J. Great Lakes Res. 30 (Supplement 1):20–40
Internat. Assoc. Great Lakes Res., 2004

Trends in the Lake Superior Water Budget Since 1948: A Weakening Seasonal Cycle

John D. Lenters[*]

School of Environmental and Physical Sciences
Lake Superior State University
650 West Easterday Ave.
Sault Ste. Marie, Michigan 49783

ABSTRACT. *An analysis of Lake Superior water levels from 1948–1999 reveals that the seasonal cycle has decreased in amplitude by 20% (from 40 cm to 32 cm). This change is manifested as a downward trend in summer and autumn lake levels (when levels are typically highest) accompanied by roughly no change in winter and spring lake levels (and an overall 4-cm drop in annual mean levels). The decreased rates of seasonal rise and fall in lake level over the 51-year interval reflect a large decrease in the net monthly influx of water during the late spring (up to –1,360* m^3/s*) coupled with a nearly compensating increase in net influx during late autumn (up to +1,100* m^3/s*). Analysis of the Lake Superior water budget indicates that these changes are primarily the result of trends in runoff and over-lake precipitation. A systematic decrease in outflow through the St. Marys River is also evident during July-December (in association with the lower lake levels), as well as a moderate shift in the seasonal pattern of lake evaporation (but not the annual mean). The observed water budget trends are primarily related to variations in climate, rather than lake regulation. Land surface effects are also important, as suggested by a 20% increase in annual mean evapotranspiration during the 51-year interval and large changes in monthly storage (e.g., snowmelt, groundwater, etc.). Significant uncertainties are present in the calculated water budget, and it is suggested that a likely source of error is in measured precipitation and (especially) runoff.*

INDEX WORDS: *Lake Superior, water budget, lake levels, trends, climate change.*

INTRODUCTION

Concerns regarding the impacts of climate change on the Laurentian Great Lakes have increased in the past few years, partly in response to the recent dramatic drop in lake levels which began in 1998. Some of the lakes subsequently rebounded to near-normal or even above-normal levels by February of 2002 (Lakes Michigan and Huron being the primary exceptions), but dry conditions during the fall and winter of 2002/2003 once again led to below-normal water levels for all lakes by early 2003. Although such changes only reflect a 5-year period, previous studies have, in fact, suggested that an overall downward trend in lake levels is to be expected if regional temperatures continue to warm in response to global climate change. For example, Smith (1991) summarizes a variety of studies which conclude lake levels will drop by 0.5 to 2.5 m as a result of doubled atmospheric CO_2 levels. A more recent investigation by Lofgren *et al.* (2002) also suggests that lake levels will drop, by up to 1.4 m by the year 2090 (for Lake Michigan-Huron). On the other hand, Lofgren *et al.* (2002) note that results from one of the climate models utilized in the study actually implies a future lake level rise (up to 0.4 m for Lake Michigan-Huron). Thus, there remains a certain degree of uncertainty regarding the potential long-term impacts of climate change on lake levels.

Aside from changes in annual mean lake level, alterations of the seasonal hydrologic cycle are also expected to occur as a result of increased temperatures. For example, earlier spring runoff has been predicted to occur in the Great Lakes region as a result of earlier spring snowmelt (Croley 1990). Indeed, a recent analysis of long-term lake level records (Lenters 2001) suggests that such changes are already occurring. From 1860 to 1998, for ex-

---

[*] Corresponding author. E-mail: jlenters@lssu.edu

ample, Lakes Erie and Ontario both exhibit a well-defined trend toward an earlier rise in lake level during the spring and earlier decline in the autumn (Lenters 2001). These results have been further corroborated by Quinn (2002). Baldwin and Lall (1999) note a similar advance in the seasonal cycle of streamflow in the upper Mississippi River since 1874. Other signs of earlier spring in the Great Lakes region (and North America in general) include increases in springtime air and water temperatures (Bolsenga and Norton 1993, McCormick and Fahnenstiel 1999, Bonsal *et al.* 2001), earlier ice melt on the Great Lakes and spring discharge through the St. Lawrence River (Hanson *et al.* 1992), reductions in spring snow cover throughout Canada and the northern hemisphere (Brown and Goodison 1996, Brown and Braaten 1998, Brown 2000), earlier occurrence of spring runoff in Canada and the western United States (Burn 1994, Westmacott and Burn 1997, Whitfield and Cannon 2000, Cayan *et al.* 2001, Zhang *et al.* 2001), and advances in spring plant phenology (Schwartz and Reiter 2000, Cayan *et al.* 2001). Recent global studies of natural systems (Parmesan and Yohe 2003, Root *et al.* 2003) have also identified coherent shifts in plant and animal species and advances in spring events that are consistent with climate change predictions.

Interestingly, the seasonal lake level changes identified by Lenters (2001) and Quinn (2002) for Lakes Erie and Ontario are rather different from those of the upper lakes. Long-term trends in net monthly water flux are certainly evident for Lake Superior and (especially) Lake Michigan-Huron (as also investigated recently by Argyilan and Forman 2003). However, the trends occur during different (and fewer) months of the year than those of Lakes Erie and Ontario (Lenters 2001). The resulting lake level changes for the upper lakes, therefore, do not exhibit the same, coherent seasonal pattern as the lower lakes. This suggests that the hydrologic effects of an “earlier spring” (or other influence) are not being felt in the same way by the upstream lakes. Reasons for this could include regional climatic differences, anthropogenic effects (e.g., regulation or ice retardation), or the increasing influence of land surface runoff on the lake water budget as one moves downstream (Brinkmann 2000). On the other hand, one of the limitations of the earlier study by Lenters (2001) is that it focused solely on the overall linear trends of the 139-year lake level record. It is noted, for example, that there is evidence for important decadal-scale variations in lake level seasonality that are masked by the longer-term linear analysis (Lenters 2001). A further limitation of this earlier study is that it does not provide a definitive analysis of the water budget and the associated mechanisms responsible for the observed trends in lake level. Similarly, Quinn (2002) discusses the potential role of anthropogenic effects in the observed trends, but does not specifically investigate the effects of climate, such as variations in seasonal precipitation, evaporation, and runoff.

The objectives of this study are to expand upon the earlier work of Lenters (2001) and Quinn (2002) by examining in greater detail the seasonal hydrologic changes associated with Lake Superior during the past half-century. In particular, an analysis of the complete water budget is provided to better understand the mechanisms associated with the observed trends in lake level seasonality. The dataset chosen for this study (Hunter and Croley 1993) provides estimates of water budget components for each of the Great Lakes, including quantities such as over-lake precipitation, runoff, evaporation, beginning-of-month (BOM) lake level, outflow, and change in storage, as well as other parameters such as air temperature and lake surface temperature. The reader is referred to Hunter and Croley (1993) for a complete description of the dataset and its sources. The data records for Lake Superior have varying lengths, beginning as early as 1860 (e.g., lake level) and as late as 1948 (evaporation) and running, typically, through 1999. In order to work with as complete a dataset as possible, the primary time period chosen for this study is 1948–1999. Since BOM lake level data are missing for January of 2000, change-in-storage values for December 1999 are also not available. Aside from data for the Long Lac diversion, this is the only missing data point from 1948 to 1999.

LAKE LEVEL TRENDS: 1948–1999

Lake levels, as a measure of water storage, represent an integration of the net water budget of a lake over an extended period of time. As such, monthly lake level data incorporate a significant amount of interannual and interdecadal variability that often obscures the more subtle seasonal variations. Therefore, in studies which focus on the seasonal cycle and its changes over time, it is common practice to first remove the longer-term variations. This is often done by subtracting the annual mean (or 12-month running mean) lake level from the monthly value (e.g., Lenters 2001, Quinn 2002).

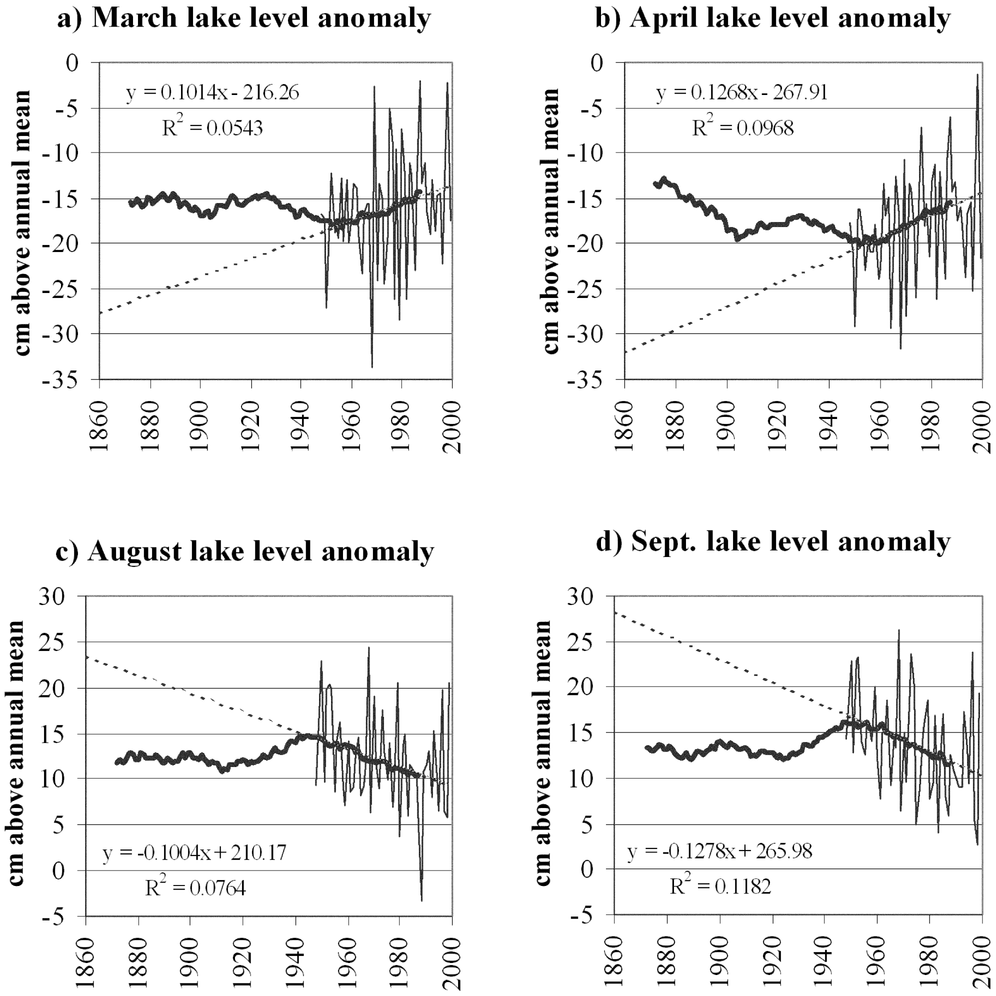
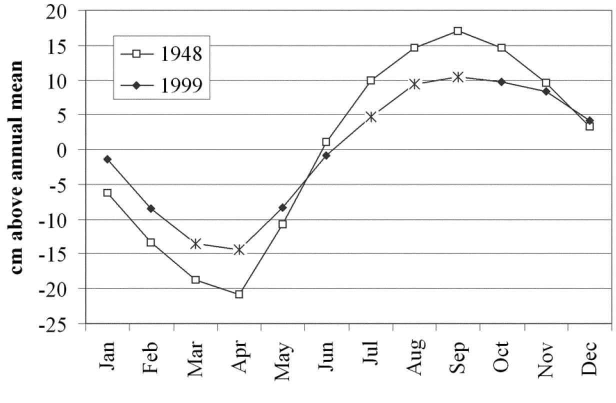
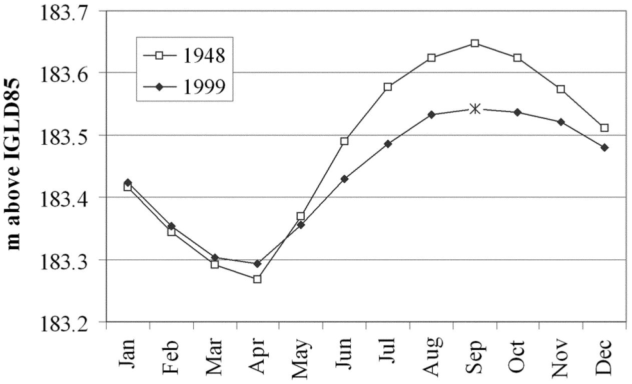


FIG. 1. Beginning-of-month (BOM) lake level anomalies (deviations from the annual mean, in cm) for Lake Superior for the months of a) March, b) April, c) August, and d) September. Thin, solid line represents individual years for the period 1948–1999, while the thick, solid line denotes the (centered) 25-year running mean for the full record (1860–1999). Also shown is the linear regression line for 1948–1999 (dashed line). All trends are significant beyond the 90% level (see Fig. 2).

