attached CO molecule oscillate horizontally while approaching another CO molecule on the surface. By doing this at different heights over the Cu surface, the authors were able to obtain a complete map of the forces and energies between the CO molecules.

As the result reported by Weymouth *et al.* show, noncontact AFM is a crucial tool in the quest to image atoms and molecules at ever higher resolution and to understand the origin of the forces that keep them together. From the measured forces, it is possible to identify the nature of the atoms (*8*) and to deduce their interaction energies. Furthermore, it opens the way for studying chemical reactions at the individual atom or molecule level. For example, one could choose a particular site on the surface of a catalyst and position an atom or molecule there, using the tip as "tweezers." By bringing another atom or molecule near to the first from various directions and at various distances and measuring the resulting forces, one could determine whether a reaction occurs and what the products are. In another scenario, the technique could be used to construct novel molecules by bringing the component atoms to the chosen locations one at a time. Such experiments are already happening in the laboratories of researchers. The possibilities are endless.

References and Notes

1. For a transcript of the lecture, see www.its.caltech.edu/~feynman/plenty.html.
2. G. Binnig, H. Rohrer, Ch. Gerber, E. Weibel, *Appl. Phys. Lett.* **40**, 178 (1982).
3. D. M. Eigler, E. K. Schweizer, *Nature* **344**, 524 (1990).
4. G. Binnig, C. F. Quate, C. Gerber, *Phys. Rev. Lett.* **56**, 930 (1986).
5. A. J. Weymouth, T. Hofmann, F. J. Giessibl, *Science* **343**, 1120 (2014); 10.1126/science.1249502.
6. L. Gross, F. Mohn, N. Moll, P. Liljeroth, G. Meyer, *Science* **325**, 1110 (2009).
7. D. M. Eigler, C. P. Lutz, W. E. Rudge, *Nature* **352**, 600 (1991).
8. Y. Sugimoto *et al.*, *Nature* **446**, 64 (2007).

10.1126/science.1251251

ENVIRONMENT

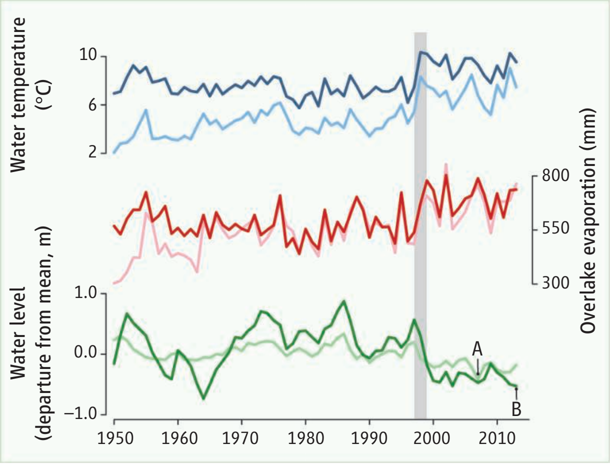
Water Loss from the Great Lakes

Andrew D. Gronewold and Craig A. Stow

Knowledge of the drivers behind recent record low water levels in the North American Great Lakes can help water resource management planning.

As marine coastal populations experience and plan for rising ocean levels (*1*), residents along the coasts of Earth's largest lake system are encountering the opposite problem: persistent low water levels and a receding shoreline. In January 2013, federal agencies from the United States and Canada documented the lowest water levels ever recorded on lakes Michigan and Huron (*2*). Only 6 years earlier, historically low water levels were recorded on Lake Superior (*3*), which feeds into the Lake Michigan-Huron system. These low water levels are symptoms of an imbalance in the water budget of the Great Lakes. Adapting to, and potentially mitigating, low water level conditions requires improved quantification of the factors that drive the imbalance.

