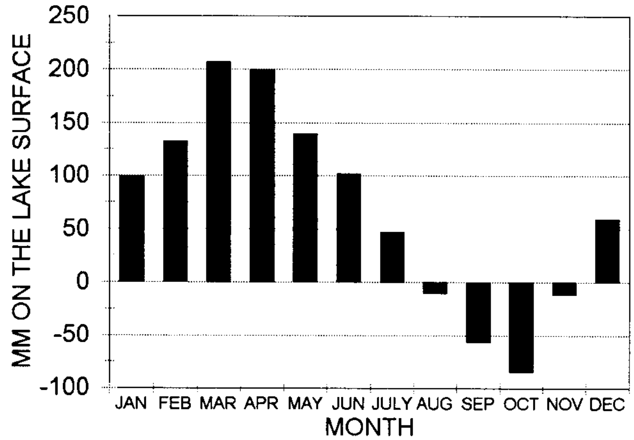

FIG. 2. Lake Erie net basin water supply (precipitation + runoff-lake evaporation).

the hydraulics of the system result in major backwater effects between Lakes Michigan-Huron, St. Clair, and Erie. Lakes Michigan and Huron are one lake hydraulically, as they are joined by the deep Straits of Mackinac. There have been major changes in the levels of Lakes Michigan and Huron due to uncompensated sand and gravel dredging and navigation projects this century between 1908 and 1960. The present hydraulic regime has been fairly constant with only small modifications since the early 1960s. There are also three interbasin diversions, the Lake Michigan Diversion at Chicago, which diverts water from Lake Michigan into the Mississippi River basin, and the Long Lac and Ogoki diversions, which divert water from the Hudson Bay watershed into Lake Superior. In addition, the Welland diversion, an intrabasin diversion, diverts water from Lake Erie to Lake Ontario.

Great Lakes water level fluctuations are governed by the hydrologic water balance expressed as equation (1).

$$P + R + Q_I = E + Q_O \pm D \pm \Delta S \qquad (1)$$

where: P is the precipitation falling on the lake surface
R is the runoff into the lake from it's tributary streams
Q_I is the connecting channel inflow
E is the evaporation from the lake surface
Q_O is the connecting channel outflow
D are diversions into or out of the basin
ΔS is the change in storage $(L_t - L_{t\text{-}1})$
L_t is the lake level at time T

Units are expressed in either mm or cm on the lake surface.

Seasonal water level variations are driven primarily by seasonal changes in the hydrologic water balance of the lakes. Figure 2 illustrates the changes in the seasonal water supply components (P, R, E) during a typical year for Lake Erie. As the precipitation is fairly uniform during the year, the seasonal water supply (P+R-E) is driven by a combination of low evaporation and high tributary runoff during the spring and high evaporation and low tributary runoff during the fall and winter. In addition, the seasonal cycle could also be affected by changes in connecting channel flows (Q_I, Q_O) resulting from water management (lake regulation) of Lakes Superior and Ontario and by navigational dredging projects and ice jamming in the St. Clair, Detroit, and Niagara rivers. The difference between the lake inflow (basin water supplies plus connecting channel inflows and diversions) and lake outflow (connecting channel outflows plus diversions) causes the lake to either rise or fall (Fig. 3). The characteristics that will be assessed for each of the lakes in this study are the monthly average seasonal values, the seasonal range, and the timing of the monthly maximum and minimum levels. The seasonal range is defined as the difference between the recorded monthly winter minimum level and the following recorded monthly summer maximum level.

METHODOLOGY

Recorded Great Lakes water level data are available from 1819–present (Foster and Whitney 1851, Fuller 1928, Tait 1983, Quinn and Sellinger 1990,

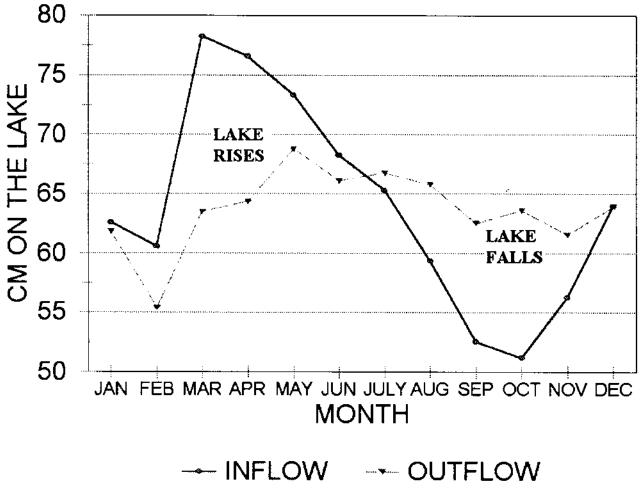

FIG. 3. Lake Erie water balance.

Angell *et al.* 1896, National Ocean Service 2001). The primary water level data used in this study are monthly values for the period 1860 to 2000, as measured at the long-term water level gages of Marquette and Marquette Coast Guard (Lake Superior), Harbor Beach (Michigan-Huron), Grosse Pointe Yacht Club and St. Clair Shores (Lake St. Clair), Cleveland (Lake Erie), and Oswego (Lake Ontario). The data for Lake St. Clair are from 1900 to 2000. Two secondary water level data sets, Lake Superior unregulated (after Quinn 1978), and Lake Ontario unregulated (International St. Lawrence River Board of Control 1997), are used to assess the role of lake regulation on changes in the seasonal cycle. These data sets simulate Lake Superior and Lake Ontario water levels under unregulated conditions. Figure 4 shows the basic monthly time series data for each of the lakes, which illustrates the interannual variability as well as a strong seasonal component.

The seasonal component is commonly extracted from the time series (Chatfield 1980) by subtracting a monthly value from a centered weighted moving average, equation (2).

$$SL_J = L_{J,M} - (.5 * L_{J-6} + \sum_{J-5}^{j+5} L_j + .5 * L_{J+6})/12 \qquad (2)$$

where: SL is the monthly seasonal water level
L is the measured water level
J is the month
M is the year.

