HYDROCLIMATIC FACTORS OF THE RECENT RECORD DROP IN LAURENTIAN GREAT LAKES WATER LEVELS

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High air temperatures resulted in unusually high evaporation rates and decreased basin runoff, producing the largest single-year drop in the levels of Lakes Michigan, Huron, and Erie in over 150 years of record.

The Laurentian Great Lakes (Fig. 1) comprise the United States' premier surface-water resource, with a basin area of 770,000 km^2 (Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data 1977). The lakes cover an area of over 245,000 km^2 and contain approximately 23,000 km^3 of water. They contain about 18% of the world's freshwater supply and over

FIG. 1. The Great Lakes system with long-term water-level gauges for Lakes: Superior (at Marquette), Michigan–Huron (at Harbor Beach), Saint Clair (not shown but located along west shore of Lake Saint Clair), Erie (at Cleveland), and Ontario (at Oswego).

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80% of the U.S. supply. Spread evenly across the conterminous United States, the lakes' water would be about 2.9 m deep. The Great Lakes coastline of over 15,000 km is the nation's longest. This water resource is shared between the United States and Canada and supports many important uses, including recreational boating, commercial navigation, sport and commercial fishing, hydroelectric power, industry, municipal water supplies, recreation, and fish and wildlife habitats. Unlike other coastal areas, the Great Lakes provide drinking water to over 40 million U.S. and Canadian citizens, and water quality (as well as water security) is, thus, an exceptionally important concern for the region. The Great Lakes provide about 254.6 billion liters of water daily for municipal, agricultural, and industrial use, a 1609-km international border, a commercial shipping route of 1931 km, and a large tourism industry.

The Great Lakes system (Fig. 1), which includes the five Great Lakes (Superior, Michigan, Huron, Erie, and Ontario) and Lake Saint Clair, and the connecting channels, is naturally well regulated due to the large lake surface areas and constricted outlet channels. Two of the lakes—Superior and Ontario—are actually regulated (International Joint Commission 1979; International Saint Lawrence River Board of Control 1963). This has resulted in the lakes fluctuating through a relatively small range in levels, about 1.8 m. Because of the small range in water levels, industrial and recreational uses are sensitive to even small changes in lake levels. The lakes were in an extremely high-levels regime from the late 1960s through the late 1990s, with record highs being set in 1973 and 1986 (NOAA/National Ocean Service 1992). However, beginning with the 1997/98 El Niño (Bell and Halpert 1998), the lakes began a dramatic decline in water levels that was notable for both the magnitude and the rapidity of the drop. In this study we compared the drop in levels with similar past events, examined the hydroclimatological factors leading to the decline in levels, and looked briefly at both positive and negative economic and environmental impacts.

LAKE LEVELS. The Great Lakes water levels have been continuously gauged since 1860, providing one of the longest unbroken time series of measured hydrologic data in North America (NOAA/National Ocean Service 2002). Prior to 1860, periodic gauge measurements are available at several locations back to the early 1800s (Angell et al. 1896). The current database for Lake Saint Clair begins in 1900. For this study, we are using water levels from the long-term water-level gauges (Fig. 1) at Marquette, Michigan

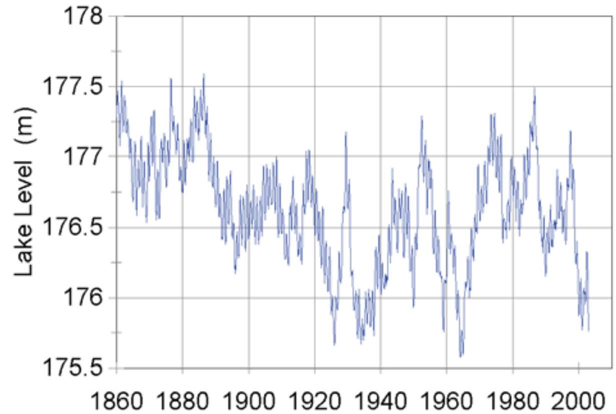


Fig. 2. Lakes Michigan–Huron water levels at Harbor Beach, MI.

(Lake Superior), Harbor Beach, Michigan (Lakes Michigan–Huron), Saint Clair Shores, Michigan (Lake Saint Clair), Cleveland, Ohio (Lake Erie), and Oswego, New York (Lake Ontario). The 1997–2000 episode is readily apparent in the long-term water-level record for Lakes Michigan–Huron (Fig. 2).

