Resolving Hydrometeorological Data Discontinuities along an International Border

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Monitoring, understanding, and forecasting the hydrologic cycle of large river and lake basins often require a broad suite of data and models ranging from in situ and satellite-derived measurements of (among other variables) precipitation, air and surface water temperature, energy fluxes, and soil moisture (Rodell et al. 2004; Trenberth et al. 2007) to conceptual and process-based models applied across varying time and space scales (Loaiciga et al. 1996; Silberstein 2006). Many North American (and other continental) hydrologic datasets and models, however, are susceptible to variations in monitoring infrastructure and data dissemination protocols when watershed, political, and jurisdictional boundaries do not align. This is a challenge facing hydrologic science professionals studying any freshwater basin that intersects an international boundary.

Reconciling hydrometeorological monitoring gaps and inconsistencies across the North American Great Lakes–St. Lawrence River basin (Fig. 1) is particularly challenging not only because of its size but also because the basin's dominant hydrologic feature is the vast surface waters of the Great Lakes (Table 1). Furthermore, the international border between the United States and Canada bisects the basin and four of the five Great Lakes. No other river basin in North America poses the same combination of hydrometeorological monitoring and data development challenges.

FIG. 1. River basins of North America (transparent blue shaded regions) that intersect either the border between the United States and Canada or the border between the United States and Mexico. U.S. land surfaces are colored dark gray; land surfaces of Canada and Mexico are colored light gray. The Great Lakes–St. Lawrence River basin is outlined in red.

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MONITORING INFRASTRUCTURE AND DATA INCONSISTENCIES: REPRESENTATIVE EXAMPLES.

Many long-term hydrometeorological monitoring platforms in and around the Great Lakes–St. Lawrence River basin are owned and operated by federal agencies, including the National Oceanic and Atmospheric Administration (NOAA),

Table 1. Lake and land surface area estimates for each of the basins of the Laurentian Great Lakes (Hunter et al. 2015). The values in parentheses indicate the percentage of the basin area.

Lake basin	Total basin area (km^2)	Lake surface area (km^2)	Land surface area (km^2)
Superior	210,100	82,100 (39%)	128,000 (61%)
Michigan–Huron	369,400	117,400 (32%)	252,000 (68%)
Erie (including St. Clair)	103,510	26,810 (26%)	76,700 (74%)
Ontario	83,000	19,000 (23%)	64,000 (77%)
Total	766,010	245,310 (32%)	520,700 (68%)

the U.S. Geological Survey (USGS), the U.S. Army Corps of Engineers (USACE), Environment and Climate Change Canada (ECCC), and the Department of Fisheries and Oceans Canada (DFO). However, the domains of each agency's platforms (and the datasets generated from them) do not typically cross the U.S.–Canadian border because they are constrained by jurisdictional (rather than basin or watershed) boundaries.

Fig. 2. Representative example of discrepancy between jurisdictional bounds of a federal agency (here, the NOAA National Weather Service RFCs; represented by brown, blue, green, and turquoise regions within the United States) and the boundaries of the Great Lakes basin (red line). The RFCs develop and disseminate broad-scale hydrometeorological data across the United States. Their products have traditionally extended across international borders within the Rio Grande, Columbia, and Yukon River basins as well but have not historically extended across the Great Lakes basin.

These inconsistencies can propagate into gaps, discontinuities, and errors in corresponding datasets. Regional precipitation datasets from NOAA, for example, typically originate from radar, satellite, and monitoring station data that are quality controlled within each of NOAA's National Weather Service (NWS) River Forecast Centers (RFCs; Fig. 2). Because the spatial domain of RFC operations aligns with jurisdictional bounds, precipitation products from the RFCs have historically only been quality controlled over land surfaces within the United States. This protocol has led to products (Fig. 3) that, in some cases, include unreliable precipitation data over the surfaces of the Great Lakes and, in other cases, exclude all data from land and lake surfaces in the Great Lakes–St. Lawrence River basin that are outside the United States. Interestingly, precipitation mosaics disseminated through NOAA's Advanced Hydrologic Prediction Service public interface (http://water.weather.gov; Fig. 3b) include quality-controlled data across the international land surfaces of the Columbia, Rio Grande, and Mississippi River basins. The discrepancy between data development and dissemination protocols for these basins and the Great Lakes–St. Lawrence River basin arises, in part, from the fact that the St. Lawrence River does not discharge along a U.S. coastline.

Discontinuities in monitoring platforms along the international border in the Great Lakes–St. Lawrence River basin also permeate into often-used global- and continental-scale data products, including the North American Land Data Assimilation System (NLDAS; Mitchell et al. 2004). A visual inspection of NLDAS spatial data (Figs. 3c,d) reveals major deficiencies for southern Ontario, for example. The temporal change in precipitation estimated for this region (in NLDAS) in 2002 and 2012 is much too large, and the spatial discontinuities at the border for both years are unrealistic. Consequently, historical precipitation data in NLDAS (and similar continental-scale products), while potentially useful in hydrological modeling studies of basins that lie entirely (or mostly) within the United States, are often inadequate for use in hydrological studies and modeling applications across North America's international basins.

ORIGINS AND HISTORICAL ROLE OF THE COORDINATING COMMITTEE.

