UNPRECEDENTED SEASONAL WATER LEVEL DYNAMICS ON ONE OF THE EARTH'S LARGEST LAKES

BY ANDREW D. GRONEWOLD AND CRAIG A. STOW

The North American Great Lakes (Fig. 1) contain roughly 20% of the Earth's unfrozen fresh surface water and cover a massive area (Lake Superior alone is the largest unfrozen freshwater surface on the planet). Water levels on the Great Lakes have been recorded continuously for more than 150 years, representing one of the longest sets of direct hydroclimate measurements. This dataset, synthesized by Quinn (1981) and Lenters (2001), among many others, indicates that water levels on each of the Great Lakes follow a strong seasonal pattern closely linked with the timing and magnitude of the major components of the regional water budget, with relatively low water levels in the winter months, rising water levels in the spring, and decreasing water levels in the late summer and early fall. Water-level measurements on Lake Erie during the 2011 and 2012 water years (October 2010 through September 2011, and October 2011 through September 2012, respectively), however, reflect dramatic and unexpected changes in the seasonal water-level cycle and in the Great Lakes regional water budget.

In the 2011 water year, monthly average water levels on Lake Erie rose more than 0.8 m from February to June, an unprecedented amplification of the historical seasonal pattern (Fig. 1). Never before had water levels on Lake Erie risen as much during a four-month period. More specifically, the water level rose 0.28 m between February and March of that period. Only twice have water levels risen more between February and March (0.31 m in both 1976 and 1985). Furthermore, the water level between April and May 2011 rose 0.26 m. Only twice have water levels risen more between April and May (0.27 m in 1943 and 0.30 m in 1947). In the 2012 water year, however, the seasonal water level cycle on Lake Erie experienced a remarkable shift (as opposed to the 2011 water-year amplification) in the historical average seasonal pattern. From November to December 2011, for example, the monthly average water level on Lake Erie rose 0.19 m (Fig. 1), the second-highest increase for that time period in recorded history (the highest was 0.20 m in 1927). Water levels then decreased continu-

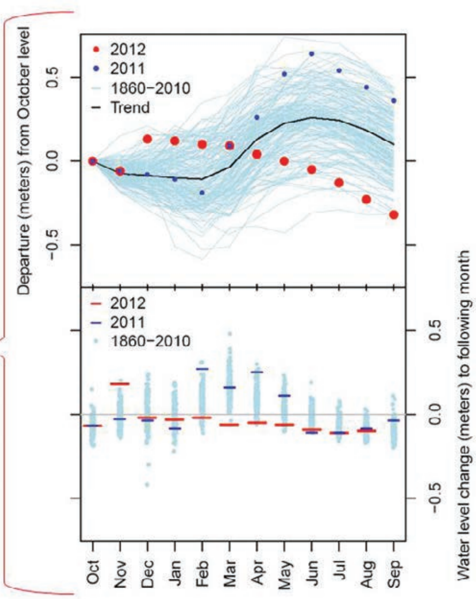

FIG. 1. Satellite image of (left) the North American Laurentian Great Lakes and (right) seasonal patterns in monthly average Lake Erie water levels. Data from 1918 to 2012 are based on a network of gauges around Lake Erie, and data from 1860 to 1917 (before a network was established) are based on a "master gauge." (Image: NASA and NOAA CoastWatch)

AFFILIATIONS: GRONEWOLD AND STOW—NOAA, Great Lakes Environmental Research Laboratory, Ann Arbor, Michigan
CORRESPONDING AUTHOR: A. D. Gronewold, NOAA, Great Lakes Environmental Research Laboratory, Ann Arbor, MI 48108
E-mail: drew.gronewold@noaa.gov