Low water levels have a profound impact on the Great Lakes region and the North American economy by limiting navigability of shipping channels, reducing hydropower capacity (e.g., at Niagara Falls, the largest electricity producer in New York State), impeding tourism and recreational activities, and increasing operational risks to industries that rely on the lakes as a source of process and cooling water. Relative to water levels on most marine coasts, annual water levels on the Great Lakes fluctuate widely. On Lake Michigan-Huron, for example, the historical range of recorded annual average water levels is close to 2 m (see the first figure). These fluctuations are mainly driven by changes in regional precipitation (including both overlake precipitation and terrestrial runoff) and overlake evaporation. Water levels on Lake Michigan-Huron previously hit record lows in the mid-1960s and peaked in the mid-1980s, causing extensive erosion-related damage.



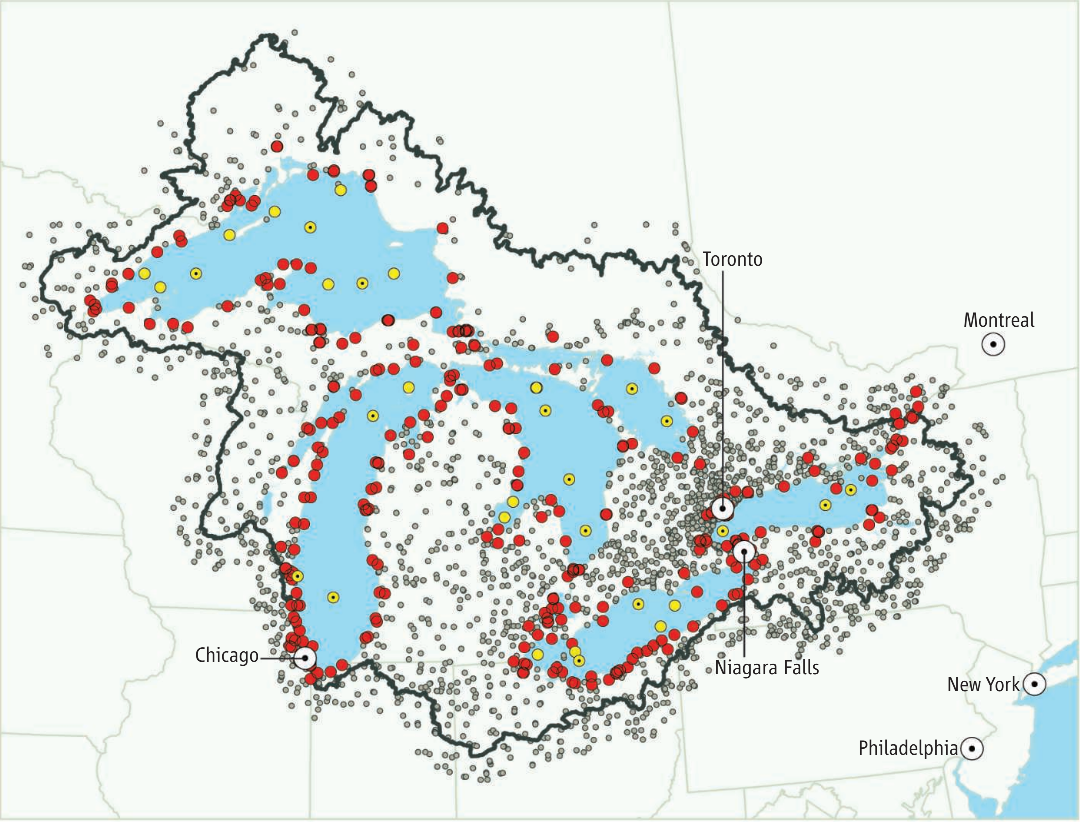
Regional climate trends. Annual climate and hydrological variables for Lake Superior (light colors) and Lake Michigan-Huron (dark colors) reflect long-term trends and abrupt shifts in surface water temperature (blue lines) and overlake evaporation (red lines). These factors have contributed to recent record low water levels on both lake systems (green lines). Water surface temperature and overlake evaporation estimates are based on computer models that assimilate measurements from a sparse network of shoreline-based stations, offshore stations (many of which are currently inactive), and seasonal offshore buoys (see second figure). Water levels are based on a comprehensive international network of shoreline monitoring stations. The vertical gray band indicates the approximate period of the 1997–1998 El Niño. Point A indicates record lows on Lake Superior for the months of August and September (both in 2007). Point B indicates record lows on Lake Michigan-Huron for the month of December (in 2012) and for all months (in January 2013). Data are from (*10*, *14*).