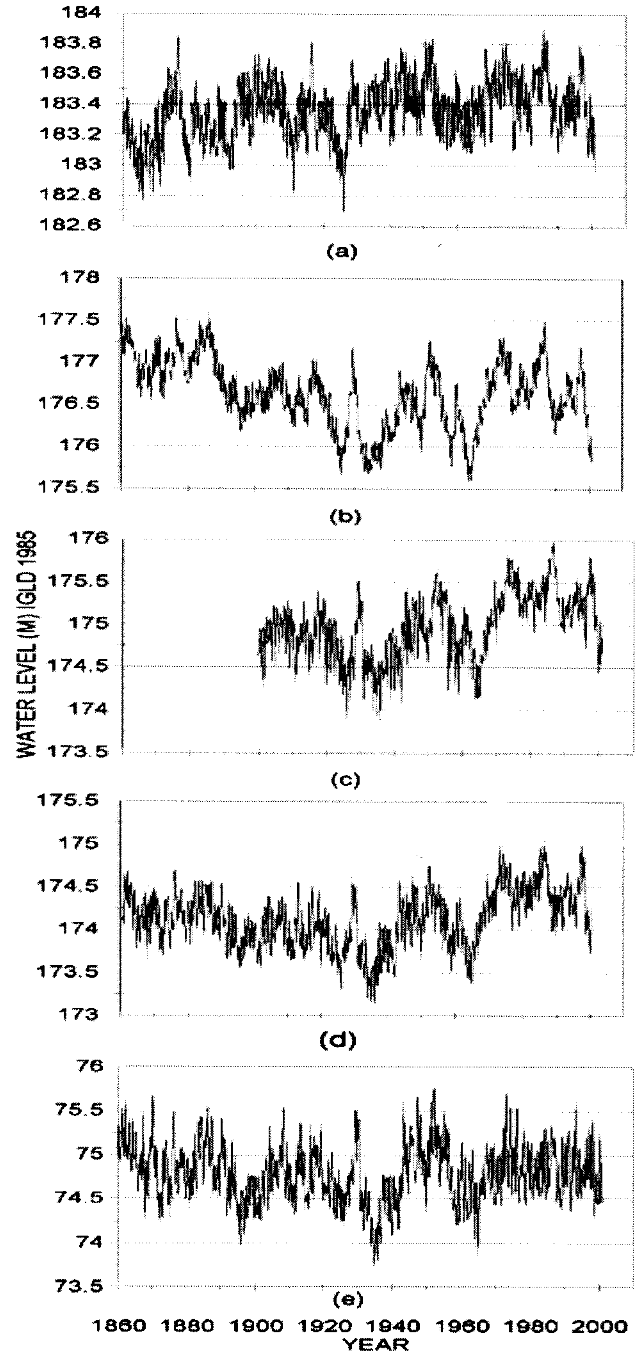

FIG. 4. Great Lakes monthly water levels. (a) Lake Superior, (b) Lake Michigan-Huron, (c) Lake St. Clair, (d) Lake Erie, (e) Lake Ontario.

Lenters (2001) took an alternative approach by analyzing the time series of incremental differences in monthly mean lake levels.

The primary analysis tool for determining changes in the seasonal cycle and range is the cu-

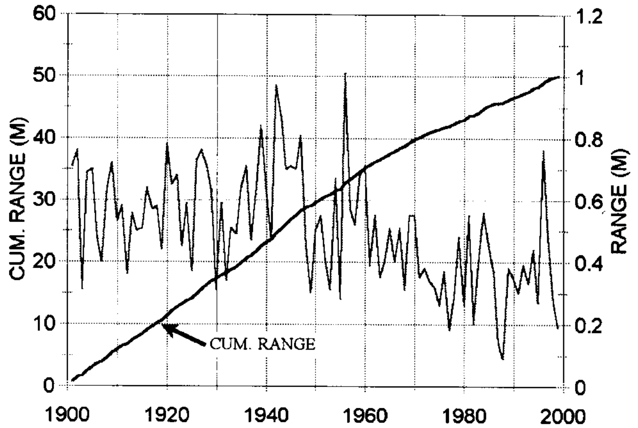

FIG. 5. Lake St. Clair seasonal range analysis.

mulative mass curve procedure (Wisler and Brater 1959). This is a common technique used in hydrologic analysis. The slope of the mass curve represents the annual range or seasonal level per year. Changes in slope reflect changes in the variable under consideration, with the inflection point determining the year of the change. This is illustrated by Figure 5 for the Lake St. Clair seasonal range. The period of time between inflection points represents a potential levels regime. Whether successive regimes in seasonal levels or range are statistically different is measured by the standard two sided T Test with a significance level of 0.05. The seasonal timing of monthly maximum and minimum levels will then be determined by assessing the months in which the minimum and maximum seasonal levels occur. Where possible, changes in the seasonal regimes will be assessed for potential anthropogenic, regulation or ice retardation, or climatic causes.

RESULTS AND DISCUSSION

Seasonal Range

As stated earlier, the seasonal range is the difference between the winter recorded monthly minimum and the following recorded summer monthly maximum. The seasonal range for each lake is shown in Figure 6. It should be noted that changes in the seasonal cycle may not necessarily result in changes to the seasonal range. This is because the seasonal maximum and minimum months may change without changing the range.

Lake Superior water levels have been influenced by both climatic and anthropological impacts. Extensive modifications have been undertaken to its outlet channel, the St. Marys River, since the late 1888s with the period 1860 to 1887 considered to represent the natural regime of the system (Coordinating Committee 1970, Freeman 1926). The first compensating gate to control lake outflows was constructed in 1900 with the final gate being completed in 1920. The lake outflows have been regulated by the operation of these compensating works, along with power diversions, since 1920 under the auspices of the International Joint Commission (Hartmann 1988). Because of its large size, 82,100 km^3, and large ratio of lake surface to drainage basin, 0.47, the lake has a major buffering effect on seasonal hydrologic fluctuations.

An assessment of Figure 6(a) and a mass curve of the seasonal range for Lake Superior indicates potential changes about the years 1888, 1916, 1943, and 1980 as shown in Table 1. The T tests indicate that only the change occurring around 1979 is statistically significant at the 0.05 level of significance when compared with the preceding period. The period from 1980 to 2000, however, is not significantly different from 1916 to 1942, another period of relatively low range. This indicates that the lower range is likely the result of normal climate variability, and not a necessary indication of cli-

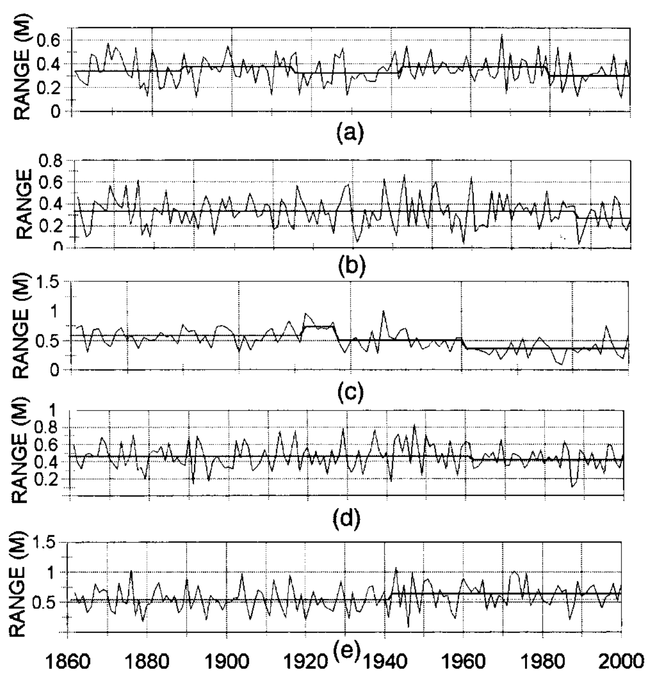

FIG. 6. Great lakes seasonal range. (a) Lake Superior, (b) Lake Michigan-Huron, (c) Lake St. Clair, (d) Lake Erie, (e) Lake Ontario.

TABLE 1. Seasonal range analysis.

Lake	Time Period	Range (m)	St. Dev (m)
Superior	1861–1887	0.34	0.13
Superior	1888–1915	0.37	0.09
Superior	1916–1942	0.32	0.11
Superior	1942–1979	0.37	0.10
Superior	1980–2000 *	0.30	0.11
MI-Huron	1861–1986	0.33	0.14
MI-Huron	1987–2000	0.27	0.12
St Clair	1901–1941	0.58	0.14
St. Clair	1948–1970*	0.50	0.16
St. Clair	1971–2000*	0.36	0.14
Erie	1861–2000	0.46	0.15
Ontario	1861–1941	0.54	0.19
Ontario	1942–2000*	0.64	0.21
Ontario	1960–2000	0.65	0.18
Ontario (unregulated)	1960–2000	0.55	0.20

* Months that are statistically different from the preceding regime at the 0.05 significance level.

mate change. Likewise, a similar analysis using the Lake Superior unregulated data set shows corresponding changes in range as in the recorded data, also indicating climatic variability as the reason for the lower range rather than changes in Lake Superior regulation. A comparison of the unregulated average range with the recorded average range for the period 1980 to 2000 shows a difference of only 1 cm, within the accuracy of the computations. Thus regulation has no significant impact on the present regime.