DOI:10.1175/BAMS-D-12-00194.1

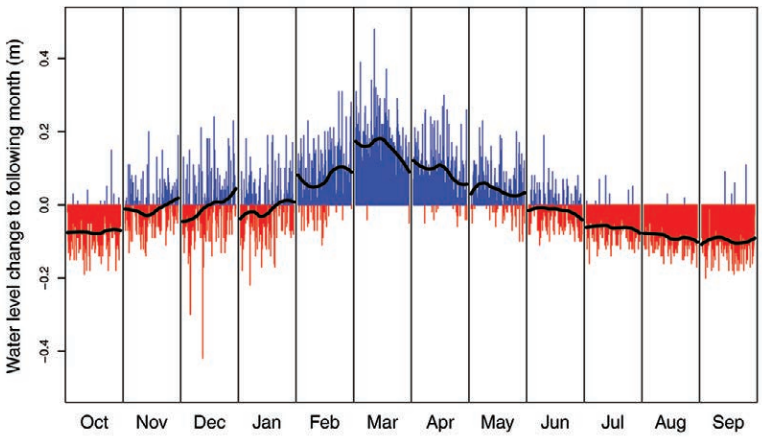

FIG. 2. Month-to-month changes in Lake Erie monthly average water levels. Vertical bars in each panel (one panel for each month) represent the water-level change (m) from the month indicated at the bottom of the panel to the following month for each year from 1860 to 2012. The left-most panel, for example, includes water-level changes from Oct to Nov. Blue vertical bars indicate an increase in monthly water level; red vertical bars indicate a decrease in monthly water level. The black line within each panel indicates the long-term trend.

ously from December 2011 to October 2012, representing the longest continuous decline in monthly water levels ever recorded on Lake Erie. Up until the 2012 water year, the historical record indicates that Lake Erie water levels had, with one exception (1892), always risen between March and April (bottom panel, Fig. 1), and generally rose between both February and March, and April and May.

Lake Erie water-level dynamics in 2011 and 2012 collectively represent unprecedented year-to-year variability in the seasonal water-level cycle, yet while the water-level cycle in 2011 represented an amplification of the average seasonal cycle (Fig. 1), the 2012 water-level cycle may, in fact, be more consistent with a long-term trend (Fig. 2). For example, from 1860 through the mid-1930s and 1940s, water levels on Lake Erie tended to decrease from November to December, from December to January, and from January to February (indicated by the relative frequency of red vertical lines, and the point at which the black trend line crosses zero, in the "Nov," "Dec," and "Jan" panels of Fig. 2). Since then, it has become increasingly common for water levels to rise during this time period (a phenomenon reflected in the month-to-month changes in Lake Erie water levels from December 2011 to January 2012). In contrast, month-to-month water level changes in the spring (i.e., March to April, April to May, and May to June), though historically positive on average, have been decreasing steadily for roughly 70 to 80 years (Fig. 2). Decreases in water levels from June to July have also become increasingly common for the past 20 to 30 years.

Further investigation will be needed to fully understand the range of factors driving the changes in the Lake Erie seasonal water cycle, and the extent to which comparable changes are taking place on the other Great Lakes. Nonetheless, the stark difference in seasonal water-level dynamics between 2011 and 2012 on Lake Erie, and the ongoing shift in the Lake Erie seasonal water level cycle, are both related to changes in the magnitude and timing of runoff, overlake precipitation, and overlake evaporation. These three variables constitute the major components of the Great Lakes water budget and are (unlike the same components of the water budget in Earth's other large basins) all roughly of the same order of magnitude. For example, it appears that opposite combinations of extremes in precipitation and evaporation are the likely cause of the 2011 to 2012 interannual seasonal water-level cycle variability. Specifically, near-record-high spring precipitation combined with below-average evaporation to produce the amplified 2011 seasonal rise, while record-high evaporation and below-average precipitation characterized much of 2012. Additionally, during the extremely mild winter of 2011–12, most precipitation fell as rain, leading to relatively low seasonal snow accumulation and, consequently, low spring runoff. The mild winter was also accompanied by minimal ice formation with almost no latent heat carryover into the spring, allowing a rapid spring water temperature increase.

While the factors driving the shift in the Lake Erie seasonal water cycle are consistent with climate change expectations (e.g., higher rain-to-snow ratios and increasing fall evaporation rates), the reversal of extremes underlying the amplified variability from 2011–12 was not anticipated, and it is unclear if similar patterns will continue into the future. More specifically, the skill of Great Lakes seasonal water-level forecasts in 2011 and 2012 was significantly diminished relative to previous time periods (for further discussion on research-oriented and operational Great Lakes water-level forecasting systems, see

Gronewold et al. 2011). Scheffer et al. (2012) propose that rising variance is a leading indicator of a pending regime shift; it appears that disruptions in the normal oscillation pattern of Lake Erie water levels could indeed be a symptom of a system in transition.

