ADVANCING GREAT LAKES HYDROLOGICAL SCIENCE THROUGH TARGETED BINATIONAL COLLABORATIVE RESEARCH

by Andrew D. Gronewold and Vincent Fortin

> **IMPROVING HYDROLOGICAL MODELING PREDICTIONS IN THE GREAT LAKES**
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> What: More than 20 scientists from the United States and Canada met to assess and recommend strategies for advancing the state of the art in Great Lakes regional climate, hydrological, and hydrodynamic modeling
> When: 11–13 October 2011
> Where: Ann Arbor, Michigan

As one of the Earth's largest surface freshwater resources, the North American Laurentian Great Lakes are an ideal test bed for understanding water balance dynamics of large hydrologic systems and for establishing effective protocols for collaborative binational water resources and ecosystem services research. To leverage ongoing and future federal government research efforts in the Great Lakes region, representatives from the National Oceanic and Atmospheric Administration (NOAA), the Cooperative Institute for Limnology and Ecosystems Research (CILER), and Environment Canada (EC) convened a workshop on Great Lakes hydrological modeling with an emphasis on improving regional hydrological and hydrodynamic science. Workshop presentations and discussions collectively underscored the following three motivating themes for current and future research:

1) utilizing investments in monitoring infrastructure and model development from the recently completed International Upper Great Lakes Study (IUGLS), a binational, multiagency, multimillion dollar effort intended to improve understanding of water-level dynamics and evaluate alternative plans for regulating Lake Superior water levels;
2) identifying appropriate roles for NOAA, CILER, and EC in post-IUGLS "adaptive management" research, while leveraging ongoing efforts and

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ensuring long-term institutional knowledge of the Great Lakes hydrologic system; and
3) assessing existing modeling tools and applications in the Great Lakes, and filling research gaps through targeted collaborative projects.

WORKSHOP ACCOMPLISHMENTS. Presentations and discussions at the workshop focused on the following three topics: understanding institutional context and ongoing research programs, assessing skill of existing operational and experimental models, and sharing ideas and discussing implementation plans for the next generation of regional hydrological and hydrodynamic models. Summaries of each are in the following subsections.

Institutional context and ongoing research programs. In the Great Lakes region, U.S. and Canadian federal hydrological and hydrodynamic modeling research and development (R&D) activities generally support operational programs that fulfill commitments under binational treaties and agreements, such as the 1909 Boundary Waters Treaty and the 1972 Great Lakes Water Quality Agreement (revised in 1978, 1987, and 2012), both of which were implemented by the International Joint Commission (IJC). In Canada, these R&D activities are performed by the science and technology (S&T) branch of EC, with operational programs being managed by the Meteorological Service of Canada (MSC), another branch of EC. Similar services in the United States are provided not only by the various line offices within NOAA, but are also distributed among other U.S. federal agencies. Consistent and frequent coordination is needed to appropriately utilize the full range of associated resources.

The Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data, a binational advisory committee established in 1953, is an ideal forum for sharing research results, but is not particularly well suited for coordinating research plans, leveraging resources, and maximizing synergies. Existing international R&D initiatives that meet this need (and target the Great Lakes as a test bed) include the Global Earth Observation System of Systems (GEOSS), the Hydrological Ensemble Prediction Experiment (HEPEX), and the Great Lakes Observing System (GLOS). Both EC and NOAA actively participate in these initiatives, and recently (in 2008) signed a Memorandum of Understanding (MoU) to facilitate and improve collaboration between the two agencies. It is critical that EC and NOAA utilize these organizational and collaborative frameworks to the fullest possible extent.