For the tens of millions of Canadian and U.S. residents that live along the shorelines and on the watersheds of the Great Lakes, seamless binational datasets are needed to better understand and predict coastal water-level fluctuations, hazards to navigation, and other conditions that could potentially threaten human and environmental health. These binational products have historically been developed and maintained by a

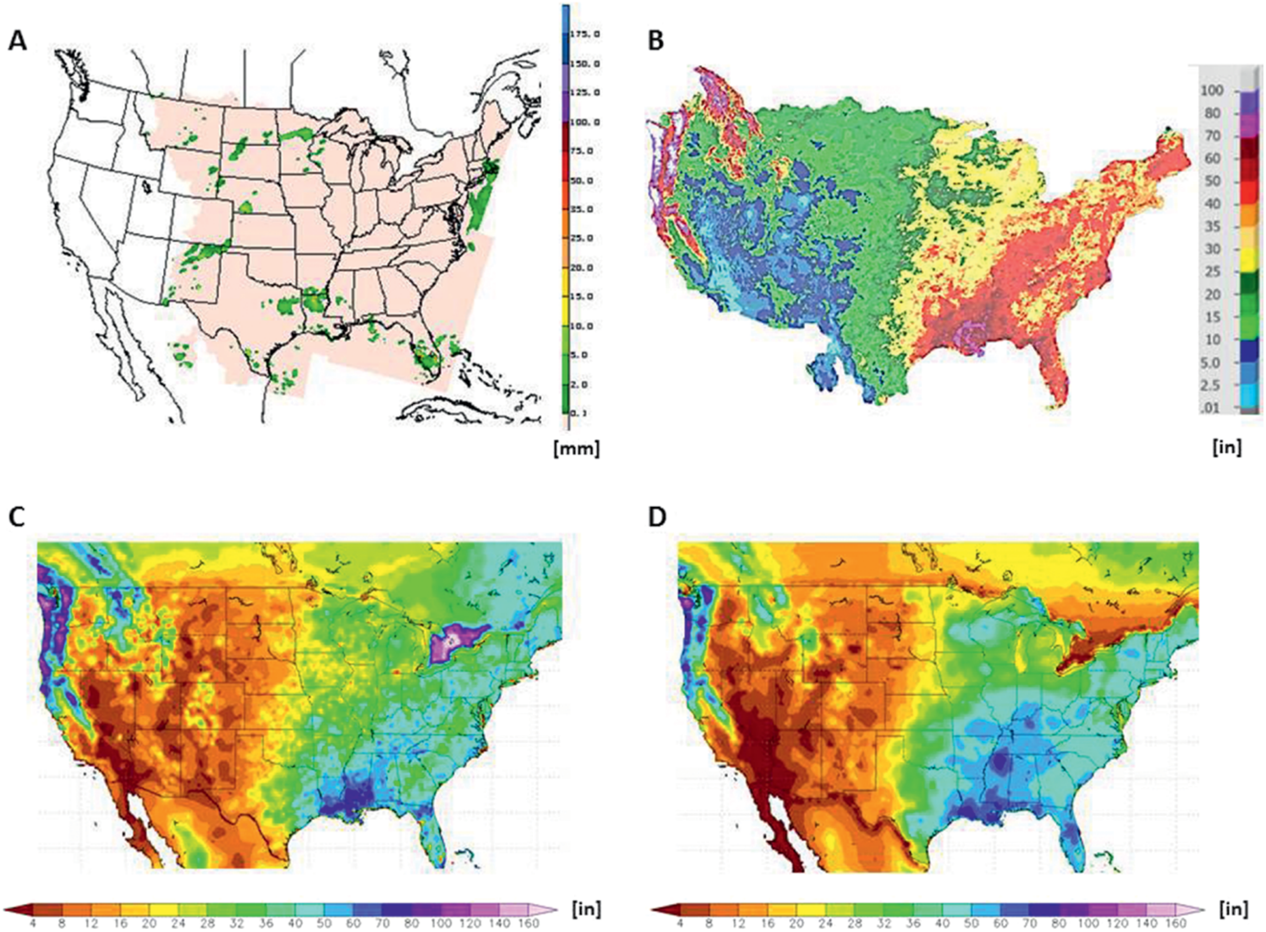

Fig. 3. Four representative precipitation datasets reflecting the influence of jurisdictional and international boundaries on spatial coverage. (a) NOAA's National Centers for Environmental Prediction (NCEP) National Stage IV quantitative precipitation estimates (QPE) that evolve out of the NOAA NWS RFCs showing 1-h cumulative precipitation on 6 Sep 2016. (b) NOAA Advanced Hydrologic Prediction Service (AHPS; http://water.weather.gov) product with cumulative precipitation for calendar year 2012. Note that boundaries of this product follow jurisdictional boundaries of the NOAA NWS RFCs (Fig. 2) and omit most of the land and lake surfaces of the Great Lakes–St. Lawrence River basin. (c) NLDAS cumulative precipitation for calendar year 2012; reflects significant anomalies along the U.S.–Canada border north of Lakes Erie and Ontario. (d) NLDAS cumulative precipitation for calendar year 2002; indicates an unrealistic precipitation gradient along most of the U.S.–Canada and U.S.–Mexico international borders. Note that precipitation color contours and scale bars for each product are from the original product source.

unique regional group, the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (CCGLBHHD; hereafter referred to as the Coordinating Committee).

The Coordinating Committee's first meeting was held in Ottawa, Ontario, in May 1953 and included a small group of federal agency representatives from the USACE and Canada's Departments of Mines and Technical Surveys, Transport, and Resources and Development. This initial gathering established protocols for resolving discrepancies between each country's respective measurements of water levels and channel flows across the Great Lakes and through the St. Lawrence River. At the time, it was considered essential that the United States and Canada distribute identical hydraulic and hydrologic records of the entire Great Lakes system and, in doing so, account for basin-scale, water-level measurement spatiotemporal variability caused by glacial isostatic rebound (Mainville and Craymer 2005) and intrinsic variability within and between monitoring platforms.

