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Long-term Trends in the Seasonal Cycle of Great Lakes Water Levels

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ABSTRACT. *Numerous long-term trends in the rate-of-change in monthly mean Great Lakes water levels are identified for the period 1860 to 1998. Statistically significant trends are found for 2, 4, 5, and 7 months of the year for Lakes Superior, Michigan-Huron, Erie, and Ontario, respectively. Many of the trends translate into large changes in net water flux (600 to 1,700 m^3/s). In each case, significant positive trends are roughly offset by negative trends during other times of the year. Together with similar trends in monthly lake level anomalies (deviations from the annual mean), these trends indicate important changes in the seasonal cycle of Great Lakes water levels. Specifically, Lakes Erie and Ontario are rising and falling (on an annual basis) roughly one month earlier than they did 139 years ago. Maximum lake levels for Lake Superior are also slightly earlier in the year, and the amplitude of the seasonal cycle of Lake Ontario is found to increase by 23% over the 139-year period. Some of the changes are consistent with the predicted impacts of global warming on spring snowmelt and runoff in the Great Lakes region. Other potential contributors to the observed trends include seasonal changes in precipitation and human-induced effects such as lake regulation and changes in land use.*

INDEX WORDS: *Lake levels, seasons, trends, Great Lakes, climate change, regulation.*

INTRODUCTION

Research on Great Lakes water levels has focused primarily on annual variations (Quinn 1981, Bishop 1990), connections with climate variability (Changnon 1987, Rodionov 1994, Brinkmann 1985), monthly changes in lake level (Quinn *et al*. 1979, Brinkmann 1983, Quinn and Guerra 1986, Brinkmann 2000), and/or impacts and regulation issues (Hartmann 1988, Changnon 1993, Meadows *et al*. 1997, Lee *et al*. 1998). Although many of these studies note significant interannual and decadal variability in Great Lakes water levels, no prolonged trends in lake levels have been observed. This partly reflects the natural "resistance" of the lakes to a long-term change in water storage: Higher (lower) lake levels lead to greater (less) outflow. Furthermore, Lake Superior and Lake Ontario have been directly regulated since 1921 and 1958, respectively (Loucks 1989), so there is also a human-induced resistance to significant changes in lake level. Nevertheless, a doubling of CO_2 has been projected to lower Great Lakes water levels by 0.5 to 2.5 m as a result of significant reductions in net basin supply (Smith 1991, Croley 1990, Hartmann 1990). Quinn (1981) and Bishop (1990) also point out that human regulation of the Great Lakes can only moderate, not eliminate, climate-induced variability. Thus, the potential impact of climate change on Great Lakes water levels remains an important concern.

A common limitation of earlier Great Lakes studies is the focus on annual lake levels and/or the mean seasonal cycle. This precludes the detection of long-term changes in the seasonal cycle itself, such as those related to earlier snowmelt. Indeed, earlier spring runoff to the Great Lakes is one of the predicted outcomes of increases in CO_2 (Croley 1990), and long-term increases in springtime temperatures have already been noted over the Great Lakes region (Bolsenga and Norton 1993). Other recent examples of change include decreases in Great Lakes ice cover (Hanson *et al*. 1992), increases in nearshore water temperature in some lo-

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cations (McCormick and Fahnenstiel 1999), and a steady advance in the seasonal cycle of Mississippi River discharge over a 123-year period (Baldwin and Lall 1999). Hanson *et al*. (1992) suggest a similar trend in the discharge of the St. Lawrence River at Cornwall, Ontario over a 35-year period. However, the significance of this relationship is never assessed. The goal of the current study is to alert the scientific community to some recently discovered long-term trends in the seasonal cycle of Great Lakes water levels. An assessment of the statistical significance is provided, but a rigorous analysis of the driving mechanisms is left for future studies.

METHODOLOGY AND DATA SOURCES

The annual rising and falling of lake levels is a well-documented feature of the Great Lakes (Quinn and Guerra 1986, Assel *et al*. 2000) and results from a combination of factors, including seasonal changes in river runoff and lake evaporation. The complete monthly water budget for a lake can be written as

$$\Delta L = P - E + k \cdot (R + I - O + G - C + D + T) / A \qquad (1)$$

where,

- ΔL = monthly change in lake level (cm)
- P = monthly total precipitation over the lake surface (cm)
- E = monthly total lake evaporation (cm)
- k = conversion factor (2.592×10^8 cm · s/m for a 30-day month)
- R = monthly mean land surface runoff into the lake (m^3/s)
- I = monthly mean inflow from an upstream lake (m^3/s)
- O = monthly mean outflow (m^3/s)
- G = monthly mean groundwater inflow (m^3/s; negative for outflow)
- C = monthly mean consumptive use (m^3/s)
- D = monthly mean water diversions (m^3/s)
- T = monthly mean rate of change in volume due to thermal expansion (m^3/s)
- A = lake area (m^2)

This study focuses on observations of ΔL and addresses the following questions: How have monthly changes in Great Lakes water levels varied over the period of record since 1860? What are some of the potential mechanisms (terms on the right hand side of Eq. (1))? What do these variations imply regarding the seasonal cycle of Great Lakes water levels? How do the observed changes differ from lake to lake?

In the present study, monthly changes in lake level are calculated as:

$$\Delta L = L_{t+1} - L_t, \qquad (2)$$

where L_t is the monthly mean lake level of the current month and L_{t+1} is that of the following month. Strictly speaking, Eq. (1) requires ΔL to be calculated as the difference between beginning-of month (or end-of-month) values, which requires careful averaging across multiple lake level gauges (Quinn *et al*. 1979). However, monthly mean lake levels are used here since such data are more readily available (and for a longer period of record) and more likely to be utilized by the user community. Furthermore, it is still possible to approximately satisfy Eq. (1) using monthly mean lake levels, so long as the terms on the right hand side of Eq. (1) represent 60-day center-weighted averages (of daily data). Nevertheless, an analysis of ΔL using beginning-of-month lake levels would be worthwhile to pursue in future studies, since it corresponds directly to monthly mean water fluxes (P, E, etc.).