Model verification and skill assessment. Both NOAA and EC conduct research on the development and application of modeling systems for simulating and forecasting Great Lakes system dynamics across a range of spatial and temporal scales. NOAA's Great Lakes Advanced Hydrologic Prediction System (AHPS) is one example of a conventional forecasting system with a history of providing seasonal water budget and water-level forecasts to the Great Lakes research and operations community. The Great Lakes AHPS has been shown to provide accurate water-

KEY FINDINGS

Key findings from the workshop include the following:

1) Ongoing and future regional research needs are to quantify two-way interactions between the land surface, lake surface, ice, and the atmosphere in model simulations, and to assess added benefits of this approach relative to conventional (i.e., either uncoupled or one-way coupled) model simulations and forecasts.
2) Advancements in Great Lakes regional hydrological and hydrodynamic models within EC, resulting from priorities in its mandate and the distribution of the Canadian population, are closely aligned with national-scale advancements in NWP models. In contrast, there is a clear need for a stronger link between the development of NOAA's national and North American NWP models and their application to the Great Lakes region.
3) Robust, computationally efficient methods for combining binational data across a broad range of time scales are needed to better understand the historical Great Lakes climatology, to better estimate historical dynamics of the Great Lakes water budget, and to establish initial conditions for forecasting systems. Monitoring networks supporting these efforts are distributed across multiple agencies from two different countries. Assembling regional data for the entire Great Lakes basin is, therefore, a challenging task that potentially limits model skill.
4) Establishing appropriate metrics for assessing model skill is a priority for Great Lakes regional hydrologic and hydraulic systems research. Rapid advancements in complex multidimensional modeling without accompanying protocols for comparing model simulations to observations will limit the utility of these models as operational and management decision support tools.

level forecasts, particularly in light of well-known but readily addressable deficiencies that limit a fair assessment of AHPS's skill in retrospective simulation mode (Gronewold et al. 2011). NOAA also runs both experimental and operational versions of the Great Lakes Coastal Forecasting System [GLCFS; or the Great Lakes Operational Forecasting System (GLOFS)], which provide short-term forecasts of lake state (Schwab and Bedford 1994).

As a contribution to the IUGLS, EC has implemented its Modélisation Environnementale—Surface et Hydrologie (MESH) model on the Great Lakes watershed (Pietroniro et al. 2007). MESH relies on atmospheric forcing from EC's Global Environmental Multiscale (GEM) NWP model and uses parameterizations for evapotranspiration and evaporation that are consistent with GEM. MESH can also be coupled to the Nucleus for European Modelling of the Ocean (NEMO) in order to simulate the hydrodynamic and thermodynamic structure of the Great Lakes. MESH and NEMO performed well during a 5-yr retrospective simulation of water supplies, water levels, and ice cover (Deacu et al. 2012; Dupont et al. 2011), but have yet to be evaluated as a forecasting tool.

Assessments of Great Lakes hydrological and hydrodynamic model skill fall into the following two broad categories: qualitative assessments over broad spatial and temporal scales, and quantitative assessments applied to narrow (and, in some cases, arbitrarily selected) time periods or small areas. Qualitative assessments, such as a noted "consistency" between model simulations and expected dynamics, while not a sufficient metric of model skill, are surprisingly common. As with other regions, a more systematic and consistent approach to model verification and skill assessment is needed to help focus Great Lakes regional collaborative research [for further discussion, see Arhonditsis and Brett (2004) and Stow et al. (2009)].

Given the range of historical and recently developed tools for assimilating Great Lakes regional hydrological data and forecasting hydrological and hydrodynamic variables (see, e.g., Schwab and Bedford 1994; Price et al. 2000; Neff and Nicholas 2005), there is a clear need for both EC and NOAA to establish and maintain a central repository of observations, model simulations, and forecasts to diagnose changes in model skill over time. This need is particularly pronounced for model-derived estimates of basin-scale components of the Great Lakes water budget, many of which are either not observable or not monitored directly, or (in the case of overland precipitation and basin-scale runoff, among others) are observed with significant intrinsic and extrinsic bias and variability (Bolsenga 1979; Holman et al. 2012).

The spatial and temporal extent of measurements for these and other critical variables define the limits of model skill and the potential usefulness of model simulations and forecasts in supporting water resource planning decisions. A particular example is the Huron to Erie Connecting Waterways Forecasting System (HECWFS; Anderson et al. 2010), which utilizes Lake Erie and Lake Huron water-level and interconnecting channel flow information as a basis for parameter conditioning and assessing forecasting skill. In this case, as in many others illustrated during the workshop, predictive skill of a model was driven not by the degree of sophistication of the model, but by the availability of sufficient observations for model calibration, verification, and initialization or forcing at the boundaries.