One is then left with a timeseries that is (for the most part) independent of changes in annual mean lake level, including long-term effects such as isostatic rebound. Examples of such timeseries are illustrated in Figure 1, which shows BOM lake level anomalies (deviations from the annual mean) for 4 months of the year. These 4 months exhibit relatively large trends in anomalous lake levels over the 52-year period, 1948–1999. (Other months also show moderate trends—see Figure 2 for a summary.) For example, BOM lake level anomalies for both March and April (when seasonal lake levels are typically lowest) have increased by just over 1 cm/decade, while lake level anomalies for August and September (when levels are typically highest) have decreased by roughly the same amount (Fig. 1). Upon reconstructing the entire month-by-month lake level anomaly curves for 1948 and 1999 (based on the endpoints of the linear regression), a systematic pattern emerges (Fig. 2a). In particular, it is observed that the annual rising and falling of Lake Superior has become significantly weaker over the



a) Reconstructed BOM lake level anomaly



b) Reconstructed BOM lake level

FIG. 2. a) Reconstructed BOM lake level anomaly curves (deviations from the annual mean, in cm) for 1948 and 1999 based on the endpoints of the linear regression for each month (see Fig. 1). Months with a star (*) indicate that the difference between 1948 and 1999 is statistically significant (for that month) at at least the 85% level (March: 90%, April: 97%, July: 94%, August: 95%, September: 98%). b) As in a), except that the trends are based on the raw, monthly lake level data, rather than anomalies. Statistical significance is highest for September (89%).

52-year period, with 5 months of the year showing trends in anomalous lake level which are statistically significant beyond the 90% level. Note that this pattern is considerably more pronounced than that found by Lenters (2001, their Fig. 6a), as a result of focusing on the more recent period of interest. Lenters (2001) also used monthly mean (rather than BOM) lake level anomalies, but this difference is minimal compared to the different periods of interest. Quinn (2002) notes a similar decrease in the amplitude of the seasonal cycle for Lake Superior between two time periods which overlap the current study (namely 1942–1979 and 1980–2000).

Although the current study focuses on the time period 1948–1999 (because of data limitations for the water budget), it is worthwhile to examine the aforementioned lake level trends in a broader temporal context. To do this, Figure 1 shows the 25-year running mean lake level anomalies for the entire period of lake level records (1860–1999). As one might expect from the rather weak 140-year trends previously identified for Lake Superior (Lenters 2001), this longer-term record indicates that the recent 52-year trends are not reflective of similar trends from 1860–1948. In fact, prior to about 1950 each of the smoothed timeseries in Figure 1 (especially April) exhibits a moderate amount of interdecadal variability, often characterized by piecewise linear trends accompanied by pronounced changes in slope. Thus, when considered within this historical context, the changes in lake level seasonality over the past 52 years, while significant (both statistically and in terms of overall magnitude), are neither unprecedented nor indicative of a broad, 140-year trend. Quinn (2002), in fact, suggests potential step-changes in the seasonal range of Lake Superior around 1888, 1916, 1943, and 1980 (based on changes in the slope of a cumulative mass curve). Therefore, it would not be appropriate to simply extrapolate the trends identified for this 52-year study period to prior or later time periods. It is hoped, however, that by identifying the driving mechanisms for these trends, we will be able to better assess whether or not such trends could be expected to continue.

As noted in Figure 1, the most recent trends in anomalous lake level actually start right around the beginning of the current study period (1948). (This is also true for most of the other months not shown in Figure 1.) It is, of course, entirely coincidental that this should happen, since the choice of study period is based solely on the availability of water budget data (rather than characteristics of the data itself, such as temporal trends in lake level). Thus, the results are not biased. Rather, we are simply presenting an analysis of the Lake Superior water budget over the longest time period for which complete data is available. It should also be noted that the relatively linear nature of the trends after 1948 suggests that the use of linear regression techniques is appropriate for analyzing the water budget over this most recent period (rather than using more sophisticated timeseries models).

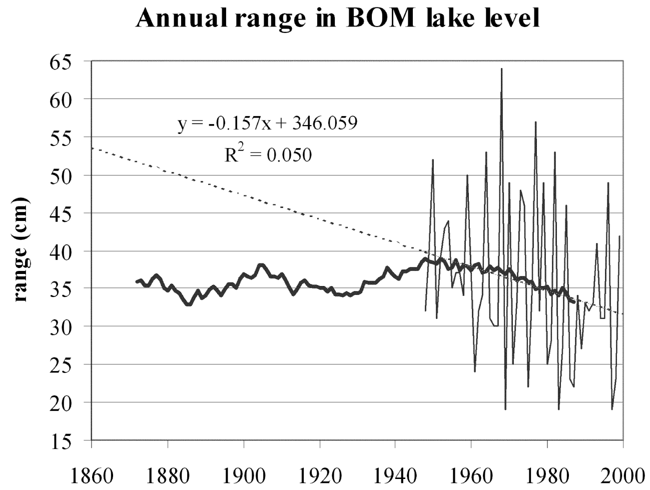


FIG. 3. Annual range in Lake Superior water levels (maximum BOM level minus minimum BOM level, in cm) for the period 1948-1999 (thin, solid line). Also shown is the (centered) 25-year running mean for the full record (1860–1999; thick, solid line) and linear regression for 1948–1999 (dashed line; 89% significant).

The weakening amplitude of Lake Superior's seasonal cycle is examined more explicitly in Figure 3, which shows the annual range in BOM lake level, along with the 52-year linear trend (1948–1999) and 25-year running mean (for the full 140 years). The results of the linear regression indicate that the annual range in lake level has decreased by 20%, from roughly 40 cm in 1948 to 32 cm in 1999 (Fig. 3). This is similar to the 7-cm decrease noted by Quinn (2002) from 1942–1979 to 1980–2000. Although not quite significant at the 90% level, the magnitude and duration of the linear trend is quite large, even when historical variations are taken into consideration (Fig. 3). It is interesting to note that Lake Ontario shows a considerably different trend in annual lake level range. For example, the annual range in (monthly mean) lake level for Lake Ontario decreased during the period 1860 to about 1930, increased rapidly from 1930 to 1950, and has remained roughly steady since then (Lenters 2001, Quinn 2002). An analysis of regulation effects (Quinn 2002) suggests that some of these differences are related to the influence that regulation has had on seasonal Lake Ontario water levels (which is considerably larger than that of Lake Superior).

As noted earlier, the analysis presented to this point has focused on lake level *anomalies*, since subtraction of the annual mean lake level is necessary to isolate seasonal variations. Without such filtering of the timeseries, the seasonal changes examined in Figure 1, for example, would be swamped by much larger interannual and interdecadal variations. (Each panel in Figure 1, in fact, would not look that much different from the annual mean lake level itself.) Furthermore, the statistical significance of the observed seasonal trends is grossly underestimated if the larger (and more persistent) annual variability is not first subtracted out. Despite these advantages, presentation of the data as anomalies can lead to misinterpretation, so one must be extremely careful in interpreting the results of Figure 2a. For example, it would be correct to say that, since 1948, December–May lake levels have increased *relative to the annual mean*, while June–November lake levels have decreased *relative to the annual mean* (Fig. 2a). Five out of the 12 months have trends which are significant at at least the 90% level. It would not, however, be appropriate to draw conclusions about changes in *absolute* lake level from Figure 2a, because the annual mean BOM lake level for Lake Superior actually decreased by 4 cm from 1948 to 1999. The effects of this are clarified in Figure 2b, which shows the reconstructed BOM lake level curves for 1948 and 1999, based on linear regressions of the raw lake level data (i.e., no filtering). When the annual mean changes are accounted for, it becomes evident that absolute lake levels for January to May have remained relatively unchanged over the 52-year period, while June to December lake levels have dropped up to 10 cm (Fig. 2b). As mentioned above, the statistical significance of the trends has also been reduced. Thus, there are important differences between Figures 2a and 2b that require careful interpretation. Note, however, that there are two conclusions that can be correctly drawn from both figures: 1) The rates of seasonal rise and fall have both decreased over time, and (consequently) 2) The amplitude of the seasonal lake level cycle has been reduced. This latter conclusion has already been addressed, but the former conclusion is examined more closely in the next two sections.

MONTHLY MEAN WATER BUDGET

In order to understand the mechanisms responsible for the observed trends in Lake Superior water levels, an analysis of the monthly water budget is presented. We begin by discussing the long-term mean seasonal cycle and then, in the next section, examine trends in the water budget components. Rather than focusing on anomalies, as was done for the lake levels (Figs. 1 and 2a), the entire water budget analysis is based on the raw data (i.e., without removing the annual mean). The reasons for doing this are many. First of all, the results are less prone to misinterpretation. For example, a downward trend in precipitation for a particular month would imply that that month is getting drier (not just drier "relative to the annual mean"). Secondly, the annual mean water budget components generally have less variability and persistence than the annual mean lake level and, therefore, do not tend to overwhelm the seasonal variability nor hinder tests of statistical significance. A third, and rather obvious reason for using the raw data is that using anomalies would (by definition) eliminate the possibility of understanding trends in annual mean quantities. Although the focus here is on changes in seasonality, there are a number of interesting changes in the annual mean water budget that would go unnoticed if anomalies were used instead. Finally, since changes in outflow through the St. Marys River are largely driven by changes in lake level (and direct regulation), use of absolute lake levels (Fig. 2b), rather than anomalies (Fig. 2a), is more appropriate for interpreting trends in St. Marys River outflow.