Another useful parameter for examining seasonal lake level variations is the monthly lake level anomaly, L^*:

$$L^* = L_t - L_{ann}, \qquad (3)$$

where L_{ann} is the annual mean lake level for the current year. Thus, L^* represents the deviation of the current month's lake level from the annual mean, and the first derivative of L^* is proportional to ΔL. It is worth noting that the analyses which follow were also performed using the 12-month running mean lake level as L_{ann}, rather than the annual mean lake level. This was found to have little effect on the end results.

Monthly mean lake level data for each of the Great Lakes were obtained from the Center for Operational Oceanographic Products and Services (CO-OPS) which resides within the National Ocean Service (NOS) of the National Oceanic and Atmospheric Administration (NOAA). Lake Michigan and Lake Huron are treated as a single, hydraulically connected lake (hereafter referred to as Lake Michigan-Huron). Records were obtained for four benchmark stations (Marquette, MI—Lake Superior; Harbor Beach, MI—Lake Michigan-Huron; Cleveland, OH—Lake Erie; Oswego, NY—Lake On-

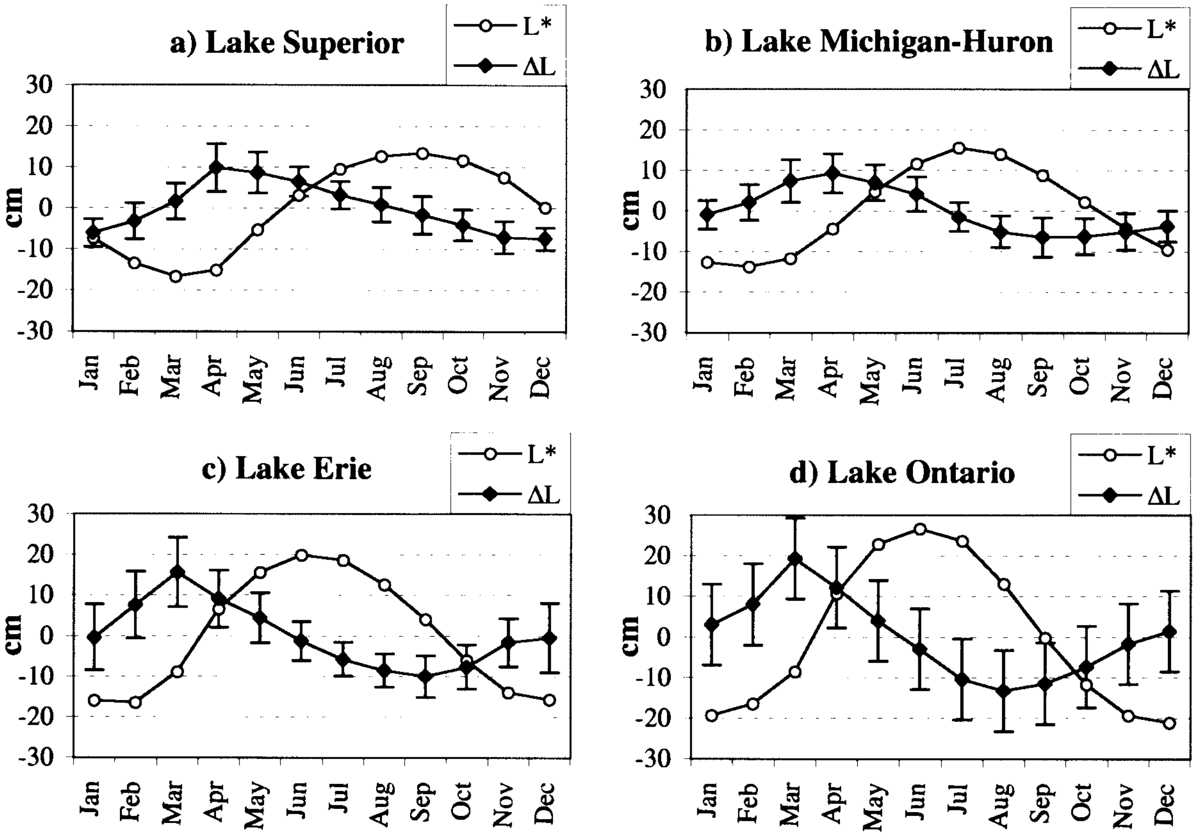

FIG. 1. Mean seasonal cycle (1860 to 1998) of change in monthly mean lake level (ΔL; closed diamonds) and lake level deviations from the annual mean (L^*; open circles). Positive (negative) ΔL in this figure corresponds to an increase (decrease) in L^* between the current and following month. Units are in cm, and error bars for ΔL denote the interannual standard deviation.

tario) for the 139-year period 1860 to 1998 (plus January of 1999). Data for Marquette, MI are missing from late 1980 onward and are filled with equivalent data from a nearby Coast Guard station. The remaining stations have complete data records. It should be noted that the use of a single station for each lake is not problematic for the data analysis for a number of reasons. First of all, short-term effects (such as seiches) are eliminated through the use of monthly mean (rather than daily) lake levels. Secondly, since the analysis focuses on month-to-month *changes* in lake level and *deviations* from the annual mean, long-term effects such as the impact of crustal movement are negligible (Quinn *et al.* 1979). Finally, the four stations selected contain some of the longest records of Great Lakes water levels (Bishop 1990) and have undergone numerous quality control checks (C. Sellinger, Great Lakes Environmental Research Laboratory, 18 July 2000, personal communication).

MEAN SEASONALITY OF LAKE LEVELS, 1860–1998

The mean seasonal cycles for both ΔL and L^* are shown in Figure 1 for each of the Great Lakes (averaged over 1860 to 1998), along with the interannual standard deviation of ΔL. As has been shown before, each lake shows a pronounced seasonal cycle, with positive ΔL during spring runoff and negative ΔL during late summer to winter, when evaporation is highest. This leads to lake level anomalies (L^* in Fig. 1) which, on average, peak in June for Lakes Erie and Ontario and July (September) for Lake Michigan-Huron (Lake Superior). Minimum L^* typically occurs during winter for all lakes except Lake Superior, which reaches its minimum in March (Fig. 1a). Note that Lake Erie and (especially) Lake Ontario (Figs. 1c–d) have a considerably stronger seasonal cycle (in both ΔL and L^*) than Lake Superior and Lake Michigan-Huron (Figs. 1a–b). This reflects their downstream position, larger drainage-to-lake area ratios, and possible differences in regional climate. Interannual variations in ΔL are also larger for Lakes Erie and Ontario, particularly during the winter and spring.