Membership in the Coordinating Committee has evolved to include representatives from multiple U.S. and Canadian federal agencies including DFO, ECCC, NOAA, Natural Resources Canada (NRCan), and the USGS. While these agencies currently represent the backbone of both nations' long-term, water balance–monitoring infrastructure and forecasting systems, other agencies with an active role and interest in large-scale hydrological and meteorological science and policy are noticeably absent, including the National Aeronautics and Space Administration (NASA) and representatives of First Nations. Increasing communication between the Coordinating Committee and these groups should be a priority.

The Coordinating Committee does, however, frequently consult with the International Joint Commission (IJC) and the IJC's Great Lakes Boards of Control. The IJC was established through the Boundary Waters Treaty of 1909 to serve as an independent advisor to both countries and to prevent and resolve disputes related to transboundary waters (Annin 2006). The IJC's Great Lakes Boards of Control employ Coordinating Committee datasets in decisions related to implementation and updates to regulation plans governing Lake Superior and Lake Ontario outflows, monitoring basin hydrologic conditions, and forecasting Great Lakes water levels and outflows. As such, the Boards of Control constitute one of the most important and consistent users of Coordinating Committee products and services.

The Coordinating Committee's scope of work and methods of water balance accounting address data and knowledge gaps that, because of factors described previously, would otherwise not be filled. Consequently, datasets (Hunter et al. 2015) and modeling resources (Deacu et al. 2012) developed by Coordinating Committee members represent most of the readily available sources of continuous, long-term, basin-scale hydrological and hydraulic data for the Great Lakes–St. Lawrence River basin. At its recent (May 2016) one-hundredth semiannual meeting, former and present Coordinating Committee members reflected on a range of historical achievements while setting clear goals for future work. In the following sections, we provide an overview of some of the most important products developed over the past six decades by the Coordinating Committee that have been employed not only by the Boards of Control but by various other regional decision-making authorities, the media, academia, consultants, and the general public as well (for a complete summary of Coordinating Committee products, see Table 2).

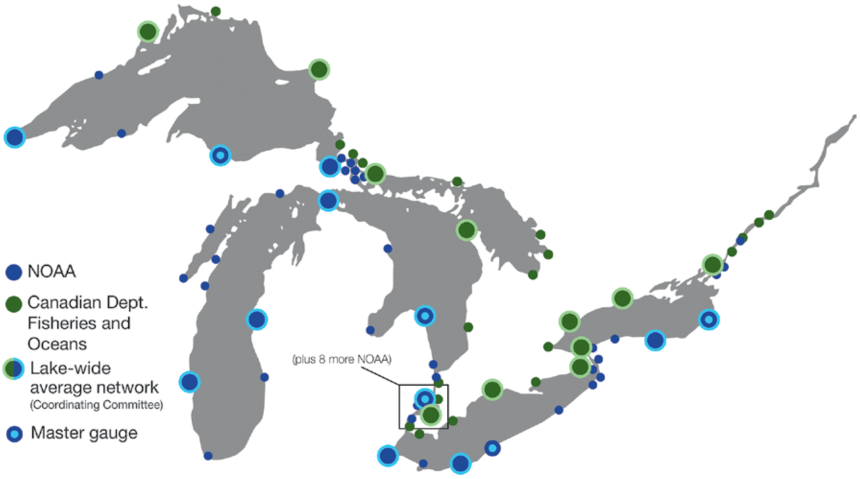

Fig. 4. Location of Great Lakes shoreline-based water-level monitoring stations maintained by NOAA (blue circles) and DFO (green circles). Large circles with a light outer ring represent stations used by the Coordinating Committee to calculate long-term, lakewide average water levels. Large circles with a light small inner circle represent the master gauging station for each lake.

Table 2. Summary of Coordinating Committee and related Great Lakes basin-scale (i.e., binational) hydrometeorological monitoring platforms and data products. "Temporal resolution" indicates whether a product is distributed to the public at a particular resolution; some products are distributed at a relatively high temporal resolution (such as the CaPA precipitation estimates) and can be aggregated to coarser scales by end users. Net basin supply (NBS) is defined as the sum of over-lake precipitation, over-lake evaporation, and lateral runoff. Datasets annotated with an asterisk are available in real time (or near–real time). GLERL is the Great Lakes Environmental Research Laboratory.

	Temporal range (for historical data)		Spatial resolution	Temporal resolution					Reference	Data distribution
	Begin	End		Annual	Monthly	1/4 monthly	Daily	Subdaily		
Official basin-scale Coordinating Committee products										
Over-lake precipitation	1900	Present	Average over lake surfaces	✖					—	www.greatlakescc.org/
Overland precipitation	1900	Present	Average over lake watersheds	✖					—	www.greatlakescc.org/
Connecting channel flows	1900	Varies	Average over channel length		✖	✖			—	www.greatlakescc.org/
Lakewide average water levels	1918	Present	Average over lake surfaces	✖	✖		✖		—	www.greatlakescc.org/
Residual net basin supplies	1900	Present	Average over lake surfaces		✖	✖			—	www.greatlakescc.org/
Seasonal water-level forecasts	—	—	Average over lake surfaces		✖				—	Monthly Bulletin of Great Lakes Water Levels
International Great Lakes datum	—	—	—						(Mainville and Craymer 2005)	Included in water-level data
Associated basin-scale products developed and maintained by Coordinating Committee members										
Over-lake precipitation (GLM-HMD)	1900	Present	Average over lake surfaces	✖	✖		✖		(Hunter et al. 2015)	NOAA-GLERL GLM-HMD
Overland precipitation (GLM-HMD)	1900	Present	Average over subwatersheds	✖					(Hunter et al. 2015)	NOAA-GLERL GLM-HMD
Over-lake evaporation (GLM-HMD)	1950	Present	Average over lake surfaces	✖	✖		✖		(Hunter et al. 2015)	NOAA-GLERL GLM-HMD
Lateral runoff into lakes (GLM-HMD)	1900	Present	Average over subwatersheds	✖	✖		✖		(Hunter et al. 2015)	NOAA-GLERL GLM-HMD
Component NBS (GLM-HMD)	1950	Present	Average over each lake surface	✖	✖		✖		(Hunter et al. 2015)	NOAA-GLERL GLM-HMD
Basinwide precipitation hindcast (CaPA)	2002	2012	Interpolated on 10-km grid				✖	✖	(Lespinas et al. 2015)	CaPA-RDPA v2.4
Basinwide precipitation operational analysis (CaPA)*	2011	Present	10-km grid (see reference for details)			✖	✖		(Fortin et al. 2015)	CaPA-RDPA real time (last month) (archive)
Component NBS (GEM system)*	2016	Present	10-km grid				✖		—	Web mapping server
Regulation and routing model	—	—	Average over channel length						—	Available from CCGLBHHD on request
International gauging stations	2015	Present	Point station data					✖	—	
Basin-scale products under development										
Water balance uncertainty estimates	1950	Present	Average over lake surfaces		✖				(Gronewold et al. 2016)	L2SWBM research site
Binational precipitation tool*	2002	Present	Gridded at 10-km resolution				✖	✖	—	http://mrcc.isws.illinois.edu/