An assessment was also undertaken to determine if the seasonal levels or the seasonal range is a function of the lake level at the seasonal minimum, taken here to be the month of March. The lake level could potentially impact the seasonal cycle by the Lake Superior regulation plan calling for the discharge of more water from the lake in the spring and summer during high winter water levels than during low ones. No correlation, $r^2 = .11$, was found between the seasonal range and water level elevation. Similarly, correlation analysis between the March water levels and the seasonal maximum and minimum water levels showed little correlation, r^2 values of 0.01 and 0.14 respectively. Similar results were obtained when correlating either the maximum or minimum seasonal levels with the water level elevation.

As is the case for Lake Superior, the large size of Lake Michigan-Huron, 117,400 km^3, and large ratio of lake surface to drainage basin, 0.64, has a major buffering effect on seasonal hydrologic fluctuations. There have been many changes to the lake's outlet, the St. Clair River, over time which have increased the flow efficiency of the river (Coordinating Committee 1998, Brunk 1961, Quinn *et al.* 1993). Derecki (1985) found that the lake levels of Lake Michigan-Huron have been permanently lowered by 27 cm during the 20th Century alone. However, the seasonal range in Lake Michigan-Huron water levels shows no apparent changes from the late 1870s through the present time. There have been small periods of scattered high and low values but no apparent persistence of high or low values. The period around 1863 to 1873 is the highest sustained period of seasonal range in the record. The period 1987 to present is the longest period of sustained low seasonal range. While not statistically significant from the prior period at the 0.05 significance level, a 0.09 significance level, it is shown on Figure 6 as a separate regime. This is because it is a trend which appears to be continuing into the future. An assessment was also conducted to determine if the seasonal range is a function of the lake level, represented by the annual maximum monthly water level. The results, similar to Lake Superior, showed no correlation between the seasonal range and water level elevation.

Lake St. Clair, with a surface area of 1,114 km^2, is the smallest lake in the Great Lakes system. With such a small surface area, the lake responds rapidly to small changes in its seasonal water supply. Also, with a land basin area of only 12,430 km^2, much of which is sewered and does not enter the lake, 98% of its water supply comes from the St. Clair River and only 2% from the lake's net basin supply. Thus the lake responds rapidly to even small seasonal changes in its connecting channel inflows and outflows, the St. Clair and Detroit rivers respectively. Unlike the Great Lakes, consistent water level data for Lake St. Clair, based upon two lake gages, is published only back to 1900. Additional data are available back to the 1860s, but most are extrapolated from other gages. The lake is dramatically affected by ice retardation primarily in the St. Clair River and secondarily in the Detroit River. Ice jams and blockages restrict the flow in the St. Clair River by up to 50%, causing major changes to the Lake St. Clair inflows. Being small, the lake levels drop sharply while water is being drawn out of storage to feed the Detroit River. Thus changes in ice retardation, due either to climatic or anthropological causes (dredging, ice breaking, etc.) will cause either an increase in the seasonal range if ice retardation increases or a decreased range if the ice retardation decreases. As is shown on Figure 6, the maximum range is slightly over 1 m. The ice retardation was fairly constant between the beginning of the record and 1941. A major decrease in the seasonal range is apparent beginning in the late 1940s through 1970 with a substantially large decrease between 1971 and 2000. These decreases were statistically significant, as shown in Table 1, resulting in a decrease of 38%, from 0.58 m to 0.36 m, between the early period and the last 30 years. This is the largest decrease recorded in any of the lakes. As there were no anthropogenic changes during the early 1950s, the change was probably due to a change in wind patterns or in ice formation at the Lake Huron outlet or in the river itself which reduced ice jamming in the river. There was a major channel improvement in the lower St. Clair River from 1956 to 1962 (Coordinating Committee 1998), which reduced the ice retardation (Korkigian 1974, Quinn 1973). This decrease is likely the result of dredging a cutoff channel for navigation which would increase the winter flow capacity of the river. Thus the changes in the seasonal range can be attributed to changes in ice retardation likely due to the channel improvements coupled with increased Coast Guard ice breaking to assist navigation and alleviate local flooding and ferry operations. The largest single month of ice retardation was in April 1984 when the flow in the St. Clair River was reduced by about 40%.

Lake Erie, with a surface area of 25,700 km^2, is the second smallest of the five Great Lakes. The lake responds rapidly to small changes in its seasonal water supply due to the relatively small surface area. Eighty five percent of its water supply comes from the upstream lakes, and only 15% from the lake's net basin supply (Quinn and Guerra 1986). Thus the lake responds to changes in the upstream water supplies, changes in the Lake Erie net basin water supplies and changes in the connecting channel ice retardation/jams. The analysis of the Lake Erie seasonal range using Figure 6 and a mass curve of Lake Erie range vs. time shows that there is basically one regime broken by a period of unusually high range in the 1940s and early 1950s. There was no significant difference between the periods 1861 to 1942 and 1962 to 2000 using the T test. What is notable is both the slightly decreased mean from 1962 to 2000 and a decrease in variability of 20% when compared with the 1861 to 1942 period. This is probably due to the installation of the Niagara River ice boom at the head of the Niagara River in the early 1960s which has greatly reduced ice jams and retardation in the upper Niagara River.

Lake Ontario, with a surface area of 18,960 km^2, is the smallest of the five Great Lakes. The lake responds rapidly to small changes in its seasonal water supply due to the relatively small surface area. The construction of the St. Lawrence Seaway the mid-1950s (Becker 1984) and the subsequent regulation of Lake Ontario (Snyder and Clark 1958) following in 1959 had a major impact on the lake's water level regime. The regulation plan, Plan 58D, has been used during most of the regulated regime. This plan was based upon the exact sequence of water supplies from 1860 to 1958. Deviations from the plan have been frequent over the past 40 years. The regulation has had a major impact during extreme lake levels. Both Figure 6(e) and a mass curve of cumulative range vs. time show a significant increase in the seasonal range beginning in around 1940. The range has increased by 19%, from an average of 54 cm for 1860 to 1941 to 64 cm for the period 1942 to 2000. This corresponds to the same increase noted in the Lake Erie analysis, but without the decrease beginning about 1962 for Lake Erie. The impact of regulation on the period 1960 to 1999 was assessed using simulated Lake Ontario unregulated levels and comparing ranges that would have occurred without regulation with the actual recorded values. Unlike the Lake Superior situation, the regulation of Lake Ontario has had a significant impact on the seasonal range. The range under regulation for the 1960 to 1999 period is 10 cm higher (16%) than it would have been without regulation. In its unregulated state Lake Ontario would have responded in similar fashion as Lake Erie in this period

Seasonal Cycle

The seasonal water levels computed by equation (2) for each lake are shown in Figure 7. For each lake individual plots and mass curves, cumulative monthly seasonal water levels, were constructed for each month for the period 1860 to 2000. Figure 8 demonstrates the changes in the seasonal cycle for the month of maximum change for each lake. Changes in slope for the mass curves for Lake Superior were noted for each month and the results were combined to yield four potential seasonal regimes, 1861 to 1930, 1931 to 1940, 1941 to 1982, and 1983 to 1999. The seasonal regimes comprise the time periods between consecutive changes in