Changes in the Lake Erie seasonal water cycle also underscore potential economic, human and environmental health, and water resource management challenges, not only for Lake Erie and the other Great Lakes but, as noted by Milly et al. (2008), for other large freshwater systems undergoing changes in the magnitude and timing of precipitation, evaporation, and runoff. Williamson et al. (2009) and Adrian et al. (2009) describe these systems, collectively, as sentinels of regional and global changes in climate, land use, and water resource management policy because they integrate the effects of multiple system drivers over broad spatial and temporal scales. Impacts from these changes, such as those documented by Clark et al. (2001) and Livingstone (2003), range from shifts in the timing and intensity of freshwater inputs and pollutant loadings, to habitat and ecosystem disruption following the invasion and spread of nonindigenous species. The formation and spread of harmful algal blooms in the Great Lakes, including the 2011 record-setting algal bloom on Lake Erie (Michalak et al. 2013), followed by the unexpected loss of nearshore fish-spawning habitats and reduced capacity of regional hydropower facilities on the Great Lakes in 2012, collectively underscore the importance of understanding linkages between changes in the regional water budget and water levels, and changes in ecosystem response.

ACKNOWLEDGMENTS. The authors thank Tim Hunter, Anne Clites, and Kent Campbell for assistance with data compilation and analysis. The authors also thank Jacob Bruxer, Rob Caldwell, and Lauren Fry for comments on early versions of this essay. Funding for this essay was provided, in part, by the Great Lakes Restoration Initiative (administered by the Environmental Protection Agency). This is NOAA-GLERL contribution No. 1665.

FOR FURTHER READING

Adrian, R., and Coauthors, 2009: Lakes as sentinels of climate change. *Limnol. Oceanogr.*, **54,** 2283.

Brown, C., W. Werick, W. Leger, and D. Fay, 2011: A decision-analytic approach to managing climate risks: Application to the Upper Great Lakes. *J. Am. Water Resour. Assoc.,* **47,** 524–534.

Clark, J., and Coauthors, 2001: Ecological forecasts: An emerging imperative. *Science,* **293,** 657–660.

de Loë, R., and R. Kreutzwiser, 2000: Climate variability, climate change and water resource management in the Great Lakes. *Clim. Change,* **45,** 163–179.

Ekman, M., 1999: Climate changes detected through the world's longest sea level series. *Global Planet. Change,* **21,** 215–224.

Groisman, P., R. Knight, T. Karl, D. Easterling, B. Sun, and J. Lawrimore, 2004: Contemporary changes of the hydrological cycle over the contiguous United States: Trends derived from in situ observations. *J. Hydrometeor.,* **5,** 64–85.

Gronewold, A. D., A. Clites, T. Hunter, and C. Stow, 2011: An appraisal of the Great Lakes advanced hydrologic prediction system. *J. Great Lakes Res.,* **37,** 577–583.

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

Livingstone, D., 2003: Global climate change strikes a tropical lake. *Science,* **301,** 468–469.

Michalak, A. M., and Coauthors, 2013: Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions. *Proc. Natl. Acad. Sci. USA,* **110,** 6448–6452, doi:10.1073/pnas.1216006110.

Millerd, F., 2011: The potential impacts of climate change on Great Lakes international shipping. *Clim. Change,* **104,** 629–652.

Milly, P. C., J. Betancourt, M. Falkenmark, R. M. Hirsch, Z. W. Kundzewicz, D. P. Lettenmaier, and R. J. Stouffer, 2008: Stationarity is dead: Whither water management? *Science,* **319,** 573–574.

Quinn, F., 1981: Secular changes in annual and seasonal Great Lakes precipitation, 1854–1979, and their implications for Great Lakes water resource studies. *Water Resour. Res.,* **17,** 1619–1624.

Scheffer, M., 2012: Anticipating critical transitions. *Science,* **338,** 344–348.

Solomon, S., G. Plattner, R. Knutti, and P. Friedlingstein, 2009: Irreversible climate change due to carbon dioxide emissions. *Proc. Natl. Acad. Sci. USA,* **106,** 1704.

Williamson, C., J. Saros, and D. Schindler, 2009: Sentinels of change. *Science,* **323,** 887–888.

Woodworth, P., 1999: High waters at Liverpool since 1768: The UK's longest sea level record. *Geophys. Res. Lett.,* **26,** 1589–1592.