Most of the episodic changes in Great Lakes water levels over the past century are attributable to corresponding changes in annual precipitation. For example, the increases in water levels across all of the Great Lakes in the late 1960s, early 1970s, and early 1980s, as well as the water level drop in the late 1980s, are more closely linked to trends in precipitation than overlake evaporation (*4*). However, the large water-level drop in the late 1990s coincided with one of the strongest El Niño events on record (see the first figure) and rising surface water temperatures (~2.5°C from 1997 to 1998) on Lakes Superior and Michigan-Huron. Strong El Niño events typically lead to abnormally mild winters in the Great Lakes, and the 1997–1998 El Niño appears to show an amplification of that relationship.

Since the late 1990s, the higher surface water temperatures have persisted, promoting increased overlake evaporation,

National Oceanic and Atmospheric Administration (NOAA), Great Lakes Environmental Research Laboratory (GLERL), Ann Arbor, MI, USA. E-mail: drew.gronewold@noaa.gov

decreased winter ice-cover, and a period of sustained low water levels. At the same time, annual precipitation throughout the Great Lakes basin has, relative to overlake evaporation, shown minimal net change, although extreme dry conditions in 2012 combined with the already below-average water levels to produce the record seasonal lows of late 2012 and early 2013.



Sparse monitoring networks. The Great Lakes basin (black outline) long-term hydrometeorological monitoring network shown here includes shoreline (red) and offshore (yellow) stations that, for at least 1 year in the historical record, reported measurements used in model simulations of overlake evaporation and lake surface water temperature. Of these shoreline and offshore stations, about half reported data for 10 years or less; many (yellow with concentric black dots) are seasonal buoys that are only deployed between May and November. The remaining stations (dark gray) are either too far from the lake shoreline to be potentially useful in overlake simulations or only monitor variables (such as precipitation) not used in overlake evaporation and surface water temperature simulations. For location sources, see (*15*).

The low levels have catalyzed demands to regulate outflows from Lake Michigan-Huron (*5*); however, the demands are often aimed at reversing reductions associated with historical dredging (*6*) and interbasin diversions (*7*). Differentiating potential justifications for raising water levels on Lake Michigan-Huron is critical; compensating for historical dredging alone would do little to alleviate low water-level problems if declines continue due to climate change. Water resource management planning decisions thus hinge critically on determining the extent to which the water-level drop in the late 1990s was a state shift resulting from a strong climate perturbation (the 1997–1998 El Niño); part of a progressive decline resulting from global climate change (*8*, *9*); or a consequence of engineering modifications to the hydrologic system, including historical channel dredging and regulation of Lake Superior outflows. Resolving these questions, however, is not straightforward.

For example, historical estimates of overlake evaporation and lake-wide surface water temperature in the Great Lakes (see the first figure) are based on computer models (*10*) that assimilate intermittent measurements from a small set of coastal and offshore meteorological monitoring stations (see the second figure). The coarse resolution of the monitoring network over the lakes themselves, coupled with spatial heterogeneity in regional meteorological and climatological conditions (particularly between the land and lake surface), presents a potential source of bias and uncertainty in the historical estimates (*11*).

These uncertainties complicate planning decisions but should be greatly reduced by a new and expanding network of year-round offshore monitoring stations. Within the past 5 years, for example, six fixed eddy-flux towers have been installed on remote lighthouses across the Great Lakes (*12*). Furthermore, scientists are exploring buoy-based sensors that could increase the spatial resolution of evaporation-related measurements substantially (*13*). Findings from these monitoring platforms may help to improve understanding of the water budget and of the drivers of water loss from Lakes Superior and Michigan-Huron.