Three aspects—the magnitude and rate of the levels' decline, the very low resulting water levels, and the duration—are important in assessing the importance of the recent episode. The available record was used to assess and compare major historic short-term changes. The relative magnitude and rapidity of the decline in the levels were examined by comparing the magnitudes of 1–3-yr declines in water levels with the current episode. The declines are computed as the difference between the maximum monthly level for 1 yr and the subsequent minimum monthly levels for 1–3 yr in the future.

Major lowering episodes occurred in the early 1930s, the latter half of the 1980s, and in 1997–2000 (Tables 1–3). As shown in Table 3, the 1997–2000 episode is the second-most severe 3-yr drop on record for Lakes Michigan–Huron, following the drought of the 1930s; the most severe on record for Lake Erie, followed by the drought of the 1930s; and is the second-most severe on Lake Superior, following the 1876–79 episode that occurred before regulation. The relative level declines for Lakes Michigan–Huron and Erie are illustrated in Figs. 3a and 3b. The relative severity of the water-level decline for Lake Ontario was substantially reduced due to lake regulation, which began in 1960. It is interesting to note that no record levels were set in any of the lakes during the three major episodes ending in the years 2000, 1989, and 1933. However, in 2001, Lake Superior was at its lowest level since 1925, and Lakes Michigan–Huron and Erie were at their lowest levels since 1965.

Table 1. One-year drop in levels by rank with ending year and drop (m).										
	Superior		**Michigan–Huron**		**Saint Clair**		**Erie**		**Ontario**	
Rank	Yr	Drop	Yr	Drop	Yr	Drop	Yr	Drop	Yr	Drop
1	1871	0.59	1999	0.92	1956	1.19	1999	1.03	1931	1.27
2	1953	0.58	1931	0.91	1931	1.16	1998	1.00	1868	1.24
3	1940	0.58	1930	0.87	1920	1.02	1931	0.99	1871	1.24
4	1944	0.58	1998	0.82	1999	0.93	1920	0.92	1974	1.19
5	1877	0.55	1987	0.81	1944	0.91	1949	0.88	1964	1.19

Table 2. Two-year drop in levels by rank with ending year and drop (m).										
	Superior		**Michigan–Huron**		**Saint Clair**		**Erie**		**Ontario**	
Rank	Yr	Drop	Yr	Drop	Yr	Drop	Yr	Drop	Yr	Drop
1	1878	0.76	1931	1.25	1931	1.39	1999	1.17	1872	1.41
2	1918	0.72	1999	1.20	2000	1.19	2000	1.12	1931	1.37
3	1999	0.67	1988	1.09	1956	1.17	1931	1.09	1949	1.33
4	1988	0.67	2000	1.09	1999	1.13	1932	1.09	1965	1.22
5	1954	0.64	1932	1.08	1988	0.99	1988	1.07	1895	1.21

Table 3. Three-year drop in levels by rank with ending year and drop (m).										
	Superior		**Michigan–Huron**		**Saint Clair**		**Erie**		**Ontario**	
Rank	Yr	Drop	Yr	Drop	Yr	Drop	Yr	Drop	Yr	Drop
1	1879	0.88	1932	1.42	2000	1.39	2000	1.26	1933	1.45
2	1999	0.73	2000	1.37	1956	1.28	1932	1.19	1873	1.43
3	1988	0.73	1989	1.31	1932	1.17	1933	1.17	1958	1.29
4	1911	0.72	1933	1.13	1958	1.13	1989	1.08	1911	1.26
5	1977	0.71	1958	1.09	1920	1.10	1964	1.02	1932	1.26