Following the nomenclature of Lenters (2001), the monthly change in lake level for Lake Superior can be written as:

$$\Delta L = P - E + R - O + G - C + D + T \qquad (1)$$

where,

ΔL = change in BOM lake level (cm),
P = monthly total precipitation over the lake surface (cm),
E = monthly total evaporation from the lake surface (cm),
R = monthly total land surface runoff into the lake (cm),
O = monthly total outflow of water through the St. Marys River (cm),
G = monthly total groundwater flow (net) into the lake (cm),
C = monthly total consumptive use (cm),
D = monthly total diversion of water into the lake (cm), and
T = monthly change in lake level due to thermal expansion (cm).

Note that each of the quantities in Eq. (1) are expressed in units of cm of water (spread over the lake surface area). Lake area is assumed to be constant in this analysis (at 8.1925×10^{10} m^2) since fractional changes in the area of Lake Superior (over this study period) are no greater than 0.3% (Lenters 2001). As such, an accumulation of 1 cm of water (per month) over the surface area of Lake Superior translates into a volumetric flux of about 316 m^3/s (for a 30-day month).

Water budget contributions from groundwater (G) are typically ignored in Eq. (1) since the amount is likely to be negligible and since reliable, lake-wide estimates of direct groundwater inputs and outputs for Lake Superior are not available. Furthermore, withdrawal of water from Lake Superior for consumptive use (C) has been estimated to be very small (roughly 7 m^3/s, or 0.02 cm/month; Hartmann 1990) relative to other quantities in the water budget. Therefore, these terms are ignored in Eq. (1), which can be simplified to:

$$\Delta L = NBS - O + D + T \qquad (2)$$

where the net basin supply (NBS) is given by

$$NBS = P - E + R \qquad (3)$$

Except for the thermal expansion term (T), which is estimated from Bennett (1978), monthly values for each of the quantities in Eqs. (2) and (3) are available from the hydrologic dataset of Hunter and Croley (1993) for varying periods of time. As mentioned previously, this study focuses on the time period 1948–1999 since 1948 is the first year in which evaporation estimates are available. (ΔL data is missing for December of 1999.) The evaporation estimates are obtained through a 1-D lake thermodynamic model (calibrated against observed water temperature and ice cover), and the modeled evaporation rates have been found to compare well with water balance estimates (Hunter and Croley 1993). The remainder of the quantities in the hydrologic dataset represent direct observations rather than model estimates. It should be noted that this dataset does not separately identify outflow from the Ogoki diversion (which flows through Lake Nipigon and into Lake Superior). Rather, it is included directly in the runoff term (R). Thus, the only diversion accounted for in D is the Long Lac diversion, which has been measured separately from the overall runoff (through 1990, which is the last year for which diversion data are available in

TABLE 1. Monthly mean water budget components for Lake Superior, averaged over the period 1948–1999. "Ann" denotes annual totals, and all units are in cm of water (spread over the area of Lake Superior; 1 cm/month ~ 320 m^3/s, 1 cm/year ~ 26 m^3/s). See text for variable definitions. Thermal expansion values (T) are from Bennett (1978), while all other data are obtained from the hydrologic dataset of Hunter and Croley (1993).

	P	E	P – E	R	NBS	O	NBS–O	ΔL	D	T	resid
Jan	6.04	10.88	–4.84	3.54	–1.30	6.66	–7.96	–6.98	0.13	0.4	0.45
Feb	3.84	6.68	–2.83	3.18	0.35	6.03	–5.68	–5.21	0.12	0.3	0.06
Mar	4.78	5.04	–0.26	3.97	3.71	6.53	–2.82	–1.62	0.11	0.1	1.00
Apr	5.16	1.97	3.19	8.78	11.97	6.45	5.52	8.04	0.09	–0.4	2.83
May	7.29	0.25	7.04	9.62	16.67	7.38	9.29	9.73	0.18	–0.5	0.77
Jun	8.04	–0.36	8.40	5.91	14.31	7.36	6.95	7.31	0.20	0.1	0.06
Jul	7.93	–0.13	8.06	4.73	12.79	7.76	5.03	4.65	0.16	0.3	–0.83
Aug	8.20	1.61	6.60	3.73	10.32	8.11	2.21	1.73	0.12	0.7	–1.30
Sep	8.58	4.96	3.63	3.81	7.44	7.69	–0.26	–1.54	0.10	0.3	–1.68
Oct	7.19	6.78	0.41	4.79	5.19	7.67	–2.48	–3.37	0.11	–0.5	–0.50
Nov	6.77	9.70	–2.92	4.72	1.80	7.39	–5.59	–5.21	0.12	–0.9	1.16
Dec	5.81	11.73	–5.92	3.98	–1.94	7.07	–9.00	–7.96	0.13	0.1	0.82
Ann	79.64	59.09	20.55	60.75	81.30	86.11	–4.81	–0.55	1.55	0.0	2.71

this dataset). Furthermore, Hunter and Croley (1993) note that between 22% and 43% of the Great Lakes drainage basin remains ungauged, indicating that some extrapolation errors are likely to exist in the runoff term (R).

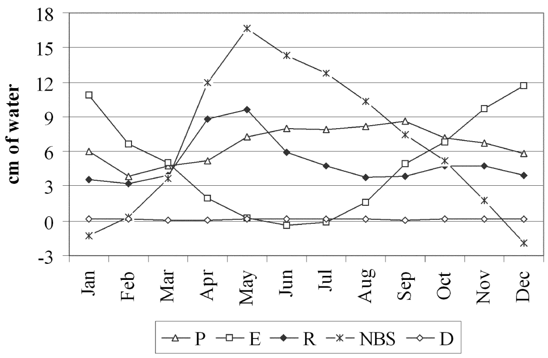
Long-term monthly mean values were calculated for each of the water budget quantities for the period 1948–1999 (1948–1990 for the Long Lac diversion). These values are shown in Table 1 and Figure 4. As necessary, volumetric fluxes were converted to cm of water (per month) for some of the water budget terms. As a means of estimating the approximate error in the overall water budget, a residual term is calculated from Eqs. (1) and (2):

$$\text{resid} = \Delta L - (\text{NBS} - \text{O} + \text{D} + \text{T}) = \text{G} - \text{C} + \text{errors} \quad (4)$$

Note that the residual term includes measurement errors from any and all of the water budget quantities (see Eq. 1), as well as the (neglected) contributions from groundwater and consumptive use. In terms of the seasonal cycle, evaporation shows the largest amplitude of all water budget components, ranging from a maximum of 11.7 cm (3,590 m^3/s) in December to a minimum of –0.4 cm (–110 m^3/s) in June (Table 1, Fig. 4a). This is followed by runoff, which has a maximum input of 9.6 cm (2,940 m^3/s) in May and a minimum of 3.2 cm (1,070 m^3/s) in February. Over-lake precipitation exhibits a moderate seasonal cycle, with maximum values attained during the months of June through September and minimum values during the winter months. Since evaporation is considerably out-of-phase with both precipitation and runoff, these three terms combine to produce a net basin supply curve that has significant seasonal variability (Fig. 4a). Values of NBS range from –1.9 cm (–590 m^3/s) in December to 16.7 cm (5,100 m^3/s) in May. These seasonal variations are broadly consistent with earlier studies of the Lake Superior water budget (e.g., Bennett 1978).

Outflow through the St. Marys River is the largest contributor to the annual water budget (86.1 cm or 2,230 m^3/s), but the seasonal range (2.1 cm or 480 m^3/s) is considerably smaller than that of P, E, and R (Table 1). On average, maximum discharge occurs during July–October, when lake levels are also at their seasonal maximum (Fig. 4b); Minimum outflow and lake levels are found during January–April. Influx through the Long Lac diversion (D) has a very low annual value (1.6 cm or 40 m^3/s) and also exhibits the least amount of seasonal variability of all the water budget components (Table 1, Fig. 4a). In addition to the fact that the monthly diversion rates have relatively minimal trends over the 1948–1999 period (less than 0.01 cm/decade, or 3 m^3/s/decade; not shown), the effects of the Long Lac diversion are neglected for the remainder of the study. The thermal expansion term, as estimated by Bennett (1978), has no annual mean component (since it is an approximately cyclic quantity), but a seasonal range which is comparable to that of the St. Marys outflow (Table 1, Fig. 4b). Maximum expansion of 0.7 cm (210 m^3/s)

a) Mean water budget (1948-1999)



b) Mean water budget (1948-1999)

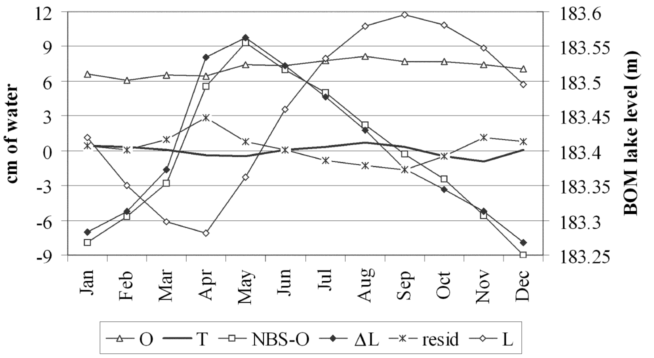


FIG. 4. Long-term monthly mean water budget for Lake Superior (1948–1999). See Table 1 for numerical values. Fluxes are in units of cm of water (per month; 1 cm/month ~ 320 m^3/s) and include a) precipitation (P), evaporation (E), runoff (R), net basin supply (NBS), and the Long Lac diversion (D), as well as b) outflow (O), thermal expansion (T), NBS – O, change in BOM lake level (ΔL), and the residual term (resid). Also shown in b) is the BOM lake level (L; in m above IGLD85). Except for the thermal expansion term, which is estimated from Bennett (1978), all other data are obtained from Hunter and Croley (1993).

occurs in August, when the lake is warming, while maximum contraction of 0.9 cm (280 m^3/s) takes place during November. A second, but weaker expansion/contraction period is found during December–May when the lake temperature is less than 4°C. Additional estimates of the thermal expansion term from Meredith (1975) are comparable in magnitude to those of Bennett (1978) for 5 months of the year (i.e., within about 0.2 cm or 60 m^3/s). However, estimates from the two studies differ by as much as 1.2–1.7 cm (360–510 m^3/s) for the months of July and August, with an overall RMS difference of 0.7 cm (220 m^3/s). Thus, there is a considerable amount of uncertainty in the thermal expansion term. For this study, the estimates of Bennett (1978) were chosen over those of Meredith (1975) because the latter study makes simplifying assumptions regarding lake temperature profiles and yields results which exhibit questionable seasonal variations (e.g., changing sign six times per year, rather than the expected four).