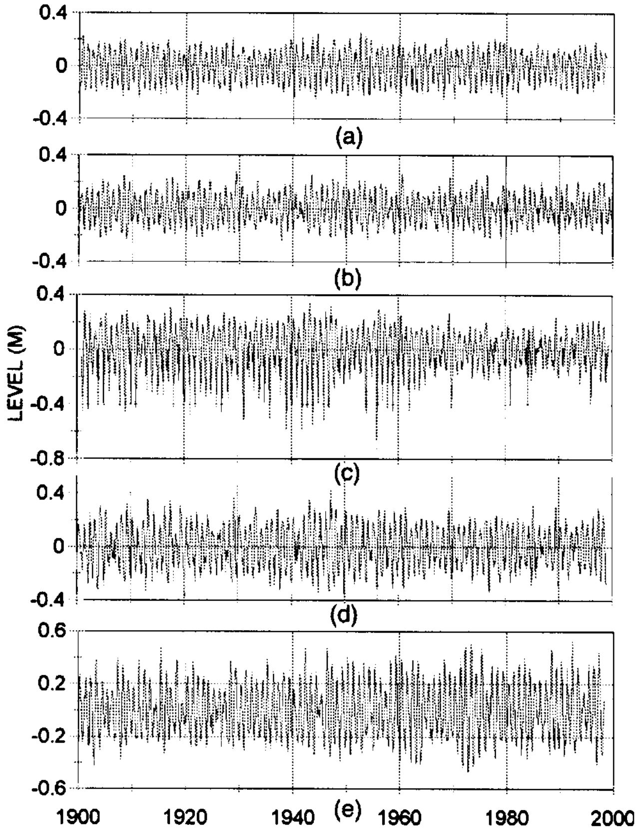

FIG. 7. Great Lakes seasonal water levels. (a) Lake Superior, (b) Lake Michigan-Huron, (c) Lake St. Clair, (d) Lake Erie, (e) Lake Ontario.

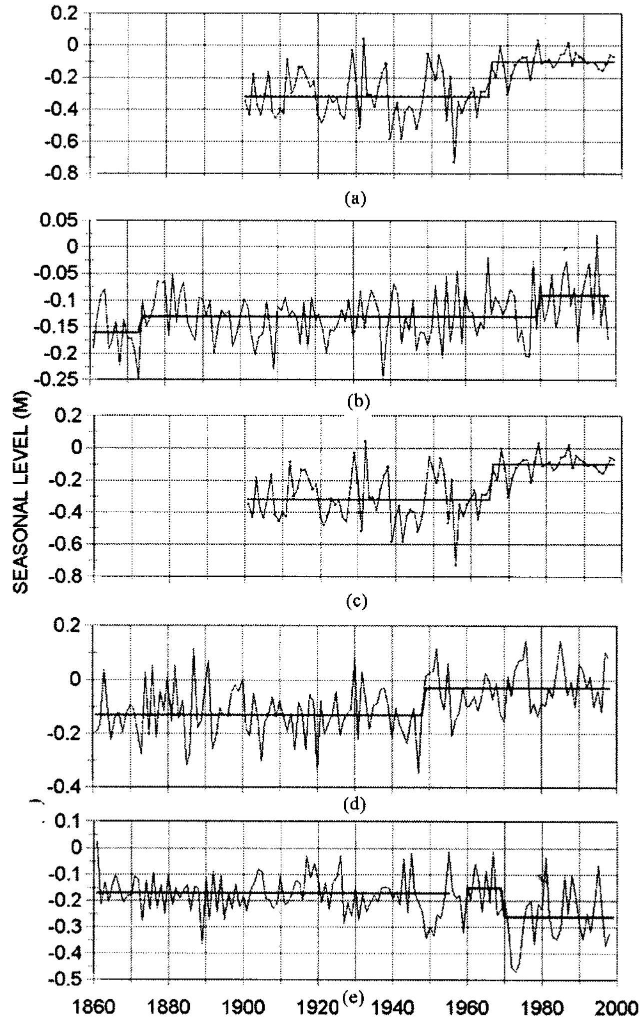

FIG. 8. Examples of monthly seasonal water level analysis. (a) Lake Superior January, (b) Lake Michigan-Huron January, (c) Lake St. Clair February, (d) Lake Erie March, (e) Lake Ontario November.

slope for the mass curves. It should be noted that the exact year of the regime change is subjective and two researchers might come up with slightly different regimes. The adjacent potential regimes were tested for statistical significance on a monthly mean basis using the standard two sided T Test. Regimes are considered as distinct if two or more monthly comparisons are significant at the .05 significance level. Table 2 gives the monthly means for the various regimes. Figure 9(a) shows the seasonal cycle comparisons for the four regimes. The significant differences are in the winter and spring seasons.

The seasonal regimes, with the exception of 1983 to 1998, correlate well with changes in the Lake Superior outlet conditions. The period from 1860 to the late 1880s is considered to be the natural regime of the system. Beginning with the construction of the International Railway Bridge until around 1900, the St. Marys River had a number of channel constrictions. The construction of the compensating gates to offset the power diversion was began in 1901. In 1914 it was decided to completely regulate the Lake Superior outflows and the last compensating gate, completely closing the outlet, was completed in 1920. In addition, Ogoki and Long Lac interbasin diversions were begun in the early 1940s from the Hudson Bay watershed into Lake Superior. These could alter the seasonal Lake Superior water supply if the diversion releases into Lake Superior, particularly the Ogoki diversion, vary seasonally. All of these changes could have impacted the seasonal cycle. An assessment of the relative roles of regulation vs. climate variability in the shifting sea-

TABLE 2. Monthly means (m) for Lake Superior seasonal regimes.

Regime	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1861–1930	–.08	–.14	–.16	–.15	–.06	.03	.09	.12	.14	.13	.08	.00
1931–1940	–.07	–.12	–.15	–.15	–.04	.06	.11	.13	.12	.08*	.05*	–.02
1941–1982	–.08	–.14	–.19*	–.16	–.05	.04	.11	.14	.14	.11*	.07	.00
1983–1999	–.04*	–.11*	–.15*	–.13	–.06	.01*	.08*	.10*	.11*	.10	.07	.02*

* Months that are statistically different from the preceding regime at the 0.05 significance level.

sonal regimes can be undertaken by comparing the recorded levels with those which would have occurred without regulation. The methodology from Quinn (1978), using a water balance model based on the natural St. Marys River rating, was applied with water supplies and diversions from 1900 to 1999 to determine unregulated water levels. These resulting levels were seasonally adjusted as per equation (2) and compared with the recorded seasonal levels. The four regimes were intercompared using T scores as noted earlier. If the regimes were significantly different, as in the case of the recorded levels, it would imply that the regime changes were due primarily to climate variability rather than changes in lake regulation. This turned out to be the case for Lake Superior. In general, averaging over a regime, differences in seasonality are small, .02 cm or less, and within the likely accuracy of the unregulated model and water supply data. However, in general, the recorded values tended toward slightly increased winter values and slightly decreased summer values, particulary in the last regime. Also of interest is the observation that there are no significant differences in the standard deviations between the unregulated and recorded seasonal levels. These findings are due to the large surface area of Lake Superior coupled with a very small outlet capacity.

The Lake Michigan-Huron seasonal water levels are shown on Figure 7(b). Potential changes in the seasonal water level regimes were examined as before, using mass curves of the cumulative monthly seasonal water levels. Three regimes, 1861 to 1973, 1874 to 1979, 1980 to 2000, were found to be statistically different at the 0.05 significance level using the standard two sided T Test. Table 3 gives the monthly means for the three regimes. Figure 9(b) shows the seasonal cycle comparisons between the three regimes. The significant differences are in the winter and spring seasons. This is probably a combination of changes in seasonal water supplies and changes in ice retardation/jams in the St. Clair River which tends to store additional water on Michigan-Huron during the winter months. This will be discussed in greater detail for Lake St. Clair. The shift to a later minimum of March for the lowest seasonal water level of the year tends to corroborate the ice retardation hypothesis.