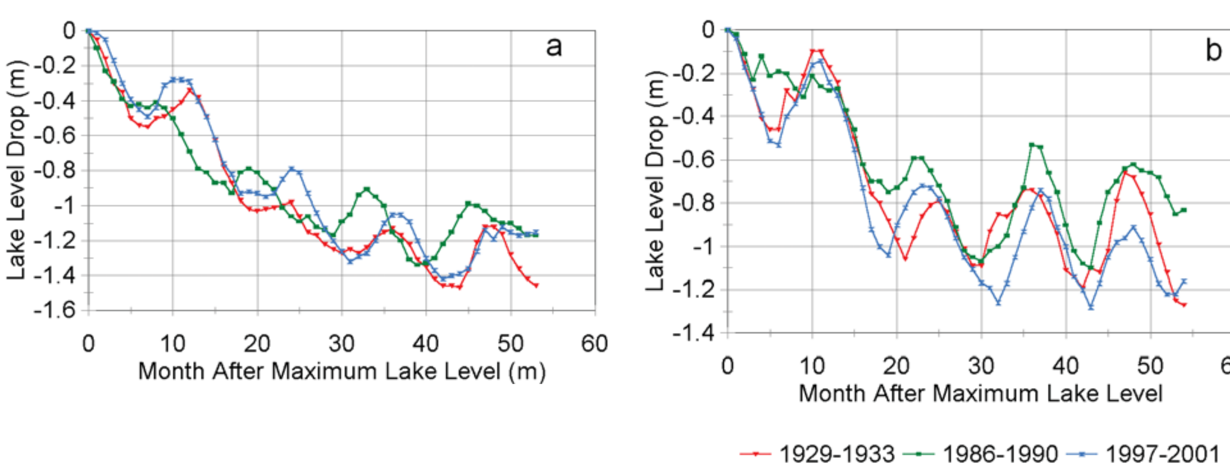


Fig. 3. Drop in levels for (a) Lakes Michigan–Huron and (b) Lake Erie.

The chronology of the decline in levels, compared with the minimum record monthly mean levels, is illustrated for Lakes Superior (Fig. 4a), Michigan–Huron (Fig. 4b), and Erie (Fig.4c). The scenarios, 1876–80, 1985–89, and 1997–2001 for Lake Superior, and 1929–33, 1960–64, 1986–90, and 1997–2001 for Lakes Michigan–Huron and Erie, were based upon the 3-yr drops. A fourth year was added to the scenarios because of the continuation of the 1997–2000 episode. The 1960–64 episode was included because it resulted in record-low lake levels for Lakes Michigan–Huron.

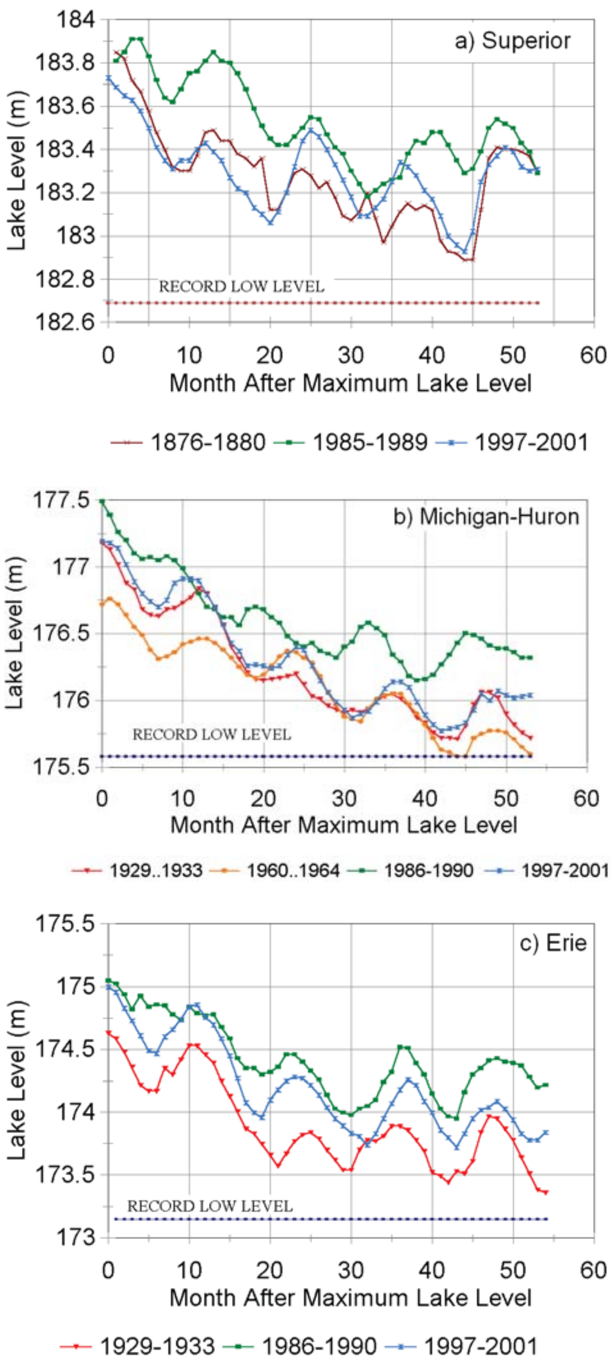


FIG. 4. Water levels for Lakes (a) Superior, (b) Michigan–Huron, and (c) Erie.

