PROJECT DOCUMENTATION REPORT

for

Great Lakes seasonal and inter-annual water supply forecasting improvements project
Phase I: Research and Development

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FINAL

November 2017

Acknowledgments

This report was prepared by representatives of the National Oceanic and Atmospheric Administration (NOAA), the United States Army Corps of Engineers (USACE), and the University Corporation for Atmospheric Research (UCAR). These agencies have no commercial interest in the results of this report or the operational practices of the New York Power Authority (NYPA), the Ontario Power Generation (OPG), and the Niagara River Control Center (NRCC).

Funding for this project was provided by NYPA, OPG, NOAA, and USACE. Funding for Becky Bolinger and Lisi Pei was administered by UCAR through its Postdocs Applying Climate Expertise (PACE) program. The authors are particularly thankful for extensive guidance and support from Peter Kowalski (NRCC), Rich Mueller (NYPA), and Laci Farczadi (OPG) before and during the course of this project. Brent Lofgren, Anne Clites, Nicole Rice (all three from NOAA-GLERL), Kaye FaFond (NOAA-GLERL contractor), Lacey Mason (University of Michigan), and Joe Smith (Cooperative Institute for Great Lakes Research, or CIGLR) provided significant scientific, graphical, and editorial support.

Description of project participants

OPG - Ontario Power Generation (OPG) is the largest energy provider in Ontario Province. It is a publicly-owned entity that owns and operates hydroelectric, nuclear, biomass, and other alternative energy facilities. OPG's interest in this project is based on their operation of the Sir Adam Beck power stations on the Niagara River, and the Robert H. Saunders generating station on the St. Lawrence River near Cornwall.

NYPA - The New York Power Authority (NYPA) is the largest state power organization in America. NYPA owns and operates 16 power generating facilities across the state of New York, and is New York's only statewide supplier of electricity. NYPA's interest in this project is based on their operation of the Niagara Power Project facility (on the Niagara River) and the St. Lawrence-Franklin D. Roosevelt Power Project (the US counterpart to the Robert H. Saunders facility on the St. Lawrence River).

NRCC - The Niagara River Control Center (NRCC) *need help with a description here.*

USACE - The United States Army Corps of Engineers Detroit District is tasked with the planning, design, construction, and maintenance of water resource projects related to multiple activities across the Great Lakes including navigation, flood control, and beach erosion. USACE-Detroit's interest in this project is based on their role in preparing and disseminating operational water level forecasts for the Great Lakes.

NOAA (GLERL) - The Great Lakes Environmental Research Laboratory (GLERL) is one of seven research laboratories within the National Oceanic and Atmospheric Administration (NOAA) Office of Oceanic and Atmospheric Research. NOAA-GLERL conducts scientific research on the Great Lakes and coastal ecosystems, and has a long history of developing water supply simulation and forecasting models for the Great Lakes.

UCAR - The University Corporation for Atmospheric Research (UCAR) is a nonprofit consortium of North American colleges and universities focused on research and training in atmospheric and related Earth system sciences. One of the scientists on this project, Dr. Lisi Pei, was sponsored through the

UCAR Postdocs Applying Climate Expertise (PACE) Postdoctoral Fellowship program. The PACE program aims to bring advances in climate science into decision making-tools and frameworks.

CIGLR - NOAA Cooperative Institutes are academic and non-profit research institutions that support NOAA mission goals. The Cooperative Institute for Great Lakes Research (CIGLR) is located in Ann Arbor, Michigan, and is a close partner of NOAA-GLERL.

Abbreviations

CCGLBHHD Coordinating committee on Great Lakes basic hydraulic and hydrologic data

CGLRRM Coordinated Great Lakes regulation and routing model

CIGLR Cooperative Institute for Great Lakes Research

CMIP Coupled model intercomparison project

CPC Climate prediction center

DDS Dynamically dimensioned search optimization

ECCC Environment and Climate Change Canada

ET Evapotranspiration

GL-AHPS Great Lakes advanced hydrologic prediction system

GLERRFS Great Lakes ensemble regulation and routing forecasting system

GLERL Great Lakes Environmental Research Laboratory (NOAA)

GLSHyFS Great Lakes seasonal hydrologic forecasting system

GLM-HMD Great Lakes monthly hydrometeorological database

LBRM Large basin runoff model

LLTM Large lake thermodynamics model

NCEP National Centers for Environmental Prediction (NOAA)

NBS Net basin supply

NMME North American multi-model ensemble

NOAA National Oceanic and Atmospheric Administration

NRCC Niagara River Control Center

NYPA New York Power Authority

OPG Ontario Power Generation

PACE Postdocs Applying Climate Expertise

RegCM Regional Climate Model system (a specific 'brand' of models for simulating regional climate)

RCM Regional climate model (a generic term for models that simulate regional climate)

RNBS Residual net basin supply

UCAR University Corporation for Atmospheric Research

USACE (Detroit) United States Army Corps of Engineers (Detroit District)

WRF Weather Research and Forecasting system

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1 Introduction

For the past several decades, Great Lakes regional hydropower authorities have relied on a suite of hydrologic and hydrodynamic models for decision support at the Niagara River Control Center (NRCC) and at the Moses-Saunders Power Dam in Cornwall, Ontario. These models have been used by NRCC, as well as the New York Power Authority (NYPA) and Ontario Power Generation (OPG), to make flow forecasts along the Niagara and St. Lawrence Rivers (figure 1) over both short (hours to days) and relatively long (multiple months to years) horizons. Following years of correspondence, as well as a workshop at the National Oceanic and Atmospheric Administration (NOAA) Great Lakes Environmental Research Laboratory (GLERL) in Ann Arbor, Michigan (in early 2015), a focus team with representatives from NOAA, the US Army Corps of Engineers (USACE), NRCC, NYPA, and OPG launched a project aimed at improving and developing new versions of these models. This report summarizes work related specifically to improving long-term forecasting systems for Great Lakes regional hydropower management. Improvements to short-term forecasting systems are documented separately.

Flows through the Niagara and St. Lawrence Rivers evolve through complicated upstream hydrological and hydraulic processes that can be generally divided into two groups. The first encompasses the meteorological and hydrological conditions that propagate into water supplies *within* each of the Great Lakes basins (i.e. through lateral tributary runoff, over-lake evaporation, and over-lake precipitation). The second includes hydraulic conditions and regulations governing lake outflows in the channels that connect each of the Great Lakes (e.g. the St. Marys, St. Clair, Detroit, Niagara, and St. Lawrence Rivers). Forecasting flows through these connecting channels typically utilizes models that encompass the entire spatial domain of the Great Lakes basin and explicitly address the two sets of relevant processes; water supplies in each lake basin, and flows through the channels that connect them.

Figure 1: Map of the North American Great Lakes drainage basin (brown shaded region) including major cities, political boundaries, interbasin diversions, and connecting channels.

2 Model development

To address the goals of this project, we developed, tested, and initiated deployment (within an operational environment) of a suite of modeling systems (table 1) capable of forecasting long-term (5-year forecast horizon) daily water supplies to each of the Great Lakes, and of propagating those supplies through the Great Lakes connecting channels (Lee et al., 1994; Clites and Quinn, 2003). This forecasting horizon and temporal resolution were specified at the beginning of the project to coincide with regional hydropower management needs.

In this section, we describe the development of those models, including our approach to developing meteorological forcings, hydrological models for simulating lake evaporation and tributary runoff, and the models that encode seasonal hydraulic conditions and regulation plans governing flows through the lake connecting channels. In section 3, we describe our approach to testing each model, and present a retrospective forecasting skill assessment.

Table 1: Summary of water supply forecasting system components. Meteorological forcings are described in detail in section 2.1. Hydrological models are described in detail in section 2.2. Models that propoagate water supplies through the Great Lakes connecting channels are described in section 2.4.

System name	Meteorology	Hydrology	
		Tributary inflows	Lake evaporation
GL-AHPS	Climatology	LBRMv1.0	LLTMv1.0
GLSHyFS-1	Climatology	LBRMv1.0	LLTMv1.0
GLSHyFS-2	Climatology	LBRMv2.0	LLTMv1.0
GLSHyFS-3	CMIP5	LBRMv2.0	LLTMv2.0
RNBS	None	Historical supply sequences	

2.1 Meteorological forcings

We employed two sets of meteorological forcings for this project. The first is based on historical (1950-2010) times series of daily maximum, average, and minimum air temperature (T_{max}, T_{avg}, T_{min}), precipitation (P), surface wind speed (U), cloud cover (A_c), and dew point temperature (T_d). These sequences are used as a basis for simulating daily water supplies for each lake basin either directly (via over-lake precipitation) or indirectly (via runoff and lake evaporation) through tributary and lake thermodynamics models (see section 2.2) within either the conventional seasonal forecasting framework of the Great Lakes Advanced Hydrologic Prediction System (Gronewold et al., 2011) or the newly-developed Great Lakes Seasonal Hydrological Forecasting System (GLSHyFS). This first set of meteorological forcings also serves as the basis for NOAA-GLERL's Great Lakes Monthly Hydrometeorological Database (or GLM-HMD). For additional details, see Hunter et al. (2015).

The second set of meteorological forcings is derived from the fifth phase of the Coupled Model Intercomparison Project (CMIP5, for details see Taylor et al., 2012; Sheffield et al., 2013) and represents an alternative approach to propagating future climate change into regional hydrologic response (Lofgren et al., 2013). A limitation of conventional seasonal forecasting methodology (i.e. using historical meteorological sequences) is that forecasts are almost always constrained within the extremes and patterns of the historical record, an approach that implicitly assumes a stationary climate (Milly et al., 2008). Our use of CMIP5 forcings is intended to address this shortcoming, and to help fill a gap in the 2-5 year forecasting horizon left by conventional seasonal and interannual scale forecasting products including those developed by NOAA CPC/NCEP (O'Lenic et al., 2008), and the National Multi-Model Ensemble (NMME) outlooks (Becker et al., 2014). This portion of the project was conducted primarily by research

fellow Dr. Lisi Pei who was funded by NYPA/OPG/NRCC and UCAR through the PACE postdoctoral research program. Details of the CMIP5-related work are included in the appendix.

It is informative to note that while T_d and A_c are used as forcings in the original version of the conventional hydrological models used in this project, they are not included in the publicly available output data from most CMIP5 models. To accommodate the need for T_d in our conventional hydrological models (when using the CMIP5 suite of variables) we calculate it from CMIP5-based simulations of surface pressure and specific humidity. However, rather than accommodate the need for A_c in our models, we modify them (see following sections for details) to use solar radiation (a variable that is readily available from CMIP5).

2.2 Hydrological models

In this subsection, we describe recent improvements to the two core hydrological models of our forecasting systems; the large basin runoff model (LBRM) for simulating tributary runoff into each lake (Croley II, 1983; Fry et al., 2014), and the large lake thermodynamics model (LLTM) for simulating over-lake evaporation (Croley II, 1989).

2.2.1 Large basin runoff model (LBRM)

The LBRM is a lumped conceptual rainfall-runoff model (Croley II, 1983) designed to simulate and forecast sub-basin scale lateral flows into each of the Great Lakes at daily time steps. Data requirements include sub-basin daily mean air temperature (calculated as an average of daily T_{max} and T_{min}), daily total precipitation (P), and sub-basin land surface area (see figure 2 for LBRM-specific sub-basin delineations). As such, the LBRM is a relatively simple model when compared to other state-of-the-art hydrological models, yet because of the complexities of assembling land surface data and meteorological forcings across the international border between the US and Canada, the LBRM is still considered by many as a "gold standard" for Great Lakes regional hydrological modeling and water supply forecasting (Gronewold and Fortin, 2012).

Applications of the LBRM in multi-decadal hydrological forecasting (see, for example Lofgren et al., 2002; Hayhoe et al., 2010; Angel and Kunkel, 2010) underscore the LBRM's tendency to significantly over-estimate evapotranspiration (and subsequently underestimate runoff in future warming scenarios) due, in part, to its formulation relating evapotranspirative (ET) loss to future air temperature and solar energy (for further discussion, see Lofgren et al., 2011, 2013; Lofgren and Gronewold, 2014). The extent to which this problem propagates into biases over shorter (e.g. seasonal and interannual) forecast horizons is uncertain. Nonetheless, to address this problem, we developed a new version of LBRM (LBRMv2.0) with a reformulated ET algorithm and with recalibrated model parameters conditioned on temperature-rainfall-runoff relationships from a relatively (compared to the calibration period of the original LBRM) recent period (January 1991 to December 2000) using the dynamically dimensioned search (DDS) optimization technique developed by Tolson and Shoemaker (2007). Details of the new ET algorithm and the LBRM recalibration procedure are included in the Appendix. For the remainder of this report, we refer to the original version of LBRM as LBRMv1.0, and the new version of LBRM as LBRMv2.0. For further discussion on alternative approaches to modeling ET, see Scheff and Frierson (2014) and Milly and Dunne (2017).

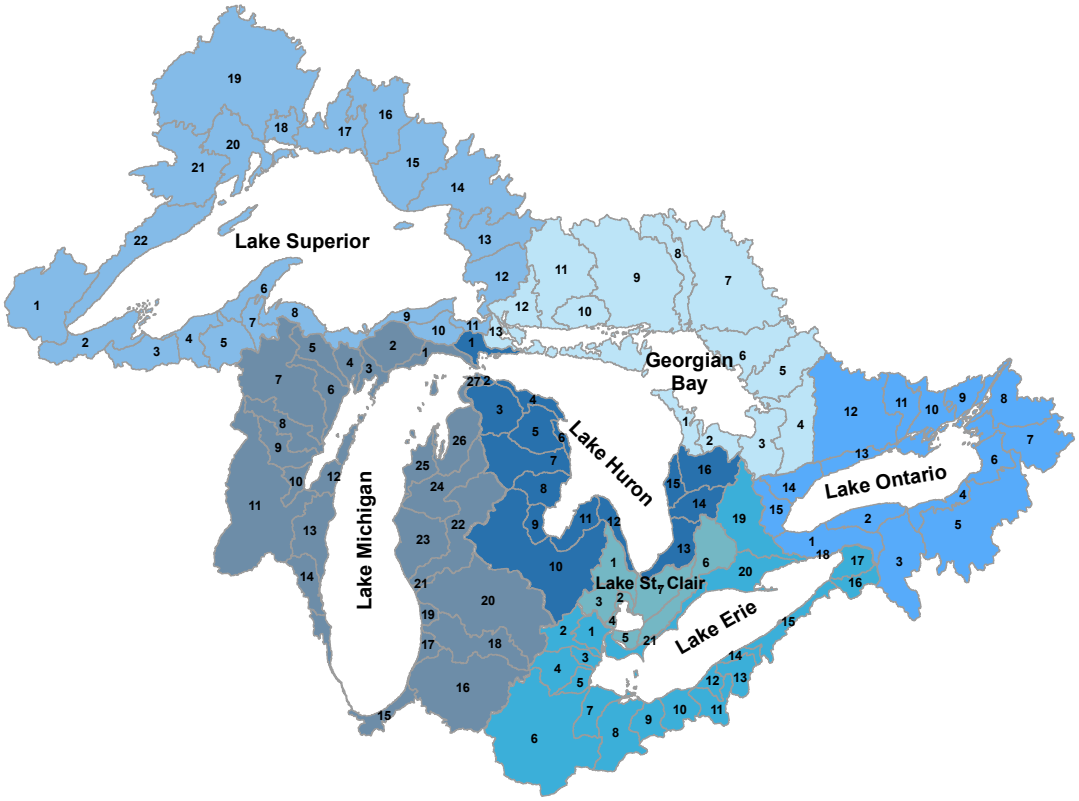

Figure 2: Customized delineation of Great Lakes sub-basins for the LBRM.

2.2.2 Large lake thermodynamics model (LLTM)

Two versions of the LLTM were employed; one for use with the conventional meteorological forcings from the historical record (as employed in the legacy GL-AHPS package), and a second for use with the new CMIP5-derived forcings. For the conventional LLTM (version 1), no significant modifications were made from the version originally developed by Croley II (1989). However, the model does include parameter values that were updated in 2014 through a joint USACE (Detroit)-NOAA (GLERL) project to reflect recent updates to lake surface temperature and ice cover data (both of which are used in LLTM model calibration). We hereafter identify the legacy version of LLTM (with updated parameter values) as LLTMv1.0. Significant changes were made, however, in an alternate configuration of LLTM that accommodates the CMIP5 forcings; this configuration is hereafter identified as LLTMv2.0 (see Appendix B for details).

2.3 Water supply forecasting systems

2.3.1 Great Lakes Advanced Hydrologic Prediction System (GL-AHPS)

Seasonal and interannual hydrological basin-scale forecasting across the Great Lakes has historically been achieved through a limited set of experimental and operational systems. One of the most (if not the most) commonly used is the Great Lakes Advanced Hydrologic Prediction System (or GL-AHPS; for further reading see Croley II and Hartmann, 1987; Croley II, 2000; Gronewold et al., 2011). The GL-AHPS was developed at NOAA-GLERL to provide seasonal projections of Great Lakes water supplies (early development of GL-AHPS is documented in Croley II and Hartmann, 1987). It is most accurately defined as a framework for propagating meteorological forcings through hydrological models (i.e. those representing terrestrial rainfall-runoff and lake thermodynamics) to simulate basin-scale estimates of the three major components of the Great Lakes' hydrologic cycle (i.e. over-lake evaporation, over-lake precipitation, and lateral tributary runoff). GL-AHPS has been employed in operational forecasting by the USACE and regional hydropower authorities (including both NYPA and OPG), and continues to be maintained for research applications at NOAA-GLERL. A climate change adaptation of GL-AHPS has also been employed in research studies projecting long-term hydrologic impacts of climate change in the Great Lakes basin (see, for example Mortsch and Quinn, 1996; Lofgren et al., 2002; Hayhoe et al., 2010; Angel and Kunkel, 2010).

The original plan for our study was to use only the legacy version of GL-AHPS (table 1) with legacy versions of LBRM and LLTM (i.e. LBRM1.0 and LLTM1.0) for generating daily water supply forecasts out to a 5-year horizon (per operational requirements of the hydropower authorities). This plan called for using the conventional version of GL-AHPS, rather than the climate change adaptation, because the climate package did not use present meteorology to generate initial conditions.

However, in the initial phases of this study, we found that software tools used to originally develop GL-AHPS were no longer functional due to changes in the Microsoft Windows operating system. It is informative to note that, until this study, NOAA-GLERL had used GL-AHPS to generate forecasts only to a one-year horizon (though NYPA had been using GL-AHPS to generate longer forecasts). Due to these challenges (and the subsequent inability to generate either future or retrospective 5-year forecasts), the project team elected to develop a new software package to replicate the functional capabilities of GL-AHPS. As such, original archived forecasts from the GL-AHPS system (provided from NYPA via Rich Mueller) serve as a performance benchmark for this study.

2.3.2 Great Lakes Seasonal Hydrologic Forecasting System (GLSHyFS)

The new water supply forecasting system, which we refer to as the Great Lakes Seasonal Hydrologic Forecasting System (GLSHyFS), is designed to use the same fundamental hydrological models (i.e. LBRM and LLTM) while implementing multiple improvements relative to the GL-AHPS. Some of these changes address the immediate needs of this project, and some address recommended improvements that have been documented over decades. Examples include cross-platform compatibility (with Linux as well as Microsoft-Windows), standardized text-style files rather than multiple disparate specialized binary files, elimination of a graphical user interface (GUI), and a simplified configuration. All of these changes in the new GLSHyFS are intended to improve the user experience and to curtail the long-term stability problems that evolved within GL-AHPS.

GLSHyFS also allows for an easier interchange of alternative meteorological forcings and hydrological model components. In this project, we utilized this new flexibility by developing and testing three configurations of GLSHyFS (table 1). The first uses conventional meteorological forcings from the historical record with LBRM1.0 and LLTM1.0. The second uses conventional meteorological forcings from the historical record with LBRM2.0 and LLTM1.0. The third version is developed explicitly to accommodate meteorological forcings from CMIP5 (and, implicitly, potential changes in future climate) and therefore employs LLTM2.0 (the version designed to use radiative forcings from CMIP5, rather than cloud cover) as well as LBRM2.0. In addition, GLSHyFS allows integration of both meteorological observations (to continually update the initial conditions) and climate change projections (using daily forcings estimated from a suite of global circulation models).

2.3.3 Historical residual net basin supply system (RNBS)

Yet another approach we employed to generate water supply sequences for ensemble forecasting is assembling historical net basin supplies. For this project, we employed net basin supplies developed by the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (refered to hereafter as CCGLBHHD or, simply, the Coordinating Committee; Gronewold et al., 2017). These supplies are calculated based on the following lake water balance equation (typically presented in units of mm or cm over the surface of a lake):

$$\Delta Z = P + R + E + Q_i - Q_o + \epsilon \tag{1}$$

where ΔZ is the change in lake storage (typically calculated as a change in lake surface water elevation) in a given month, and P, R, and E are corresponding monthly over-lake precipitation, lateral runoff, and over-lake evaporation. Q_i and Q_o represent monthly total inflow and outflow, respectively, through upstream and downstream connecting channels, and ϵ represents unexplained variability (for details, see Gronewold et al., 2016). Net basin supplies are typically defined as the sum of P, E, and R, however because these values are historically difficult to measure and therefore uncertain, 'residual' net basin supplies can also be calculated (by rearranging equation 1) as:

$$NBS_r = \Delta Z - Q_i + Q_o \tag{2}$$

Historical records of NBS_r for each of the Great Lakes are readily available from the CCGLBHHD. Forecasts based on NBS_r are generated for each day using all of the historical daily 5-year sequences from the historical record starting on the same calendar day. For example, a forecast made on June 1,

2016 would include an ensemble of 60 members, one from every five-year daily sequence starting in June 1 from year 1950 through 2011. It is informative to note that NBS_r records are available dating back to 1900, however current operational protocols only employ records dating back to 1950 in order to align with the historical meteorological record that serves as the basis for weighting individual members of the probabilistic ensemble.

2.4 Routing and regulation models

2.4.1 Coordinated Great Lakes Regulation and Routing Model (CGLRRM)

Translation of net basin supply to water levels requires simultaneous simulation of flows through connecting channels. These inflows and outflows are controlled by lake-to-lake differences in water levels, channel characteristics, retardation resulting from ice and weeds, and, in the case of the St. Marys and St. Lawrence Rivers, operation of control structures. These natural and anthropological controls on the connecting channels are traditionally simulated through the use of models incorporating stage-fall-discharge relationships, estimates of ice and weed retardation factors, and coding of regulation rules. The Coordinated Great Lakes Regulation and Routing Model (CGLRRM) represents a multi-agency, binational effort to coordinate simulation of flows. Building on the Mid-Lakes Routing Model that was developed at NOAA-GLERL (Clites and Lee, 1998), the CGLRRM was develop in the 1990s, and has been used for regulation and forecasting purposes since the early 2000s. Routing coefficients used within the CGLRRM (e.g. ice and weed retardation factors and stage-fall-discharge equation parameters) are routinely updated and maintained by the Coordinating Committee. As a result of this coordinated effort to maintain the CGLRRM and the use of the CGLRRM in Lake Superior regulation decisions, the CGLRRM is the recommended model for translating NBS to water levels and connecting channel flows for Lakes Superior, Michigan-Huron, St. Clair, and Erie. Accordingly, the ensemble forecasting framework developed for this project routes NBS through the CGLRRM for Lakes Superior through Erie.

It is worth noting that the CCGLBHHD is currently undertaking a project to develop a replacement to the CGLRRM, and several members of this hydropower improvement project are also engaged in the CGLRRM improvements project. This new regulation and routing modeling product will likely be available in the 1-2 year timeframe. At that point, any forecast products used by USACE (including the 5-year ensemble forecast developed for this project) will transition to using the new routing and regulation model.

2.4.2 Lake Ontario Routing and Regulation Model

Although it includes code for simulating Lake Ontario regulation and routing, the CGLRRM has only been rigorously tested for Lakes Superior through Erie (USACE, 2001), and therefore is not currently recommended for use in simulating Lake Ontario outflows and water levels. Additionally, the Lake Ontario regulation and routing routines in the CGLRRM do not include Plan 2014, implementation of which began in January of 2017. Instead, Environment and Climate Change Canada and USACE have maintained independent regulation and routing models for Lake Ontario. Accordingly, Lake Ontario regulation and routing is accomplished with a second (separate) routing and regulation model; the Lake Ontario Routing and Regulation Model. As with the CGLRRM, the Lake Ontario Routing and Regulation Model will be replaced by an updated routing and regulation product that is under development by the Coordinating Committee.

2.5 Ensemble processing

The Great Lakes Ensemble Regulation and Routing Forecasting System (GLERRFS) is designed to run an ensemble of NBS sequences through the CGLRRM and Lake Ontario regulation and routing model, resulting in an ensemble of water level and outflow projections for each of the Great Lakes. GLERRFS also includes a sub-routine that combines the ensemble output with user-specified weights to develop 'weighted' probabilistic forecasts of water levels and flows for the Great Lakes. This ensemble processing is graphically depicted in the blue box in Figure 3. The full system consists of a framework that first ingests an ensemble of NBS sequences into the CGLRRM and the Ontario Regulation and Routing Model and then computes an outlook based on the ensemble output using an outlook package. This outlook package includes the option to weigh ensemble members according to a climate forecast. Each component of this forecasting system is described in detail in the following subsections.

2.5.1 Outlook module

Subsequent to routing of the NBS through the regulation and routing models, the ensembles of NBS, water levels, and flows are used to develop outlooks. In the outlook package, the ensemble output for each day of a forecast is used to estimate quantile values on a daily basis. The outlook package can be run using one of two configurations: unweighted or weighted. In the unweighted configuration, the ensemble of water levels and flows is used, as is, to compute quantile values. In the weighted configuration, the ensemble members are replicated according to user-specified weights prior to computing quantiles. The main constraint in computing weights is that the sum of the weights must equal the number of ensemble members. A simple example of how weights are used to replicate ensemble members before computing statistics is shown in Table 2.

Table 2: Simple demonstration of how weights are applied in the outlook module using a 4-member ensemble.

Member	Value	Weight	Replications
A	5	0	
B	10	0.5	10
C	15	2.0	15, 15, 15, 15
D	20	1.5	20, 20, 20
Mean	12.5		
Weighted ensemble mean			16.25

While the user-specified weights can be determined in a variety of ways, the operational protocol used for the 5-year forecasts developed for OPG and NYPA is to use the `NOAAwgts.exe` tool associated with the GL-AHPS distribution. This tool, developed by GLERL and described in Croley II (1996) and Croley II (2000), relies on optimization methods to determine weights that result in a best match between an ensemble of historical climate data and probabilistic seasonal forecasts of precipitation and temperature (for example, those provided in NOAAs Climate Prediction Center Outlook Maps). When using this tool to develop weights, it often becomes difficult or impossible to meet all constraints (i.e. match the ensemble climatology with the forecast climate) for the full forecast horizon. Accordingly, weights are typically based only on the first one to three months of the forecast horizon.

Finally, after weighting has been applied and the resulting daily quantile values are computed, a plotting script is run as part of the outlook package. Example plots for Lake Erie NBS, water levels, and outflow are shown in Figure 4.

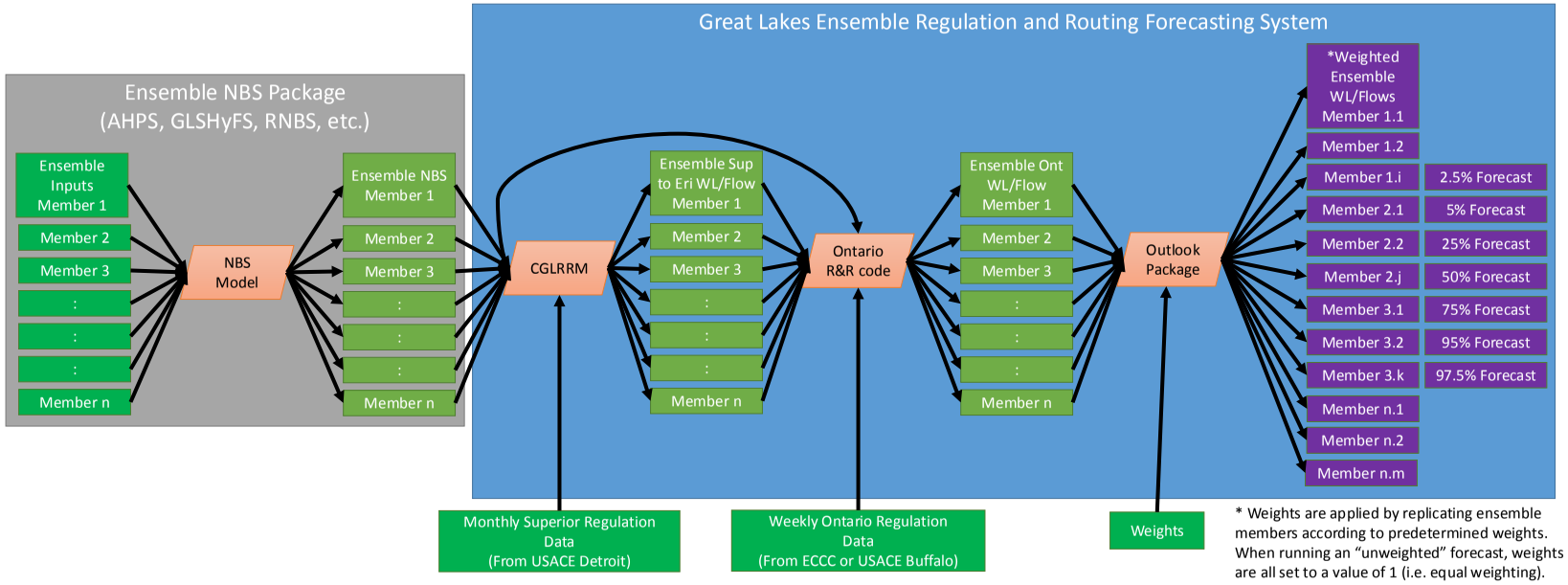

Figure 3: Graphical overview of the Great Lakes Ensemble Regulation and Routing Forecasting System (GLERRFS). Any ensemble NBS package can be used to produce an ensemble of NBS sequences for ingestion into GLERRFS. Additional inputs include regulation data from Lake Superior and Lake Ontario regulation and, optionally, a set of predetermined weights to adjust the output according to a particular climate outlook.

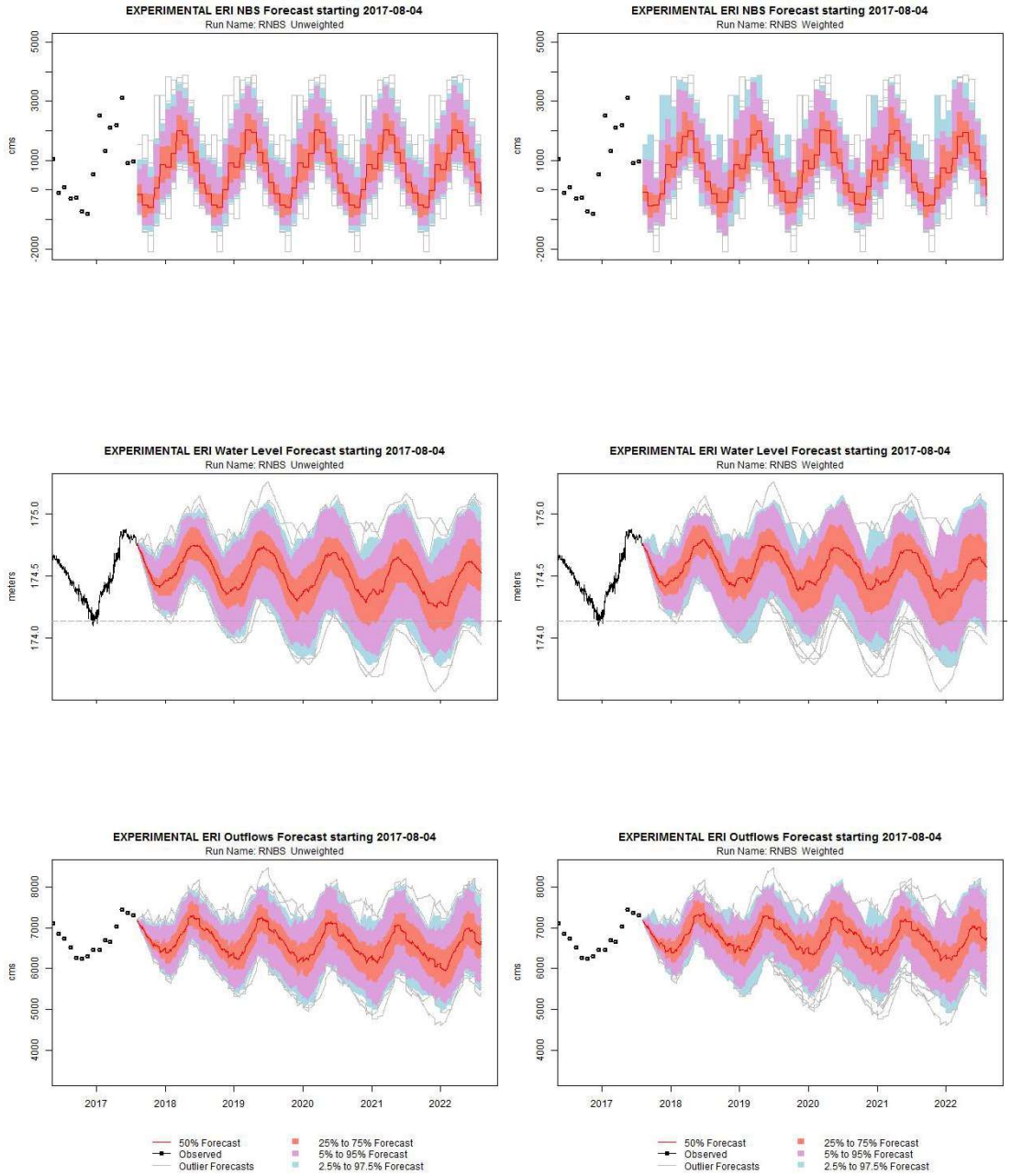

Figure 4: Preliminary operational forecasts of Lake Erie NBS (top panels), water levels, (middle panels), and outflow (bottom panels) with (left column) and without (right column) ensemble member weighting.

3 Model testing and skill assessment

Throughout the course of this project, team members conducted extensive testing of each forecasting system (i.e. table 1) to ensure (to the maximum extent possible) continuity, ease of implementation, and computational efficiency. Improvements in each of these areas were made continually and not all are formally documented. In this section, we describe our approach to assessing the comprehensive skill of each modeling platform, including our rationale for selecting model endpoints and comparisons between retrospective forecasts and observations.

For each of the modeling configurations in this study (i.e. in table 1), we evaluated forecasts for two key hydrologic variables; Niagara River flows, and Lake Ontario cumulative NBS. While we recognize that hydropower management decisions for facilities downstream of Lake Ontario are ultimately based on St. Lawrence River flow forecasts, the regulation model for Lake Ontario does not currently accommodate the range of potential management decisions that might affect St. Lawrence River flows. By assessing the skill of both Niagara River forecasts and Lake Ontario water supplies, our analysis effectively identifies potential sources of error (aside from those arising within the Lake Ontario regulation model) that might propagate into St. Lawrence River flow forecast errors. It is informative to note that previous studies have assessed the forecasting skill of the conventional GL-AHPS (Gronewold et al., 2011). Results from these studies, while informative, included only forecasts on a 1 to 6-month horizon.

3.1 Niagara River (Lake Erie outflow) forecast verification

We assessed the skill of Niagara River flow forecasts through three Niagara River flow statistics; average monthly flow, the maximum daily flow within each month, and the minimum daily flow within each month. Daily Niagara River flow observations were obtained from historical records maintained by the Buffalo District of the USACE. Although each forecasting system is designed to generate a 5-year horizon of daily forecasts executed at least once per month, here we generate retrospective forecasts on the first Friday of each month (an approach which we believe is consistent with expected operational practice) and assess them at 1-, 6-, 12-, 24-, 36-, and 60-month horizons.

3.1.1 Calculation of observed Niagara River flows

As part of its role on the Coordinating Committee, the USACE Detroit District maintains records of monthly Niagara River and Lake Erie outflows. These flows are generated from daily reports from the International Niagara Committee (INC) which include water levels and discharge at the Ashland Avenue Gage (Maid of the Mist Pool), Canadian and U.S. power plant diversion flows, outflows from the Grass Island Pool, and flows over the Niagara Falls. Because the CGLRRM does not allow outputting Niagara River flow, Lake Erie outflows are used as a proxy. The "observed" Lake Erie outflow Q_{eri} is computed from data provided in the INC reports as the sum of the flows computed at Buffalo Q_{buf} and the Welland Canal Diversion flows Q_{wcd}:

$$Q_{eri} = Q_{buf} + Q_{wcd} \tag{3}$$

Niagara River flow at Buffalo Q_{buf} is computed as the sum of the outflow from the Maid of the Mist Pool Q_{mom}, discharge from the Sir Adam Beck Hydroelectric Generating Stations Q_{sab}, discharge from the Robert Moses Niagara Power Plant Q_{rmp}, diversion from the New York State Barge Canal Q_{sbc}, minus inflow from the Welland River Q_{wrv} and local inflows Q_l:

$$Q_{buf} = Q_{mom} + Q_{sab} + Q_{rmp} - Q_{wrv} + Q_{sbc} - Q_l \quad (4)$$

where local inflows are monthly average values calculated using an area ratio method (for description, see Hunter et al., 2015) applied to the Grand River in Ontario, and the Genesee River in New York (International Niagara Working Committee, 1962). Outflows from the Maid of the Mist Pool Q_{mom} are computed using a stage-discharge relationship, or rating equation developed for the Ashland Avenue gauging station (NOAA gage 9063007), located in Niagara Falls, New York. In 2009, this rating equation was revised as:

$$Q_{mom} = 0.6429(Z_{aa} - 82.814)^3 \quad (5)$$

where Z_{aa} is the stage observed at Ashland Avenue.

While the Ashland Avenue rating equation is appropriate when inflows are steady, this relationship cannot be used on a real-time basis during the tourist season when operational changes in flow from day to night are conducted to meet the Niagara Treaty of 1950. These rapid flow variations can cause the water level in the Maid of the Mist Pool to change by 10 feet or more. During these transition periods, a modified expression for outflow from the Maid of the Mist Pool is used:

$$Q^t_{mom} = Q^p_{mom} + M(Q_{mom} - Q^p_{mom}) + \frac{854,700}{3600}(Z_{aa} - Z^p_{aa}) \quad (6)$$

where Q^t_{mom} is the Maid of the Mist Pool outflow during the transition period, Q^p_{mom} is the Maid of the Mist Pool outflow during the previous hour, M is referred to as an M-factor and is associated with Q^p_{mom}, and Z^p_{aa} is the previous hour's stage at Ashland Avenue.

Following the revision of the Ashland Avenue rating equation in 2009, daily Maid of the Mist flows and flows at Buffalo were revised for 2007-2009. In order to build a complete record of "observed" Lake Erie outflow for assessment of the hindcasts in this project, it was necessary to revise daily Lake Erie outflows for the period of 1997-2006. These daily flows were computed using archived daily flows required in Equation 4, except for the Maid of the Mist Pool outflows. Daily Maid of the Mist Pool outflows were recomputed using Equations 5 and 6 with hourly stage measurements at Ashland Avenue retrieved from the NOAA Tides and Currents website (`https://tidesandcurrents.noaa.gov/stationhome.html?id=9063007`). The revised Lake Erie outflows are shown in Figure 5, along with prior (unrevised) Lake Erie outflow estimates.

3.1.2 Comparison to flow forecasts

Visual inspection of the time series comparing 1, 6, and 12-month forecasts to observations (figures 6 through 8) indicates that all of the new forecasting systems reflect a strong seasonal cycle and that forecast uncertainty appears generally consistent with the range of observed variability. It is informative to note that Lake Erie experienced a record-setting surge in water levels (and outflows) in 2011, followed by a record-setting continuous period of water level decline (through 2012) that are clearly evident in the observation record (Gronewold and Stow, 2014), but were only reflected in one-month-ahead forecasts. Furthermore, we note that the late 1990s was punctuated by a significant water level decline across all of the Great Lakes (Assel et al., 2004), and that the RNBS and GLSHyFS-1 and -2 packages appear to follow that decline, although we have not fully differentiated the relative dependence of forecasting skill on initial conditions compared to the dependence on meteorological forcings.

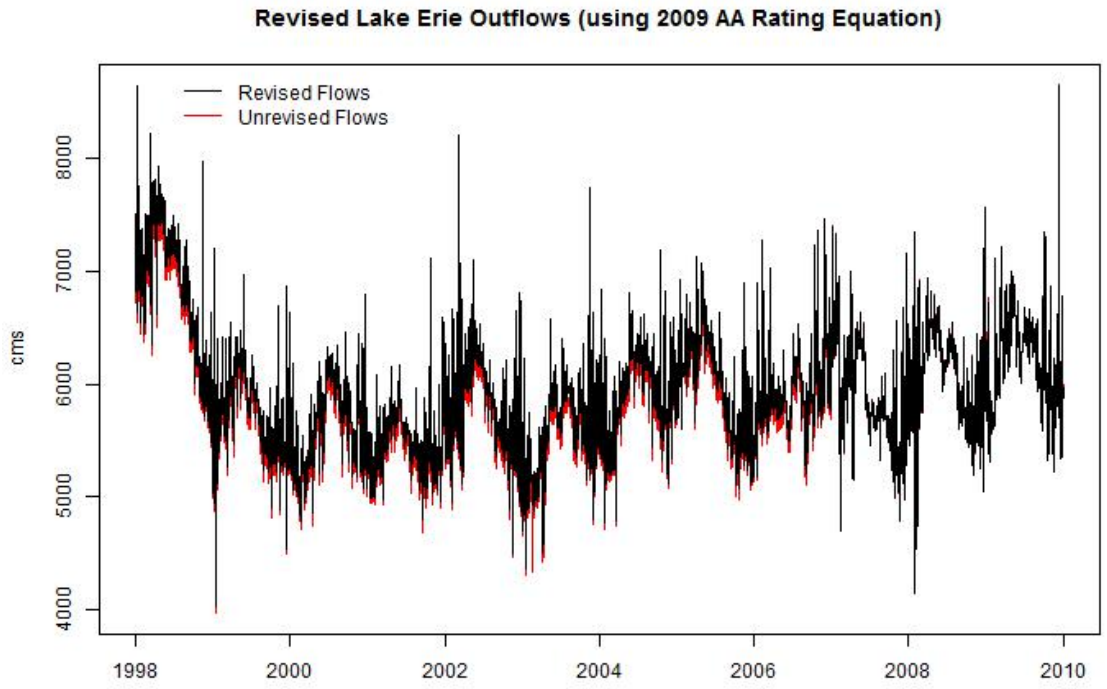

Figure 5: Revised and unrevised Lake Erie outflows. Note that the revision using the 2009 Ashland Avenue rating equation was only required for data prior to 2007, because 2007-2009 data had already been revised after implementation of the 2009 rating equation.

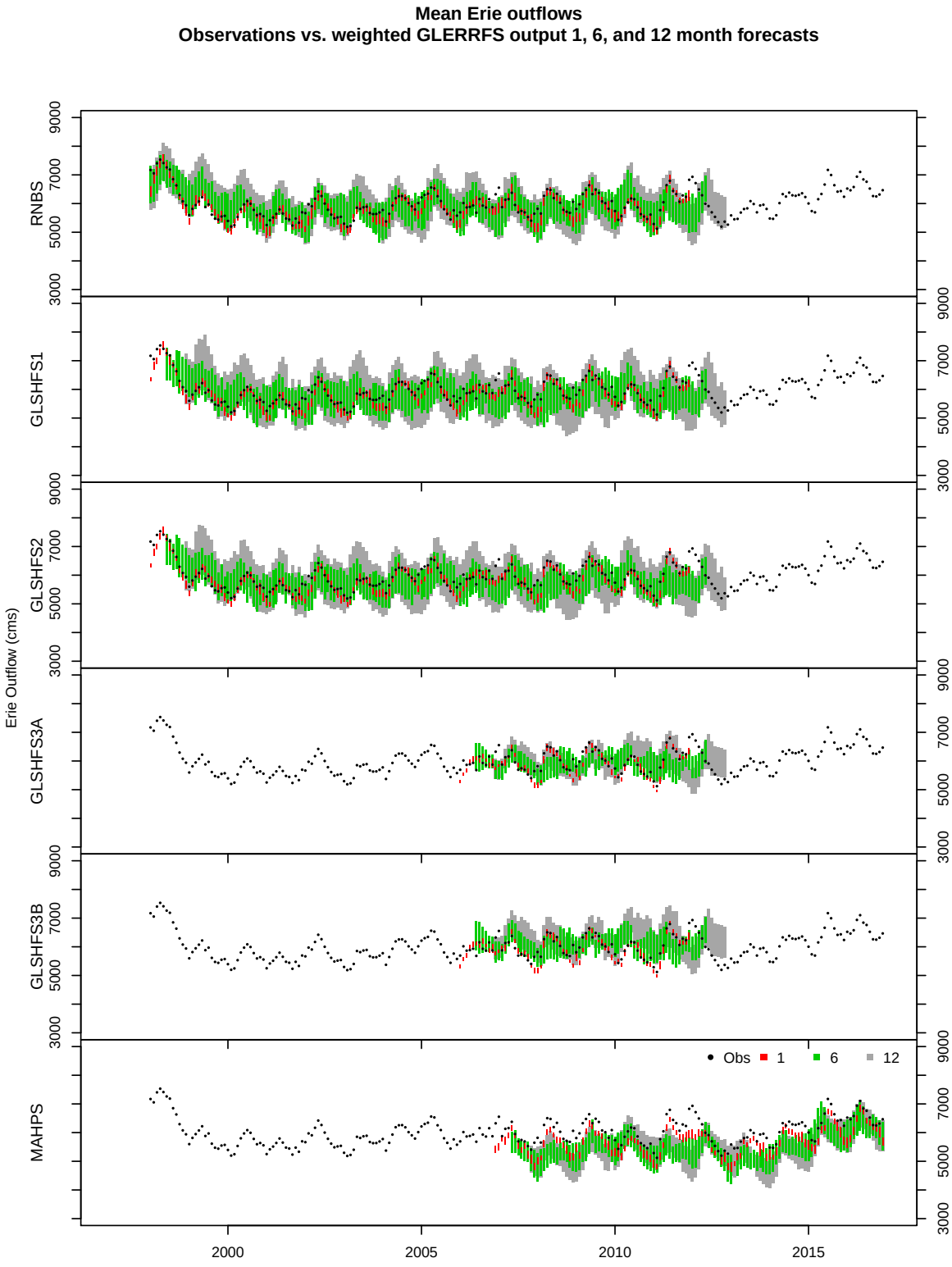

Figure 6: Comparison between observed (black dots) and forecasted (95% prediction intervals; vertical colored bars) mean monthly Lake Erie outflows (in cms) for 1, 6, and 12-month forecast horizons. The time period for GLFHyFS-3 forecasts is dictated by the forecast period of CMIP5 (which begins January 2006).

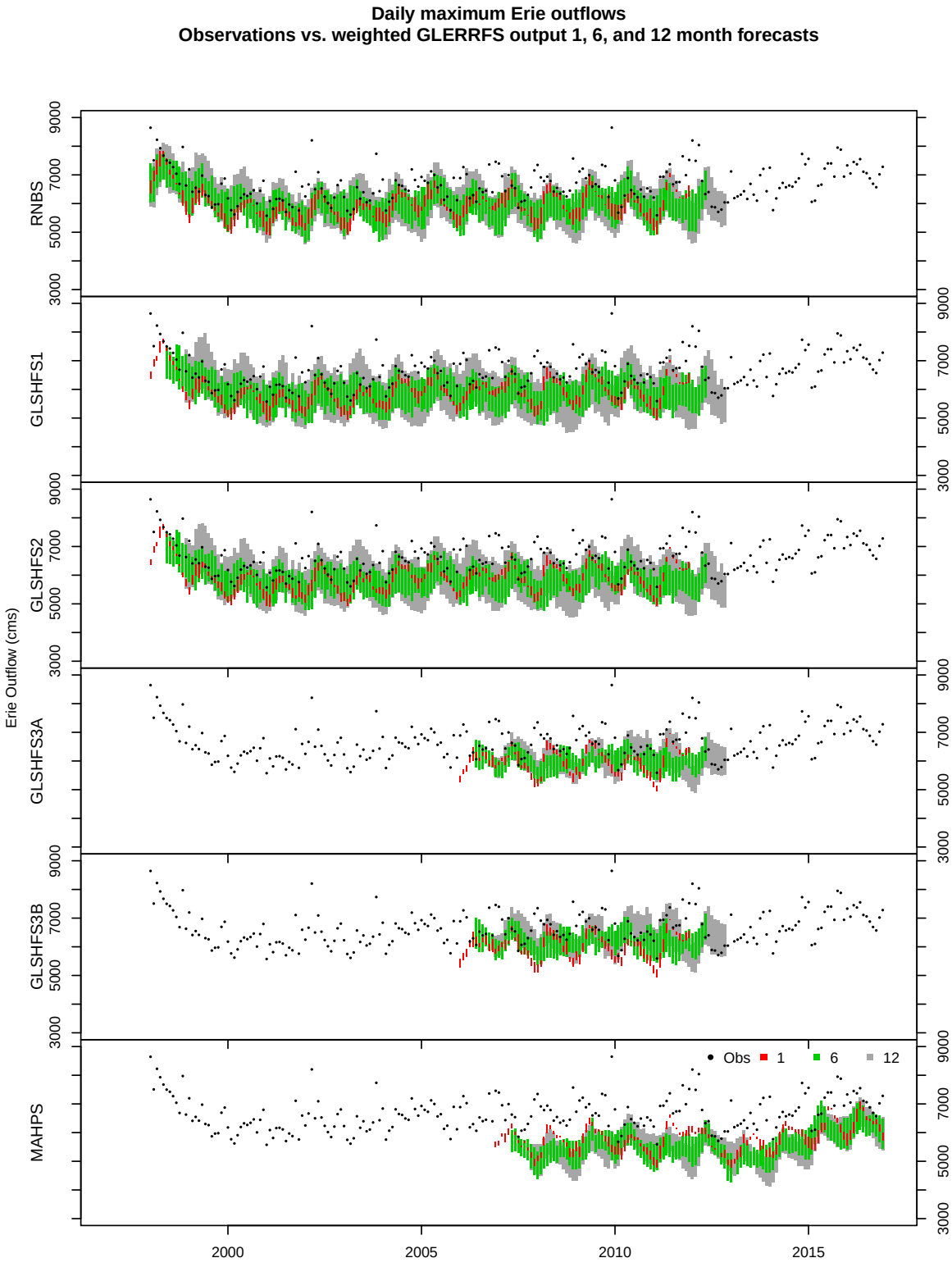

Figure 7: Comparison between observed (black dots) and forecasted (95% prediction intervals; vertical colored bars) maximum daily (within a given month) Lake Erie outflow (in cms) for 1, 6, and 12-month forecast horizons. Forecasts employ seasonal weighting. The time period for GLFHyFS-3 forecasts is dictated by the forecast period of CMIP5 (which begins January 2006).

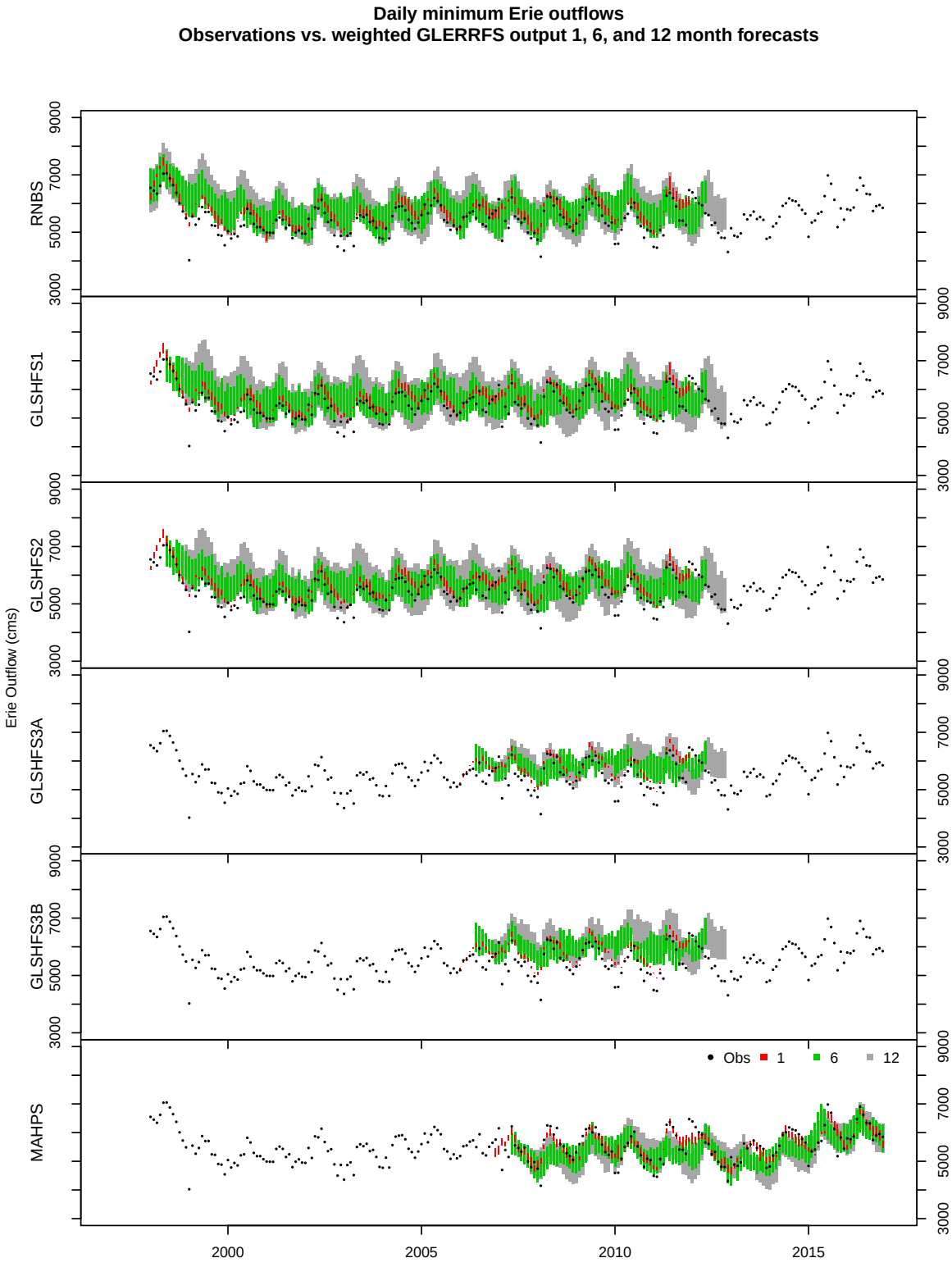

Figure 8: Comparison between observed (black dots) and forecasted (95% prediction intervals; vertical colored bars) minimum dailiy (within a given month) Lake Erie outflow (in cms) for 1, 6, and 12-month forecast horizons. Forecasts employ seasonal weighting. The time period for GLFHyFS-3 forecasts is dictated by the forecast period of CMIP5 (which begins January 2006).

Similarly, a visual inspection of results for longer forecasting periods (figures 9 through 11) indicates reasonable forecasting skill, albeit with rather wide uncertainty bounds. We also observe very little difference between average monthly, maximum daily, and minimum daily forecasts.

For a more quantitative assessment of skill, we calculate the predictive p-value (Elmore, 2005) for each forecasting system. This approach allows us to assess not only bias in each forecasting system, but also the extent to which the range of uncertainty in each forecasting system either exceeds (i.e. overdispersal) or is less than (i.e. underdispersal) the range of variability in observed flow. The predictive p-values for one-month forecasts of Lake Erie average monthly outflow, for example (figure 12), indicate significant underdispersion across all of our forecasting systems. In other words, it is quite common for observations to be entirely above or below the limits of the one-month 95% prediction intervals. Underdispersion is also evident in 6-month forecasts for all of the systems. The uncertainty bounds of 12-, 24, 36, and 60-month forecasts for the RNBS, GLSHyFS-1, and GLSHyFS-2 systems appear to reflect the variability of the observations; however, there does appear to be a significant bias in RNBS-based forecasts across these multi-year horizons. Finally, there appears to be significant bias in the 2 to 5-year forecasts from the new CMIP5-based GLSHyFS system, though it is informative to note that the CMIP5-based forecasts are based on an ensemble of only 19 members, whereas forecasts for other GLSHyFS systems include roughly 60 ensemble members. Additional plots of p-values from our forecasts are included in the Appendix.

3.2 Lake Ontario cumulative water supply (St. Lawrence River flow proxy) verification

We assessed the skill of Lake Ontario cumulative water supply forecasts (and, indirectly, St. Lawrence River flow forecasts) by comparing the cumulative monthly forecasted water supplies to corresponding observations between January 1998 and December 2016. Monthly Lake Ontario cumulative water supplies are estimated using coordinated residual net basin supplies (i.e. NBS_r) maintained by the CCGLBHHD.

3.2.1 St. Lawrence River flow computations

St. Lawrence River flow estimates were provided by USACE Buffalo District, which maintains records of daily flows as part of its role with the Lake Ontario and St. Lawrence River Board of Control. These daily flows are shown in Figure 13.

3.2.2 Comparison between observations and forecasts

Verification of Lake Ontario cumulative NBS forecasts indicates that, in general, the RNBS system has the most consistently unbiased forecasts across the entire range of forecasting horizons.

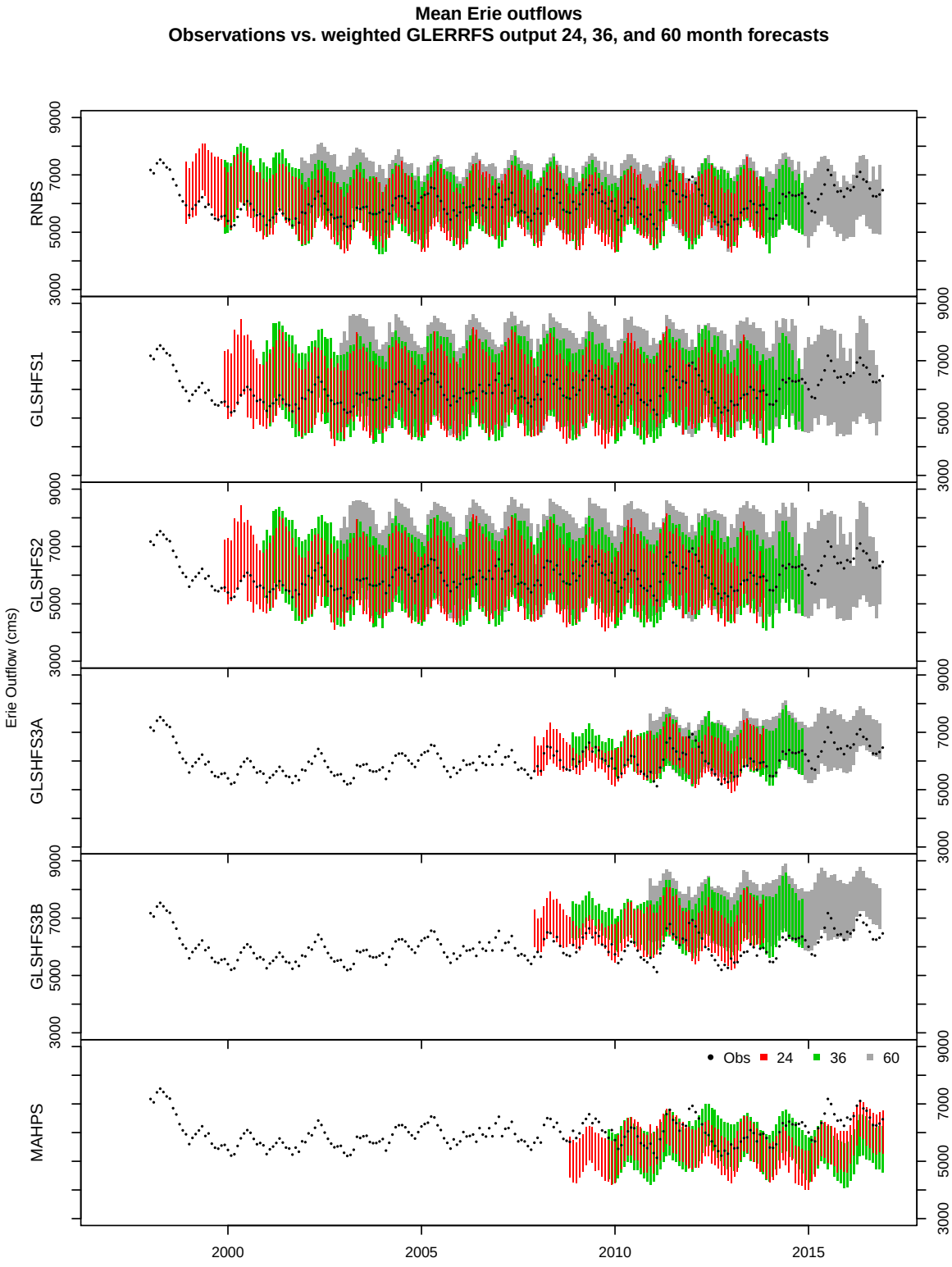

Figure 9: Comparison between observed (black dots) and forecasted (95% prediction intervals; vertical colored bars) mean monthly Lake Erie outflows (in cms) for 24, 36, and 60-month forecast horizons. Forecasts employ seasonal weighting. The time period for GLFHyFS-3 forecasts is dictated by the forecast period of CMIP5 (which begins January 2006).

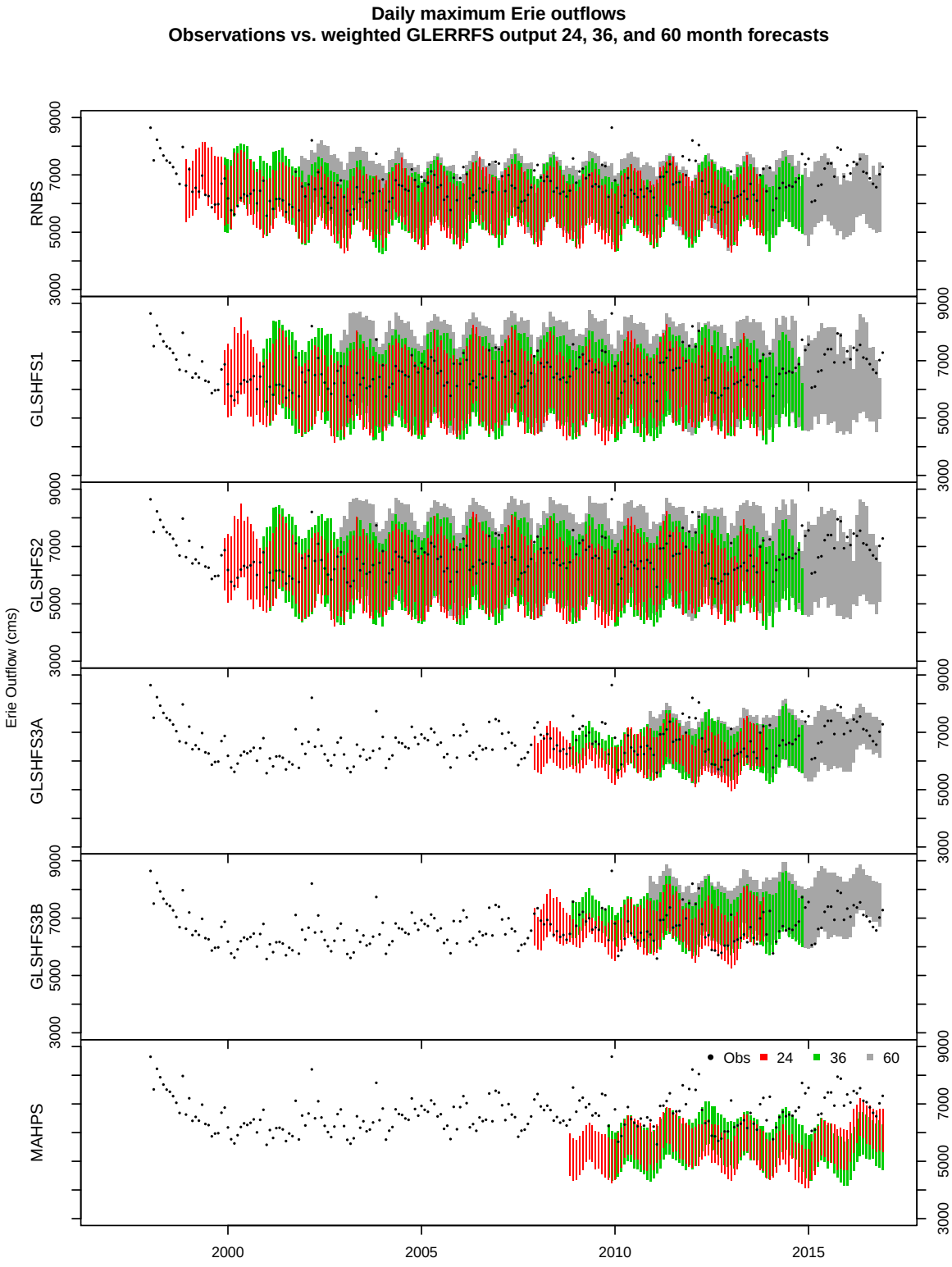

Figure 10: Comparison between observed (black dots) and forecasted (95% prediction intervals; vertical colored bars) maximum daily (within a given month) Lake Erie outflow (in cms) for 24, 36, and 60-month forecast horizons. Forecasts employ seasonal weighting. The time period for GLFHyFS-3 forecasts is dictated by the forecast period of CMIP5 (which begins January 2006).

