GREAT LAKES ICE AND CLIMATE: FROM RESEARCH TO FORECAST

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Contents

Summary

This chapter describes recent progress made by a team from the NOAA Great Lakes Environmental Research Laboratory (GLERL) and the University of Michigan (UMich) Cooperative Institute for Limnology and Ecosystems Research (CILER). Over the past six years (from 2007-2012), this team has studied Great Lakes ice and regional climate in response to global climate changes and how to transfer scientific research results into predictions of lake ice on the scales of several days to several months. The Great Lakes are located at the edge of the action centers of the North Atlantic Oscillation (NAO) and the nodal points of the action centers of the Pacific-North America (PNA) pattern. Aloft, there exists a strong highly-fluctuating annual south-north displacement of the westerly jet. Great Lakes ice responds linearly to the NAO and nonlinearly (quadratically) to the El Niño and South Oscillation (ENSO or Nino3.4). As a result, both NAO and ENSO have impacts on lake ice, but neither of them solely dominates the Great Lakes regional climate and lake ice cover. The combined effects of both NAO and ENSO on lake ice provide high predictability skills using statistical regression models. For the first time, fully-coupled Great Lakes Ice-circulation Models (GLIM) with both dynamics and thermodynamics have been developed at GLERL/CILER to simulate and investigate the lake ice variations on the synoptic, seasonal, interannual, and decadal time scales. The hindcast results were validated using in situ, airborne, and satellite measurements for various periods. The validated GLIM has been used since the 2010-2011 ice season to forecast Great Lakes ice cover concentration, thickness, velocity, and associated air-ice-sea variables for up to five days in advance.

1. Introduction

The Laurentian Great Lakes, located in the mid-latitude of eastern North America, contain about 95% of the U.S. and 20% of the world's fresh surface water supply. Nearly one eighth of the population of the United States and one third of the population of Canada live within their drainage basins. The Great Lakes can be considered a mini climate system, even though small compared to the global climate system or Arctic regional climate system, since all five important climate components are included (Figure 1): regional atmosphere and climate, hydrosphere (hydrodynamics), cryosphere (lake ice), biosphere (aquatic ecosystem and terrestrial ecosystem), and land process (hydrology). In addition, the human dimension is another important component affecting the Great Lakes climate system. In this mini-climate system, there are strong interactions and associations among the components. Because of this concentration of population (human dimension), the ice cover that forms on the Great Lakes each winter and its year-to-year variability affect the regional economy (Niim, 1982). It also affects the lake's abiotic environment and ecosystems (Vanderploeg et al. 1992) in addition to influencing summer hypoxia, lake effect snow, water level variability, and the overall hydrologic cycle of the region (Assel et al. 2004b).

From the late 1990s to the early 2000s, the volume of lake ice cover was much lower than normal, which enhanced evaporation and might have contributed to a significant water level drop (Spence et al. 2013), as much as 1.3 meters. Lower water levels have a significant impact on the Great Lakes economy. For example, more than 200 million tons of cargo are shipped every year through the Great Lakes. Since 1998—when water levels took a severe drop—commercial ships have been forced to lighten their loads. For every inch of clearance that these ocean-going vessels sacrificed due to low water levels, each ship lost US$11,000–22,000 per day in profits. Lake ice loss can cause other problems, including the destruction of the eggs of fall-spawning fish by winter wave and storm stirring or mixing and erosion of coastal areas unprotected by shore ice

(Brown et al. 1993). Ice loss also compromises the safety of people engaging in winter recreational activities such as snowmobiling or ice fishing.