The water level at the beginning of an episode is extremely important, because the unregulated lake outflow though the connecting channels increases exponentially with the lake level. Thus, for a similar decrease in water supplies, we would have a larger lake-level decline at higher beginning lake levels than at lower levels. The 1980s event is a good case in point. It started at record-high lake levels on Lakes Michigan–Huron and, while the decrease was substantial, the resulting water levels ended at around the long-term mean. The influence of the beginning water level is illustrated by Fig. 4. The comparison between the 1929–32 and 1997–2000 episodes is interesting because both started at about the same water level on Lakes Michigan–Huron (Fig. 4b). Thus, while not setting any lake-level records, the 1997–2000 episode ranks with the 1930s and 1960s as one of the most important low-water scenarios on record.

The duration of a low-water episode for Lakes Michigan–Huron is determined by the number of years its average water level was at or below an elevation of 176.10 m. By this definition, the major low-water episodes were 1925–26 (2 yr), 1932–37 (6 yr), 1958–59 (2 yr), 1963–65 (3 yr), and 2000–present (4 yr). The 1986–90 episode, while intense, only lasted about 2 yr and was not a low-water-levels episode. At the end of the episode, lake levels were near the long-term mean.

HYDROCLIMATOLOGY. The relationship between lake levels and hydroclimatological variables is given by the hydrologic water balance for any of the lakes expressed as Eq. (1),

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

where P is the precipitation falling on the lake surface, R is the runoff into the lake from its tributary streams, Q_I is the connecting channel inflow, E is the evaporation from the lake surface, Q_o is the connecting channel outflow, D are diversions into or out of the basin, ΔS is the change in storage ($L_t - L_{t-1}$), and L_t is the lake level at time T.

Units are expressed in either millimeters or centimeters on the lake surface by dividing the volume by the lake area. The groundwater flow into and out of the lakes is neglected because it is extremely small in terms of the other components and has not been adequately quantified.

Hydrologic water balance of the lakes. In addition to the individual variables, we will look at the net basin water supply (NBS), in Eq. (2) and the total water supply (NTS) expressed as Eq. (3):

$$NBS = P + R - E, \quad (2)$$
$$NTS = P + R - E + Q_1, \quad (3)$$

where both NBS and NTS are likewise expressed as millimeters or centimeters on the lake surface.

The NBS serves as a good measure of change in the basin's contribution to a lake, while the NTS measures the total water supply to a lake and is a function of the upstream lake levels, as well as the contribution of the individual basin. If a drought starts at high lake levels, the NBS will be immediately affected, while the NTS may not show a corresponding change due to high connecting channel flows. Each of the water supply factors was examined using data updated from Croley and Hunter (1994). The period 1954–97 was chosen as the period for comparison based on the availability of estimated monthly runoff and evaporation data and the start of the most recent episode. Monthly precipitation and connecting channel flow data are available from 1900 and 1860, respectively.

Onset of the 1998 episode. The onset of the 1998 episode, from the NBS perspective, appears to begin around April 1998 (Fig. 5a). The drop in April is indicative of a low snowpack and of a record-low ice cover the previous winter (Assel et al. 2000), making the latefall and winter seasons of 1997 part of the episode. Lakes Michigan–Huron had the most severe decline, followed by Lake Superior. Lake Erie had a respite in the late spring and early summer of 2000, but the water supplies again declined during the first half of 2001. While the NTS for Lakes Michigan–Huron dropped throughout the episode (Fig. 5b), Lake Erie water supplies initially benefited by above-average inflows from the Detroit River. The total water supplies then began to drop, with reduced upstream water levels during the summer of 1998 with the resulting cumulative NTS deficit anomaly surpassing that of Lakes Michigan–Huron. The Lake Erie data illustrate the downstream lag in drought impacts. For Lake Superior, because there is no connecting channel inflow, the NTS is equal to the NBS. It should be noted that the Long Lac and Ogoki diversions are not included as part of the NTS.