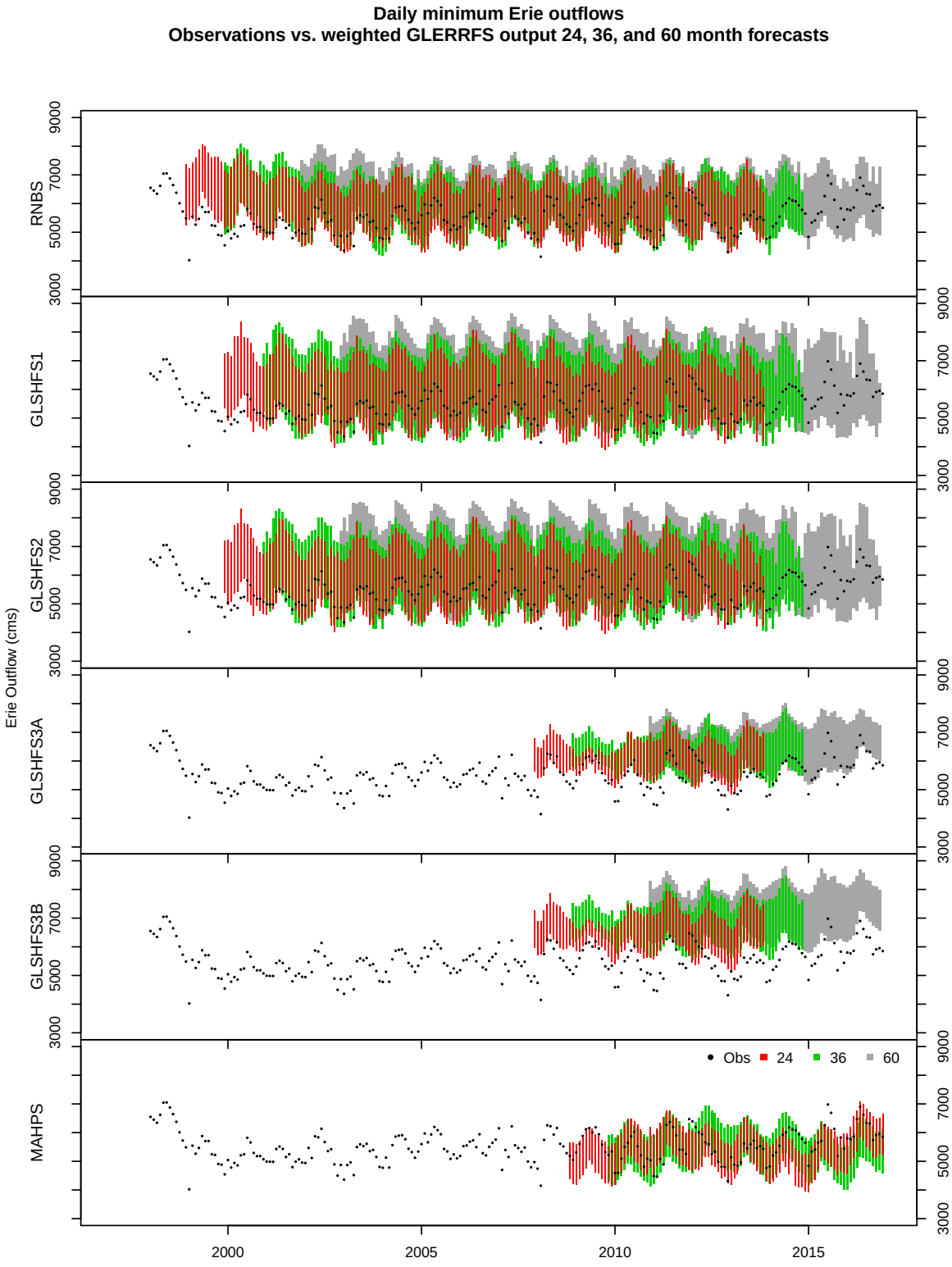

Figure 11: Comparison between observed (black dots) and forecasted (95% prediction intervals; vertical colored bars) minimum daily (within a given month) Lake Erie outflow (in cms) for 24, 36, and 60-month forecast horizons. Forecasts employ seasonal weighting. The time period for GLFHyFS-3 forecasts is dictated by the forecast period of CMIP5 (which begins January 2006).

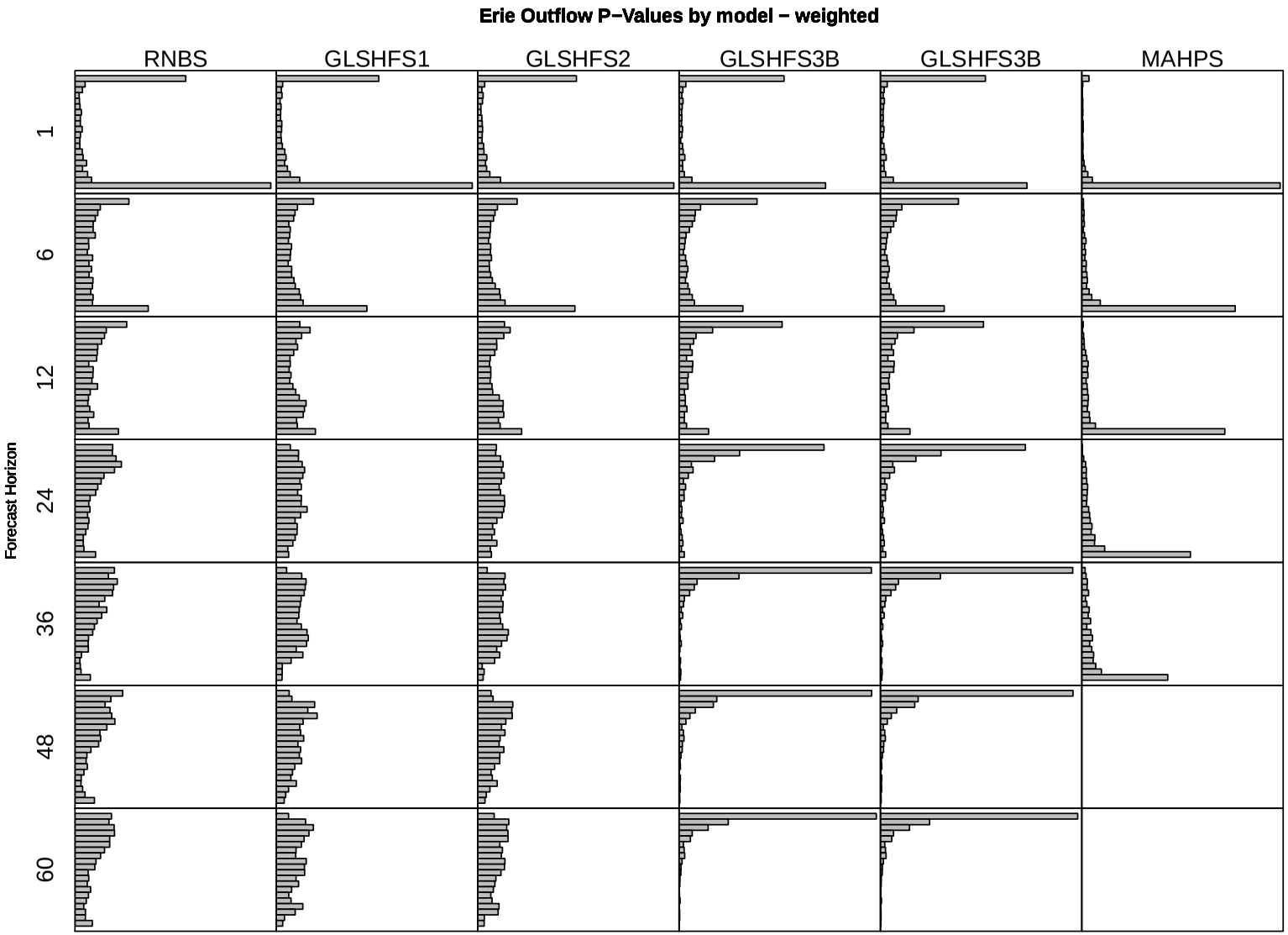

Figure 12: Histograms of posterior predictive p-values of daily Lake Erie outflow forecasts from each forecasting system (columns) across 1, 6, 12, 24, 36, and 60-month forecasting horizons.

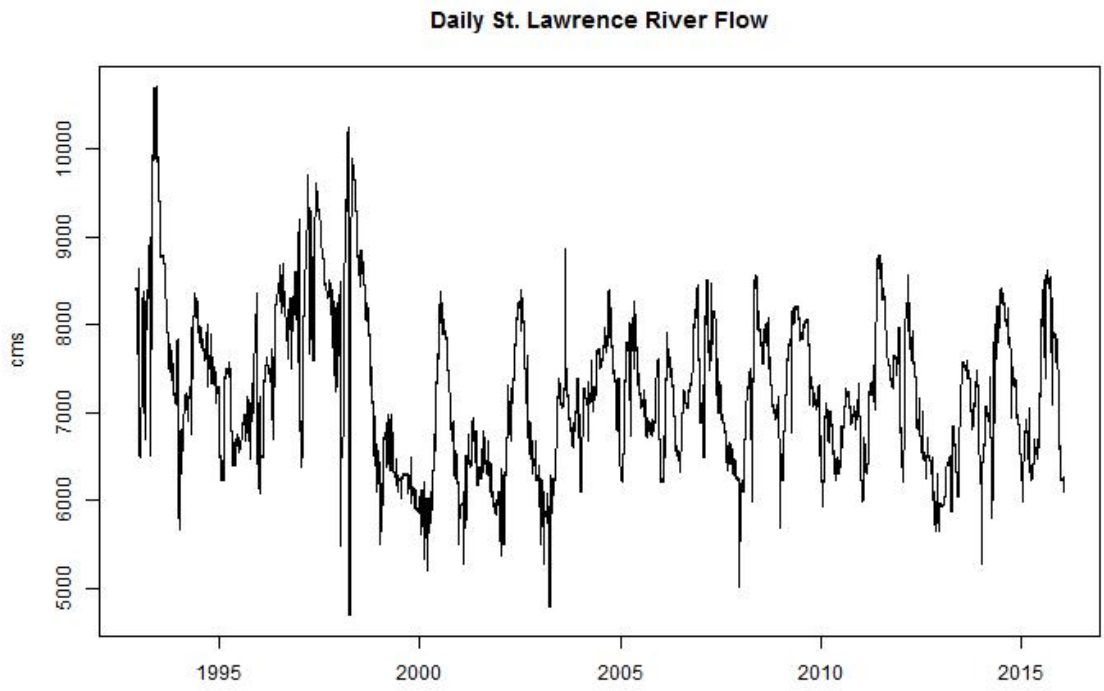

Figure 13: Daily St. Lawrence River flows provided by USACE-Buffalo.

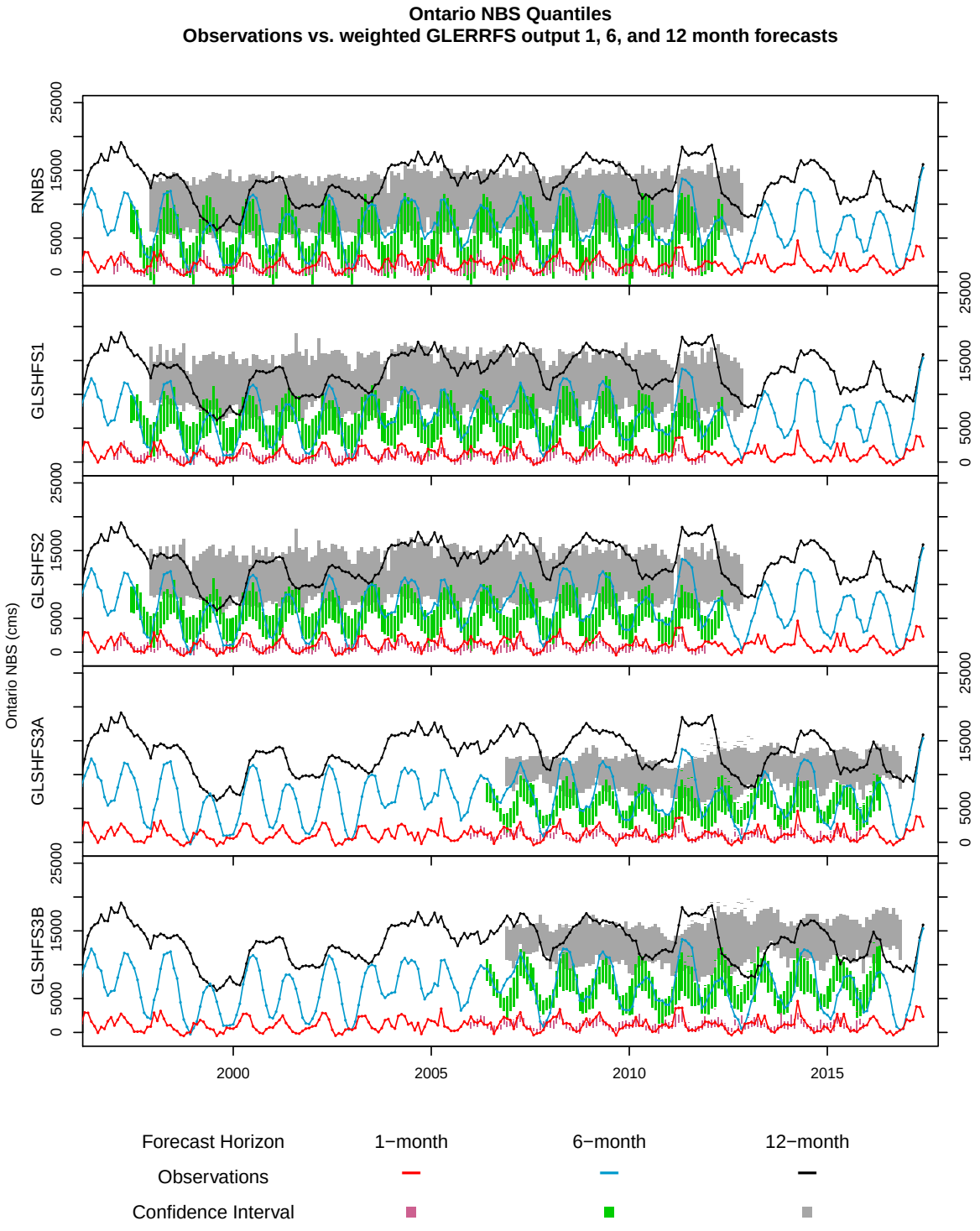

Figure 14: Comparison between observed (black dots) and forecasted (95% prediction intervals; vertical colored bars) mean cumulative monthly Lake Ontario NBS (in cms) for 1, 6, and 12-month forecast horizons. The time period for GLFHyFS-3 forecasts is dictated by the forecast period of CMIP5 (which begins January 2006).

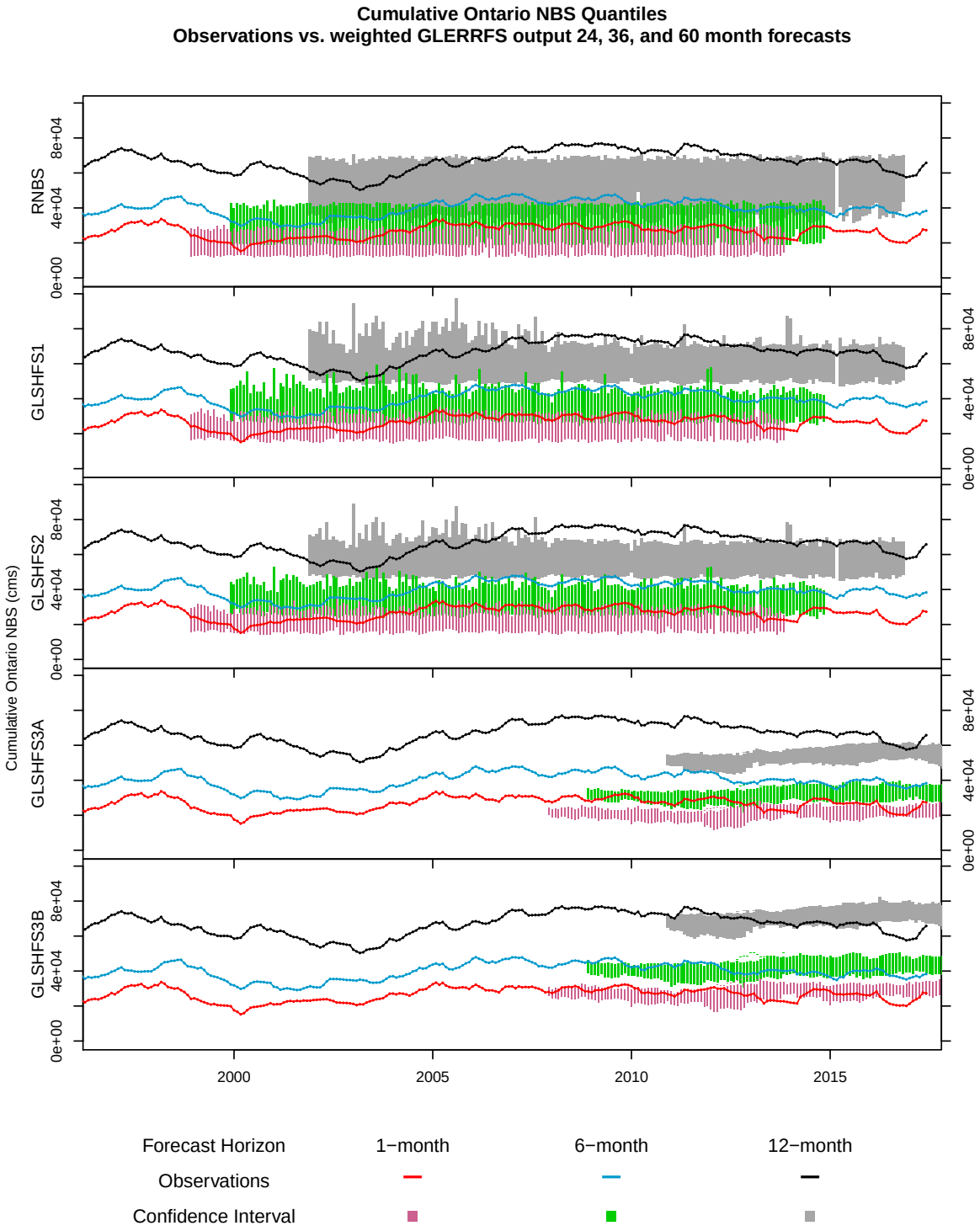

Figure 15: Comparison between observed (black dots) and forecasted (95% prediction intervals; vertical colored bars) mean monthly cumulative Lake Ontario NBS (in cms) for 24, 36, and 60-month forecast horizons. Forecasts employ seasonal weighting. The time period for GLFHyFS-3 forecasts is dictated by the forecast period of CMIP5 (which begins January 2006).

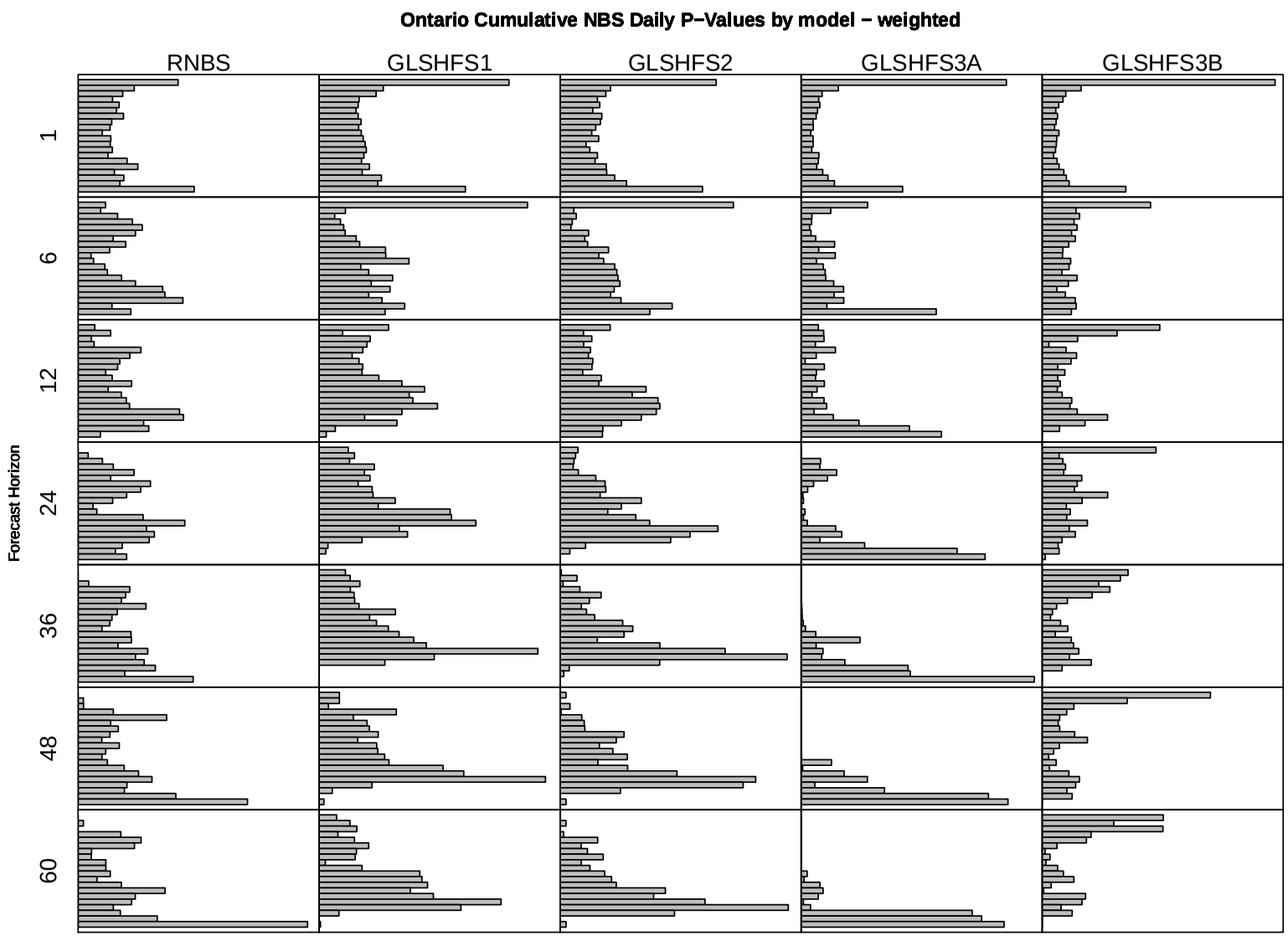

Figure 16: Histograms of posterior predictive p-values of cumulative Lake Ontario NBS forecasts from each forecasting system (columns) across 1, 6, 12, 24, 36, and 60-month forecasting horizons.

4 Additional considerations for operational deployment

The following is a summary of important considerations for operational deployment of the models developed for this project. These considerations are documented for reference only; details of implementation (if any) are expected to be coordinated directly between USACE - Detroit, NYPA, OPG, and NRCC.

- Ongoing flow verification - USACE-Detroit is working to establish operational protocols for routine forecast verification. In addition to visual comparison of ensemble output relative to observed Niagara and St. Lawrence flows, USACE-Detroit is investigating methods for evaluating ensemble forecasts in both the hydrological forecasting community and the meteorological forecasting community (for examples, see Franz and Hogue, 2011). Over the next several months to year, this protocol and necessary operational code will be developed. Routine verification outputs will be made available to NYPA/OPG/NRCC, and will add to the knowledge base built during the initial hindcast assessment.

- Schedule of operation - Forecasts are updated at USACE-Detroit each Thursday, consistent with the Lake Ontario regulation cycle. Lake Ontario regulation decisions are made by ECCC and USACE-Buffalo each Thursday, with changes applied the following day. Accordingly, forecasts produced on Thursdays have a Friday start date. Seasonal climate projections are updated by CPC and NMME on the third Thursday of each month. After these are made available, a new weighting scheme is developed for application in the outlook package (when weighting is applied). Forecast data are currently made available to OPG, NYPA, and the USACE-GLERL research team through an unadvertised website. The forecast data are not currently advertised to the public due to the complexity of interpreting multiple probabilistic forecasts and the need for additional skill assessment. However, they are available to USACE-Detroit forecasters for guidance when preparing seasonal forecasts.

- Forecast delivery All forecast output data are made available online via an unadvertised website: `http://lre-wm.usace.army.mil/ForecastData/OPG_NYPA_5yrForecast/`. Currently, the website offers no forecast discussion, as it is meant solely to provide output data to NYPA and OPG. Following evaluation via the hindcast assessment and routine operational assessment, USACE-Detroit will likely begin to implement one or more configurations of this forecast into its operational forecasts for public consumption. At that point, further development of the website and added forecast discussion will likely be required.

- Model calibration - hydrologic models, particularly LBRM and LLTM, may need to be (re)calibrated as climate conditions change, or if existing parameter sets are determined to be inadequate.

- Model selection - it is understood that USACE - Detroit will run several models in parallel for a period of roughly 6 months to a year in order to establish baseline performance. It is expected that, through coordination with NYPA, OPG, and NOAA-GLERL, some models may be removed from the operational pathway if they are found to be redundant, or to provide very low skill. It is expected, for example, that the conventional GL-AHPS model may be removed from service if newly-developed models provide equal or improved forecasting skill. It is also expected that any plan to retire, add, or modify models would be based on a collaborative process involving USACE, NOAA, NYPA, and OPG. It is informative to note that NOAA-GLERL will continue providing station data updates for the legacy AHPS system until it is officially retired and formally replaced in an operational environment by GLSHyFS or RNBS (or both).

- Future model updates - it is recognized that several components of the modeling systems may be upgraded in the future. For example, there are significant advancements being made in Great Lakes regional hydrological and climatological modeling (aside from those in this project), including applications of the well-known Weather Research and Forecasting (WRF) model and the Regional Climate Model (RegCM), among others. Similarly, there is ongoing research aimed at improving (and quantifying uncertainty in) estimates of historical over-lake precipitation. These new estimates could be used as an alternative basis for the meteorological forcings of GL-AHPS and GLSHyFS. It will likely take several more years of testing and development, however, before these systems will be suitable for routine basin-scale hydrological operational forecasting across seasonal and multi-year horizons, and across the entire Great Lakes domain (for further reading on WRF and other RCM applications, see Holman et al., 2012; Wright et al., 2013; Gu et al., 2013). It is also informative to note that the international border between the United States and Canada effectively bisects the Great Lakes basin, four of the five lakes themselves, and each of the interconnecting channels. While there is a long history of research aimed at reconciling differences in hydrometeorological model and dataset development protocols on either side of the border (Gronewold and Fortin, 2012), the challenge of developing hydrological models across this domain (including the need to simulate physical processes across the vast surfaces of the lakes themselves) has profoundly impacted the historical and current trajectory of Great Lakes regional hydrological model development.

- User's guide - project leads have determined that a GLSHyFS user's guide should be developed for future generations of regional water supply forecasters. Developing this guide was not a formal element of this project; however it was initiated as part of it.

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A Meteorological forcings from CMIP5

Appendix: Applying Climate Change Projections in Near Future Seasonal to Interannual Great Lakes Regional Hydrological Forecasting

November 10, 2017

Abstract

This appendix provides an overview of procedures for applying Coupled Model Intercomparison Project Phase 5 (CMIP5) future projections to the Great Lakes Seasonal Hydrologic Forecasting System (GLSHyFS), a new seasonal to interannual hydrological forecasting system for the Laurentian Great Lakes. Future monthly meteorological fields from 19 CMIP5 model ensembles were bias corrected using the Quantile Delta Mapping method (QDM) across CONUS and the Great Lakes region for the period 2006 to 2095. Historical observations of land surface meteorological fields (e.g. precipitation, air temperature, radiation, wind speed, etc.) employed in QDM bias correction were derived from a comprehensive selection of observational proxies including the forcing data for North American Land Data Assimilation System Phase 2 (NLDAS2), the Canadian Precipitation Analysis (CaPA), and the Midwest-Great Lakes Meteorological Datasets (MGLMD) developed by University of Notre Dame. These future bias-corrected monthly meteorological fields were temporally disaggregated into daily values and propagated through GLSHyFS for the period coinciding with the forecasting needs of regional hydropower authorities (2006 through 2035). For year 2006 to 2015, the hydrologic simulations forced by the bias-corrected CMIP5 products are validated by comparing to observed values of the major components of the Great Lakes hydrological cycle.

1 Introduction

Over the past several decades, the Great Lakes Advanced Hydrological Prediction System (GL-AHPS) has served as one of the only readily available computing resources for

simulating and forecasting the water balance of the Laurentian Great Lakes (including binational land and water surfaces) across seasonal and interannual time scales (Gronewold et al., 2011). The limited number of readily available seasonal and interannual forecasting systems in the Great Lakes region is most likely a consequence of the complications of accurately simulating energy and water fluxes over Earth's largest freshwater surfaces (Gronewold et al., 2013), the contrast between natural and jurisdictional boundaries of the basin, and spatial discontinuities in federal agency-based hydrometeorological monitoring infrastructure (Gronewold and Fortin, 2012; Gronewold et al., 2017, Submitted). Some studies have employed the land surface and lake physics models from GL-AHPS across multi-decadal future periods (Angel and Kunkel, 2010; Hayhoe et al., 2010). While the projections from these studies have been widely cited and distributed through multiple outlets (including the 2009 National Climate Assessment), they have also been criticized for explicit assumptions of climate stationarity (Milly et al., 2008), misrepresentation of seasonal over-lake precipitation related to unique regional atmospheric stability dynamics (Holman et al., 2012), and a tendency of the GL-AHPS conventional land surface model (the Large Basin Runoff Model, or LBRM, as described in Croley II, 1983; Croley II and He, 2005) to overestimate evapotranspirative water loss over the land portion of the basin under future warming scenarios (Lofgren et al., 2011). More specifically, the evapotranspiration algorithm encoded in the LBRM is believed to lead to significantly underestimated future lake inflows from lateral tributaries and connecting channels, as well as future lake surface water elevations (Appendix B; Lofgren et al., 2013; Lofgren and Gronewold, 2013; Lofgren and Rouhana, 2016).

Also within the past decade or so, a small suite of regional climate models has been applied to the Great Lakes region to simulate hydrologic response over multi-decadal historical and future periods (see, for example MacKay and Seglenieks, 2012; Notaro et al., 2015; Xiao et al., 2017, Under Revision). Projections from these studies, however, are intended to improve general understanding of regional impacts of climate change, and not necessarily for supporting specific water resources management questions (including those posed by the hydropower management community) or routine forecasting in an operational environment. Because GL-AHPS has been employed operationally by regional offices of the U.S. Army Corps of Engineers (USACE), the New York Power Authority (NYPA), and Ontario Power Generation (OPG), we focus here on developing a new approach to generating meteorological forcings for a significantly improved version of the GL-AHPS. In this appendix, we describe the evolution of meteorological forcings from the CMIP5 suite of models that serve as inputs to one of the configurations of GLSHyFS.

2 Methods

The newly developed GLSHyFS simulates historical and future Great Lakes water supplies by propagating 8 meteorological variables (i.e. forcings) at daily timestep through two conventional hydrologic modules (Fig. 1). Five of these variables (air temperature, dew point temperature, near-surface wind speed, and downward longwave and shortwave radiation) are averaged over the surfaces of each of the lakes and serve as inputs to the Large Lake Thermodynamics Model (LLTM, Croley II, 1992; Croley II and Assel, 1994) for simulating over-lake evaporation. Similarly, three of these variables (aggregated daily precipitation, and daily averaged minimum and maximum 2-m air temperature, Tmin and Tmax afterwards) over the surfaces of 121 custom Great Lakes watershed-scale catchments (Fig. 2) are forcings to the LBRM for simulating daily lateral runoffs into each of the lakes (Hunter et al., 2015). Precipitation aggregated over each lake surface is also used as a direct contribution to each lake's water supply.

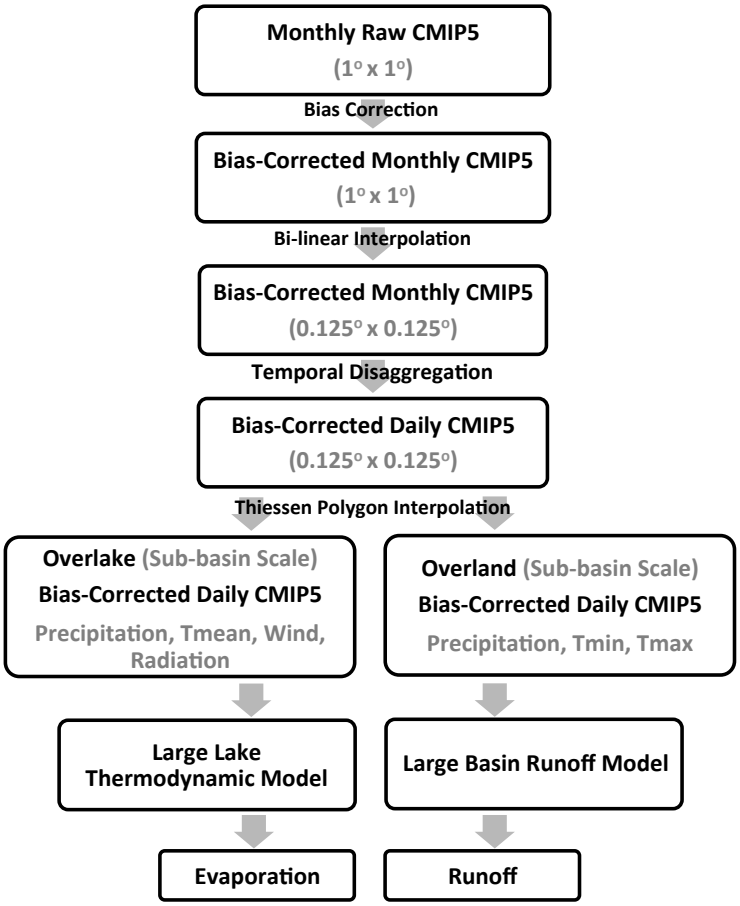

Figure 1: Schematic representations of steps for bias corrections, spatial and temporal disaggregation of CMIP5 meteorological forcings for use in GLSHyFS.

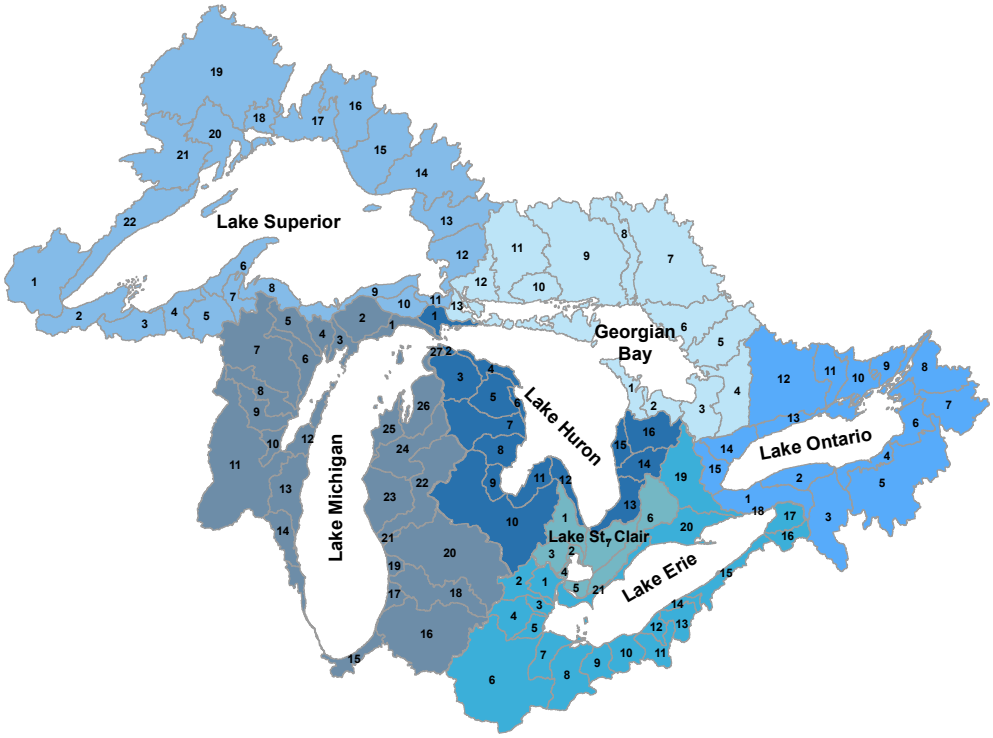

Figure 2: 121 Great Lakes watershed-scale catchments

2.1 Selection of meteorological forcings

To accommodate requests from hydropower authorities that new forecasting systems acknowledge potential changes in the climate of the Great Lakes and also to advance regional hydrological forecasting beyond conventional methods that implicitly presume a stationary climate system (Milly et al., 2008), we derive meteorological forcings from Phase 5 of the Coupled Model Intercomparison Project (CMIP5, Taylor et al., 2012). The CMIP5 framework synthesizes model results from over 20 coordinated climate change modeling groups from around the world (Fig. 3). Of these, 17 are identified by the Intergovernmental Panel on Climate Change (IPCC) as 'core' models based on model evaluation results (Sheffield et al., 2013). We utilized 16 of these core models along with 3 core model expansions (providing more variety in spatial resolution), resulting in an ensemble of the following 19 models: bcc-csm1-1, CCSM4, CSIRO-Mk3-6-0, GFDL-ESM2G, GISS-E2-R, HadGEM2-ES, IPSL-CM5A-LR, MIROC5, MPI-ESM-MR, NorESM1-M, CanESM2, CNRM-CM5, GFDL-CM3, GFDL-ESM2M, HadGEM2-CC, inmcm4, IPSL-CM5A-MR, MIROC-ESM, and MRI-CGCM3. Each CMIP5 model includes up to four different radiative forcing scenarios, each reflecting a particular rate of future human socioeconomic development and greenhouse gas emissions. These forcings

are identified in CMIP5 as representative concentration pathways (or RCPs, Taylor et al., 2012). As these radiative forcings in the CMIP5 modeling framework are expected to take effect in the decadal scale, we are not expecting a big difference between different scenarios in the near future (5 to 10 years). A preliminary comparison between projected changes in the monthly accumulated precipitation and average 2-m air temperature across all 19 members of our CMIP5 ensemble under the RCP 4.5 and RCP 8.5 scenarios (Fig. 4) indicates that there is little difference between the two for the next decade (2018-2027) comparing to the past decade (2008-2017). For precipitation, a subtle difference of less than 1 mm/month is found, and for temperature, it is smaller than 0.1 K. Therefore, for this study, our projections will be based entirely on the RCP 4.5 scenario. This RCP scenario presupposes a medium rate of socioeconomic development in which radiative forcings will ultimately stabilize at (but not exceed) 4.5 W/m^2 by the year 2100. Seven of the 8 forcing variables needed by GLSHyFS are the CMIP5 direct output variables, while the dew point temperature is a derived variable from the CMIP5's direct output of surface air pressure, specific humidity, and air temperature.

TABLE 1. CMIP5 models evaluated and their attributes. Model types are atmosphere–ocean coupled (AO), ocean–atmosphere–chemistry coupled (ChemOA), Earth system model, and Earth system model chemistry coupled.

Model	Model expansion	Center	Type	Atmospheric horizontal resolution (lon × lat)	No. of model levels	Reference
ACCESS1.0	Australian Community Climate and Earth-System Simulator, version 1.0	Commonwealth Scientific and Industrial Research Organization/Bureau of Meteorology, Australia	AO	1.875 × 1.25	38	Bi et al. 2012
BCC-CSM1.1*	Beijing Climate Center, Climate System Model, version 1.1	Beijing Climate Center, China Meteorological Administration, China	ESM	2.8 × 2.8	26	Xin et al. 2012
CanCM4	Fourth Generation Canadian Coupled Global Climate Model	Canadian Centre for Climate Modeling and Analysis, Canada	AO	2.8 × 2.8	35	Merryfield et al. 2013
CanESM2*	Second Generation Canadian Earth System Model	Canadian Centre for Climate Modeling and Analysis, Canada	ESM	2.8 × 2.8	35	Arora et al. 2011
CCSM4*	Community Climate System Model, version 4	National Center for Atmospheric Research, United States	AO	1.25 × 0.94	26	Gent et al. 2011
CESM1 (CAM5)–1-FV2	Community Earth System Model, version 1 (Community Atmosphere Model, version 5)	Community Earth System Model Contributors [National Science Foundation (NSF), DOE, and NCAR]	AO	1.4 × 1.4	26	Gent et al. 2011
CNRM-CM5.1*	Centre National de Recherches Météorologiques Coupled Global Climate Model, version 5.1	National Centre for Meteorological Research, France	AO	1.4 × 1.4	31	Voldoire et al. 2013
CSIRO Mk3.6.0*	Commonwealth Scientific and Industrial Research Organisation Mark, version 3.6.0	Commonwealth Scientific and Industrial Research Organization/Queensland Climate Change Centre of Excellence, Australia	AO	1.8 × 1.8	18	Rotstayn et al. 2010
EC-EARTH	EC-Earth Consortium	EC-Earth Consortium	AO	1.125 × 1.12	62	Hazeleger et al. 2010
FGOALS-s2	Flexible Global Ocean–Atmosphere–Land System Model gridpoint, second spectral version	State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics, Chinese Academy of Sciences	AO	2.8 × 1.6	26	Bao et al. 2012
GFDL CM3*	Geophysical Fluid Dynamics Laboratory Climate Model, version 3	NOAA/Geophysical Fluid Dynamics Laboratory, United States	AO	2.5 × 2.0	48	Donner et al. 2011
GFDL-ESM2G/M*	Geophysical Fluid Dynamics Laboratory Earth System Model with Generalized Ocean Layer Dynamics (GOLD) component (ESM2G) and with Modular Ocean Model 4 (MOM4) component (ESM2M)	NOAA/Geophysical Fluid Dynamics Laboratory, United States	ESM	2.5 × 2.0	48	Donner et al. 2011
GISS-E2H/E2-R*	Goddard Institute for Space Studies Model E, coupled with the HYCOM ocean model (E2H) and with the Russell ocean model (E2-R)	National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies, United States	ChemAO	2.5 × 2.0	40	Kim et al. 2012

TABLE 1. (*Continued*)

Model	Model expansion	Center	Type	Atmospheric horizontal resolution (lon × lat)	No. of model levels	Reference
HadCM3*	Hadley Centre Coupled Model, version 3	Met Office Hadley Centre, United Kingdom	AO	3.75 × 2.5	19	Collins et al. 2001
HADGEM2-CC	Hadley Centre Global Environment Model, version 2–Carbon Cycle	Met Office Hadley Centre, United Kingdom	ESM	1.875 × 1.25	60	Jones et al. 2011
HadGEM2-ES*	Hadley Centre Global Environment Model, version 2–Earth System	Met Office Hadley Centre, United Kingdom	ChemESM	1.875 × 1.25	60	Jones et al. 2011
INM-CM4.0*	Institute of Numerical Mathematics Coupled Model, version 4.0	Institute for Numerical Mathematics, Russia	AO	2 × 1.5	21	Volodin et al. 2010
IPSL-CM5A-LR*	L'Institut Pierre-Simon Laplace Coupled Model, version 5, coupled with NEMO, low resolution	L'Institut Pierre-Simon Laplace, France	ChemESM	3.75 × 1.8	39	Dufresne et al. 2013
IPSL-CM5A-MR	L'Institut Pierre-Simon Laplace Coupled Model, version 5, coupled with NEMO, mid resolution	L'Institut Pierre-Simon Laplace, France	ChemESM	2.5 × 1.25	39	Dufresne et al. 2013
MIROC4h	Model for Interdisciplinary Research on Climate, version 4 (high resolution)	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology, Japan	AO	0.56 × 0.56	56	Sakamoto et al. 2012
MIROC5*	Model for Interdisciplinary Research on Climate, version 5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology, Japan	AO	1.4 × 1.4	40	Watanabe et al. 2010
MIROC-ESM*	Model for Interdisciplinary Research on Climate, Earth System Model	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	ESM	2.8 × 2.8	80	Watanabe et al. 2010
MIROC-ESM-CHEM	Model for Interdisciplinary Research on Climate, Earth System Model, Chemistry Coupled	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	ChemESM	2.8 × 2.8	80	Watanabe et al. 2010
MPI-ESM-LR*	Max Planck Institute Earth System Model, low resolution	Max Planck Institute for Meteorology, Germany	ESM	1.9 × 1.9	47	Zanchettin et al. 2012
MRI-CGCM3*	Meteorological Research Institute Coupled Atmosphere–Ocean General Circulation Model, version 3	Meteorological Research Institute, Japan	AO	1.1 × 1.1	48	Yukimoto et al. 2012
NorESM1-M*	Norwegian Earth System Model, version 1 (intermediate resolution)	Norwegian Climate Center, Norway	ESM	2.5 × 1.9	26	Zhang et al. 2012

* Core set of 17 models.

Figure 3: Some of the CMIP5 models from Sheffield et al. (2013). Core models are identified with *.

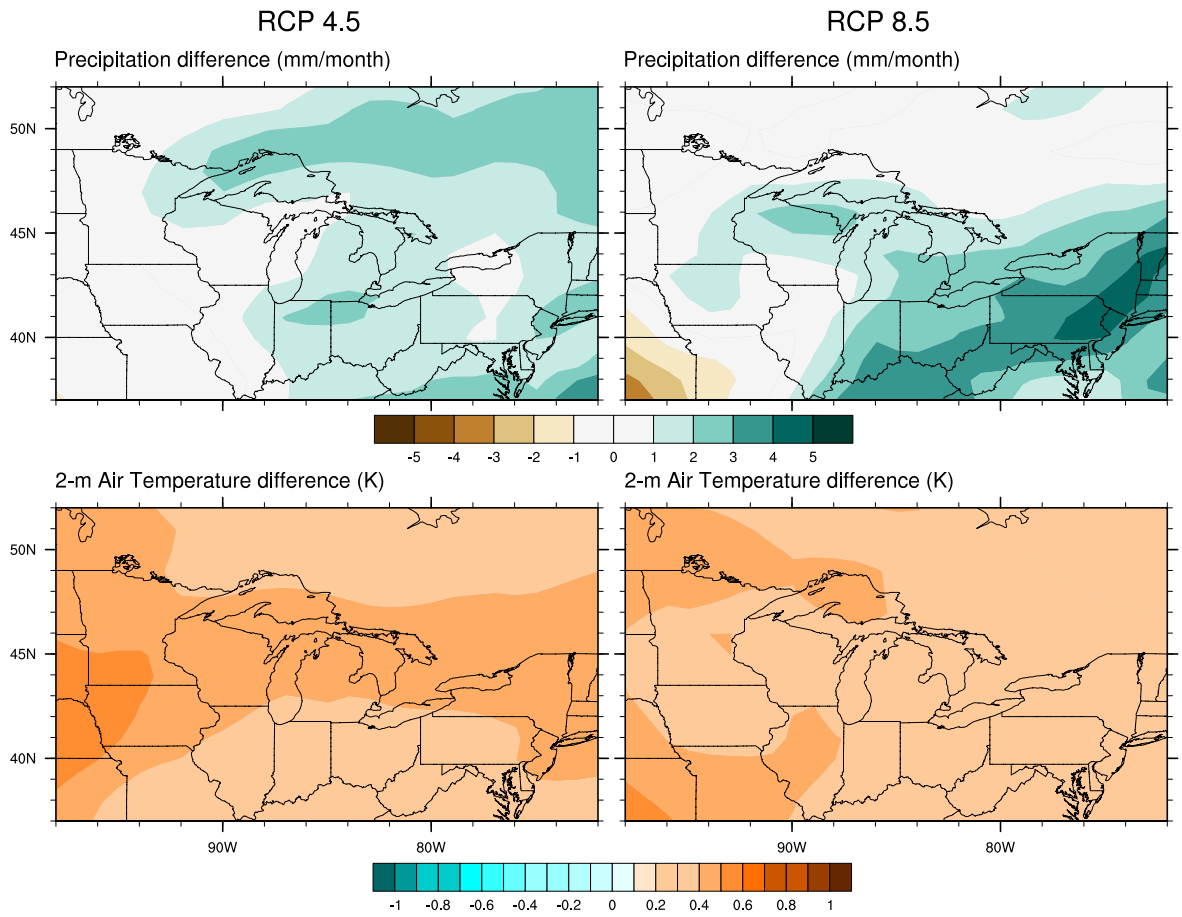

Figure 4: Projected changes in monthly accumulated precipitation (top panels) and averaged 2-m air temperature (bottom panels) from the most recent decade (2008-2017) to the next (2018-2027) based on the mean of the 19 CMIP5 models in scenario RCP 4.5 (left panels) and RCP 8.5 (right panels).

2.2 Bias correction and Spatial Disaggregation (BCSD)

2.2.1 Quantile Delta Mapping

Previous research indicates that raw (model direct outputs without bias correction) CMIP5 projections can be significantly biased (Cannon et al., 2015). Consequently, bias correction is a common step in any model-based future climate change impact studies. For this project, we employed the Quantile Delta Mapping (QDM, Cannon et al., 2015) method to bias-correct internal errors in CMIP5 future projections (Fig. 5). This bias correction method contains two major steps: first, bias correct model's future simulations based on historical observations using direct Quantile Mapping method (Fig. 5, stationary performance of CMIP5 models in its historical and future simulations are assumed); second, impose the 'Delta' change in each quantile of a certain variable to the corresponding bias-corrected

future distributions from the first step (more details and equations available in Cannon et al., 2015). For each variable, the word 'Delta' reflects the climate change signal acquired from the difference between the model historical (1979-2005) and future (each of the respective 30-year period from 2006: 2006-2035, 2036-2065, 2066-2095) cumulative distribution functions (CDFs) in each quantile. For all the variables except air temperature, the 'Delta' is applied in a multiplicative way; for air temperature, an additive way is conducted to better conserve the temperature-moisture relationship.

Fig. 4 illustrates the schematic of the methodology. For example, for a certain grid cell, the point A represents the accumulated monthly precipitation of 25 mm in the CMIP5 model's raw future projection (green line), corresponding to a cumulative probability of 0.49 among all its samples. For the same cumulative probability, the historical observation (point B in the blue line) indicates a value of 16.67 mm while the CMIP5 raw historical simulation (point C in the red line) indicates a value of 20 mm. To bias-correct the point A's value in the future projection, first we adjust it to the historical observation of 16.67 mm at the same quantile to remove its systematic bias (also called Quantile Mapping), then for precipitation the 'Delta' change is calculated in a multiplicative way by dividing 25 mm in the model's raw future simulations by the 20 mm from the historical simulations at the same quantile. The resulted 'Delta' of 1.25 is imposed back to the 16.67 mm to preserve the signal of change and resulted in a bias-corrected value of 20.84 mm (point D). This procedure is conducted on all the 9 CMIP5 variables, and for each variable, bias correction is conducted on each quantile, resulting the QDM bias-corrected distribution illustrated by the dashed green line. By applying this method, the CMIP5 model's systematic error has been reduced throughout the full distribution, along with preserving climate change signals archived between the CMIP5 historical and future simulations in each quantile. The main advantage that the QDM method has compared to the conventional (commonly used) Quantile Mapping method is that it helps preserve the climate change signals in the future projections with the least corruption, especially for the projected extreme values.

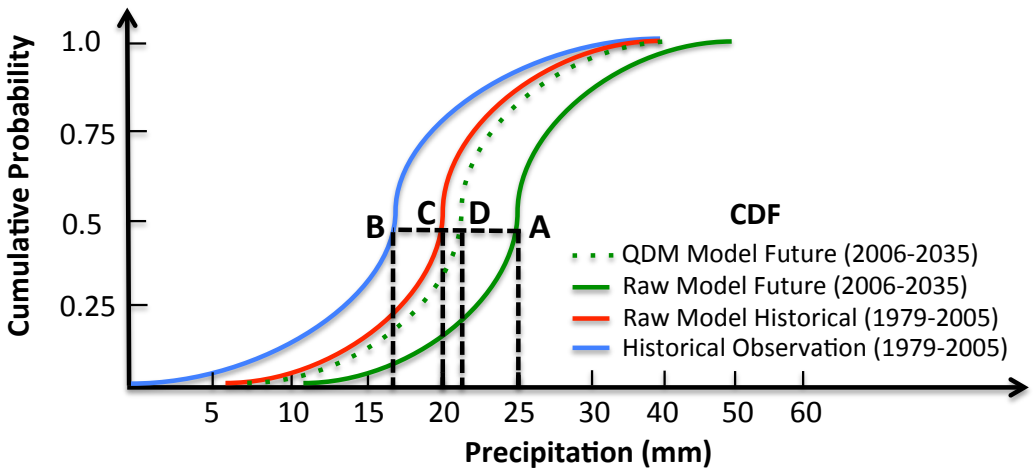

Figure 5: Conceptual schematic of the Quantile Delta Mapping (QDM) method.

Given the relatively poor skill in predicting the daily meteorological variability (especially for precipitation) in the coarse-resolution global climate models (such as CMIP5), in this project we used the CMIP5 monthly outputs for the bias-correction process to reduce uncertainties and extra errors in the daily time scale. During the QDM bias-correction process for precipitation, we tested two different ways in constructing the CDFs at each 1-degree resolution grid to ensure the best bias-correction result for precipitation. One uses annual-scale data pool, which means all the monthly accumulated precipitation (from 1979 to 2005 for both historical observations and CMIP5 simulations, and from 2006 to 2035 as one of the example for the future projections) are mixed together to form three sets of CDFs with total 324 sample months in the historical distributions and 360 sample months in the projected distribution. The quantile values are then determined based on all these three annual-scale CDFs for the QDM. The other way employs monthly-scale data pool, using only data from the same month to build up the CDFs. In this way, only 27 representative months are available for the historical (1979-2005) CDFs and 30 sample months available for the future projection at each month for each grid during the QDM process. Although the monthly-scale approach uses relatively small samples, it does help improve the representations of the precipitation's seasonal variability by eliminating 'noises' from other months. As all other variables (except near-surface wind) are less dynamic in nature and evolve more continuously cross the seasonal and interannual scale compared to precipitation, the annual scale is thus applied. For the near-surface wind, both of the NLDAS2 historical data and the CMIP5 outputs in about 1 to 3-degree resolution are vertically interpolated from the upper level atmospheric winds (NLDAS2's near-surface wind speed is interpolated from the NARR reanalysis without quality control). It is thus

not resolving the complicated nonlinear turbulence processes in the lower atmospheric boundary layer and is not directly comparable to the observed surface winds. Given this limited skill in the model's wind representation, the annual-scale construction is also used in debiasing the wind speed to allow more samples.

Due to the fact that the QDM bias-correction method applies to each individual grid cell based on its historical and future distributions for a certain variable, more grid points would provide a larger sample data pool in favor of validation of the methodology. The bias correction is thus processed over all the CONUS grids as well as the Great Lakes basin in the 1-degree resolution, from 2006 to 2095 at the monthly time step in three respective time windows (2006-2035, 2036-2065, 2066-2095. Fig. 6). It is mainly out of research interest to extend the bias-correction to the end of this century. Since the observational proxies are also available from 2006 to 2015, the overlaying 2006-2015 ten-year period is used for validation of this bias-correction method (Fig. 6).

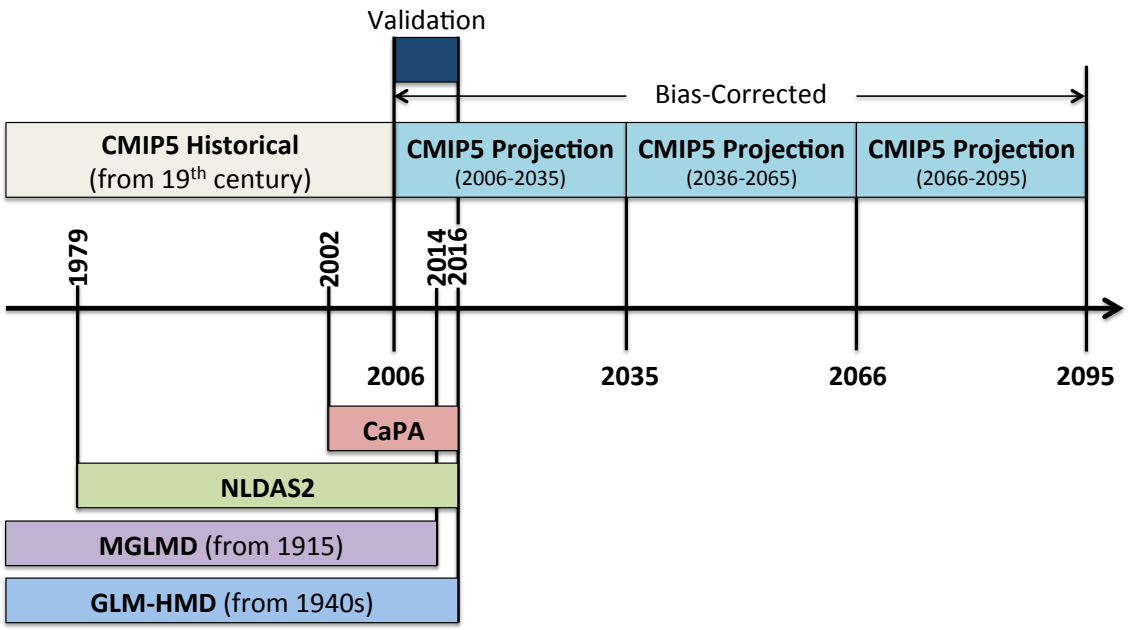

Figure 6: Illustration of the datasets used in bias-correction and validation

2.2.2 Selection of historical reference data

A common first step in climate model bias correction is the selection of a historical reference data set. For this project, we sought historical reference data that aligns with the historical simulation period for CMIP5 which, for most models, ranges from the mid 1800s through December 2005 (Fig. 6). The period of 'projections' for CMIP5 models is January 2006 through the end of the 21st century according to the CMIP5 project

design (some projections extend to the end of the 22nd and 23rd centuries, Fig. 6). To bias-correct all the 9 CMIP5 variables (precipitation, 2-m air temperature, Tmin, Tmax, surface air pressure, specific humidity, wind speed, longwave and shortwave radiation) for our project, a historical reference data set including all these variables with a length of at least 20 years is needed. This length is commonly assumed as a minimum period to be representative of the historical climatology for a certain meteorological variable. A longer historical reference period if available would also provide a larger sample pool to form a more representative CDF in the bias-correction process.

To meet this requirement, here we use the forcing datasets for the North American Land Data Assimilation System Phase 2 (NLDAS2, Cosgrove et al., 2003; Luo et al., 2003; Xia et al., 2012) as the main observational proxy giving its complete inclusion of all the variables needed. NLDAS2 is generally considered a valid and robust observation proxy across the entire CONUS (Xia et al., 2012), and remains the best available land surface meteorological datasets for the binational Great Lakes basin, which is available at a relative high resolution (0.125 degree at hourly intervals) for a relatively long period of record (1979-current). More specifically, 7 of the NLDAS2 variables needed for bias-correction (surface air pressure, specific humidity, daily mean temperature, Tmin, Tmax, wind speed and longwave radiation) are interpolated from the North American Regional Reanalysis (NARR, Mesinger et al., 2006), and the other two (precipitation and shortwave radiation) are considered as observational datasets rather than model outputs (Cosgrove et al., 2003). The hourly precipitation in NLDAS2 is first spatially interpolated from the NOAA Climate Prediction Center (CPC) daily rain gauge datasets, and then temporally disaggregated into hourly scale using Doppler Radar hourly observations.

However, recent research indicates that NLDAS2 precipitation has spatial and temporal discontinuities along the international border between U.S. and Canada, and is therefore not ideal for precipitation estimation across the Great Lakes basin. Recent research (**?**), along with our preliminary comparison between NLDAS2 and the Canadian Precipitation Analysis (or CaPA, as described in Lespinas et al., 2015) (Fig. 7) also indicated that NLDAS2 precipitation estimates can be severely biased over eastern portions of the Great Lakes basin in recent years (specifically, in 2012 and 2013, Fig. 7). This bias has also been confirmed by comparisons with Thiessen Polygon interpolated historical precipitation based on point-scale rain gauge observations (GLM-HMD, Hunter et al., 2015) over several of the sub-basins (Lake Huron, Lake Erie, Lake Ontario, Georgian Bay and Lake St. Clair, spurious spikes in NLDAS2 during 2012-2013, Fig. 8). CaPA precipitation estimates appear to not be as susceptible to these biases; however they also do not extend as far back (available from January 2002) in the historical record (Fig. 8). Therefore, one of our historical precipitation reference data (in 1979-2005) that serve as a basis

for debiasing the CMIP5 projections are based on NLDAS2 precipitation from 1979 to 2001 and, for the midwestern United States and Great Lakes region only, CaPA from January 2002 through December 2005. For all other variables, data from NLDAS2 alone is used for the bias-correction process. In the 10-year validation period of 2006-2015 (see more in Section 2.2.1) for precipitation, NLDAS2 data is employed from 2006-2015 to be consistent with a majority of the calibration data pool (1979-2001 NLDAS2 and 2002-2005 CaPA), with 2012-2013 replaced by CaPA to remove the aforementioned error. One set of combined precipitation dataset based on NLDAS2 and CaPA is thus built up to serve the purpose of both the bias-correction and validation of precipitation. In the following sections, we use NLDAS2-CaPA to refer to this precipitation dataset. In section 3, the seasonal variability time series are spatially averaged over the majority of the Great Lakes basin denoted in the red box in Fig. 7 (Latitude 40.938 to 48.938; Longitude: -90.938 to -78.938). This domain is deliberately selected to avoid majority of the significant biases in the NLDAS2 precipitation along the binational border for the analysis.

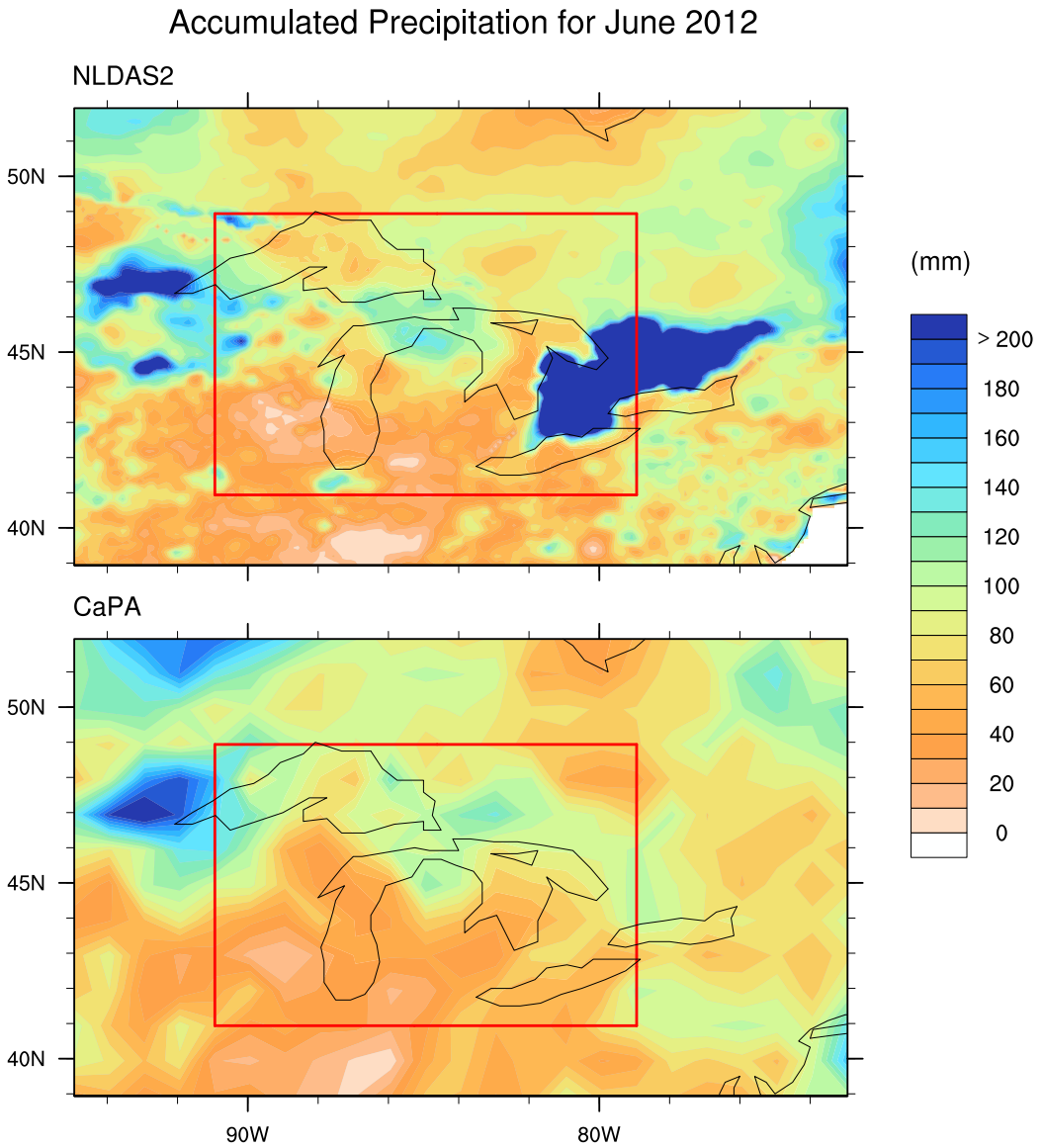

Figure 7: Comparison between June 2012 accumulated precipitation from NLDAS2 (top panel) and CaPA (bottom panel) indicating potentially severe biases in NLDAS2 precipitation across the eastern portion of the Great Lakes basin (about 400-600 mm/month between Lake Huron, Lake Erie, and Lake Ontario in the top panel). Red box denotes the spatial domain that the seasonal variability is averaged over in Fig. 10 to Fig. 19.

Due to the complexity and uncertainties in the historical precipitation observations (both in NLDAS2 and CaPA) cross the U.S.-Canada boundary over the Great Lakes, we investigated a second observation-based data set for over-land precipitation and temperature (available from January 1915 to December 2013) developed by the University of Notre Dame called the gridded Midwest-Great Lakes Meteorological Dataset (MGLMD, including daily precipitation, Tmin and Tmax in 0.0625 degree resolution, Chiu and

Hamlet, 2016, Submitted). The precipitation data from MGLMD reflects rain gauge undercatch corrections on the CPC daily precipitation with wind factors. A comparison of the MGLMD monthly accumulated over-land precipitation with that from NLDAS2, CaPA and the GLM-HMD over all the 7 Great Lakes sub-basins from 1979 to 2015 is shown in Fig. 8. Although good agreement in seasonal and interannual variability are revealed by all of the four precipitation datasets (except the NLDAS2 in 2012 and 2013 which has been replaced by CaPA in all applications), the MGLMD precipitation has generally higher estimates than all the other three datasets due to its rain gauge undercatch correction, while the NLDAS2 precipitation provides the lowest estimation throughout the entire Great Lakes basin (Fig. 8).