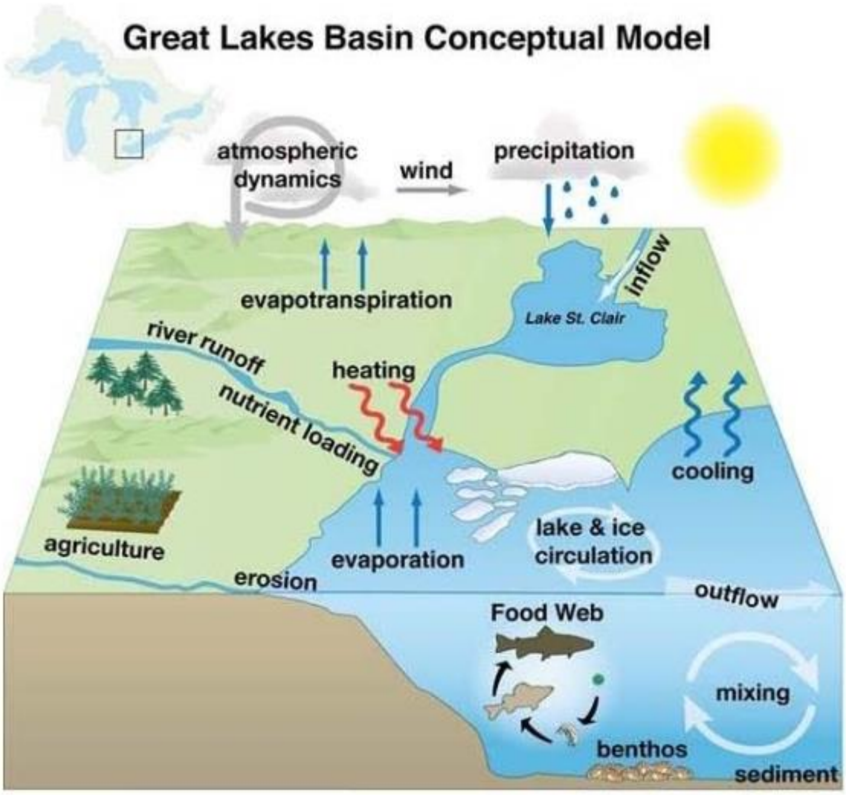

Figure 1. The Great Lakes mini-climate system involving all five climate components: the regional climate/atmosphere, cryosphere, hydrosphere (hydrodynamics), aquatic ecosystem, and land processes, which are highly interrelated.

The presence (or absence) of ice cover on lakes during the winter months is also known to have significant effects on both regional climate and weather events (such as thermal moderation and lake effect snow) (Brown and Duguay 2010). Lake ice cover is a sensitive indicator of regional climate and climate change (Smith 1991; Hanson et al. 1992; Assel and Robertson 1995; Assel et al. 2003). Seasonal ice cover repeats from year to year but has a large interannual variability (Assel 2003). For example, the maximum ice coverage was 95% in 1979 and only 11% in 2002. The relationship between air temperature and ice phenology is well established (Assel 1976; Bilello 1980; Palecki and Barry 1986; Williams 1965) whereby the preceding air temperature, for weeks to months depending on the location, can be used as a predictor of freeze-up/break-up. For the Northern Hemisphere from 1846 to 1995, Magnuson et al. (2000) estimated that an increase in air temperature of 1.2 °C would have been necessary to result in the shift of freeze-up and break-up dates (5.7 days/100 years later and 6.3 days/100 years earlier, respectively) (Brown and Duguay 2010). In the Northern Hemisphere, freeze-up in northern areas (e.g., Lake Kallavesi, Finland) reflects the climate conditions around October and November, while freeze-up in areas further south (e.g., Grand Traverse Bay, Lake Michigan) reflects the climate from January to February (Magnuson et al. 2000).

Lake ice cover can modify the lake circulation patterns and thermal structure because: 1) momentum transfer into the water column from wind stress drag is considerably greater over the water surface than over the water surface beneath the ice cover (Fujisaaki et al. 2013); 2) the albedo over ice vs. water differs, and 3) heat and moisture exchange between the atmosphere and the lake water can differ significantly (as much as orders of magnitude different) with and without lake ice (Walter et al. 2006), thus leading to striking differences in evaporation in wintertime due to strong cooling and wind mixing. Thus, prediction of the lake ice extent (i.e., ice cover) is crucial for predicting lake circulation, temperature and lake water level, and thus for predicting primary and secondary productivity. In addition, the timing of ice melt, determined by surface air temperature (SAT) that is controlled by climate variability, will determine the timing of spring phytoplankton and zooplankton blooms (Vanderploeg et al. 1992). As a result, lake ice cover, although relatively thin, is an important physical parameter for other ice-associated systems such as ecosystems and habitats for fisheries. This is in part because lake ice dynamics and thermodynamics significantly modify the water temperature, heat flux, mixing intensity, and water column stratification, which are important factors controlling phytoplankton blooms.