Upon combining the major water budget components, NBS – O is found to approximately match the monthly change in lake level, ΔL (Table 1, Fig. 4b), as it should (based on Eq. 2). This is encouraging since it verifies that the hydrologic dataset is physically consistent (i.e., it has a reasonably closed water budget). On the other hand, the difference between the two curves should be somewhat non-zero since, according to Eq. (4):

$$\Delta L - (NBS - O) = D + T + resid \qquad (5)$$

If there were no errors or neglected terms in the water budget (i.e., resid = 0) the difference between ΔL and NBS–O would be matched exactly by D + T. Understandably, this is not the case, as the balance is not perfect. The residual term is significantly non-zero for some months of the year (Table 1), with a maximum positive error of 2.8 cm (890 m^3/s) in April and maximum negative error of –1.6 cm (–530 m^3/s) in September. The RMS monthly error for the full year is 1.2 cm (370 m^3/s), while the total annual discrepancy amounts to just 2.7 cm (70 m^3/s). Interestingly, there is a systematic seasonal pattern in the residual error (Fig. 4b), with lake levels rising (falling) more rapidly from November–June (July–October) than is indicated by the sum of the water budget components. Assuming that the change in lake level measurements are relatively robust, this indicates that the water budget components are underestimating the net flux of water to the lake during winter and spring and overestimating the net flux during summer and autumn. Some of the larger errors are most likely the result of measurement errors in P, E, R, and/or O, since these terms are generally of much greater magnitude than the Long Lac diversion (D) and the neglected terms (G and C). And although another source of uncertainty is the thermal expansion term (T), its seasonal behavior is considerably out of phase with the residual term, indicating that larger values of T would simply exacerbate the errors already present. Furthermore, an artificial reduction of T to zero would still leave a significant residual for many months of the year. Thus, the predominant errors in the residual term are not likely to be associated with the effects of thermal expansion.

Comparison with the results of Bennett (1978) would suggest that the springtime errors are likely due to underestimated runoff, while the errors later in the year are the result of overestimated precipitation. Such a comparison, however, only offers a preliminary explanation, since the two study periods do not overlap in time, and the results of Bennett (1978) contain measurement errors as well. On the other hand, considering that portions of the Lake Superior watershed are ungauged (Hunter and Croley 1993), the potential certainly exists for significant errors in the runoff term (especially during spring, when runoff rates are high). Furthermore, given the likelihood that the majority of the ungauged portion of the watershed is made up of smaller streams (with shorter residence times), some of the errors may be reflected in the seasonal timing of runoff. For example, the underestimated net influx in March and April (Fig. 4b) may be the result of unmeasured early spring snowmelt running off into the lake through smaller streams. This potential "large stream bias" in the runoff term could also lead to an unrealistic seasonal delay toward drier conditions, something there is indeed evidence of during July–October (Fig. 4b, Table 1).

WATER BUDGET TRENDS: 1948–1999

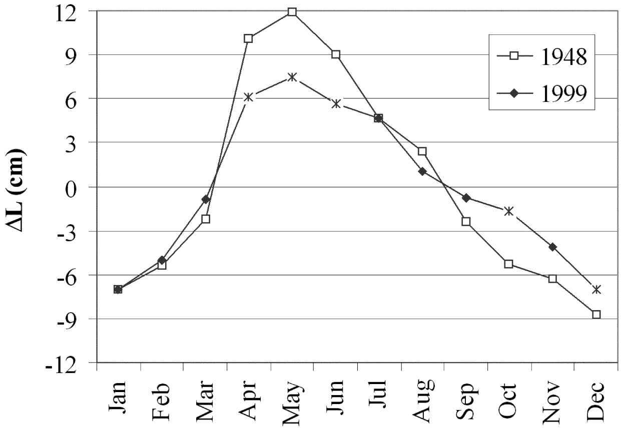
Having examined the mean water budget for 1948–1999, we now investigate how the various components of the budget have changed over the 51-year interval of time. (Although there are 52 years in the study period, the trends are calculated over a 51-year *change* in time.) As was done for the lake level data, linear regression techniques are applied to the water budget components to examine first-order linear trends. The trends are calculated for the raw monthly data (rather than anomalies) in order to include consideration of possible trends in annual mean as well as seasonal quantities. Based on Eqs. (1) and (2), trends in the monthly change in lake level can be approximated as:

$$\Delta L' \approx NBS' - O' = P' - E' + R' - O' \qquad (6)$$

where the prime (′) indicates the linear regression-based rate of change from 1948 to 1999 (in units of cm/decade or m^3/s/decade). Equation (6) is an approximation since it assumes that trends in groundwater, consumptive use, the Long Lac diversion, and thermal expansion are negligible compared to trends in the terms on the right hand side of Eq. (6). This has been verified for the Long Lac diversion and is almost certainly a valid assumption for groundwater and consumptive use. The thermal expansion term is a more significant component of the mean water budget, but long-term trends in monthly thermal expansion are not likely to be significant. This is because such trends would actually require significant changes in the seasonal water temperature cycle of Lake Superior. (Annual mean trends would simply lead to negligibly slow thermal expansion, which would then drain through the St. Marys River.) An examination of trends in surface water temperature indicates that the seasonal rate of increase or decrease in monthly mean temperature has changed by at most 0.25°C/month/decade. This amounts to a 13% (per decade) increase in the rate of change in monthly temperature, but occurs at a time of year (May to June) when the lake is close to 4°C. Thus, the impact on thermal expansion is likely to be minimal (particularly since the above argument does not include the even smaller changes in deep-water temperature). Other months of the year generally show trends of less than 3% per decade. Thus, we would conclude that, for certain months, the thermal expansion term may have changed by (at most) 15% over the 51-year interval. This is equivalent to a trend in monthly water flux of less than 0.03 cm/decade (roughly 10 m^3/s/decade) and is much smaller than some of the other trends yet to be discussed.

Calculations of trends for the remaining terms in Eq. (6) were first performed for the monthly change in lake level, ΔL. Based on the slope and intercept of the linear regression, the monthly change in lake level was then reconstructed for the beginning and end of the time period (1948 and 1999). These two curves are plotted in Figure 5a and, consistent with the lake level trends (Fig. 2), clearly illustrate a systematic seasonal change in the monthly rate of water storage in Lake Superior. In particular, over the 51-year interval Lake Superior received progressively less net influx of water during April–June and progressively more net influx during the months of September–December. The statistical significance of the 51-year change in storage exceeds 85% for five of the months (ranging from 88% to 96% significant; Table 2). More importantly, the magnitude of the change is very large at certain times of the year (Table 2). For example, the linear trends for May ($\Delta L'$ = –0.87 cm/decade or

a) Reconstructed change in lake level



b) Reconstructed NBS - O

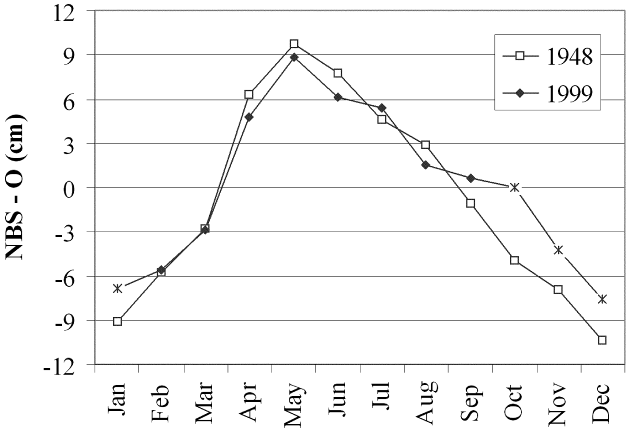


FIG. 5. a) Reconstructed 1948 and 1999 change in BOM lake level (ΔL) for Lake Superior based on the endpoints of the 52-year linear regression (for each month). Units are in cm of water (multiply by ~320 for m^3/s), and significance levels are noted in Table 2 (greater than 85% significant shown as stars, *). b) As in a), except that the reconstructed quantity is NBS – O (i.e., the difference between net basin supply and St. Marys River outflow).

–267 m^3/s/decade) and October ($\Delta L' = 0.71$ cm/decade or 216 m^3/s/decade) imply changes of 46% and 107%, respectively, in their monthly mean values (Table 1) over the 51-year interval (1948–1999). These large changes in monthly flux (1,100–1,360 m^3/s over the past half century) are equivalent to roughly 50–60% of the annual mean discharge of the St. Marys River. For comparison with Figure 5a, Figure 5b shows the reconstructed NBS – O curves for 1948 and 1999. Qualitatively, the two sets of curves show good agreement, suggesting that Eq. (6) is appropriate for assessing the mechanisms responsible for the downward (upward) trends in net spring (autumn) influx into Lake Superior. On the other hand, Figure 5b shows a decrease in net spring influx that is not as dramatic as that of the ΔL term (Fig. 5a). This indicates that a portion of the downward trend in spring water storage is unaccounted for by trends in P, E, R, and/or O, probably because of errors in these same water budget components. (Trends in other water budget components, such as thermal expansion, are not likely to be large enough to make up for the difference.)

The long-term trends for each of the remaining water budget components are shown in Figure 6 and Table 2. An assessment of statistical significance is provided (Table 2), although the primary objective here is to ascertain the mechanisms responsible for the observed trends in water storage (Fig. 5a). For example, Lake Superior has experienced a relatively large upward trend in over-lake precipitation during the months of January, July, September, and especially October (where the 51-year change exceeds 50% of the long-term mean value). April precipitation, on the other hand, has dropped by roughly 25% over the 51-year interval (Fig. 6a, Table 2). Thus, the observed trends in precipitation contribute partially to the downward trend in April storage (Fig. 6b) and can account completely for the upward trends in September and October storage (assuming no offset from other water budget components). The long-term trends in monthly evaporation (Fig. 6a) are generally comparable in magnitude to those of precipitation (up to 0.34 cm/decade or 103 m^3/s/decade) and show a very systematic seasonal pattern. From 1948 to 1999 Lake Superior experienced an increase in summer and autumn evaporation rates (June–October) and a decrease in winter and early spring evaporation (November–March). When combined with precipitation to form $(P - E)'$ (Fig. 6a), the evaporation trends are found to contribute significantly to the downward (upward) trend in August (December) lake level change (Fig. 6b). For most of the remaining months, however, the evaporation trends are largely offset by opposite trends in other water budget components.

Except for October and November, runoff into Lake Superior has experienced a downward trend for every month of the year (Fig. 6a). This is especially true for February and August, where runoff

TABLE 2. Trends in monthly Lake Superior water budget components over the period 1948–1999, based on linear regression analysis. "Ann" denotes trends in total annual flux, and all units are in cm/decade (1 cm/month/decade ~ 320 m^3/s/decade, 1 cm/year/decade ~ 26 m^3/s/decade). Levels of statistical significance are noted in parentheses (for those greater than 85%). See text for variable definitions.