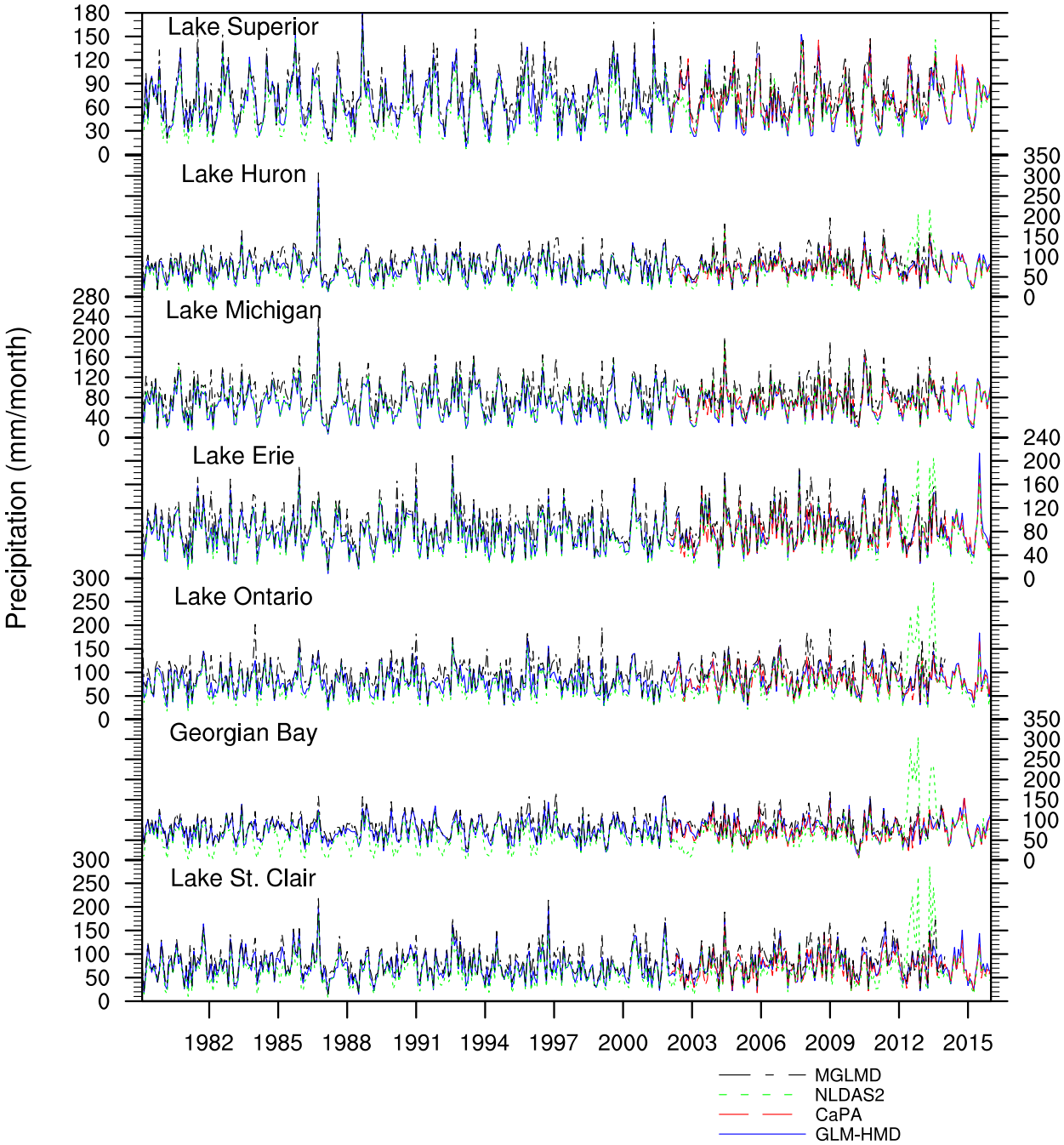

Figure 8: Over-land monthly accumulated precipitation for each of the seven Great Lakes basin from MGLMD, NLDAS2, CaPA (available from 2002), and Thiessen Polygon interpolated rain gauge observations (GLM-HMD, Hunter et al., 2015).

The spatial variations of the MGLMD and NLDAS2-CaPA monthly accumulated precipitation is also illustrated in Fig. 9, averaged both in the calibration (1979-2005) and validation (2006-2015 for NLDAS2-CaPA and 2006-2013 for MGLMD) period. In

general the MGLMD precipitation is ~ 10 mm/month higher than NLDAS2-CaPA across the entire Great Lakes basin throughout both periods, and there is no clear trend of change in this data for the past decade (2006-2013) relative to the historical period of 1979-2005 (Fig. 9c,d); while NLDAS2-CaPA dataset has a noticeably lower record in the same historical period over the northern part of the Great Lakes basin (Fig. 9a) and thus reveals a trend of increased precipitation ($20 \sim 25$ mm/month) over the past decade (Fig. 9b).

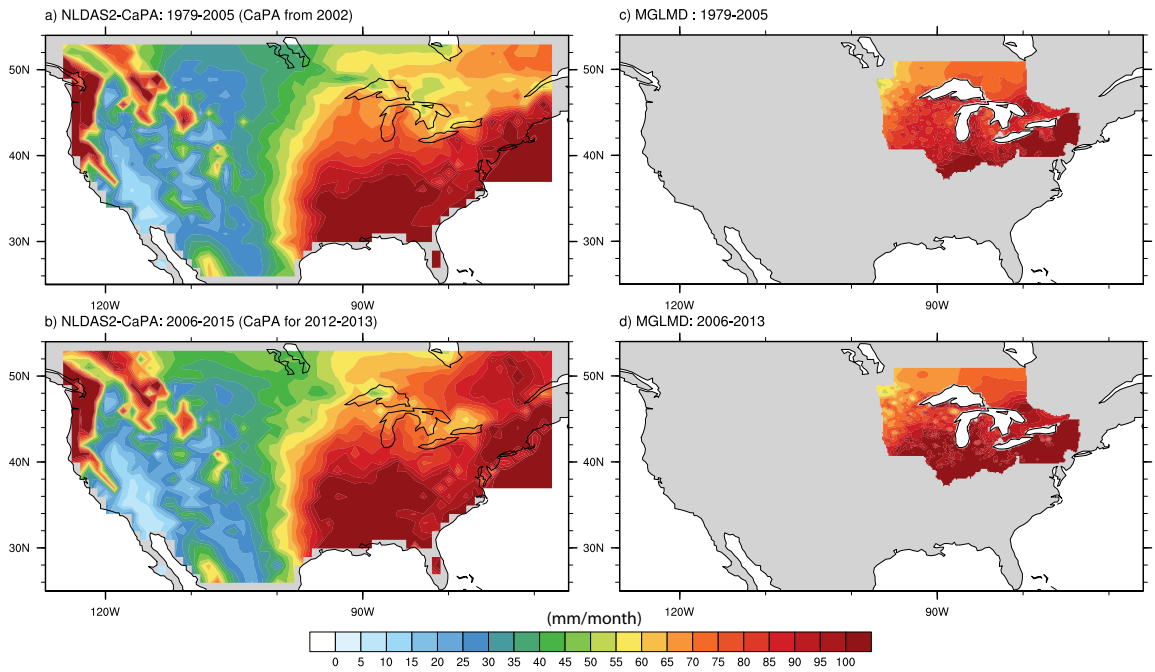

Figure 9: Monthly accumulated precipitation from NLDAS2-CaPA and MGLMD, averaged among 1979-2005 (calibration period) and 2006-2015/2013 (validation period) respectively.

Since the MGLMD dataset covers the land portion only in the Midwest and the Great Lakes region, it thus only supports the bias-correction of the over-land precipitation and Tmin, Tmax in all the sub-basins and propagated into LBRM only to provide a spectrum of possible runoff estimates supplementary to that from the bias-corrected CMIP5 forcings based on NLDAS2-CaPA. For LLTM, all the variables from CMIP5 are bias corrected with the NLDAS2-CaPA dataset. As the most important hydrological driver, precipitation is known to have significant impact on the corresponding hydrologic responses cross all short-term and long-term scale. In section 3 we further discuss how these different precipitation reference datasets affect the CMIP5 QDM bias-correction process, as well as how the future projected hydrological cycle is impacted by these differences (Section 3.2.1).

2.2.3 Spatial and temporal downscaling

As designed originally to simulate large-scale decadal evolutions of global climate, the native spatial (often $1 \sim 3$ degree, Fig. 3) resolutions of the CMIP5 model outputs are not compatible with regional basin-scale hydrological models. Also as introduced above, since the monthly CMIP5 outputs are de-biased to ensure the best quality of the projected intraseasonal to interannual climate variability in the interested domain, temporal downscaling is thus also needed because GLSHyFS requires daily forcings. In this section, we describe our approach to downscaling the CMIP5 data into space and time scales that are compatible with GLSHyFS.

The CMIP5 and the historical observational dataset (NLDAS2-CaPA in 0.125 degree and MGLMD in 0.0625 degree resolution) were first interpolated/aggregated into a common 1-degree resolution for the bias-correction using the bi-linear interpolation method (Fig. 1). Here 1-degree resolution is selected as the common resolution because further disaggregation of the CMIP5 from $1 \sim 3$ degree into finer than 1 degree may introduce more uncertainties and error. After QDM is completed for all the 19 CMIP5 models at the monthly timestep in this resolution, all the derived CMIP5 forcing variables are disaggregated back into the 0.125-degree resolution to be compatible with the GLSHyFS' sub-basin scale (Fig. 2). A bias-corrected future projections at monthly timestep from all the CMIP5 19 model ensembles across all the 9 forcing variables are thus derived in the 0.125-degree resolution.

To satisfy the requirement of daily timestep in GLSHyFS, all these variables over the Great Lakes region are disaggregated temporally from monthly values (monthly accumulation for precipitation, and monthly average for all other variables) into daily patterns using randomly selected daily variation patterns from the same historical calendar month in 1979-2005, along with constraining the monthly accumulated or averaged values of the derived daily variations with the target month's QDM value. For example, to downscale all the variables in the projected month of January 2020 into a daily variation proxy, a random historical January from 1979 to 2005 is selected, and the daily patterns of all the corresponding variables from this selected month will be used to build up the January 2020's daily sequence, with the monthly values of all variables in the derived daily dataset constrained by its target QDM value. This temporal disaggregation method was first applied by Wood et al. (2004) to generate daily meteorological forcings to drive the VIC (Variable Infiltration Capacity) model, and the simulated monthly averaged streamflow presented good agreement with observations in Northwest basins. Previous research also indicated that this random sampling technique for temporal downscaling exhibits comparable skill in simulating the monthly hydrologic response with that driven by the directly bias-corrected daily coarse model outputs (Maurer and Hidalgo, 2008).

With GLSHyFS' internal Thiessen Polygon interpolation module, these derived CMIP5 daily forcings in 0.125-degree resolution are consolidated into the sub-basin scale (Fig. 2) and propagated into LBRM and LLTM. LBRM uses daily precipitation, Tmin and Tmax to generate the sub-basin runoffs into the Great Lakes, and LLTM uses daily dew point temperature, mean air temperature, wind speed, longwave and shortwave radiations to calculate the daily evaporation over the lake surface. With these two simulated hydrological variables (runoff and evaporation) and the CMIP5 over-lake precipitation (bias corrected using NLDAS2-CaPA), the Net Basin Supply (NBS) for the entire Great Lakes is derived and propagated into the Coordinated Great Lakes Routing and Regulation Model (CGLRRM) at USACE, Detroit, to forecast the water level in the Niagara River.

3 Results

3.1 Validation of meteorological forcings

A comparison between the raw CMIP5 seasonal variations spatially averaged over the Great Lakes region (red box in Fig. 7) for the historical reference period (1979-2005) and corresponding values from NLDAS2 (Fig. 10, NLDAS2-CaPA for precipitation only) indicates that although several CMIP5 ensemble members have significant biases in either precipitation, surface air pressure, or wind speed (though there does not appear to be any particular model with a consistent bias across all three of these), the model ensemble means exhibit reasonable skill in capturing the historical seasonal variability over the Great Lakes region across all the variables, both in phase and magnitude. Interestingly, the CMIP5 ensemble mean is not particularly biased for surface air pressure and wind speed, but it does appear to have a consistent positive bias for precipitation from January through July relative to NLDAS2-CaPA. Given the significant direct impact of precipitation on the Great Lakes water balance, we consider correcting this bias a high priority. In the following sections, we illustrate how the QDM bias-correction method reduces the CMIP5 model's biases in the 2006-2015 validation period.

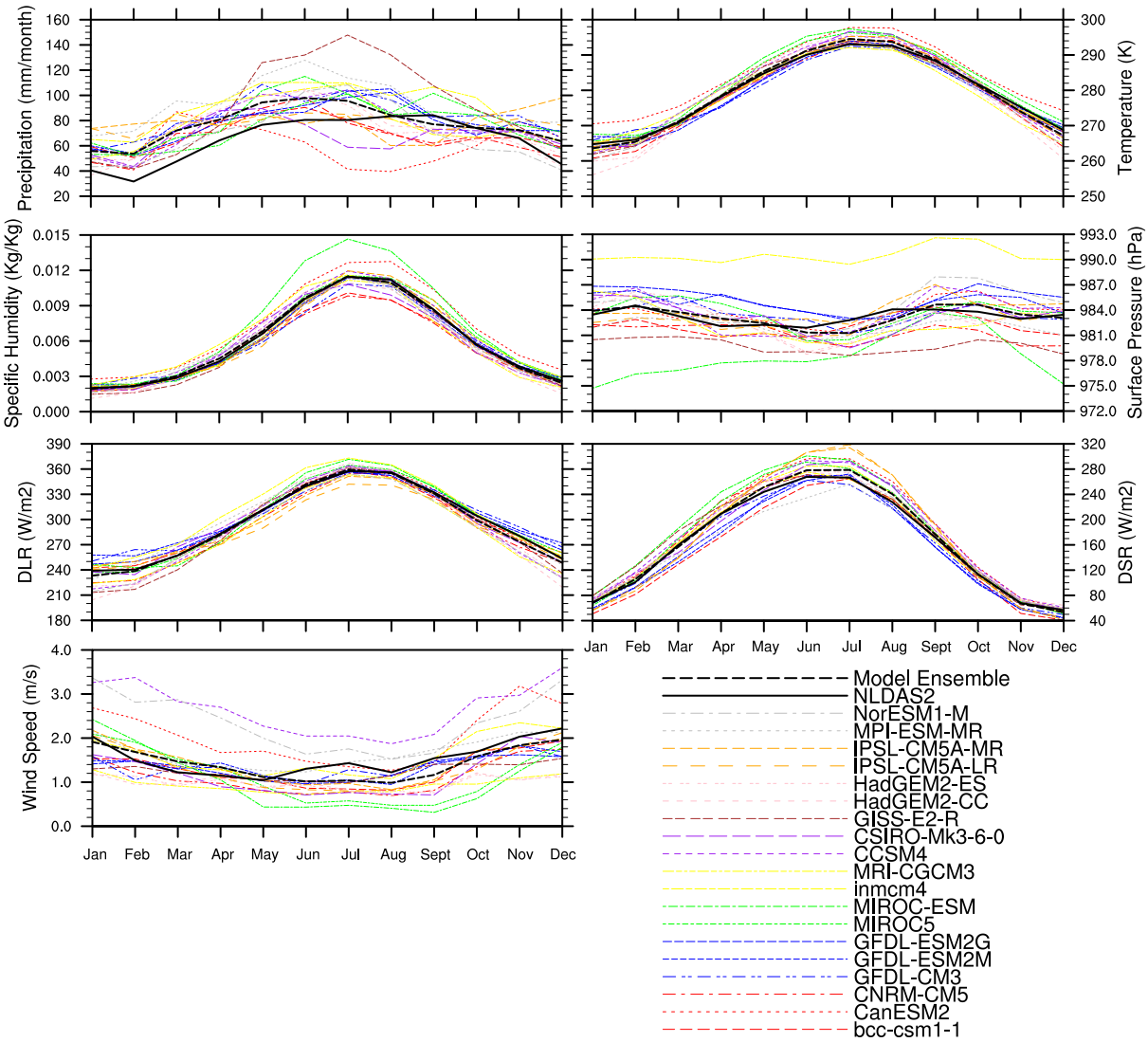

Figure 10: Comparison between historical (1979-2005) averaged monthly values for meteorological variables from NLDAS2 (black line), the full ensemble (19 members) of raw CMIP5 models (dashed colored lines), and the mean of the raw CMIP5 ensemble (dashed black line). Values are spatially averaged across the Great Lakes domain denoted by the red box in Fig. 7.

3.1.1 Validation of bias correction using NLDAS2 and CaPA

A detailed comparison between results from the monthly- and annual-scale precipitation bias correction procedures for each of the models in our CMIP5 ensemble for the model validation period (i.e. 2006 through 2015, Fig. 11) indicates not only which models have the most significant precipitation bias, but also relative benefits of improved seasonal variability by the monthly-scale approach (see, for example, results for the CanESM2

model; top row, third column in figure 11). These seasonal variations are the spatially averaged values over the Great Lakes basin denoted by the red box in Fig. 7. By introducing the monthly-scale approach, the seasonal variations in the precipitation during late summer and early fall has been greatly improved (Fig. 11). Bias-correction validation results for all other CMIP5 variables (figures 11 through 19) are based only on annual-scale corrections, and appear to provide reasonable values relative to the NLDAS2 dataset, especially by the model ensemble means (upper-left panel of each figure).

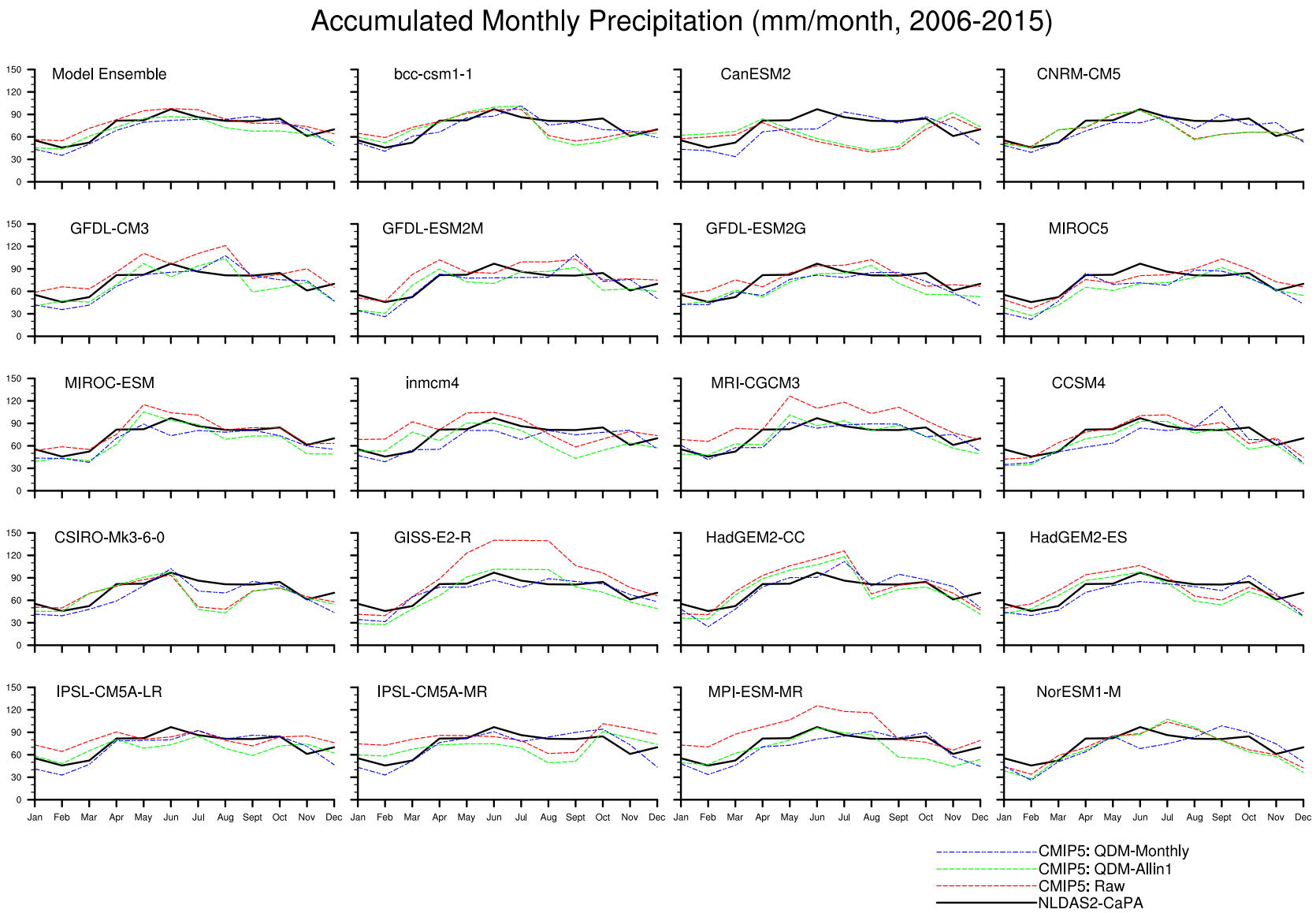

Figure 11: Comparison between raw output (red line), bias-corrected output using annual data (green line), and bias-corrected output using monthly data (blue line) of averaged monthly (from 2006 to 2015) accumulated precipitation across the Great Lakes domain from all CMIP5 models and (upper-left panel) the mean of the CMIP5 ensemble.

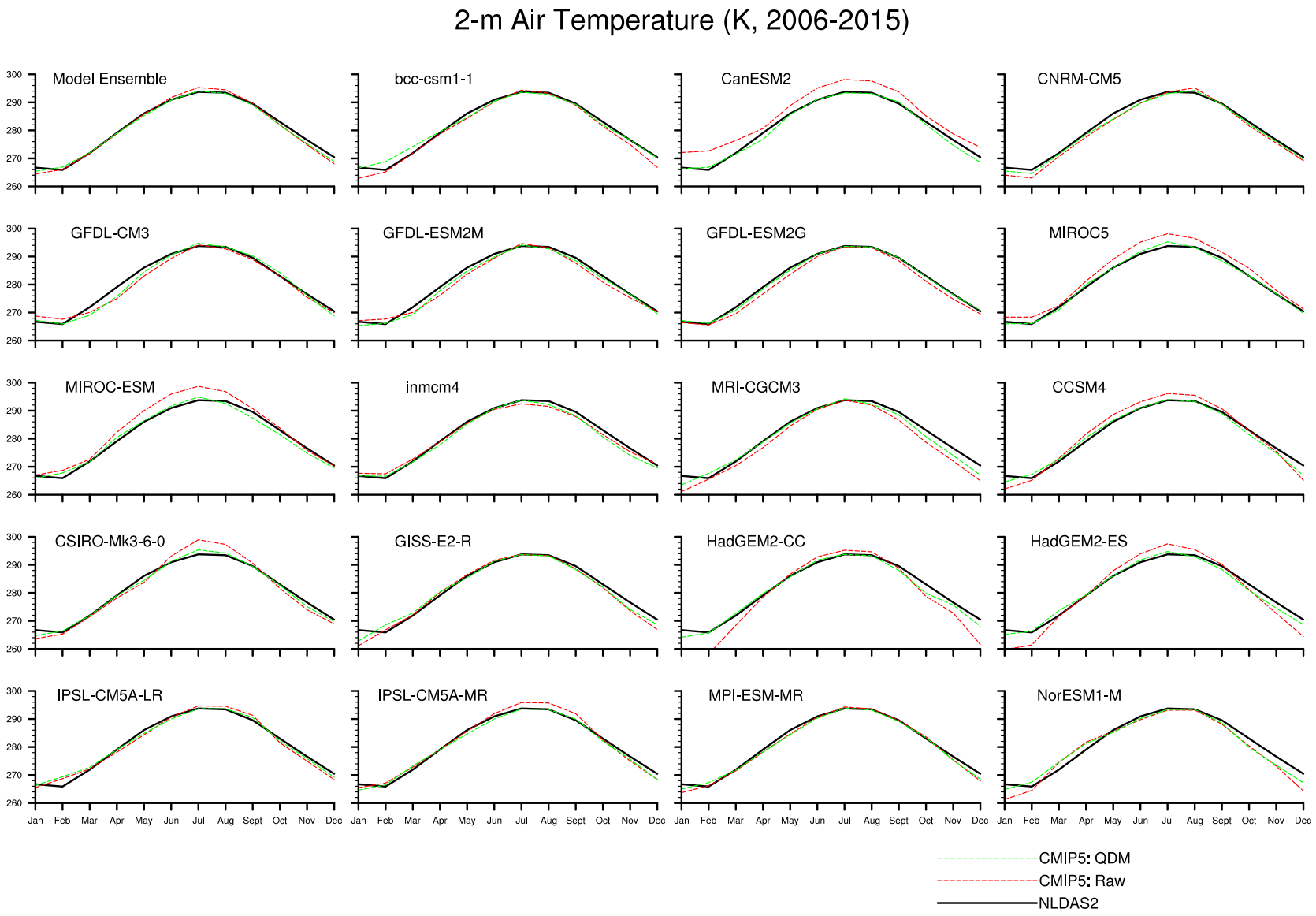

Figure 12: Seasonal variability of monthly averaged 2-m air temperature in the bias-corrected (QDM) CMIP5 model ensembles comparing to the model raw output (without bias correction) in 2006-2015.

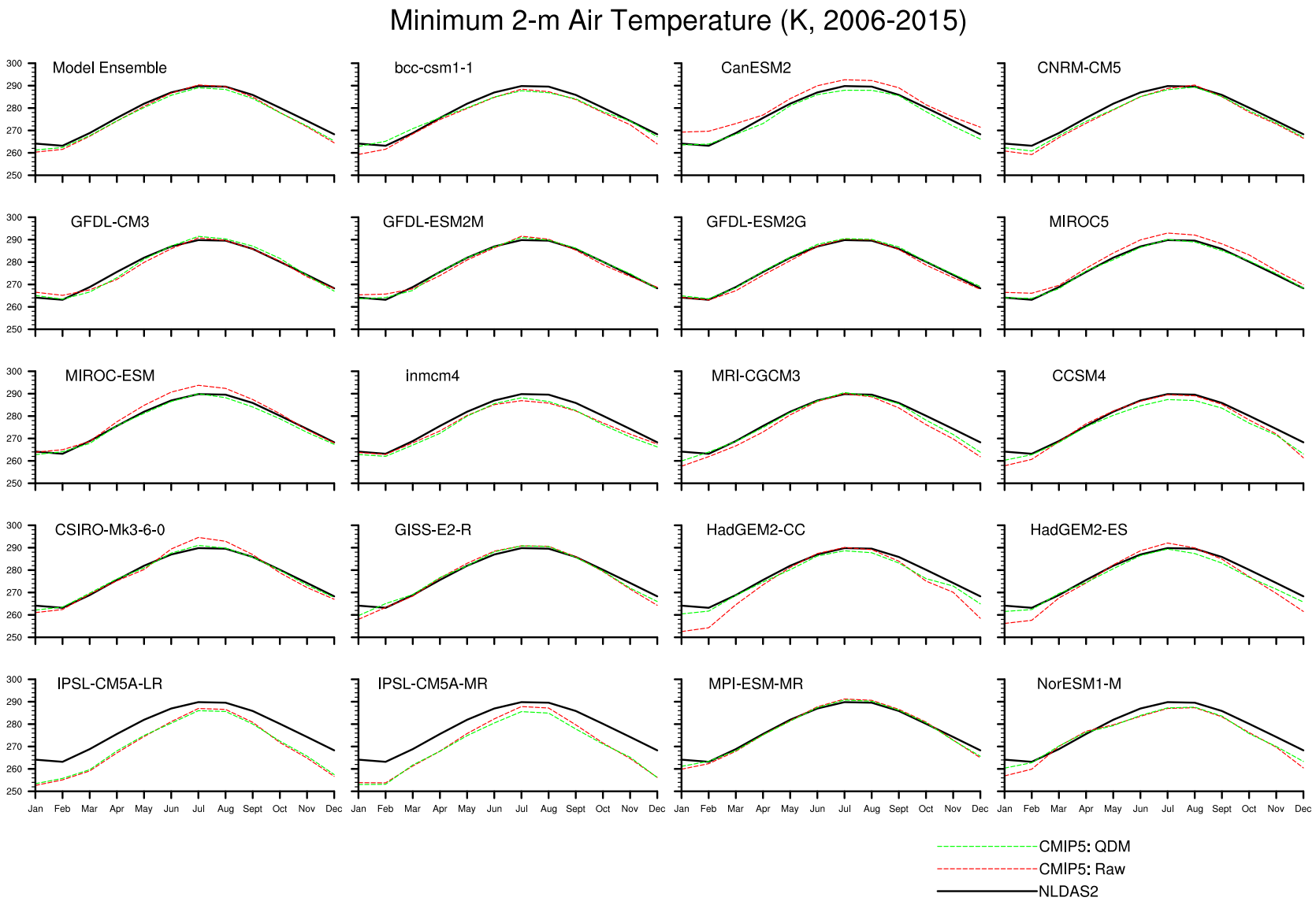

Figure 13: Seasonal variability of monthly averaged minimum 2-m air temperature in the bias-corrected (QDM) CMIP5 model ensembles comparing to the model raw output (without bias correction) in 2006-2015.

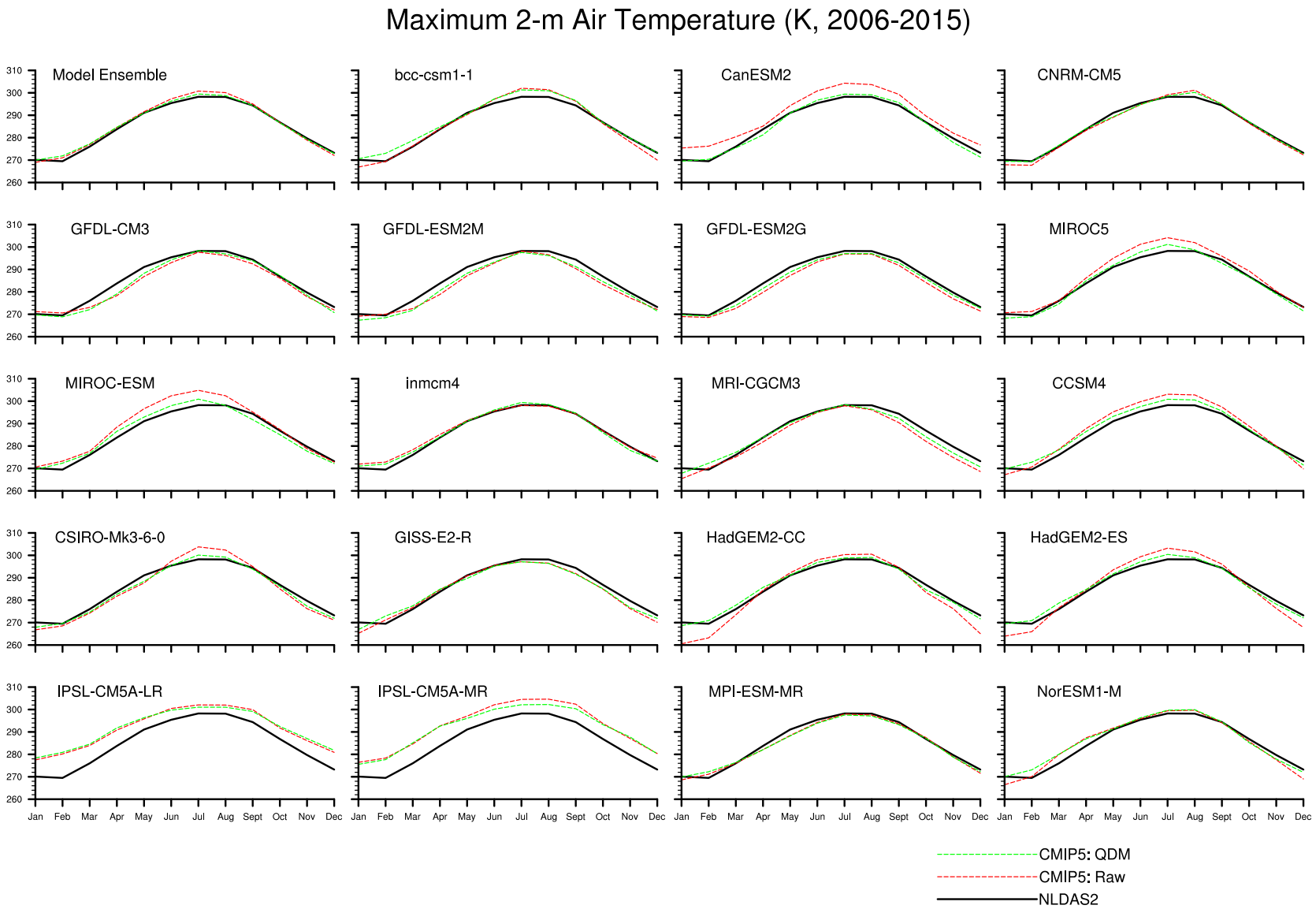

Figure 14: Seasonal variability of monthly averaged maximum 2-m air temperature in the bias-corrected (QDM) CMIP5 model ensembles comparing to the model raw output (without bias correction) in 2006-2015.

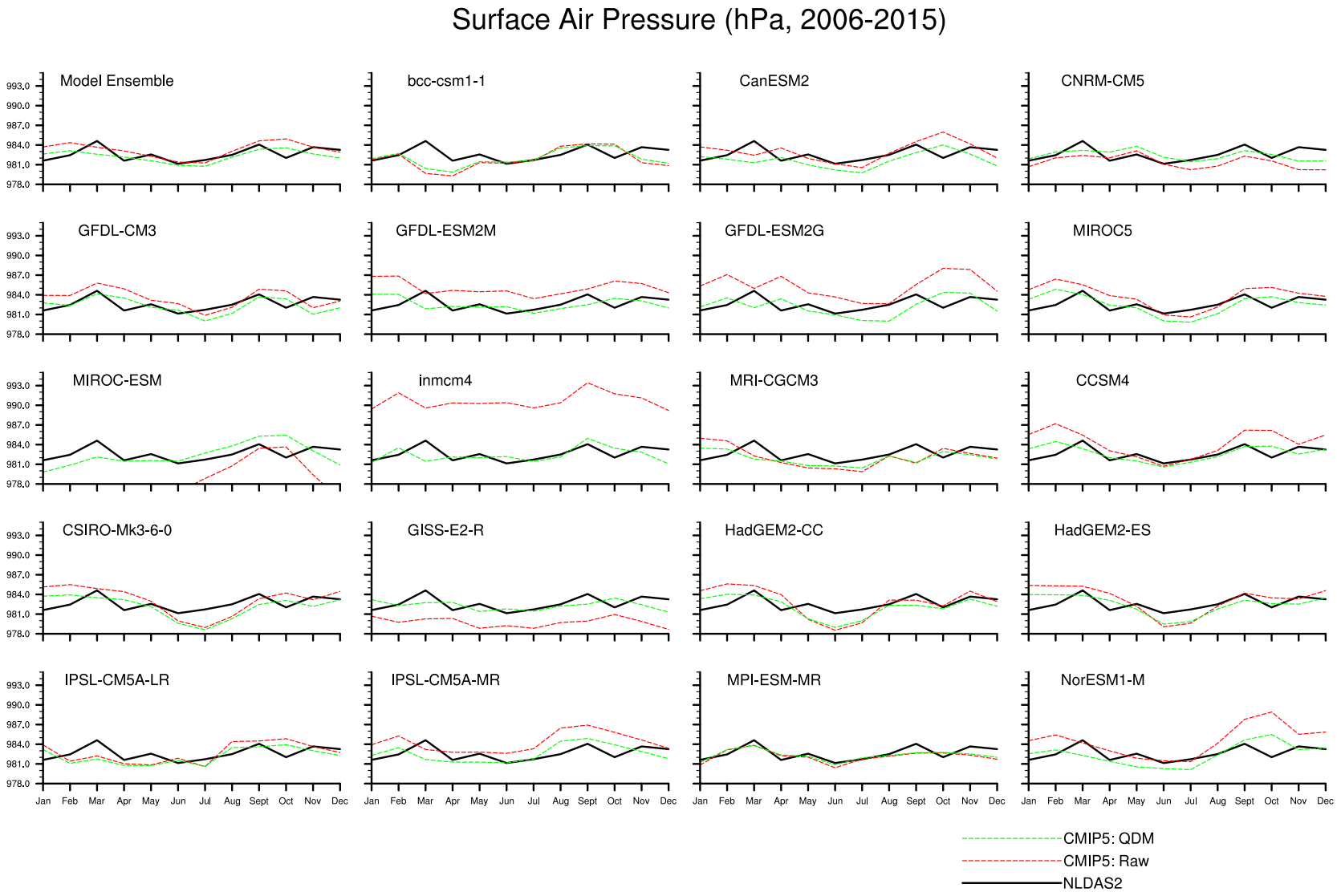

Figure 15: Seasonal variability of monthly averaged surface air pressure in the bias-corrected (QDM) CMIP5 model ensembles comparing to the model raw output (without bias correction) in 2006-2015.

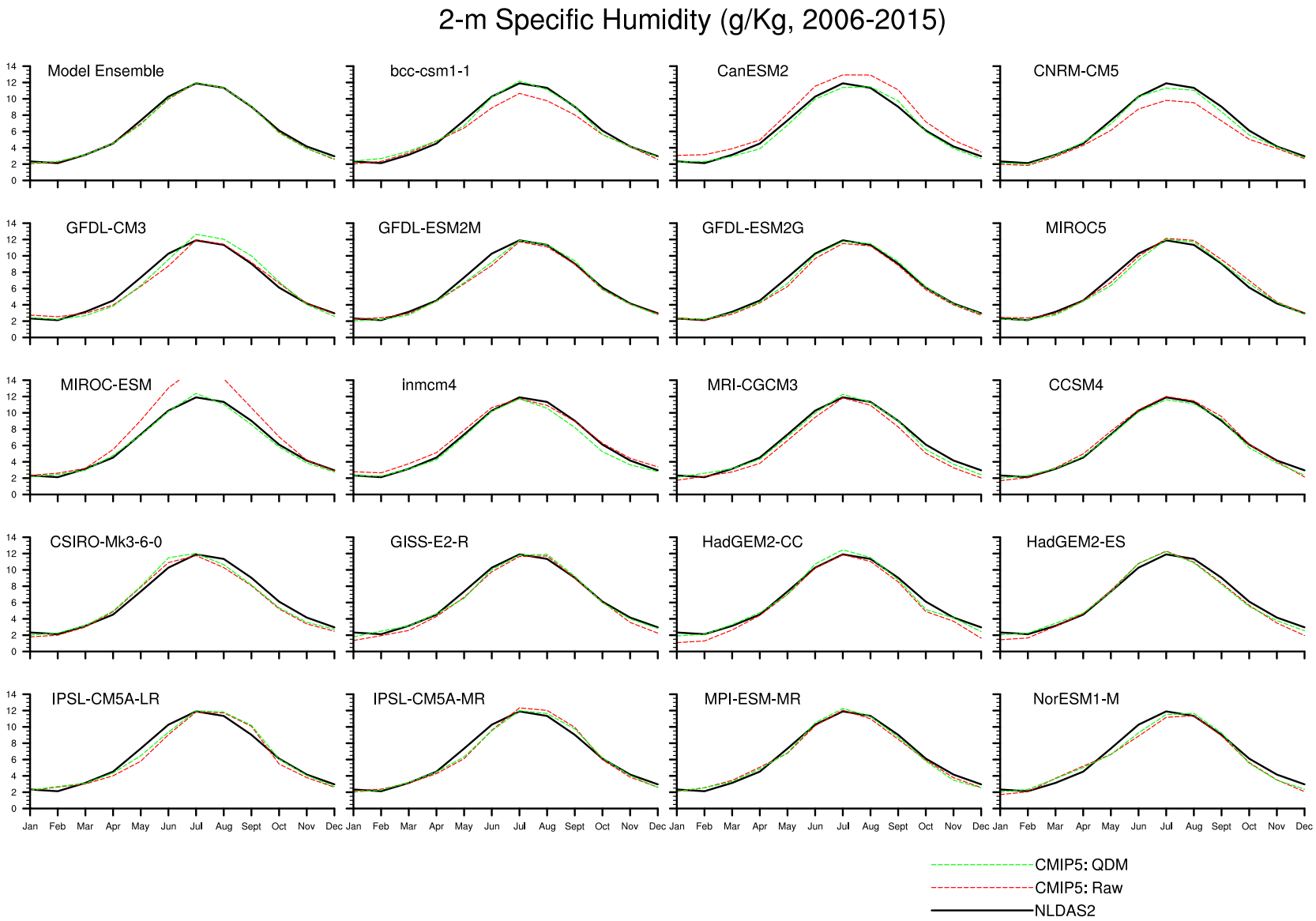

Figure 16: Seasonal variability of monthly averaged 2-m specific humidity in the bias-corrected (QDM) CMIP5 model ensembles comparing to the model raw output (without bias correction) in 2006-2015.

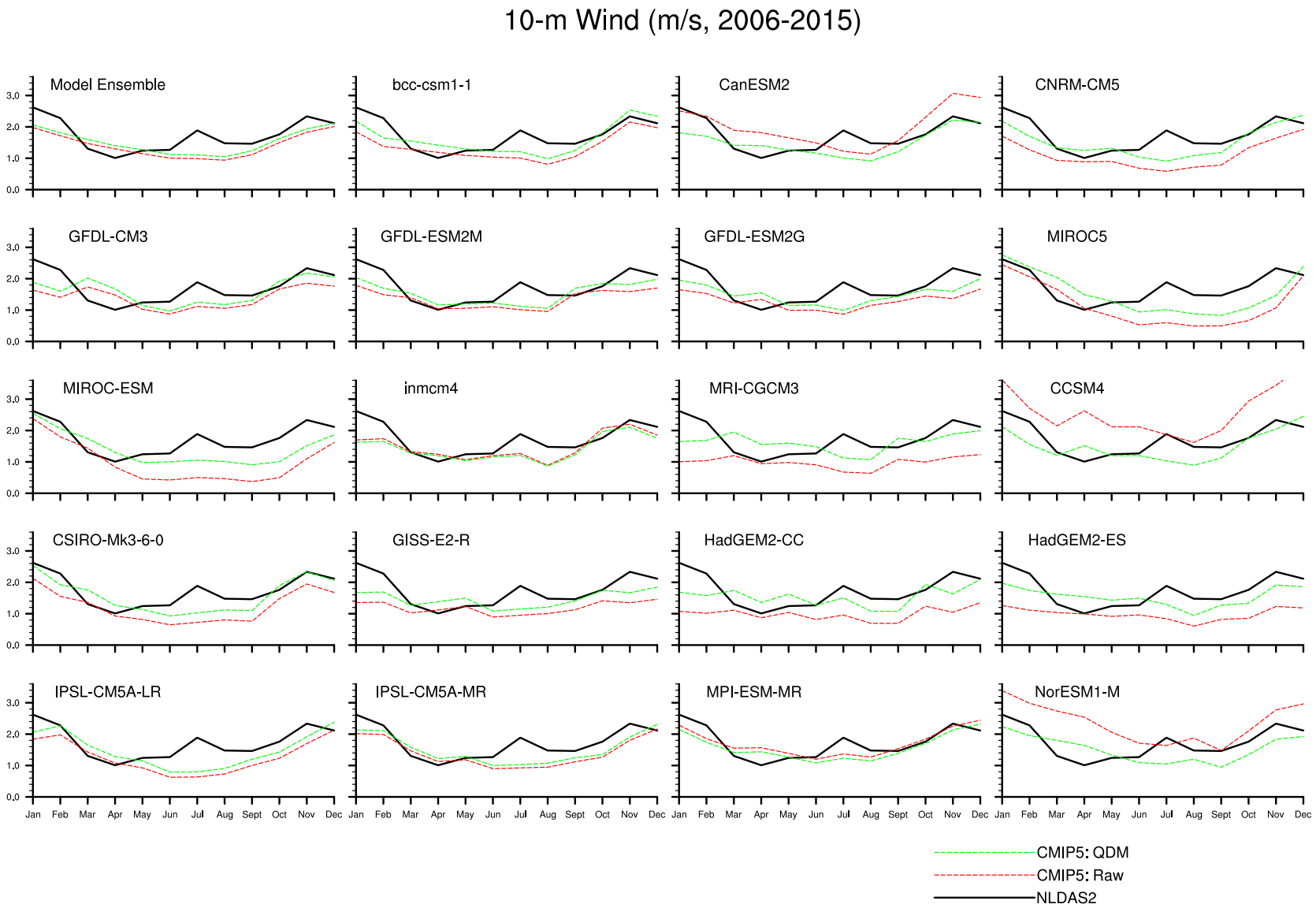

Figure 17: Seasonal variability of monthly averaged near-surface winds in the bias-corrected (QDM) CMIP5 model ensembles comparing to the model raw output (without bias correction) in 2006-2015.

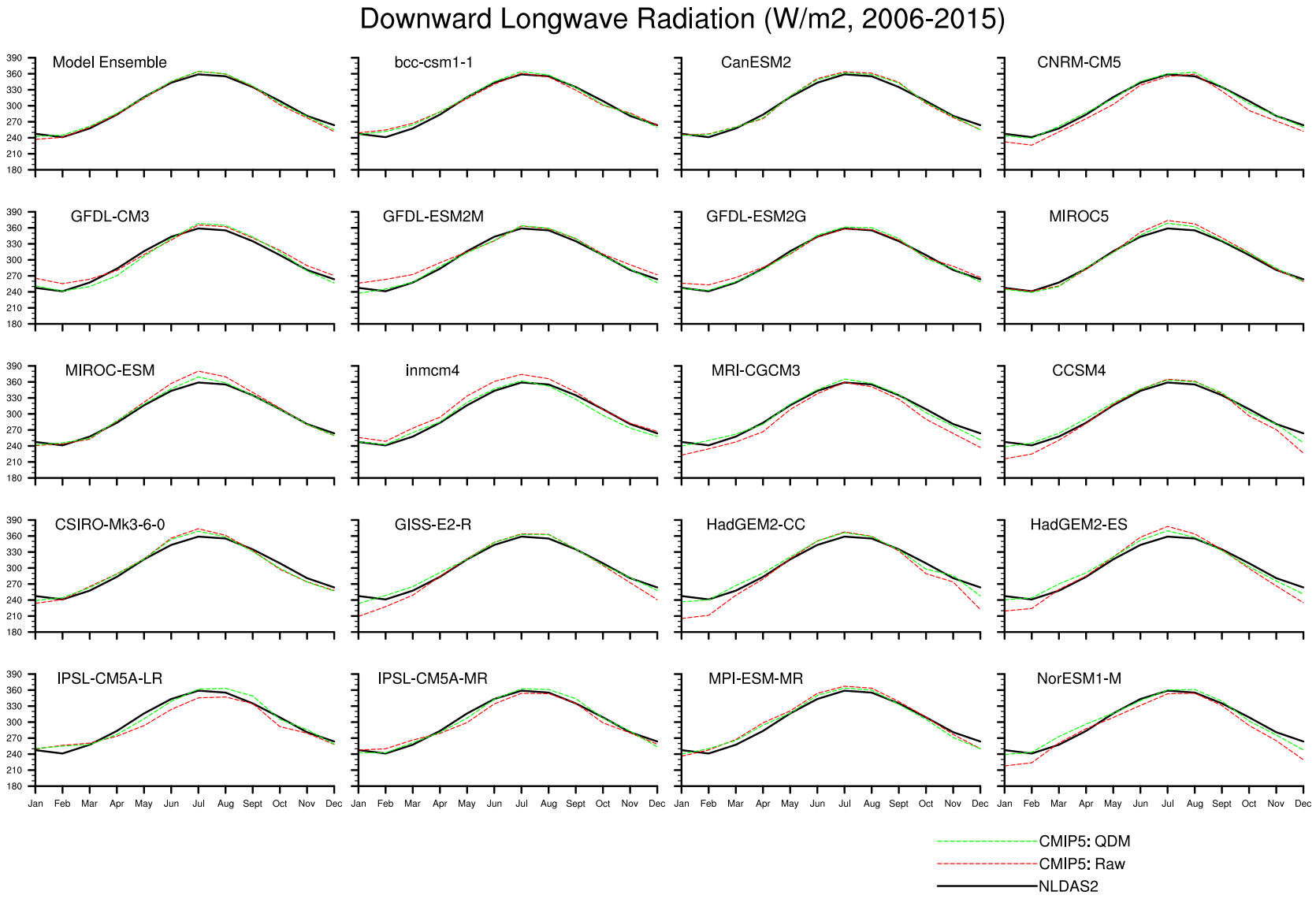

Figure 18: Seasonal variability of monthly averaged downward longwave radiation in the bias-corrected (QDM) CMIP5 model ensembles comparing to the model raw output (without bias correction) in 2006-2015.

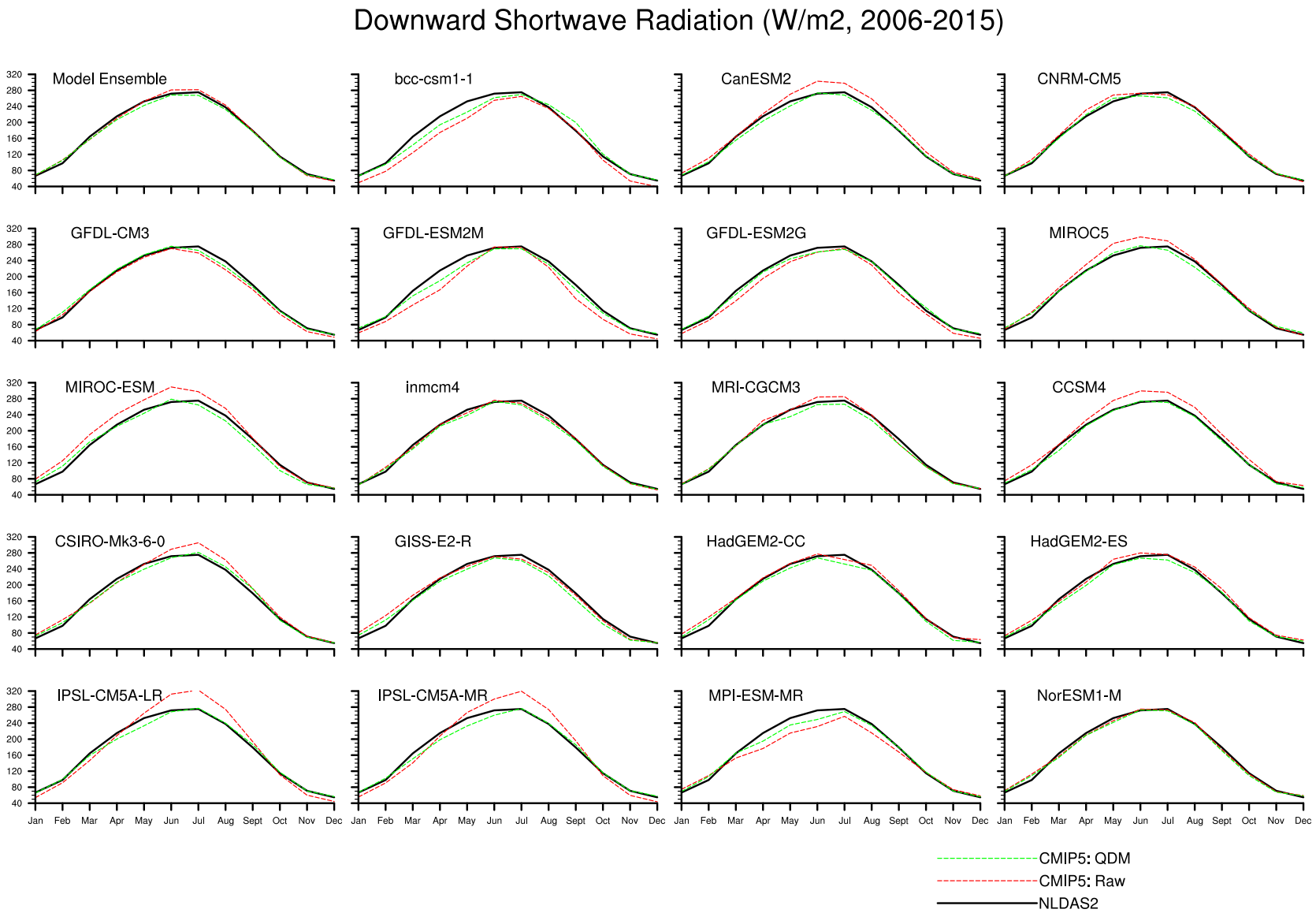

Figure 19: Seasonal variability of monthly averaged downward shortwave radiation in the bias-corrected (QDM) CMIP5 model ensembles comparing to the model raw output (without bias correction) in 2006-2015.

An analysis of spatial variability in bias correction results across the entire Great Lakes - CONUS domain (Fig. 20 to Fig. 28) using NLDAS2 and (for precipitation over the Midwest and Great Lakes region only) NLDAS2-CaPA as observation proxies indicates that, for most model variables, our procedure led to a noticeable reduction in biases. Taking precipitation and air temperature as an example, over the Great Lakes region, the bias (relative to NLDAS2-CaPA) of the CMIP5 19 model ensemble's monthly accumulated precipitation averaged in 2006-2015 dropped from originally (raw model output without bias-correction) an overestimation of $5 \sim 15$ mm/month to $-5 \sim 5$ mm/month over a majority of the entire basin after bias correction. The bias of the mean 2-m air temperature declined from $-1.5 \sim 0.5$ K to $-0.2 \sim 0.2$ K as well.

For the Great Lakes region, the bias correction in precipitation remains most challenging, due in large part to the binational border issue in the NLDAS2-CaPA calibration precipitation datasets (contributed mainly by NLDAS2 from 1979-2001), while all other variables show a notable decline in the model errors. The precipitation bias shown in Fig. 20 over the Great Lakes region has already reflected some extra effort to improve the skill of bias-correction, which include: 1), introducing the CaPA precipitation datasets into the Great Lakes and 2), using a monthly-scale data pool as introduced above. The mean air temperature, specific humidity, surface air pressure, and radiations from the CMIP5 model's raw output show continuously good agreement with the observations while after bias correction the biases are further reduced. The CMIP5 raw minimum and maximum temperature have larger spatial biases nationwide, as the coarse resolution CMIP5 experiments are not designed to capture these diurnal temperature extremes. But after bias-correction, the cold bias of the minimum temperature has been constrained within $-1 \sim -2$ K, and the warm bias in maximum temperature has been reduced to lower than 2 K. The annual-scale bias correction also exhbits strong skill in reducing the biases of wind speed relative to the NLDAS2 dataset. Since the wind speed data in NLDAS2 is systematically biased as introduced above, a simple adjustment on the mean magnitude of the bias-corrected wind speed is conducted before applying it to the LLTM simulations.

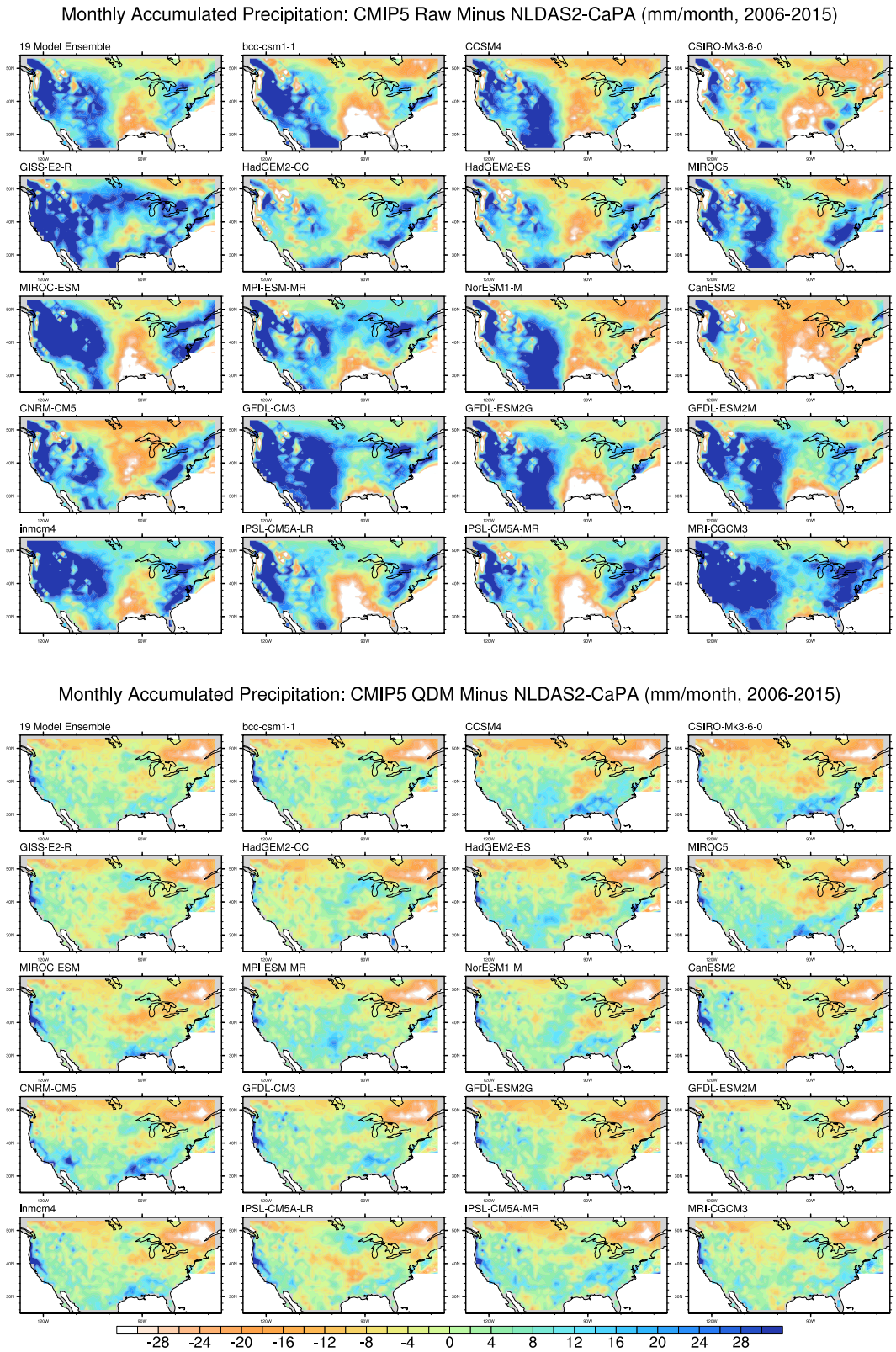

Figure 20: Average precipitation bias before (top panels) and after (bottom panels) bias correction for the 2006 to 2015 validation period. Each panel includes results for one of the 19 CMIP5 models, and the upper-left panel is based on the CMIP5 model ensemble mean. Bias correction was based on NLDAS2-CaPA during the 1979 to 2005 'calibration' period; bias validation results shown here are based on comparison of the bias corrected results to NLDAS2-CaPA from 2006 to 2015.

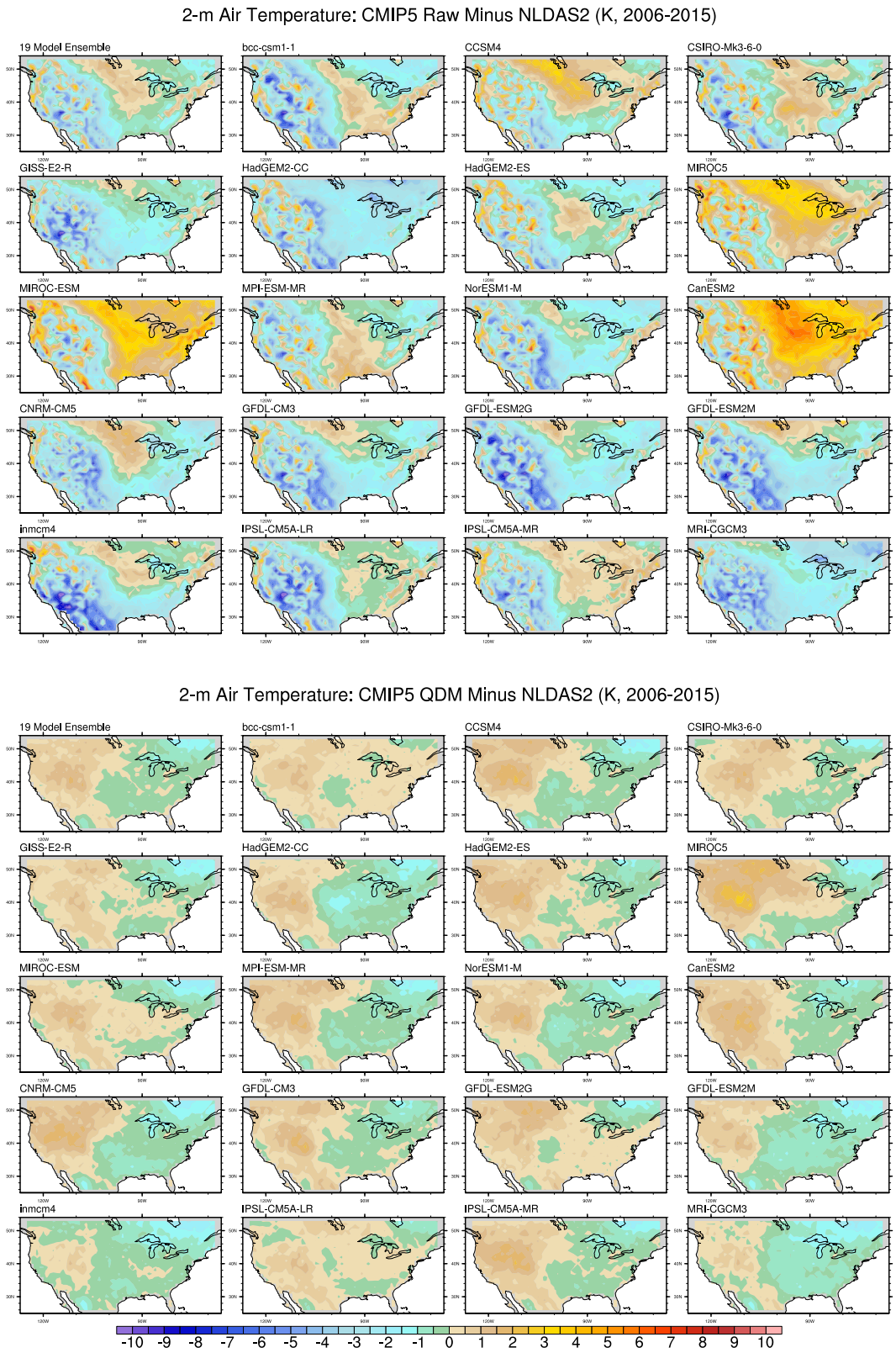

Figure 21: Comparison between monthly mean 2-m air temperature bias from 2006 to 2015 for all 19 CMIP5 models (and the mean of the ensemble, upper-left panel) before (top panels) and after (bottom panels) bias correction. Bias is calculated relative to NLDAS2.

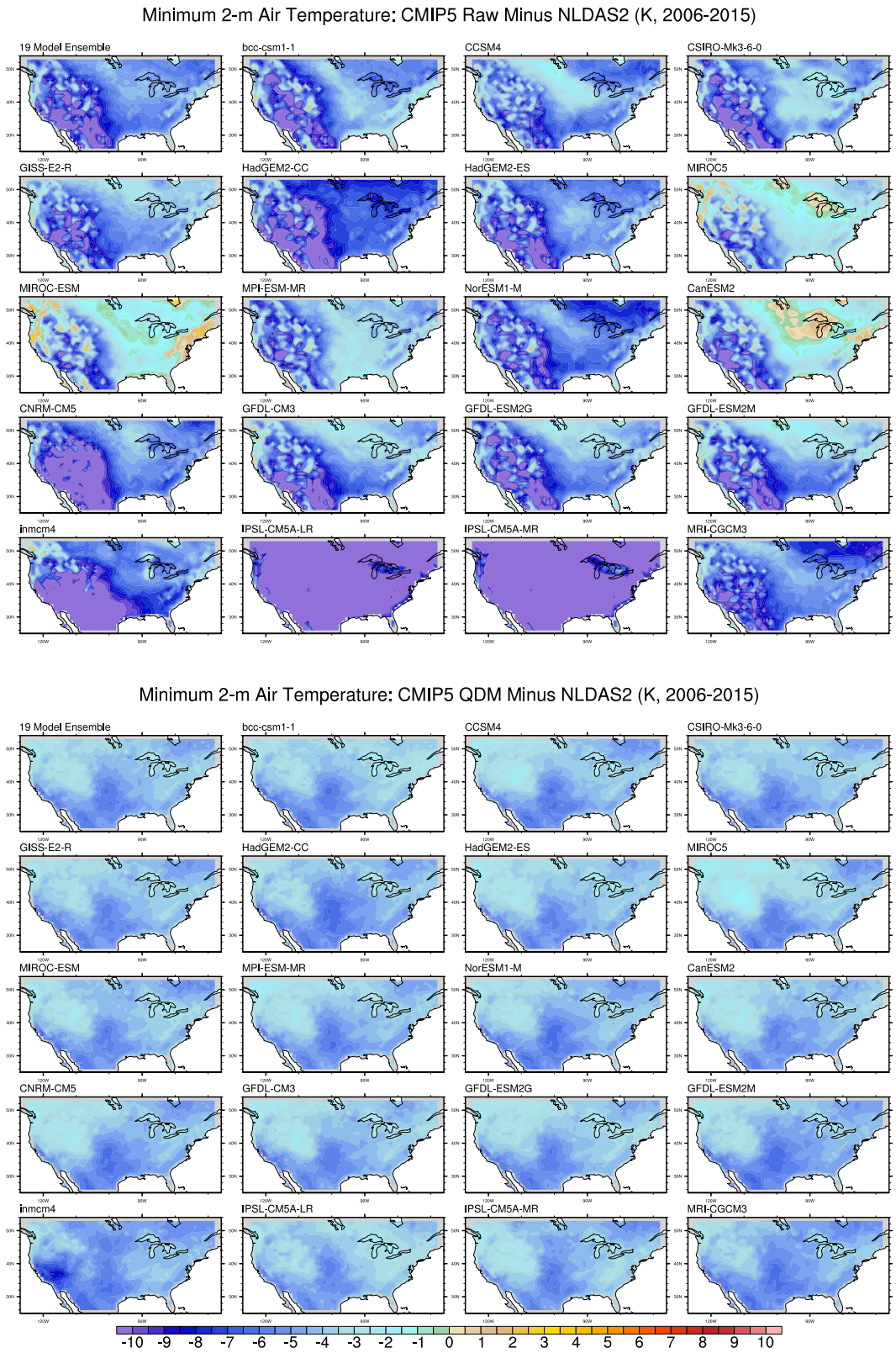

Figure 22: Comparison between monthly minimum 2-m air temperature bias from 2006 to 2015 for all 19 CMIP5 models (and the mean of the ensemble, upper-left panel) before (top panels) and after (bottom panels) bias correction. Bias is calculated relative to NLDAS2.