LONG-TERM TRENDS

Upon plotting ΔL as a function of time over the 139-year period (separately for each month and each lake), a number of striking trends are apparent. Eighteen of the 48 timeseries (4 lakes, 12 months) exhibit linear trends which are statistically significant at the 90% level (10 exceed the 99% level). Statistical significance is assessed using a standard F test (Wilks 1995), which assumes the residuals of the linear regression to be independent and normally distributed. Both ΔL and L^* exhibit little year-to-year correlation, and the distribution of residuals is roughly Gaussian (not shown).

The 18 timeseries with significant trends are shown in Figures 2 through 5, along with the 25-year running mean and 139-year linear trend (regressed against the raw ΔL). In all, two significant trends in monthly ΔL are found for Lake Superior (Fig. 2), four for Lake Michigan (Fig. 3), five for Lake Erie (Fig. 4), and seven for Lake Ontario (Fig. 5). Note that for each of the four lakes, significant positive trends in one month are nearly balanced by significant negative trends in another month (Figs. 2 through 5). This indicates important changes in the seasonality of ΔL over time, but with little or no change in the annual mean ΔL. (None of the lakes show trends in annual ΔL that exceed the 30% significance level.) Also note that all of the positive trends in ΔL occur between the months of November and April, while the negative trends occur most frequently in the spring and summer. For Lakes Superior and Michigan-Huron, for example, both show negative trends in February–March ΔL (Figs. 2a and 3b) and positive trends in November–December ΔL (Figs. 2b and 3d). Even the 25-year running mean timeseries are remarkably similar. In contrast to the upper lakes, Lakes Erie and Ontario both show positive trends in December–January ΔL (Figs. 4e and 5g) and January–February ΔL (Figs. 4a and 5a), but negative trends in May–June ΔL (Figs. 4d and 5c). Thus, there are some interesting

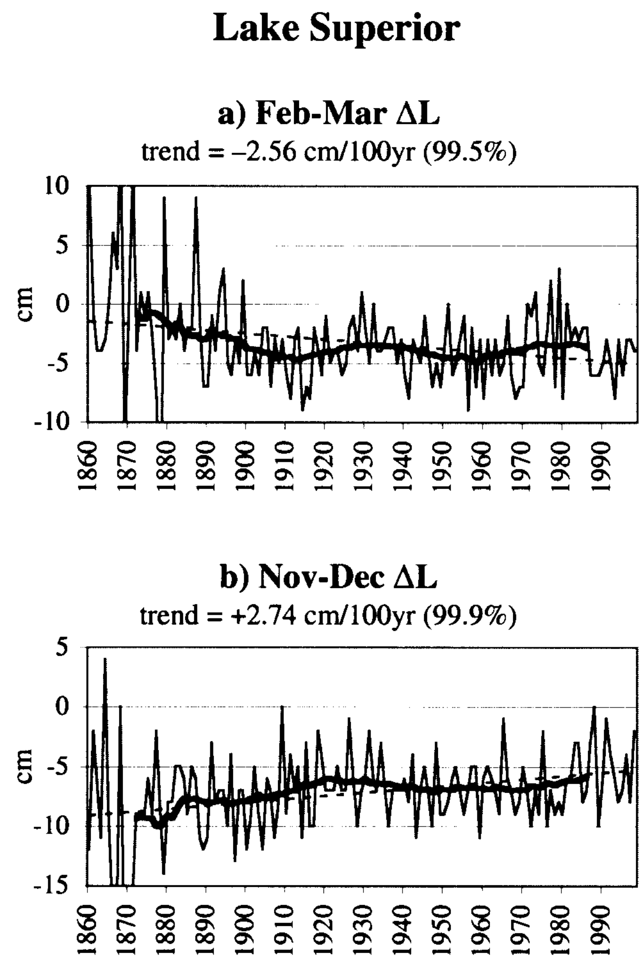

FIG. 2. Timeseries of a) February to March and b) November to December change in monthly mean lake level (ΔL, in cm) for Lake Superior over the period 1860 to 1998. Also shown are the 25-year running mean (thick, solid line) and 139-year linear trend (dotted line). Trend values and significance levels are noted.

contrasts between the ΔL trends of the upper and lower Great Lakes.

It is important to note that while some of the timeseries shown in Figures 2–5 follow the linear trend quite closely (e.g., Figs. 3d and 5d), others do not. For example, April–May values of ΔL for Lake Erie (Fig. 4c) hover around 10 cm from 1860 to the mid 1950s and then drop rapidly thereafter to less than 5 cm. Similarly, December–January ΔL for Lake Ontario (Fig. 5g) experiences a rise following the early 1960s which is much larger than that of the linear trend. Furthermore, there are a number of timeseries (not shown) which exhibit considerable