Individual components. The component analysis (Fig. 6), using cumulative anomalies (differences) from the 1954–97 means, shows that the drop in levels was primarily driven by greatly decreased runoff (Fig. 6a) and high lake evaporation (Fig. 6b), due to high air temperatures (Fig. 6c). A decrease in precipitation (Fig. 6d) and a major reduction in outflows from upstream Lake Superior also contributed to the low water supplies. The unusually high Lake Superior precipitation in the summer and fall of 1999 (Fig. 6d) moderated the impact of the episode (Fig. 4a). The most remarkable factor was the sustained rise in air temperatures, particularly over the Lake Superior basin (Fig. 6c). Many times, Lake Superior has a moderating effect with extreme low water supplies out of sequence with those of Lakes Michigan–Huron. This did not occur in the recent episode. The higher air temperatures during the winter of 1997–98 that hastened lake evaporation and lowered water levels also produced a winter with much-below-average ice cover (Fig. 7) throughout

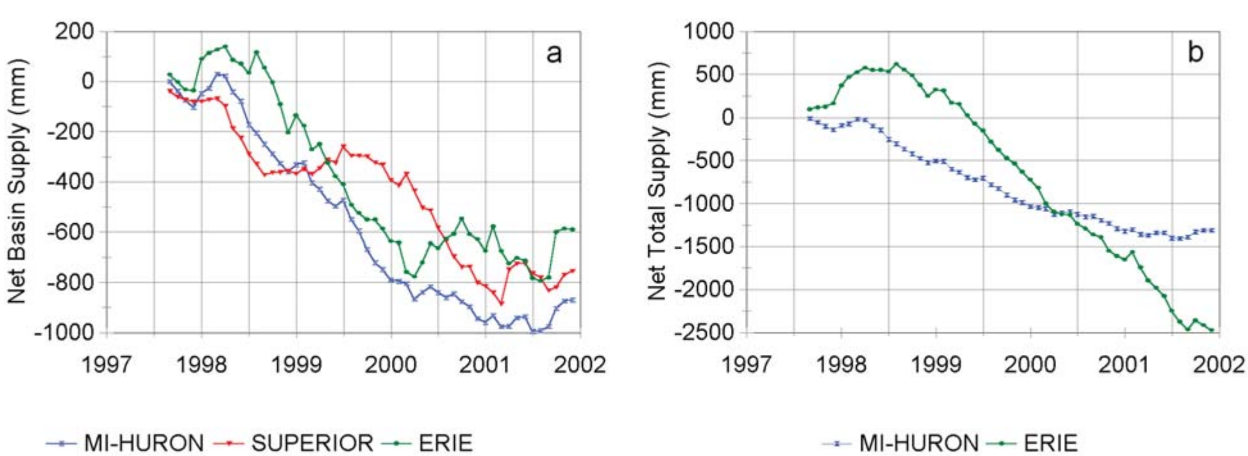


FIG. 5. Cumulative differences from average (mm) on lake surface of (a) NBS and (b) NTS.