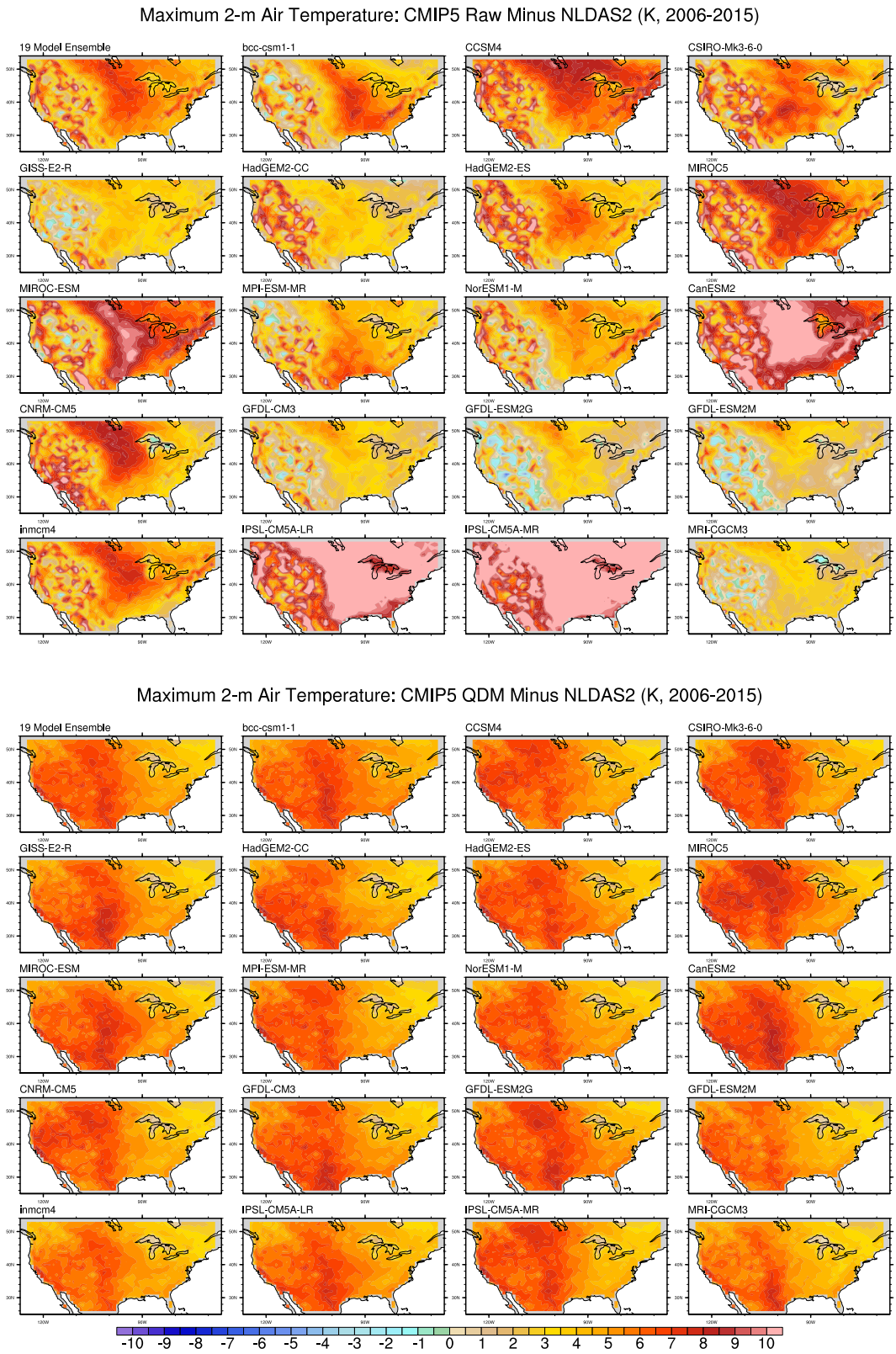

Figure 23: Comparison between monthly maximum 2-m air temperature bias from 2006 to 2015 for all 19 CMIP5 models (and the mean of the ensemble, upper-left panel) before (top panels) and after (bottom panels) bias correction. Bias is calculated relative to NLDAS2.

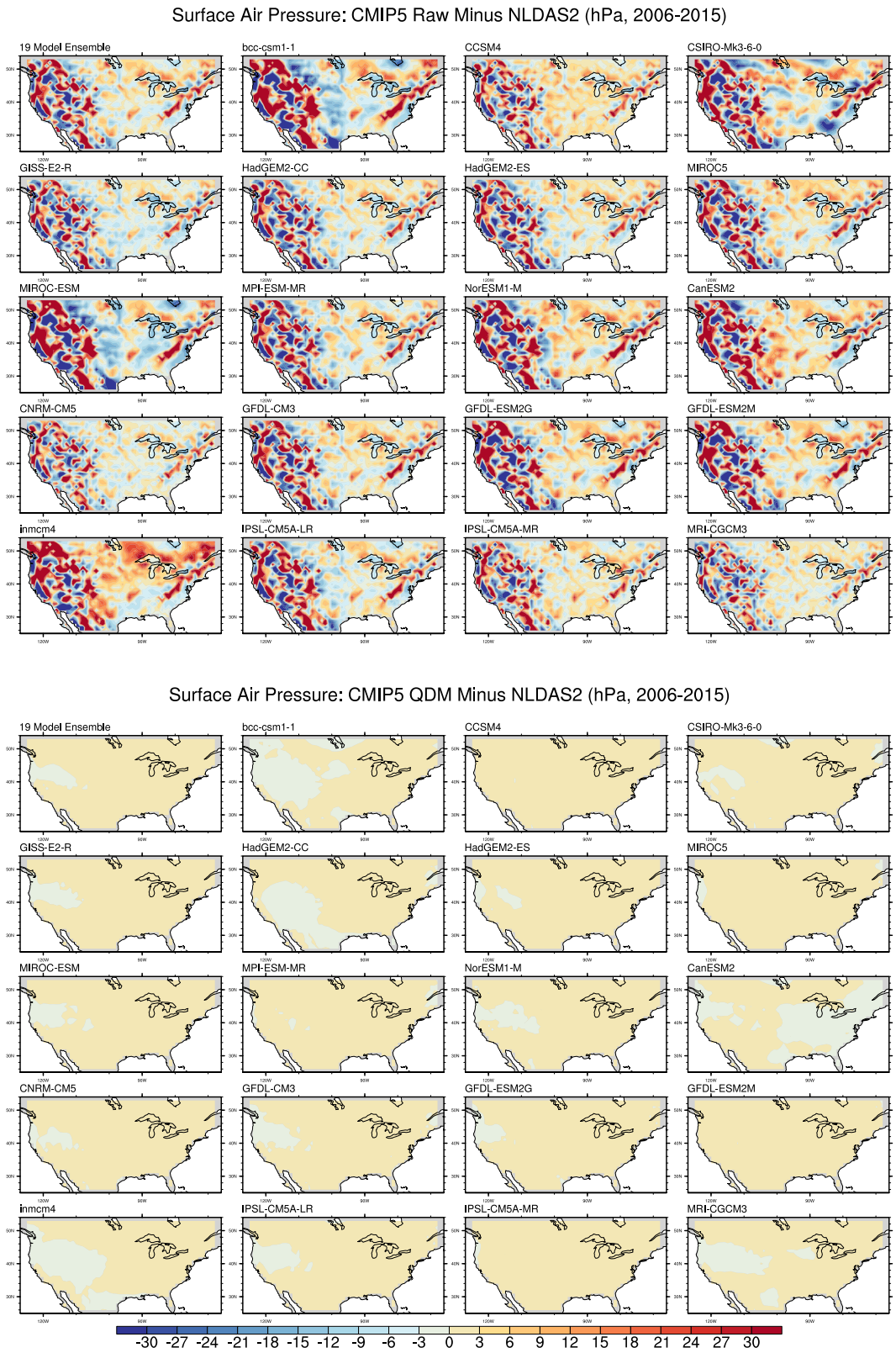

Figure 24: Comparison between average bias in mean surface air pressure from 2006 to 2015 for all 19 CMIP5 models (and the mean of the ensemble, upper-left panel) before (top panels) and after (bottom panels) bias correction. Bias is calculated relative to NLDAS2.

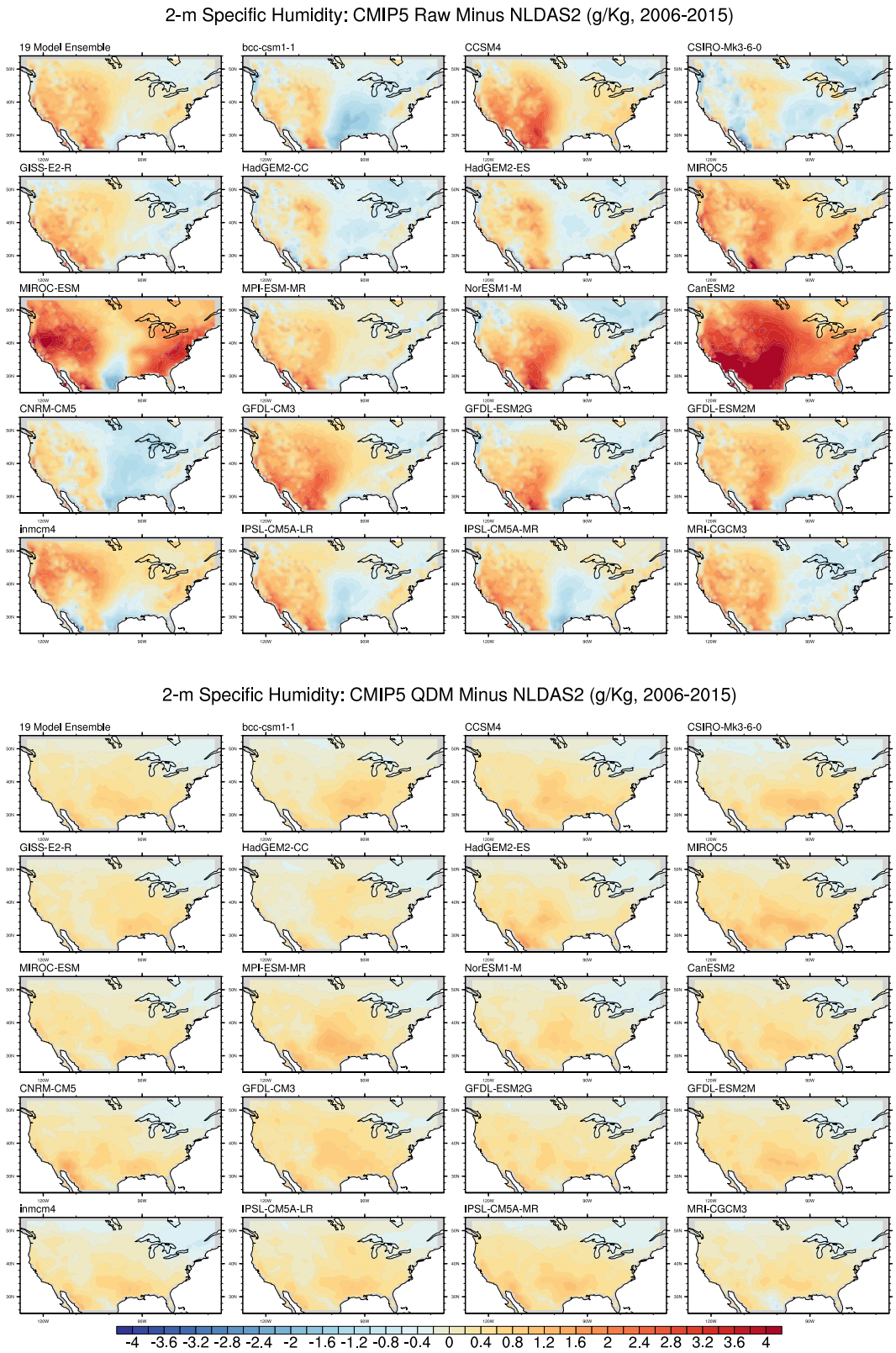

Figure 25: Comparison between average bias in mean near-surface specific humidity from 2006 to 2015 for all 19 CMIP5 models (and the mean of the ensemble, upper-left panel) before (top panels) and after (bottom panels) bias correction. Bias is calculated relative to NLDAS2.

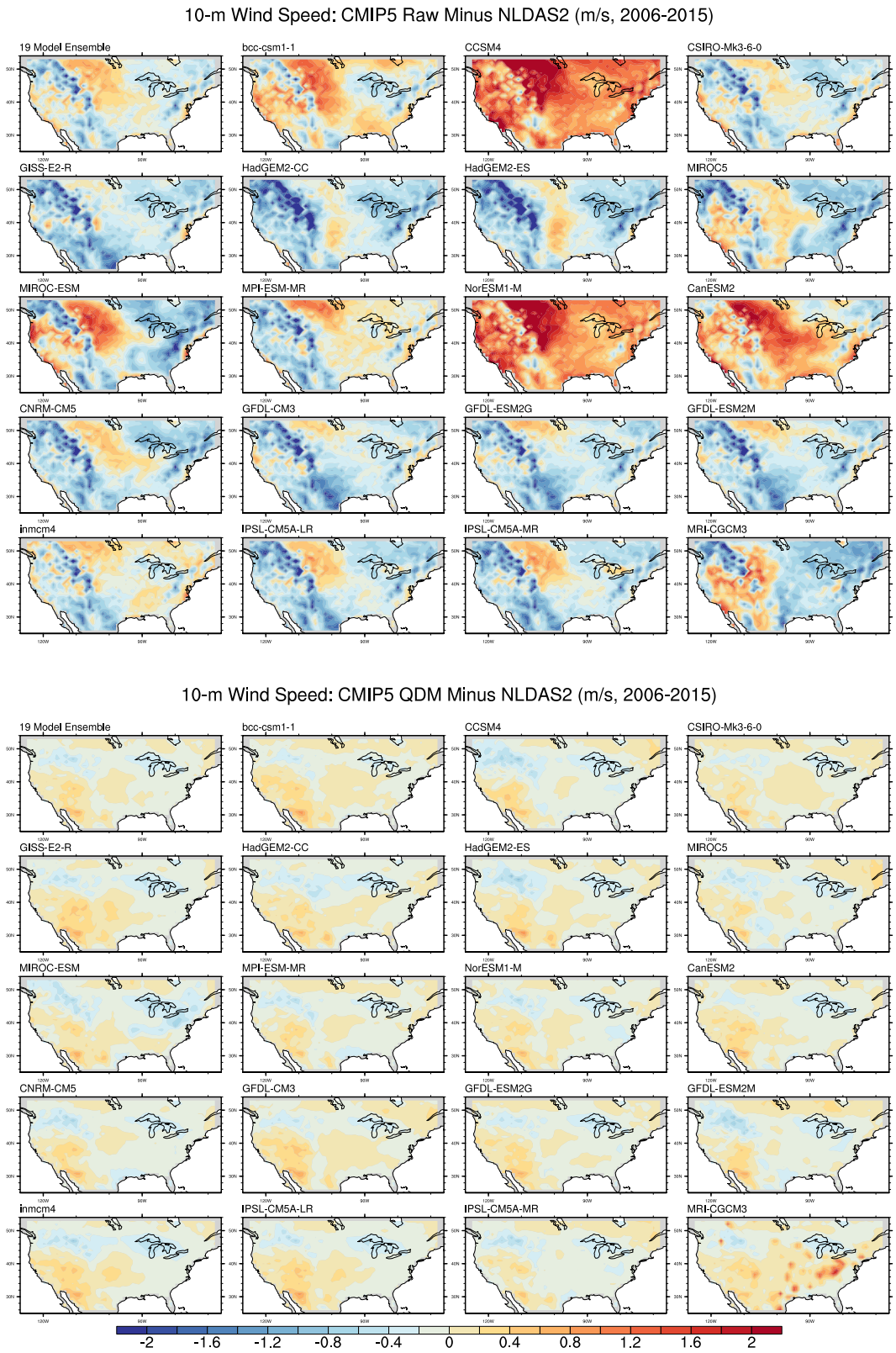

Figure 26: Comparison between average wind speed bias from 2006 to 2015 for all 19 CMIP5 models (and the mean of the ensemble, upper-left panel) before (top panels) and after (bottom panels) bias correction. Bias is calculated relative to NLDAS2.

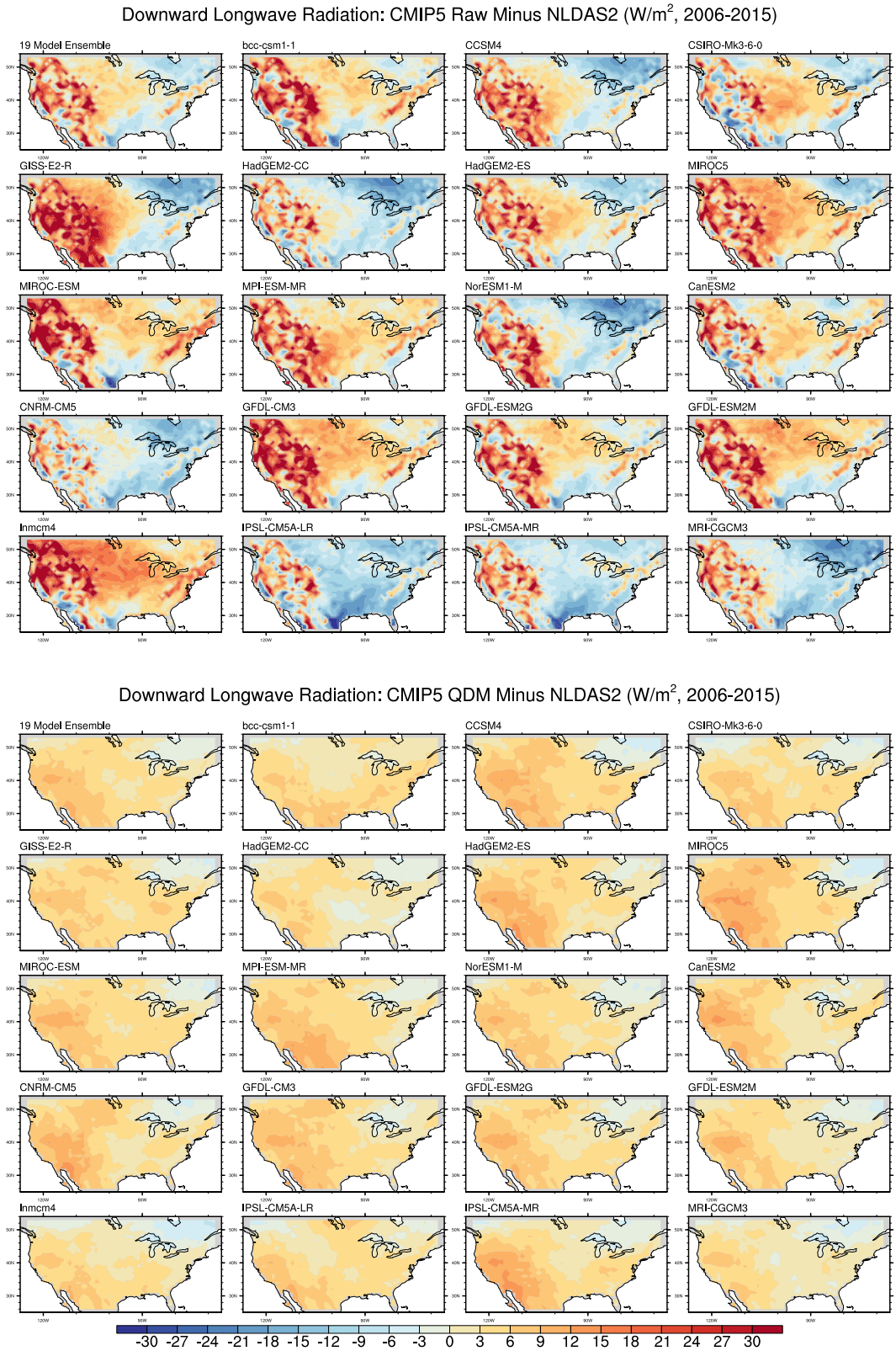

Figure 27: Comparison between average downward longwave radiation bias from 2006 to 2015 for all 19 CMIP5 models (and the mean of the ensemble, upper-left panel) before (top panels) and after (bottom panels) bias correction. Bias is calculated relative to NLDAS2.

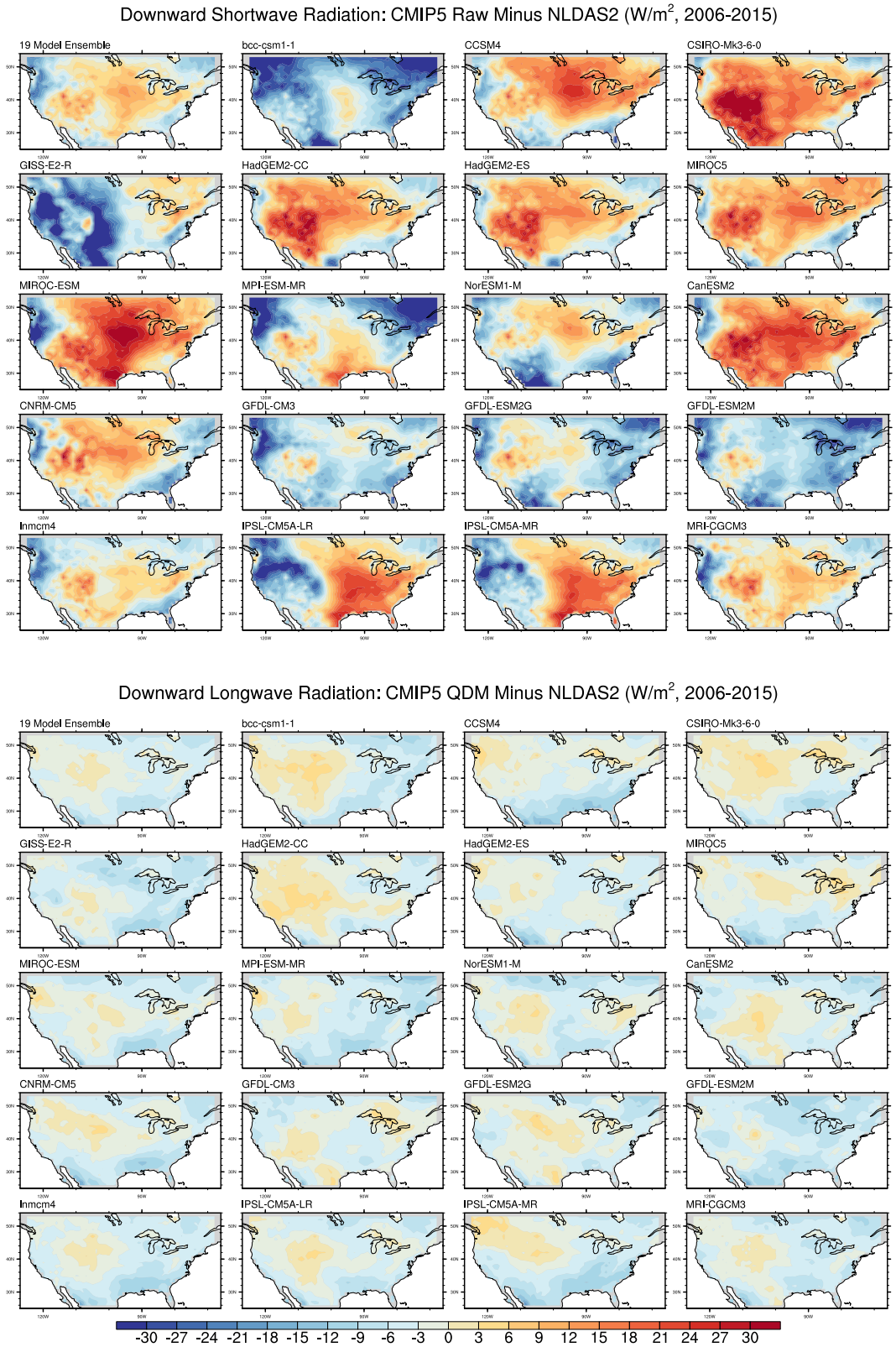

Figure 28: Comparison between average downward shortwave radiation from 2006 to 2015 for all 19 CMIP5 models (and the mean of the ensemble, upper-left panel) before (top panels) and after (bottom panels) bias correction. Bias is calculated relative to NLDAS2.

3.1.2 Validation of bias correction using MGLMD

Because of the aforementioned differences between the NLDAS2-CaPA and the MGLMD precipitation (Fig. 9), for year 2006 to 2015 (2013 for MGLMD), the magnitude of the averaged monthly CMIP5 raw precipitation output appears to be smaller than the MGLMD dataset (dry bias, Fig. 29, top panel), but larger than the NLDAS2 precipitation (wet bias, Fig. 20, top panel). Also a warm bias was found over the Great Lakes region in the CMIP5's minimum temperature when compared to MGLMD (Fig. 30), as opposed to the cold biases relative to NLDAS2 (Fig. 22). The CMIP5 raw maximum temperature also reveals a combination of subtle warm and cold biases over the Great Lakes region ($-1 \sim 1$ K) relative to MGLMD rather than a warm bias of $2 \sim 4$ K compared with NLDAS2 (Fig. 23). It thus brings in uncertainties and difficulties to clearly understand the CMIP5 model's bias in precipitation and temperature over the Great Lakes basin, although differences in the magnitude of temperature are rather small. A uniform high-quality observational meteorological datasets over the Great Lakes region is strongly needed for our current model validation and forecasting application, which is not yet available. Despite discrepancies in the precipitation and temeprature between NLDAS2-CaPA and MGLMD, the debiased CMIP5 19 model ensemble's outputs exhibit comparable skill using these two different datasets, when they are validated with their corresponding calibration dataset consistently during the validation period (bottom panels in Fig. 20, Fig. 29, Fig. 22, Fig. 30, Fig. 23, and Fig. 31). It thus proved the strong skill of the QDM bias-correction method.

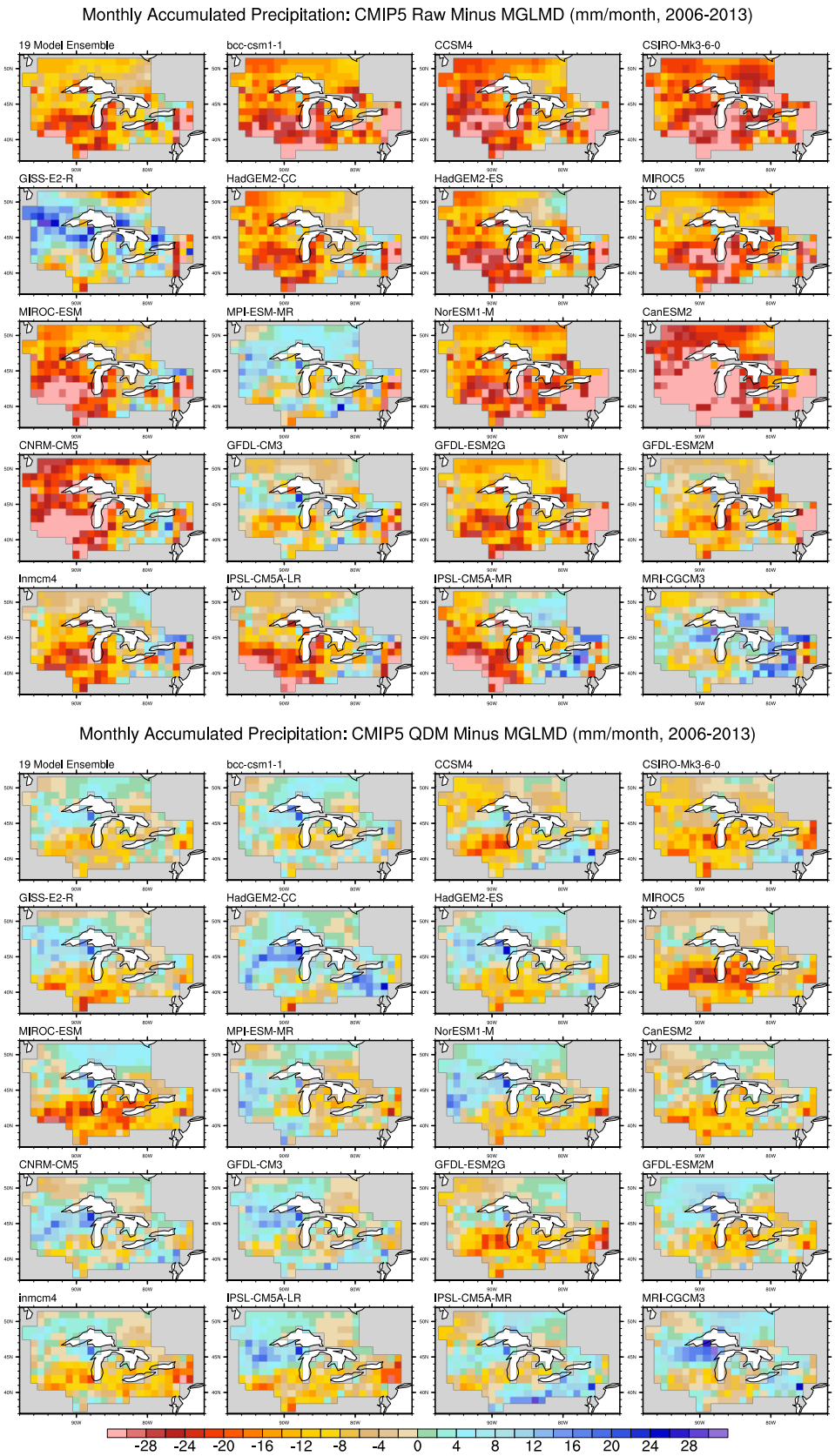

Figure 29: Bias comparison between the CMIP5 bias-corrected (QDM) monthly accumulated precipitation (bottom) and the raw outputs (without bias correction, top) relative to the MGLMD datasets averaged over 2006-2013.

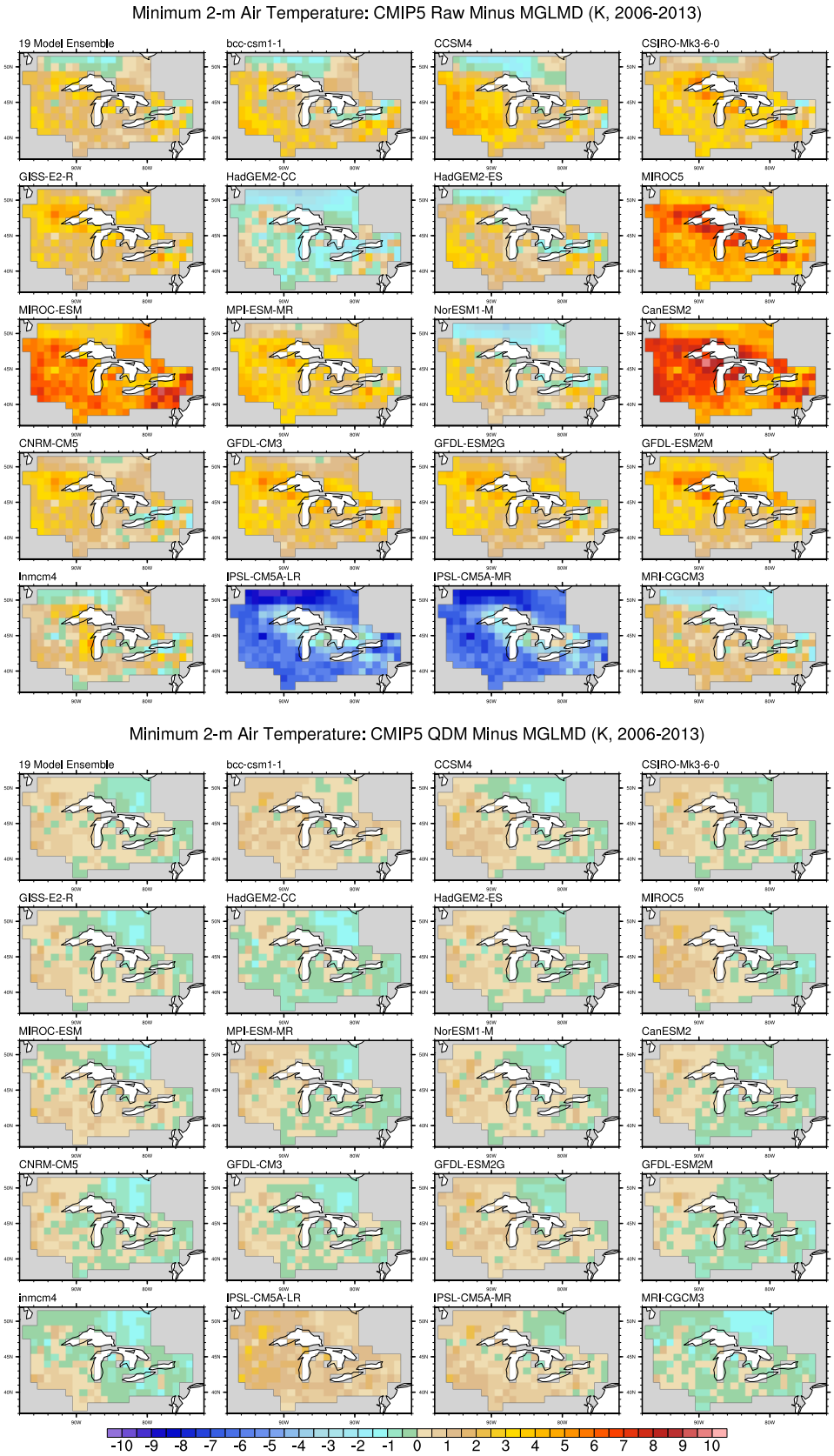

Figure 30: Bias comparison between the CMIP5 bias-corrected (QDM) monthly minimum 2-m air temperature (bottom) and the raw outputs (without bias correction, top) relative to the MGLMD datasets averaged over 2006-2013.

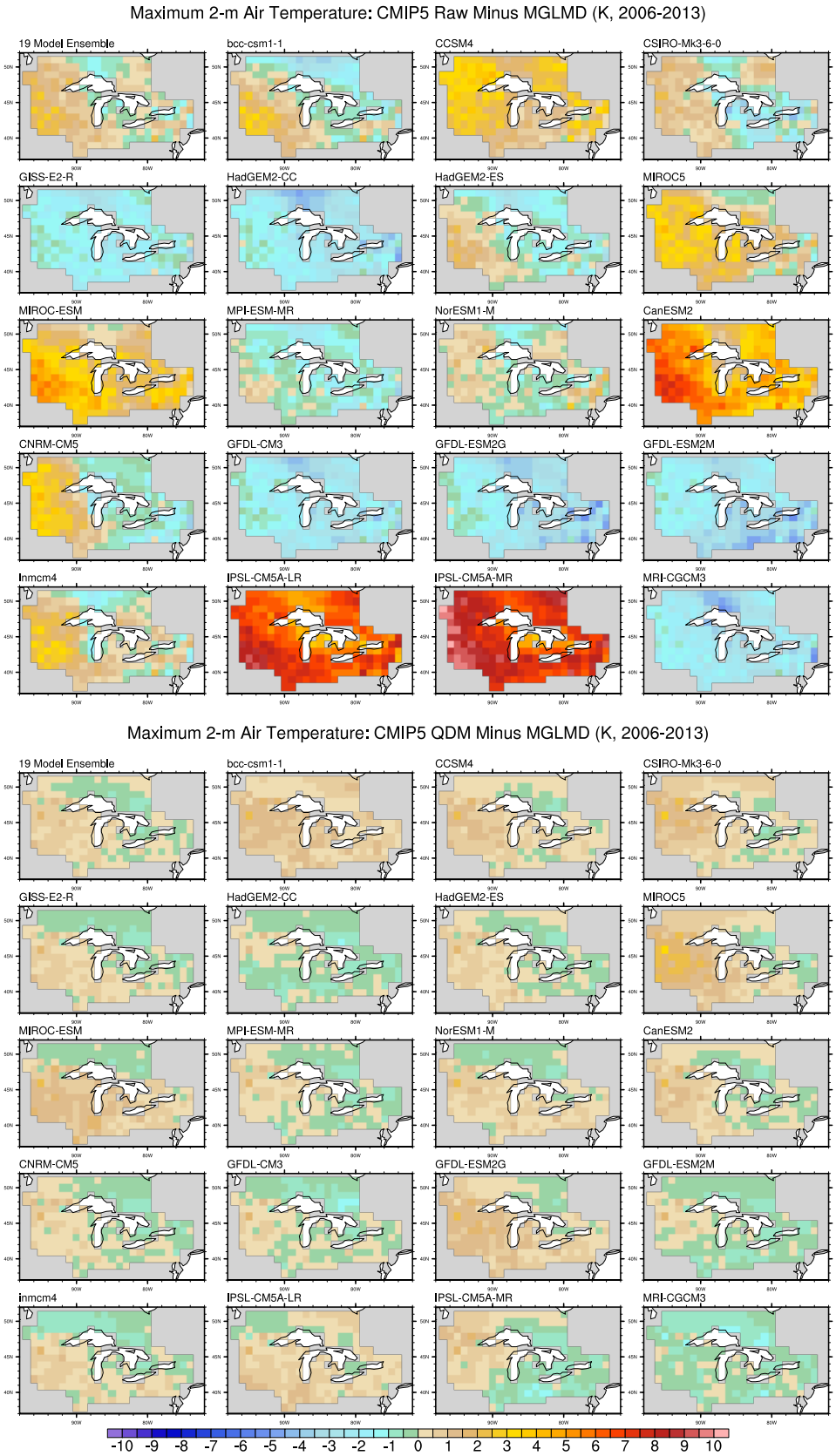

Figure 31: Bias comparison between the CMIP5 bias-corrected (QDM) monthly maximum 2-m air temperature (bottom) and the raw outputs (without bias correction, top) relative to the MGLMD datasets averaged over 2006-2013.

3.1.3 Forcings for LBRM: precipitation, Tmin, and Tmax in 2006-2015

The LBRM requires daily inputs of precipitation, Tmin and Tmax over all the land portion of the 121 sub-basins (Fig. 2) as meteorological forcings to simulate the runoffs from the sub-basins into the Great Lakes. For the 10-year validation period, we have propagated the two sets of CMIP5 QDM outputs (NLDAS2-CaPA based and MGLMD based) into the LBRM after temporally downscaling them into the daily variations with the random sampling technique discussed in Section 2.2.3, together with four sets of daily observational proxies as forcings which are: a), daily precipitation, Tmin and Tmax from NLDAS2; b), daily precipitation from CaPA but Tmin and Tmax from NLDAS2 (due to the fact that CaPA does not have temperature data available); c), daily precipitation, Tmin and Tmax from GLM-HMD; and d), daily precipitation, Tmin and Tmax from MGLMD. Comparisons of these six different forcing datasets in the monthly timestep are shown in Fig. 32 - 34 with data from all the four observational proxies shaded in blue.

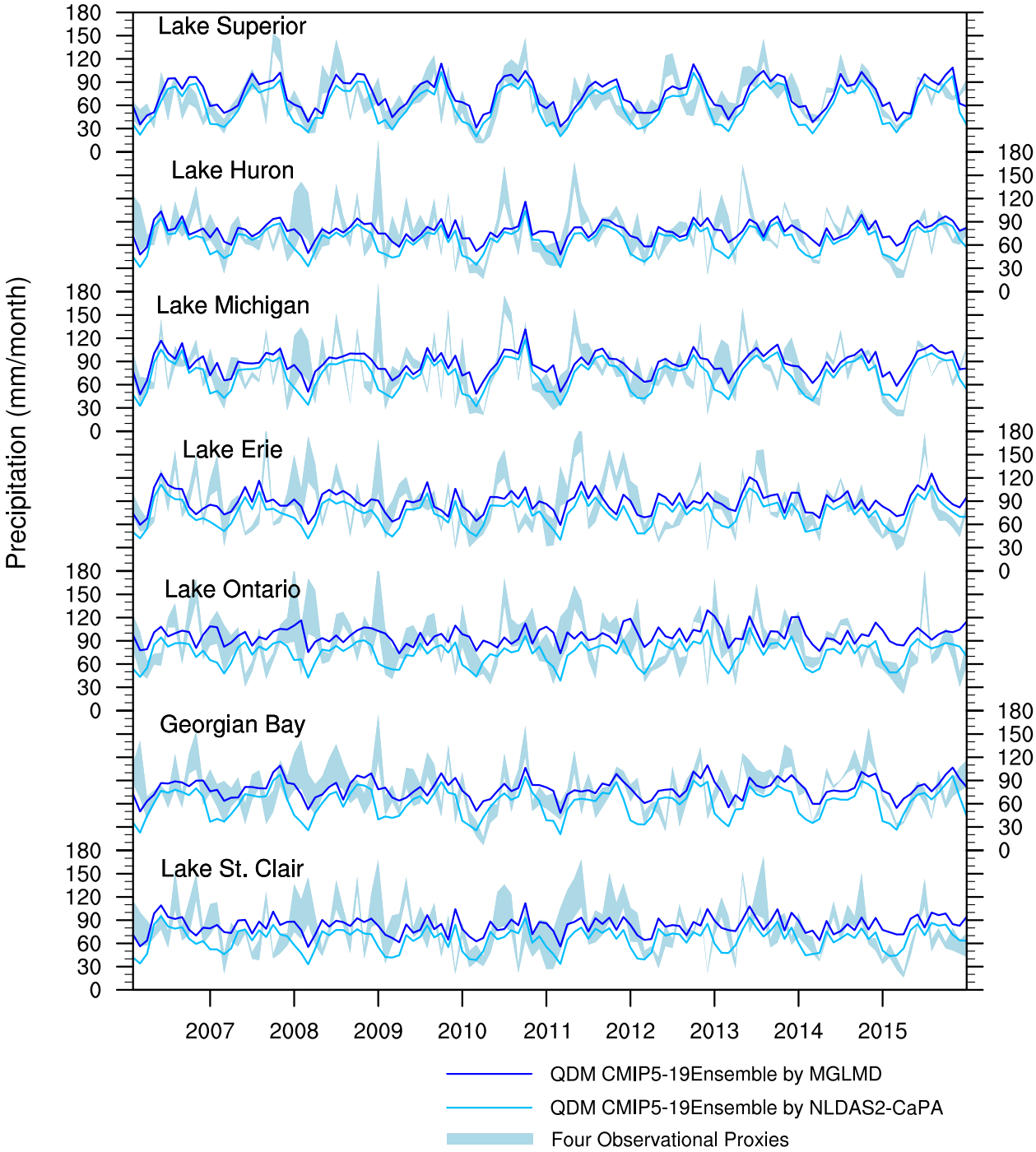

Figure 32: 2006-2015 monthly accumulated precipitation over the land portion of the Great Lakes basin from CMIP5 QDM outputs (NLDAS2-CaPA based and MGLMD based) and observational proxies (shaded in blue).

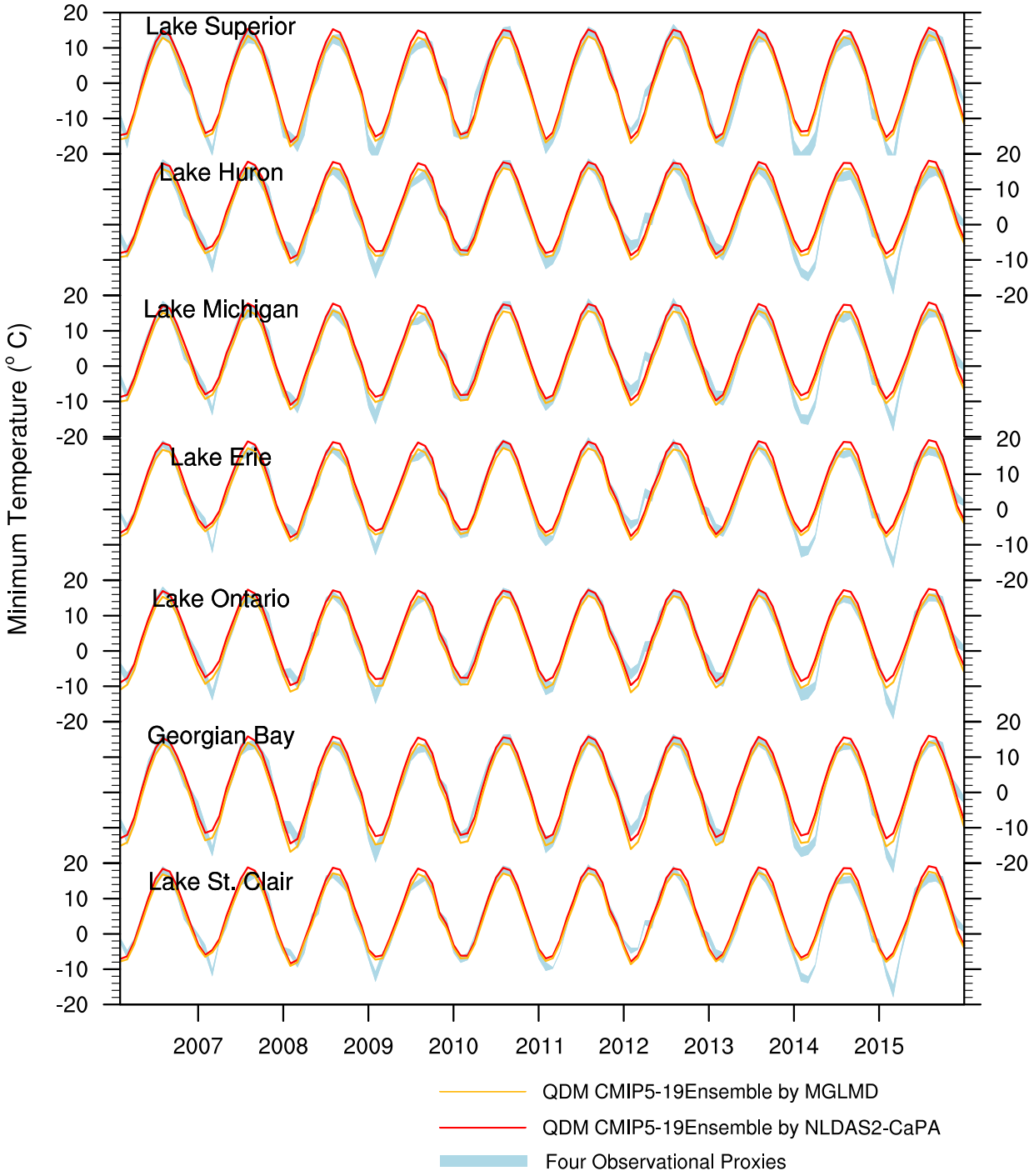

Figure 33: 2006-2015 monthly averaged daily minimum air temperature over the land portion of the Great Lakes basin from CMIP5 QDM outputs (NLDAS2-CaPA based and MGLMD based) and observational proxies (shaded in blue).

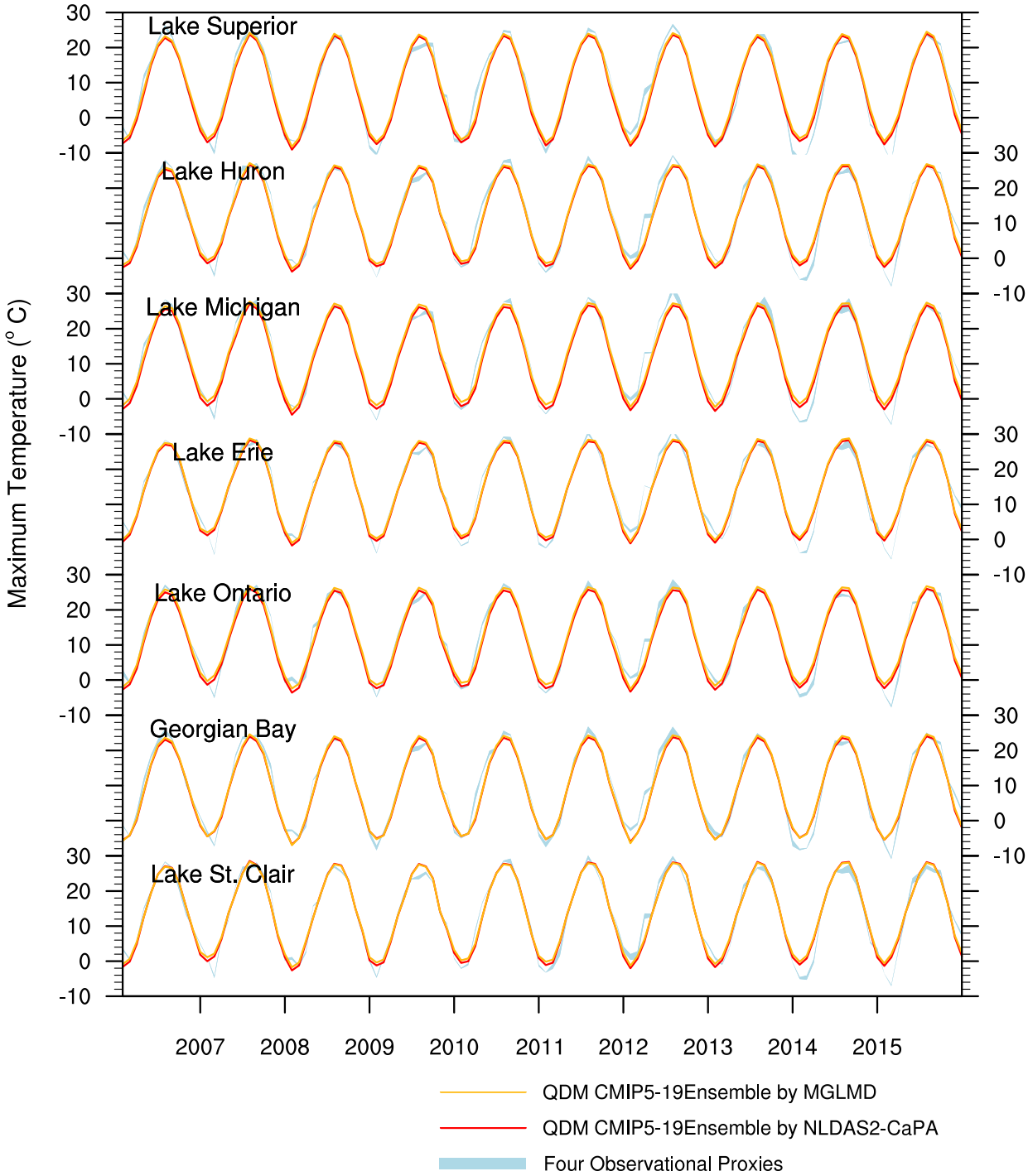

Figure 34: 2006-2015 monthly averaged daily maximum air temperature over the land portion of the Great Lakes basin from CMIP5 QDM outputs (NLDAS2-CaPA based and MGLMD based) and observational proxies (shaded in blue).

While both Tmin and Tmax demonstrate consistently good agreement among all the

CMIP5 QDM and observational datasets (Fig. 33-34), precipitation reveals larger uncertainties both among the observational proxies (shaded area) and between the CMIP5 QDM outputs based on their corresponding calibration datasets (Fig. 32). More uncertainties in precipitation are also seen from relatively smaller watersheds (i.e. Fig. 32: Lake Erie, Lake Ontario, Georgian Bay and Lake St. Clair), as bias-correction and downscaling skill are limited by a smaller pool of spatial sample points. In general, since the MGLMD precipitation estimates are larger than those from NLDAS2-CaPA (Fig. 9), higher MGLMD based CMIP5 QDM precipitation is found across all the sub-basins at magnitudes of ~ 10 mm/month. The NLDAS2-CaPA based CMIP5 QDM precipitation tends to match the variations in the low precipitation events better, while the MGLMD based CMIP5 QDM precipitation show advantages in replicating the peak values. The resulting LBRM runoffs are discussed in Section 3.2, validated with two observation-based runoff estimates over several of the sub-basins.

3.1.4 Preserved future climate change signals after QDM bias-correction

Since the QDM method is designed to bias-correct the model's internal error without corrupting its possible climate change signals in the CMIP5 suite of model projections, it is important to understand how well the method preserves these signals. Fig. 35 illustrates the projected monthly precipitation and temperature (minimum and maximum) change over the Great Lakes region in the next decade (2018-2027) relative to the past decade (2008-2017) under the RCP 4.5 scenario, from the CMIP5 raw projections without bias-correction, and from the CMIP5 QDM outputs based on both the NLDAS2-CaPA and MGLMD datasets. Slight projected increases in the precipitation ($0 \sim 3$ mm/month) are consistently revealed by both of the QDM outputs, matching the projected changes in the raw CMIP5 outputs both in pattern and magnitude. Both the QDM minimum and maximum temperature preserved the original slight warming trend as well, at magnitudes of $0.1 \sim 0.3$ K. These signals are considered subtle enough to possibly not being recognized by the current GLSHyFS modeling skill, and the model's inherent capability (with LBRM and LLTM) in simulating the intraseasonal and interannual variability still dominates the forecasting skill.

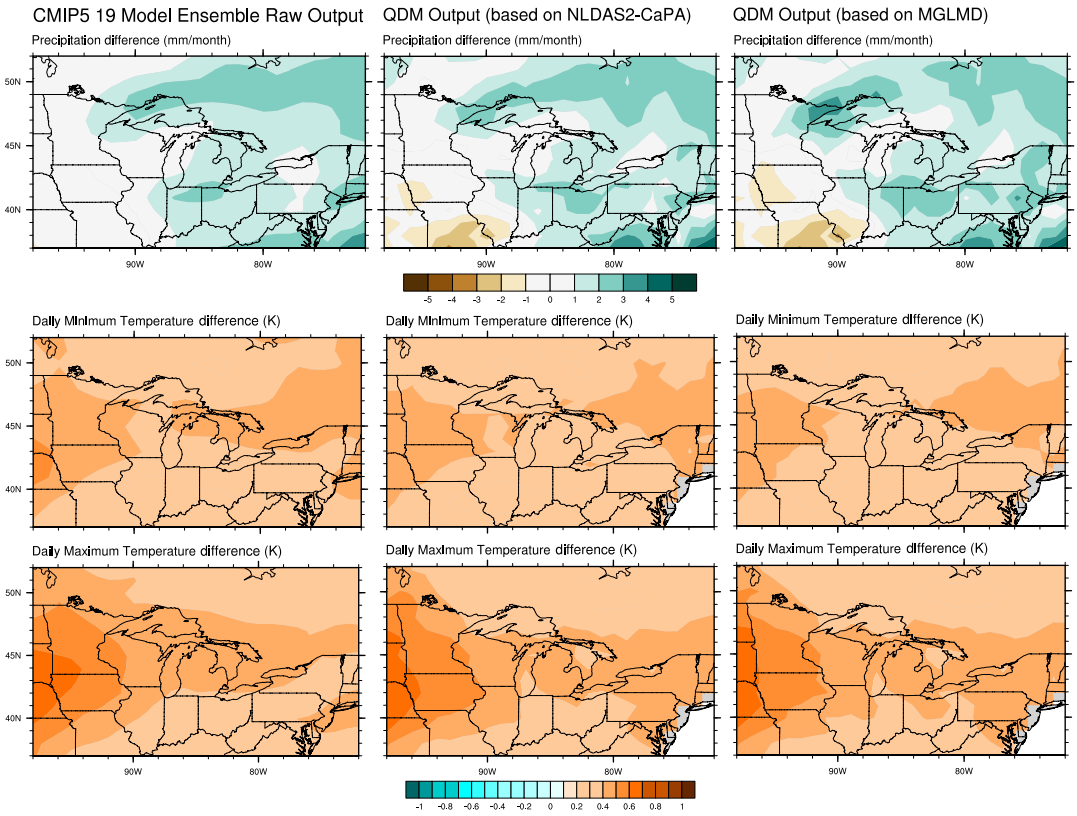

Figure 35: Projected 10-year monthly accumulated precipitation and averaged minimum, maximum air temperature change (average of 2018-2027 minus average of 2008-2017) under RCP 4.5 scenario by CMIP5 raw outputs, CMIP5 QDM-NLDAS2-CaPA outputs, and CMIP5 QDM-MGLMD outputs.

3.2 Validation of simulated hydrologic response

The LBRM and LLTM are the two main model components of the GLSHyFS framework to provide sub-basin runoff and over-lake evaporation estimates over the Great Lakes. In the GLSHyFS forced by CMIP5, the LBRM module has been armed with an improved evapotranspiration (ET) scheme which has been proved to correct most of the long-term ET overestimation issue over the land portion of the Great Lakes basin (Lofgren and Rouhana, 2016). LLTM conventionally uses cloud cover as a proxy to estimate the downward longwave and shortwave radiation, but in the current CMIP5-GLSHyFS framework, it is utilizing both types of radiation directly from the CMIP5 QDM outputs. With these upgrades and changes, the LBRM has been recalibrated and an ongoing effort has been made to recalibrate the LLTM. Following the validation strategy shown in Fig. 6, in this section we assessed the performance of LBRM and LLTM in simulating the runoffs and water temperature (key variable to calculate over-lake evaporation) in 2006-2015. Results here are reflecting the recalibrated LBRM simulations with the new ET algorithm, and the LLTM using its original parameters which are calibrated with cloud cover. Each of

the 19 model members in the CMIP5 QDM bias-corrected outputs are propagated into LBRM and LLTM respectively, and the mean of the model ensembles are analyzed in the following sections.

3.2.1 Runoff by LBRM: forced by CMIP5 and observational proxies in 2006-2015

In this section, all the LBRM simulated runoffs forced by the aforementioned six forcing datasets (see Section 3.1.3) are compared with that from the Water Budget Closure Model (WBCM, Gronewold et al., 2016; Smith and Gronewold, 2017, Submitted) as well as the gauge-based Area Ratio Method (ARM) estimates over Lake Superior, Lake Michigan, Lake Erie, and Lake Ontario (Fig. 36). The estimates from WBCM are considered as the best observational proxies, as the runoffs are derived based on the closure of the water budget over the entire Great Lakes giving multiple observational inputs in precipitation, runoff, and evaporation. Here the runoffs are converted into the lake water level increase in the unit of centimeters over the lake area contributed by all the corresponding sub-basin tributaries. LBRM model outputs are in daily timestep and here the monthly accumulated values are shown. For Lake Michigan, it is worth mentioning that both the WBCM and ARM estimates refer to the water level rise at the entire water surface of the connected Lake Michigan, Huron and Georgian Bay, while the LBRM simulated runoffs are destined for Lake Michigan only. It is thus more realistic to examine the revealed correlation relationship between the simulated and observed intraseasonal and interannual fluctuations rather than comparing the absolute magnitudes for the Lake Michigan basin. For all three other basins, the results from LBRM, WBCM and ARM are directly comparable. Currently the recalibrated parameters for some sub-basins in Lake Huron and Georgian Bay remain uncertain (results not shown), and efforts are ongoing to further improve it.

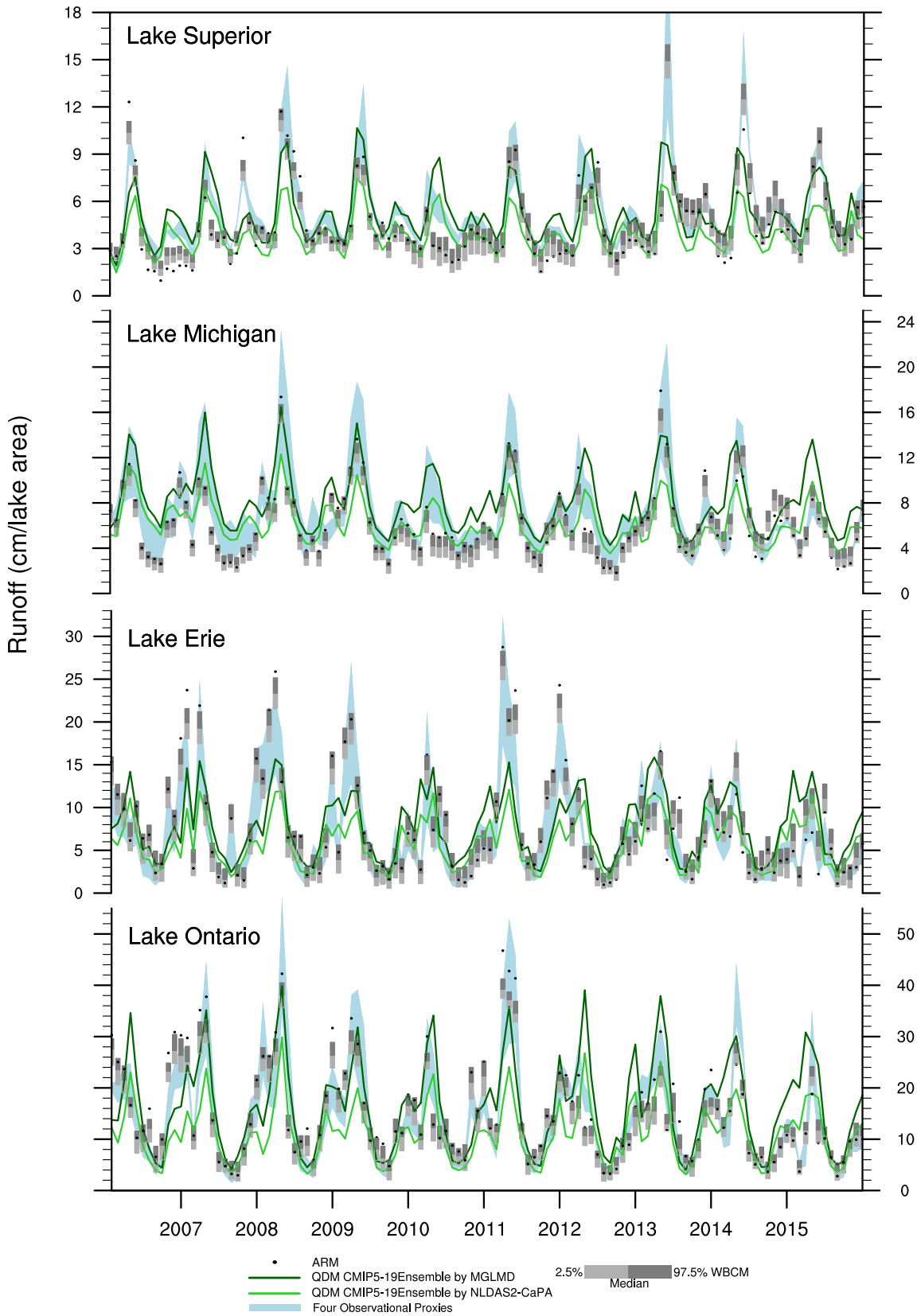

Figure 36: Runoffs by LBRM forced by the observational proxies (shaded in blue), CMIP5 QDM outputs, and from WBCM and ARM estimates in 2006-2015 over the land portion of the Great Lakes basin.

As the Tmin and Tmax propagated into these LBRM simulations contain relatively small variabilities among all the observational proxies and the CMIP5 QDM outputs (Fig. 33-34), the LBRM simulated runoffs (Fig. 36) exhibit strong sensitivity to the uncertainties in the precipitation forcings (Fig. 32). For Lake Superior, Erie, and Ontario, the runoffs resulted from the NLDAS2-CaPA based CMIP5 QDM forcings are in general matching the observed base-flow better in the dry seasons (fall and winter), while the runoffs resulted from the MGLMD based CMIP5 QDM forcings capture the peak-flow events better in wet seasons (spring and summer), consistent with their corresponding precipitation dataset. The simulated runoffs responded from the four observational proxies (shaded area) agree well with the WBCM and ARM estimations over Lake Erie and Lake Ontario, both in phase and magnitude, suggesting advanced skill of the new LBRM and a successful recalibration over these two basins. Runoffs simulated over the Lake Superior basin appears to be systematically shifted comparing to the observations, implying possible problems in the recalibrated parameters. Despite of uncertainties in the simulated runoff magnitude, the overall intraseasonal and interannual variability in the 10-year validation period was well represented when forced by the CMIP5 QDM outputs.

3.3 Runoff by LBRM: Projections in 2018-2027 forced by CMIP5

Forced by the CMIP5 bias-corrected future projections, the monthly accumulated runoffs simulated by LBRM averaged in the future 10 years (2018-2027) are shown in Fig. 37, comparing with the historical runoff estimations (averaged over 2006-2015 and 1986-2015) from ARM data over Lake Superior, Lake Michigan (ARM for combined Lake Michigan, Huron and Georgian Bay as mentioned above), Lake Erie and Lake Ontario. Runoff results forced by the two sets of CMIP5 QDM forcings are illustrated in red and green lines, and the historical data from ARM are shown in the dots. As very subtle changes in precipitation and temperature are projected in the next decade by the CMIP5 models (Fig. 35), we are expecting the projected runoffs to match the historical record in general. In Fig. 37, the simulated future runoffs forced by the CMIP5 projections align reasonably well with the historical record from ARM, which proved advanced skill of the new LBRM within current CMIP5-GLSHyFS framework.

It is also clear that the differences between the CMIP5 QDM precipitations calibrated by NLDAS2-CaPA and MGLMD still dominate the discrepancies between the projected future runoffs, with MGLMD based CMIP5 QDM forcings resulting in a higher lake level prediction in $2 \sim 4$ cm/lake area per month in general. Despite of this difference in magnitude, in Lake Erie and Lake Ontario basins where the LBRM demonstrated strong skill (Fig. 36), both of the two predicted future runoffs seem to replicate the historical record, with the MGLMD based predictions suggesting slightly more runoffs during spring

and summer than the historical period. Since uncertainties in the parameter sets of Lake Superior, Lake Huron and Georgian Bay still remain, recalibration might be needed to further lower the model's systematic errors currently seen from these basins.