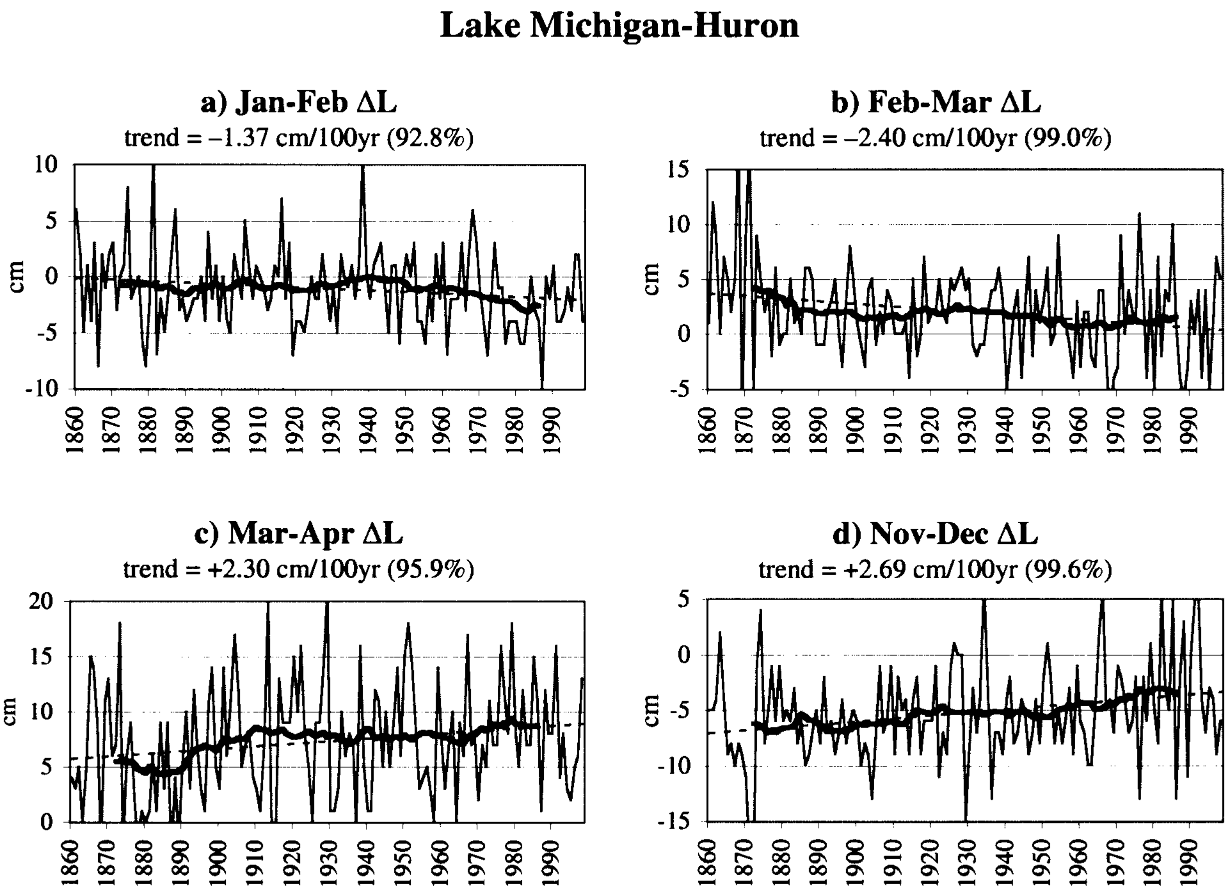

FIG. 3. As in Figure 2, but for Lake Michigan-Huron during a) January to February, b) February to March, c) March to April, and d) November to December.

decadal-scale variability, but with no significant linear trend over the 139-year period. Thus, the linear trends presented in this study are only meant to approximate the real long-term changes in lake hydrology. More extensive timeseries analyses of the precise interannual to decadal variations are left for future study.

In order to provide a better perspective of the magnitude of the observed trends in ΔL, Table 1 shows the same trends converted to an equivalent change in water flux over the 139-year period. Here cm/month have been converted to m^3/s by multiplying by lake area (assumed constant), and statistically significant trends are shown in bold. Some of the largest trends in Table 1 range from roughly 580 m^3/s for Lake Ontario to 1,670 m^3/s for Michigan-Huron. By comparison, the annual mean precipitation and evaporation over Lake Erie is roughly 730 m^3/s and 560 m^3/s, respectively, while the annual mean discharge of the Niagara River is roughly 5,800 m^3/s (Quinn and Guerra 1986). Thus, many of the trends in Table 1 represent non-trivial changes in the seasonal hydrology of the Great Lakes. Also evident in Table 1 is the tendency for seasonal trends to "accumulate and propagate" downstream. For example, one significant positive trend each for Lakes Superior and Michigan-Huron (in November–December) is followed by three significant positive trends each for Lakes Erie and Ontario later in the year (December to April). The negative trends show a similar pattern of being more frequent and later in the year for the downstream lakes. An exception to this pattern is the significant positive trend for Michigan-Huron during March-April.

Given the significant trends in ΔL, many of the same sign for adjacent months (Table 1), one might expect there to also be trends in L^* (lake level