	P′	E′	(P – E)′	R′	NBS′	O′	(NBS–O)′	ΔL′
Jan	0.286 (85)	–0.268 (91)	0.554 (99)	–0.110 (85)	0.444 (96)	0.007	0.437 (97)	0.000
Feb	–0.105	–0.262 (92)	0.157	–0.131 (95)	0.026	–0.006	0.032	0.067
Mar	–0.098	–0.156	0.059	–0.057	0.001	0.011	–0.009	0.254
Apr	–0.256	0.024	–0.280 (85)	–0.042	–0.322	–0.024	–0.298	–0.768 (96)
May	0.003	–0.011	0.014	–0.125	–0.111	0.074	–0.185	–0.870 (88)
Jun	–0.068	0.108 (99)	–0.176	–0.106	–0.282	0.046	–0.328	–0.647 (89)
Jul	0.386 (85)	0.158 (99)	0.228	–0.134	0.094	–0.066	0.160	0.014
Aug	0.006	0.262 (99)	–0.255	–0.215 (97)	–0.471	–0.198	–0.273	–0.274
Sep	0.316	0.131	0.184	–0.093	0.091	–0.249	0.340	0.326
Oct	0.742 (99)	0.261 (93)	0.480 (90)	0.195	0.675 (92)	–0.303 (88)	0.978 (98)	0.706 (89)
Nov	–0.052	–0.059	0.007	0.195 (86)	0.201	–0.318 (92)	0.520 (90)	0.435
Dec	0.138	–0.336 (96)	0.474 (99)	–0.043	0.431 (97)	–0.117	0.548 (99)	0.347 (92)
Ann	1.298	–0.148	1.446	–0.667	0.778	–1.144	1.922 (87)	–0.609

has declined by 20–30% over the 51-year interval (Tables 1 and 2). The August trend (along with evaporation) contributes significantly to the downward trend in water storage, whereas the February trend is counteracted by an opposite trend in P – E. The observed increases in October and November runoff, on the other hand, contribute roughly 28% and 45% to the associated upward trends in water storage, respectively (Table 2). Thus, runoff plays an important role in the increased net influx to Lake Superior during autumn, as well as a modest role in the reduced spring influx. Taking all three trends into account (P′, E′, and R′), it is clear that changes in net basin supply are able to account for the majority of the trends in lake water storage (Fig. 6b). This is particularly true for the months of August–December, which show considerable correspondence between NBS′ and ΔL′. During April–June, on the other hand, only 13–44% of the decline in net influx (ΔL′) is accounted for by downward trends in monthly NBS.

The remaining trend to be considered is that of outflow through the St. Marys River (O′). Similar to evaporation, St. Marys River discharge shows a very systematic trend in seasonality, namely a slight increase in May and June outflow followed by a significant decrease in July–December outflow (Fig. 6b). Some of the larger trends in autumn correspond to a 20% reduction in monthly mean outflow over the 51-year interval, which contributes significantly to the upward trend in water storage (since ΔL′ is proportional to –O′; see Eq. 6). Considering the fact that Lake Superior has been regulated since 1921 (Clites and Quinn 2003), one might at first suspect that the downward trends in autumn outflow reflect some sort of anthropogenic

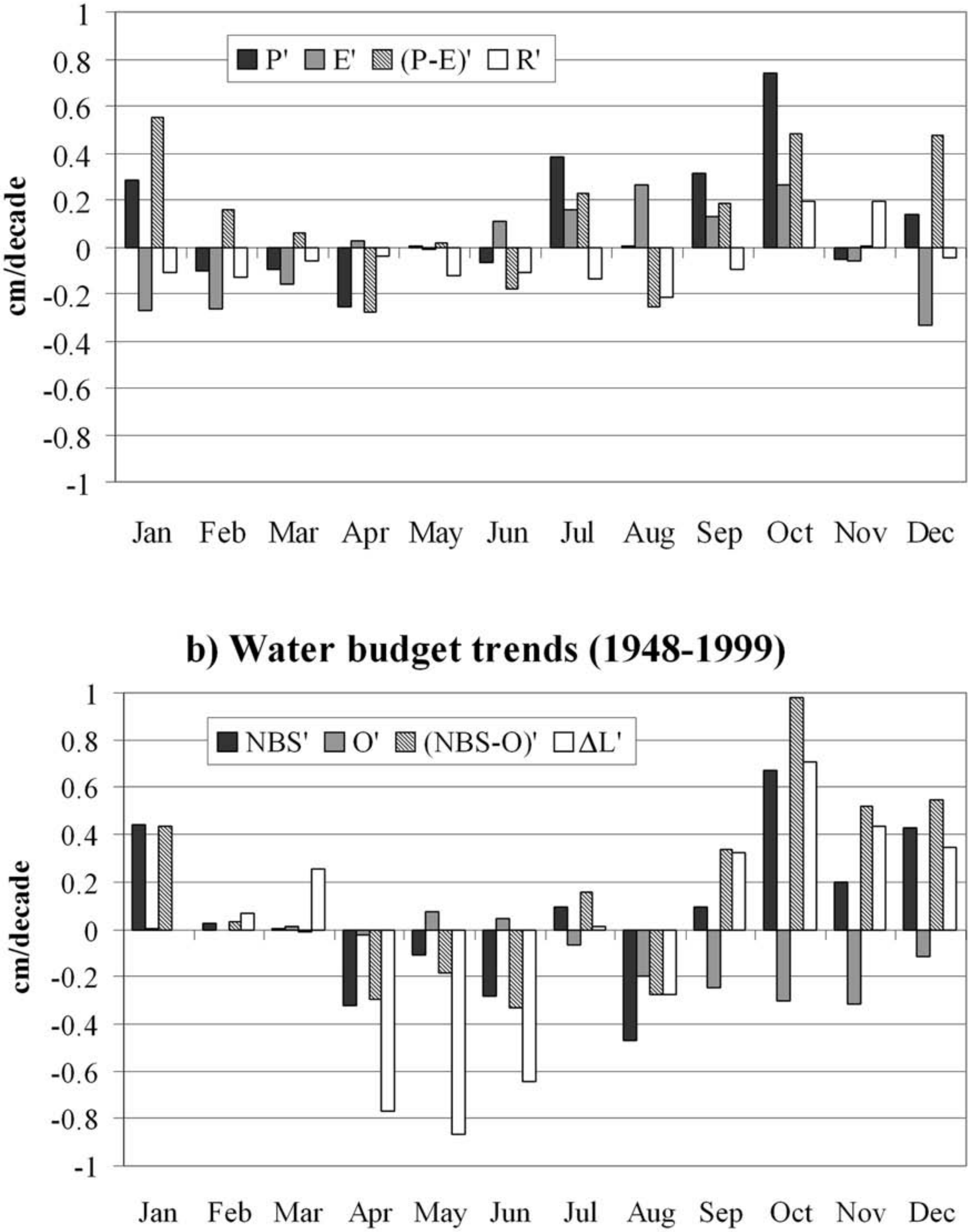


FIG. 6. Trends in the monthly Lake Superior water budget based on linear regressions for 1948-1999. Values are given in units of cm/decade (multiply by ~320 for m^3/s/decade) and are also listed in Table 2 (along with significance levels). See text and Figure 4 for variable definitions. Primes (′) indicate long-term rates of change (over the 51-year interval).

influence. However, such an explanation is not required, since the distinct seasonal pattern in O′ (Fig. 6b) corresponds closely with what would naturally be expected to occur in response to the BOM lake level changes (Fig. 2b), based on linear reservoir theory. In other words, autumn outflow through the St. Marys River has been dropping over time simply because autumn lake levels are also dropping (which reduces the hydraulic head and cross-sectional area that drives the outflow in the first place). In this sense, then, the trends in St. Marys River outflow, while contributing to the trends in lake water storage (and, therefore, having an impact on lake levels), should not be considered a fundamental "cause" of the overall trends in lake level seasonality. Rather it is more appropriate to view the trends in outflow as being simply a response to (and subsequent modifier of) changes in lake level, which are *ultimately* driven by changes in net basin supply. This is not to say that changes in regulation have had absolutely no impact on the trends in seasonal lake levels. Linear reservoir theory simply suggests that such effects are not likely to be significant. This is corroborated by recent modeling results from Quinn (2002), who indicates that temporal changes in the seasonal range in Lake Superior water levels (as simulated by a hydrologic model) are relatively unaffected by regulation.

In terms of the water storage trends (Figs. 5a and 6b), the decline in autumn outflow accounts for a considerable fraction of the upward trend in monthly lake level change during autumn (roughly 30–75%). Thus, the combined trend in outflow and net basin supply, (NBS – O)′, corresponds quite closely to the trends in water storage (ΔL′), at least for the months of July–December and February (Fig. 6b). January, on the other hand, shows a strong upward trend in NBS – O that is not reflected in the water storage term, while the decreased ΔL during April–June (and a slight increase in March) remains only partially accounted for by trends in NBS – O. Some of the discrepancies, such as during May (when $NBS' - O' - \Delta L' \approx 0.7$ cm/decade or 210 m^3/s/decade) are even too large to be legitimately explained by trends in thermal expansion. This suggests, therefore, that the changes in spring storage rates from 1948 to 1999 (which are based on robust measurements of lake level) are simply underestimated by one or more of the terms on the right hand side of Eq. (6). Given the likely extrapolation errors in the runoff term (as well as its relatively large magnitude in the springtime), the most probable explanation for the discrepancies in spring appears to be errors in observed runoff. Even the unaccounted-for upward trend in March storage (Fig. 6b) may be a reflection of the potential runoff bias toward larger streams (e.g., unmeasured snowmelt runoff trends from smaller catchments). On the other hand, the discrepancies in March and (especially) January, when evaporation rates are higher (Fig. 4a), may be due to inaccurate trends in evaporation rate (Fig. 6a).

POTENTIAL MECHANISMS

The preceding section has demonstrated a close connection between 51-year changes in monthly water storage in Lake Superior and corresponding trends in precipitation, runoff, and evaporation. It is worthwhile at this point to examine some of the possible mechanisms responsible for the observed trends in net basin supply. Regarding precipitation, the upward trend in autumn precipitation has been documented in a number of studies, as reviewed recently by Grover and Sousounis (2002). In an analysis of nine different precipitation classification types over the period 1935–1995, Grover and Sousounis (2002) found that both the intensity and frequency of autumn precipitation events has been increasing over the Great Lakes region, particularly for events associated with warm, stationary, and occluded fronts. Further analysis suggests that these changes are associated with increased zonal flow over the United States during the latter decade of their study (1980–1989), as well as stronger low-level flow from the Gulf of Mexico and a stronger upper-tropospheric subtropical jet. Grover and Sousounis (2002) also speculate that some of the observed changes may have been influenced by the Pacific Decadal Oscillation (PDO). Earlier studies have investigated the influence of extratropical systems on the Great Lakes region as well (e.g., Angel and Isard 1998, Isard *et al.* 2000). For example, Angel and Isard (1998) found a significant increase in the number of strong Great Lakes cyclones during the cold season (November–April) over the period 1900–1990. In addition to the results of Grover and Sousounis (2002), this may help to explain some of the increases in over-lake precipitation noted for December and January (Fig. 6a). As noted by Rodionov (1994), such changes in storm tracks and cyclone frequency are directly related to wintertime precipitation variability and lake level changes in the Great Lakes region. Unfortunately, these studies do not offer an explanation for the prominent increase in July precipitation found in the current study (Fig. 6a), nor the systematic (but less significant) downward trends during February–April. Such explanations will have to await a more comprehensive analysis of seasonal precipitation trends and the associated climatic mechanisms. A potentially important factor in such an analysis (at least for the cold months) would be accounting for trends in lake-effect snowfall which have recently been documented for the Great Lakes region (e.g., Norton and Bolsenga 1993, Leathers and Ellis 1996, Burnett *et al.* 2003).

Turning to the trends in runoff and evaporation, a potentially important mechanism for the observed changes involves the effects of regional warming. Air temperatures have been increasing over the Great Lakes region, particularly during the springtime (Bolsenga and Norton 1993), suggesting possible effects on lake temperature and evaporation. Furthermore, such temperature changes are also likely to influence land surface runoff through changes in snowmelt, evapotranspiration, and soil water storage. On the other hand, runoff is also impacted directly by changes in over-land precipitation, which may or may not be similar to those already identified for over-lake precipitation. A preliminary analysis of some of these influences on runoff and evaporation is presented in this section. It would be worthwhile in future studies to undertake more detailed modeling investigations of these issues.