Unlike the Great Lakes, consistent water level data for Lake St. Clair are published only back to 1900. Additional data are available back to the 1860s, but much is extrapolated from other gages. The monthly levels (Fig. 4c) shows the same interannual variability as the large lakes with a high levels regime from 1969 to 1998. A major change in the lake's seasonal cycle is apparent beginning in the early 1960s. Six potential changes in the seasonal water level regimes, based upon mass curves of the cumulative monthly seasonal water levels, were identified. Three regimes, 1901 to 1950, 1951 to 1965, and 1966 to 2000, are identified as meeting the criteria for being statistically significant using the T Tests. Table 4 gives the monthly means for the three regimes. Figure 9 shows the seasonal cycle comparisons between the three regimes. Large differences are observed in both the winter and summer seasons with a major decrease in the robustness of the seasonal cycle from 1966 to present.

Lake St. Clair has experienced the largest changes in the seasonal cycle of any of the Great Lakes. The St. Clair River flow provides about 97 percent of the total water supply with the local net basin water supply providing the other three percent. Therefore the only cause of major changes in the seasonal cycle are changes in the seasonal distribution of St. Clair River and Detroit River flows resulting from changes in the winter ice retardation. The lake first shows a statistically significant change in the seasonal cycle affecting the month of March about 1950. The magnitude of the March seasonal level drops by about two-thirds, while the variability as measured by the standard deviations drops about 50% for the 1951 to 1965 regime. As there were no anthropogenic changes during the early 1950s, the change was probably due to a change in wind patterns or in ice formation at the

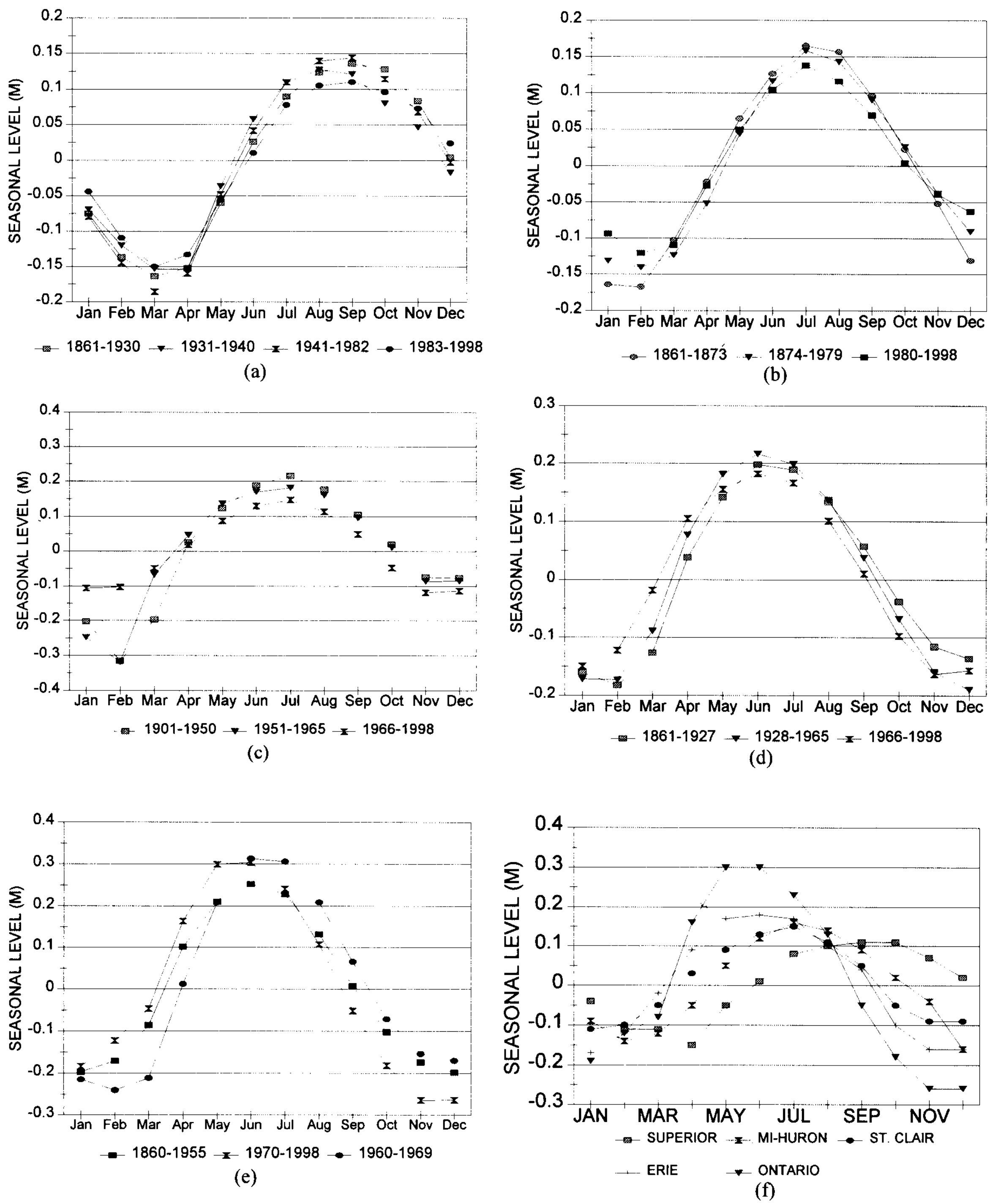

FIG. 9. Great Lakes seasonal cycles. (a) Lake Superior, (b) Lake Michigan-Huron, (c) Lake St. Clair, (d) Lake Erie, (e) Lake Ontario, (f) lake comparison.

TABLE 3. Monthly means (m) for Lake Michigan-Huron seasonal regimes.

Regime	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1861–1873	–.16	–.17	–.10	–.02	.06	.13	.17	.16	.10	.02	–.05	–.13
1874–1979	–.13*	–.14	–.13	–.05	.04	.12	.16	.14	.09	.03	–.04	–.09*
1980–1998	–.09*	–.13	–.11	–.03	.05	.10	.14	.12	.07	0.01	–.04	–.07*

* Months that are statistically different from the preceding regime at the 0.05 significance level.

TABLE 4. Monthly means (m) for Lake St. Clair seasonal regimes.

Regime	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1901–50	–.21	–.32	–.20	.03	.12	.19	.22	.18	.11	.02	–.07	–.08
1951–65	–.25	–.32	–.07*	.05	.14	.17	.18*	.16	.09	.01	.09	–.08.
1966–98	.11*	.10*	.05	02	09*	.13*	.15*	.11*	.05*	.05*	.12	–.11

* Months that are statistically different from the preceding regime at the 0.05 significance level.

Lake Huron outlet or in the river itself which reduced ice jamming in the river. Similar changes in the mean and standard deviation of the seasonal levels appeared around 1965 for the months of January and February. There was a major channel improvement in the lower St. Clair River from 1956 to 1962 (Coordinating Committee 1998), which reduced the ice retardation (Korkigian 1974, Quinn 1973). This decrease is likely the result of dredging a cutoff channel for navigation which would increase the winter flow capacity of the river. These seasonal changes were likely due to the channel improvements coupled with increased Coast Guard ice breaking to assist navigation and ferry operations and alleviate local flooding. The largest single month of ice retardation was in April 1984 when the flow in the St. Clair River was reduced by about 40%. Figure 10 shows the seasonal cycle for that year compared with the average for the current regime. The extreme impact of the ice retardation is readily apparent in April.