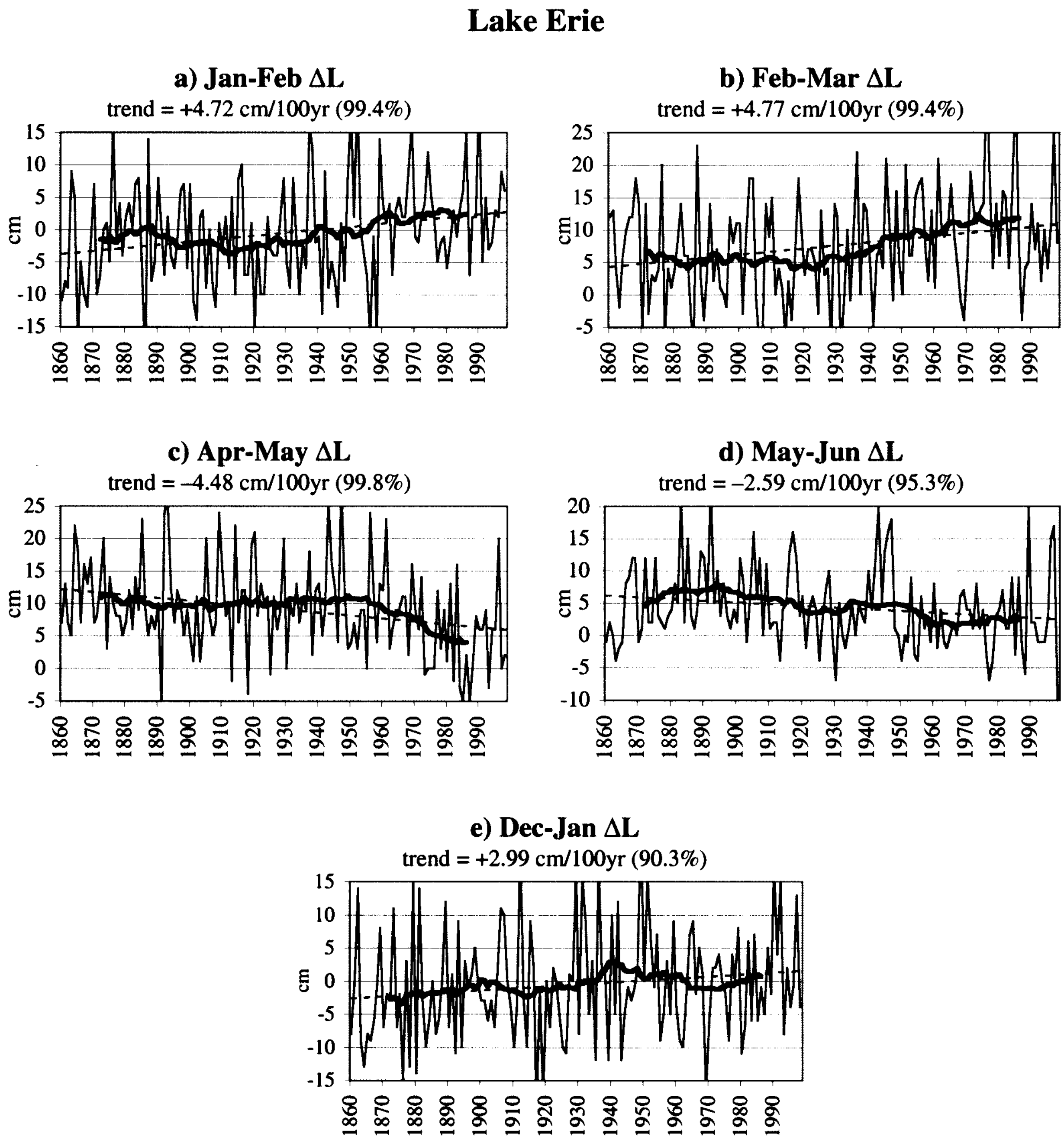

FIG. 4. As in Figure 2, but for Lake Erie during a) January to February, b) February to March, c) April to May, d) May to June, and e) December to January.

anomalies). This is indeed the case, as 14 of the 48 L^* timeseries exhibit significant trends (not shown). In particular, Lakes Erie and Ontario both show 139-year trends toward higher lake level anomalies during the first half of the year and lower anomalies thereafter. This is consistent with the pattern of ΔL trends already noted in Table 1. Lakes Superior and Michigan-Huron, however, show considerably weaker trends in L^* (consistent with the fewer trends in ΔL). In this case only one month (October, for Lake Superior) shows a significant (downward) trend. These results are best summarized in Figure 6, which shows the reconstructed seasonal cycle of L^* for the beginning (1860) and end (1998) of the

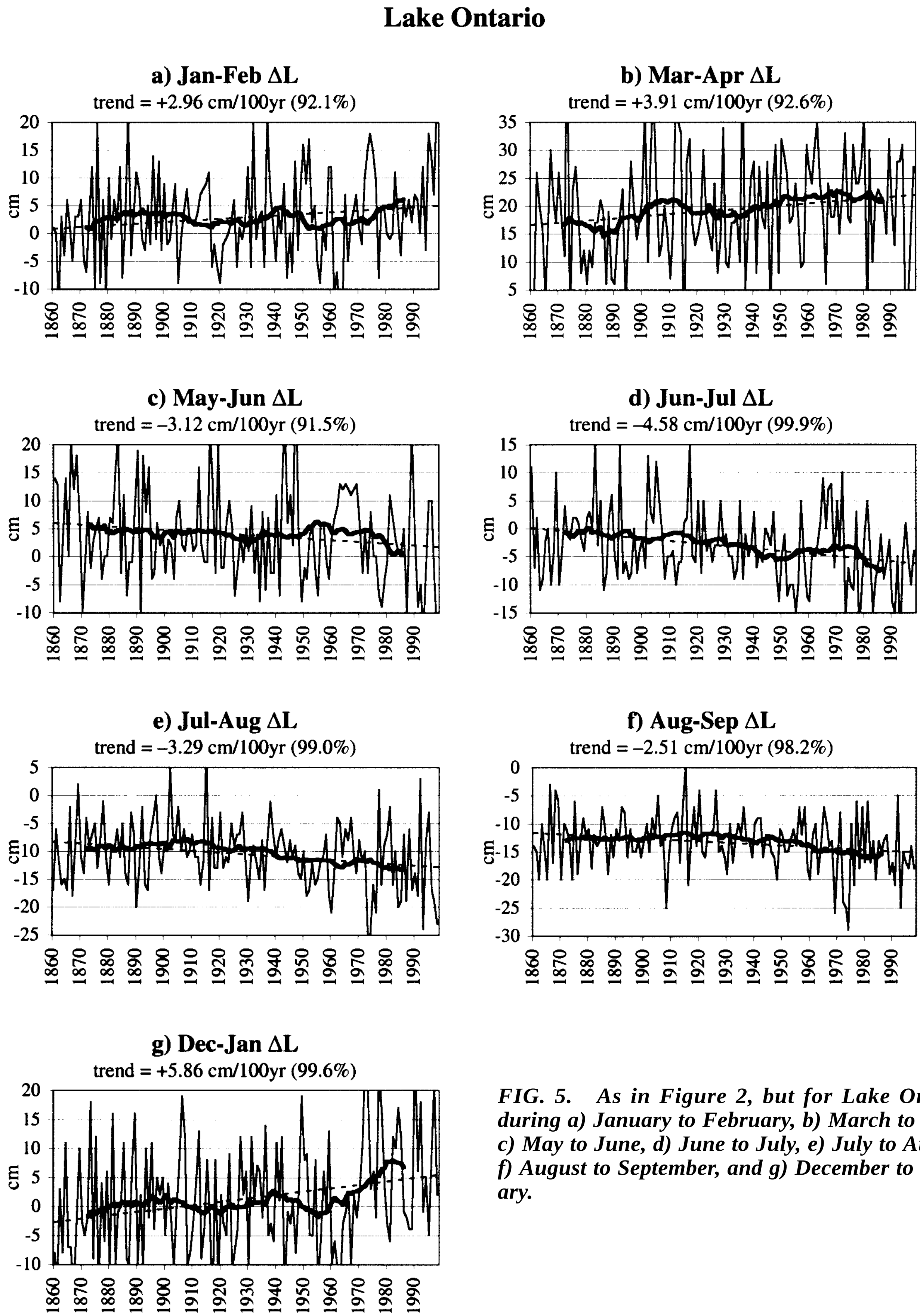

FIG. 5. As in Figure 2, but for Lake Ontario during a) January to February, b) March to April, c) May to June, d) June to July, e) July to August, f) August to September, and g) December to January.