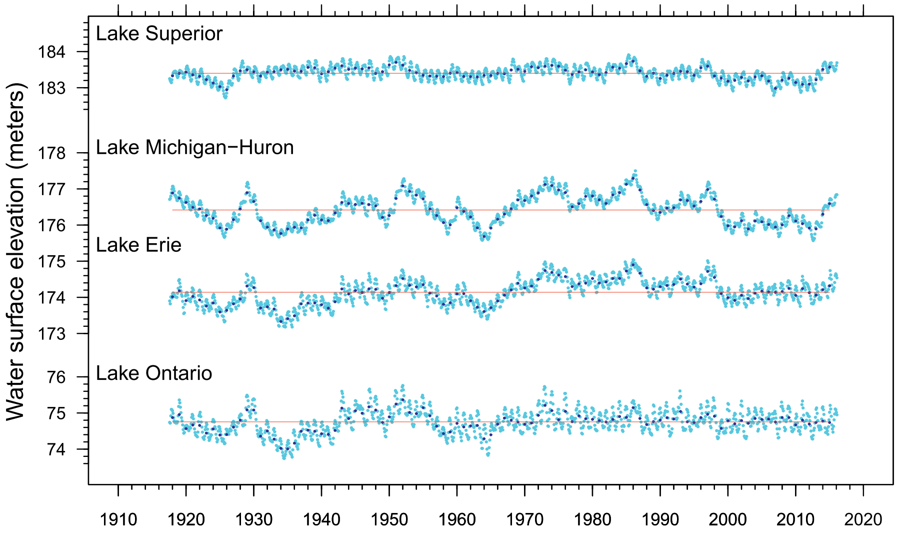

FIG. 5. Historical monthly (light blue) and annual average (dark blue) water levels of the North American Great Lakes. The long-term average water level from 1918 to 2016 for each lake is represented by horizontal red line.

REPRESENTATIVE LEGACY DATASETS OF THE COORDINATING COMMITTEE.

Lake storage (surface water elevations). Historical Great Lakes surface water elevations have been measured and evaluated using a variety of monitoring platforms and inference techniques including in situ shoreline-based gauges (Gronewold et al. 2013), paleoclimate reconstructions from tree rings (Baedke and Thompson 2000; Quinn and Sellinger 2006), and satellite radar altimeter data (Morris and Gill 1994). The Coordinating Committee has historically calculated lakewide surface water elevations using the arithmetic mean of measurements from a select set of gauges owned and operated by both the NOAA National Ocean Service and the DFO Canadian Hydrographic Service (Fig. 4). The resulting dataset of historical, coordinated Great Lakes water levels (Fig. 5) constitutes one of the longest sets of continuous hydrologic measurements for any aquatic (marine or freshwater) system on Earth. Importantly, this dataset has served as the basis for analyzing extraordinary regional hydrological and climatological phenomena, including (for Lakes Superior, Michigan–Huron, and Erie) record-high water levels in the mid-1980s and a sharp decline in water levels in the late 1990s coincident with the very strong 1997–98 winter El Niño (Assel et al. 2004) as well as a recent record-setting water-level increase (on Lakes Superior and Michigan–Huron) coincident with the 2013–14 Arctic polar vortex deformation (Clites et al. 2014). Historical Coordinating Committee water-level records also provide critical reference information for regional operational water resources management planning decisions, including the regulation of outflows from Lakes Superior and Ontario.

Maintenance of historical Great Lakes water-level data requires periodic modifications conducted in parallel with updates of the regional reference datum [commonly referred to as the International Great Lakes Datum (IGLD)]. These updates are needed to account for ongoing long-term effects of glacial isostatic adjustment (Mainville and Craymer 2005). Efforts are under way to update the most recent reference datum, commonly referred to as IGLD85 because it was based on water-level information collected between 1982 and 1988.

Lateral inflows to the Great Lakes. The water balance of the Great Lakes and St. Lawrence River system is composed primarily of over-lake precipitation, over-lake evaporation, and lateral runoff from adjacent tributaries and overland flow. While each of these components are of a similar magnitude on annual scales (Hunter et al. 2015), the water balance of each lake follows a strong seasonal cycle (Lenters 2004) that depends on propagation of the spring freshet through tributaries and the channels that connect the lakes (Fortin and Gronewold 2012) and on increases in lake evaporation in the late fall and early winter. Measurement and forecast uncertainty associated with tributary flows is relatively high because there are many ungauged rivers (Fig. 6), and measurements are not accurate when ice is present. Models that could be used for simulating flow in ungauged basins require transboundary geophysical, meteorological, and hydrological datasets that are, for much of the Great Lakes basin, not readily available (Deacu et al. 2012; Kult et al. 2014).