Ice cover is an effective insulator to surface heat flux exchange between the atmosphere and the water, which affects water temperature. The Great Lakes are usually at least partially covered with ice from December to April. Initially, ice begins to form in shallow bays, and then gradually grows offshore. On the Great Lakes, maximum ice extent is normally observed in late February to early March, when ice typically covers from 24% of Lake Ontario to 90% of Lake Erie (Assel et al. 1983). Naturally-formed ice thickness can vary from a few centimeters to a meter or more (Rondy 1976). Brash ice, deformed by wind and waves, can reach several meters. Ice decay and breakup usually begin in March as solar radiation increases, and the thinner ice can then be more easily broken up by the action of wind and waves. Recent observations of sensible and latent heat fluxes over Lake Erie (Gerbush et al. 2008) show a rapid decrease in flux magnitude as ice concentration approaches 100%.

The presence of ice cover also affects momentum transfer between the atmosphere and the water column, which determines waves and circulation patterns in a large lake. Momentum transfer is generally reduced by the presence of ice. Measurements of ice movement in Lake Erie using drifting buoys in winter 1984 show that wind is the major forcing to ice transport in the Great Lakes (Campbell et al. 1987). In particular, they reported that the mean observed speed of the buoys in ice is about 8 cm/s, half the mean speed observed in open water.

Studies showed that teleconnection patterns such as the Pacific/North America (PNA; Wallace and Guztler 1981) (Figure 2a), North Atlantic Oscillation (NAO) (Figure 2), Pacific Decadal Oscillation (PDO), and West Pacific (WP), are associated with anomalous ice cover on the Great Lakes (Assel and Rodionov 1998; Rodionov and Assel 2000, 2001, 2003; Rodionov et al. 2001) and other small lakes in North America (Anderson et al. 1996; Robertson et al. 2000; Bonsal et al. 2006; Mishra et al. 2011). Assel and Rodionov (1998) pointed out that ice cover on the Great Lakes tends to be below average during strong El Niño events, but association between La Niña events and above-average ice cover in the Great Lakes basin is much weaker and less stable.

Rodionov and Assel (2000, 2001, 2003), and Rodionov et al. (2001) found that the relationship between ENSO (El Niño and Southern Oscillation) and severity of winters in the Great Lakes is highly nonlinear. Strong El Niño events are associated with warmer temperatures in the Great Lakes region. The stronger the event, the milder the winter. Ice-off dates for Lake Mendota, Wisconsin, have been associated with El Niño events (Anderson et al. 1996; Robertson et al. 2000). The observed changes in Canada's lake ice cover have also been influenced by large-scale atmospheric teleconnections (Bonsal et al. 2006). Ice phenology was shown to be more responsive to the extreme phases of the teleconnections, with the Pacific indices (PNA, PDO, SOI, and NP) having the strongest correlation to ice cover, with the exception of the extreme eastern areas, which were more affected by NAO (Bonsal et al. 2006). A recent study (Mishra et al. 2011) also shows that lake ice phenology of small lakes around the Great Lakes region is associated with these major climate teleconnection patterns, including NAO, AO (Arctic Oscillation), and AMO (Atlantic Multidecadal Oscillation).