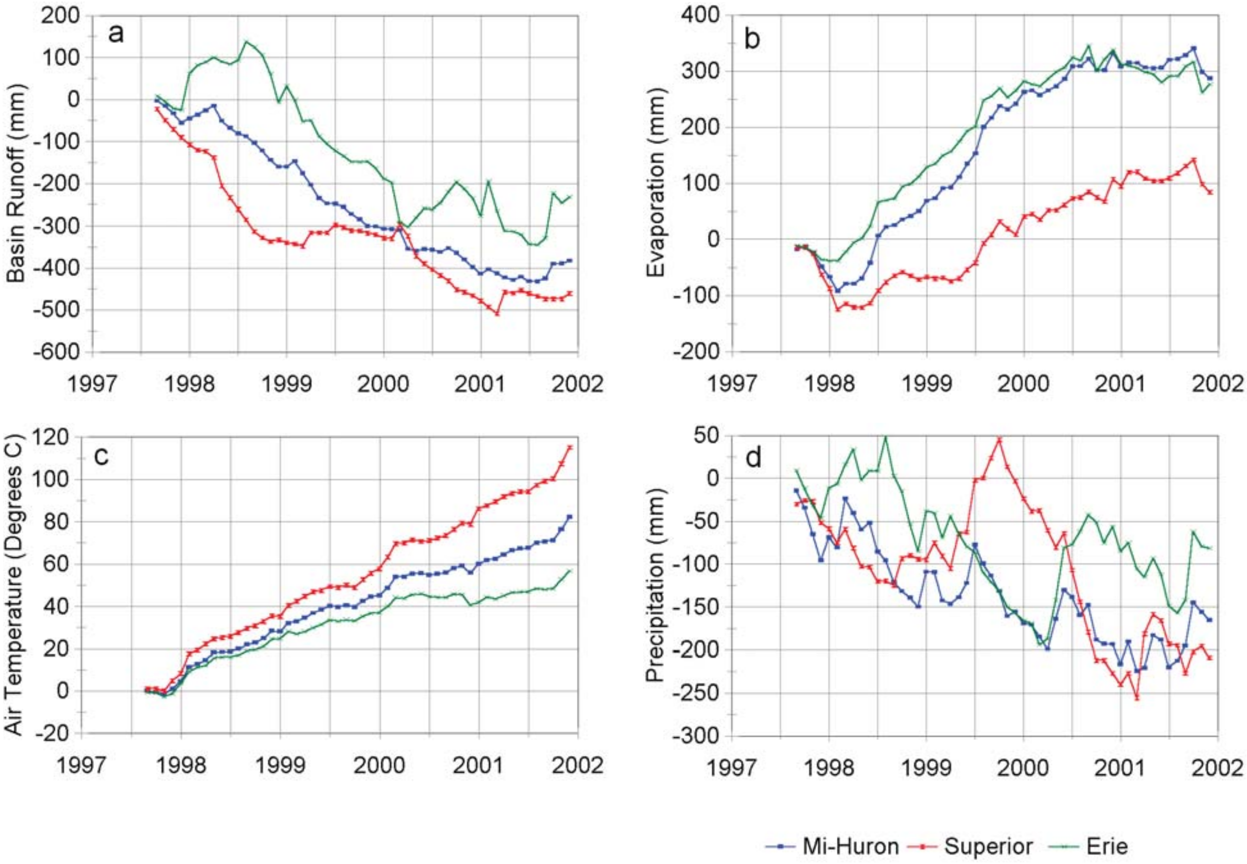


FIG. 6. Cumulative anomalies for Lakes Michigan–Huron, Superior, and Erie of (a) runoff, (b) evaporation, (c) temperature, and (d) precipitation.

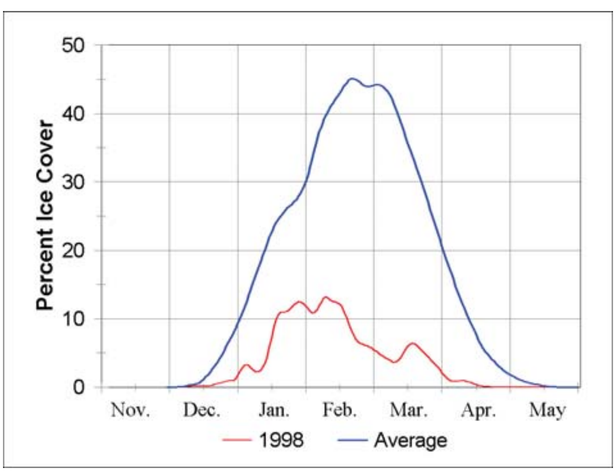
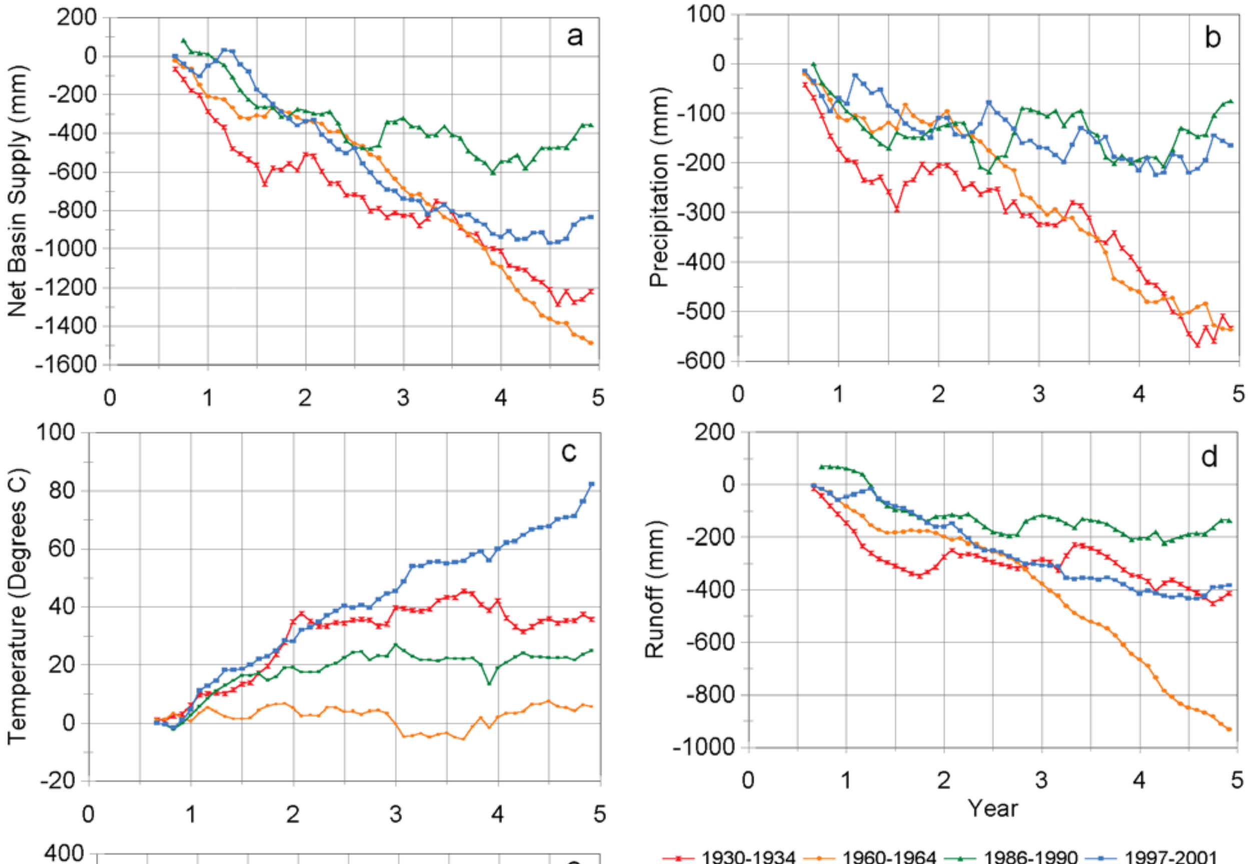