Runoff into Lake Superior ultimately originates from over-land precipitation, but the magnitude and timing of river discharge into the lake is modified significantly by evapotranspiration and storage effects (primarily snowpack, soil moisture, groundwater, and river storage). Similar to the lake water budget of Eq. (1), the monthly land surface water budget can be written as:

$$\Delta S_{land} = P_{land} - ET - R \qquad (7)$$

where,

ΔS_{land} = monthly change in water storage on the land surface (cm),

P_{land} = monthly total over-land precipitation (cm),

ET = monthly total evapotranspiration from the land surface (cm), and

R = monthly total land surface runoff into Lake Superior (cm).

In contrast to Eq. (1), Eq. (7) treats R as a net loss of water from the land surface (rather than a gain), and the units are in cm of water spread over the land area of the Lake Superior drainage basin (roughly 1.28×10^{11} m^2). Rewriting Eq. (7) in the form:

$$R = P_{land} - (ET + \Delta S_{land}) \qquad (8)$$

one can readily see that long-term trends in over-land precipitation will lead to similar trends in runoff unless significant trends also exist in ET and/or water storage:

$$R' = P_{land}' - (ET + \Delta S_{land})' \qquad (9)$$

In fact, considering the significant lag between precipitation and runoff for a basin the size of Lake Superior, it is rather unlikely that (on a monthly timescale) precipitation trends will lead directly to matching trends in runoff. Using estimates of P_{land} from the dataset of Hunter and Croley (1993), a preliminary analysis of trends in the land surface water budget is presented here.

Similar to Figure 6, Figure 7 shows the 51-year linear regression-based values for P_{land}', R', and $(ET + \Delta S_{land})'$ (calculated as $[P_{land} - R]'$), as well as the long-term trend in over-land air temperature. Perhaps the most important conclusion from Figure 7 is that there are, indeed, significant differences between the trends in precipitation and runoff. For example, although over-land precipitation has declined over the 51-year interval during the months of February to June (by roughly 10–20% of the monthly mean), the decline is generally much larger than the corresponding decrease in runoff. This suggests, according to Eq. (9), that ET and/or water storage on the land surface have been dropping during these months as well (as indicated by the negative values of $(P_{land} - R)'$ in Fig. 7). Given the large increases in February and March air temperatures (up to 0.5°C/decade), it is certainly conceivable that more snowmelt (i.e., less water storage) could be occurring during these months than has occurred in the past, especially if snowfall has been increasing as well (e.g., December and January; Fig. 7). This would contribute more runoff to Lake Superior during early spring (but, according to Fig. 7, still not enough to overcome the downward trends in over-land precipitation), while leaving less water to run off later in the spring and early summer. Such a mechanism is consistent with the results of Zhang *et al.* (2001), which show increases in Canadian streamflow during early spring, followed by reduced streamflow in subsequent months. The con-

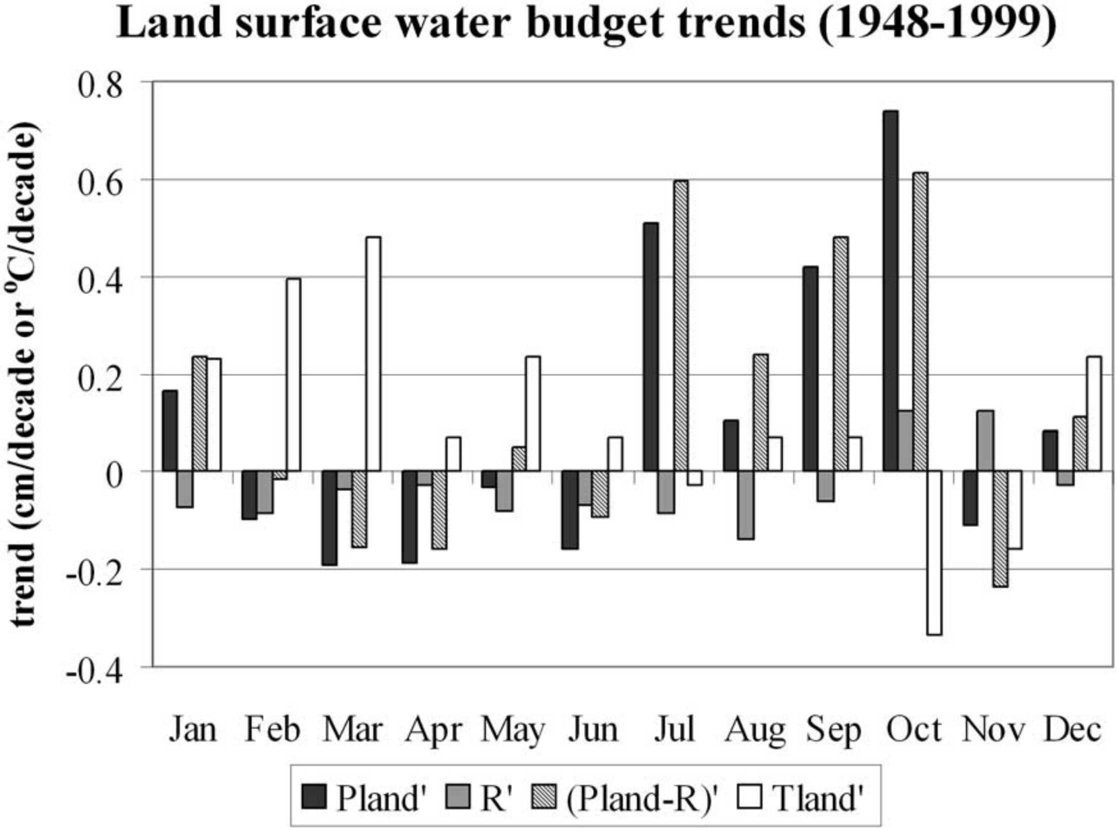


FIG. 7. Trends in the monthly land surface water budget and air temperature of the Lake Superior basin for 1948-1999 based on data from Hunter and Croley (1993). Variables include trends in over-land precipitation (P_{land}'), runoff (R'), (P_{land}-R)$'$ (equivalent to ($ET + \Delta S_{land}$)$'$), and over-land air temperature (T_{land}'). Primes ($'$) indicate long-term rates of change (over the 51-year interval) and are in units of °C/decade or cm/decade (cm of water over the land area, not lake area). Trends are most strongly significant (beyond the 95% level) for the months of February (R), March (T_{land}), July (P_{land} and P_{land}-R), August (R), and October (T_{land}, P_{land}, and P_{land}-R). Runoff trends are also listed in Table 2 (in cm/decade over the lake area).

nection with earlier spring snowmelt is further corroborated by observations of downward trends in Canadian snow cover during spring, particularly February and March (Brown and Goodison 1996, Brown and Braaten 1998). On the other hand, it is important to keep in mind that potential extrapolation errors in the runoff data used in the current study may simply be causing an underestimation of the drop in spring runoff that might be implied by the trends in precipitation (Fig. 7).

Even larger differences exist between the trends in P_{land} and R during the months of July–October. Very strong upward trends in over-land precipitation (roughly 20–50% increases over the 51-year interval) are accompanied by relatively small trends in runoff (Fig. 7), most of which are even negative. Aside from potential errors in the dataset, this again implies important changes in ET and/or water storage during the summer and autumn months. In particular, the significant lag typically introduced by water storage in soil, groundwater, and rivers is almost certainly playing a role. That is, one interpretation of Fig. 7 is that the increased precipitation during July–October is simply being stored in the soil and rivers and eventually routed into the lake as increased runoff during October and November. This mechanism would be especially effective if the land surface were pre-conditioned toward drier conditions during late spring, something which has already been noted in the precipitation and runoff data (and potentially ET and/or snowmelt as well; Fig. 7).

Besides water storage, one must also consider the possibility that changes in evapotranspiration are affecting the balance between trends in over-land precipitation and trends in runoff. For example, one might note from Figure 7 that the trends in runoff are opposite in sign to those of air temperature for eleven of the twelve months. And since warmer (colder) temperatures generally lead to higher (lower) ET, the juxtaposition of runoff and temperature trends is physically consistent with possible changes in ET. Changnon (1987) has suggested similar temperature-related changes in evapotranspiration for the Lake Michigan basin. On the other hand, it is possible that the temperature trends (which are somewhat anti-correlated with the trends in precipitation) are simply related to the fact that cooler (warmer) months are the result of wet, cloudy (dry, sunny) conditions. Either way, it would be worthwhile to examine these potential connections in future modeling studies. A particularly convincing argument that ET has, indeed, changed over the past half century is based on the fact that the trend in annual total ET + ΔS_{land} is significantly non-zero (roughly 1.7 cm/decade, $p < 0.01$, as calculated from $[P_{land} - R]'$). Since annual changes in water storage on the land surface generally fluctuate about zero (over the long-term), one can reasonably conclude that $\Delta S_{land}' \approx 0$ (for annual values) and, therefore, that annual $ET' \approx 1.7$ cm/decade. Thus, the upward trend in ET + ΔS_{land} is indicative of an 8.6-cm increase in annual total ET over the Lake Superior drainage basin for the 51-year interval (1948–1999). This represents a roughly 20% increase over the long-term mean value of 43 cm. (For reference, the annual mean air temperature has increased by approximately 0.6°C over the same time interval.) Interestingly, Milly and Dunne (2001) have noted a 0.95 cm/decade increase in annual total evapotranspiration for the Mississippi basin over a similar time period (1949–1997). They suggest that the trend is due primarily to increases in precipitation, secondarily to human water use (e.g., irrigation), and that the trend is moderated somewhat by regional cooling and downward trends in net radiation. In contrast, the warming which has occurred over the Lake Superior basin during the past half century may account for the somewhat larger trend in annual ET for this region.

The potential connections between regional warming and the observed trends in lake evaporation are examined in Fig. 8. Like other deep lakes in temperate regions, Lake Superior has an annual cycle of evaporation which is nearly out-of-phase with that of air temperature (Fig. 8a). Evaporation rates are highest during the months of November–January, close to the time of year when air temperature is at its lowest (December–February). Similarly, evaporation rates decline to low (even negative) values during May–July, when air temperatures have attained relatively high values (highest during July and August). This behavior is relatively easily explained in terms of the lake's thermal inertia and lake-air vapor pressure differences. That is, since Lake Superior is so deep, seasonal variations in surface water temperature are considerably less than those of air temperature (Fig. 8a), even lagging air temperature variations by about one month. Thus, when cold, dry winter air overrides the relatively warmer water, a large vapor pressure difference leads to high evaporation rates. Air temperatures then increase more rapidly than the water so that by April, the air temperature is warmer than the underlying lake surface. Accompanied by high absolute humidity, the warm, summertime air produces a low vapor pressure gradient, leading to low evaporation rates or even condensation. Thus, seasonal variations in evaporation on Lake Superior do not match those of air temperature nor water temperature, but instead correspond more closely to variations in lake-air temperature *difference* (Fig. 8a).