EC and NOAA are thus now designing observation campaigns to provide information for model skill assessment and improvement [including, e.g., continued collaborations with scientists from the academic research community who recently installed eddy covariance stations, as described in Spence et al. (2011)]. This effort also facilitates quantification of uncertainty and variability associated with model predictions for unobservable variables, such as overlake evaporation. Many presentations emphasized the fact that hydrologists need to look beyond surface observations to NWP products for model initialization and forcing.

The next generation of regional hydrological and hydrodynamic models. Current Great Lakes water-level prediction systems rely on a one-way cascade of simple models, while state-of-the-art prediction systems rely on two-way coupling of sophisticated components. Convincing arguments were made for two-way coupling, including recently documented reductions in the amplitude of expected changes to water levels in a warming climate when a consistent representation of evapotranspiration is used in both climate and hydrological models (Lofgren et al. 2011).

Moving to two-way coupled prediction systems requires hydrologists to work closely with atmospheric scientists from both the NWP and climate prediction communities. This cross-disciplinary collaboration would promote an explicit distinction between Great Lakes basin land and water surfaces in the next generation of NWP and regional climate models, an evolution that would improve Great Lakes runoff estimates and, subsequently, Great

Lakes water-level and hydrodynamic forecasts. EC, NOAA, and CILER are well positioned to foster this collaboration, although EC, given their organizational structure and the role that the Great Lakes and St. Lawrence River watershed plays in Canadian socioeconomics, has already made demonstrable progress towards this goal. EC is, for example, currently running (in experimental mode) a high-resolution deterministic prediction system (HRDPS) with a horizontal resolution of 2.5 km that provides 1-day weather forecasts over the entire Great Lakes watershed, to which MESH can be linked for hydrological forecasting purposes.

Improvements to land surface and water surface representation in hydrological, hydrodynamic, and atmospheric models are likely to have an even greater importance for medium- and long-range forecasting, because frequent updating of initial conditions can help limit the impacts of model deficiencies for short-range forecasting. As forecast range is increased, moving toward probabilistic (or at least ensemble) forecasting is imperative. As results obtained with the North American Ensemble Forecasting System (NAEFS) have demonstrated, there is value in combining forecasts from two or more forecasting centers. Testing a similar approach for water cycle prediction in the Great Lakes is desirable, yet participants felt that targeting model deficiencies identified during the IUGLS, together with the development of a robust procedure for assessing model skill, could, in the short term, lead to a significant improvement of prediction skill as well as increase confidence in model predictions.

CONCLUSIONS. The workshop concluded with the identification of four representative projects that leverage ongoing collaborative binational efforts, address pressing research and applied science problems, and can be completed within a reasonable time frame. Successful completion of these projects would serve as tangible progress toward the goal of fostering research-based collaborations between EC, NOAA, and CILER, and of advancing Great Lakes regional hydrological science. These projects include the following:

1) improving runoff predictions for the entire Great Lakes basin, starting with the hindcast mode (assimilating streamflow observations), then the nowcast mode (with atmospheric forcings provided by observations or short-term forecasts), and finally the monthly to seasonal forecast mode;
2) assembling lake ice area and thickness data to verify model simulations and forecasts over a variety of temporal scales;
3) improving the representation of the thermocline structure, in particular for Lake Erie, because existing hydrodynamic models exhibit a thermocline that is too diffuse (this limitation not only leads to difficulties in simulating the water balance of the lakes, but more importantly, reduces model utility in water quality and ecosystem applications); and
4) improving flow projections from Lake Ontario and propagating those improvements into hydrodynamic models linking the St. Lawrence River with the Gulf of St. Lawrence.

A subsequent workshop was held in Burlington, Ontario, Canada, in May 2012, with a focus on tracking progress on the projects listed above, setting up a shared database and defining procedures for model skill assessment, and broadening the strategic planning dialogue to more explicitly include representatives from the ecosystem dynamics and services communities.

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