To help quantify and resolve these uncertainties while advancing the state of the art in Great Lakes

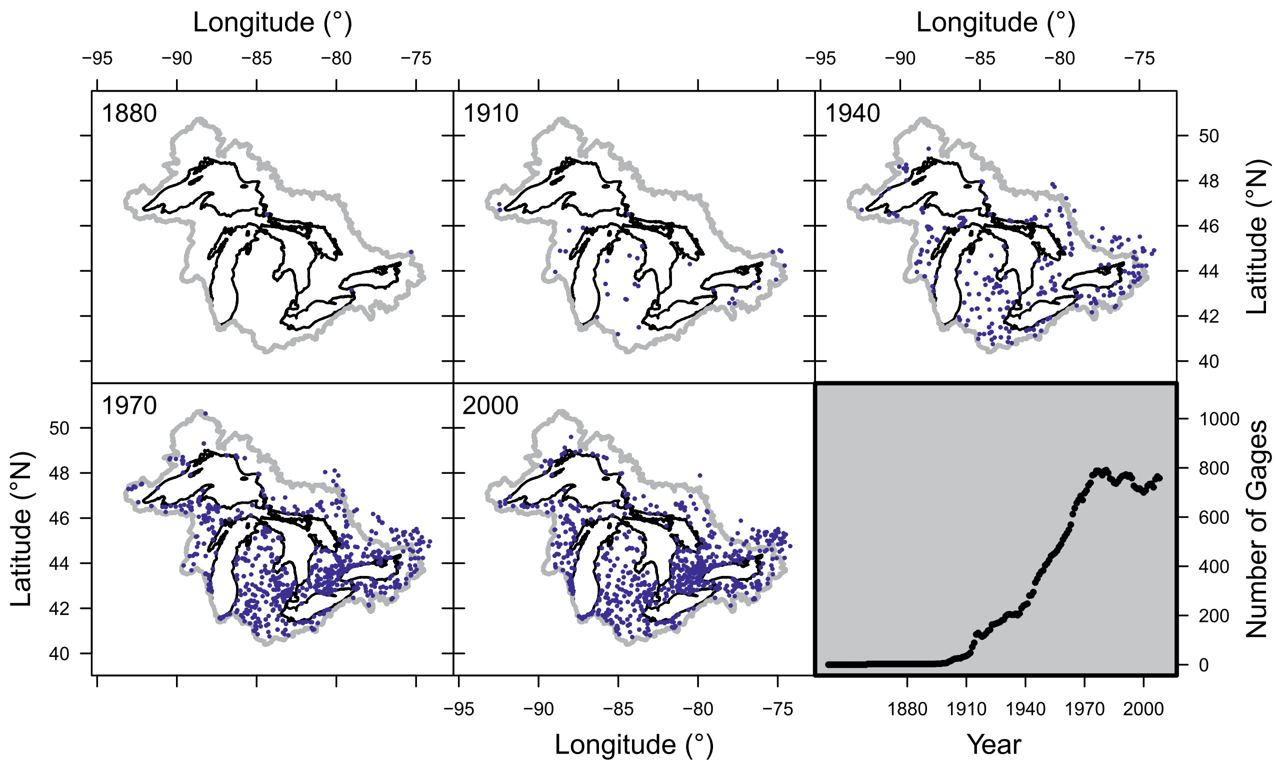

Fig. 6. Spatial and temporal distribution of USGS and Water Survey of Canada (WSC) streamflow gauges across the Great Lakes basin used in basin-scale historical runoff estimates. (bottom right) Number of gauges installed across the entire Great Lakes basin each year from 1840 to present. Note that the figure is modified from Hunter et al. (2015).

regional hydrological modeling, the Coordinating Committee initiated the Great Lakes Runoff Intercomparison Project (GRIP). Following its inception, GRIP has been implemented through a phased approach that focused first on Lake Michigan (Fry et al. 2014), with a second phase on Lake Ontario (Gaborit et al. 2017). Future GRIP study efforts are expected to shift to Lake Erie with an emphasis on coupled atmospheric, hydrologic, and hydrodynamic models for forecasting not only water levels but also water quality constituents that contribute to harmful algal blooms (HABs) and other human and environmental health concerns. This potential future work is particularly significant following increasing concern over (and increased spatial extent of) recent HAB events on the Great Lakes (Obenour et al. 2014) and speculation among the scientific community that nutrient loadings from the Detroit River (the connecting channel upstream of Lake Erie) may be underestimated relative to inflow from Lake Erie tributaries, including the Maumee and Sandusky Rivers (Davis et al. 2015).

RECENT INITIATIVES AND FUTURE CHALLENGES.

Over-lake water and energy fluxes. In light of the relatively sparse historical year-round hydrometeorological monitoring network across the surfaces of the Great Lakes, estimates of lake surface water and energy fluxes constitute a significant source of uncertainty in the regional hydrologic cycle (Gronewold and Stow 2014). Over the past decade, research projects initiated by Coordinating Committee members and colleagues have focused on adapting regional climate models to the Great Lakes basin to improve estimates of over-lake precipitation (Watkins et al. 2007; Holman et al. 2012) and on installing new eddy flux towers on offshore lighthouses to improve estimates of lake latent and sensible heat fluxes (Spence et al. 2013). Though the Coordinating Committee has not developed its own set of homogeneous evaporation data, members of the Coordinating Committee (through their respective agencies) have published evaporation estimates that are used widely in regional water supply and water-level management planning and related research (see Table 1).