References and Notes

1. J. K. Willis, J. A. Church, *Science* **336**, 550 (2012).
2. A. D. Gronewold *et al.*, *Clim. Change* **120**, 697 (2013).
3. E. C. Lamon, C. A. Stow, *J. Great Lakes Res.* **36**, 172 (2010).
4. R. A. Assel, F. H. Quinn, C. E. Sellinger, *Bull. Am. Meteorol. Soc.* **85**, 1143 (2004).
5. See, for example, *International Joint Commission's Advice to Governments on the Recommendations of the International Upper Great Lakes Study*, 15 April 2013; see http://ijc.org/iuglsreport/?page_id=1024.
6. F. H. Quinn, *J. Great Lakes Res.* **11**, 400 (1985).
7. B. T. Heinmiller, *Governance* **20**, 655 (2007).
8. U.S. Global Change Research Program, *Global Climate Change Impacts in the United States*, T. R. Karl, J. M. Melillo, T. C. Peterson, Eds. (Cambridge Univ. Press, New York, 2009).
9. S. Sherwood, Q. Fu, *Science* **343**, 737 (2014).
10. Lake thermodynamics model simulations; www.glerl.noaa.gov/data/arc/hydro/mnth-hydro.html.
11. K. Holman, A. Gronewold, M. Notaro, A. Zarrin, *Geophys. Res. Lett.* **39**, L03405 (2012).
12. C. Spence *et al.*, *J. Hydrometeorol.* **14**, 1647 (2013).
13. N. F. Laird, D. A. Kristovich, *J. Hydrometeorol.* **3**, 3 (2002).
14. For water-level summaries, see www.lre.usace.army.mil/Missions/GreatLakesInformation/GreatLakesWaterLevels.aspx and www.glerl.noaa.gov/data/now/wlevels/levels.html.
15. The monitoring station locations in the second figure are from the following sources: NOAA NCDC "Surface Land Daily Cooperative Summary of the Day" Data Set 3200 (available at ftp.ncdc.noaa.gov/pub/data/ghcn/daily); NOAA NCDC "Integrated Surface Data" Data Set 3505 (available at ftp.ncdc.noaa.gov/pub/data/noaa); and Meteorological Service of Canada (MSC) DLY04, DLY02, and HLY01 data sets (available at http://climate.weather.gc.ca/index_e.html#access).

Acknowledgments: We thank J. Lenters, J. Bratton, and B. Lofgren for thoughtful discussions and J. Smith, L. Fry, T. Hunter, K. Campbell, and C. Darnell for help with the figures. This is NOAA-GLERL contribution no. 1700.

10.1126/science.1249978

EXTENDED PDF FORMAT
SPONSORED BY
Travel Grants Available
9th FENS Forum of Neuroscience
Application Deadline:
April 30 Apply Now
R&D SYSTEMS
www.rndsystems.com

Water Loss from the Great Lakes

Andrew D. Gronewold and Craig A. Stow

Science **343**, 1084 (2014);
DOI: 10.1126/science.1249978

This copy is for your personal, non-commercial use only.

If you wish to distribute this article to others, you can order high-quality copies for your colleagues, clients, or customers by clicking here.

Permission to republish or repurpose articles or portions of articles can be obtained by following the guidelines here.

The following resources related to this article are available online at www.sciencemag.org (this information is current as of March 6, 2014):

Updated information and services, including high-resolution figures, can be found in the online version of this article at:
http://www.sciencemag.org/content/343/6175/1084.full.html

This article **cites 10 articles**, 2 of which can be accessed free:
http://www.sciencemag.org/content/343/6175/1084.full.html#ref-list-1

This article appears in the following **subject collections:**
Geochemistry, Geophysics
http://www.sciencemag.org/cgi/collection/geochem_phys

Downloaded from www.sciencemag.org on March 6, 2014

Science (print ISSN 0036-8075; online ISSN 1095-9203) is published weekly, except the last week in December, by the American Association for the Advancement of Science, 1200 New York Avenue NW, Washington, DC 20005. Copyright 2014 by the American Association for the Advancement of Science; all rights reserved. The title *Science* is a registered trademark of AAAS.