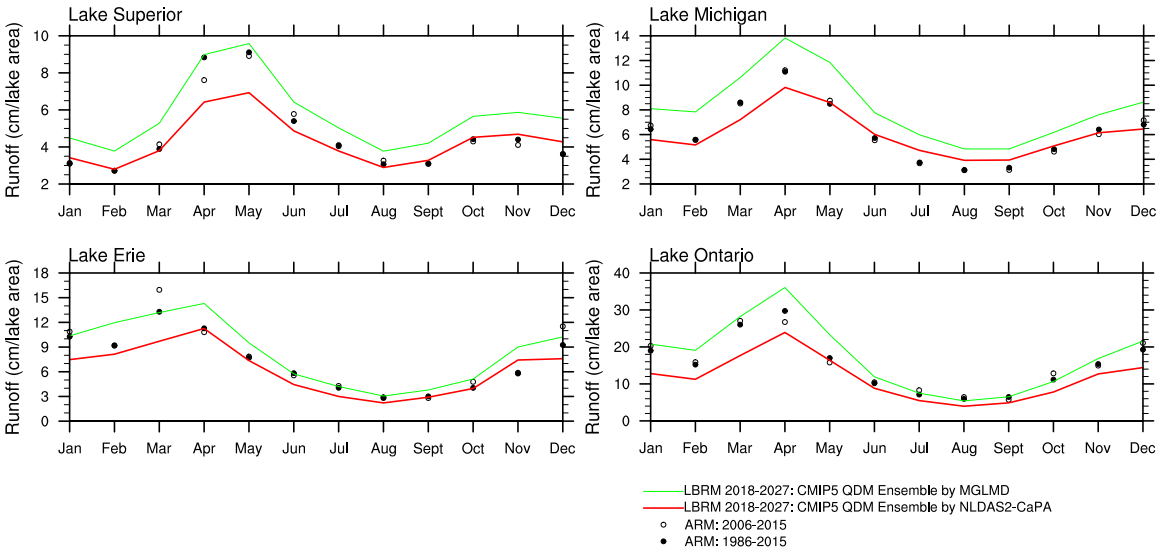

Figure 37: Comparisons between the projected mean monthly runoffs in 2018-2027 forced by CMIP5 QDM outputs and the historical records from ARM.

3.4 Water temperature simulated by LLTM in 2006-2015

Historically, the LLTM model used daily mean air temperature, dew point air temperature, wind speed, and cloud cover to simulate the over-lake evaporation for the Great Lakes basin. Cloud cover plays an important role in this set of framework to estimate the incoming shortwave radiations and the net (incoming minus outgoing) longwave radiations received by the water surface. In this newly developed CMIP5-GLSHyFS framework, it has been upgraded to incorporate the shortwave and longwave radiations directly from the CMIP5 QDM outputs as the forcing instead of using the cloud cover as a proxy. Recalibration is needed to reflect this change in the forcing field and the effort is ongoing. Here we are showing the preliminary result of the LLTM simulated water temperature using the old parameter sets (calibrated using the cloud cover as the forcing against the water temperature) as a baseline for the future development, and more analysis are on the way pending on completion of the recalibration.

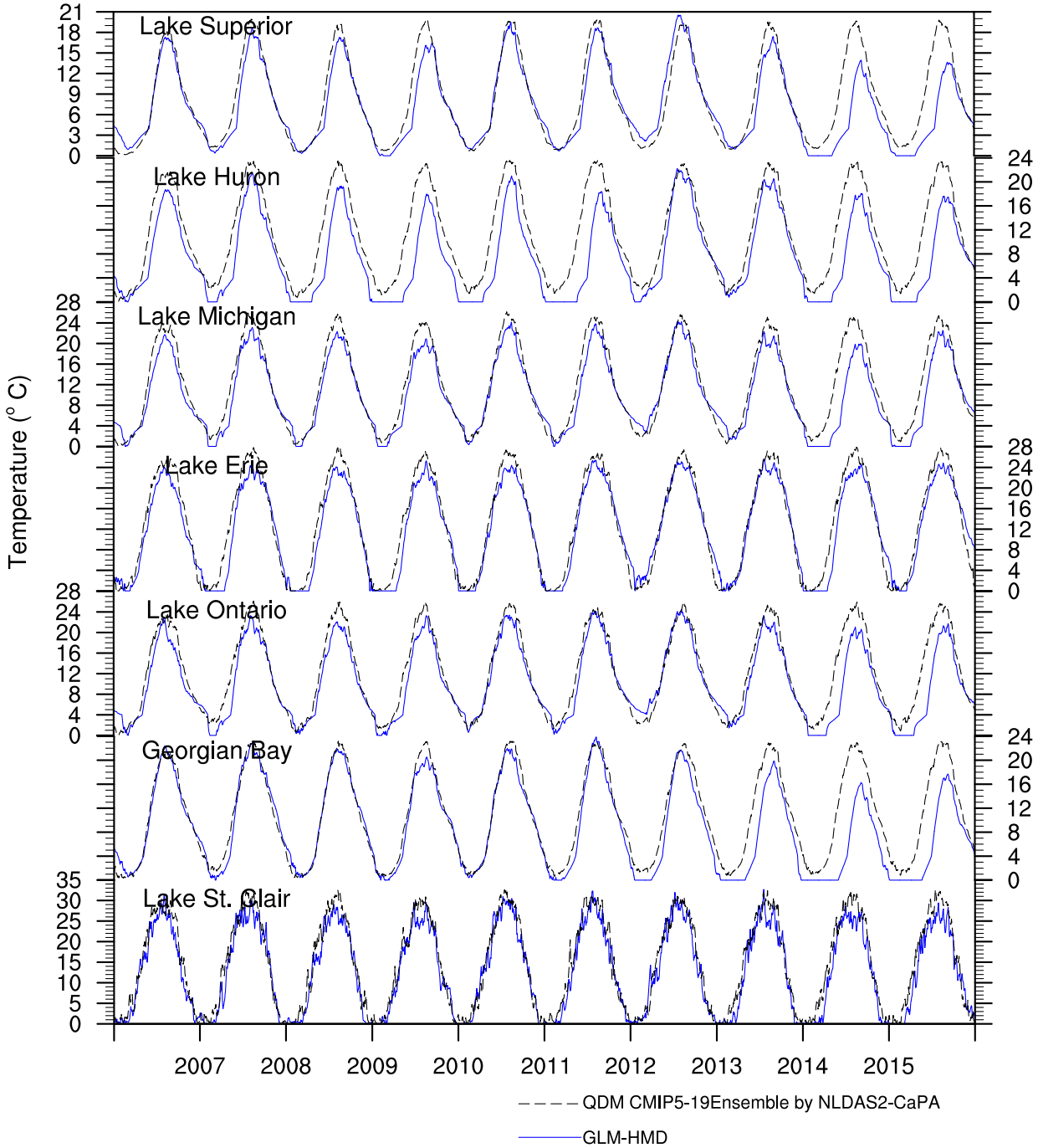

Figure 38: LLTM simulated water temperature in 2006-2015 forced by the CMIP5 NLDAS2-CaPA based QDM outputs and the GLM-HMD dataset.

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B LBRM and LLTM modifications

B.1 Reformulation of LBRM evapotranspiration algorithm

The LBRM is a conventional conceptual tank-cascade model designed for application to very large basins. The land surface and subsurface are represented by three conceptual layers (see figure B.1); an upper soil zone (the void space in surface soil that controls infiltration), a lower soil zone (the vertical space between the upper soil zone and the water table), and groundwater. The water balance in each of these tanks at a particular time step is dictated by initial storage, contributions from precipitation p and snowmelt m (or supply $s = m + p$), percolation, outflows, and evapotranspiration. Outflows from a particular tank are proportional to storage in that tank.

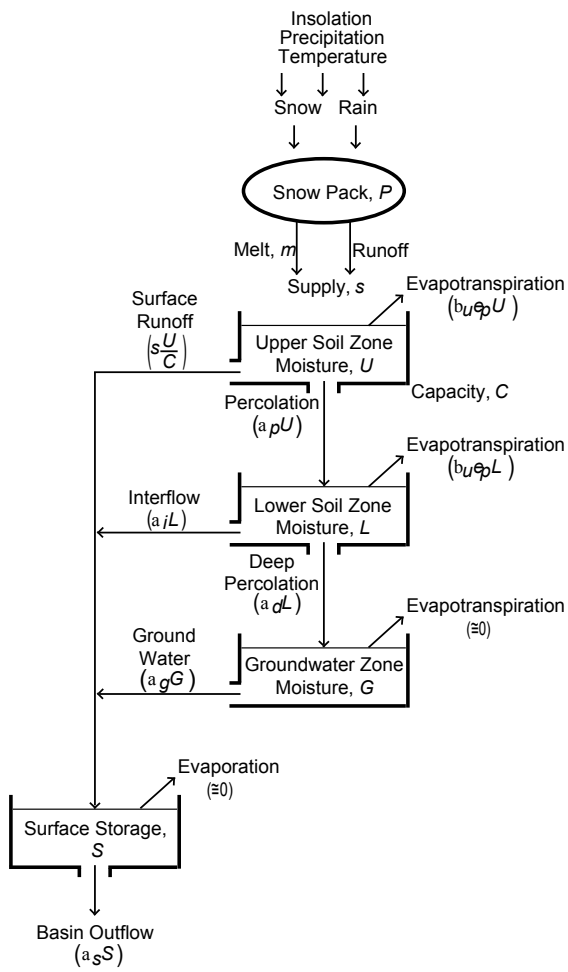


Figure B.1: Schematic representation of cascading 'tanks' within LBRM.

For example, upper soil zone moisture storage (USZM) at the end of each time step includes the portion of snowmelt and precipitation (s) that does not propagate into surface runoff (i.e. infiltration f), where surface runoff is calculated as:

$$r = s\frac{U}{C} \tag{7}$$

and f is therefore:

$$f = s - r \tag{8}$$
$$= s(1 - \frac{U}{C}) \tag{9}$$

where C is the capacity of the upper soil zone.
Over the same time step, percolation from the upper soil zone to the lower soil zone (z_p) is a linear function of USZM:

$$z_p = \alpha_p U \tag{10}$$

Evapotranspiration is computed only for the upper and lower soil zones (e_u and e_l) and is a linear function of a partial linear reservoir constant β, available moisture storage, and potential evapotranspiration e_p:

$$e_u = \beta_u U e_p \tag{11}$$
$$e_l = \beta_l L e_p \tag{12}$$

This leaves a total of five parameters describing the rate of flow from each zone:

$$\alpha_p = \text{Percolation coefficient (from U to L)} \tag{13}$$
$$\alpha_i = \text{Interflow coefficient (lateral flow from L)} \tag{14}$$
$$\alpha_d = \text{Deep percolation coefficient (from L to G)} \tag{15}$$
$$\alpha_g = \text{Groundwater flow coefficient (lateral flow from G)} \tag{16}$$
$$\alpha_s = \text{Surface storage flow coefficient} \tag{17}$$

and two parameters describing rate of evapotranspiration:

$$\beta_u = \text{Partial linear reservoir coefficient for U} \tag{18}$$
$$\beta_l = \text{Partial lienar reservoir coefficient for L} \tag{19}$$

Potential evapotranspiration e_p is then calculated as a function of non-latent (sensible) heat transfer:

$$e_p = \frac{dh}{dt} / \rho_w \gamma_v \tag{20}$$

where γ_v is the latent heat of vaporization $\approxeq$ 596-0.52T and ρ_w is the density of water.

One of the more significant modifications of the LBRM for the NYPA/OPG project is the modification of the formulation for the heat available for evapotranspiration (ψ). In the original formulation of LBRM, this quantity was expressed as follows:

$$\psi = k \exp(T_a / T_b) \tag{21}$$

Recent research, however, has indicated that this approach leads to overestimates of ET and, potentially, underestimates of runoff (Lofgren et al., 2011, 2013; Lofgren and Gronewold, 2013). Lofgren et al. (2011) proposed an alternative formulation:

$$\psi' \quad = \quad k \exp(T_L/T_b) \exp(T'/15.4) \tag{22}$$

where T_a is the air temperature (for a given day), T_b is a base scaling parameter, and T' is the difference between the daily air temperature (T_a) and the long-term historical average temperature (T_L) for that particular day .

```
*****************************************************************************************************
*****************************************************************************************************
*****************************************************************************************************

Code snippet from main program, where
Ta = today's mean air temperature;  (Tmax+TMin)/2:

         IF (PET_Method .EQ. 1) THEN             ! 1982 method (old)
            HIndx = HeatIndexMethod1(Ta, TBase)
         ELSE IF (PET_Method .EQ. 2) THEN        ! 2016 method (new)
            CALL SequenceDate(DD, MM, YY, Seq)              ! get today's day,month,year
            TL = AirTemps(MM, DD)             ! long-term air temp for this day/month
            TPrime = Ta - TL
            HIndx = HeatIndexMethod2(TL, TPrime, TBase)
         END IF

Subroutines being called:
      !-------------------------------------------------------------------------
      !  This is the original method as described by Dr. Thomas Croley when
      !  he developed the LBRM.
      !-------------------------------------------------------------------------
      REAL FUNCTION HeatIndexMethod1(Ta, Tbase)
      IMPLICIT NONE
      REAL, INTENT(IN) :: Ta, Tbase
      HeatIndexMethod1 = EXP(Ta/Tbase)
      END FUNCTION HeatIndexMethod1

      !-------------------------------------------------------------------------
      !  This revised method for computation of the heat index is based on the
      !  work of Dr. Brent Lofgren around 2011-2016.  This was added in 2016.
      !-------------------------------------------------------------------------
      REAL FUNCTION HeatIndexMethod2(TL, Tprime, Tbase)
      IMPLICIT NONE
      REAL, INTENT(IN) :: TL, TPrime, Tbase
      HeatIndexMethod2 = EXP(TL/Tbase) * EXP(Tprime/15.4)
      RETURN
      END FUNCTION HeatIndexMethod2



Method 1 (old):
Use today's daily mean air temperature value and the Tbase value (calibrated parameter)

Method 2 (new):
Use the long-term average daily air temperature for this date (e.g. June 21) and
the difference between today's daily mean air temp and that long-term value along with
the Tbase value (also calibrated, and usually a different value from method 1)

*****************************************************************************************************
*****************************************************************************************************
*****************************************************************************************************
```

B.2 LBRM recalibration

Prior to our study, parameters encoded in LBRM (v1.0) were based on a calibration conducted in the early to mid 1980s. To accommodate changes in the ET formulation for LBRMv2.0, we conditioned a new set of model parameters on historical flow, temperature, and precipitation data from 1991 through 2000 using the dynamically-dimensioned search (DDS) optimization technique developed by Tolson and Shoemaker (2007). The period of record for the LBRM 2.0 calibration was based, in part, on availability of synthetic historical flow records and meteorological forcings from the NOAA-GLERL GLM-HMD (Hunter et al., 2015) for all of the LBRM sub-basins. A representative time series plot of T_{max}, T_{min}, and P during the calibration period are presented in figure B.2. A representative plot of the resulting storage in each LBRM 'layer', along with a comparison between observed and simulated surface runoff, is included in figure B.3.

B.3 Reformulation of LLTM cloud cover algorithm

The snippets of code below are from the revised LLTM executable, and reflect two approaches to estimating radiation values. If cloud cover data is used, the following general steps are executed:

- incident shortwave radiation is calculated by first computing (via interpolation) incoming insolation radiation (for a given day) assuming clear skies, and then reducing that value in proportion to the amount of observed cloud cover.
- daily net longwave radiation is calculated as a combination of incoming and outgoing energy via water surface temperature, air temperature, daily cloud cover, and vapor pressure (as a function of humidity).

If CMIP5 radiation is used directly, the following steps are executed:

- incident shortwave radiation is derived directly from CMIP without modification.
- longwave radiation from CMIP is only the INCOMING longwave. Outgoing radiation is based on surface water temperature.

```
*****************************************************************************************************
*****************************************************************************************************
*****************************************************************************************************


      !-----------------------------------------------------------------------
      !  DailyIncidentSolarRadiation = Daily total solar radiation incident to the
      !     water surface in langleys (calories/square cm)
      !  Dy, Mn, Yr = Calendar day, month, and year of the date.
      !  CloudCover = average daily fraction of sky covered with clouds
      !-----------------------------------------------------------------------
      REAL FUNCTION DailyIncidentSolarRadiation (Dy, Mn, Yr, CloudCover)
      IMPLICIT NONE
      INTEGER, INTENT(IN) :: Dy, Mn, Yr
      REAL,    INTENT(IN) :: CloudCover       ! (range = 0.0 - 1.0)

      INTEGER :: II
      REAL    :: X, NDYS, NDY
```

```
!
!  INDPM  = number of days per month cumulative from the 1st of the year, days
!
INTEGER, PARAMETER :: INDPM(13) = (/  0,  31,  59,  90, 120, 151,       &
                                 181, 212, 243, 273, 304, 334, 365/)

!
!  R = AVERAGE MID-MONTH CLOUDLESS-DAY INSOLATION in langleys
!          (note that before aug99 this was declared as a REAL array,
!           but the DATA statement contains integers.  This violates
!           good practice [and maybe the Fortran standard], and it
!           was not necessary that R be a REAL, so I've changed the
!           declaration to an INTEGER.   TSH 04aug99]
!
!         Dec,Jan,Feb,Mar,Apr,May,Jun,Jul,Aug,Sep,Oct,Nov,Dec,Jan
INTEGER, DIMENSION(14,8), PARAMETER :: R = RESHAPE(                 &
       (/ 150,190,330,490,640,770,790,770,670,510,360,200,150,190,   &  ! SUP
          190,220,340,480,620,700,730,700,610,490,360,240,190,220,   &  ! MIC
          150,190,330,490,640,770,790,770,670,510,360,200,150,190,   &  ! HUR
          150,190,330,490,640,770,790,770,670,510,360,200,150,190,   &  ! GEO
          190,220,335,470,610,710,755,725,635,515,380,250,190,220,   &  ! STC
          190,220,335,470,610,710,755,725,635,515,380,250,190,220,   &  ! ERI
          180,200,320,460,595,695,740,705,615,495,360,230,180,200,   &  ! ONT
          150,190,330,490,640,770,790,770,670,510,360,200,150,190/), &  ! HGB
        SHAPE(R))


!
!  LkNum = 1 (Superior), 2 (Michigan), 3 (Huron without Georgian Bay),
!          4 (Georgian Bay), 5 (St. Clair), 6 (Erie), 7 (Ontario),
!          8 (Huron with Georgian Bay).
!
IF (Dy .GT. 15) THEN
   II = INDPM(Mn + 1) - INDPM(Mn)
   IF (II .EQ. 28 .AND. INT((FLOAT(Yr) + .5) / 4.) * 4 .EQ. Yr) II = 29
   NDYS = FLOAT(II)
   NDY  = FLOAT(Dy) - 15.
   X    = (R(Mn+2, g_LkNum) - R(Mn+1, g_LkNum)) / NDYS * NDY + R(Mn+1, g_LkNum)
ELSE
   IF (Mn .EQ. 1) THEN
      II = 31
   ELSE
      II = INDPM(Mn) - INDPM(Mn-1)
      IF (II .EQ. 28 .AND. INT((FLOAT(Yr) + .5) / 4.) * 4 .EQ. Yr) II = 29
   END IF
   NDYS = FLOAT(II)
   NDY  = NDYS - 15. + FLOAT(Dy)
   X    = (R(Mn+1,g_LkNum) - R(Mn,g_LkNum)) / NDYS * NDY + R(Mn,g_LkNum)
END IF
DailyIncidentSolarRadiation = X * (0.355 + 0.68 * (1. - CloudCover))
RETURN

END FUNCTION DailyIncidentSolarRadiation


!-----------------------------------------------------------------------
!  DailyNetLongwaveRadiation = Daily net longwave radiation exchange between
!        the atmosphere and the body of water in langleys (calories/square cm)
!     AirTemperature = temperature of atmosphere above water body in degrees C
!     WaterTemperature = (surface) temperature of water body in degrees Celcius
!     CloudCover = average daily fraction of sky covered with clouds
!     VaporPressureOfAir = mean vapor pressure in the air (@ 2m) in millibars
!     IncLW = incoming longwave radiation in langleys (calories/square cm)
!
!  RadIn  = radiation air -> water
!  RadOut = radiation water -> air
!-----------------------------------------------------------------------
REAL FUNCTION DailyNetLongwaveRadiation (WaterTemperature,          &
```

```
                AirTemperature, CloudCover, VaporPressureOfAir, IncLW)
      IMPLICIT NONE
      REAL, INTENT(IN) :: WaterTemperature, AirTemperature, CloudCover
      REAL, INTENT(IN) :: VaporPressureOfAir, IncLW
      REAL :: P9, Emissivity, ATemp, WTemp, RadIn, RadOut

      IF (ModelCfg%RadiationMethod .EQ. 1) THEN
         Emissivity = 0.53 + 0.065 * SQRT(VaporPressureOfAir)
         ATemp = AirTemperature   + 273.16
         P9    = ModelParms%Parms(9)
         RadIn = 1.17e-7 * ATemp ** 4 * Emissivity                      &
                 * (P9 + (1.0 - P9) * (1.0 - CloudCover))
      ELSE IF (ModelCfg%RadiationMethod .EQ. 2) THEN
         RadIn = IncLW
      ENDIF
      WTemp = WaterTemperature + 273.16
      RadOut = 0.97 * 1.17e-7 * WTemp ** 4
      DailyNetLongwaveRadiation = RadIn - RadOut
      RETURN

      END FUNCTION DailyNetLongwaveRadiation
```

****
****
****

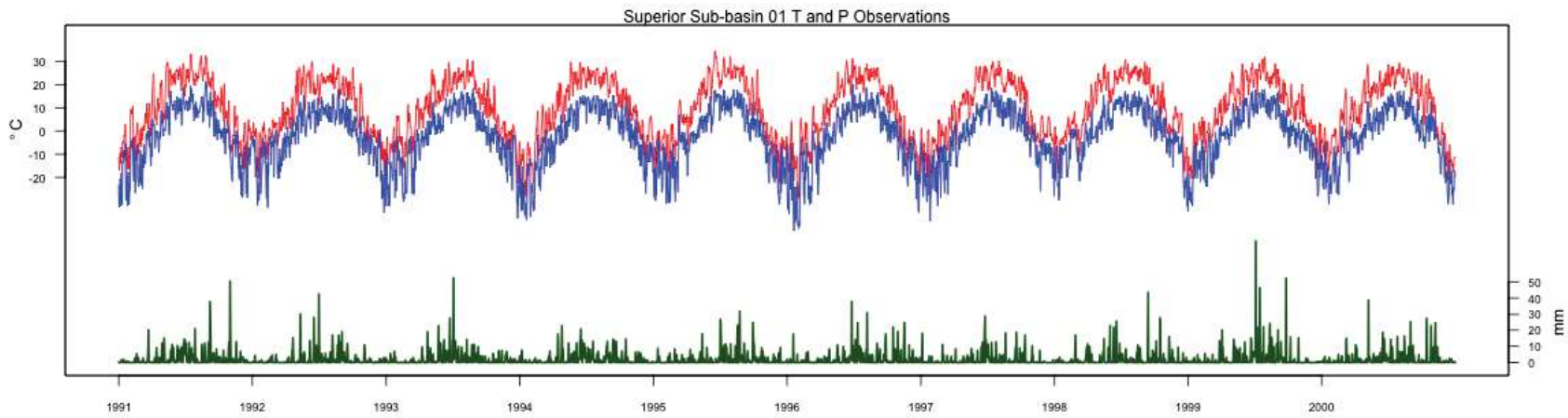


Figure B.2: A representative time series plot of T_{max}, T_{min}, and P during the LBRM calibration period.

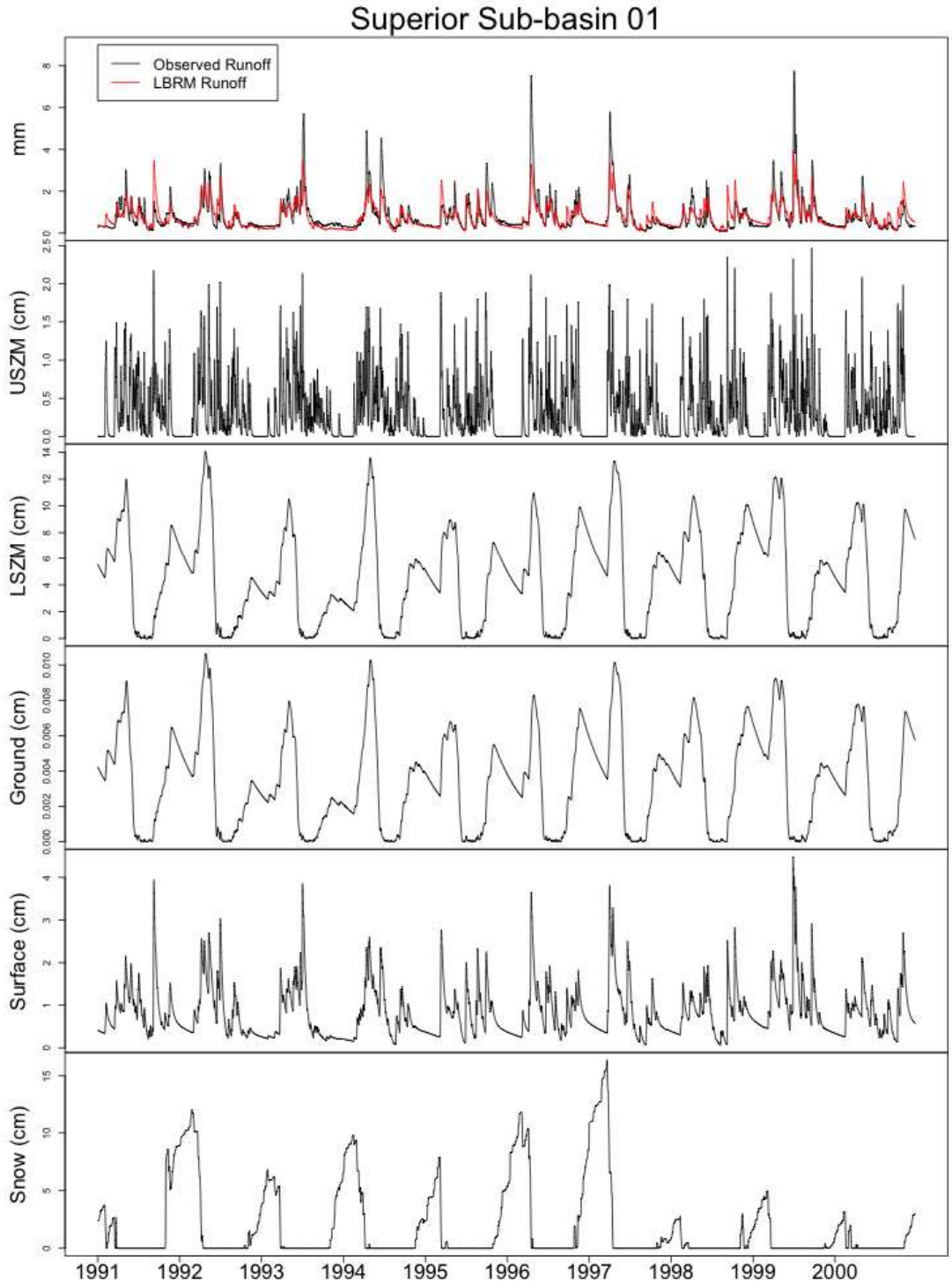
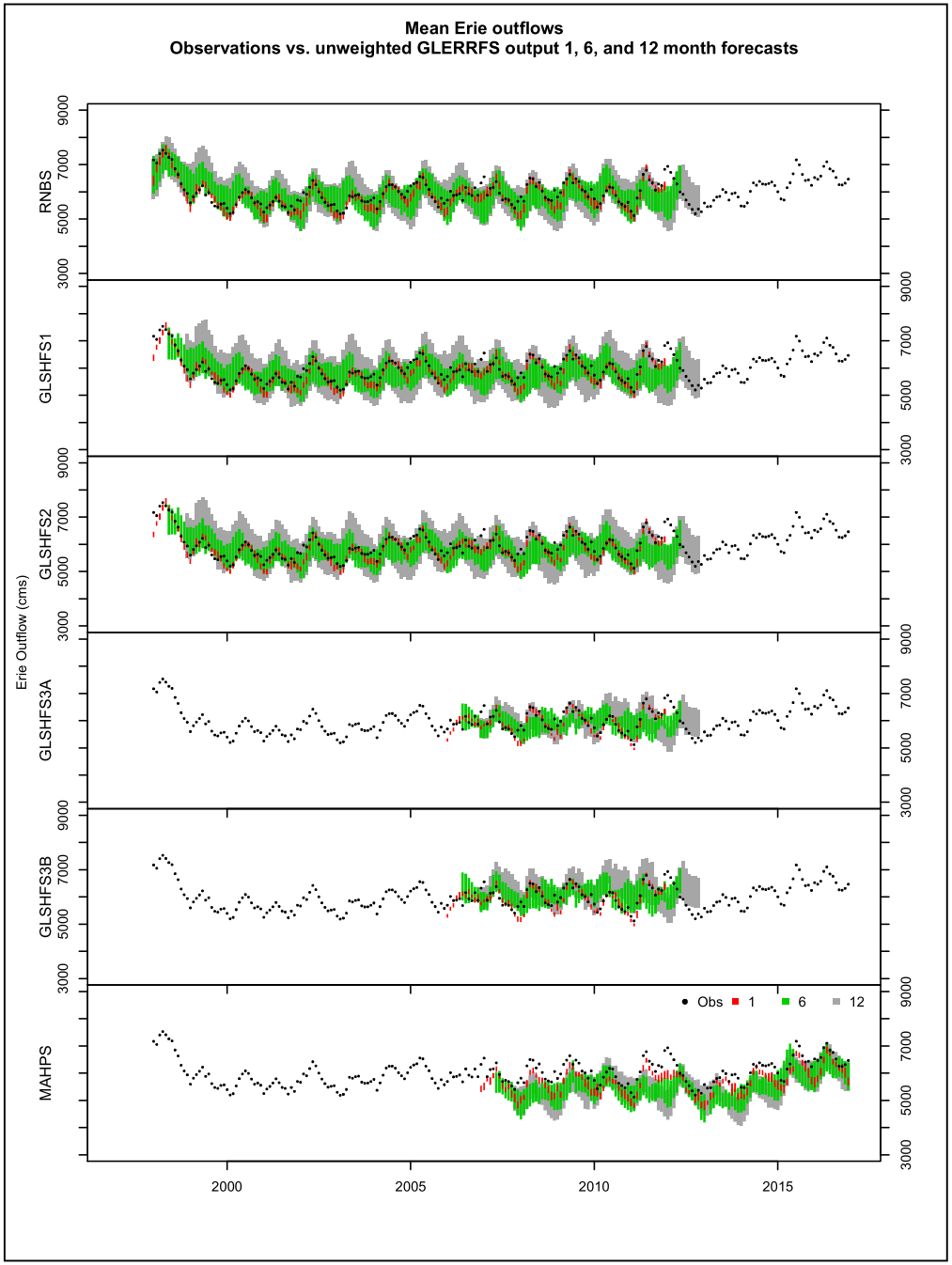


Figure B.3: A representative time series plot of simulated and observed runoff, along with simulations of storage in the cascading tanks of LBRM.

C Supplementary skill assessments

This section includes a suite of figures representing retrospective skill assessments based on Lake Erie outflow, and Lake Ontario cumulative NBS.