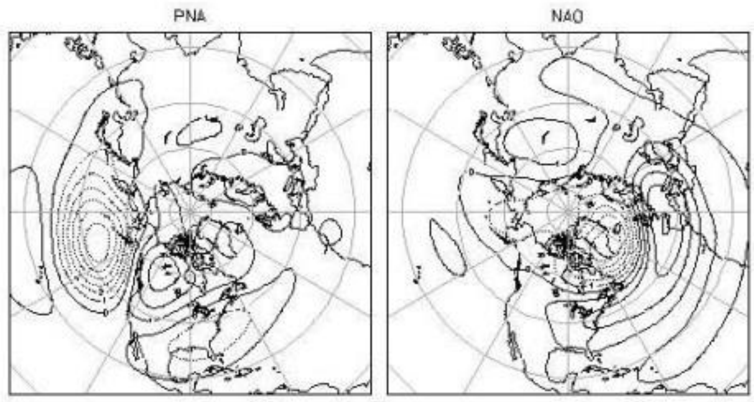

Figure 2. The positive phase of PNA (left) and NAO (right) patterns (interval: 1dam). The patterns were obtained by regressing the PNA and NAO index upon the winter mean 500-hPa geopotential height anomaly for the period 1951-2011.

Before 2007, although there was some trials to develop numerical models of ice transport in the Great Lakes (Rumer et al. 1981) based on Hibler's (1979) dynamic-thermodynamic sea-ice model. There existed no viable ice model for use as a research or as an operational forecast tool in the Great Lakes. However, there had been some successful efforts in coupled ice-ocean modeling in many subpolar seas and bays, such as in Hudson Bay (Wang et al., 1994; Saucier et al. 1998, 2004), in the Gulf of St. Lawrence (Saucier et al. 2003, 2004), in the Baltic Sea (Meier et al. 2002 a, b; Haapala 2000; Haapala et al. 2001), and in the Labrador Sea (Yao et al. 2000). These areas are similar (except for salinity) to the Great Lakes because they do not have perennial ice cover.

Ice-ocean coupled models have proven to be useful for understanding the ice-water coupling and predict the regional circulation system. Wang et al. (2010a) made a first attempt to develop the Great Lakes Ice-circulation Model (GLIM) and applied it to Lake Erie. They performed a hindcast from April 2003 to December 2004 with a spatial resolution of 2 km, reproducing the seasonal variation of ice cover as well as the water surface temperature. Recent studies have incorporated an ice model into Great Lakes hydrodynamic models. Bennington et al. (2010) investigated the general circulation of Lake Superior from 1979 to 2006 using the MIT general ocean circulation model. Their model accounted for the presence of ice by modifying the surface fluxes of heat and momentum, as well as evaporation as a function of ice concentration in a cell, using an ice concentration analysis. White et al. (2012) applied a Regional Oceanic Modeling System (ROMS) that includes a dynamic and thermodynamic ice model and a biochemical model to Lake Superior, successfully reproducing the observed long-term warming of lake surface temperature. They showed that the annual gross primary production correlated positively with mean annual temperature and negatively with mean winter ice cover. The most recent modeling work that includes ice processes in the Great Lakes was performed based on NEMO (Nucleus for European Modelling of the Ocean) along with the model-derived atmospheric forcing and river inputs (Dupont et al. 2012). Their model reasonably well reproduced the variation of lake levels and ice concentrations, but the lake thermal structures and lake currents were not discussed. On the other hand, the influences of anomalous ice cover on lake circulation and thermal structure have not been known well. Recent studies by Fujisaki et al. (2012, 2013) showed that ice cover could significantly dampen the coastal flow in winter due to the ice-water stress coupling, based on a sensitivity study in 2003-2004 using the ice-lake model for Lake Erie.

Based on the GLIM, the Great Lakes Coastal Forecasting System (GLCFS) predicts not only lake water circulation, temperature, and surface waves, but also lake ice cover concentration, thickness, velocity, and vessel icing (http://www.glerl.noaa.gov/res/glcfs/). Since it currently has a lake-ice component, empirical methods, which have been used for decades to keep the system running over winter, have been continued. Wave forecasts are also improved as ice cover dampens surface waves significantly during winter. Thus, significant progress has been made in ice-lake modeling and forecasting since the GLIM was developed in the Great Lakes. Increasing needs for predicting lake ice such as for navigation, weather forecasting, rescue efforts, and ecosystems studies are preliminarily met with the efforts of Great Lakes ice-circulation modeling.