Five potential seasonal regime changes for Lake Erie were indicated by mass curves of the cumulative monthly seasonal water levels and the seasonal levels for January, February, and March. Three regimes, 1861 to 1927, 1928 to 1964, and 1965 to 2000, met the criteria for being statistically significant. The month of March shows a sharp change in seasonal levels occurring around 1950 which corresponds to a similar dramatic change on Lake St. Clair. This is expected as the Detroit River inflows to Lake Erie are a function of the Lake St. Clair water level. The remaining 11 months however showed no significant changes occurring around 1950. Therefore 1950 is not considered a breakpoint for regime changes. Table 5 gives the monthly means for the three regimes. Where there is no significant difference between the regimes, the average for the total period is used. Figure 9 (d) shows the seasonal cycle comparisons between the three regimes. Significant differences are observed in both the winter and summer seasons with a major changes in the January to March time frame. Lake Erie demonstrated a change in the seasonal cycle similar to Lake St. Clair. The monthly values in February and March show a pronounced shift upward with a corresponding drop in the summer maximum levels. This can be reasonably attributed to decreases in St. Clair River ice retardation. The Niagara River ice retardation was also dramatically reduced in 1963 with the placement of the Lake Erie ice boom at the head of the Niagara River. This

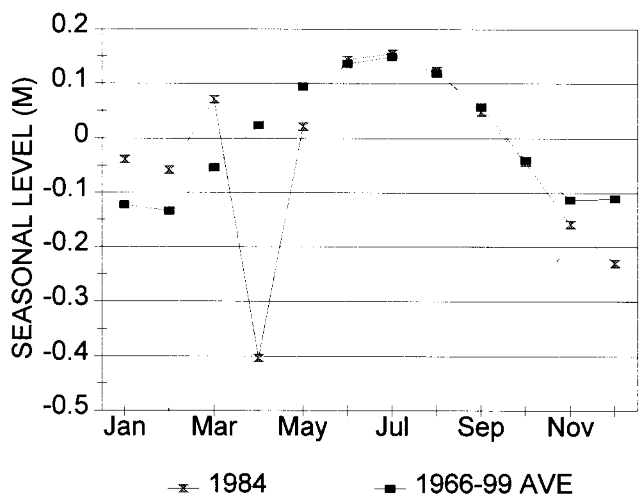

FIG. 10. Lake St. Clair 1984 seasonal cycle compared with the 1966-1999 average.

TABLE 5. Monthly means (m) for Lake Erie seasonal regimes.

Regime	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1860–1927	–.16	–.18	–.13	.04	.14	.20	.19	.13	.06	–.04	–.12	–.14
1928–65	–.17	–.17	–.09	.08*	.18*	.22	.20	.14	.04	–.07*	–.16*	–.19*
1966–98	–.15	–.12*	–.02*	.10	.15	.18*	.17*	.10*	.01	–.10*	–.16	–.16*

* Months that are statistically different from the preceding regime at the 0.05 significance level.

TABLE 6. Monthly means (m) for Lake Ontario seasonal regimes.

Regime	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1860–1955	–.20	–.17	–.09	.10	.21	.25	.23	.13	.01	–.10	–.17	–.20
1960–69	–.22	–.24	–.21*	.01*	.21	.31	.31*	.21*	.07*	–.07	–.15	–.17
1970–98[2]	–.18	–.12*	–.05	.16*	.30*	.30	.24*	.11	–.05*	–.18*	–.26*	–.26*
1960–69[1]	–.18	–.16	–.09	.10	.22	.25	.21	.10	–.02	–.14	–.19	–.15
1970–98[1]	–.15	–.14	–.04	.19	.30	.25	.18	.05	–.08	–.17	–.21	–.18

* Months that are statistically different from the preceding regime at the 0.05 significance level.
[1] Unregulated simulated levels.
[2] Compared with the 1660–1955 regime.

would tend to have an offsetting effect on the winter levels, reducing the impact of the St. Clair River changes in the ice retardation

Four seasonal regimes for Lake Ontario, 1860 to 1955, 1960 to 1969, 1970 to 1994, and 1985 to 2000, based upon mass curves of the cumulative monthly seasonal water levels, were investigated. Only the first four regimes met the criteria for being statistically significant from the adjacent regime. Therefore the last two regimes, 1970 to 2000, were combined. Table 6 gives the monthly means for the four selected regimes, while Figure 9 (e) shows the seasonal cycle comparisons. With the exception of the 1960 to 1969 low lake level period, the average for the total period is used where there are no significant difference between the regimes. The 1956 to 1959 period is not assessed as it includes the period of construction for the St. Lawrence Seaway. Significant differences are observed in both the winter and summer seasons with a major changes in the January to March time frame.

Lake Ontario is interesting because of its relatively recent regulation. The St. Lawrence Seaway construction on the St. Lawrence River took place between 1955 and 1959. Thus there are approximately 100 years of record prior to regulation and 40 years of record since regulation began. There have been some notable shifts in the seasonal cycle. There was a pronounced shift in the seasonal cycle in the 10 years following the onset of regulation. The regulation plan could not cope well with the extremely low water supply sequence in the mid-1960s, which resulted in a lowering of the winter levels and a delayed rise in the spring coupled with a delayed fall drop. The major impact of regulation is observed during the period 1970 to 1998. Regulation has resulted in a more robust seasonal cycle than pre-regulation with higher summer maximums and lower fall minimums. The timing also changes to an earlier spring rise and an earlier fall decline. The impact of regulation on these regimes was assessed using simulated unregulated levels (International St. Lawrence River Board of Control 1997), and comparing levels that would have occurred without regulation with the actual recorded values. Unlike the Lake Superior regulation, the regulation of Lake Ontario has had a significant impact on the seasonal water levels as illustrated in Table 6. These findings also support separating the impacts of regulation between high water supply periods, 1970 to 1999, and the low water supply regime of the 1960s for future water management studies.

Figure 9 (f) presents an intercomparison of the seasonal cycle for all of the lakes. The impacts of lake surface area and latitude are readily apparent. In general, the lakes with the smallest surface area will have the largest seasonal cycle. Lake Ontario with the smallest surface has the largest seasonal cycle followed by Lake Erie. Lakes Superior and Michigan-Huron have the smallest seasonal cycles. The role of latitude, reflecting snowfall and snowmelt, gives Lake Superior the latest seasonal peak. Lake St. Clair is driven by both Lakes Erie and Michigan-Huron.