Mean Erie outflows
Observations vs. unweighted GLERRFS output 1, 6, and 12 month forecasts
Erie Outflow (cms)
RNBS
GLSHFS1
GLSHFS2
GLSHFS3A
GLSHFS3B
MAHPS
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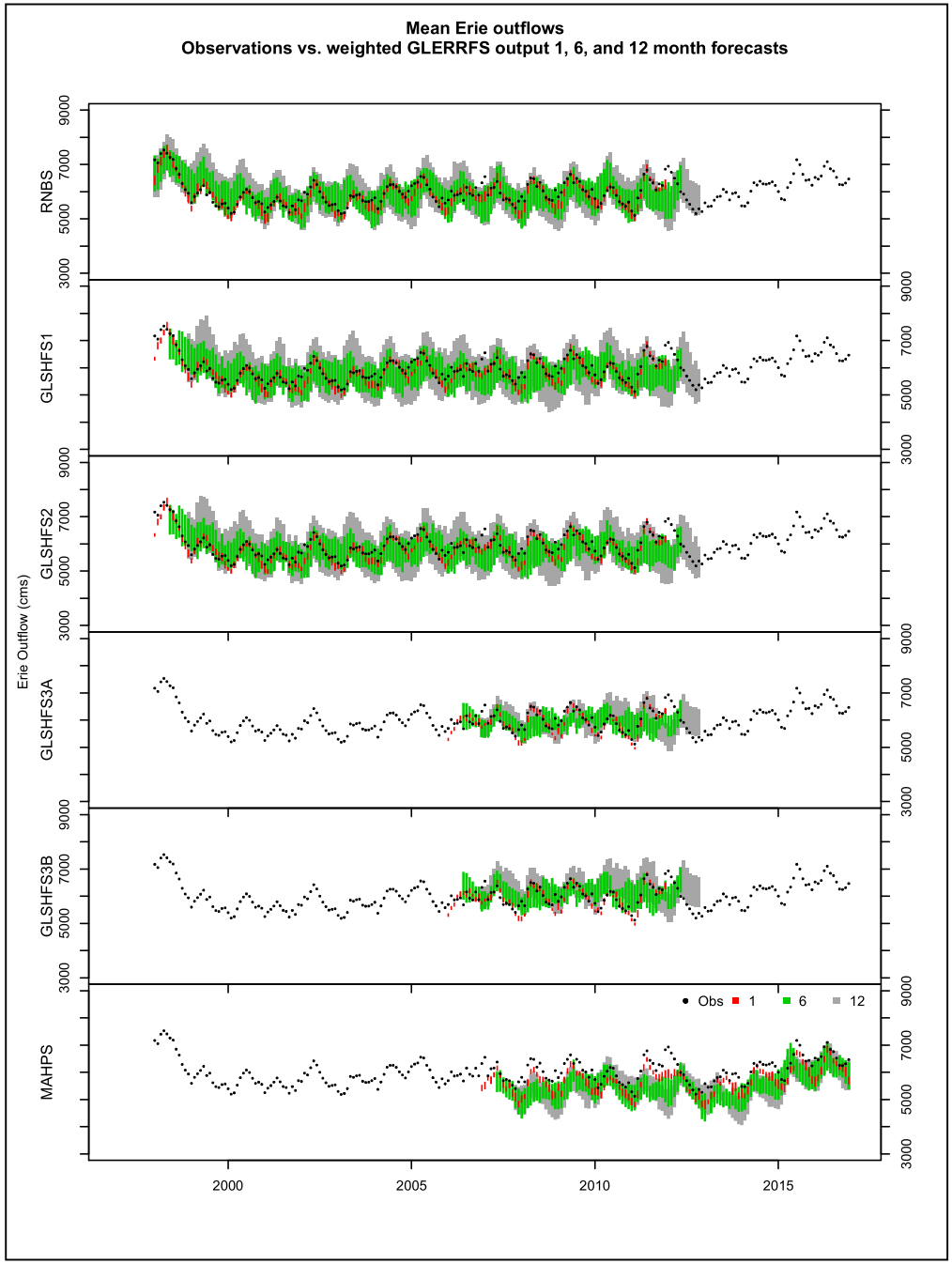
Mean Erie outflows
Observations vs. weighted GLERRFS output 1, 6, and 12 month forecasts
Erie Outflow (cms)
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GLSHFS1
GLSHFS2
GLSHFS3A
GLSHFS3B
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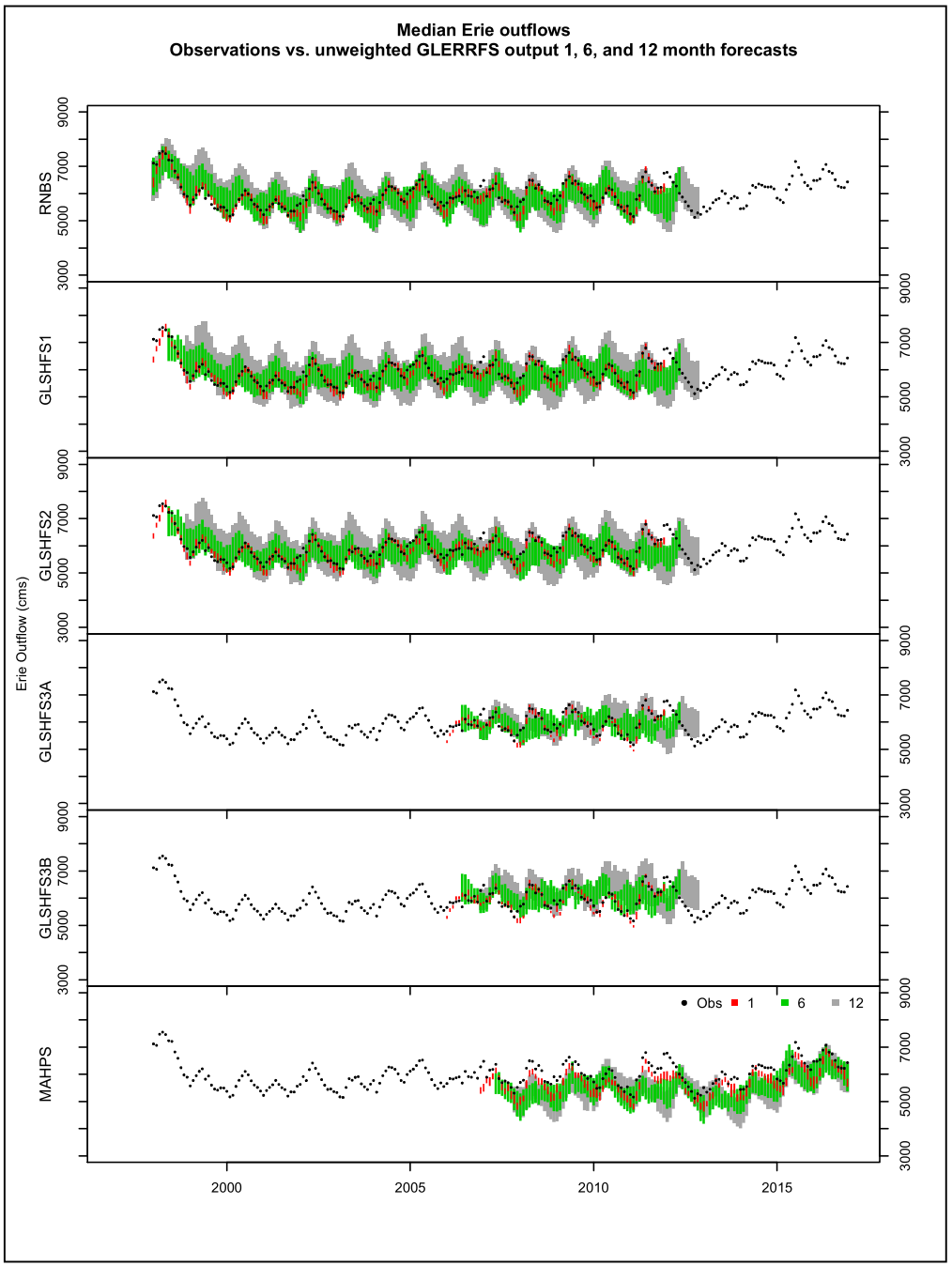
Median Erie outflows
Observations vs. unweighted GLERRFS output 1, 6, and 12 month forecasts
Erie Outflow (cms)
RNBS
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GLSHFS2
GLSHFS3A
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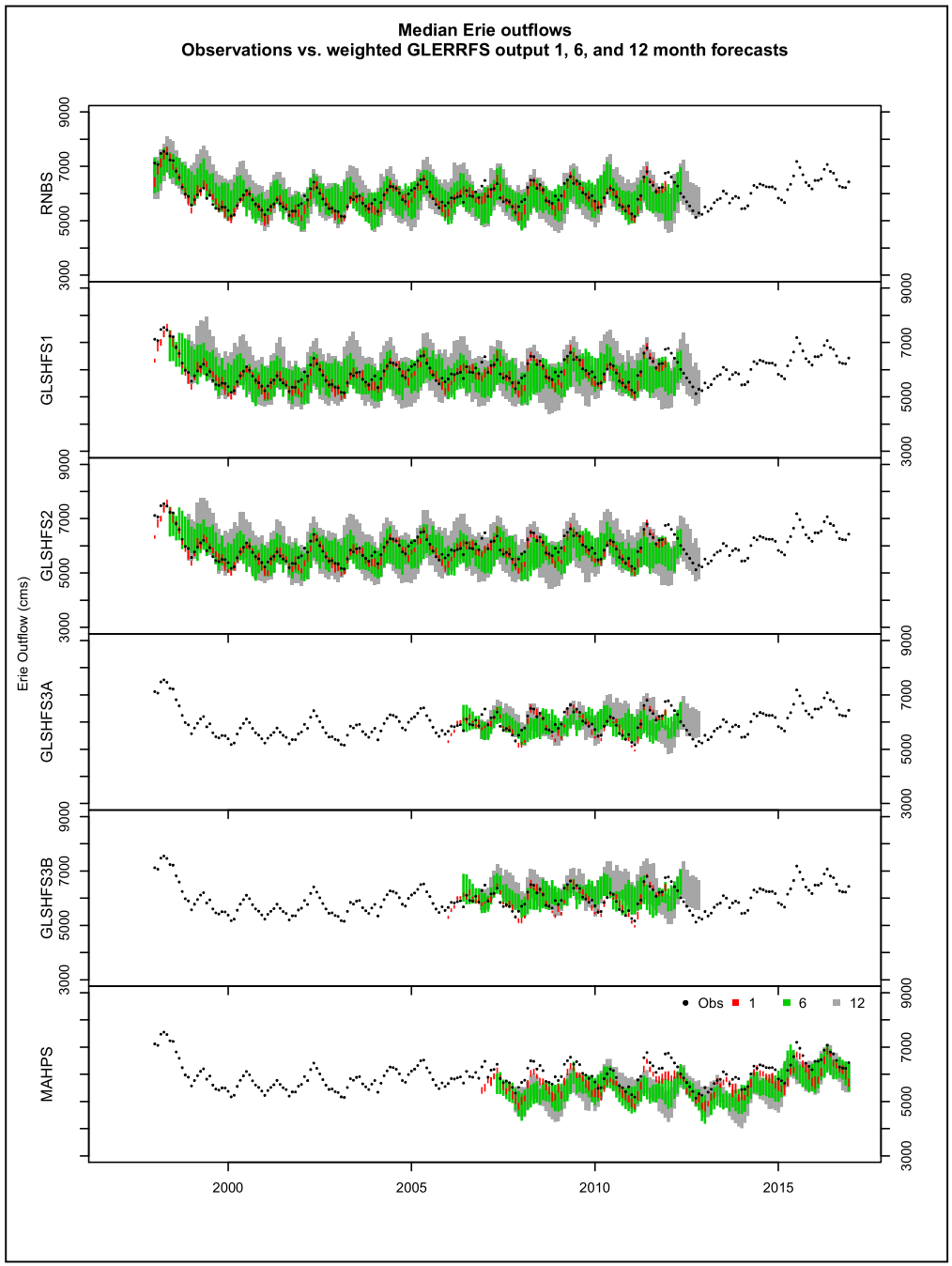
Median Erie outflows
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Erie Outflow (cms)
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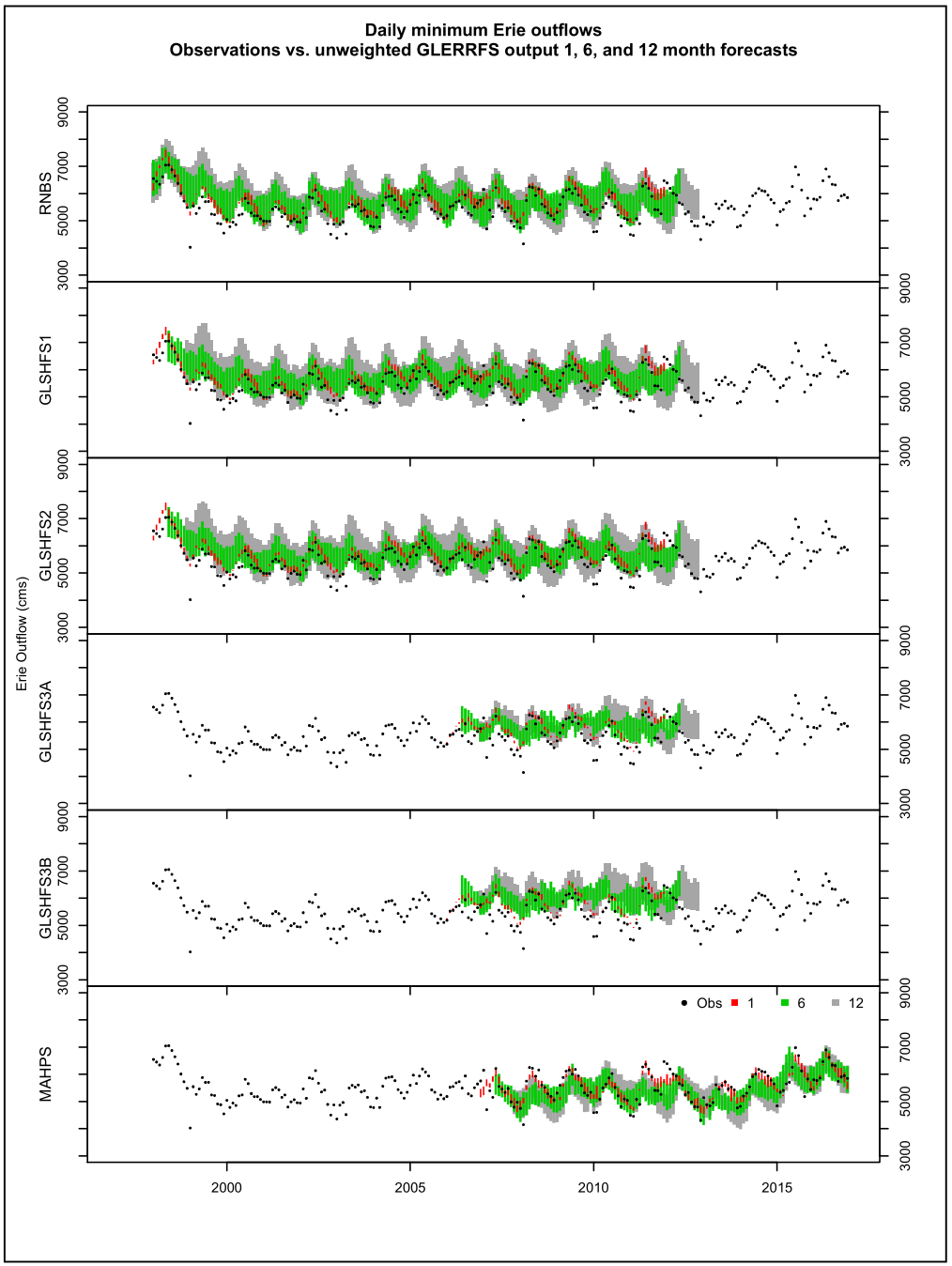
Daily minimum Erie outflows
Observations vs. unweighted GLERRFS output 1, 6, and 12 month forecasts
Erie Outflow (cms)
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GLSHFS1
GLSHFS2
GLSHFS3A
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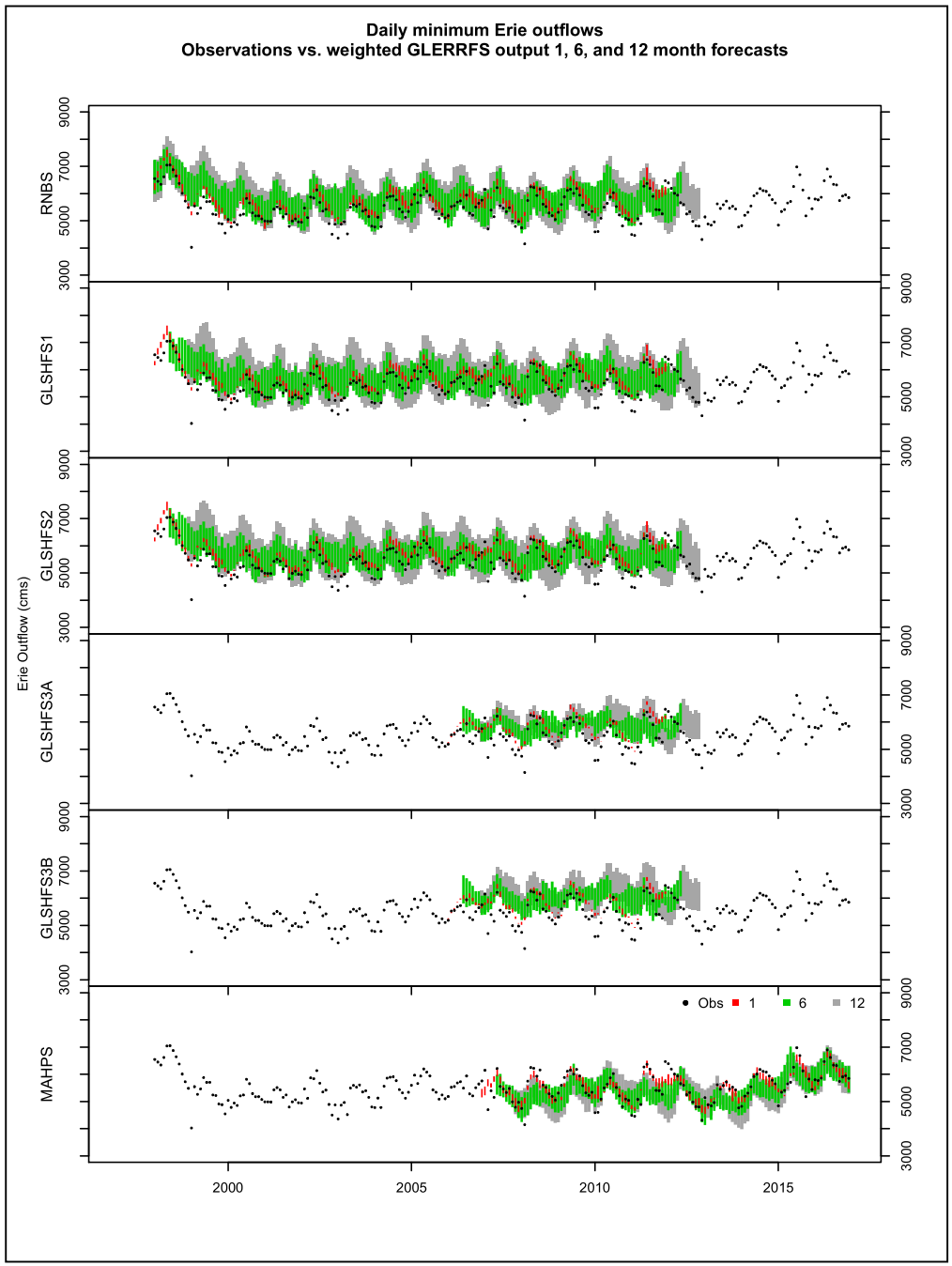
Daily minimum Erie outflows
Observations vs. weighted GLERRFS output 1, 6, and 12 month forecasts
Erie Outflow (cms)
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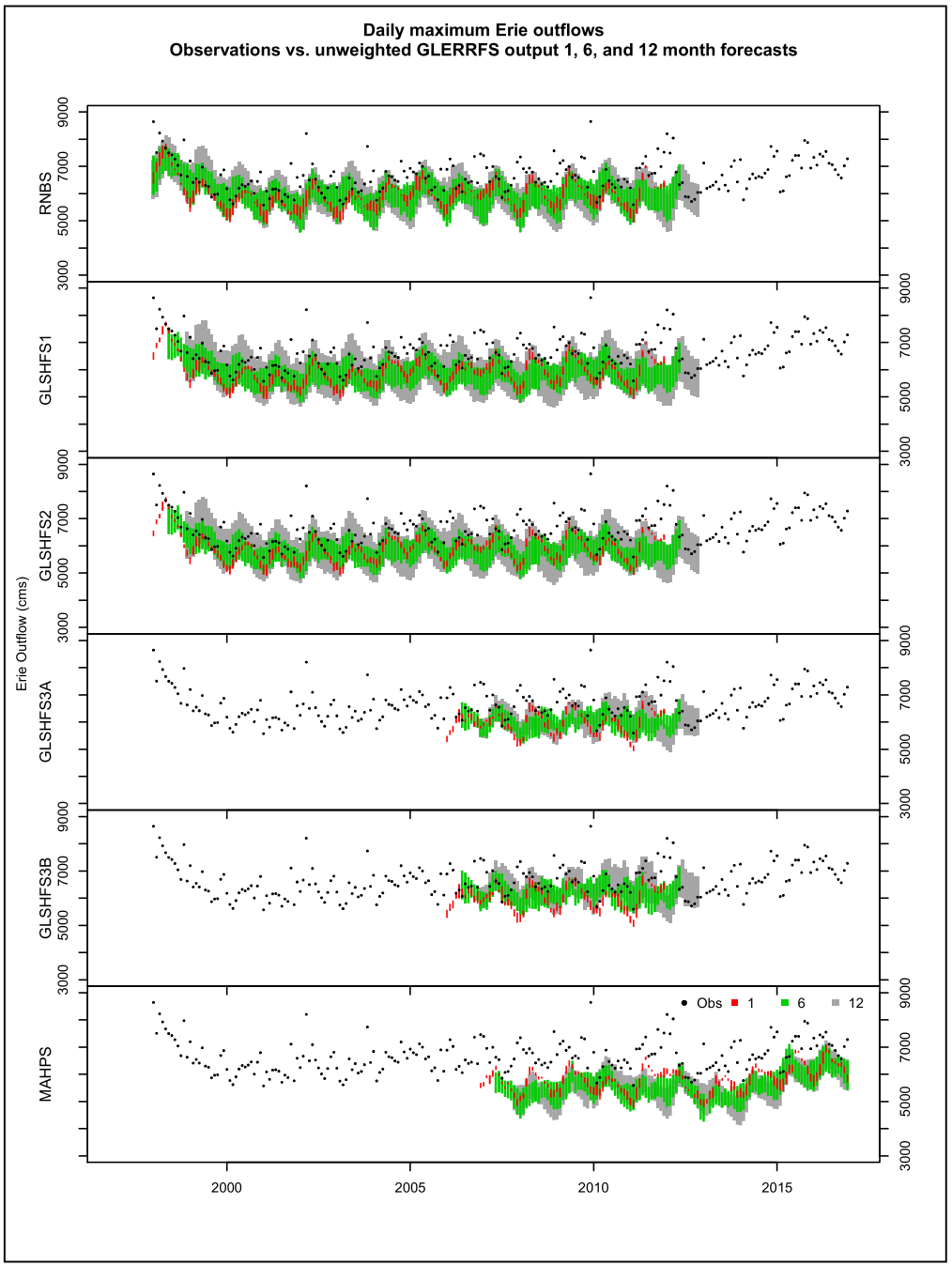
Daily maximum Erie outflows
Observations vs. unweighted GLERRFS output 1, 6, and 12 month forecasts
Erie Outflow (cms)
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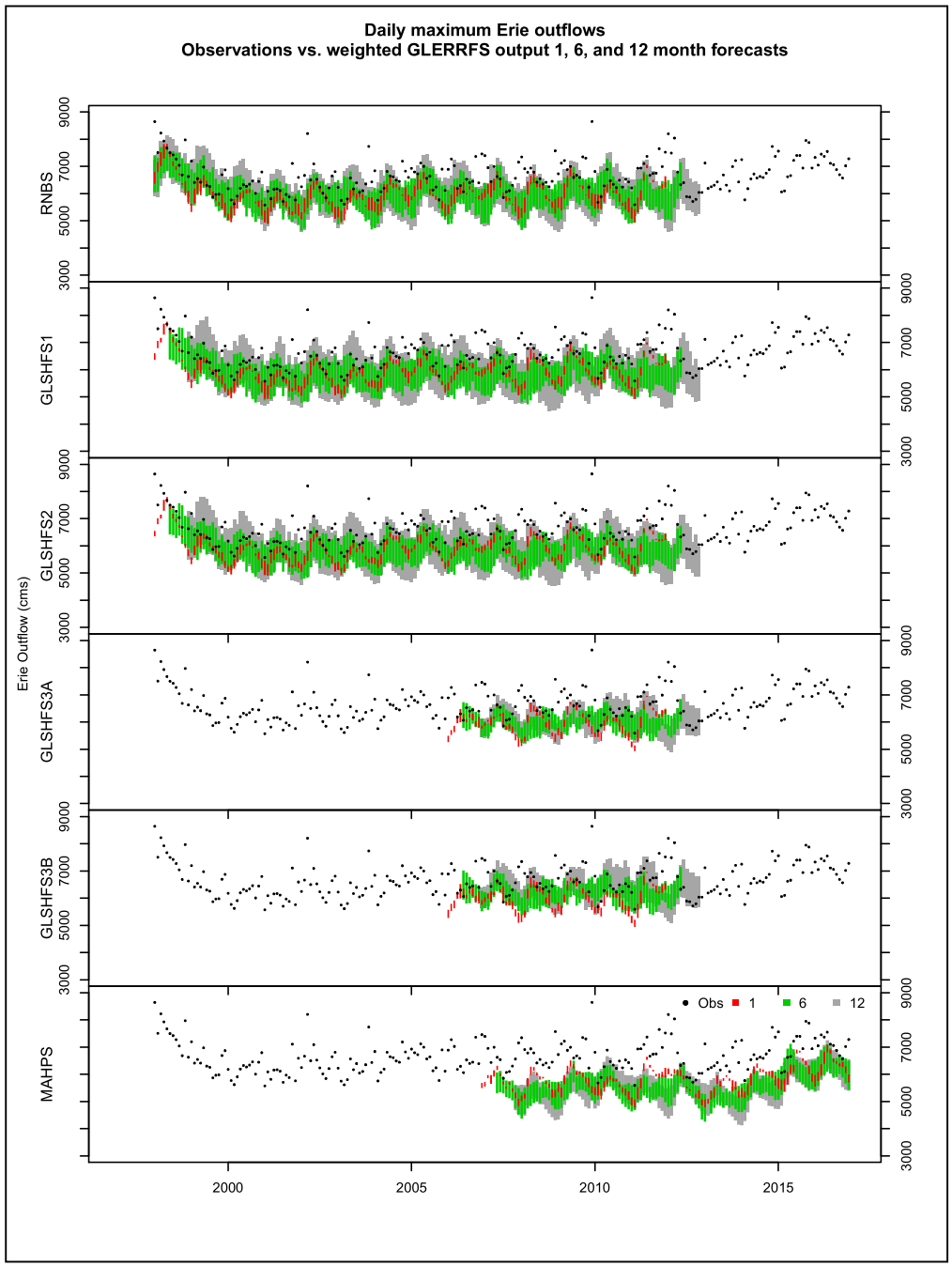
Daily maximum Erie outflows
Observations vs. weighted GLERRFS output 1, 6, and 12 month forecasts
Erie Outflow (cms)
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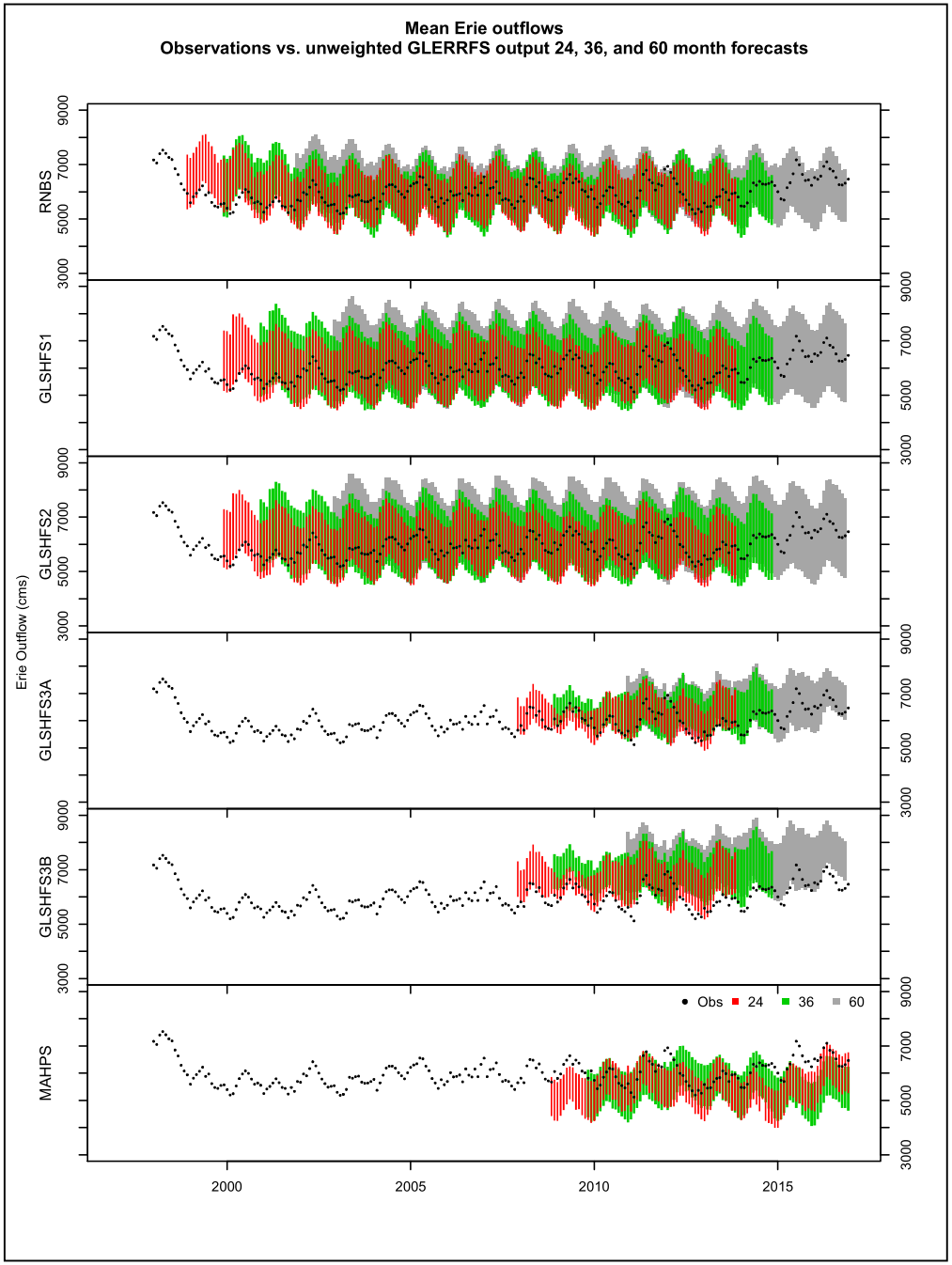
Mean Erie outflows
Observations vs. unweighted GLERRFS output 24, 36, and 60 month forecasts
Erie Outflow (cms)
RNBS
GLSHFS1
GLSHFS2
GLSHFS3A
GLSHFS3B
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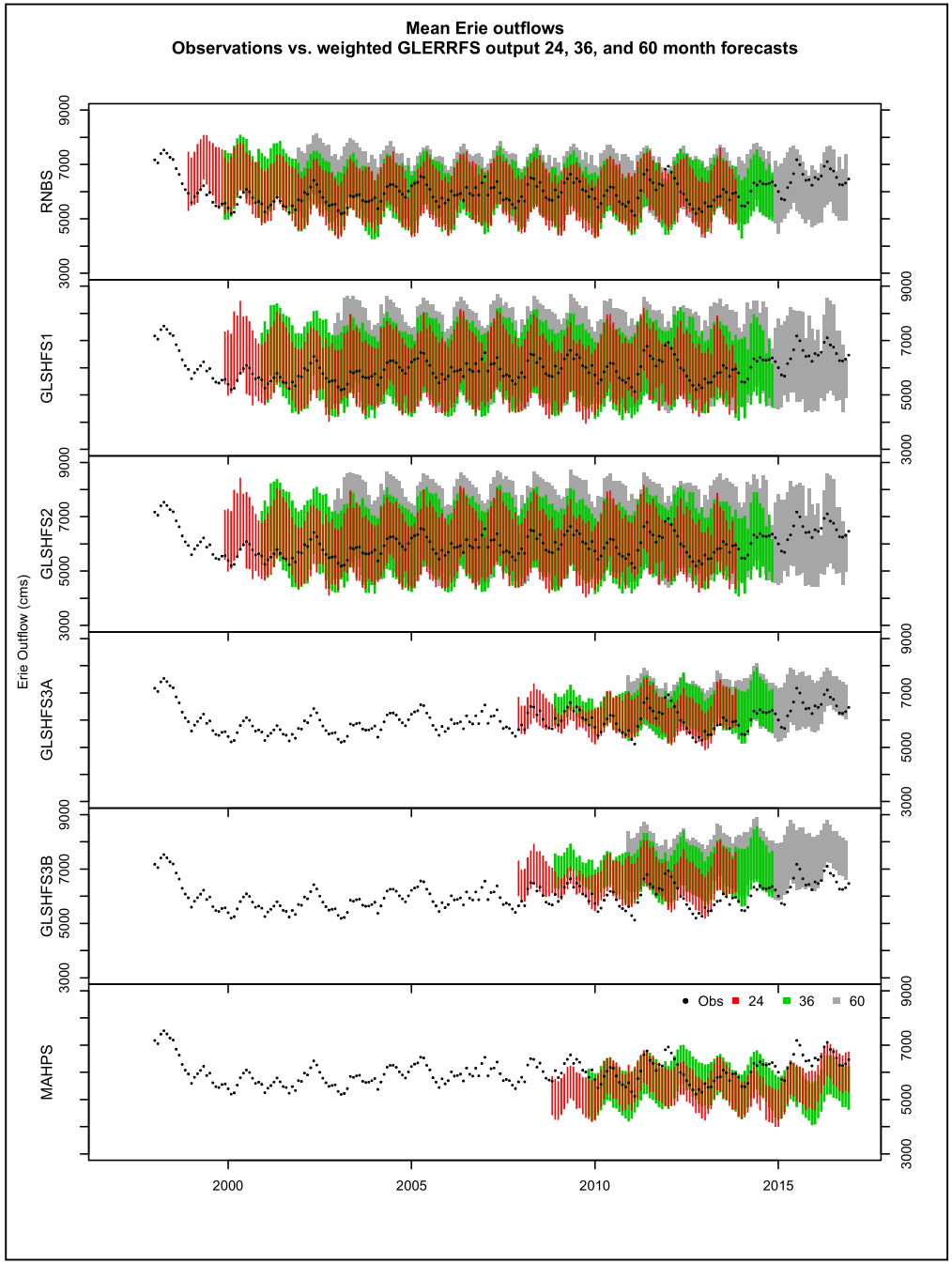
Mean Erie outflows
Observations vs. weighted GLERRFS output 24, 36, and 60 month forecasts
Erie Outflow (cms)
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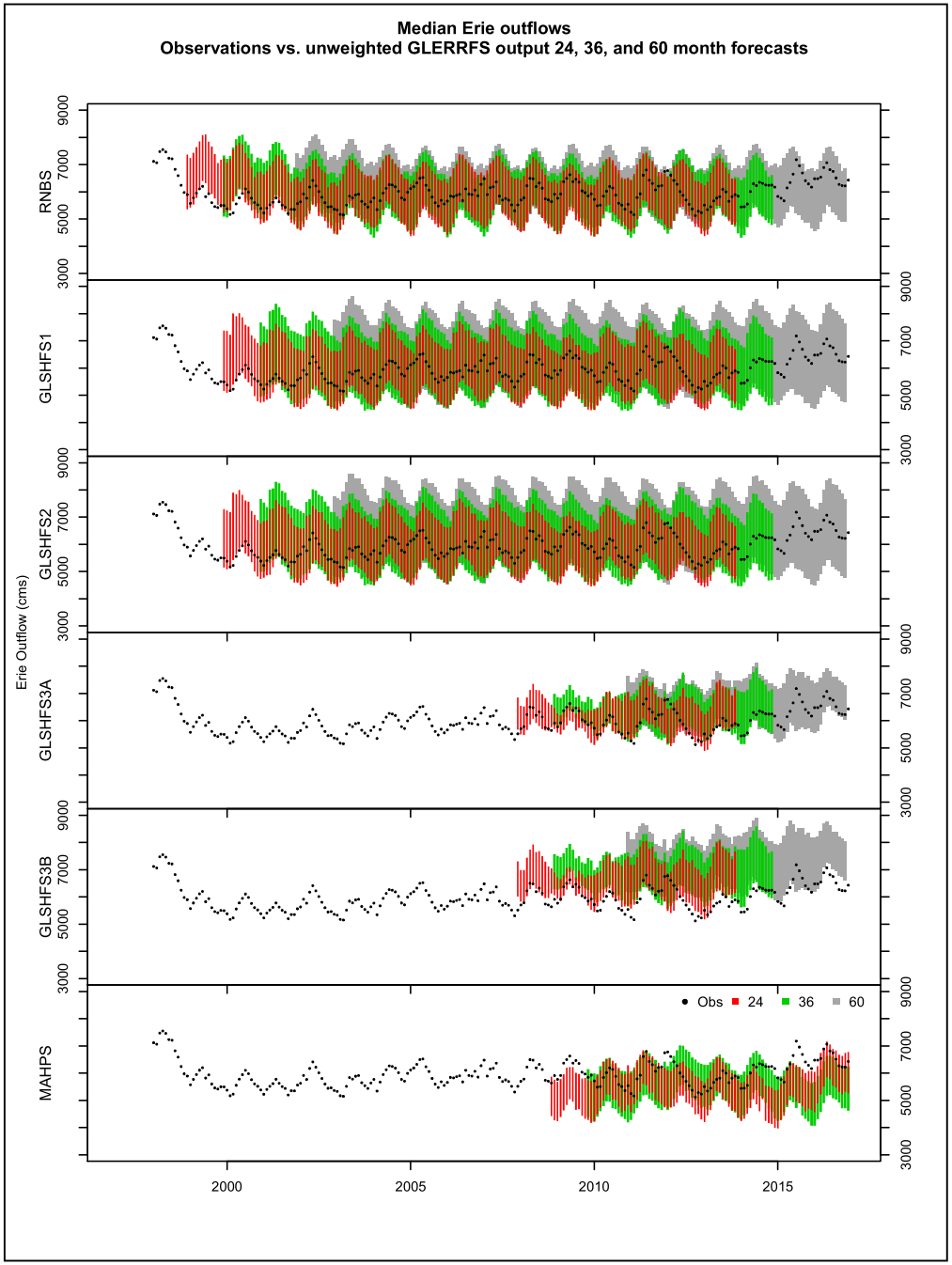
Median Erie outflows
Observations vs. unweighted GLERRFS output 24, 36, and 60 month forecasts
Erie Outflow (cms)
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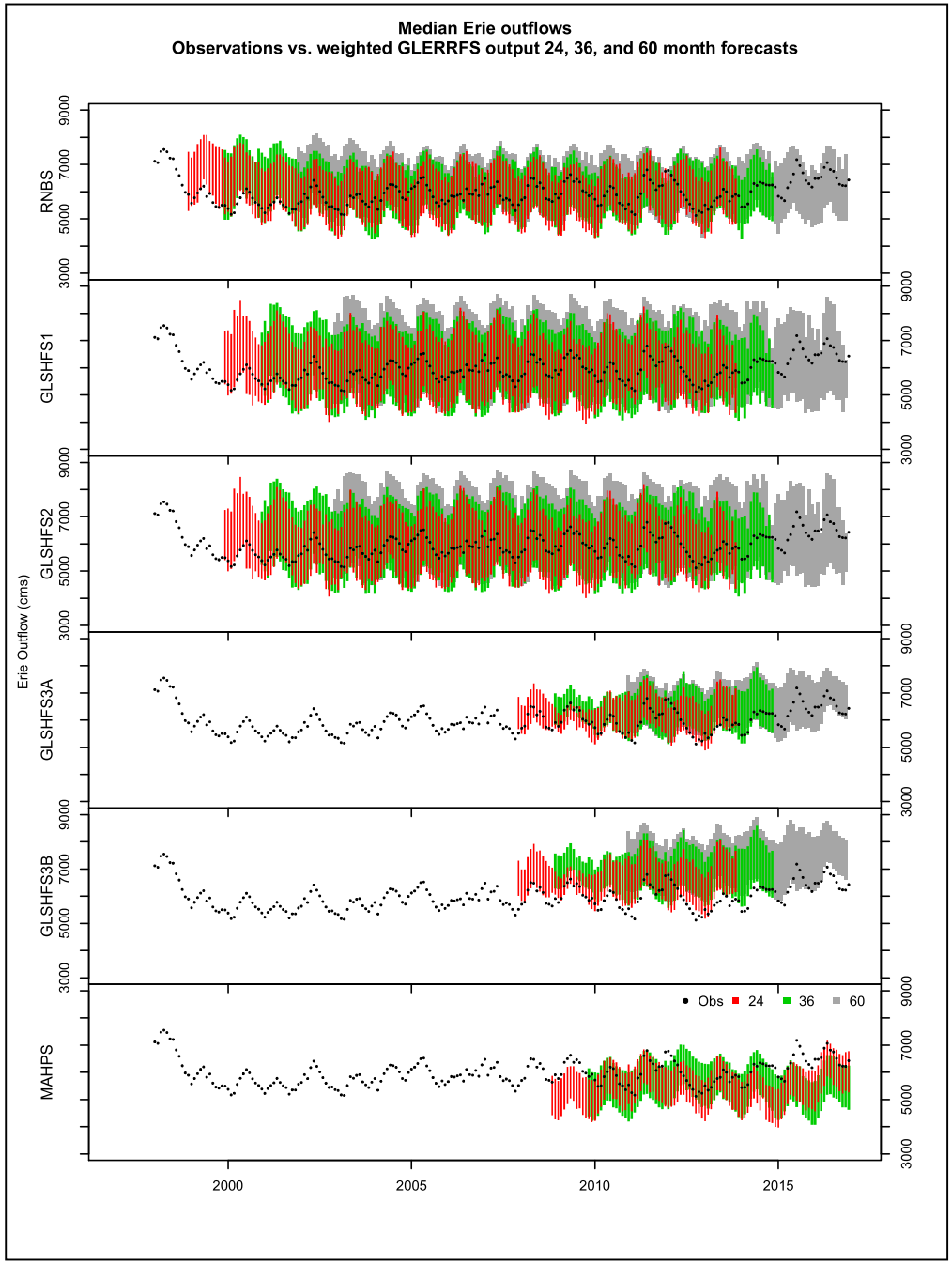
Median Erie outflows
Observations vs. weighted GLERRFS output 24, 36, and 60 month forecasts
Erie Outflow (cms)
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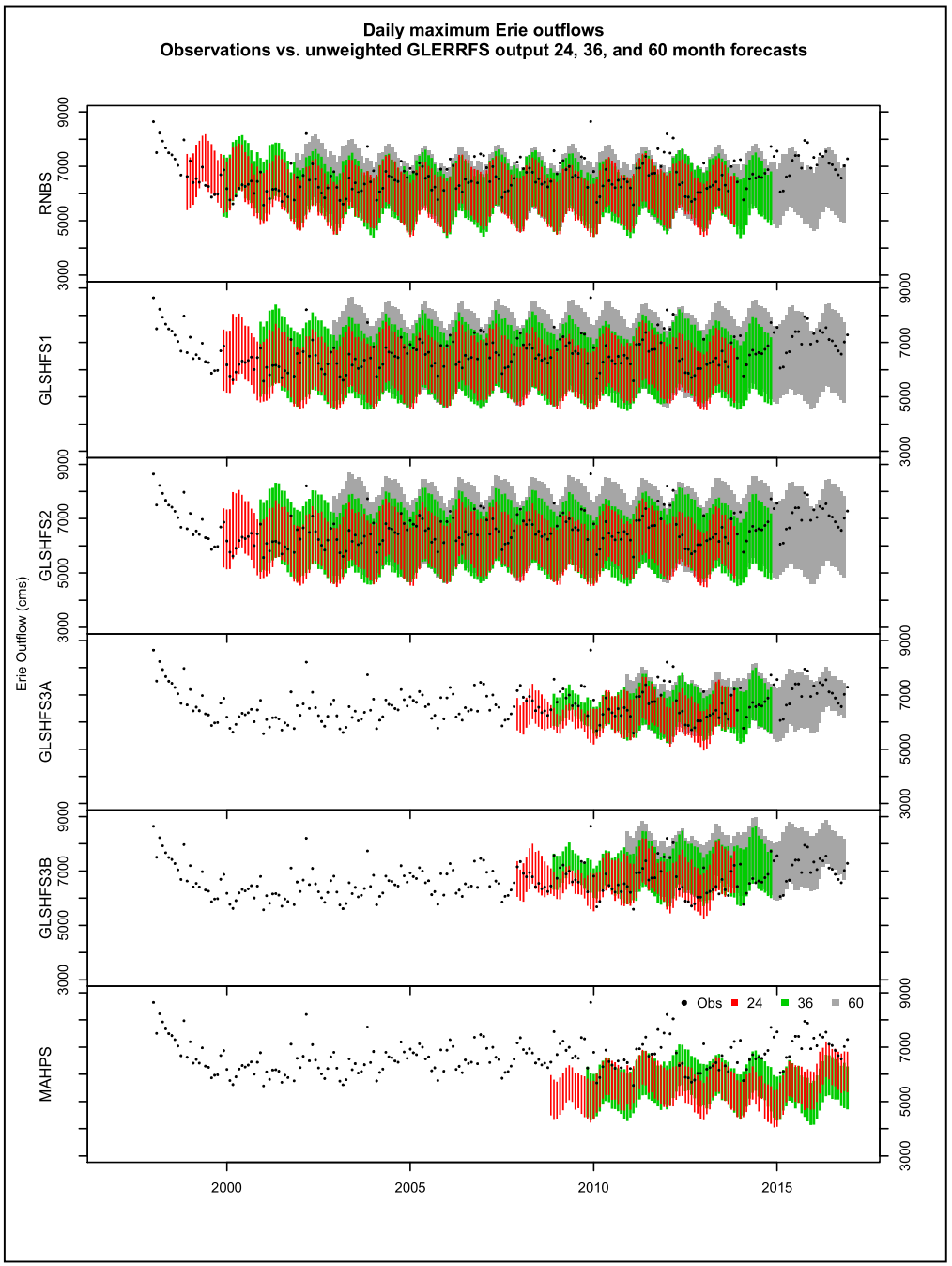
Daily maximum Erie outflows
Observations vs. unweighted GLERRFS output 24, 36, and 60 month forecasts
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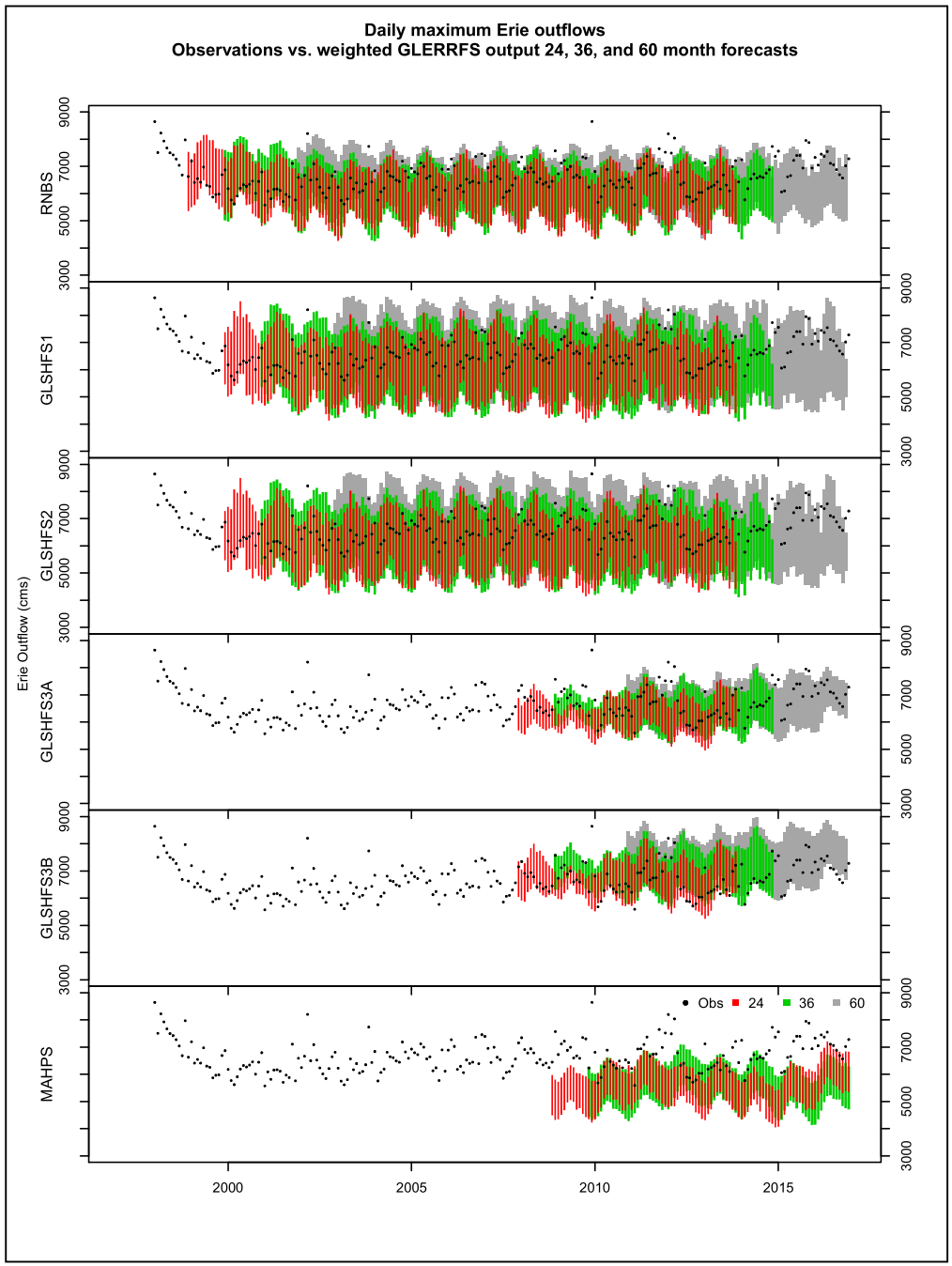
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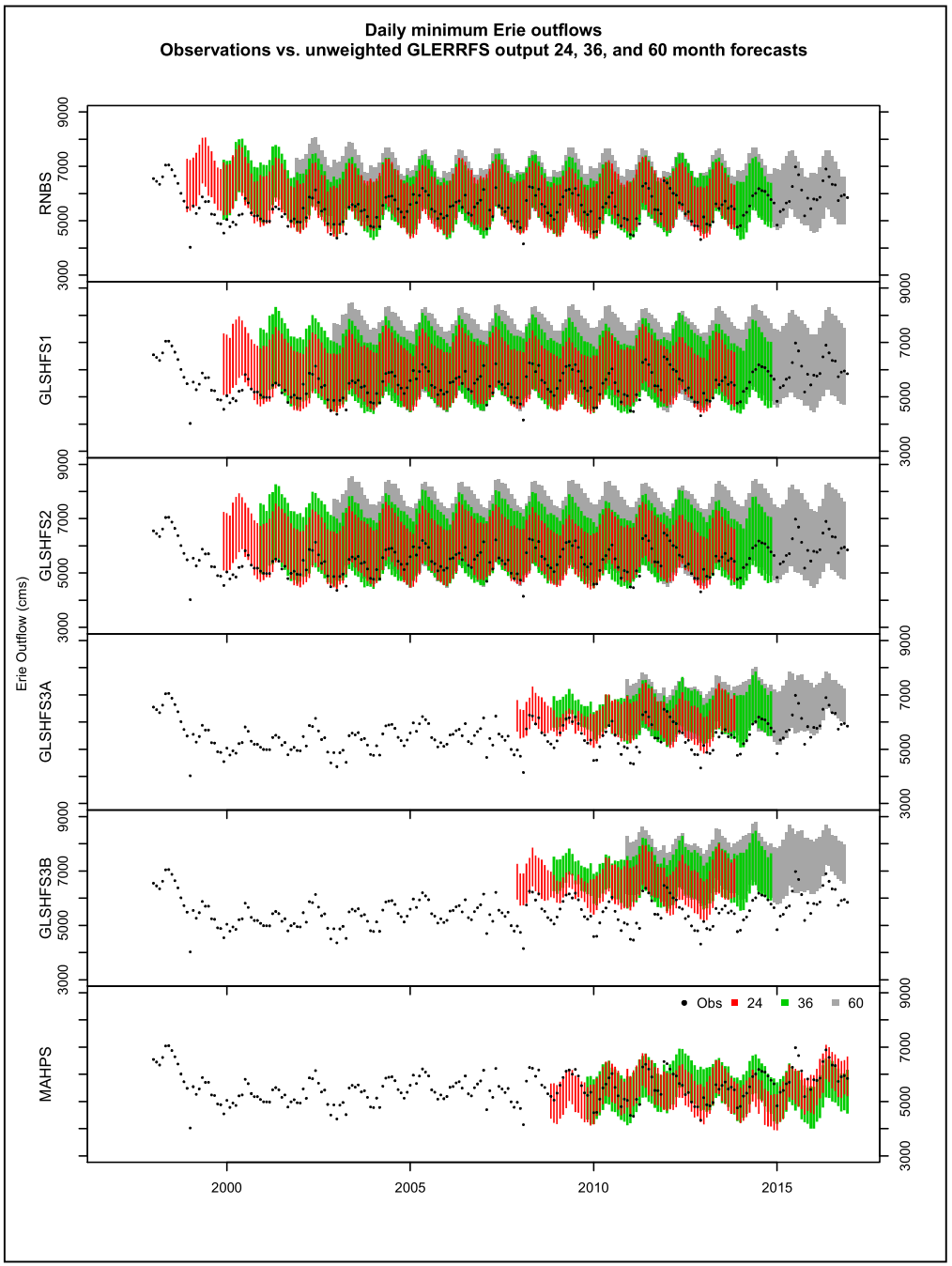
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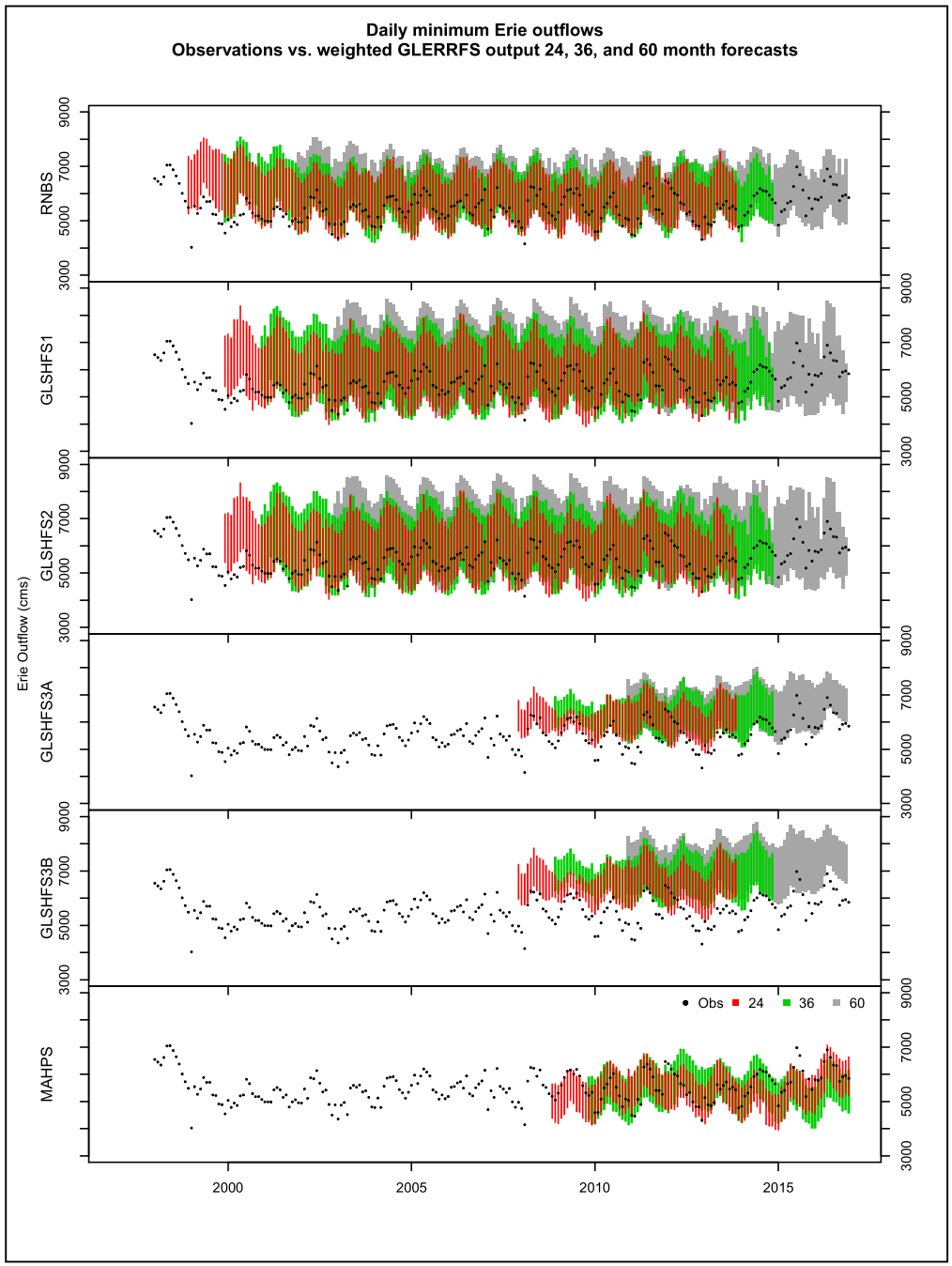
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Observations vs. weighted GLERRFS output 24, 36, and 60 month forecasts
Erie Outflow (cms)
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GLSHFS2
GLSHFS3A
GLSHFS3B
MAHPS
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Erie Outflow P−Values by model − unweighted
RNBS
GLSHFS1
GLSHFS2
GLSHFS3A
GLSHFS3B
MAHPS
Forecast Horizon
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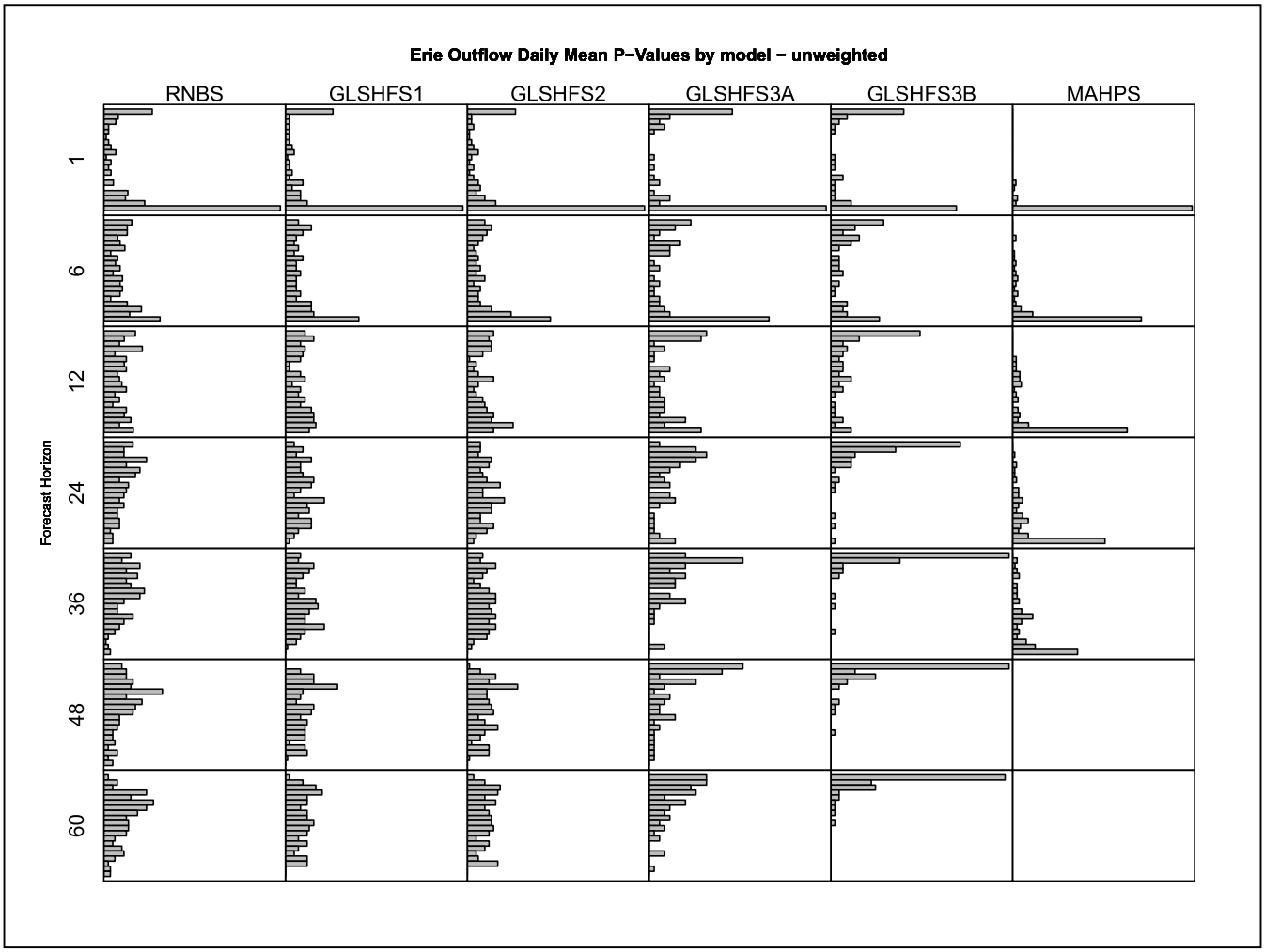
Erie Outflow Daily Mean P−Values by model − unweighted
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GLSHFS3A
GLSHFS3B
MAHPS
Forecast Horizon
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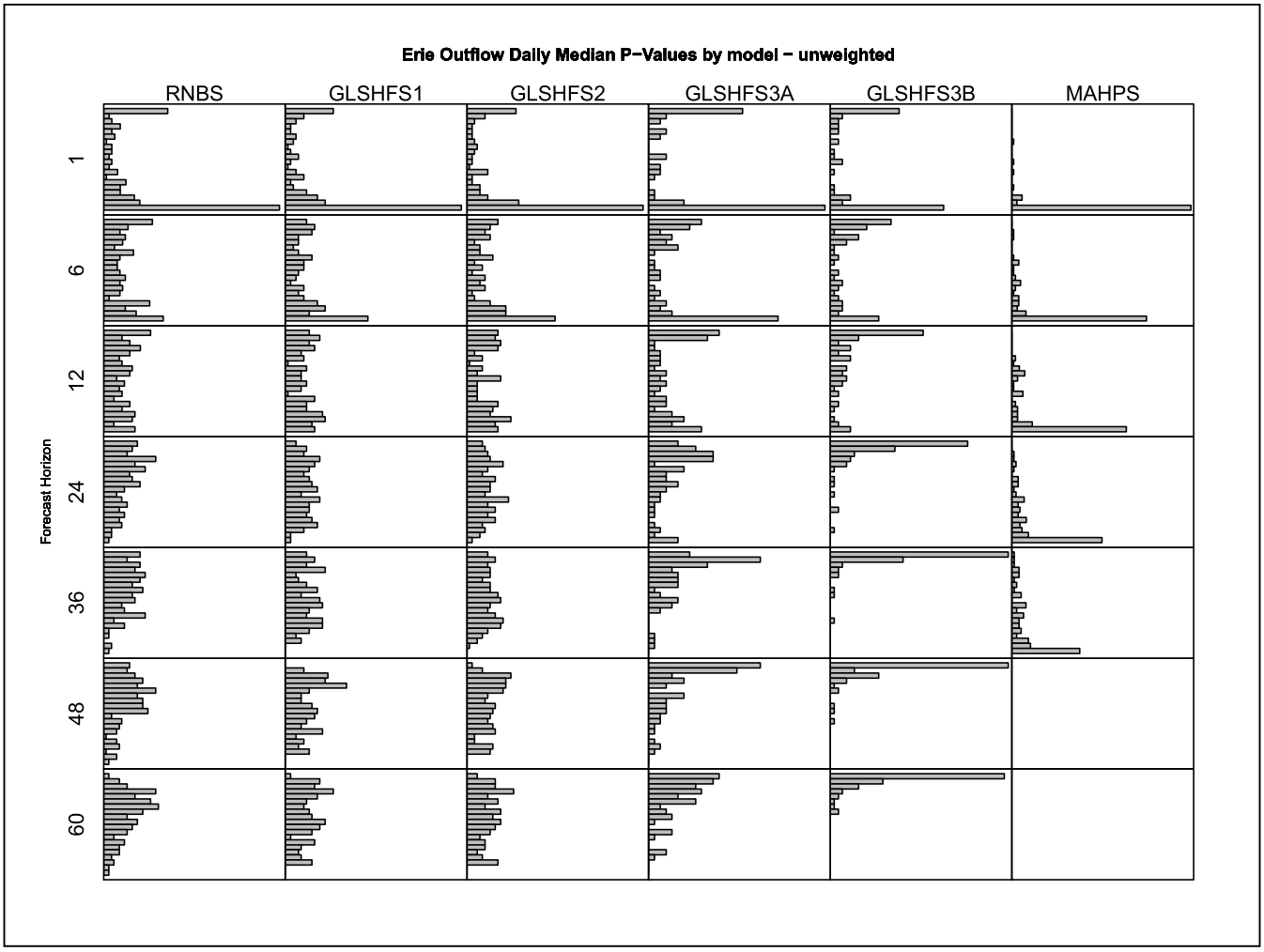
Erie Outflow Daily Median P−Values by model − unweighted
RNBS
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GLSHFS2
GLSHFS3A
GLSHFS3B
MAHPS
Forecast Horizon
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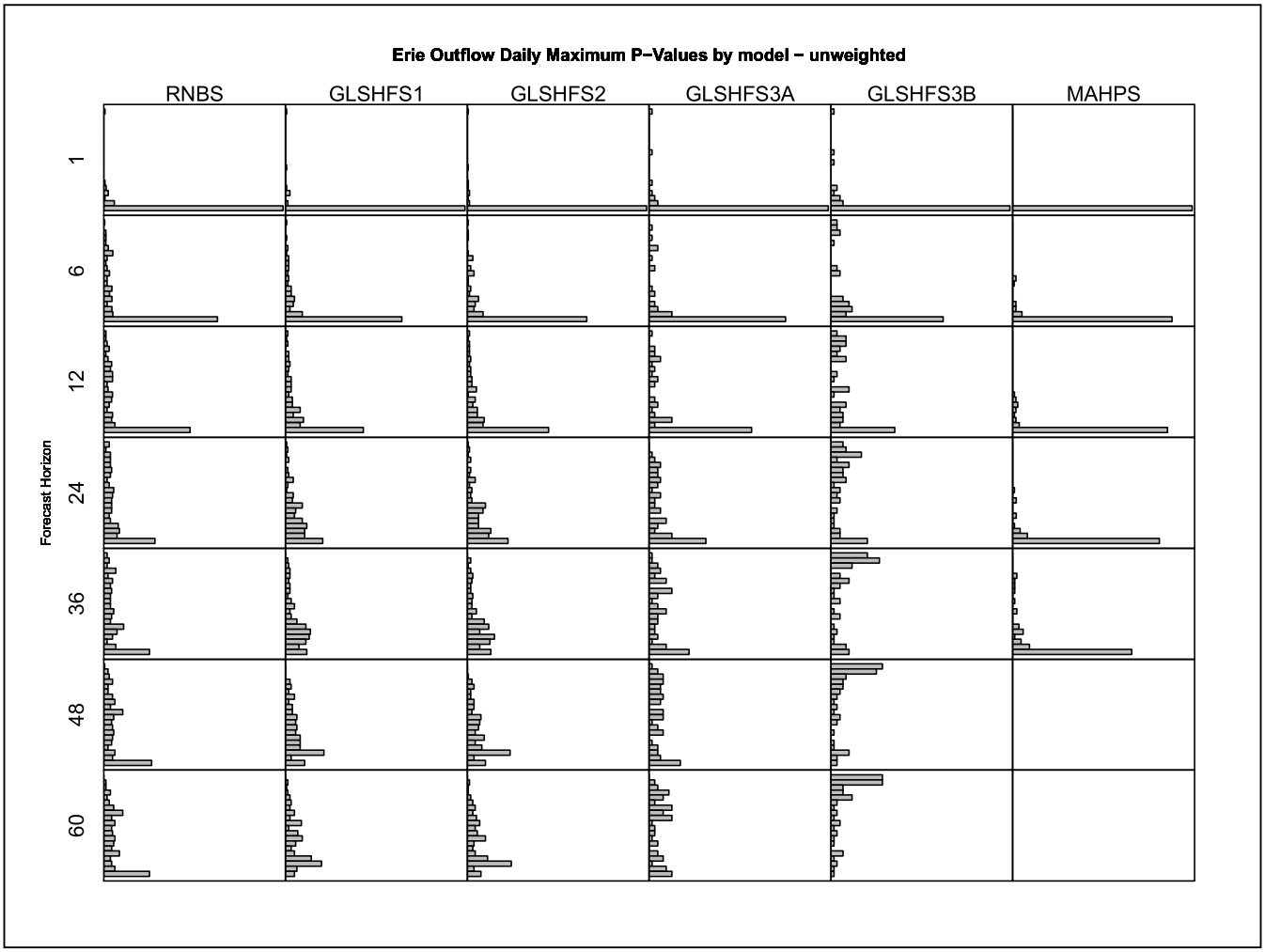
Erie Outflow Daily Maximum P−Values by model − unweighted
RNBS
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GLSHFS2
GLSHFS3A
GLSHFS3B
MAHPS
Forecast Horizon
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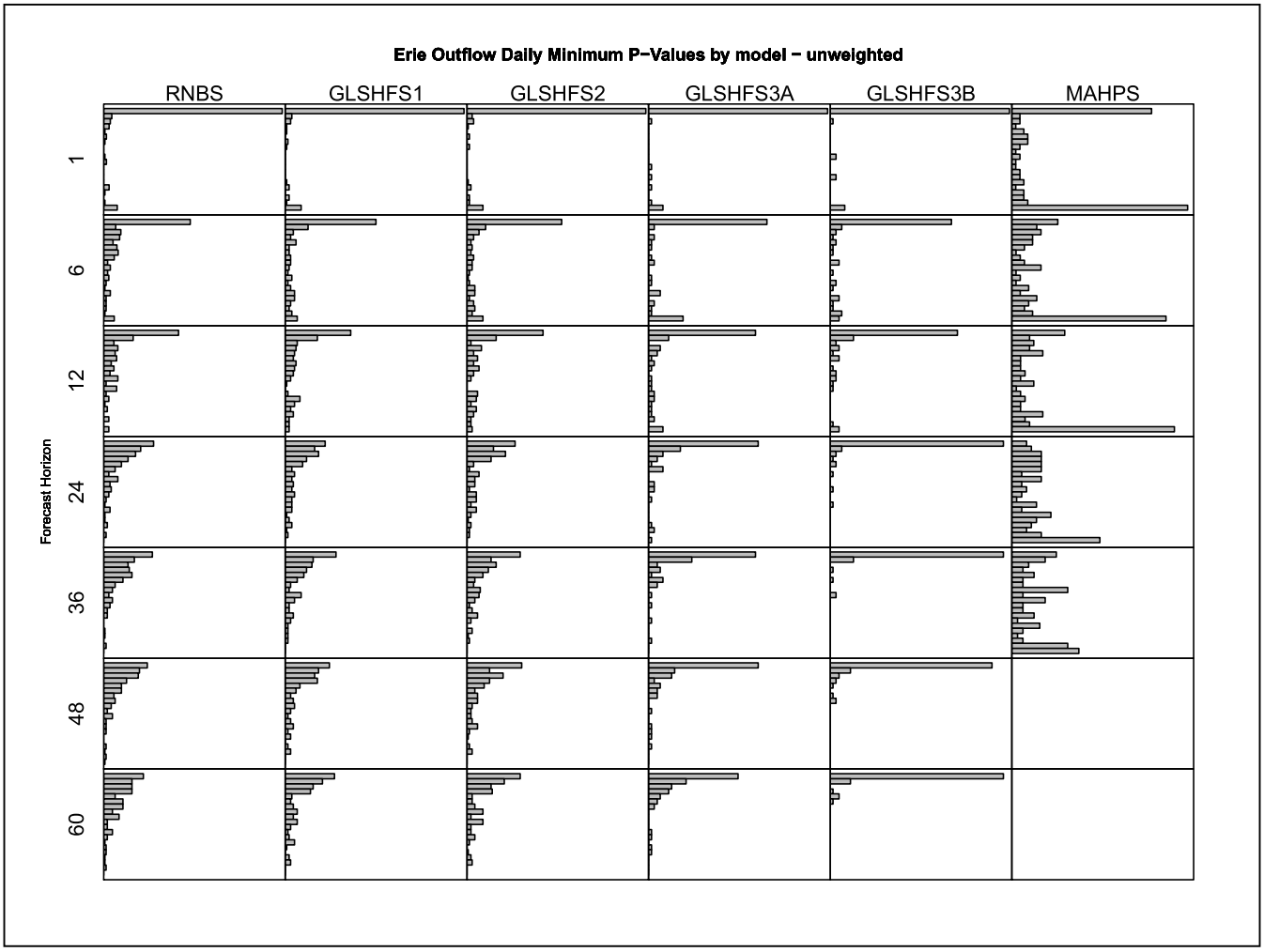
Erie Outflow Daily Minimum P−Values by model − unweighted
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MAHPS
Forecast Horizon
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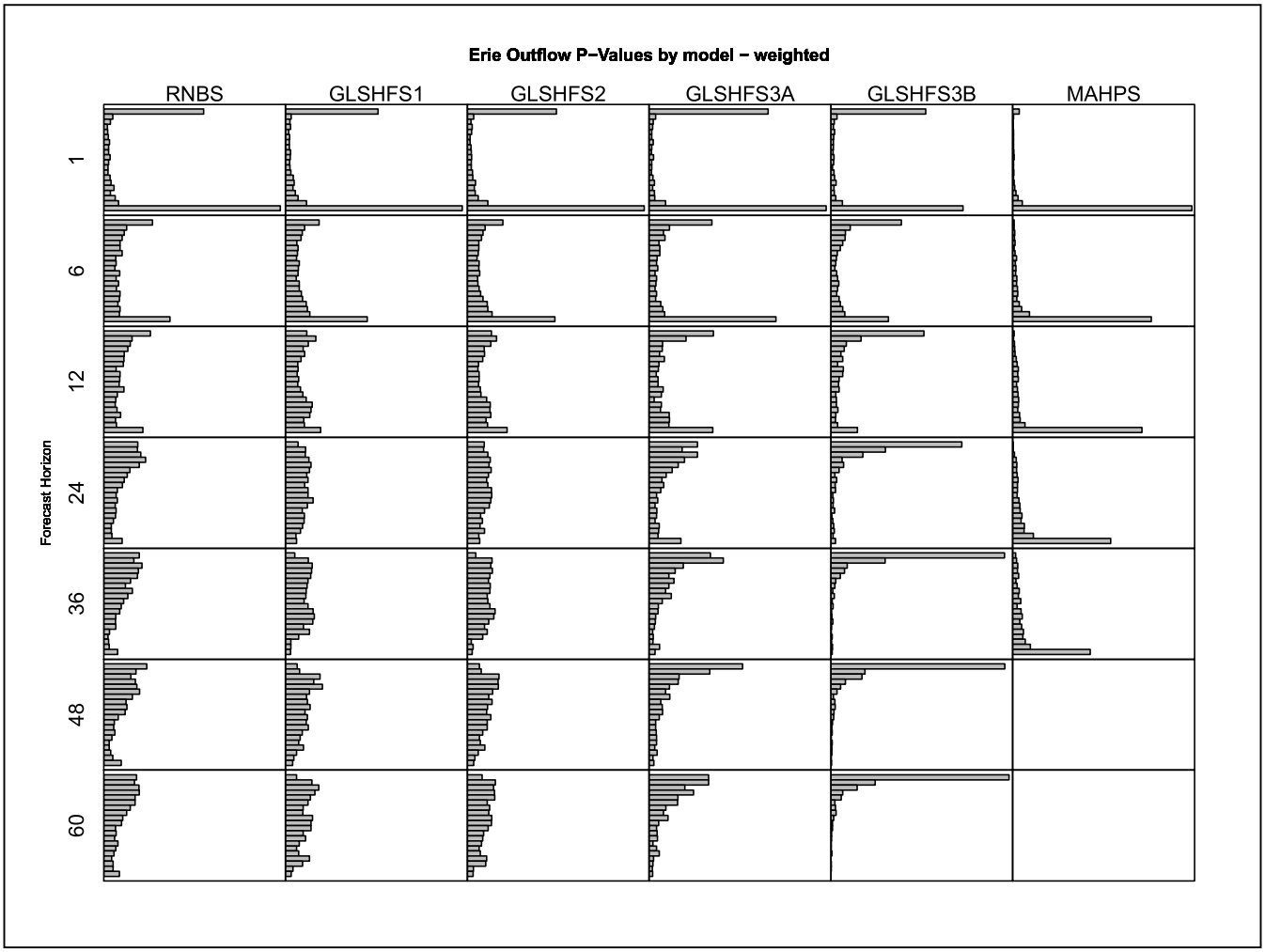
Erie Outflow P−Values by model − weighted
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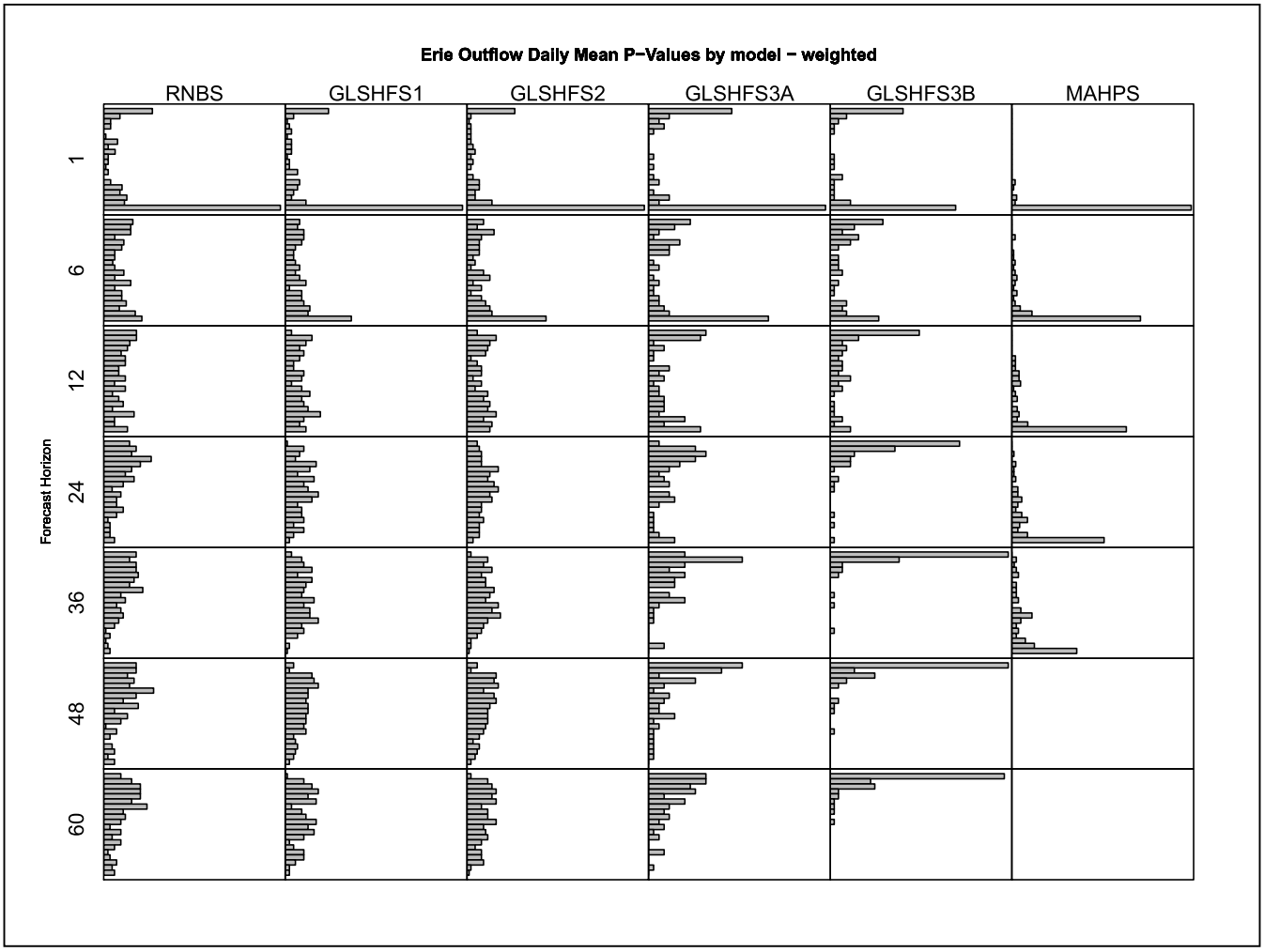
Erie Outflow Daily Mean P−Values by model − weighted
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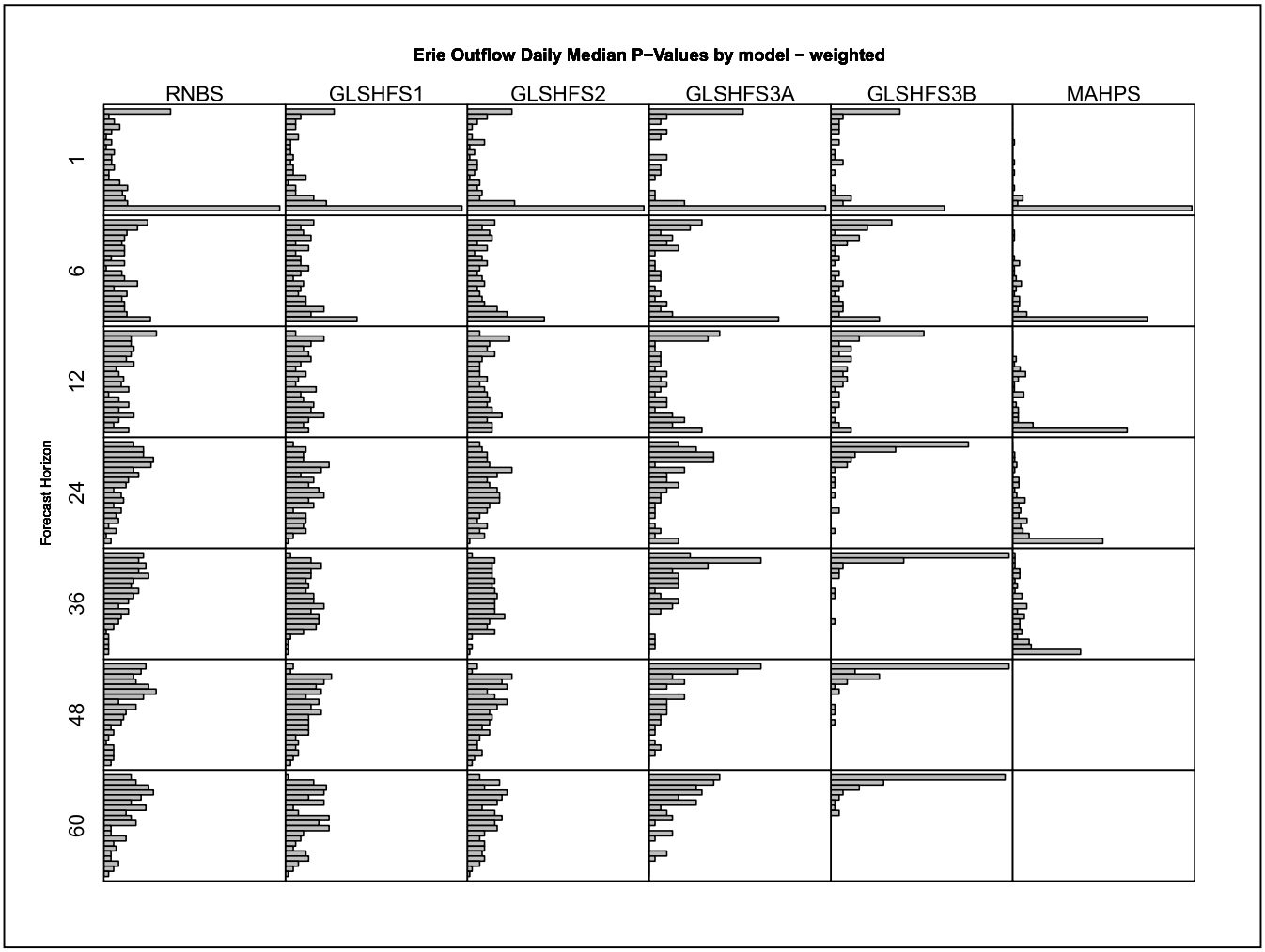
Erie Outflow Daily Median P−Values by model − weighted
RNBS
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GLSHFS3A
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MAHPS
Forecast Horizon
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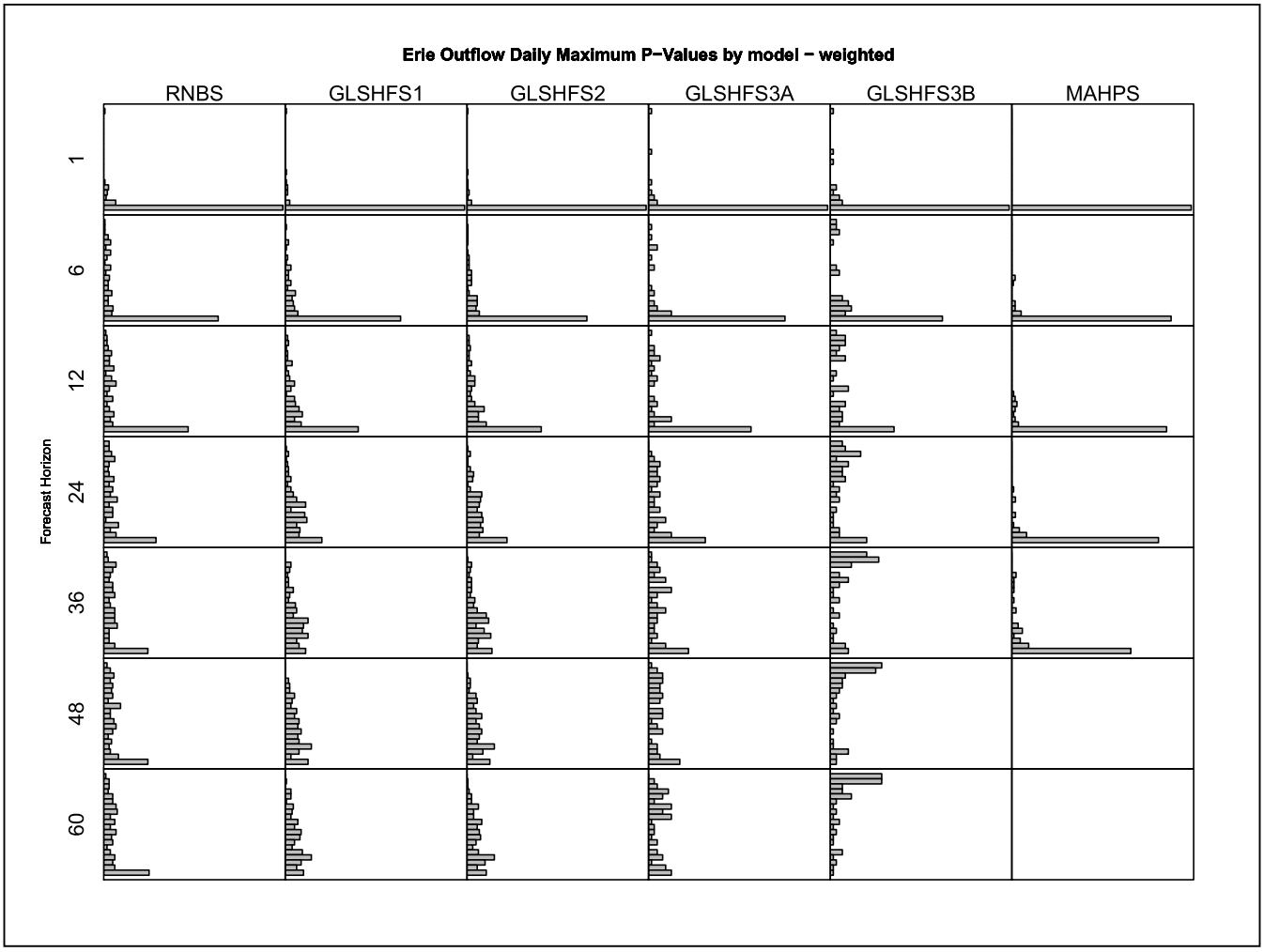
Erie Outflow Daily Maximum P−Values by model − weighted
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GLSHFS3A
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MAHPS
Forecast Horizon
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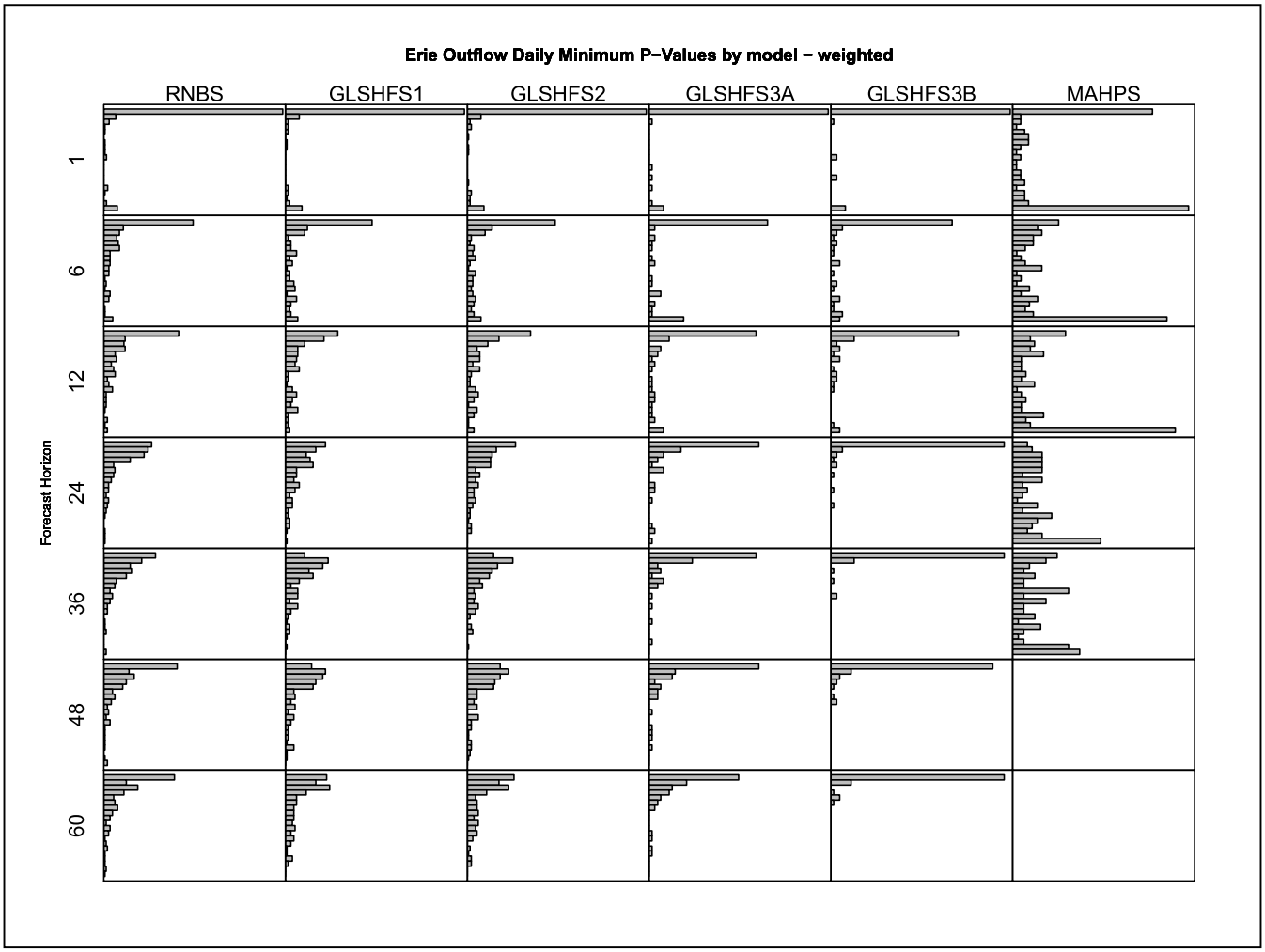
Erie Outflow Daily Minimum P−Values by model − weighted
RNBS
GLSHFS1
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GLSHFS3A
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MAHPS
Forecast Horizon
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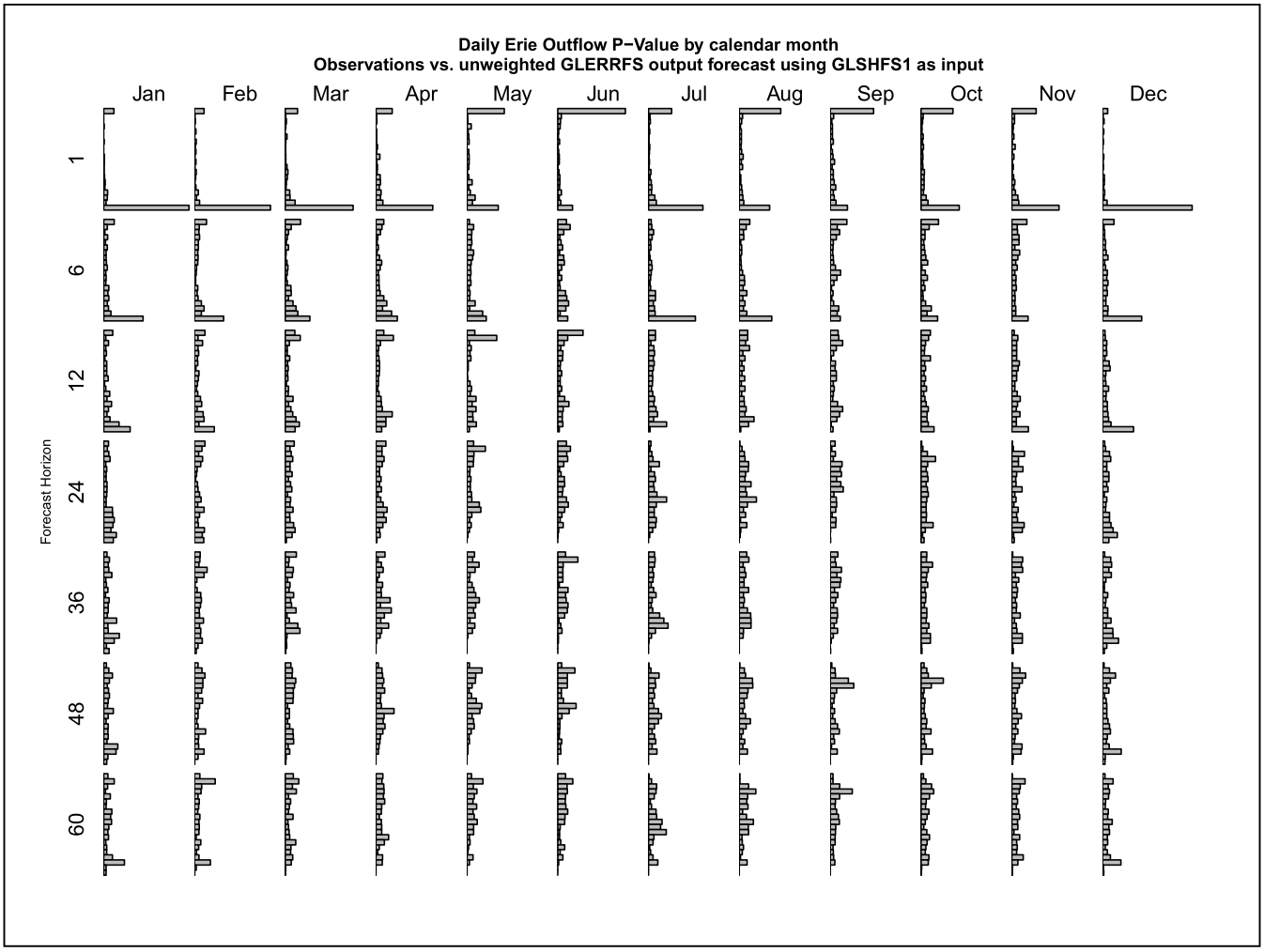
Daily Erie Outflow P−Value by calendar month
Observations vs. unweighted GLERRFS output forecast using GLSHFS1 as input
Jan
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Forecast Horizon
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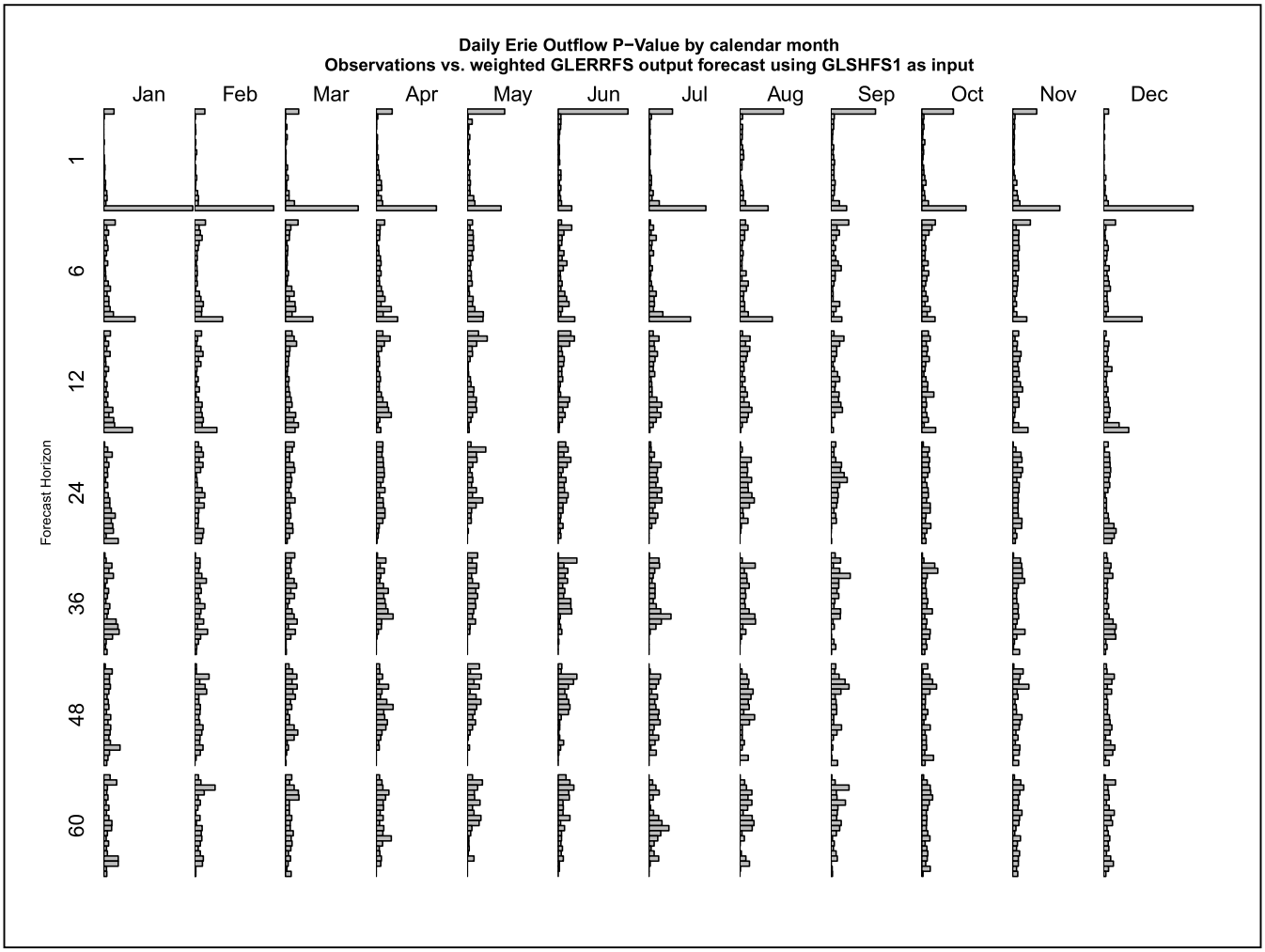
Daily Erie Outflow P−Value by calendar month
Observations vs. weighted GLERRFS output forecast using GLSHFS1 as input
Jan
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Forecast Horizon
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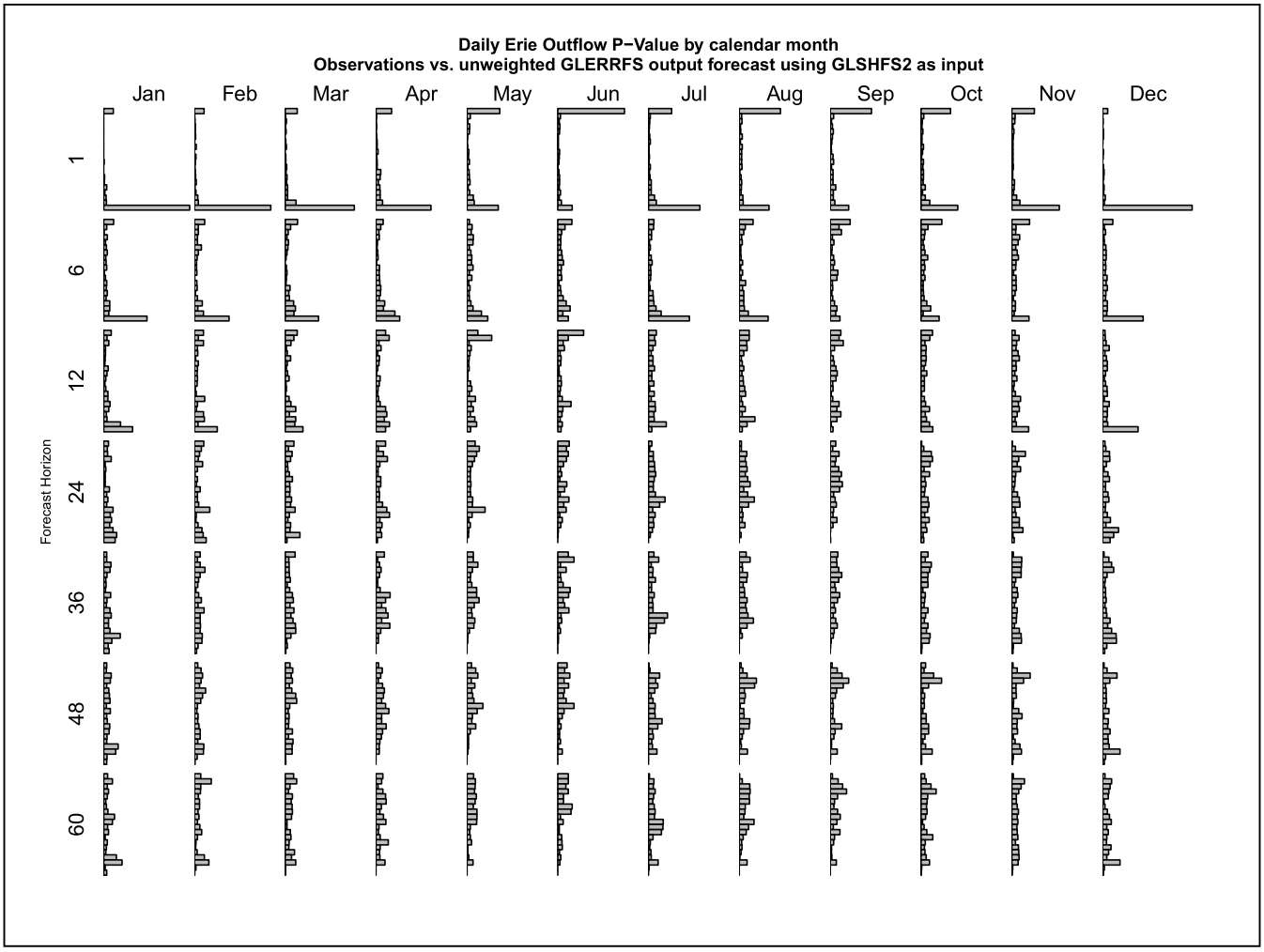
Daily Erie Outflow P−Value by calendar month
Observations vs. unweighted GLERRFS output forecast using GLSHFS2 as input
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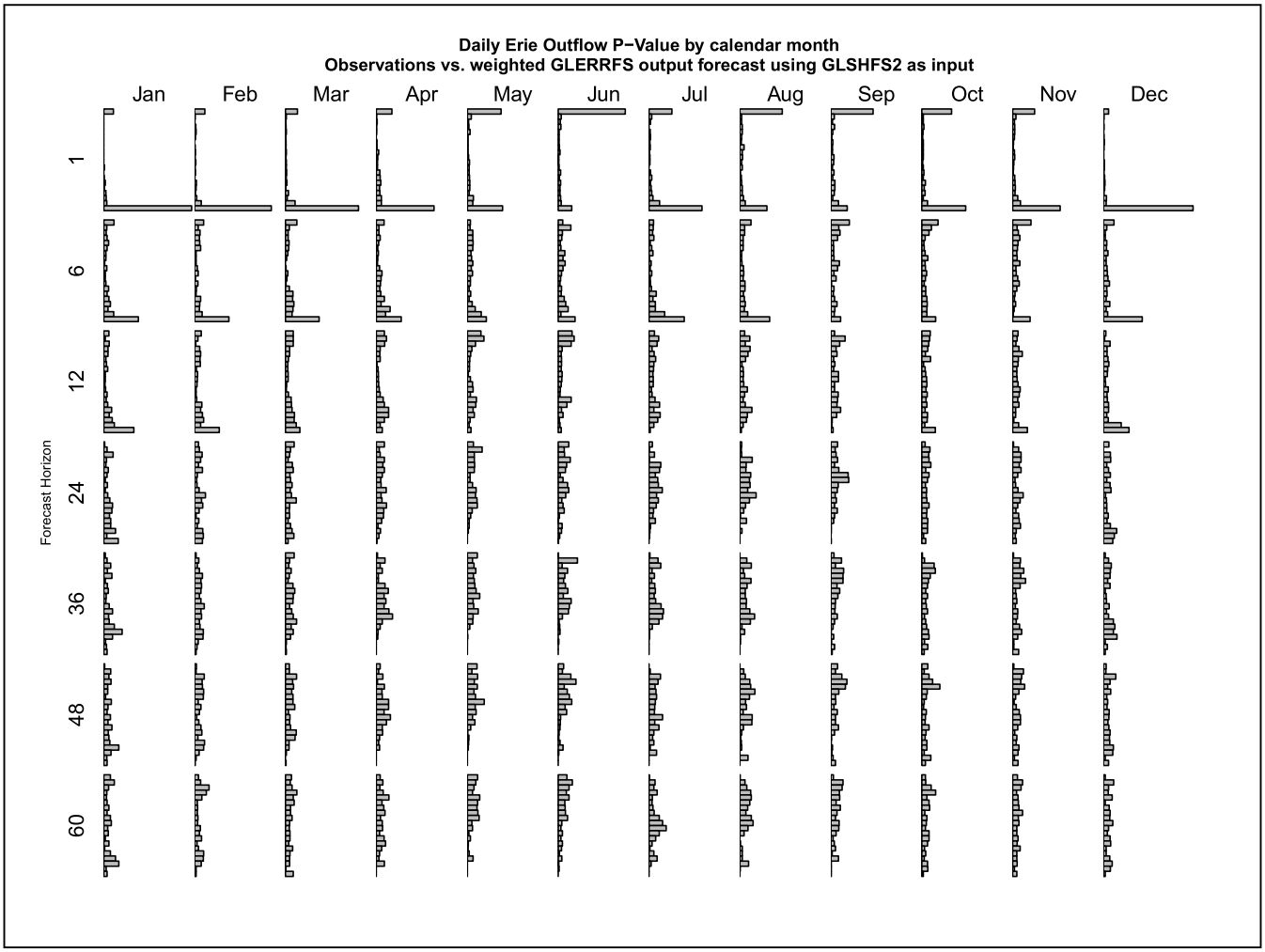
Daily Erie Outflow P−Value by calendar month
Observations vs. weighted GLERRFS output forecast using GLSHFS2 as input
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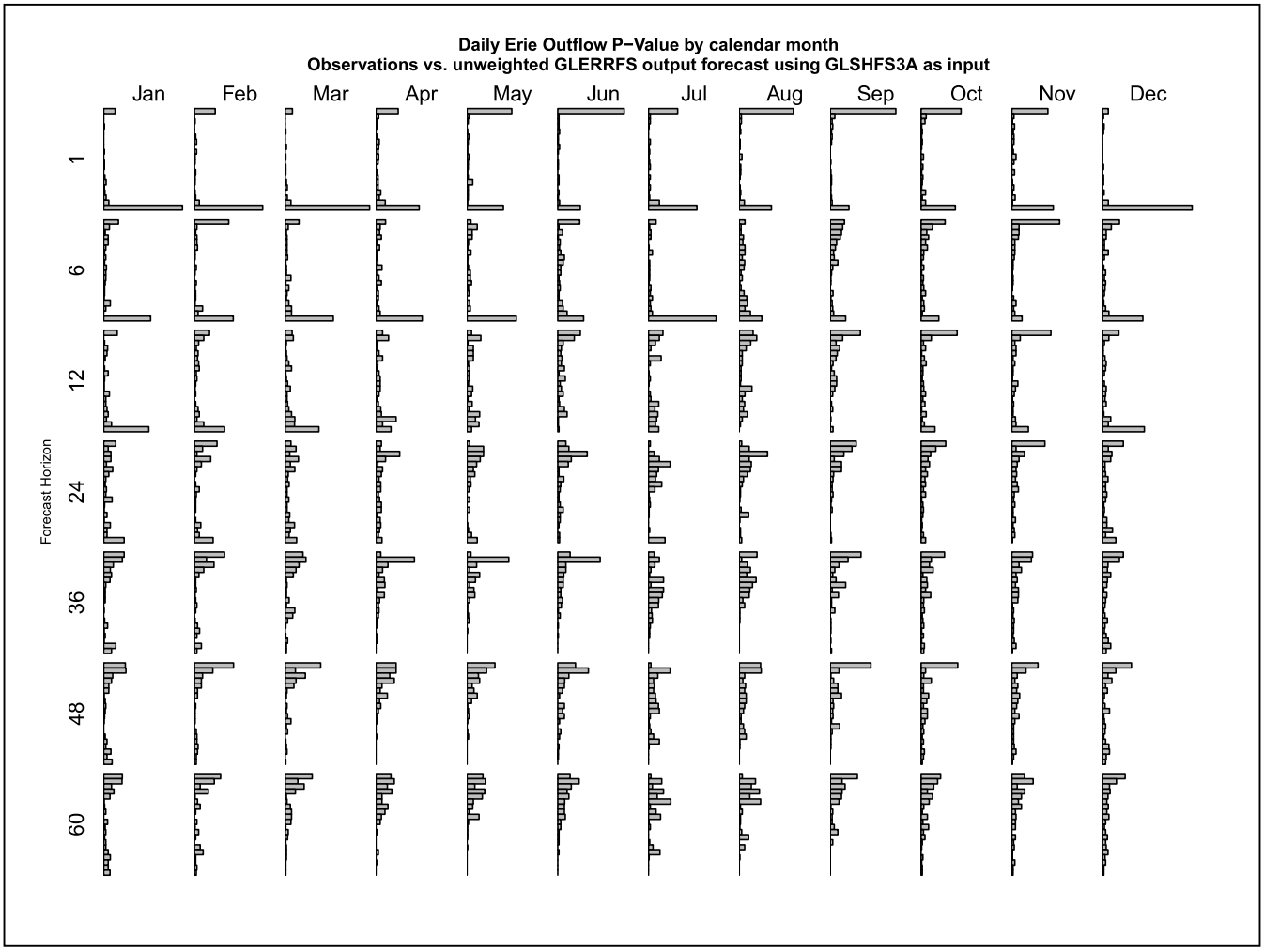
Daily Erie Outflow P−Value by calendar month
Observations vs. unweighted GLERRFS output forecast using GLSHFS3A as input
Jan
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Oct
Nov
Dec
Forecast Horizon
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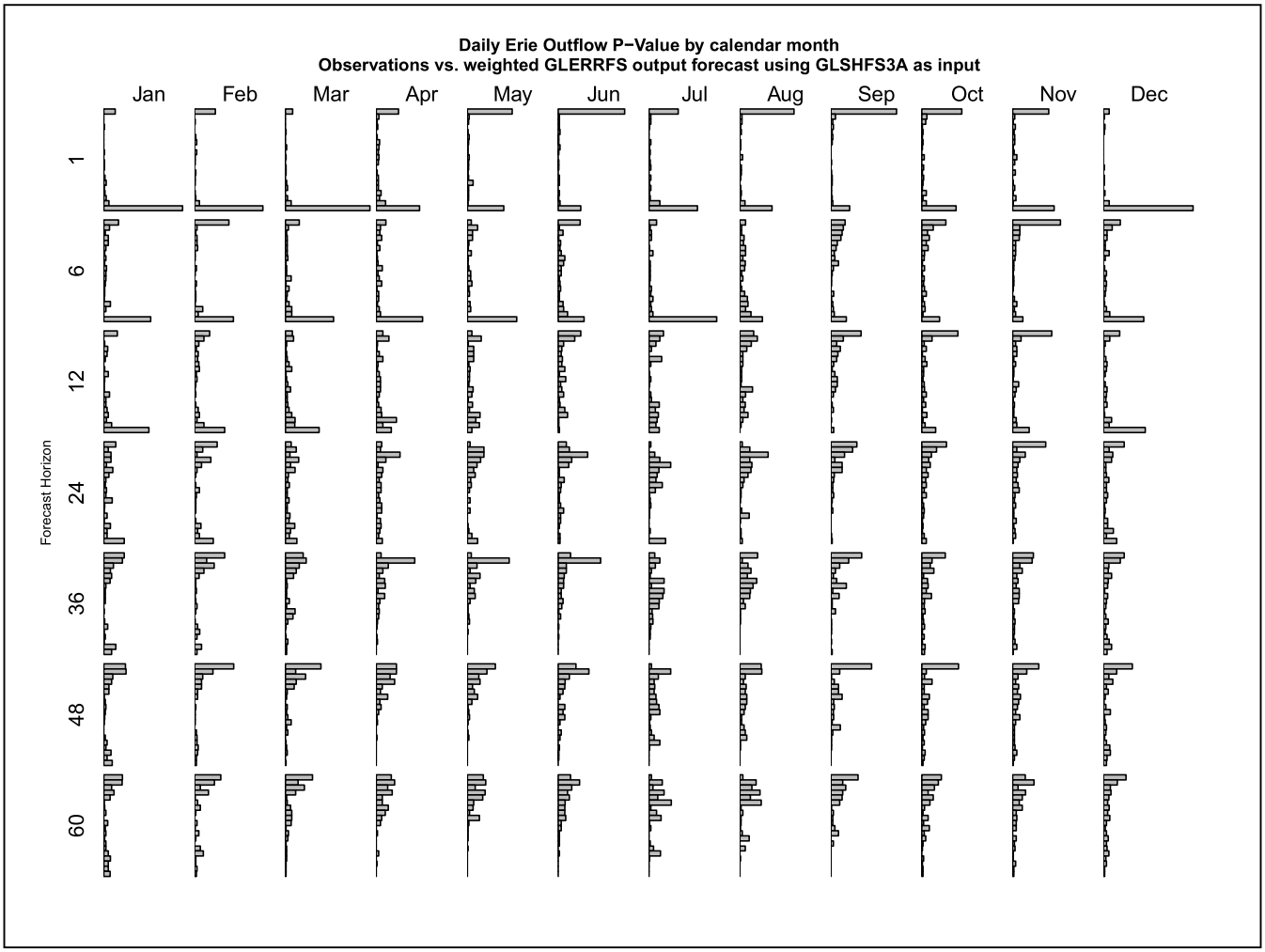
Daily Erie Outflow P−Value by calendar month
Observations vs. weighted GLERRFS output forecast using GLSHFS3A as input
Jan
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Forecast Horizon
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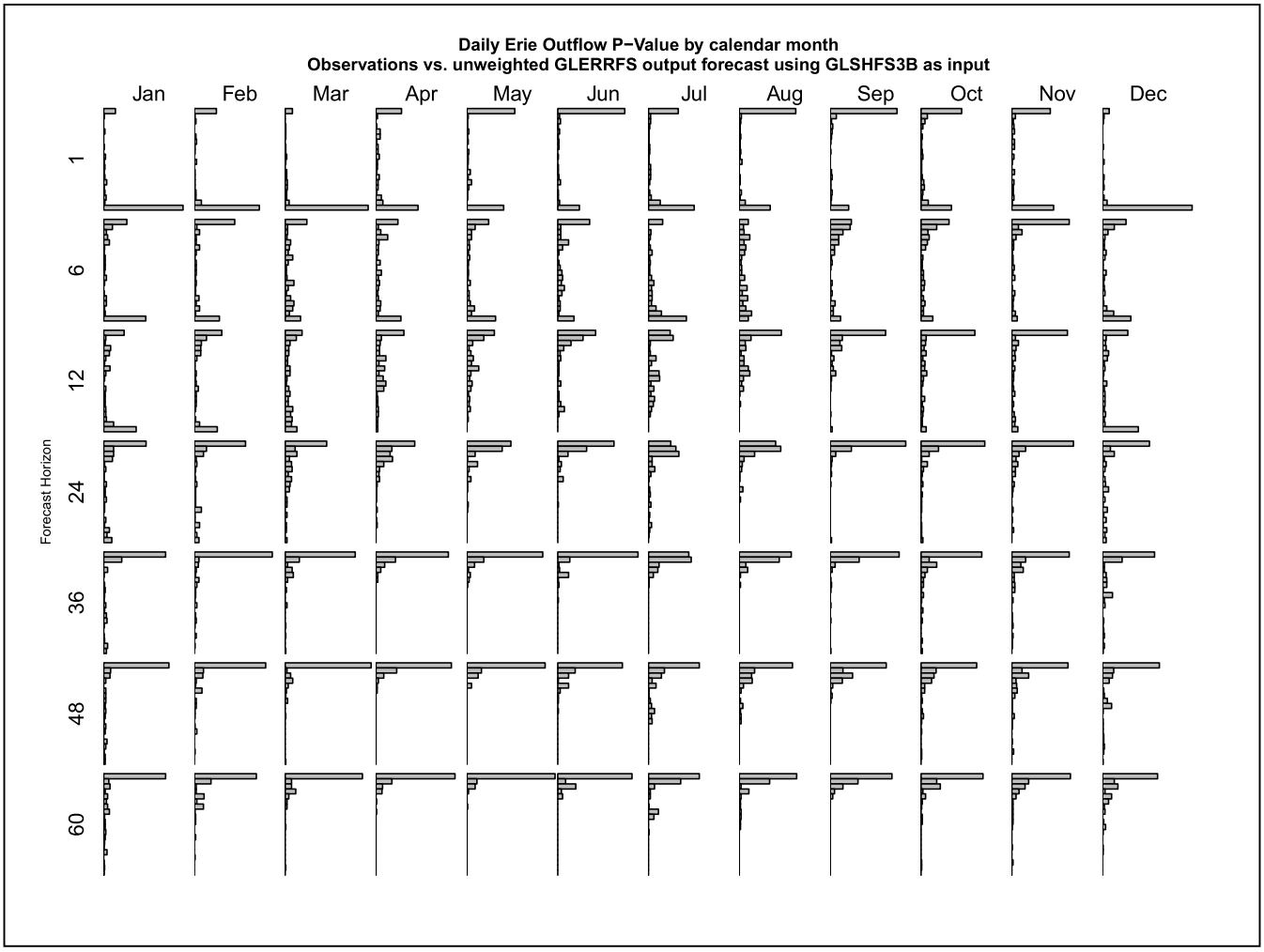
Daily Erie Outflow P−Value by calendar month
Observations vs. unweighted GLERRFS output forecast using GLSHFS3B as input
Jan
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Forecast Horizon
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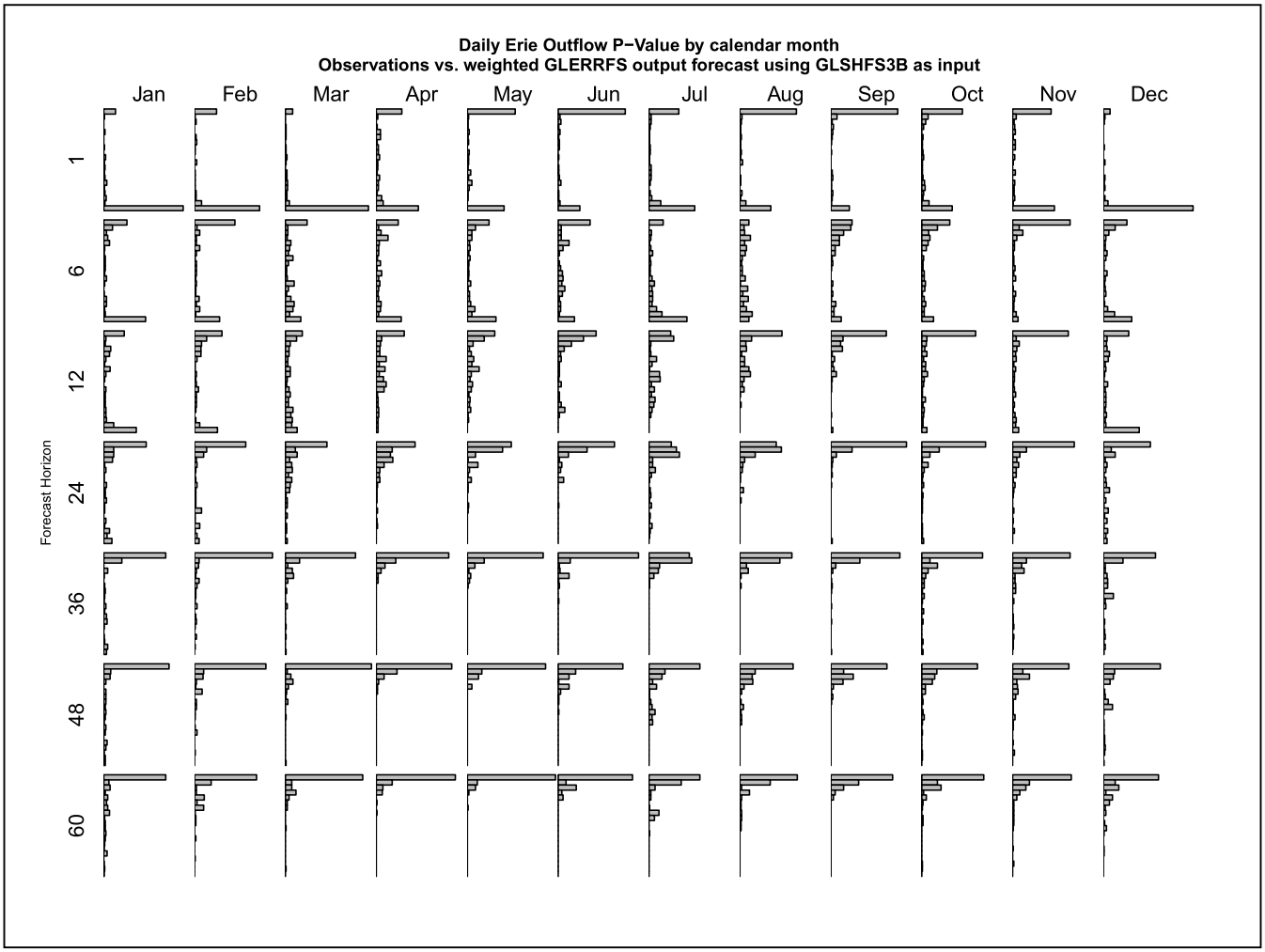
Daily Erie Outflow P−Value by calendar month
Observations vs. weighted GLERRFS output forecast using GLSHFS3B as input
Jan
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Forecast Horizon
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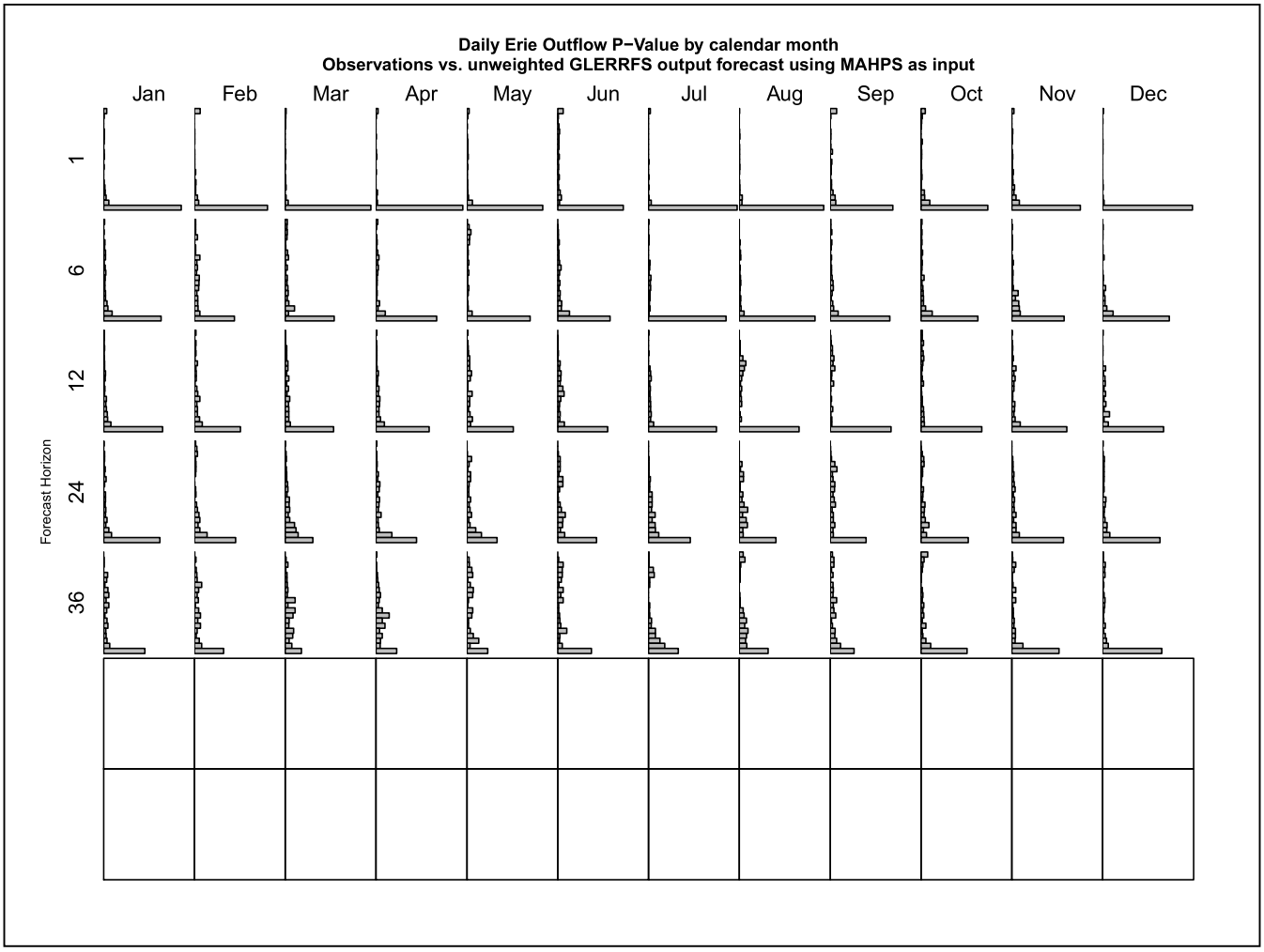
Daily Erie Outflow P−Value by calendar month
Observations vs. unweighted GLERRFS output forecast using MAHPS as input
Jan
Feb
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Sep
Oct
Nov
Dec
Forecast Horizon
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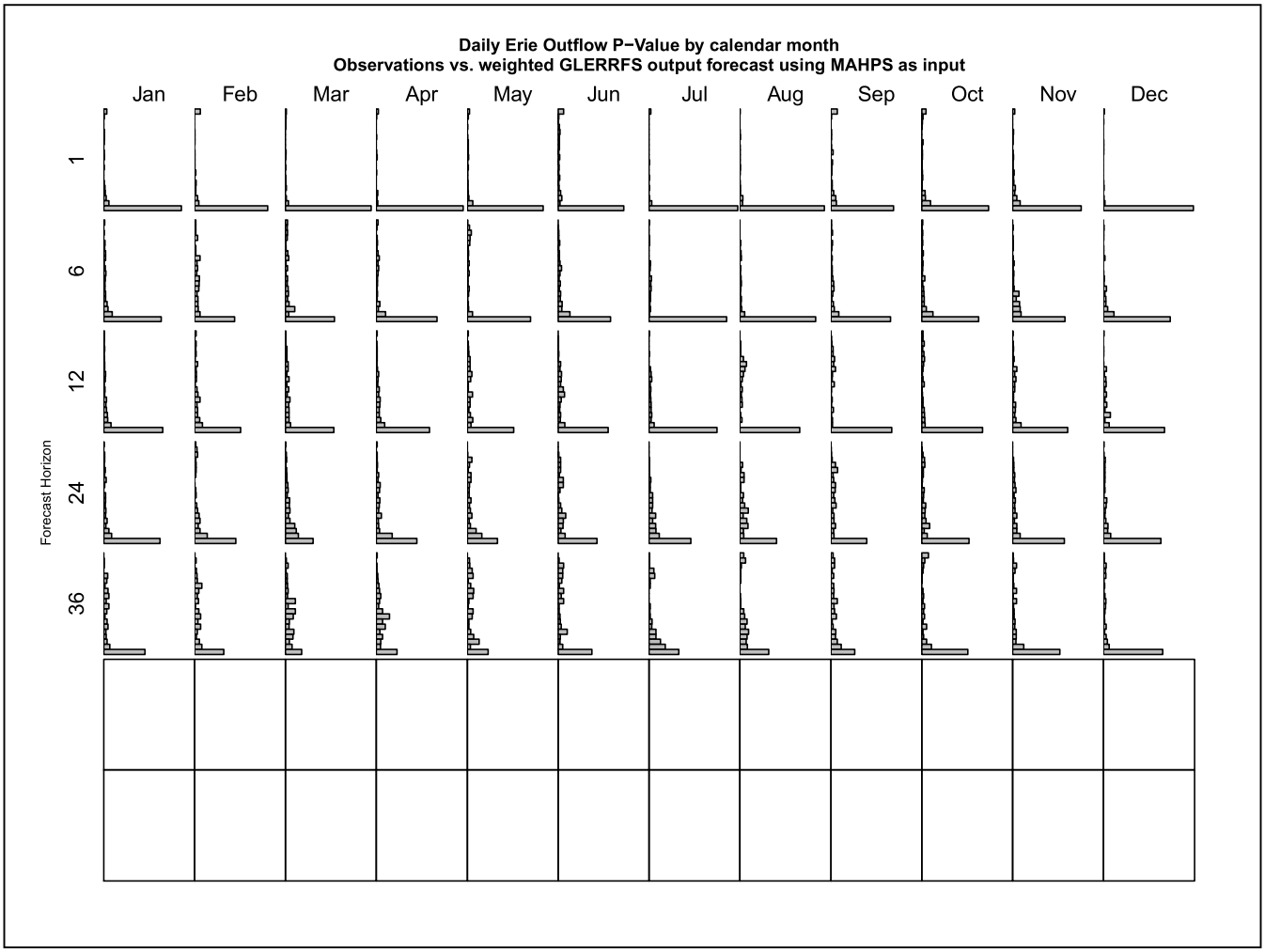
12
24
36