FIG. 7. Ice-covered surface of the entire Great Lakes for winter 1998 and for a 30-winter (1973–2002) average.

the system. The lower-than-average ice cover likely enhanced evaporation during the winter months.

Lakes Michigan–Huron case study. Lakes Michigan–Huron were the closest to their record-low lake level during 1997–2001. It is, therefore, informative to compare the present episode with those encompassing the record low of 1964 (1960–64), the prior record low of 1934 (1930–34), and the recent late 1980s (1986–90) episode. The cumulative anomalies in NBS, precipitation, air temperature, runoff, and evaporation for the four episodes are illustrated in Figs. 8a, 8b, 8c, 8d, and 8e, respectively. Evaporation estimates are not available prior to 1948 (Croley and Hunter 1994) and so are not shown for the 1930–34 episode. Data for the 1930–34 episode consist of precipitation, residual net basin supplies, and the Saint Marys flows.

The maximum of the cumulative monthly anomalies given in Figs. 8a–8e, the starting lake levels, the Saint Marys River flow anomalies, and the maximum NTS for the four episodes, are summarized in Table 4. As can be seen from Table 4 (and Figs. 8c, 8e, 8b, respectively), the 1997–2001 episode was driven by extremely high temperatures, high lake evaporation, and a moderate decrease in precipitation. The 1960–64 episode had near-average air temperatures, average lake evaporation, and was driven by well-below-average precipitation, resulting in low runoff (Fig. 8d). For precipitation, the 1986–90 and current episode are similar (Table 4, Fig. 8b), but the higher air tem-



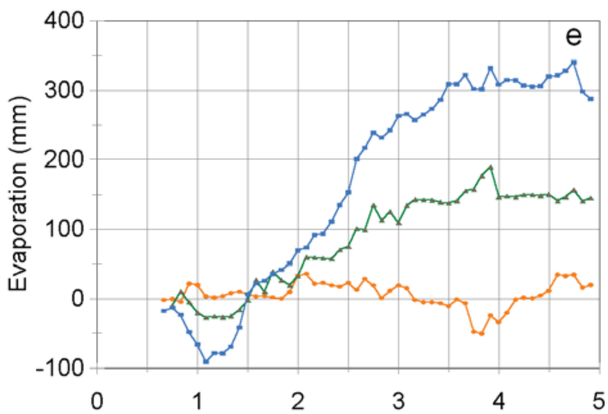


Fig. 8. Lakes Michigan–Huron cumulative anomalies of (a) NBS, (b) precipitation, (c) temperature, (d) runoff, and (e) evaporation.