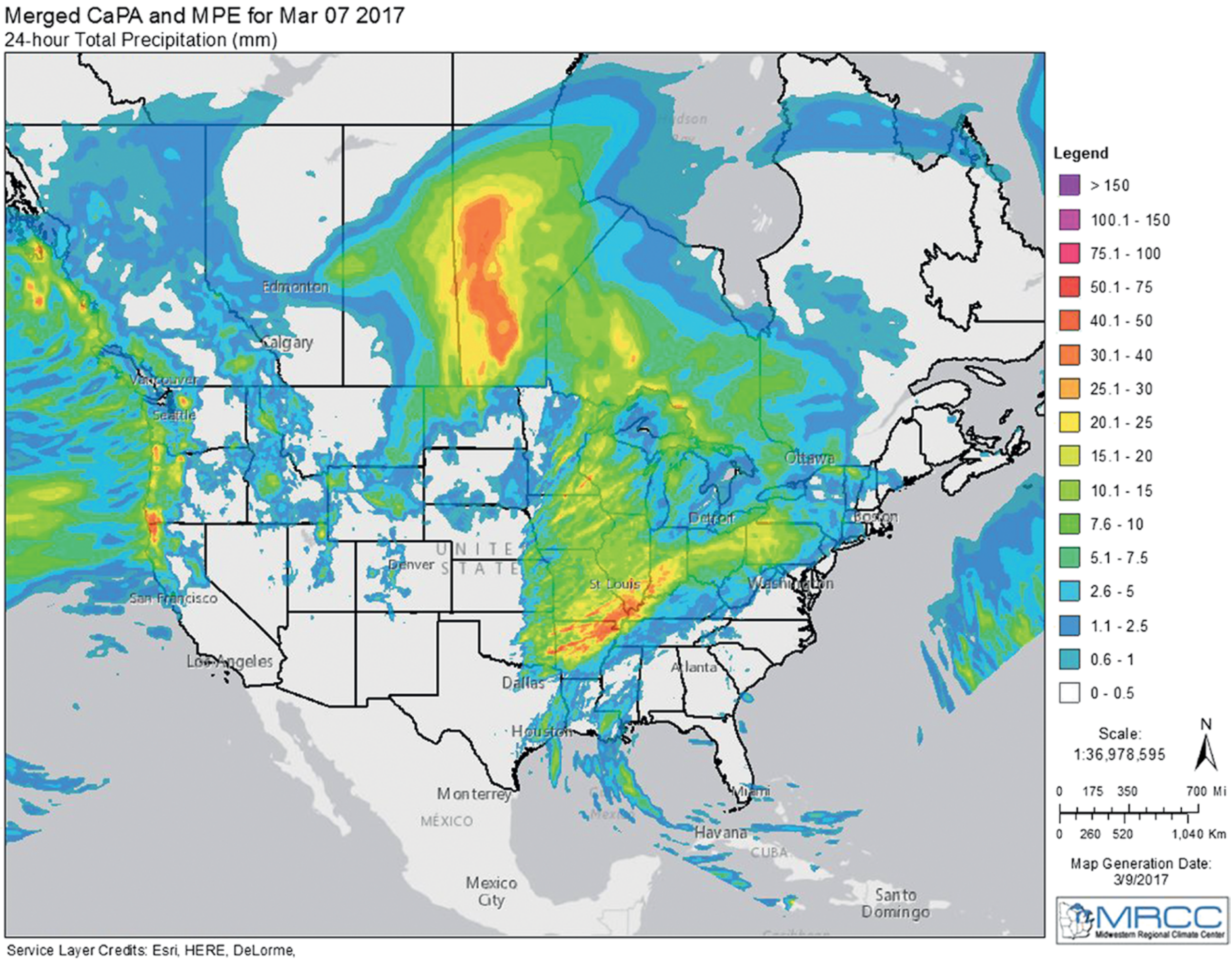

Fig. 7. Screen snapshot from newly developed (experimental) precipitation product with data blended from U.S. (NOAA) and Canadian (ECCC) federal agencies. U.S. data are from MPE and Canadian data are from the CaPA system. This new product seamlessly blends state-of-the-art precipitation data and model simulations from the United States and Canada across the U.S.–Canada international boundary.

More recently, the Coordinating Committee, after synthesizing and assessing currently available sources of information on over-lake precipitation, identified the Meteorological Service of Canada's Canadian Precipitation Analysis (CaPA) and National Weather Service Multisensor Precipitation Estimate (MPE) data (Kitzmiller et al. 2013; Fortin et al. 2015) as the two most promising sources of precipitation for long-term application to the Great Lakes. Both products combine gauge and radar data to provide a best estimate of precipitation in near–real time. In the case of CaPA, a numerical weather prediction model is also used (Lespinas et al. 2015).

Although gauge and radar data are shared in real time by both countries, quality-controlled radar data were, until recently, only available over Canada for CaPA and only available over the United States for MPE (Fig. 3). Following discussions at Coordinating Committee meetings, both organizations agreed to expand the domain of their quality-controlled radar data to cover the water surfaces of the Great Lakes. As a direct consequence of these discussions, a new version of CaPA that assimilates all U.S. radar data over the Great Lakes watershed was recently developed and is now fully operational. Similarly, quality-controlled precipitation estimates from MPE over the water surfaces of the Great Lakes are now available to the public. Furthermore, the Midwestern Regional Climate Center (MRCC) has partnered with the Coordinating Committee to develop a new binational precipitation product that merges CaPA and MPE data over the Great Lakes basin (Fig. 7), relying on CaPA over land in Canada, MPE over land in the United States, and an arithmetic average of CaPA and MPE over water.