Daily Erie Outflow P−Value by calendar month
Observations vs. weighted GLERRFS output forecast using MAHPS as input
Jan
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Jul
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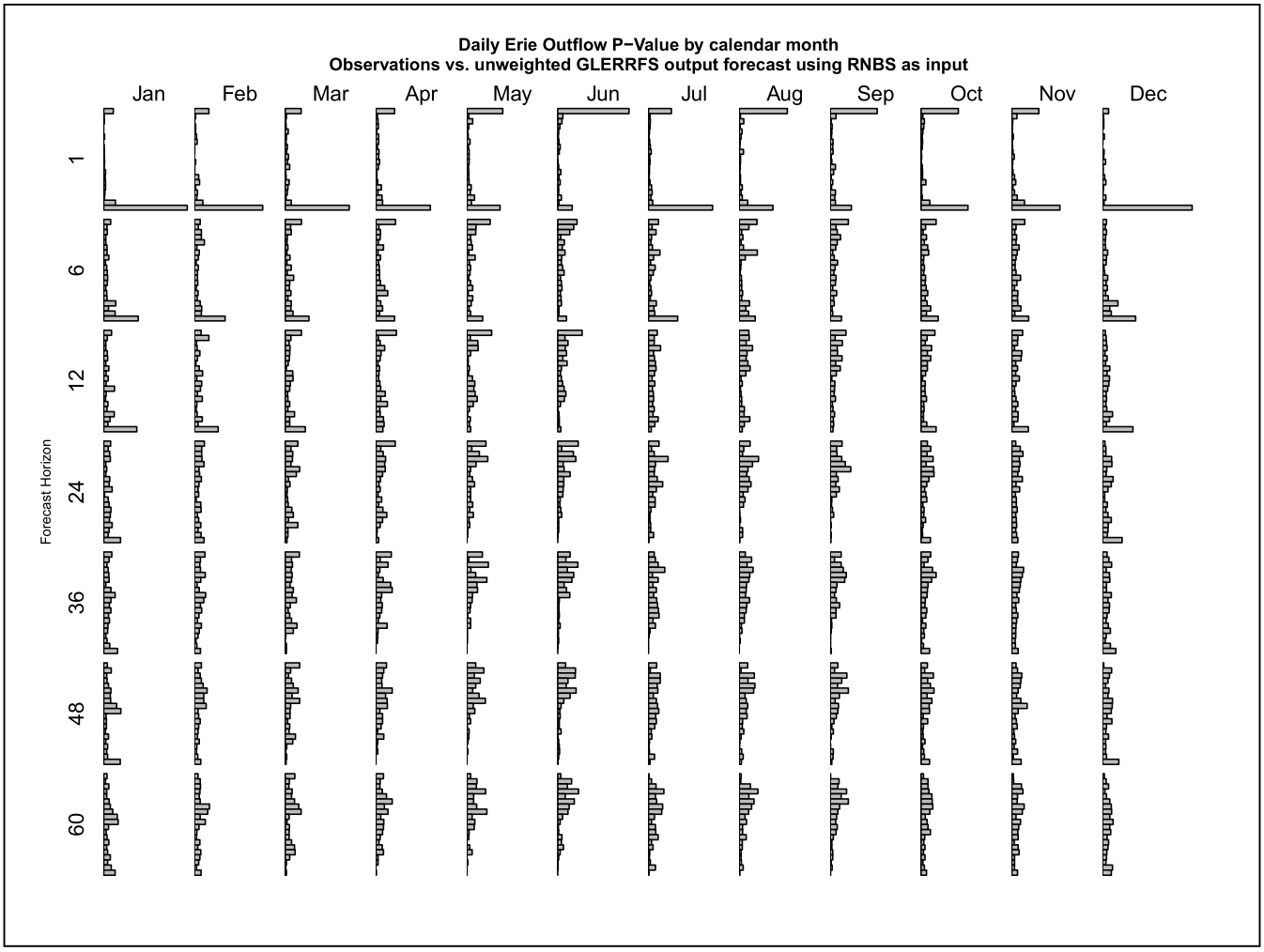
Sep
Oct
Nov
Dec
Forecast Horizon
1
6
12
24
36


Daily Erie Outflow P−Value by calendar month
Observations vs. unweighted GLERRFS output forecast using RNBS as input
Jan
Feb
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May
Jun
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Nov
Dec
Forecast Horizon
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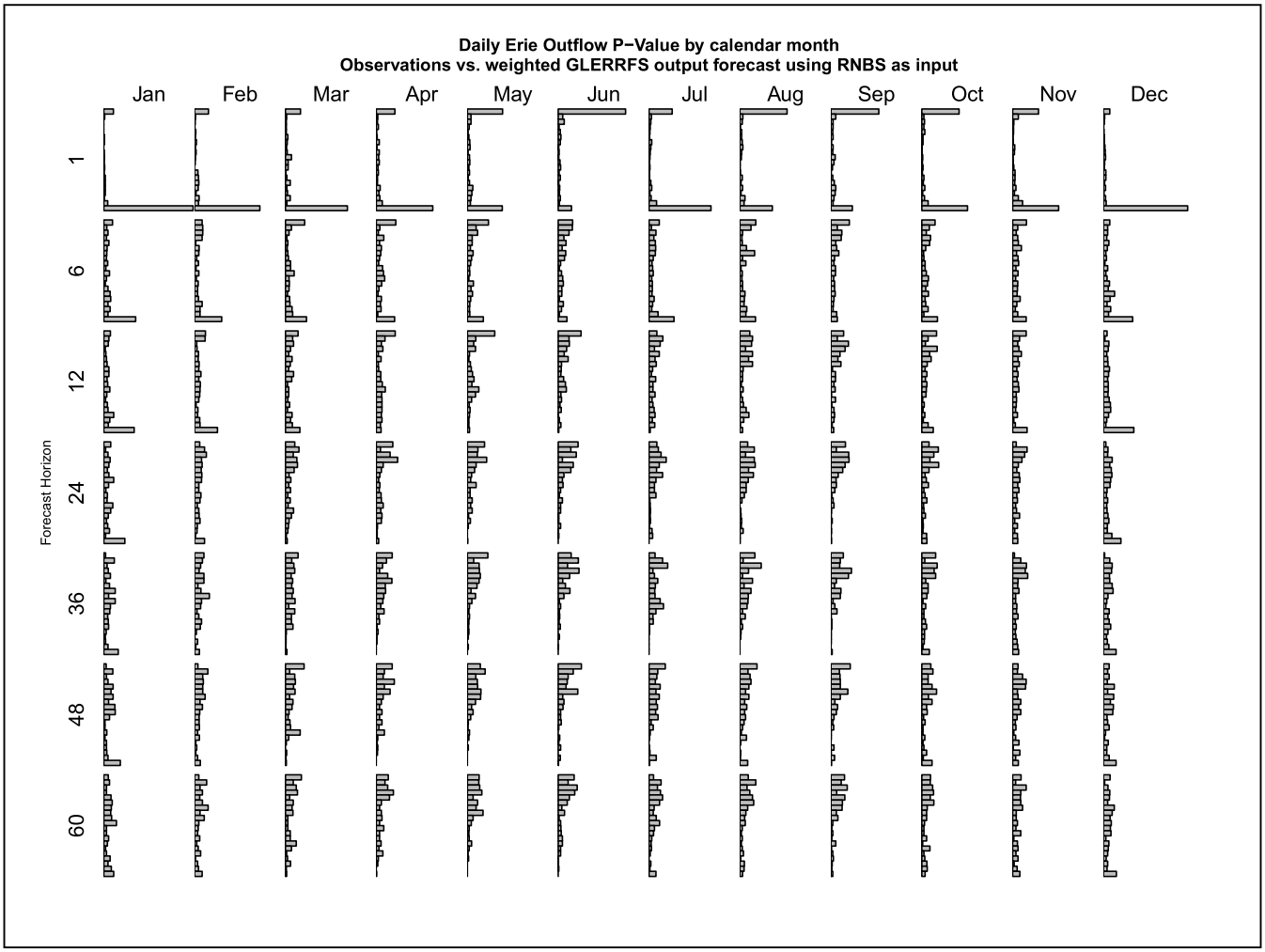
36
48
60


Daily Erie Outflow P−Value by calendar month
Observations vs. weighted GLERRFS output forecast using RNBS as input
Jan
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Forecast Horizon
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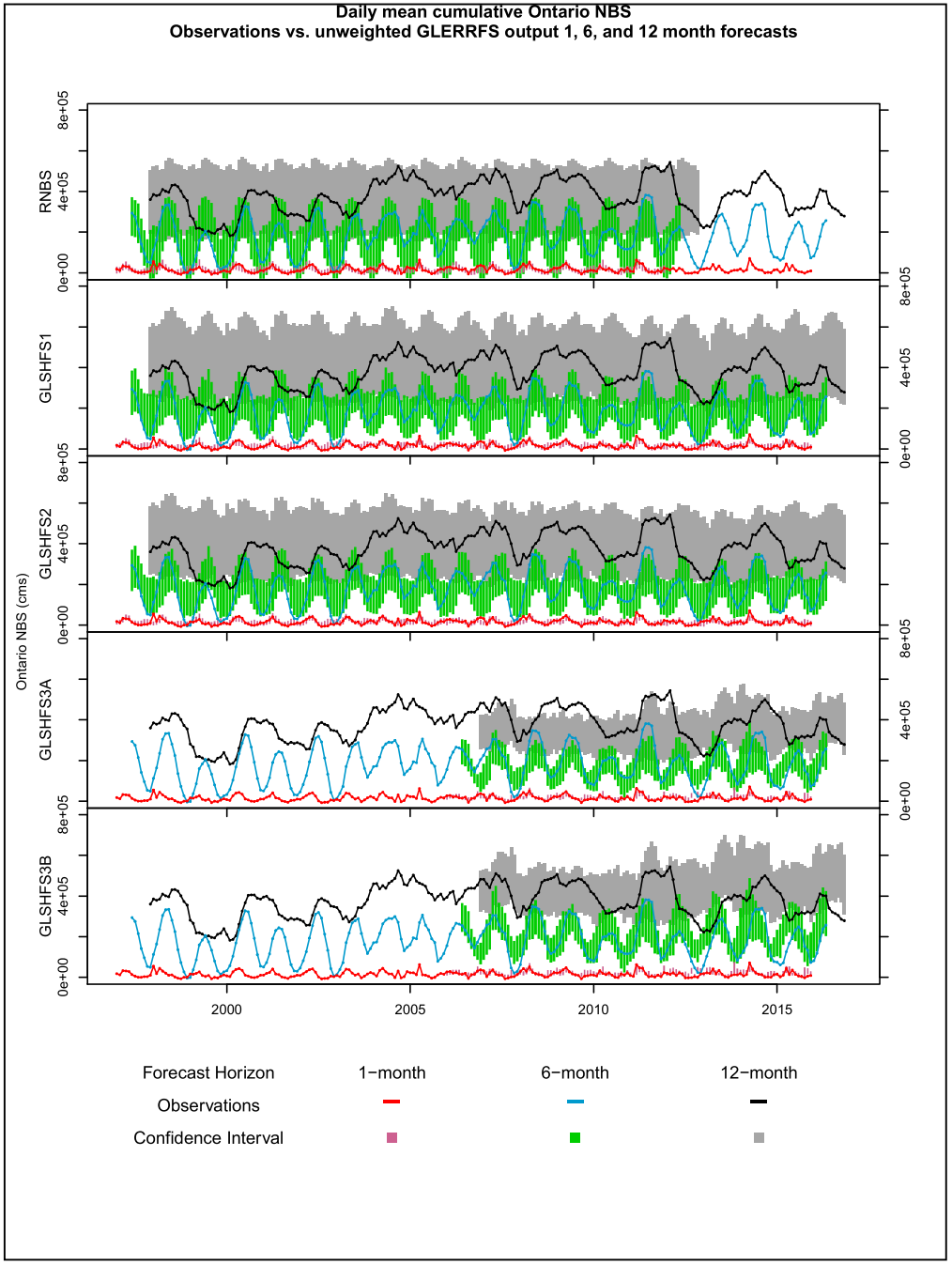
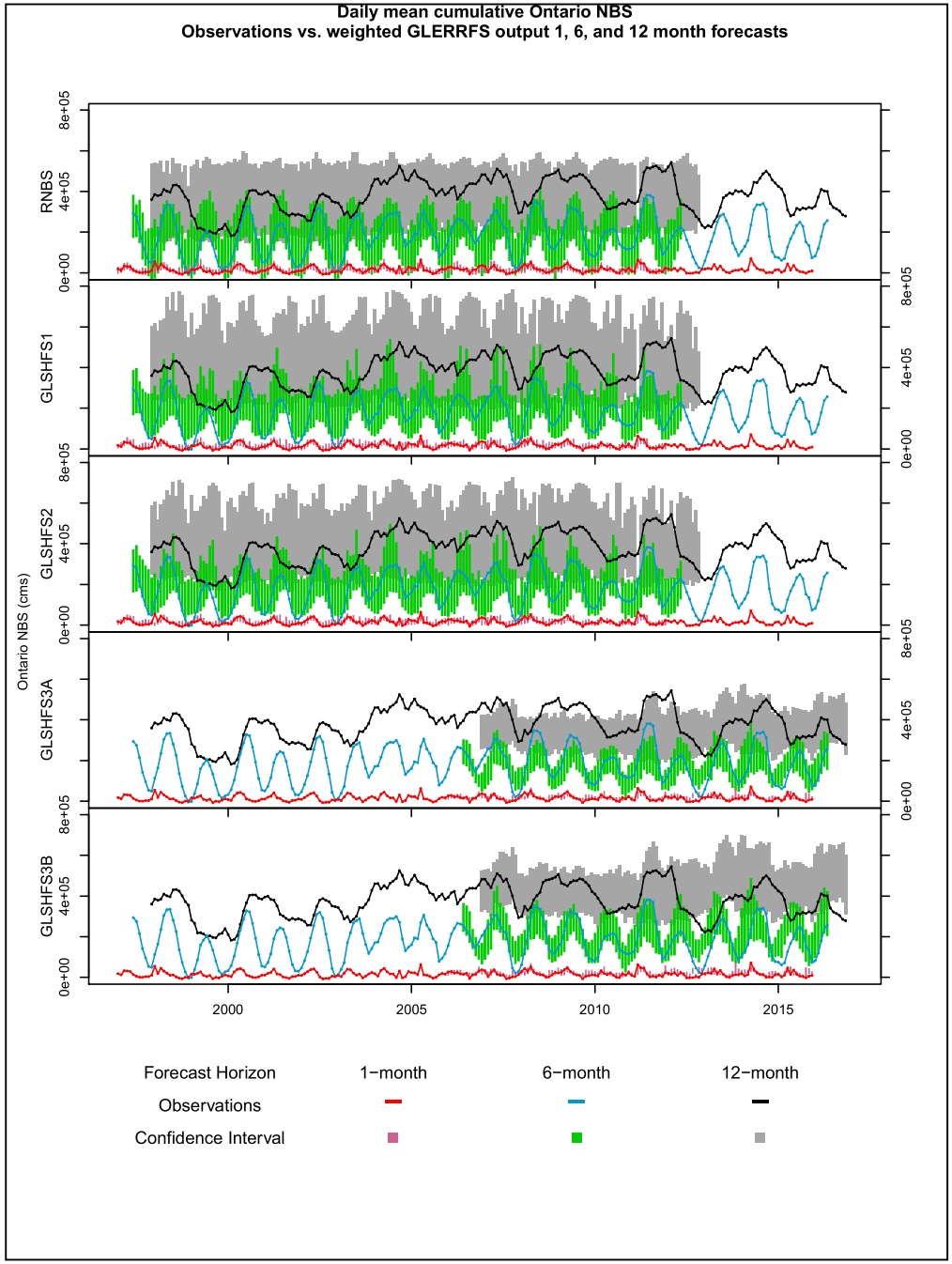
48
60


Daily mean cumulative Ontario NBS
Observations vs. unweighted GLERRFS output 1, 6, and 12 month forecasts
Ontario NBS (cms)
RNBS
GLSHFS1
GLSHFS2
GLSHFS3A
GLSHFS3B
0e+00
4e+05
8e+05
2000
2005
2010
2015
Forecast Horizon
1−month
6−month
12−month
Observations
Confidence Interval


Daily mean cumulative Ontario NBS
Observations vs. weighted GLERRFS output 1, 6, and 12 month forecasts
Ontario NBS (cms)
RNBS
GLSHFS1
GLSHFS2
GLSHFS3A
GLSHFS3B
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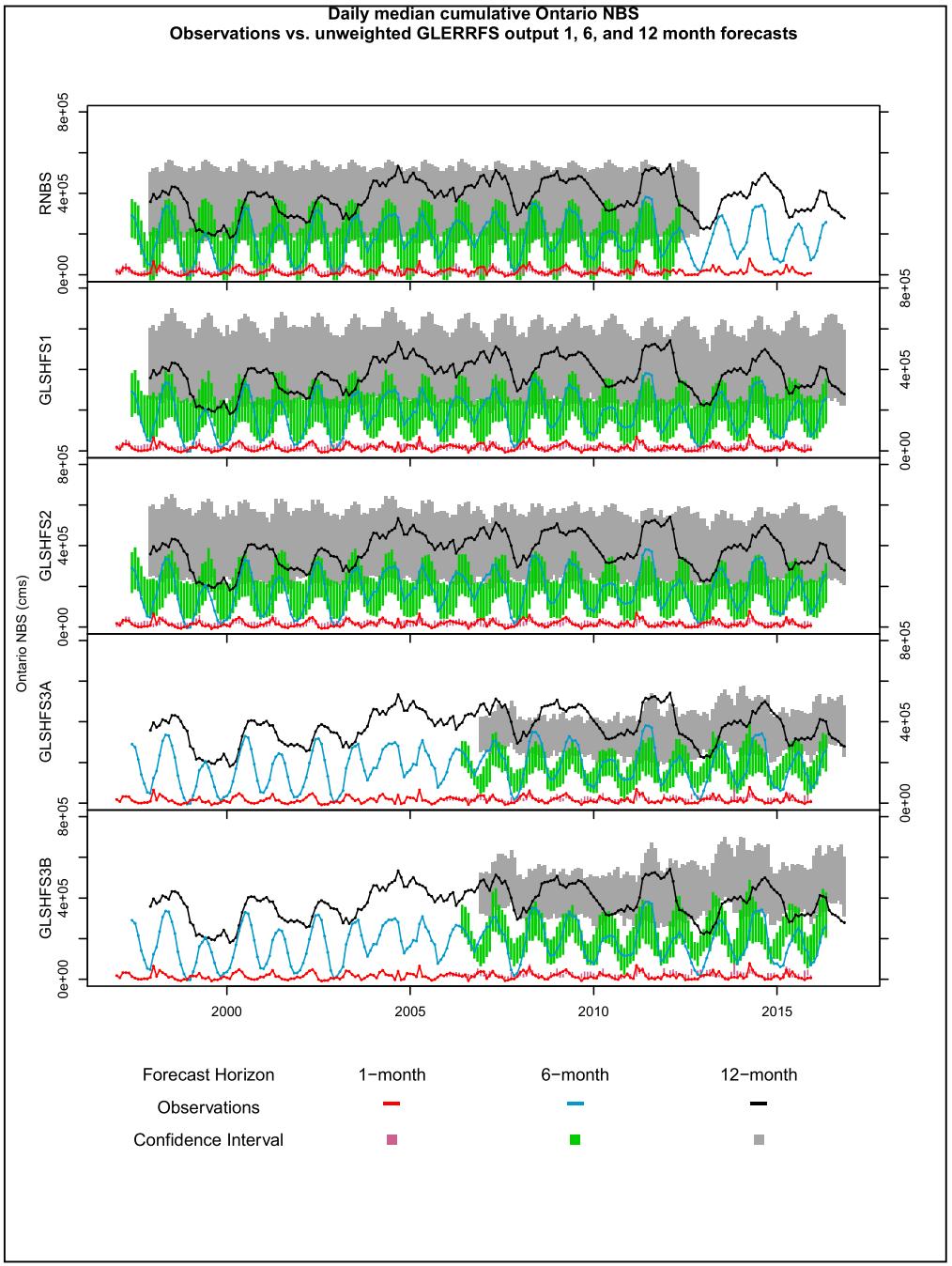
2010
2015
Forecast Horizon
1−month
6−month
12−month
Observations
Confidence Interval


Daily median cumulative Ontario NBS
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Ontario NBS (cms)
RNBS
GLSHFS1
GLSHFS2
GLSHFS3A
GLSHFS3B
0e+00
4e+05
8e+05
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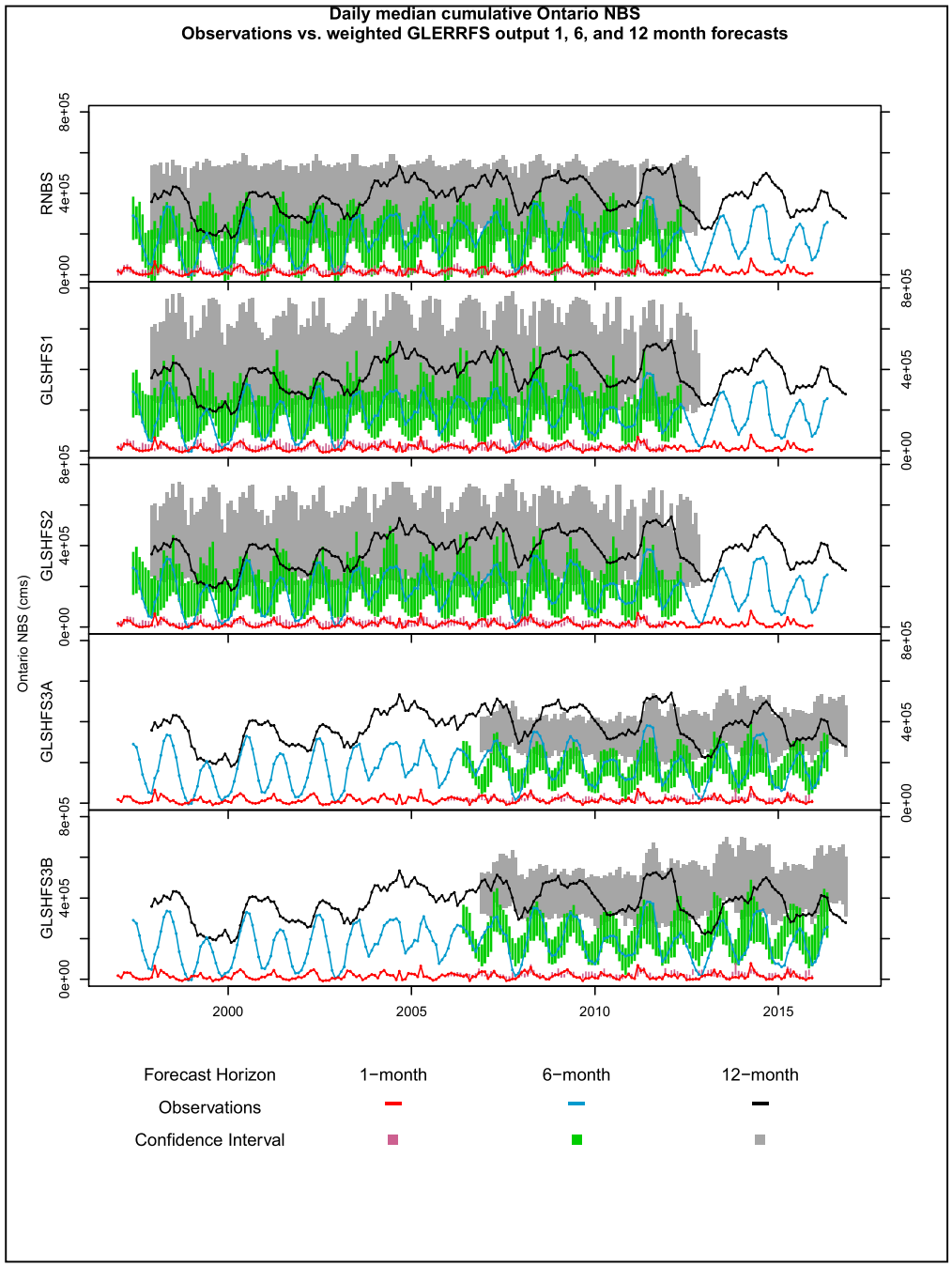
2005
2010
2015
Forecast Horizon
1−month
6−month
12−month
Observations
Confidence Interval


Daily median cumulative Ontario NBS
Observations vs. weighted GLERRFS output 1, 6, and 12 month forecasts
Ontario NBS (cms)
RNBS
GLSHFS1
GLSHFS2
GLSHFS3A
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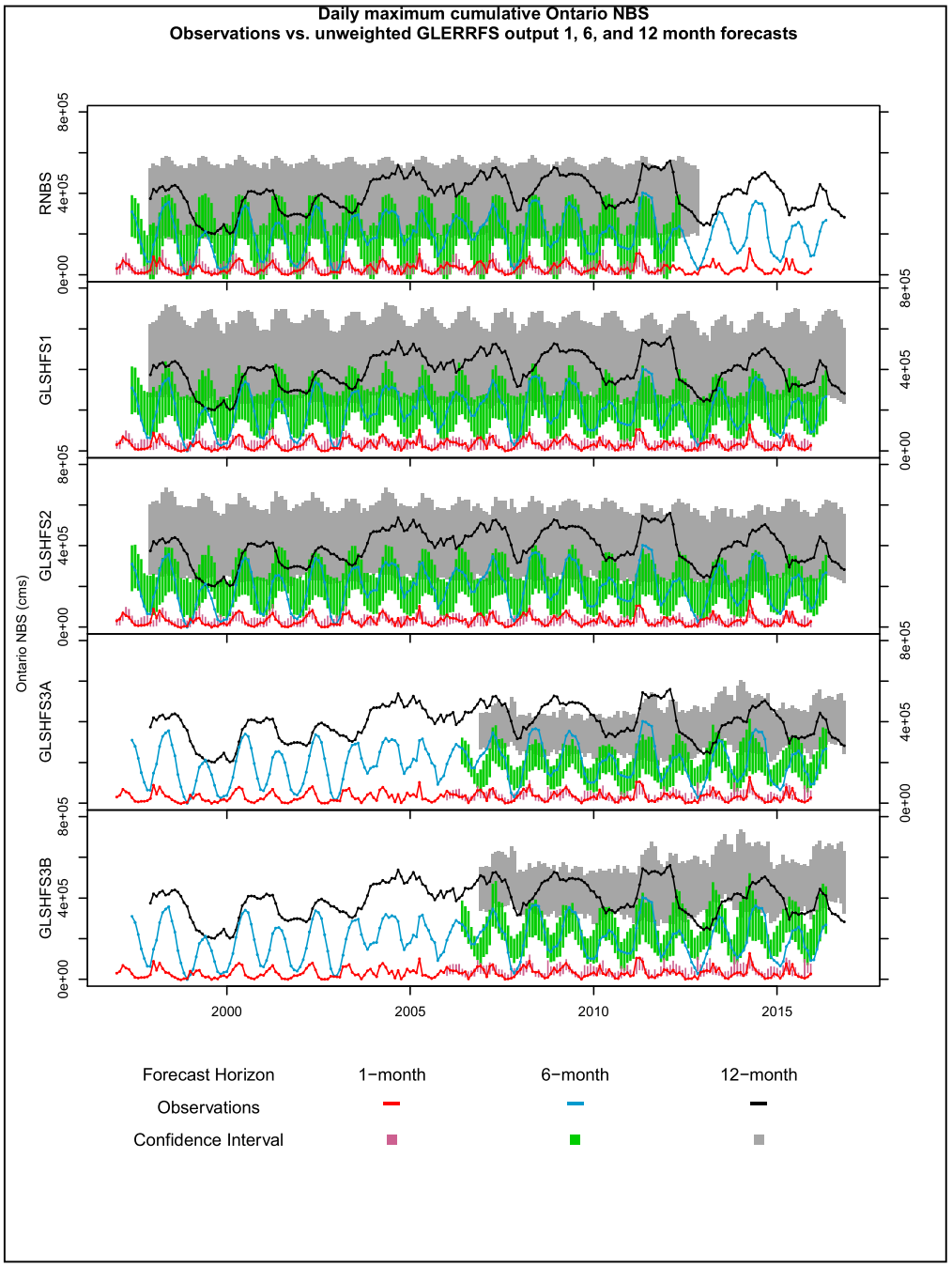
Forecast Horizon
1−month
6−month
12−month
Observations
Confidence Interval


Daily maximum cumulative Ontario NBS
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Ontario NBS (cms)
RNBS
GLSHFS1
GLSHFS2
GLSHFS3A
GLSHFS3B
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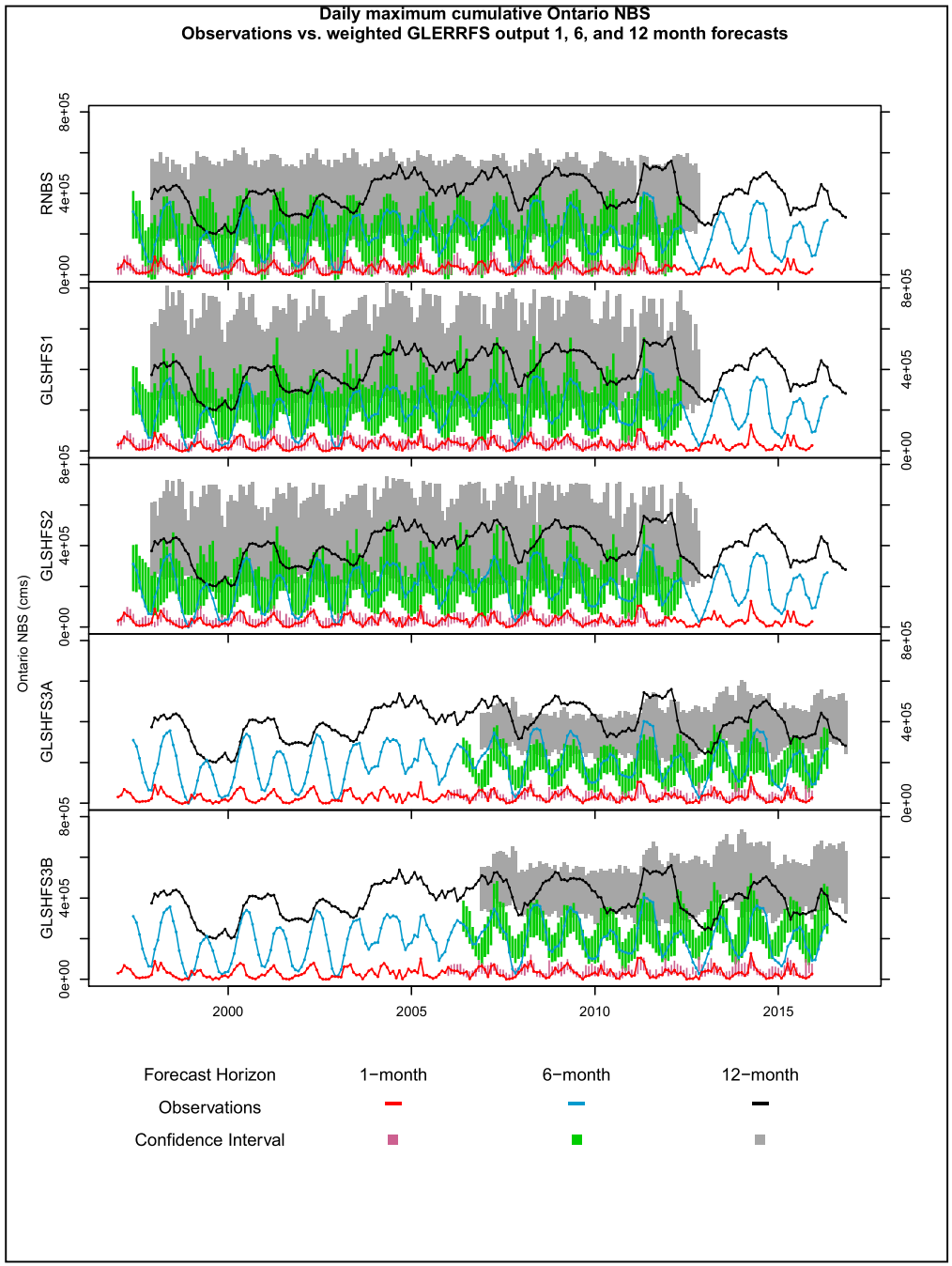
Forecast Horizon
1−month
6−month
12−month
Observations
Confidence Interval


Daily maximum cumulative Ontario NBS
Observations vs. weighted GLERRFS output 1, 6, and 12 month forecasts
Ontario NBS (cms)
RNBS
GLSHFS1
GLSHFS2
GLSHFS3A
GLSHFS3B
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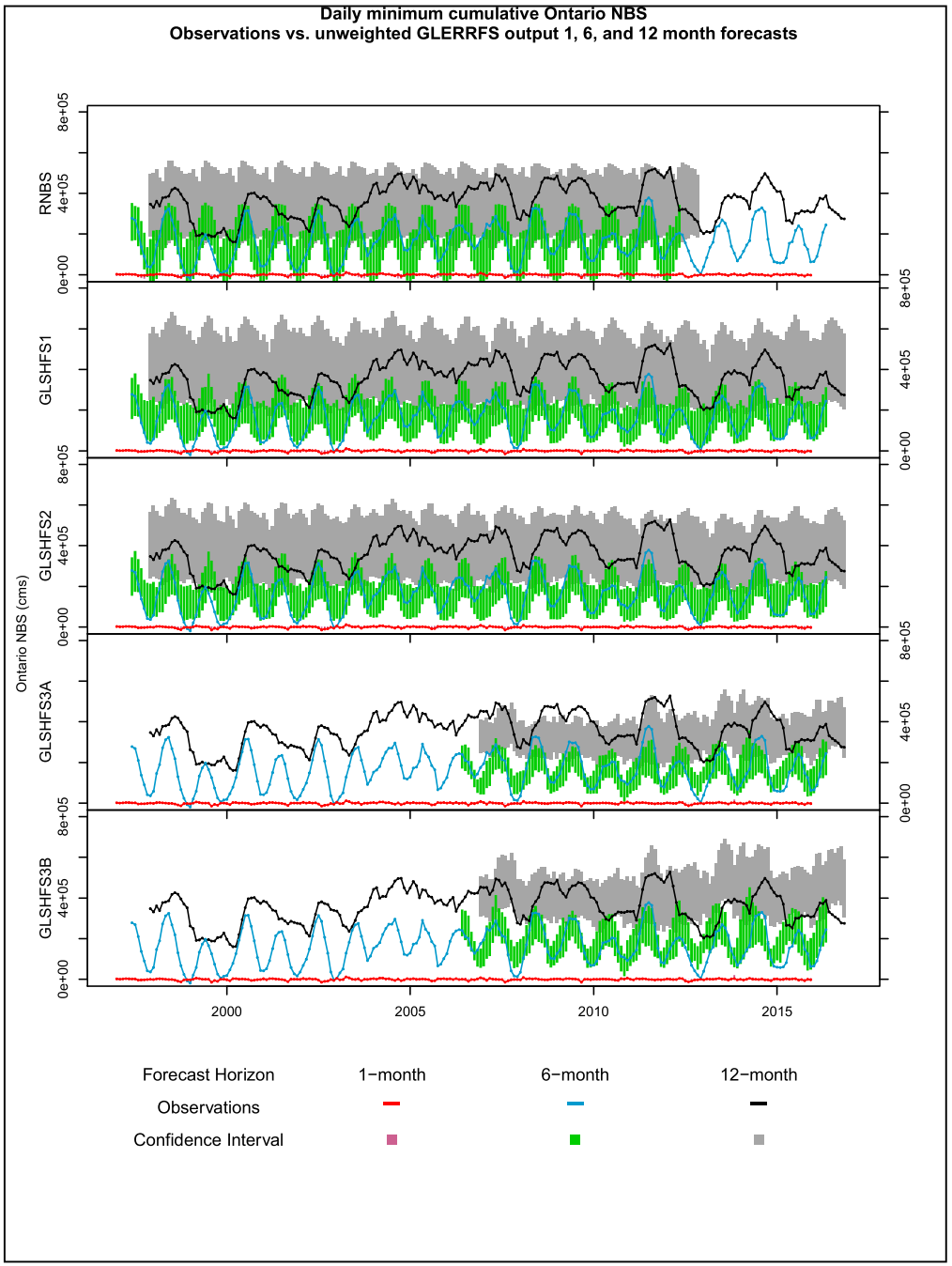
2015
Forecast Horizon
1−month
6−month
12−month
Observations
Confidence Interval