peratures for the latter episode (1997–2001) resulted in considerably less runoff and higher lake evaporation (Table 4, Figs. 8d, 8e). The impact of Lake Superior, given by the Saint Marys River flows, was the greatest in the 1930s, followed by the present episode (Table 4). Looking at the total water supplies (NTS in Table 4), the 1930s and 1960s episodes are equivalent, followed by the present episode. Thus, the most significant aspects of the present low-water episode for Lakes Michigan–Huron are the extremely high air temperatures and the lack of inflow from Lake Superior.

IMPACTS. Positive effects of lower lake levels include larger beaches, lower property losses and shore damage for beachfront property, and natural regeneration of Great Lakes wetlands. Coastal wetlands are important habitat for both plants and animals (Maynard and Wilcox 1997). Low water levels expose the sediment in wetlands. This allows germination from the seed bank and, thus, wetlands to revegetate. Coupled with the intervening high lake levels, it is the driving force that maintains Great Lakes wetlands. When water levels go back up again, the reflooded vegetated wetlands will provide much-improved habitat for invertebrates, small fish, and larger fish in the food web (Wilcox 1995; D. Wilcox 2004, personal communication).

Negative impacts of lower levels include reduction in commercial lake shipping cargo capacity,[1] a reduced sport fishing industry and recreational boating

[1] Great Lakes freighters carry about 28–106 tons of cargo for each 1 cm of draft. Thus, the lower water levels have negatively impacted waterborne commerce in recent years (Lake Carriers' Association 2002).

TABLE 4. Component comparison (maximum cumulative difference from average) for low-supply episodes.

Episode	1930–34	1960–64	1986–90	1997–2001
Starting lake level (m)	176.84	176.72	177.49	177.19
Max precipitation anomaly (mm)	–567	–537	–218	–224
Max runoff anomaly (mm)	–450	–932	–221	–431
Max air temperature anomaly (°C)	+46	+7	+27	+82
Max evaporation anomaly (mm)	*	+36	+178	+340
Max net basin supply anomaly (mm)	–1286	–1488	–600	–992
Max Saint Marys River flow anomaly (mm)	–598	–370	–303	–442
Max NTS anomaly (mm)	–1907	–1784	–800	–1403

*Data not available.

industry,[2] and a reduction in hydropower generation at power plants along the Niagara and the Saint Lawrence Rivers. The Niagara Power Project near Niagara Falls and the Saint Lawrence Power Project in northern New York could not generate enough energy during 2001 to provide hundreds of local businesses with needed electricity, forcing them to buy electric power elsewhere at a higher price (Hill 2002).

CONCLUSIONS. This low-levels episode is remarkable for both the amount of lowering and the rapidity with which it occurred. It set the historical record for a 1-yr drop in levels and is second in 2- and 3-yr drops; only the Dust Bowl episode of the 1930s produced a larger drop in levels. This episode is apparently not over yet, with lake levels currently (2002) only slightly above than their 2001 values for Lakes Michigan–Huron and Erie. It remains to be seen whether any new record lows will be set. This episode also ranks third in terms of water supplies over the past 150 yr, following the record-setting episodes of the 1930s and 1960s. Record-low levels might also have been set during this episode if it had begun at lower lake levels. This episode was unusual, particularly when compared to the record-low water episode of the mid-1960s, in that the primary hydroclimatological driver was high air temperatures, not extremely low precipitation. The high air temperatures resulted in unusually high lake evaporation rates and decreased basin runoff. This episode is important from a water-management perspective as well. The impacts of extreme low levels and flows are not known as well as are the challenges of high lake levels. We have had a great deal of experience over the past 30 yr in dealing with high lake levels, but relatively little experience on the low side. This is particularly important because of the new interests, such as recreational boating and the environment, which have developed since the last low-levels episode of the 1960s. Finally, this episode should be viewed in the context of changing water levels over the past 4700 yr (Baedke and Thompson 2000). Our recorded history is but a small time slice out of the overall existence of the Great Lakes water-level fluctuations.

[2] To support the sports fishing industry and recreational boaters, millions of dollars were spent to dredge boat slips, channels, and harbors along the Great Lakes' coasts.

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