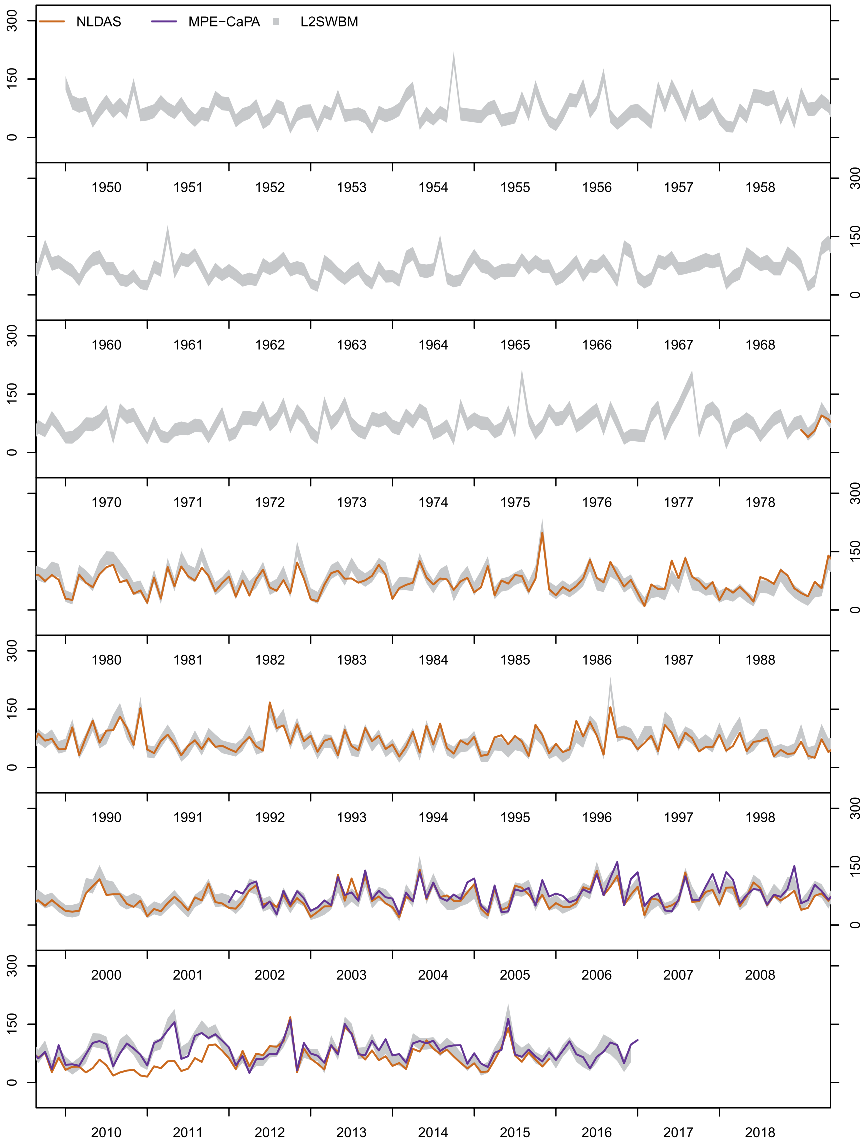

Fig. 8. Time series of historical monthly precipitation (mm) over the surface of Lake Erie from NLDAS, the new blended MPE–CaPA product, and (as 95% credible intervals) the new L2SWBM. Note that while the MPE–CaPA product addresses spatial inconsistencies (see Fig. 7), the new L2SWBM more explicitly addresses temporal inconsistencies and uncertainty.

A visual inspection of spatial maps generated from this new product indicates that while CaPA and MPE were developed by independent agencies, no sharp discontinuities show up at the border in the blend between the two. A visual inspection of the precipitation time series from this product, however (Fig. 8), reflects the fact that the new merged CaPA–MPE product does not include an expression of uncertainty nor does it have a length of record suitable for supporting robust long-term assessments of climatological and hydrological variability and change. Extending the historical record of state-of-the-art, high-resolution precipitation models and reanalysis products further into the historical record is computationally expensive, and the resulting products are likely to be relatively uncertain. To address this challenge, members of the Coordinating Committee recently developed a complimentary product: the Large Lake Statistical Water Balance Model (L2SWBM) that extends over multiple decades includes explicit expressions of time-evolving accuracy and bias and fills in gaps in the data record from in situ monitoring networks (Gronewold et al. 2016). The L2SWBM employs a Bayesian Markov chain Monte Carlo routine to infer magnitudes of each of the major components of the Great Lakes' hydrologic cycle by resolving a simple lake water balance model while assimilating data from multiple data sources for each component, including (for example) water-level monitoring stations (for lake storage), thermodynamics model simulations (for over-lake evaporation), and tributary flow gauging stations (for runoff into each of the Great Lakes).

Here, we present estimates of precipitation over Lake Erie from a recent L2SWBM run (Figs. 8 and 9) that (for precipitation estimates) used only the results of a conventional interpolation method documented in the NOAA Great Lakes monthly hydrometeorological database (GLM-HMD; Hunter et al. 2015). This approach allows us to use the L2SWBM as a basis for verifying the NLDAS and MPE–CaPA precipitation