These physical considerations are helpful for understanding the observed trends in lake evaporation, which are shown in Figure 8b, along with the corresponding trends in monthly mean temperature. As noted earlier, the trends in monthly evaporation show a very systematic seasonal pattern (increasing during June–October, but decreasing during November–March). The patterns for air and water temperature are quite different from evaporation, showing increasing trends for nearly every month of the year (October and November air temperatures being the exception). Note, however, that air temperature has been increasing at a considerably greater rate than water temperature during the months of February and March. This corresponds to a downward trend in lake-air temperature difference (Fig. 8b), which could potentially explain the decrease in February–March evaporation rates. (This is not true for January, which is also when evaporation trends have been suggested to be suspect because of disagreements with lake level trends. An additional caveat concerning the temperature dataset is that water temperatures are fixed at 0°C

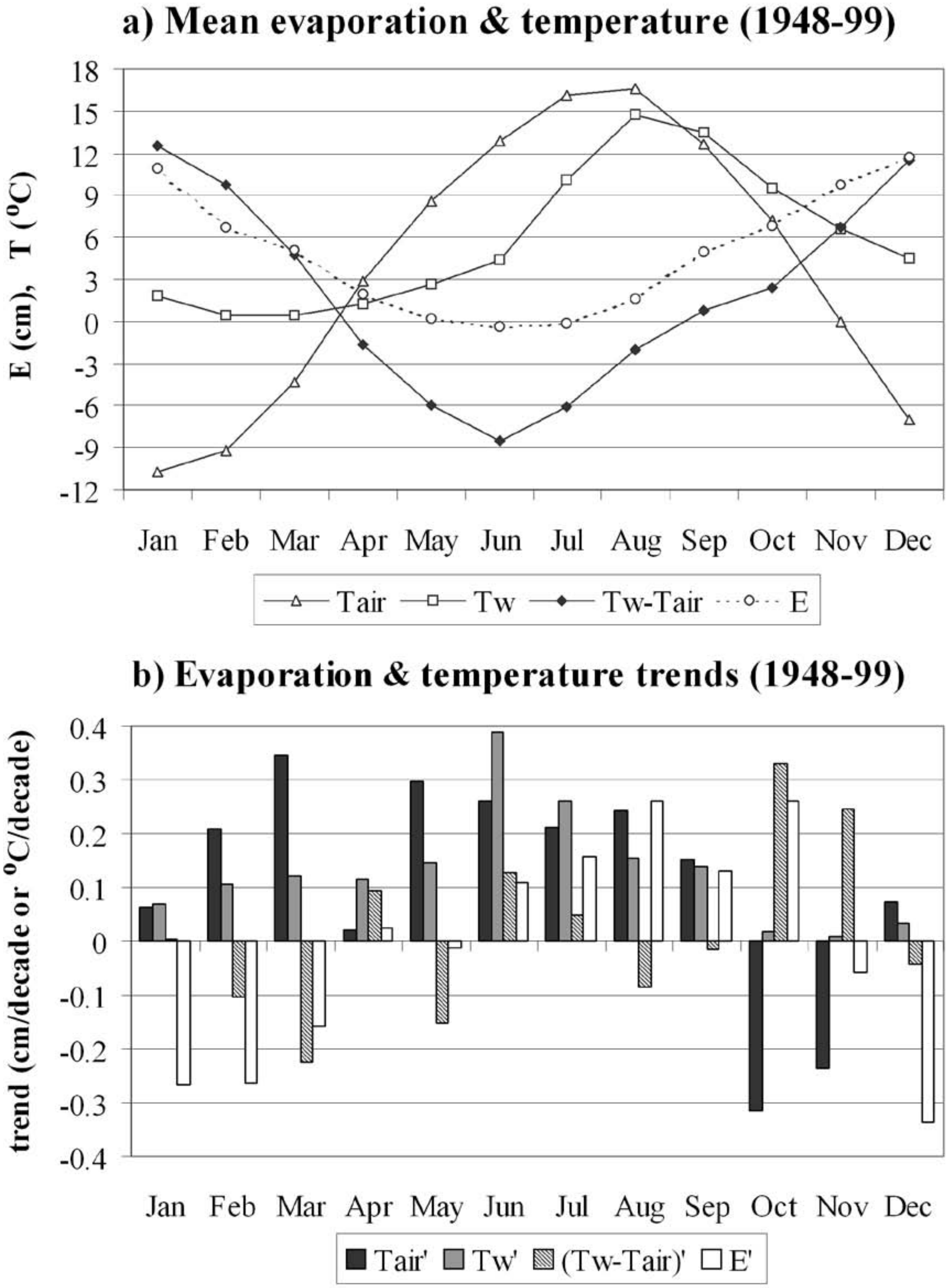


FIG. 8. a) Long-term monthly mean over-lake air temperature (T_{air}), water surface temperature (T_w), water-air temperature difference (T_w-T_{air}), and lake evaporation (E) for the period 1948–1999. Data are obtained from Hunter and Croley (1993) and are in units of °C or cm of water (per month; 1 cm/month ~ 320 m^3/s). b) Trends in T_{air}, T_w, T_w-T_{air}, and E based on linear regression of the individual monthly values from 1948–1999. Primes (′) indicate long-term rates of change (over the 51-year interval) and are in units of °C/decade or cm/decade (multiply by ~320 for m^3/s/decade). Temperature trends are statistically significant at the 95% level for the months of March (T_w), May (T_{air} and T_w), June (T_{air} and T_w), and October (T_{air} and T_w-T_{air}). Evaporation trends are also listed in Table 2.

when ice is present. Thus, trends in wintertime water temperature may also reflect trends in ice cover.) In contrast, during June-October, the trends in air temperature are nearly matched or even exceeded by those of water temperature, leading to an upward trend in lake-air temperature difference for 3 of the 5 months (when evaporation is also increasing). Although the results of Figure 8b are by no means conclusive (ignoring factors such as radiation, relative humidity, and wind speed), they at least suggest that temperature changes play a moderate role in the observed evaporation trends. More importantly, these results highlight the somewhat complex nature of evaporation from deep lakes, namely that (depending on the time of year) increases in air temperature may actually lead to decreases in evaporation. Future observational or modeling studies may shed more light on the reasons for these seasonally varying trends, including the relative roles of ice cover, thermal lags, mixing depth, and climatic influences not considered here (e.g., humidity and cloud cover).

DISCUSSION AND CONCLUSIONS

During a typical year, Lake Superior water levels experience a pronounced annual cycle as a result of seasonally varying inputs and losses of water, primarily those of evaporation and runoff. The results of this study indicate that the magnitude of this seasonal lake level cycle has decreased by 20% over the past half century, from an annual lake level range of about 40 cm in 1948 to 32 cm in 1999. This change is manifested as a 5–10 cm drop in June–November lake levels (when seasonal levels are typically highest) accompanied by roughly no change in lake levels during winter and spring (when levels are typically lowest). An examination of the water budget reveals that the cause of the weakening seasonal cycle is not due to one single factor, but is instead the result of a variety of trends in the regional water balance over the period 1948-1999.

First of all, there has been an increase in the net influx of water to Lake Superior during the months of September to December, a time of year when water levels are typically decreasing. This increased net influx is due to a combination of upward trends in over-lake precipitation (primarily during September and October) and runoff (October and November) as well as decreases in outflow through the St. Marys River (July–December). Increases in lake evaporation moderate the trends in September and October, while decreases in evaporation during December–March help to weaken the rate of lake level decline. A brief analysis of the land surface water budget suggests that the increased autumn runoff into Lake Superior is primarily the result of lagged over-land precipitation increases during September and October. The amount of increased runoff, however, is considerably less than that of the over-land precipitation, suggesting an increase in evapotranspiration as well (and/or soil water storage). Indeed, a 20% increase in annual mean evapotranspiration is required in order for the land surface water budget to remain in balance over the 51-year interval (assuming minimal measurement error). Similar (but weaker) trends have been calculated for the Mississippi basin (Milly and Dunne 2001). It is important to note that, aside from the possible effects of regulation (which appear to be minimal in this study), the reduced autumn outflow through the St. Marys River is primarily a response to the reduction in autumn lake levels from 1948–1999. Thus, the changes in outflow modify but do not fundamentally *cause* the long-term trends in lake level seasonality (which are instead ultimately driven by changes in net basin supply). Similar to the results of Quinn (2002), therefore, it can be concluded from this study that the observed trends in seasonal lake levels for Lake Superior are primarily the result of climate variations, rather than regulation. Given the observed trends in the land surface water budget, it is also possible that changes in land cover, land use, and/or water use within the drainage basin have affected lake levels as well (through runoff, ET, and storage effects). A more detailed analysis of the relative influences of climate, regulation, and human land use on the Lake Superior water budget would make a valuable contribution to this area of research.

The upward trend in net autumn influx to Lake Superior, if acting alone, would lead to a significant increase in overall lake level over the 51-year interval. This does not occur, however, because of a compensating downward trend in net influx during the late spring (April–June). Taken together, the autumn trends lead to a less rapid seasonal drop in lake levels during September–December, while the spring trends lead to a less rapid rise in lake levels during April–June. The net result is a significant decrease in seasonal amplitude from 1948 to 1999, but minimal change in annual mean lake level (a drop of only 4 cm). Analysis of the water budget reveals that the decrease in net spring influx is primarily the result of downward trends in over-lake precipitation (during April and June) and runoff (April–June), with some contributions from increasing evaporation (June) and St. Marys River outflow (May–June). As is the case for the autumn trends, the decreases in spring runoff appear to be at least partly related to reductions in over-land precipitation during preceding months (primarily March and April). Also similar to autumn, the decreases in spring runoff are not as strong as the decreases in over-land precipitation, suggesting some additional input of runoff from snowmelt, groundwater, and/or reduced evapotranspiration. Given the significant increases in springtime temperatures over the 51-year interval (more than 2°C for both February and March) as well as observed reductions in spring snow cover (e.g., Brown and Braaten 1998), it appears that earlier inputs from snowmelt are the most likely explanation (or possibly underestimated drops in runoff). Earlier snowmelt would also help to explain the reduced runoff later in the spring and early summer.

A valuable characteristic of this type of study is the ability to assess the accuracy of the observed water budget trends through comparison with trends in lake water storage (calculated from robust measurements of beginning-of-month lake level). Aside from errors in the hydrologic dataset and contributions from neglected water budget components, trends in net basin supply and outflow (i.e., [NBS – O]′) should closely match those of lake water storage. This is approximately the case for 7 months of the year (February and July–December). The upward trends in water storage are somewhat overestimated by (NBS – O)′ during October–December, but for the most part the trends depicting increased autumn influx are adequately reproduced. This is not the case for the months of April–June, however, where the trends in net basin supply and outflow can only account for 20–50% of the downward trend in lake water storage. (Additional discrepancies occur in January and March.) The differences are too large to be attributed to neglected budget terms (including thermal expansion) or errors in evaporation rates, which are too small during April–June (but may contribute errors during January and March). Thus, aside from potential errors in St. Marys River discharge, the "missing sink" in spring is most likely due to errors in measured precipitation and/or runoff (which would also have important implications for conclusions regarding the land surface water budget). In particular, the discrepancy implies that, at the beginning of the 52-year period (1948), Lake Superior experienced considerably more April–June precipitation and/or runoff than is actually recorded in the dataset (and/or less-than-observed influx at the end of the 52-year period). Comparisons with the results of Bennett (1978) do seem to suggest that long-term mean spring runoff is underestimated in the present study. Together with the fact that some of the Lake Superior watershed is ungauged, and that the 3 months of highest runoff into the lake are April, May, and June, it certainly seems likely that runoff errors are the primary source of uncertainty. Such errors might even reflect a "large stream bias" as a result of the tendency for smaller streams to be ungauged. These conclusions are preliminary, however, and it would be worthwhile to undertake a thorough evaluation of springtime precipitation and runoff datasets for the Lake Superior basin (and the Great Lakes as a whole). The discrepancies in the water budget also point out the need for increased investment in hydrologic observation networks, in contrast to the current climate of stagnant or even reduced budgets for hydrologic monitoring.