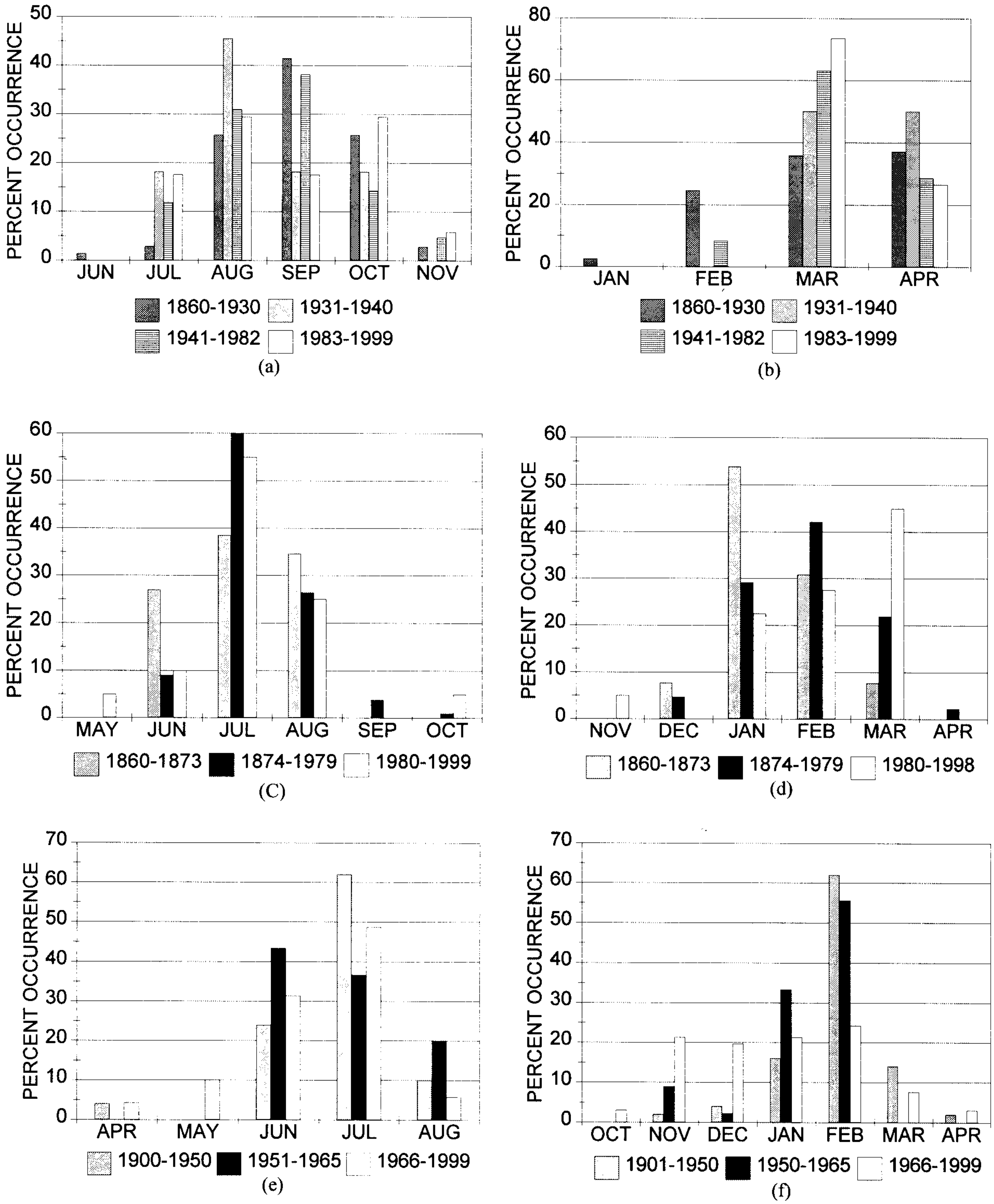

FIG. 11. Monthly distributions of maximum and minimum levels. (a) Lake Superior maximum levels, (b) Lake Superior minimum levels, (c) Lake Michigan-Huron maximum levels, (d) Lake Michigan-Huron minimum levels, (e) Lake St. Clair maximum levels, (f) Lake St. Clair minimum levels, (g) Lake Erie maximum levels, (h) Lake Erie Minimum levels, (i) Lake Ontario maximum levels, (j) Lake Ontario minimum levels.

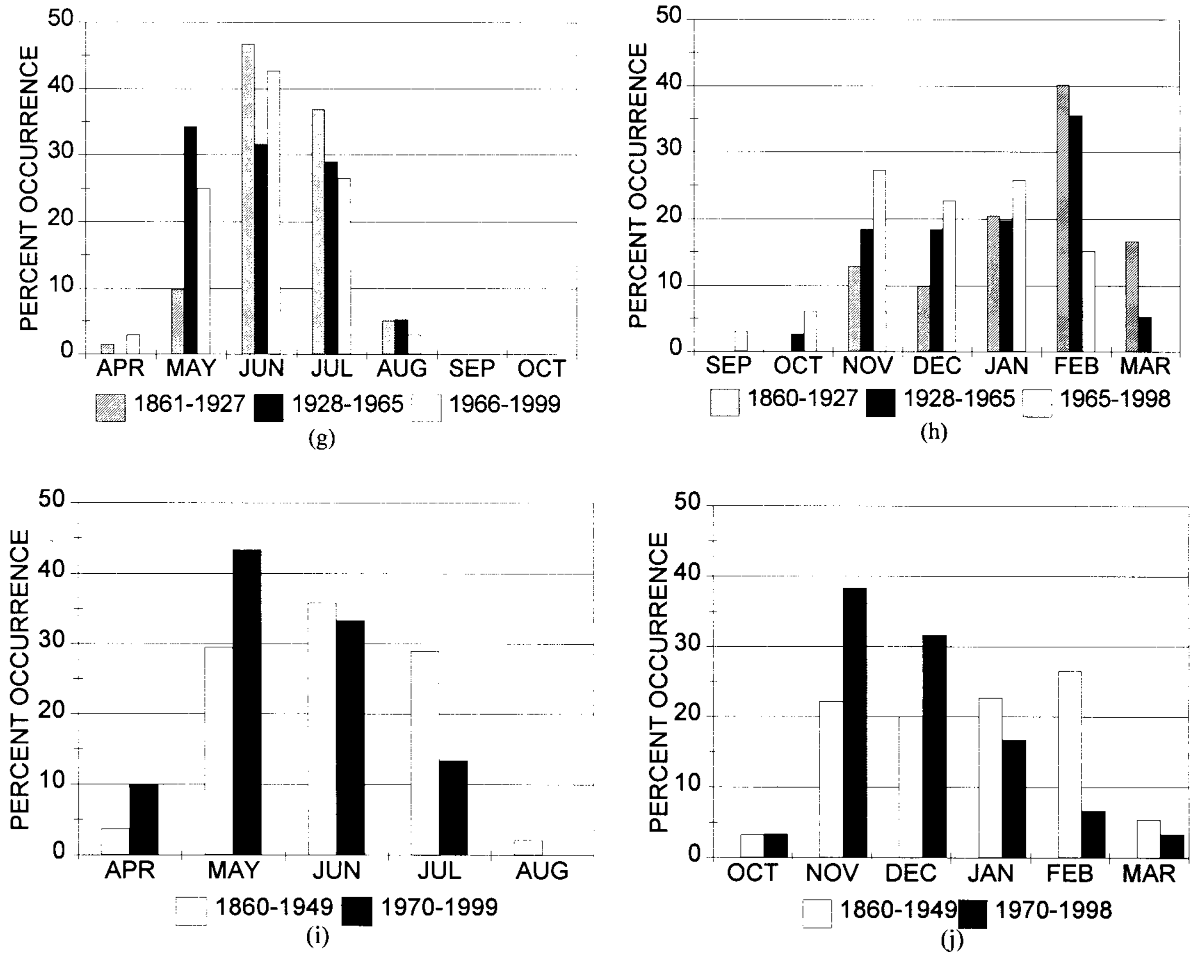

FIG. 11. (Continued).

Timing of Seasonal Maximum and Minimum Months

The final characteristic to be examined in this study is the distribution of months in which the seasonal maximum and minimum levels occur. The seasonal cycle presents a one-dimensional approach showing the month in which the average seasonal maximum and minimum levels occur. In reality, there is a distribution of months in each regime (Fig. 11) in which the minimum and maximum levels occur. The shifting of the distributions represents a measure of changing seasonality. The timing of the maximum and minimum months of the seasonal cycle for Lake Superior is illustrated in Figures 11(a)and 11(b). The distributions for the maximum regimes show a shift of 1 month from September to October as the month of most likely occurrence for the annual maximum and a major broadening of the distribution. The minimum distribution shows a shift of the minimum from either March or April for the earlier regimes to a predominance of March in the present regime. The occurrence of the minimum month being January or February was also dramatically reduced.

The distribution of months during which the seasonal maximum and minimum water levels occur for Lake Michigan is presented in Figures 11(c) and 11(d), respectively. There has been no significant shift in the month in which the seasonal maximum occurs. A significant increase in the frequency of March occurrences with a corresponding drop in January and February was observed. March is now the most frequent month for the minimum seasonal level to occur.