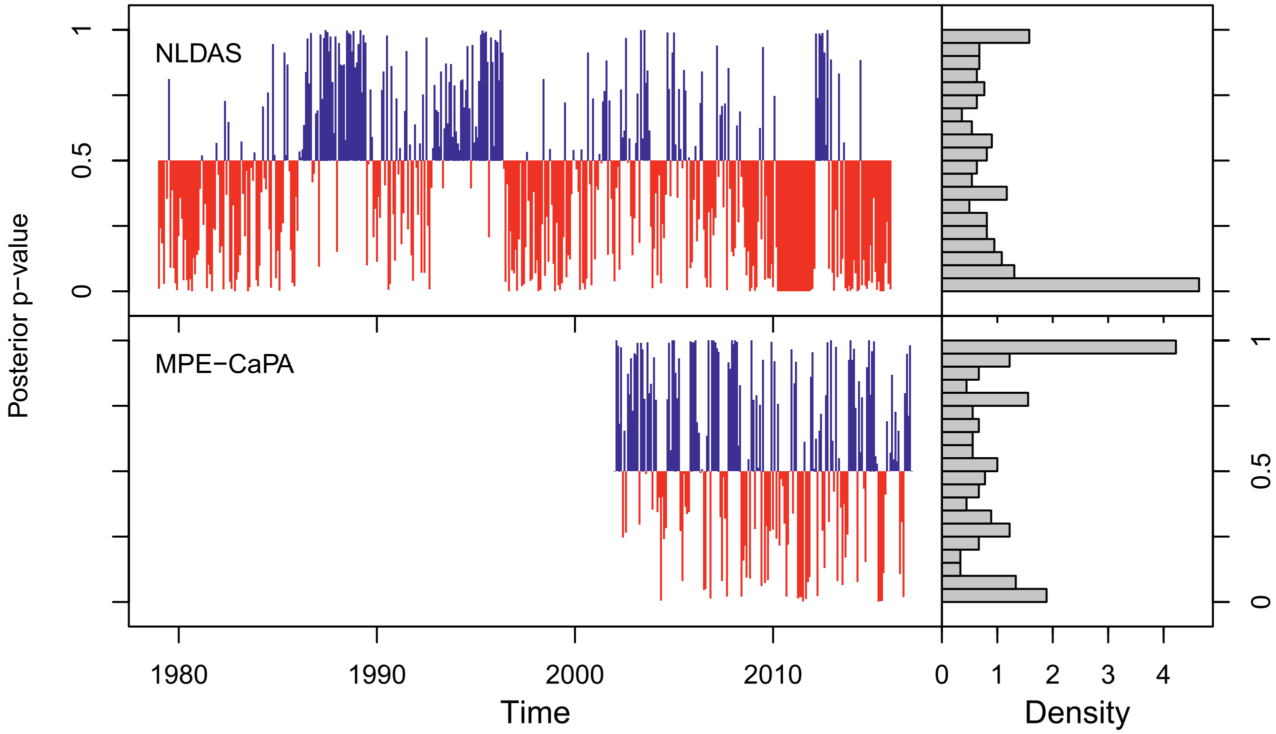

Fig. 9. (left) Time series and (right) histograms of posterior *p* values for (top) NLDAS and (bottom) MPE–CaPA monthly precipitation values over Lake Erie based on a comparison with probabilistic estimates from the L2SWBM. Blue and red lines differentiate *p* values above and below 0.5, respectively.

estimates. To more explicitly demonstrate this capability, we present posterior predictive *p* values (Elmore 2005) for each monthly precipitation estimate from both MPE–CaPA blend and NLDAS. The results (Fig. 9) provide insights above and beyond those of the spatial analysis alone and indicate that NLDAS has chronic biases that persist for multiyear periods. From roughly 1980 to 1986, for example, most NLDAS precipitation estimates were negatively biased, while from 1986 to 1989, they were almost all positively biased. Periodic biases in the MPE–CaPA blend are not nearly as persistent; however, there are a disproportionate number of positively biased MPE–CaPA precipitation estimates (indicated by the relatively high frequency of posterior *p* values with a value of 1).

The new blended CaPA–MPE product and the L2SWBM are indicative of a broader suite of datasets that have been developed through the strong binational partnership of the Coordinating Committee and that are critical to regional decision-making and public education. The "Quarterly Climate Impacts and Outlook" for the Great Lakes region (available at http://mrcc.isws.illinois.edu/pubs/docs/GL-201703Winter_FINAL.pdf), aimed at improving understanding of historical and future changes in regional climatological variables, is another example. Moving forward, we believe these products (and the binational data coordination protocols employed in developing them) could readily be applied to other large transboundary lakes and watersheds around the world that are not well instrumented but where issues of water scarcity and political conflict are perhaps more dire.

Forecasting. While the primary objective of the Coordinating Committee is the development of fundamental hydrometeorological datasets that integrate binational measurements and model simulations across the entire Great Lakes basin, it also has vested interest in the rapid evolution of hydrological forecasting systems. Over the past decade, relatively few advanced forecasting systems have been applied systematically to the entire Great Lakes basin (Gronewold and Fortin 2012). Part of the reason is that customizing state-of-the-art oceanographic and Earth system models to represent the hydrodynamics, thermodynamics, and atmospheric interactions of Earth's largest freshwater system requires regional content expertise, computational resources, and datasets that are not readily available in most research settings. We suspect it is far more likely for graduate students, postdoctorate researchers, and faculty, many of whom operate on a roughly 2–5-yr funding cycle, to study a freshwater basin where the datasets are readily available, are relatively homogeneous over the basin's land surface, and where over-lake evaporation, over-lake precipitation, and lake–ice cover interactions are not significant (Snover et al. 2003; Mote et al. 2005; Hamlet and Lettenmaier 1999). One of the current objectives of the Coordinating Committee, therefore, is to promote the ongoing customization of state-of-the-art hydrologic systems across the entire Great Lakes basin including, for example, Modélisation Environmentale–Surface et Hydrologie (MESH; Haghnegahdar et al. 2014); GEM-Hydro, a specific hydrologic routing configuration of the Global Environmental Multi-Scale (GEM) land-surface scheme (Deacu et al. 2012; Gaborit et al. 2017); the Variable Infiltration Capacity Model (Liang et al. 1994); and Weather Research and Forecasting (WRF) Model Hydrological modeling system (WRF-Hydro; Arnault et al. 2016).

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