TABLE 1. 139-year trends in month-to-month change in lake level (ΔL) for each of the Great Lakes. Trends are based on linear regressions over the period 1860 to 1998 and have been converted from cm/month to m³/s by multiplying by lake area. Statistically significant trends are shown in bold (90% level or greater), and insignificant trends are bracketed.

	Superior	Mich-Huron	Erie	Ontario
Oct–Nov	[432]	[736]	[46]	[–75]
Nov–Dec	**1,187**	**1,668**	[216]	[183]
Dec–Jan	[158]	[–244]	**398**	**577**
Jan–Feb	[–345]	**–873**	**658**	**304**
Feb–Mar	**–1,143**	**–1,529**	**666**	[–69]
Mar–Apr	[232]	**1,425**	[–357]	**391**
Apr–May	[222]	[108]	**–607**	[277]
May–Jun	[–313]	[–786]	**–352**	**–312**
Jun–Jul	[377]	[–32]	[–111]	**–458**
Jul-Aug	[–246]	[–87]	[–106]	**–324**
Aug-Sep	[–405]	[648]	[–187]	**–251**
Sep–Oct	[–685]	[–56]	[–74]	[–216]

139-year record. The reconstruction is based on the linear regression of L^* versus time (done separately for each month of the year). Months for which the two curves are statistically distinct (the linear trend in L^* is significant at at least the 90% level) are indicated in Figure 6 by the "+" symbol.

Most striking in Figure 6 is a distinct shift in the seasonal cycles of Lakes Erie and Ontario, by approximately 1 month. Given the course nature of the monthly timescale, neither the magnitude nor the statistical significance of this phase shift is being precisely assessed in this study (only the trend for individual months). A more detailed time-series analysis of daily lake levels is left for future studies. Nevertheless, the preliminary results of this analysis suggest that the annual rising and falling of Lakes Erie and Ontario are occurring roughly 1 month earlier than they did 139 years ago (Figs. 6c–d). Lakes Superior and Michigan-Huron show less pronounced seasonal shifts, but there is some indication that the autumn peak in the level of Lake

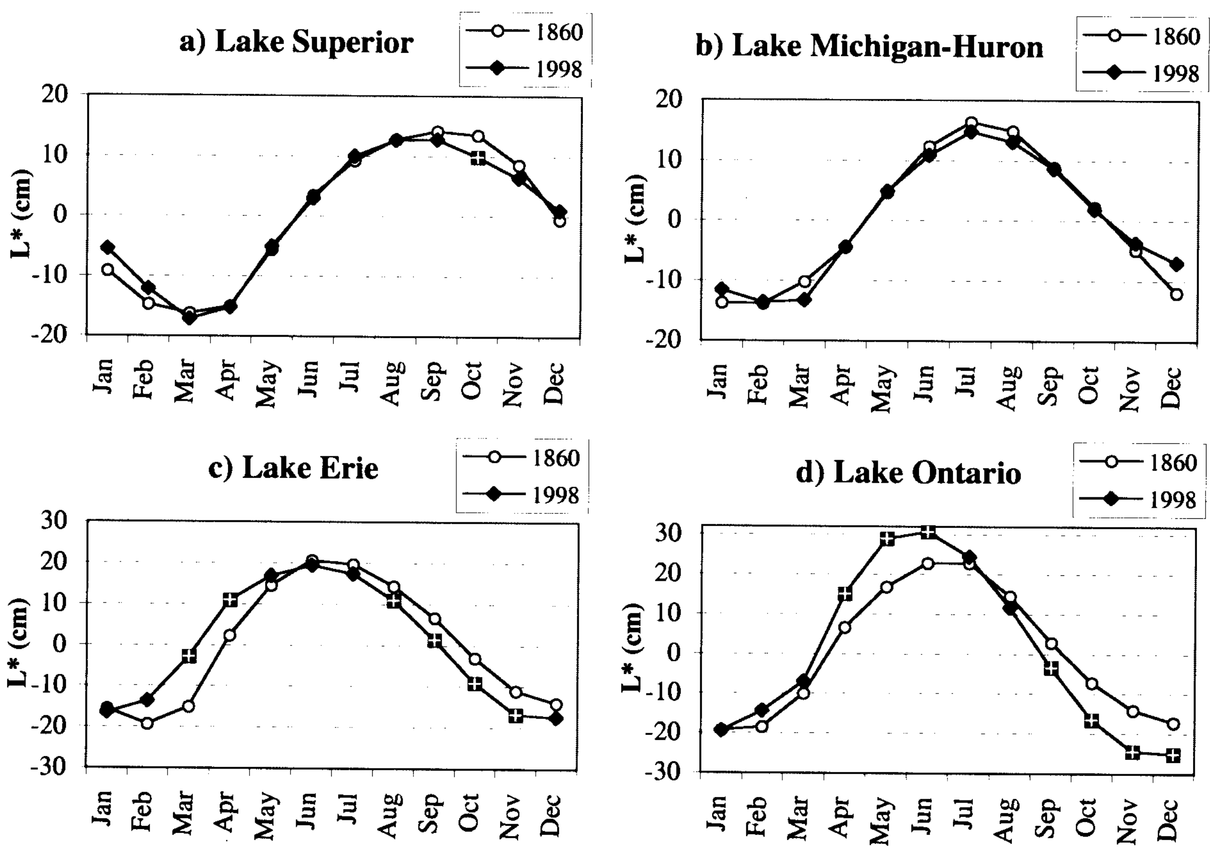

FIG. 6. Reconstructed lake level anomalies (in cm) for 1860 (open circles) and 1998 (closed diamonds or "+" symbol) based on the endpoints of the linear regression of L* vs. time. Months for which the linear trend in L* is statistically significant (at at least the 90% level) are denoted by the "+" symbol.