The minimum and maximum monthly distributions for Lake St. Clair for the two regimes, 1900 to 1960 and 1961 to 1998, are shown in Figures 11(e) and 11(f) for the months of maximum and minimum seasonal levels. The month of seasonal maximum still occurs in June. However there is a pronounced shift in the seasonal minimum, from 60 percent occurrence in February for the 1900 to 1965 regime to an approximately equal spread from November through April for the 1965 to 1998 regime.

The distributions for the maximum and minimum months of the seasonal cycle for Lake Erie are shown on Figures 11(g) and 11(h), respectively. A shift toward an earlier seasonal maximum is observed with a wider spread over May, June, and July for the present regime than occurred during the last century. A pattern of earlier minimums is also observed beginning about 1920. The winter minimum shows a major change from a 40% chance of a February minimum in the earlier periods to a minimum spread broadly over the November to February months for the present regime.

The distributions for the Lake Ontario maximum and minimum months are shown in Figures 11(i) and 11(j). Only the first and last regimes have enough data for a relevant comparison. A shift toward an earlier seasonal maximum beginning with a substantial increase in the occurrence of May maximums from June and July. The winter minimum also shows a significant change toward an earlier minimum with a shift from November to February for the 1860 to 1949 regime, to November and December for the present regime. November has replaced February as the most frequent month for the seasonal minimum. The past 30 years have seen unusually high water supplies to Lake Ontario accompanied by many deviations from the regulation plan which may account for the shift.

CONCLUSIONS

All of the Great Lakes and Lake St. Clair have experienced changes in their seasonal cycle over the past 140 years. Most of these changes appear to be due to anthropogenic rather than naturally occurring seasonal changes in climate. Four specific conclusions regarding the robustness of the seasonal cycle, the timing of the seasonal cycle, and the impacts of regulation on the seasonal cycles can be drawn from this study. All of the lakes, with the exception of Lake Ontario, have less robust seasonal cycles at the present time than in the 19th and first half of the 20th century. This decrease is dramatic for Lakes St. Clair and Erie where the seasonal range has decreased as much as 40 percent. The largest changes are in the winter months of December through March and appear to be associated with changes in the connecting channels ice retardation and jamming. The summer maximums are also reduced by the reduced ice retardation not holding the water back on Lake Michigan-Huron during the winter for release during the summer. Because of the importance of this phenomenon a careful investigation of the impacts of changed ice retardation should be undertaken, both to the extent of the changes as well as the physical mechanisms resulting in the change. The impacts of the Lake Erie ice boom are easily assessed, but the impacts on the St. Clair and Detroit rivers are harder to discern.

The seasonal cycle is independent of the interannual lake level elevation. There is no correlation between the seasonal maximum or minimum level and the lake level. Thus the average seasonal cycle is relevant and can be used for simulations under both high and low lake levels in a given regime.

The timing of the summer maximum monthly levels has changed from a month earlier peak for Lake Superior to a month later peak for Lake Ontario. In general, the winter minimum monthly levels are spread over a wider period. The Lake Michigan-Huron seasonal level has also shifted 2 months later, January to March, over the past 100 years.

The impact of lake regulation on the seasonal cycle is negligible for Lake Superior but important for Lake Ontario. The regulation has increased the seasonal range and shifted the seasonal cycle for Lake Ontario. These changes have resulted in detrimental impacts on the ecosystem, including wetlands and other habitat, and on recreational boating. However, changes due to regulation have increased benefits for commercial navigation, hydropower, and in some instances, resulted in reduced flooding and shore damage for riparians. The changed seasonal cycle should be considered in ongoing studies and analysis to modify the existing lake regulation plans.

ACKNOWLEDGMENTS

The author appreciates the excellent suggestions of the associate editor and reviewers in improving the manuscript. This manuscript is GLERL contribution #1229.

REFERENCES

Angell, J.R., Russell, J.E., and Cooley, L.E. 1896. *Report of the United States Deep Waterways Commis-*

sion. Washington, D.C: 54th Congress, House of Representatives, Document No. 192. Government Printing Office.

Becker, W.F. 1984. *From the Atlantic to the Great Lakes, A history of the U.S. Army Corps of Engineers and the St. Lawrence Seaway.* Washington, D.C.: U.S. Government printing Office.

Brunk, I.W. 1961. Changes in the levels of Lakes Michigan and Huron. *Journal of Geophysical Research* 66:3329–3335.

Chatfield, C. 1980. *The Analysis of Time Series: An Introduction.* Second Edition. London & New York: Chapman & Hall.

Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data. 1970. *Lake Superior outflow, 1860–1968.* Chicago Il.

______. 1998. *Hydraulic discharge measurements and regimen changes on the Great Lakes connecting channels and the International Section of the St. Lawrence River 1841–1993., Appendix B, Chronological summaries of construction and dredging.* Chicago Il.

Derecki, J.A. 1985. Effect of channel changes in the St. Clair River during the present century. *J. Great Lakes Res.* 11(3):201–207.

Foster, J.W., and Whitney, J.D. 1851. *Report of the Geology of the Lake Superior Land District. Part II, The Iron Region.* Special session of the U.S. Senate. March 1851.

Freeman, J.R. 1926. *Regulation of Elevation and Discharge of the Great Lakes.* Chicago, IL: Sanitary District of Chicago.

Fuller, G.N. ed. 1928. *Geological reports of Douglass Houghton, first state geologist of Michigan, 1837–1845.* Lansing, MI: The Michigan Historical Commission.

Hartmann, H.C. 1988. Historical basis for limits on Lake Superior water level regulations. *J. Great Lakes Res.* 14(3):316–324.

International St. Lawrence River Board of Control. 1997. *An updated regulation plan for the Lake Ontario-St. Lawrence River System.* Report to the International Joint Commission. Buffalo, NY.

Korkigian, I. 1974. Effect of ice on lakes levels. *Hydrologic Sciences Bulletin* XIX(1):35–51.

Lenters, J.D. 2001. Long-term trends in the seasonal cycle of Great Lakes water levels. *J. Great Lakes Res.* 27(3):342–353.

National Ocean Service. 2000. *Great Lakes water levels.* Silver Spring, MD: U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

Quinn, F.H. 1973. Effects of ice retardation on Great Lakes water levels. In *Proc. 16th Conf. Great Lakes Res.,* pp. 549–555. Internat. Assoc. Great Lakes Res.

______. 1978. Lake Superior regulation effects. *Water Resour. Bull.* 14:1129–1142.

______, and Guerra, B. 1986. Current perspectives on the Lake Erie water balance. *J. Great Lakes Res.* 12(2):109–116.

______, and C.E. Sellinger. 1990. Lake Michigan record levels of 1838, a present perspective. *J. Great Lakes Res.* 16(1):133–138.

______, Derecki J.A., and Sellinger, C.E . 1993. Pre-1900 St. Clair River flow regime. *J. Great Lakes Res.* 19(4):660–664

Snyder, F.F., and Clark, R.H. 1958. Regulation of Lake Ontario. *J. Hydraulics Division, ASCE,* Vol. HY3, Paper 1660, pp. 1–21.

Tait, B.J. 1983. *Conversion of historical Lake Erie water level elevations to International Great Lakes Datum (1955).* Ottawa, Ontario: Canadian Hydrographic Services.

Wisler, C.O., and. Brater, E.F. 1959. *Hydrology.* New York: John Wiley & Sons, Inc.

Submitted: 18 July 2001
Accepted: 20 May 2002
Editorial handling: Barry M. Lesht