2. Seasonal Cycle of Great Lakes Ice Cover

2.1. Seasonal Cycle

The spatial long-term (1973-2002) mean annual maximum ice cover in the Great Lakes was constructed (Figure 3) using the updated ice dataset (Wang et al. 2012b). The seasonal ice cover cycle (Figs. 4-5) is computed based on the 1973-2011 data for the six lakes. The typical seasonal ice cycle of the Great Lakes consists of an initial formation (ice onset) period, followed by a growing period in which the annual maximum areal extent is reached, then a melting (break-up) period (Assel 2005). The typical ice cycle has an ice-on date on all lakes occurring in December. The growth of ice cover is remarkably similar in all of the Great Lakes. Figure 4 also shows the progression of maximum ice cover for each lake.

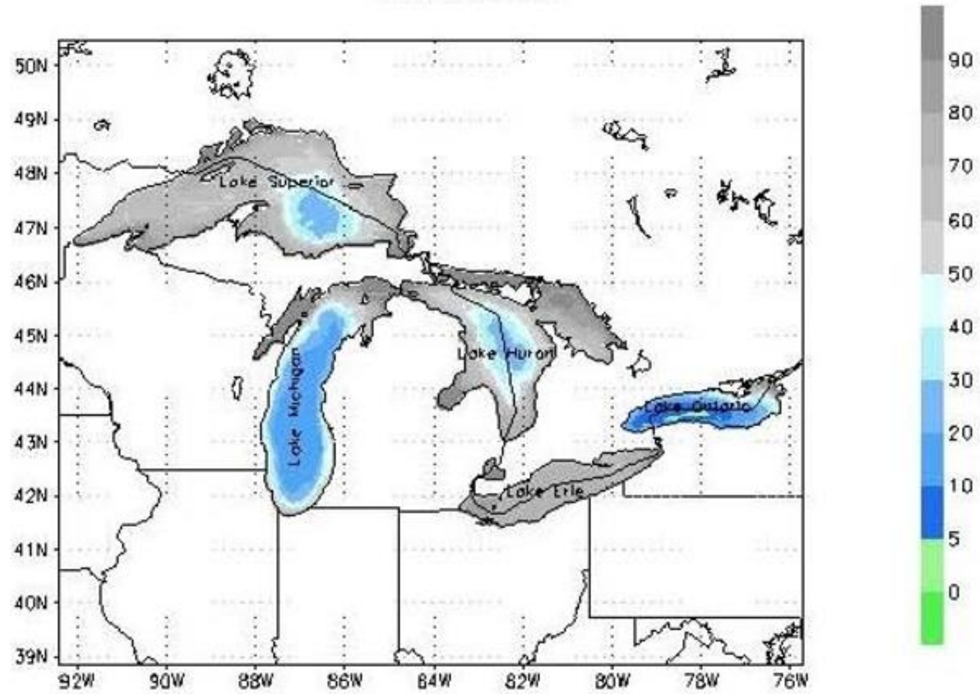

Figure 3. Long-term (1973-2002) mean annual maximum ice cover (in percentage) in the Great Lakes. Note that ice cover (or concentration) ranges from 0% (ice free) to 100% (complete ice cover). (from Bai et al. 2011).