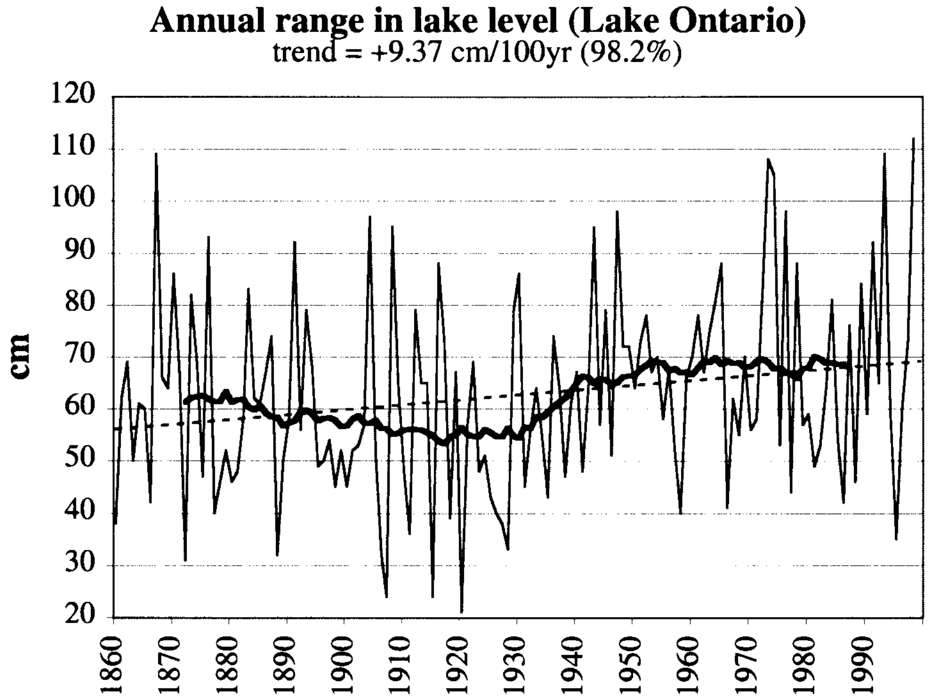

FIG. 7. Timeseries of the annual range in monthly mean Lake Ontario water levels (maximum minus minimum) for 1860 to 1998. Also shown are the 25-year running mean (thick, solid line) and 139-year linear trend (dotted line). The trend value and significance level are noted.

Superior is occurring earlier in the year, as evidenced by the drop in October L^* (and adjacent months).

Also evident in Figure 6d is an increase in the amplitude of the seasonal cycle of L^* for Lake Ontario. This change in amplitude has been determined more rigorously by calculating the annual range in Lake Ontario water levels (maximum minus minimum) for each year. This is shown in Figure 7, along with the 25-year running mean and 139-year linear trend. (The 98% significance level is based on the F test, as the annual range is serially independent and normally distributed.) The 25-year timeseries shows a slight downward trend from 1870 to 1920, followed by a sharp increase from 1930 to 1955, after which time the timeseries remains relatively level (Fig. 7). The linear fit to the raw data indicates an overall 13-cm (23%) increase in annual range (from 56 cm in 1860 to 69 cm in 1998). Although this trend is statistically significant, it would be worthwhile to investigate more closely the non-linear variability, such as the step change evident around 1930 to 1940.

DISCUSSION AND CONCLUSIONS

The results of this study reveal numerous statistically significant trends in the seasonal cycle of Great Lakes water levels over the period 1860 to 1998. Most prominent are the higher spring and lower autumn lake levels for Lakes Erie and Ontario (relative to the annual mean), which suggest a roughly 1 month advance in the seasonal cycle. The shift also leads to a 23% increase in the amplitude of the seasonal cycle of Lake Ontario. These 139-year trends are associated with increasingly positive ΔL (monthly changes in lake level) during the late fall to spring and increasingly negative ΔL in the summertime. Lakes Superior and Michigan-Huron behave similar to each other, but rather differently from Lakes Erie and Ontario. Significant positive (negative) trends are found in November-to-December (February-to-March) changes in lake level, and there is also evidence of an earlier autumn maximum in the level of Lake Superior. Some of the largest trends in ΔL translate into 139-year changes in water flux on the order of 600 m^3/s for Lake Ontario to 1,700 m^3/s for Lake Michigan-Huron. This is roughly 10 to 30% of the annual mean discharge of the Niagara River and represents a large change in the water budget of any of the Great Lakes.

Although a rigorous analysis of the various mechanisms is beyond the scope of this study, it is worthwhile to speculate on the potential causes of the observed trends in ΔL (and, by inference, L^*). Long-term trends in ΔL can be represented by the first derivative of Eq. (1):

$$\frac{d(\Delta L)}{dt} = \frac{dP}{dt} - \frac{dE}{dt} + \left(\frac{dx}{dt} - \left[\frac{x}{A}\right]\cdot\left[\frac{dA}{dt}\right]\right)\cdot\left(\frac{k}{A}\right) \qquad (4)$$

where,

$\frac{d}{dt}$ = long-term derivative with respect to time (over the 139 years)

$x = R + I - O + G - C + D + T$ (see Eq. 1)

Fractional changes in lake area, dA/A, are very small over the period of record, ranging from 0.3% for Lake Superior to 1.7% for Lake Erie (based on bathymetry estimates and observed maximum ranges in lake level). Thus, effects of lake area variations on long-term trends in ΔL are also small (less than 0.1 cm/100 yr for Lake Erie) and are ignored in Eq. 4. Estimates of consumptive use (C) and diversion rates (D) on the Great Lakes range from 7 m^3/s to 63 m^3/s and 40 m^3/s to 260 m^3/s, respectively (Hartmann 1990), and groundwater contributions (G) are generally taken to be small (Croley and Lee 1993). More importantly, long-term trends in C, D, and/or G have not been documented and are likely to be even less significant than their long-term means. Therefore, these terms are also ignored as being significant contributors to the observed trends in ΔL (Table 1), which simplifies Eq. (4) to:

$$\frac{d(\Delta L)}{dt} = \frac{dP}{dt} - \frac{dE}{dt} + \left(\frac{dR}{dt} + \frac{dI}{dt} - \frac{dO}{dt} + \frac{dT}{dt}\right)\cdot\left(\frac{k}{A}\right) \qquad (5)$$