The results of this study raise a number of interesting questions regarding the future of Lake Superior and its water supplies. For example, should we expect these recent 50-year trends in the water budget to continue? If so, what might be the impacts of a significantly reduced seasonal lake level cycle? Given the statistical significance of some of the observed trends, it certainly appears that the recent changes are not purely random in nature, but rather are part of an overall systematic shift in behavior. On the other hand, such trends cannot continue ad infinitum due to the constrained nature of some of the hydrologic variables (e.g., runoff is always greater than zero). Therefore, it would be useful to investigate the underlying climatic mechanisms responsible for the observed shifts in precipitation, evaporation, and runoff to aid in understanding and predicting future variations. Some potential factors have already been suggested (e.g., shifting storm tracks and regional warming), but significantly more work is needed to understand these issues. It is particularly important that future studies include a close examination of land surface processes (including land use change) since it appears that a significant portion of the runoff trends are related to changes in evapotranspiration and water storage.

Another intriguing question relates to the compensating nature of the spring and autumn trends in net influx (i.e., water storage rate), a phenomenon that has been occurring not only for Lake Superior, but the rest of the Great Lakes as well (Lenters

2001, Argyilan and Forman 2003). It is somewhat peculiar (and fortunate!) that the near cancellation of such large trends should even occur, and causes one to question whether the offsetting trends are purely coincidental. Perhaps there is an overriding climatic influence which is simply shifting the timing of the seasonal hydrologic budget, rather than changing the overall annual mean fluxes. For example, it is possible that changes in large-scale circulation patterns and storm tracks could somehow be leading to conditions whereby precipitation in the Great Lakes region is increasing during autumn, while simultaneously decreasing during spring and summer. Such mechanisms, however, are not known at this time. Perhaps a more likely mechanism (involving runoff) is that seasonal shifts in water stored on the land surface (primarily snow pack, but also soil moisture and groundwater) are leading to large, but compensatory changes in monthly runoff (i.e., such that annual mean changes are less dramatic). Furthermore, the trends in lake evaporation (for Lake Superior) clearly exhibit systematic (and sometimes large) changes in monthly mean values, with very little change in annual mean rates. Preliminary analysis of temperature trends suggests that this may be related to the somewhat complex interaction between increases in air temperature and changes in lake surface temperature (and, perhaps, ice cover). Regardless of the cause, it appears that understanding future long-term changes in Great Lakes water levels may hinge on whether the current compensation of seasonal trends continues or if, instead, one of the positive or negative trends begins to dominate (if the trends even continue at all). Grover and Sousounis (2002), for example, note that the upward trend in autumn precipitation in the Great Lakes region began to decline in the mid 1990s, which helped lead to low lake levels by the end of the decade. More recently, the fall and winter of 2002/2003 were drier than normal throughout much of the Great Lakes basin, dropping lake levels even further. Such deviations from the autumn trends identified in the current study could, if combined with continued reductions in net spring influx, lead to dramatically low lake levels. Future investigations should also examine the potential effects of regional warming. For instance, is there a threshold at which further increases in air temperature will lead to dramatic increases in annual mean lake evaporation (e.g., through significant reductions in ice cover or seasonal mixing)? Given the growing recognition of the widespread nature of some of these trends (Lenters 2001, Quinn 2002, Argyilan and Forman 2003), it appears that these questions may be relevant not only to Lake Superior, but the Great Lakes region as a whole.

ACKNOWLEDGMENTS

The author thanks NOAA's Great Lakes Environmental Research Laboratory (GLERL) for providing the comprehensive hydrologic dataset used in this study. Constructive comments were provided by Brent M. Lofgren and an anonymous reviewer and have led to significant improvements in the manuscript. A portion of this research was performed while the author was a visiting assistant professor at the Center for Sustainability and the Global Environment (SAGE) of the Gaylord Nelson Institute for Environmental Studies (IES), University of Wisconsin-Madison. Funding was provided by the National Aeronautics and Space Administration (NASA; NAG13-99008) through the Upper Midwest Regional Earth Science Applications Center (RESAC).

REFERENCES

Angel, J.R., and Isard, S.A. 1998. The frequency and intensity of Great Lake cyclones. *J. Climate.* 11:61–71.

Argyilan, E.P., and Forman, S.L. 2003. Lake level response to seasonal climatic variability in the Lake Michigan-Huron system from 1920 to 1995. *J. Great Lakes Res.* 29:488–500.

Baldwin, C.K., and Lall, U. 1999. Seasonality of streamflow: The upper Mississippi River. *Water Res. Res.* 35 (4):1143–1154.

Bennett, E.B. 1978. Water budgets for Lake Superior and Whitefish Bay. *J. Great Lakes Res.* 4:331–342.

Bolsenga, S.J., and Norton, D.C. 1993. Great Lakes air temperature trends for land stations, 1901–1987. *J. Great Lakes Res.* 19:379–388.

Bonsal, B.R., Zhang, X., Vincent, L.A., and Hogg, W.D. 2001. Characteristics of daily and extreme temperatures over Canada. *J. Climate*. 14:1959–1976.

Brinkmann, W.A.R. 2000. Causes of variability in monthly Great Lakes water supplies and lake levels. *Climate Res.* 15:151–160.

Brown, R.D. 2000. Northern hemisphere snow cover variability and change, 1915–97. *J. Climate*. 13:2339–2355.

_____, and Braaten, R.O. 1998. Spatial and temporal variability of Canadian monthly snow depths, 1946–1995. *Atmosphere-Ocean*. 36 (1):37–54.

_____, and Goodison, B.E. 1996. Interannual variability in reconstructed Canadian snow cover, 1915–1992. *J. Climate*. 9 (6):1299–1318.

Burn, D.H. 1994. Hydrologic effects of climatic change in west-central Canada. *J. Hydrol*. 160:53–70.

Burnett, A.W., Kirby, M.G., Mullins, H.T., and Patterson, W.P. 2003. Increasing Great Lake-effect snowfall during the twentieth century: A regional response to global warming? *J. Climate.* 16(21):3535–3542.

Cayan, D.R., Kammerdiener, S.A., Dettinger, M.D., Caprio, J.M., and Peterson, D.H. 2001. Changes in the onset of spring in the western United States. *Bull. Am. Meteor. Soc.* 82 (3):399–415.

Changnon, S.A. 1987. Climate fluctuations and record-high levels of Lake Michigan. *Bull. Am. Meteor. Soc.* 68 (11):1394–1402.

Clites, A.H., and Quinn, F.H. 2003. The history of Lake Superior regulation: implications for the future. *J. Great Lakes Res.* 29:157–171.

Croley, T.E., II 1990. Laurentian Great Lakes double-CO2 climate change hydrological impacts. *Climatic Change* 17:27–47.

Grover, E.K., and Sousounis, P.J. 2002. The influence of large-scale flow on fall precipitation systems in the Great Lakes basin. *J. Climate.* 15:1943–1956.

Hanson, H.P., Hanson, C.S., and Yoo, B.H. 1992. Recent Great Lakes ice trends. *Bull. Am. Meteor. Soc.* 73 (5):577–584.

Hartmann, H.C. 1990. Climate change impacts on Laurentian Great Lakes levels. *Climatic Change* 17:49–67.

Hunter, T.S. and Croley, T.E., II. 1993. *Great Lakes monthly hydrologic data.* NOAA Data Report ERL GLERL, National Technical Information Service, Springfield, Virginia, 22161 (http://www.glerl.noaa.gov/data/arc/hydro/mnth-hydro.html; accessed May 2002).

Isard, S.A., Angel, J.R., and VanDyke, G.T. 2000. Zones of origin for Great Lakes cyclones in North America, 1899–1996. *Monthly Weather Rev.* 128:474–485.

Leathers, D.J., and Ellis, A.W. 1996. Synoptic mechanisms associated with snowfall increases to the lee of Lakes Erie and Ontario. *Internat. J. Climat.* 16:1117–1135.

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

Lofgren, B.M., Quinn, F.H., Clites, A.H., Assel, R.A., Eberhardt, A.J., and Luukkonen, C.L. 2002. Evaluation of potential impacts on Great Lakes water resources based on climate scenarios of two GCMs. *J. Great Lakes Res.* 28:537–554.

McCormick, M.J., and Fahnenstiel, G.L. 1999. Recent climatic trends in nearshore water temperatures in the St. Lawrence Great Lakes. *Limnol. Oceanogr.* 44 (3):530–540.

Meredith, D.D. 1975. Temperature effects on Great Lakes water balance studies. *Wat. Res. Bull.* 11 (1):60–68.

Milly, P.C.D., and Dunne, K.A. 2001. Trends in evaporation and surface cooling in the Mississippi River basin. *Geophys. Res. Lett.* 28 (7):1219–1222.

Norton, D.C., and Bolsenga, S.J. 1993. Spatiotemporal trends in lake effect and continental snowfall in the Laurentian Great Lakes 1950–1980. *J. Climate.* 6:1943–1956.

Parmesan, C., and Yohe, G. 2003. A globally coherent fingerprint of climate change impacts across natural systems. *Nature* 421:37–42.

Quinn, F.H. 2002. Secular changes in Great Lakes water level seasonal cycles. *J. Great Lakes Res.* 28:451–465.

Rodionov, S.N. 1994. Association between winter precipitation and water level fluctuations in the Great Lakes and atmospheric circulation patterns. *J. Climate.* 7:1693–1706.

Root, T.L., Price, J.T., Hall, K.R., Schneider, S.H., Rosenzweig, C., and Pounds, J.A. 2003. Fingerprints of global warming on wild animals and plants. *Nature* 421:57–60.

Schwartz, M.D., and Reiter, B.E. 2000. Changes in North American spring. *International J. Climate.* 20:929–932.

Smith, J.B. 1991. The potential impacts of climate change on the Great Lakes. *Bull. Am. Meteor. Soc.* 72 (1):21–28.

Westmacott, J.R., and Burn, D.H. 1997. Climate change effects on the hydrologic regime within the Churchill-Nelson River Basin. *J. Hydrol.* 202:263–279.

Whitfield, P.H., and Cannon, A.J. 2000. Recent variations in climate and hydrology in Canada. *Can. Wat. Res. J.* 25 (1):19–65.

Zhang, X., Harvey, K.D., Hogg, W.D., and Yuzyk, T.R. 2001. Trends in Canadian streamflow. *Wat. Res. Res.* 37:987–998.

Submitted: 6 July 2002
Accepted: 2 October 2003
Editorial handling: Martin T. Auer