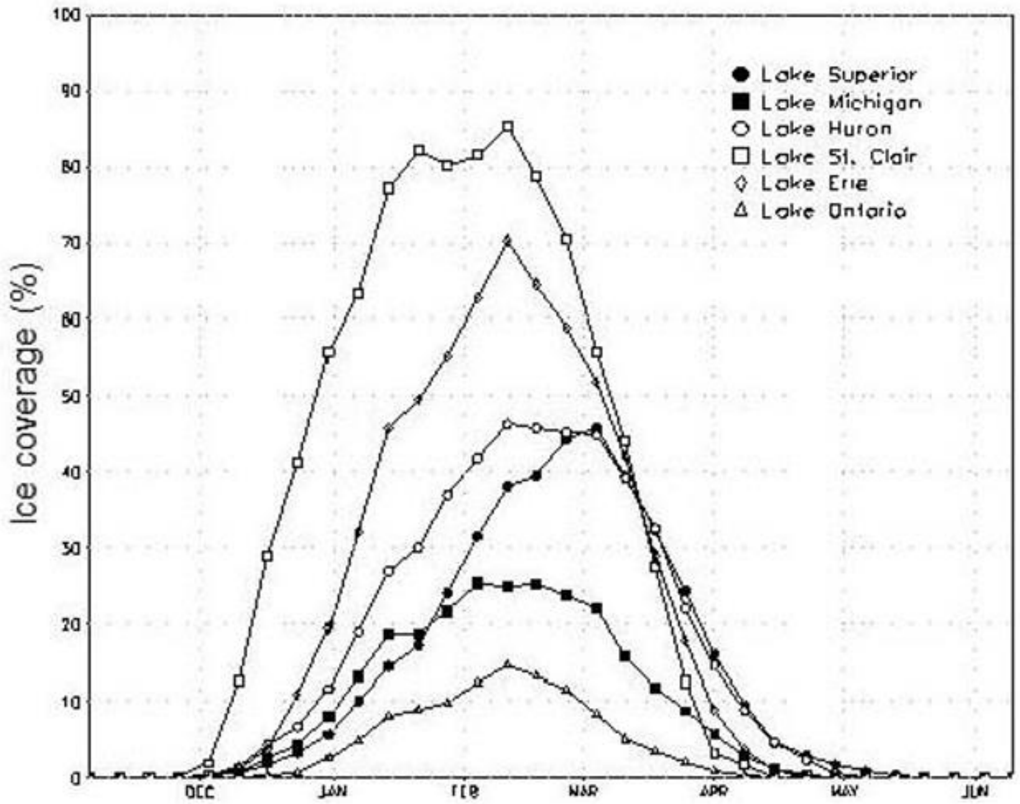

Figure 4. The NIC twice-weekly climatology of ice cover (in percentage) in the Great Lakes averaged from the period 1973-2011.

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Jia Wang (Ph.D.) received his undergraduate training in physical oceanography at Ocean University of China and continued his M.S. degree also in the same field at the same institution in 1984, and received his Ph.D. in Physical Oceanography from Institute of Oceanology, Chinese Academy of Sciences in 1987, and in Meteorology at McGill University, Canada in 1993. He joined National Oceanic and Atmospheric Administration (NOAA) Great Lakes Environmental Research Laboratory (GLERL) in July 2007 after serving the University of Alaska Fairbanks from 1998 to 2006 as a research professor. Jia Wang is a physical scientist/climatologist at NOAA GLERL as a team lead in Ice and Climate Diagnosis and Modeling. His research interests include coupled ice-ocean modeling from coastal to basin scales, Great Lakes, polar and subpolar climate change and lake/sea variability, and oceanography, He recently extends his interests also to numerical modeling of coupled physical-biological system, and regional Great Lakes Earth System Model. He holds several professional memberships: AGU, AMS, and IAGLR. He received several awards and certificates, including NOAA GLERL Director’s Award for Scientific Productivity of 2007, Outstanding Productivity and Excellence in Science of the Year 2000, JAMSTEC, Japan, 2000. He actively involves public services. He has also served as a chair of more than 10 sessions at national and international conferences/meetings and organizer for several workshops/conferences. He was often the invited speaker and keynote speaker in conferences/meeting. He has published 112 refereed journal articles, 10 proceedings papers, and 21 internal reports. Wang is an IAHR Ice Committee member since 2012.

Xuezhi Bai (Ph.D.) received his B.S. and M.S. degree in atmospheric sciences from Nanjing University, China in 1993 and 1996, respectively, and his Ph.D. in Physical Oceanography from Chinese Academy of Sciences in 2001. He was appointed as an Associate Professor in the Institute of Oceanology, Chinese Academy of Sciences in 2001. He has visited Florida State University for a year (2005-2006) as a visiting scholar. In 2008, he moved to the University of Michigan as a Research Fellow. He was a National Research Council Senior Research Associate at NOAA/Great Lakes Environmental Research Laboratory during 2009-2011. He is a member of American Geophysical Union and American Meteorological Society. His primary interests are in the climate dynamics, ocean circulation and its relation to climate variability, and ice-ocean modeling. He has published 40 refereed journal articles, and 4 internal reports.