The effects of thermal expansion (T) on monthly ΔL are generally less than 120 m^3/s for Lakes Erie and Ontario (Meredith 1975), but can be considerably larger for Lakes Superior and Michigan-Huron (up to 1,000 m^3/s). Thus, it is conceivable (from an order-of-magnitude standpoint) that trends in T could be contributing to the observed trends in ΔL listed in Table 1, especially for Lakes Superior and Michigan-Huron. However, such trends would require a shift in the seasonal cycle of lake temperature. Although the results of McCormick and Fahnenstiel (1999) suggest that the spring (fall) 4°C temperature transition for the Great Lakes may be occurring earlier (later) in the year, this shift appears to be associated with an overall increase in annual mean temperature (which would not affect T). Thus, it appears that a more intensive study of lake temperature profiles is needed to determine if significant seasonal trends exist in the thermal expansion term.

Changes in the seasonal cycle of precipitation (P) and lake evaporation (E) may also be contributing to the observed trends in ΔL (since P and E are such large contributors to the water budget). As with the thermal expansion term, however, such changes have not been documented in the literature. Future studies should examine these issues to see if indeed the seasonal cycle of P, E, or T has changed over time. Unfortunately, records of Great Lakes precipitation, evaporation, and lake temperature do not extend as far back as lake level records, but it would be worthwhile to examine the trends over a common data period.

Lake inflow (I) and outflow (O) are significant components of the water budget for each of the Great Lakes (except I for Lake Superior), but one must be careful when attributing trends in ΔL to changes in I or O. This is because changes in I or O are often the result of (rather than causes of) changes in lake level. For example, a trend toward earlier seasonality has been suggested by Hanson *et al*. (1992) for the St. Lawrence River (Lake Ontario outflow). This corroborates the results of the current study since the reported changes may very well be a direct response to the lake level changes illustrated in Figure 6d. On the other hand, the human-induced effects of regulation and dredging on I and O do, indeed, have an important and direct impact on ΔL. The regulation of Lakes Superior and Ontario, for example, affects the outflow of both lakes, as well as the inflow into Lakes Michigan-Huron and (indirectly) Erie. Lake Erie has also had an ice boom in place near the Niagara River since 1964 (R. Assel, Great Lakes Environmental Research Laboratory, 19 July 2000, personal communication), which is likely to have some effect on the seasonality of the Niagara River and, therefore, the seasonal cycle of the water levels of Lakes Erie and Ontario. Thus, direct anthropogenic effects on Great Lakes hydrology cannot be overlooked when considering the various factors for the trends identified in this study.

It is important to note, however, that many of the trends in Figures 2 through 5 begin well before regulation was initiated (1921 for Lake Superior, 1958 for Lake Ontario). Furthermore, trends have been found for all five Great Lakes, regulated and unregulated. And although the "unregulated" lakes (Michigan-Huron and Erie) are affected by the regulation of Lake Superior, the effect is reversed. (For example, regulating an increase in the level of Lake Superior causes Lake Michigan-Huron to drop.) This is contrary to the synchronous behavior exhibited in Table 1. Thus, it is unlikely that lake regulation is the primary cause of the observed trends in ΔL. It would, however, be especially worthwhile to explore the potential effects of step changes (placement of control structures, changes in regulation plans, dredging operations) on some of the noted non-linear changes in ΔL.

The seasonality of the remaining term in Eq. (1), land surface runoff (R), is strongly determined by the timing of spring snowmelt. Given the observed increases in springtime temperatures in the Great Lakes region (Bolsenga and Norton 1993), it would be reasonable to expect earlier spring snowmelt and subsequently lower runoff in early summer. This explanation is consistent with the observed advances in the seasonal cycle of Lakes Erie and Ontario (Figs. 6c–d), as well as streamflow in the Mississippi (Baldwin and Lall 1999), and model predictions of global warming in the Great Lakes region (Croley 1990). Warmer temperatures may also lead to a greater fraction of precipitation which falls as rain in the late fall and early spring, thereby generating more immediate runoff to the lakes. Note that changes in both rain/snow fraction and snowmelt can lead to large changes in monthly runoff, while leaving annual mean amounts relatively unchanged. Thus, both explanations are consistent with the fact that all of the Great Lakes show positive trends in ΔL that are nearly balanced by offsetting negative trends. In addition to climatic effects, land surface runoff is also impacted by human effects such as changes in land use. Future observational and modeling studies of river discharge into the Great Lakes will hopefully shed considerable light on the various roles of anthropogenic and climatic effects in the observed seasonal trends in Great Lakes water levels.

It is not clear at this point why Lakes Superior and Michigan-Huron show rather different trends from Lakes Erie and Ontario, such as downward trends in ΔL during January-March, (rather than April-September), fewer months with significant trends, and less dramatic seasonal shifts in L^*. The explanation may simply be related to the integrated (and delayed) hydraulic response of the more downstream lakes and/or spatial variations in regional climate trends (such as temperature). This could also explain (in addition to regulation) the unique increase in amplitude of the seasonal cycle of Lake Ontario. On the other hand, Brinkmann (2000) has noted that interannual variability in monthly net basin supply for the lower (upper) Great Lakes is largely driven by land surface runoff (over-lake precipitation). Together with the higher ratio of land to lake area (3.0 to 3.4 for the lower lakes versus 1.6 to 2.1 for the upper lakes), the more significant trends for Lakes Erie and Ontario may be a reflection of the stronger role of land surface runoff (especially spring snowmelt).

It is interesting to note that, after the particularly warm El Niño winter of 1997/98, all four of the Great Lakes reached their annual maximum roughly 2 months earlier than normal. This suggests that the lakes do, in fact, respond synchronously to more dramatic, large-scale warming events (and in a manner consistent with the snowmelt hypothesis offered above). Thus, if temperatures continue to increase in the Great Lakes region, it may only be a matter of time before Lakes Superior and Michigan-Huron show seasonal advances similar to those of the downstream lakes.

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