Haoguo Hu is a research computer specialist at the University of Michigan, Ann Arbor. He developed and maintains sea ice-ocean-ecosystem models. He provides insight into ocean mixing and sea ice modeling.

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Raymond Assel, a GLERL Scientist Emeritus, authored or co-authored of over 100 scientific publications including a benchmark NOAA Atlas of Great Lakes Ice Cover Climatology for winters 1973-2002. He received the NOAA Distinguished Career Award for sustained Career Excellence for improved understanding and prediction of Great Lakes Ice Cover and is a past Chairman of the International Great Lakes–St. Lawrence Ice Information Working Group.

George Leshkevich is a Physical Scientist and remote sensing researcher at the National Oceanic and Atmospheric Administration (NOAA) Great Lakes Environmental Research Laboratory and Manager of the NOAA CoastWatch Great Lakes Program. Author and co-author of 71 scientific publications and recipient of the NOAA Bronze Metal Award. Associate Editor of the *Journal of Great Lakes Research*.

Anne Clites is a physical scientist at the NOAA Great Lakes Environmental Research Laboratory. She assists with processing and communication of ice cover and water level data.

Gregory Lang is a research support scientist working at NOAA's Great Lakes Environmental Research Laboratory for over 30 years. His fields of interest include real-time modeling of environmental systems, data acquisition and management, and website design and maintenance. Contributor to over 50 scientific publications covering Great Lakes and coastal topics.

Eric Anderson (Ph.D.) is a research physical scientist at the NOAA Great Lakes Environmental Research Laboratory with expertise in hydrodynamic modeling of the Great Lakes, connecting channels, and coastal zones. Dr. Anderson is leading the development of real-time hydrodynamic nowcast and forecast models for the Great Lakes as part of NOAA's operational modeling program. These models provide predictions of physical variables such as currents, temperatures, water levels, and waves as well as form the basis for prediction of nearshore water quality (fecal indicator bacteria) and harmful algal bloom transport.

Nathan Hawley (Ph.D.) has been a full-time research scientist at the Great Lakes Environmental Research Laboratory for over 30 years. He has conducted numerous field studies on sediment transport, wave and current action, and ice processes in the Laurentian Great Lakes.

Brent Lofgren (Ph.D.) has studied Great Lakes regional climate and climate change for over 20 years at the NOAA Great Lakes Environmental Research Laboratory, and has worked on revising the prevailing methodologies for projecting hydrologic impacts of climate change. He holds a B.S. degree in physics from Augsburg College and a Ph.D. in atmospheric and oceanic sciences from Princeton University. He is an author of 30 articles and numerous conference presentations, and has served as a reviewer for the Intergovernmental Panel on Climate Change's assessment reports for both Working Group I and Working Group II.

Steven A. Ruberg is the acting supervisor of the Observing Systems and Advanced Technology branch at NOAA’s Great Lakes Environmental Research Lab. He currently leads the Great Lakes Restoration Initiative funded Synthesis, Observations and Response project. His current research interest is the development of real-time coastal observation networks applied to beach impacts, algal bloom forecasts, and hypoxia effects on ecosystems and drinking water.

Dave Schwab (Ph.D.) is a world-renowned expert on hydrodynamic modeling of the Great Lakes and other coastal regions. Before joining the Water Center in 2013, Schwab was a research scientist and division chief at NOAA's Great Lakes Environmental Research Laboratory for 37 years. His work covered a wide range of topics in geophysical fluid dynamics including theoretical, numerical, and observational investigations of circulation, thermal structure, seiches, storm surges, wind waves, and air-sea interaction. Schwab was instrumental in designing, developing, and implementing a comprehensive coastal forecasting system for the Great Lakes which is currently in use by NOAA for operational marine forecasting, oil spill response, and search and rescue support for the US Coast Guard. The Great Lakes Coastal Forecasting System was the first of its kind in the country and has served as a model for several other systems around the world. In 2013, Schwab was awarded two awards for his sustained scientific contributions to Great Lakes research: the Distinguished Career Award from the National Oceanic & Atmospheric Administration (NOAA) and the Lifetime Achievement Award from the International Association for Great Lakes Research (IAGLR).

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