Daily minimum cumulative Ontario NBS
Observations vs. unweighted GLERRFS output 1, 6, and 12 month forecasts
Ontario NBS (cms)
RNBS
GLSHFS1
GLSHFS2
GLSHFS3A
GLSHFS3B
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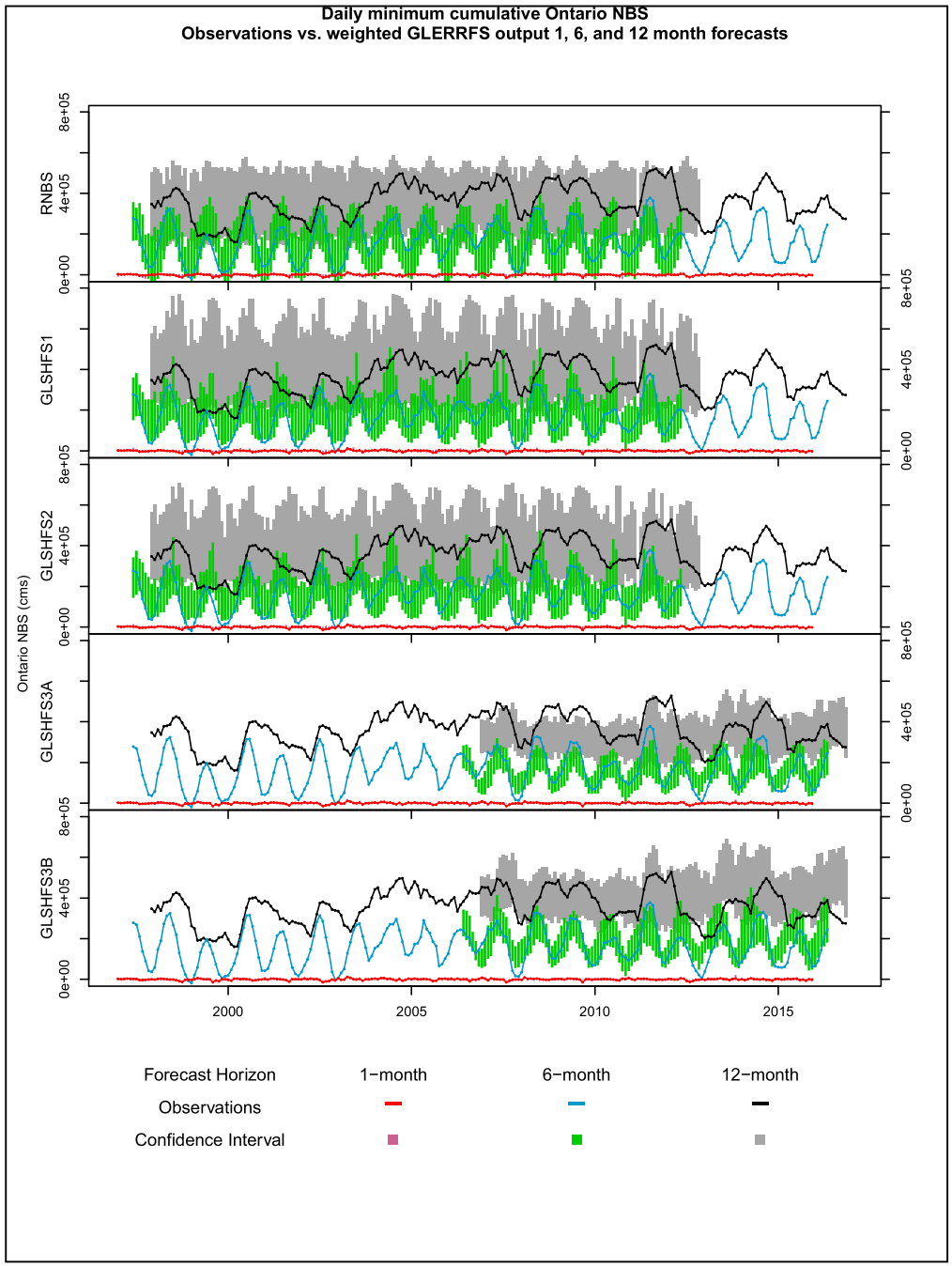
Forecast Horizon
1−month
6−month
12−month
Observations
Confidence Interval


Daily minimum cumulative Ontario NBS
Observations vs. weighted GLERRFS output 1, 6, and 12 month forecasts
Ontario NBS (cms)
RNBS
GLSHFS1
GLSHFS2
GLSHFS3A
GLSHFS3B
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Forecast Horizon
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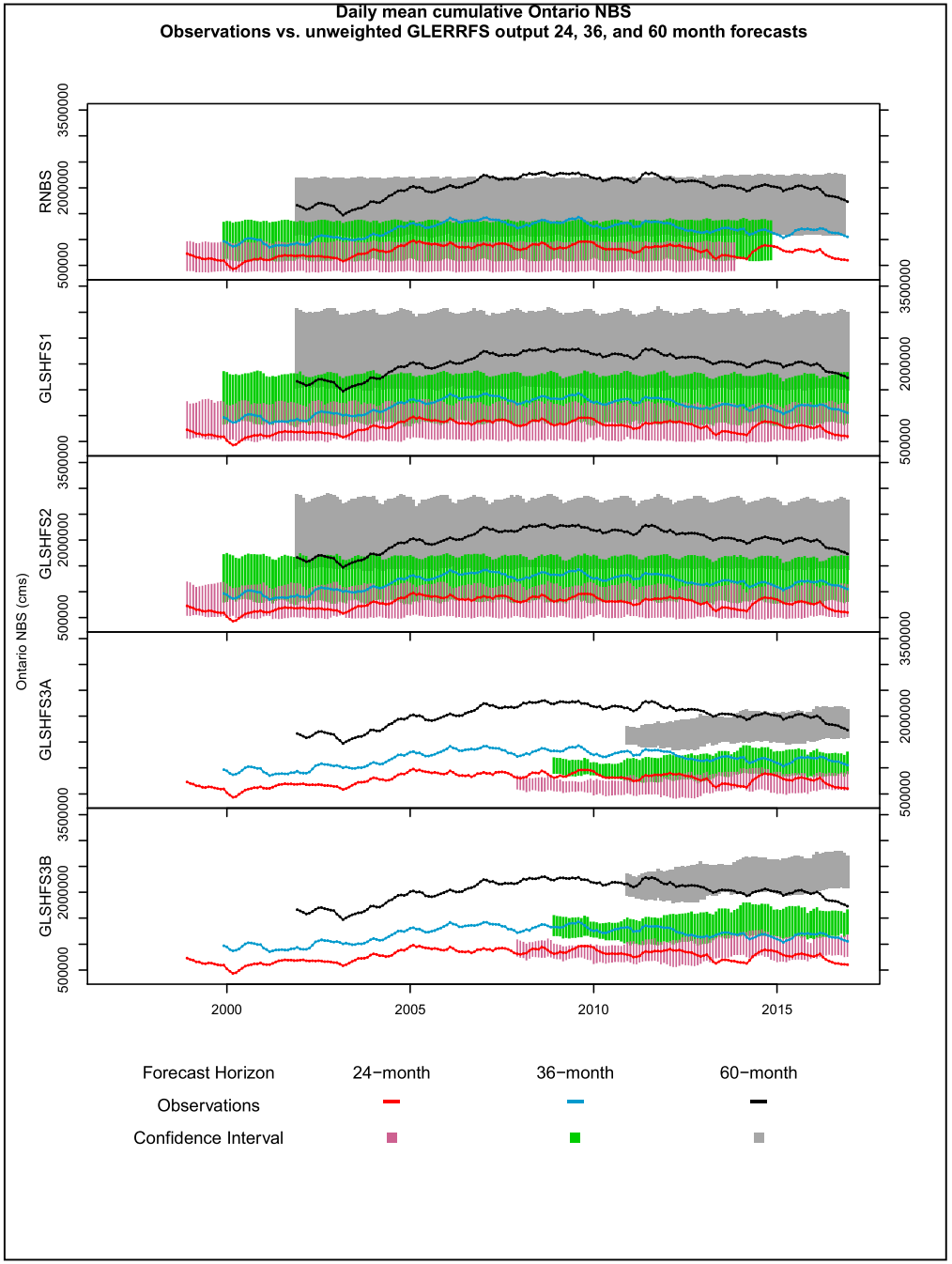
6−month
12−month
Observations
Confidence Interval


Daily mean cumulative Ontario NBS
Observations vs. unweighted GLERRFS output 24, 36, and 60 month forecasts
Ontario NBS (cms)
RNBS
GLSHFS1
GLSHFS2
GLSHFS3A
GLSHFS3B
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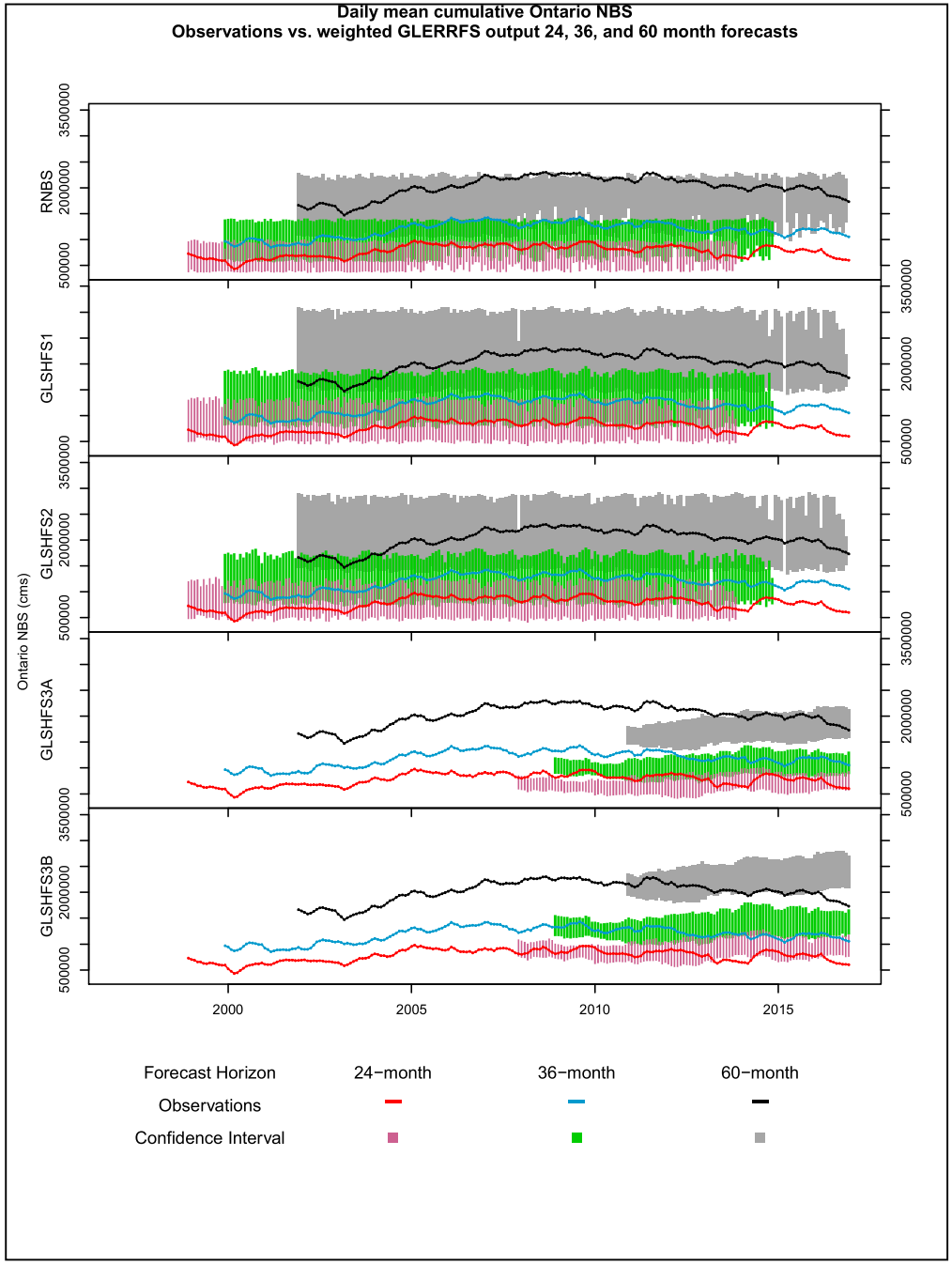
2000
2005
2010
2015
Forecast Horizon
24−month
36−month
60−month
Observations
Confidence Interval


Daily mean cumulative Ontario NBS
Observations vs. weighted GLERRFS output 24, 36, and 60 month forecasts
Ontario NBS (cms)
RNBS
GLSHFS1
GLSHFS2
GLSHFS3A
GLSHFS3B
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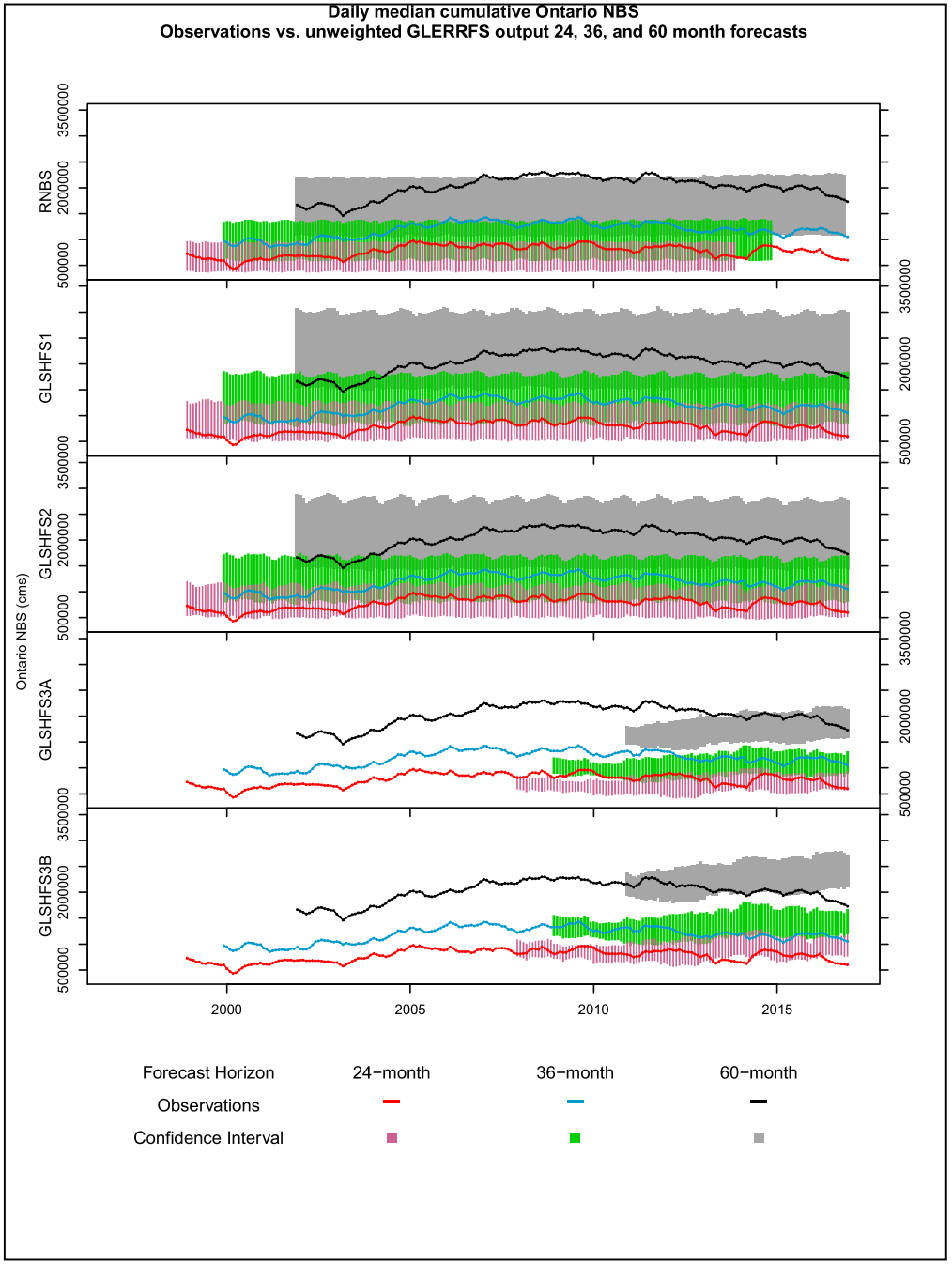
2015
Forecast Horizon
24−month
36−month
60−month
Observations
Confidence Interval


Daily median cumulative Ontario NBS
Observations vs. unweighted GLERRFS output 24, 36, and 60 month forecasts
Ontario NBS (cms)
RNBS
GLSHFS1
GLSHFS2
GLSHFS3A
GLSHFS3B
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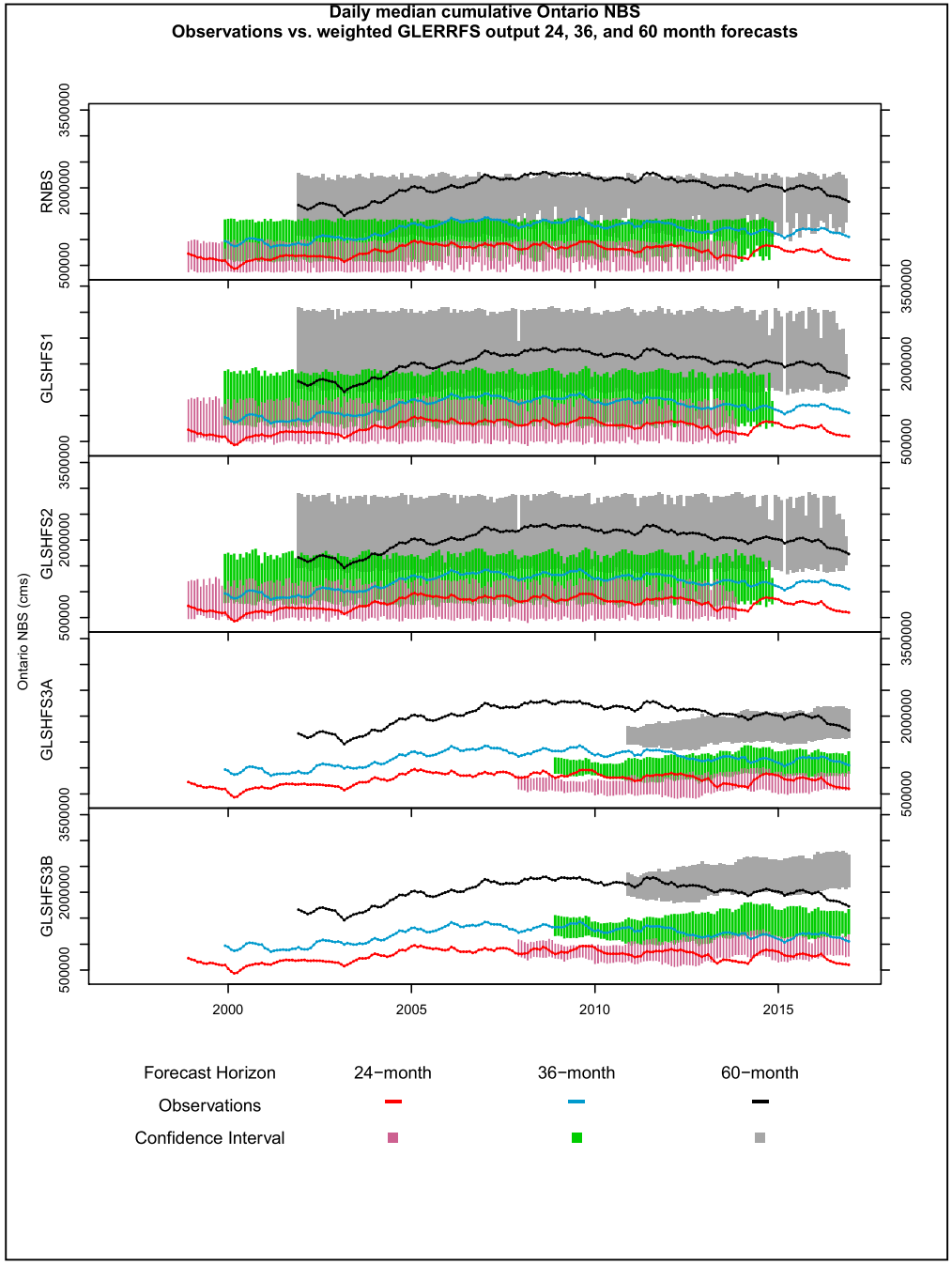
Forecast Horizon
24−month
36−month
60−month
Observations
Confidence Interval


Daily median cumulative Ontario NBS
Observations vs. weighted GLERRFS output 24, 36, and 60 month forecasts
Ontario NBS (cms)
RNBS
GLSHFS1
GLSHFS2
GLSHFS3A
GLSHFS3B
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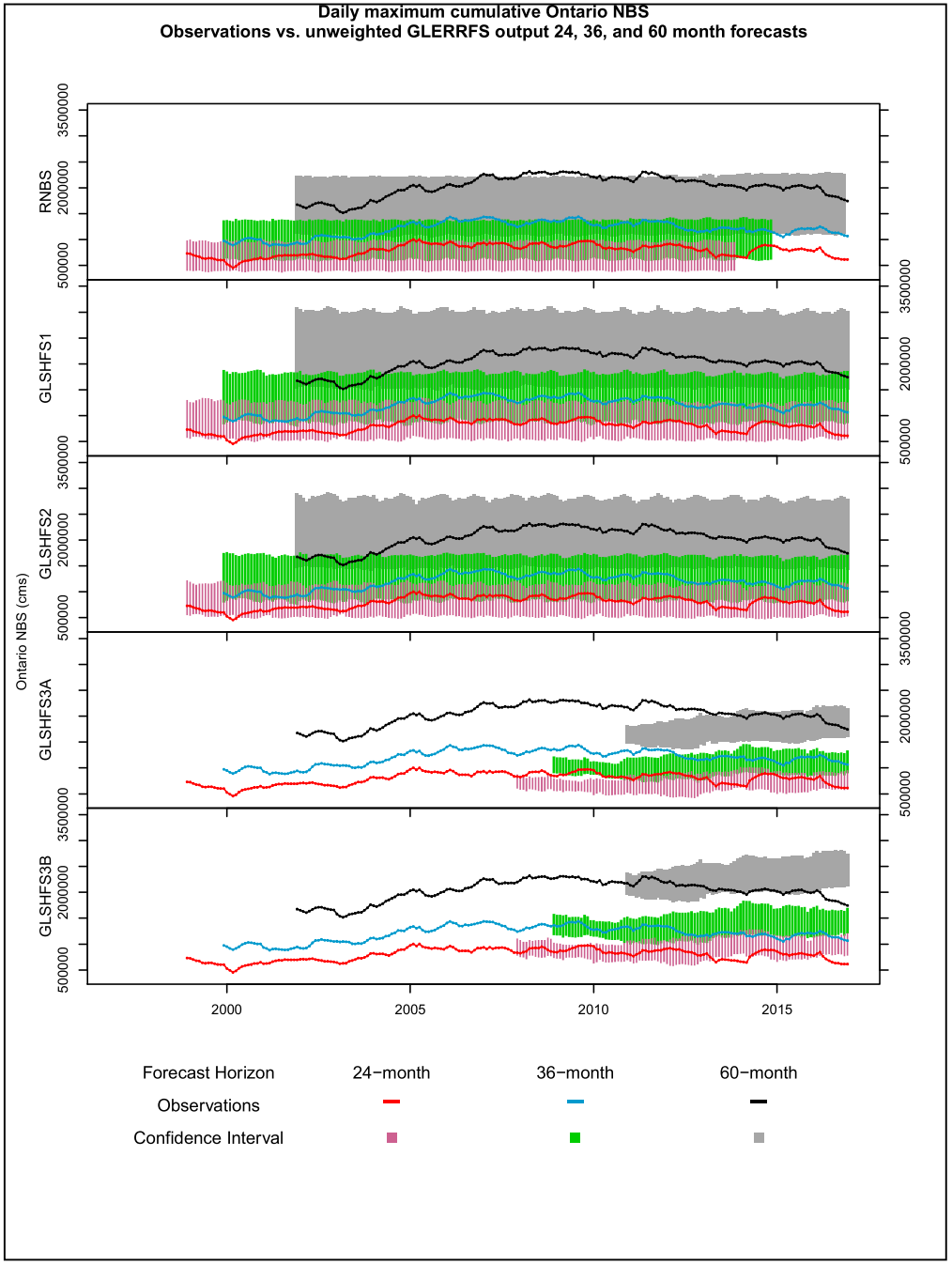
Forecast Horizon
24−month
36−month
60−month
Observations
Confidence Interval


Daily maximum cumulative Ontario NBS
Observations vs. unweighted GLERRFS output 24, 36, and 60 month forecasts
Ontario NBS (cms)
RNBS
GLSHFS1
GLSHFS2
GLSHFS3A
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Forecast Horizon
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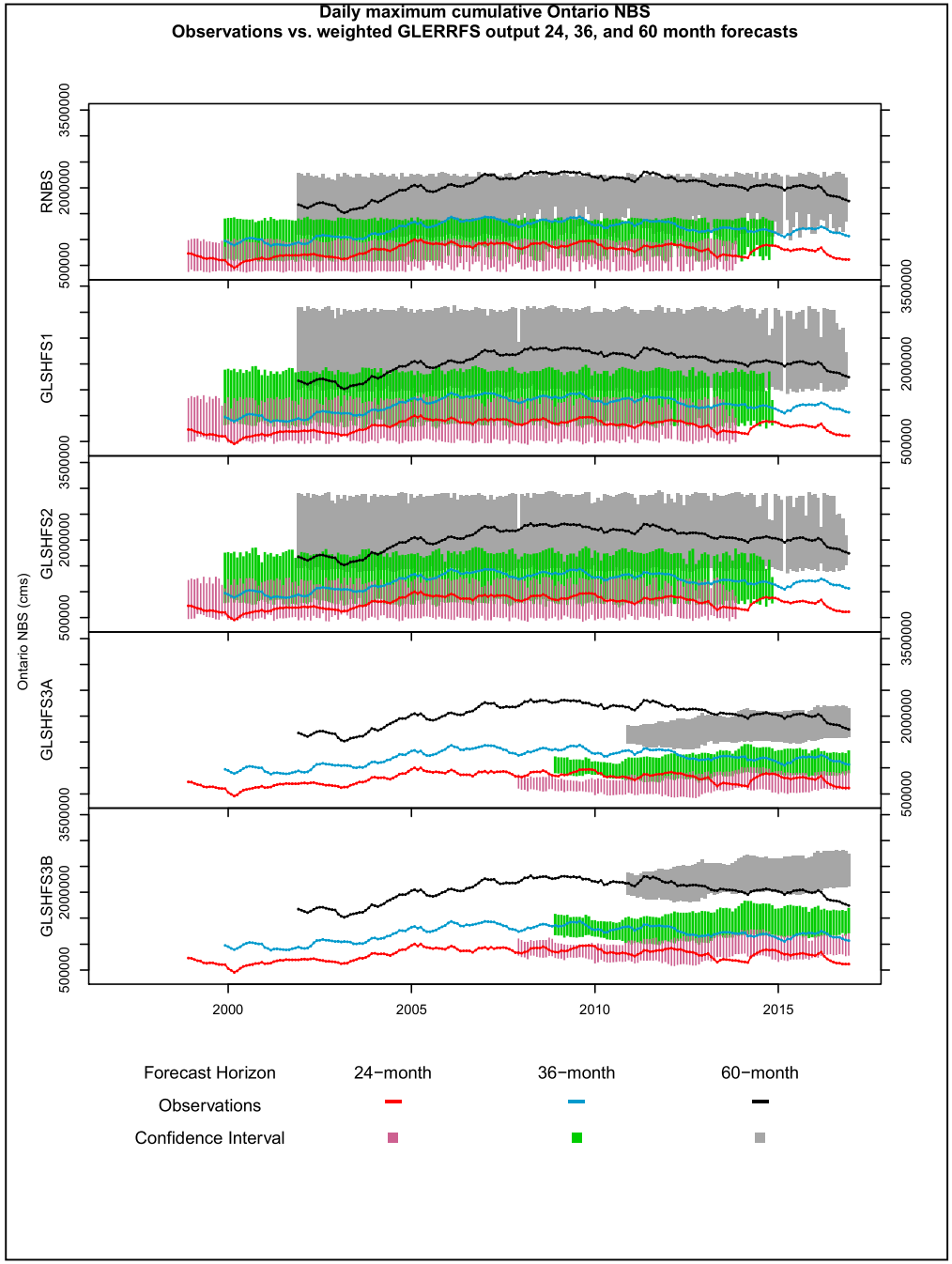
36−month
60−month
Observations
Confidence Interval


Daily maximum cumulative Ontario NBS
Observations vs. weighted GLERRFS output 24, 36, and 60 month forecasts
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RNBS
GLSHFS1
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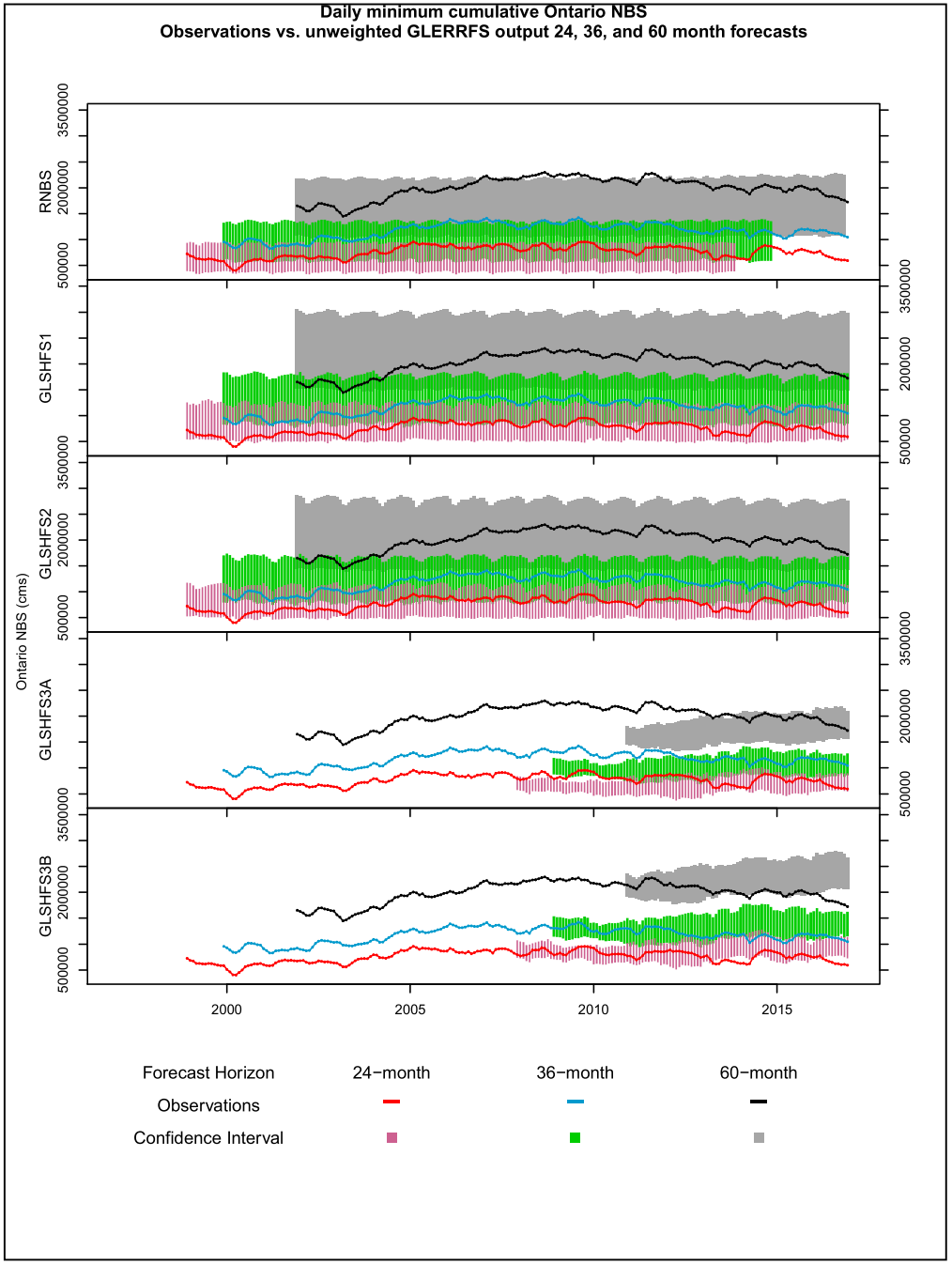
Forecast Horizon
24−month
36−month
60−month
Observations
Confidence Interval


Daily minimum cumulative Ontario NBS
Observations vs. unweighted GLERRFS output 24, 36, and 60 month forecasts
Ontario NBS (cms)
RNBS
GLSHFS1
GLSHFS2
GLSHFS3A
GLSHFS3B
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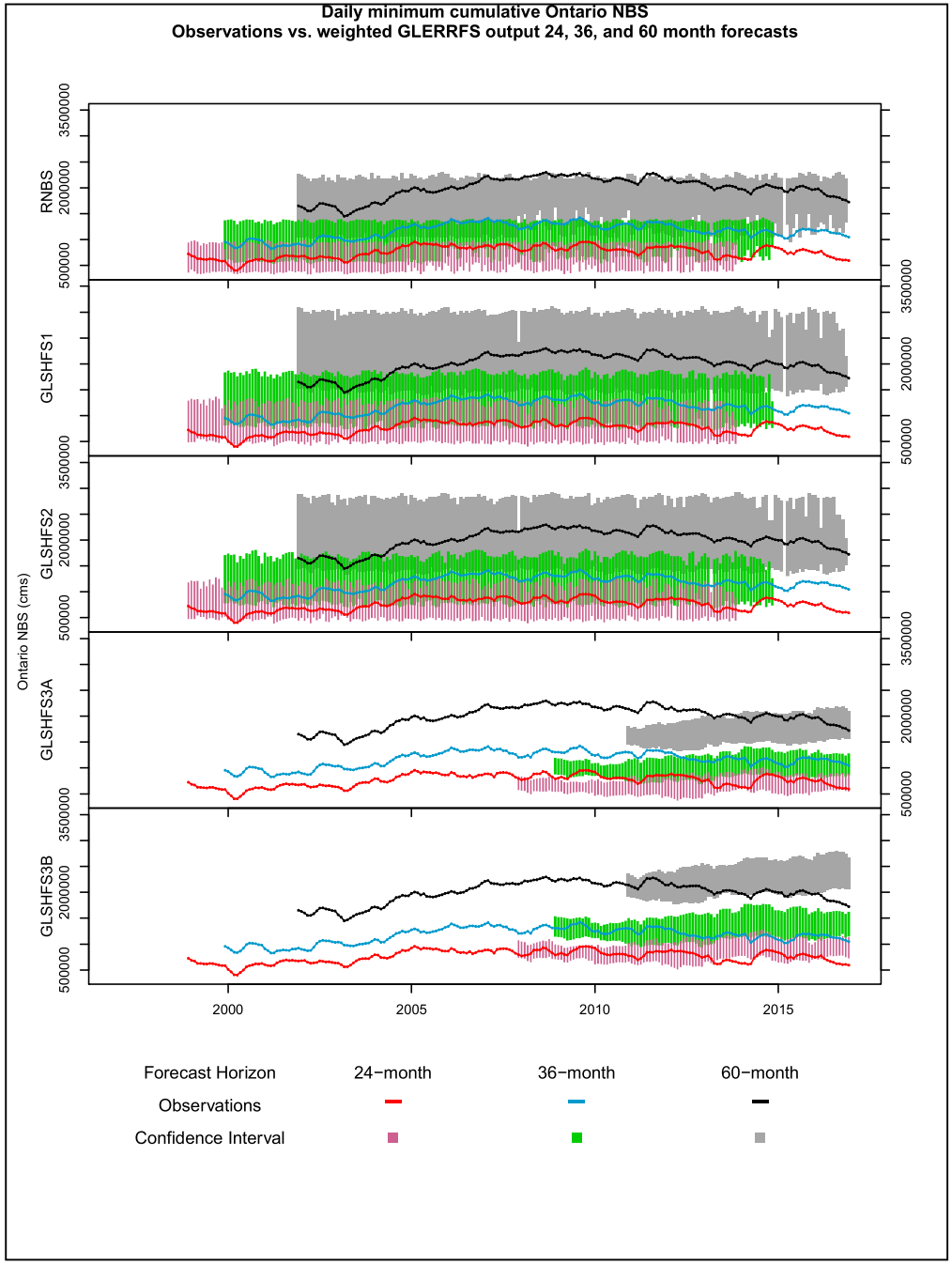
Forecast Horizon
24−month
36−month
60−month
Observations
Confidence Interval


Daily minimum cumulative Ontario NBS
Observations vs. weighted GLERRFS output 24, 36, and 60 month forecasts
Ontario NBS (cms)
RNBS
GLSHFS1
GLSHFS2
GLSHFS3A
GLSHFS3B
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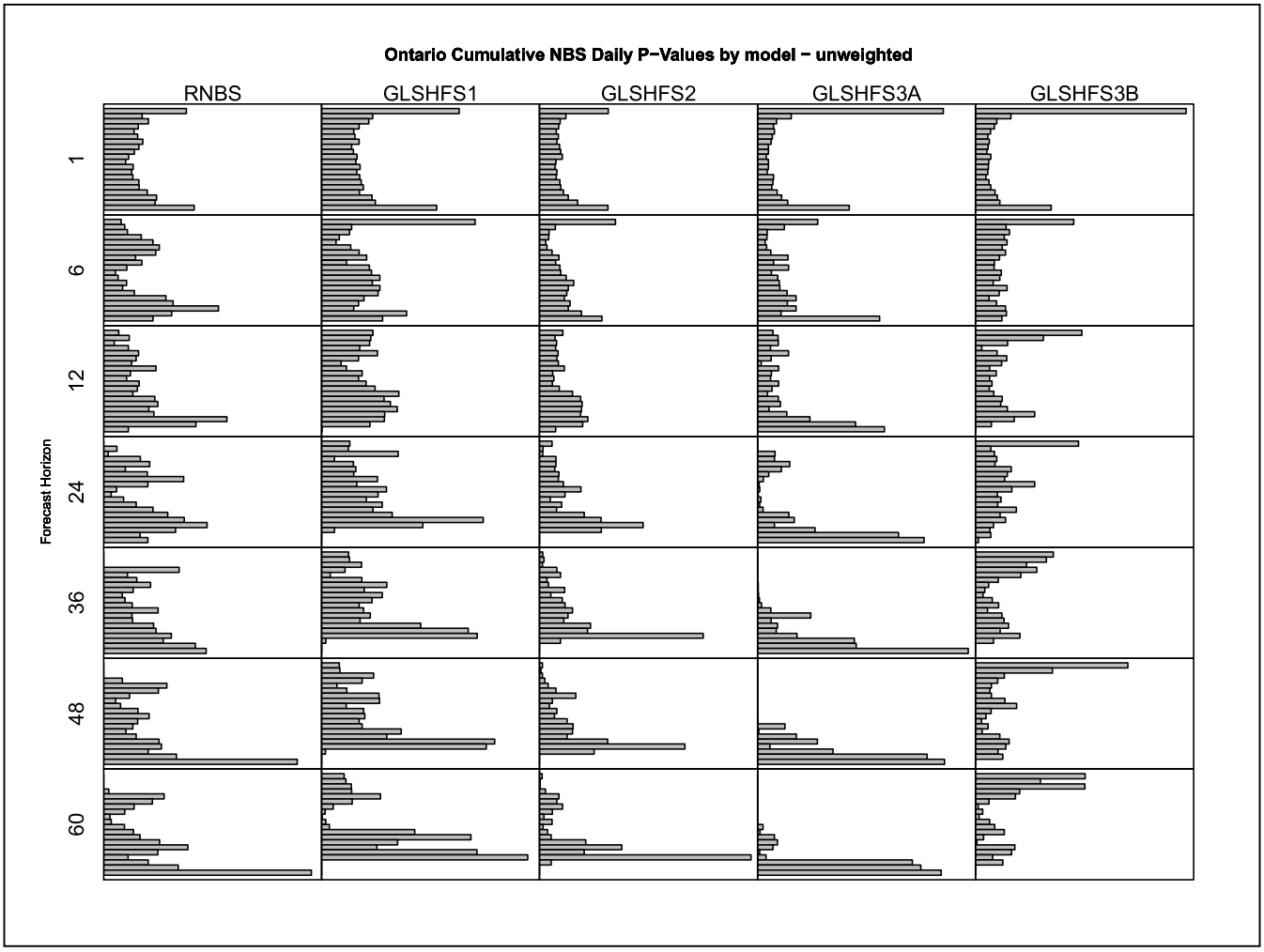
Forecast Horizon
24−month
36−month
60−month
Observations
Confidence Interval


Ontario Cumulative NBS Daily P−Values by model − unweighted
RNBS
GLSHFS1
GLSHFS2
GLSHFS3A
GLSHFS3B
Forecast Horizon
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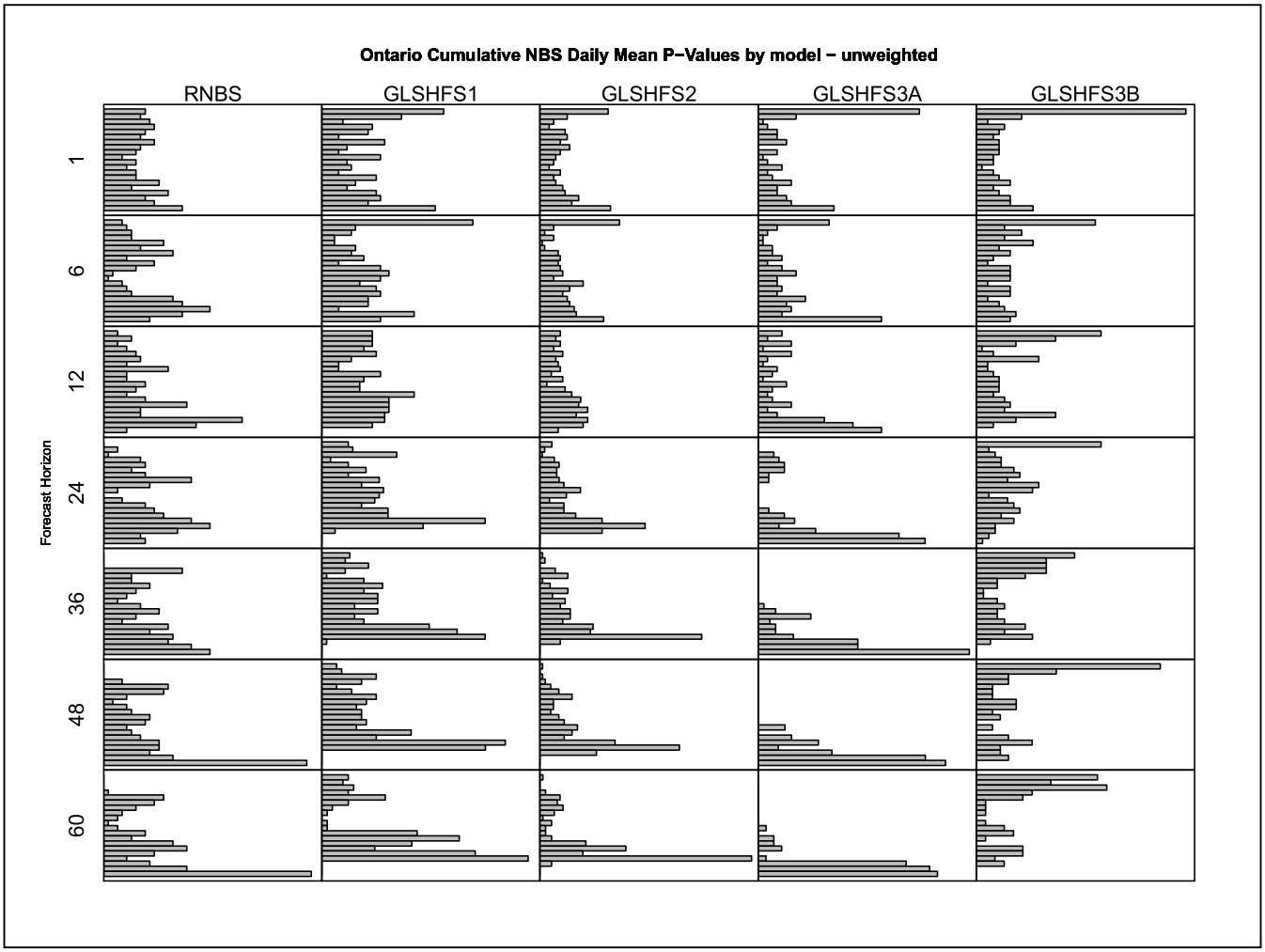
Ontario Cumulative NBS Daily Mean P−Values by model − unweighted
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GLSHFS2
GLSHFS3A
GLSHFS3B
Forecast Horizon
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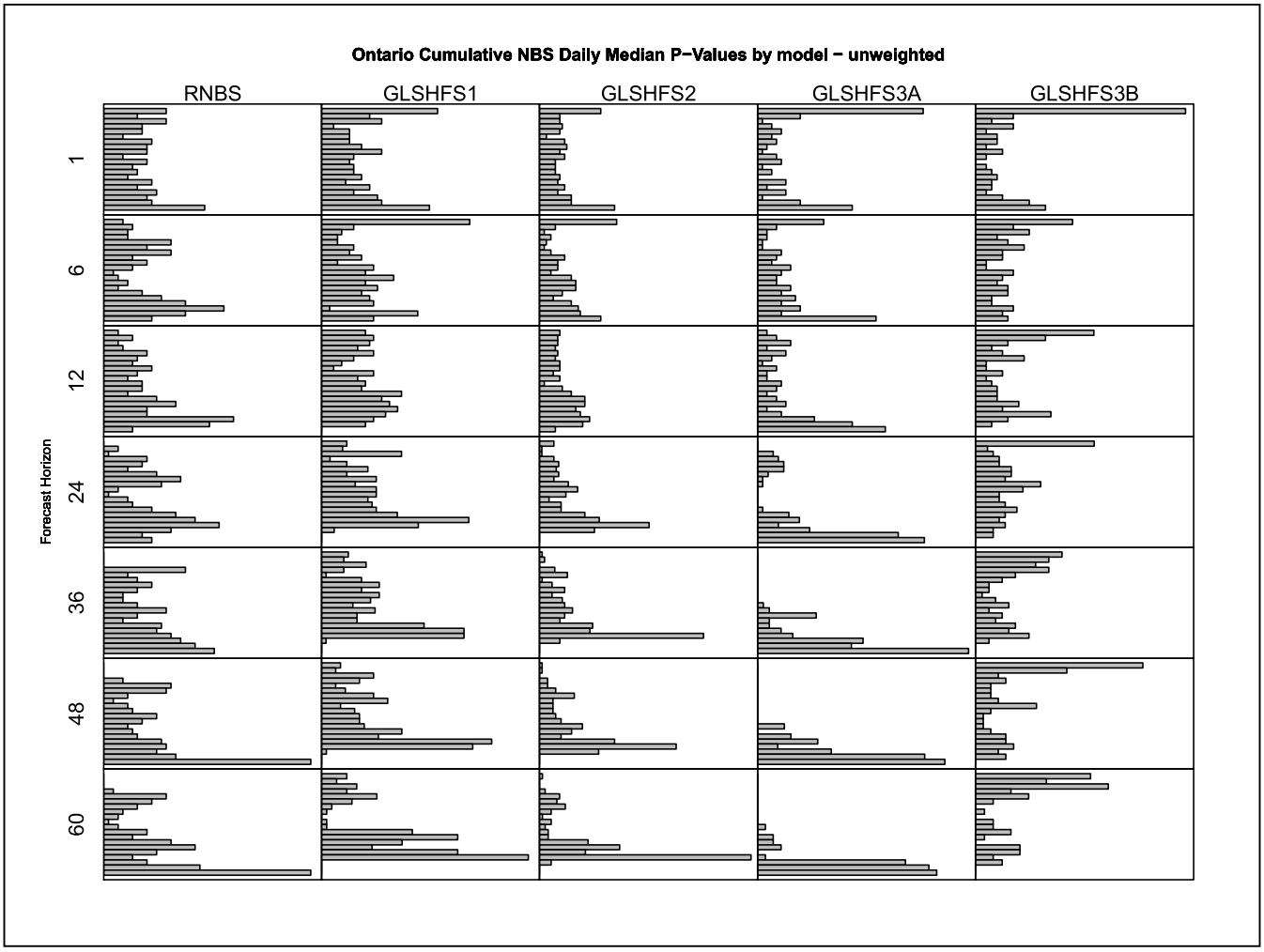
Ontario Cumulative NBS Daily Median P−Values by model − unweighted
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GLSHFS3A
GLSHFS3B
Forecast Horizon
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48
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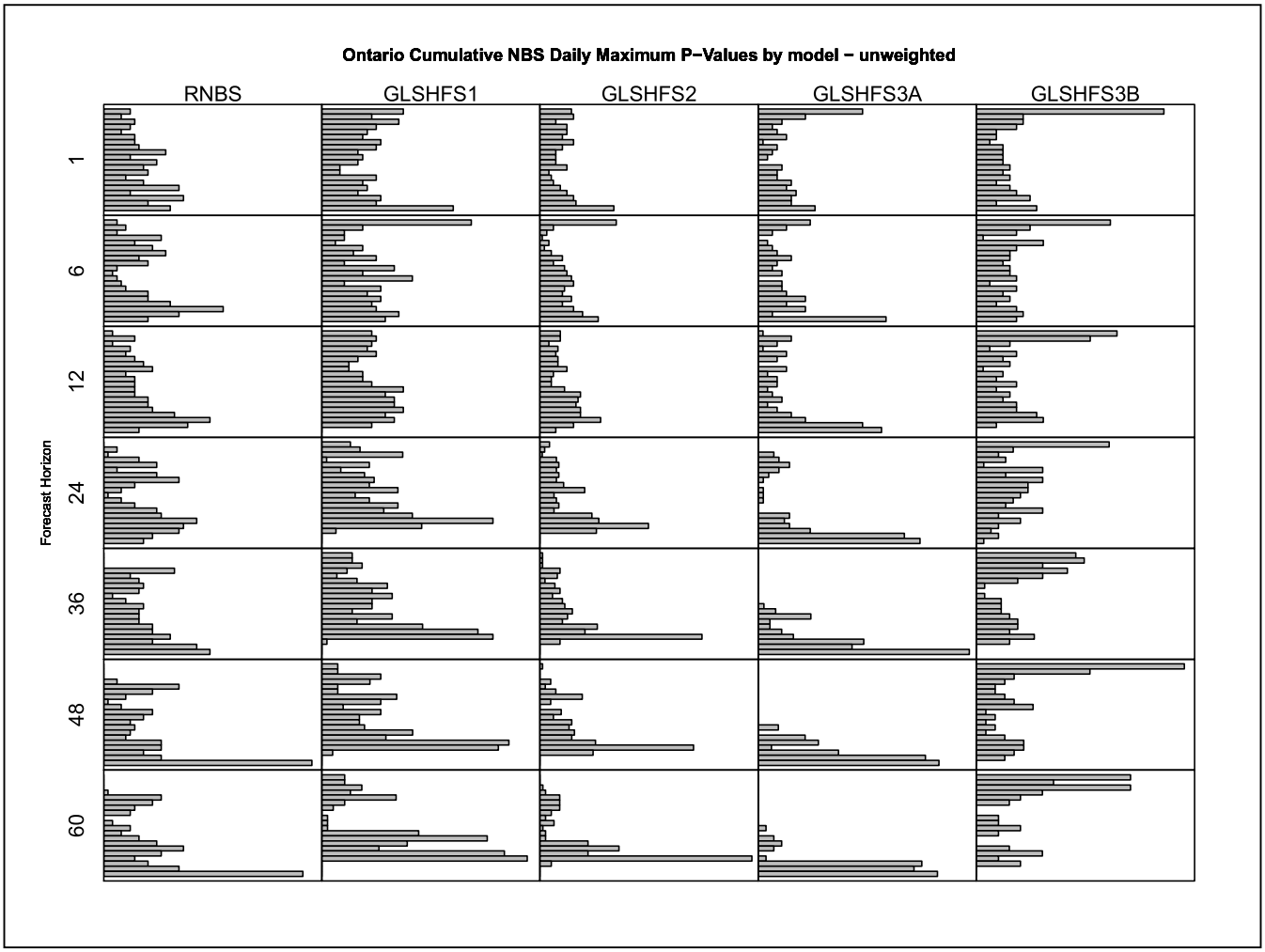
Ontario Cumulative NBS Daily Maximum P−Values by model − unweighted
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GLSHFS2
GLSHFS3A
GLSHFS3B
Forecast Horizon
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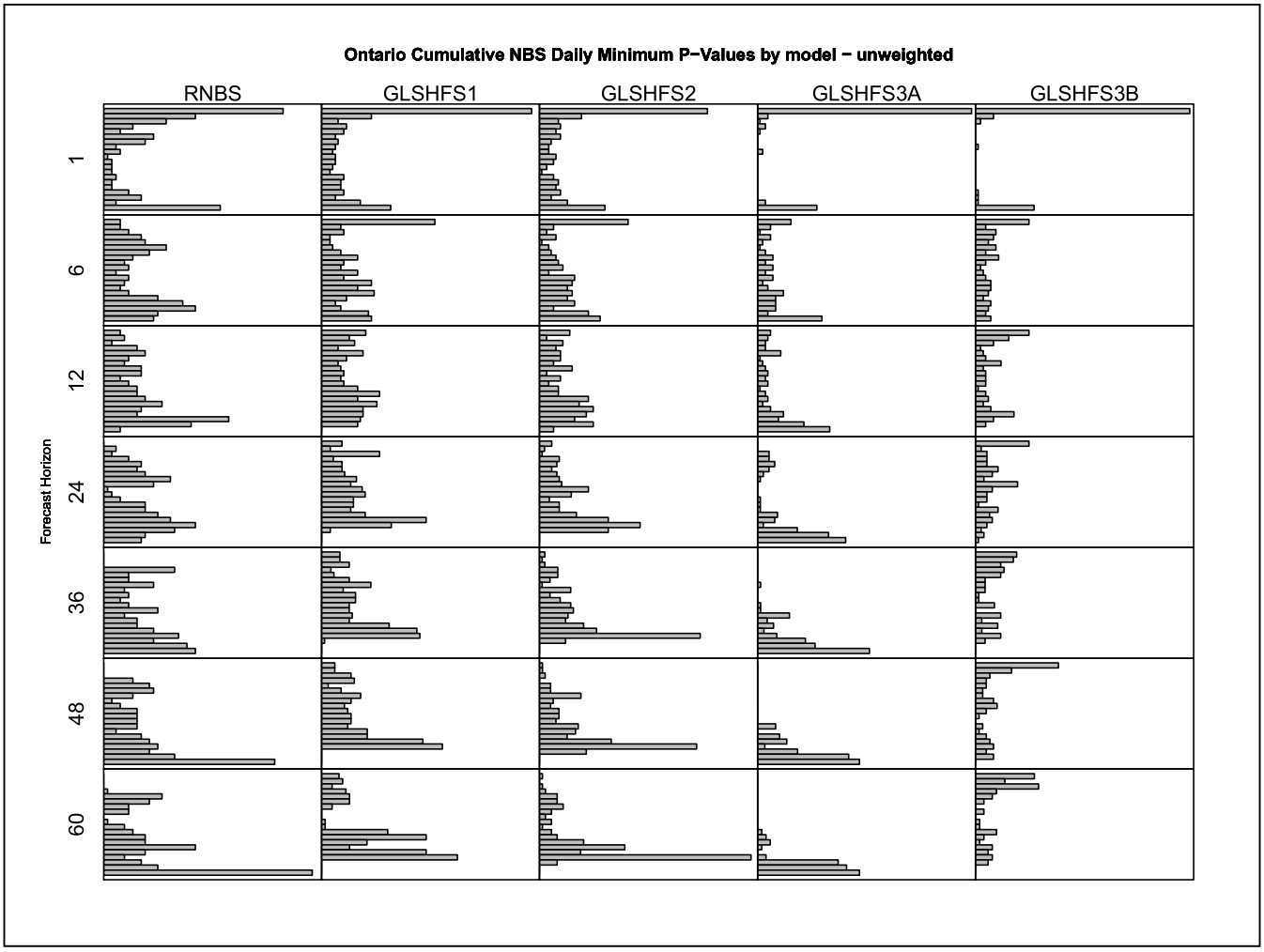
Ontario Cumulative NBS Daily Minimum P−Values by model − unweighted
RNBS
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GLSHFS2
GLSHFS3A
GLSHFS3B
Forecast Horizon
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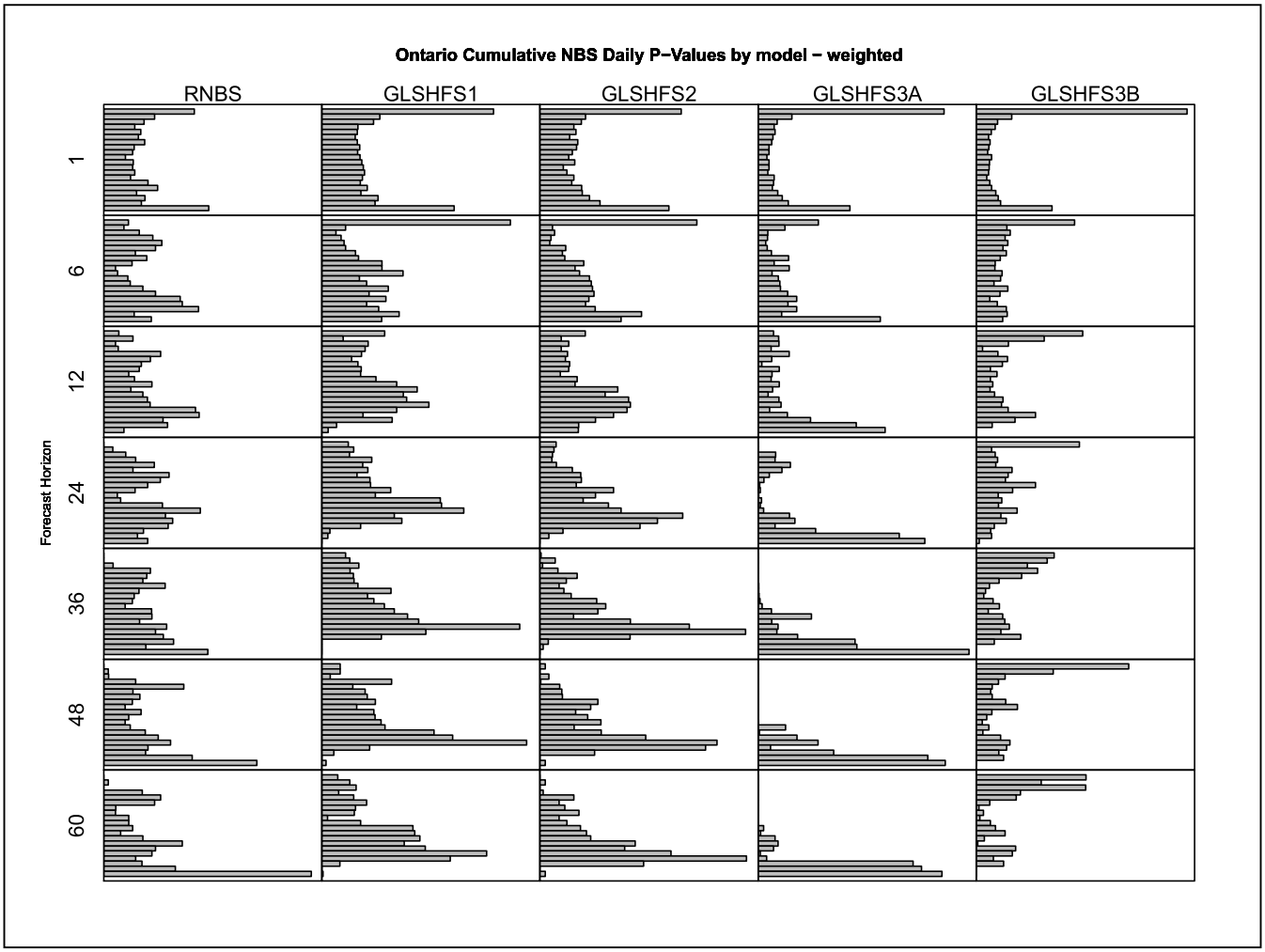
Ontario Cumulative NBS Daily P−Values by model − weighted
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GLSHFS2
GLSHFS3A
GLSHFS3B
Forecast Horizon
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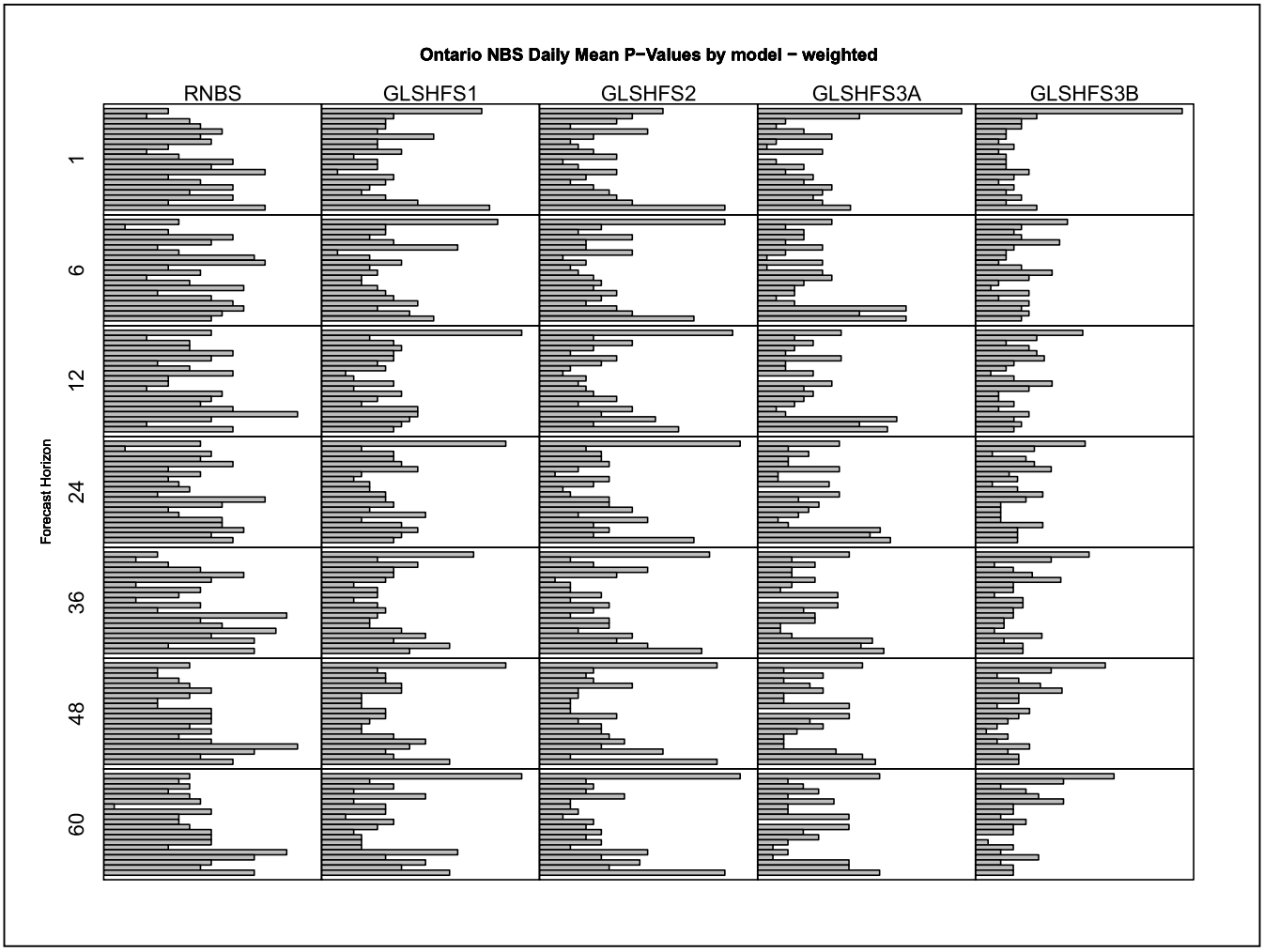
Ontario NBS Daily Mean P−Values by model − weighted
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GLSHFS1
GLSHFS2
GLSHFS3A
GLSHFS3B
Forecast Horizon
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48
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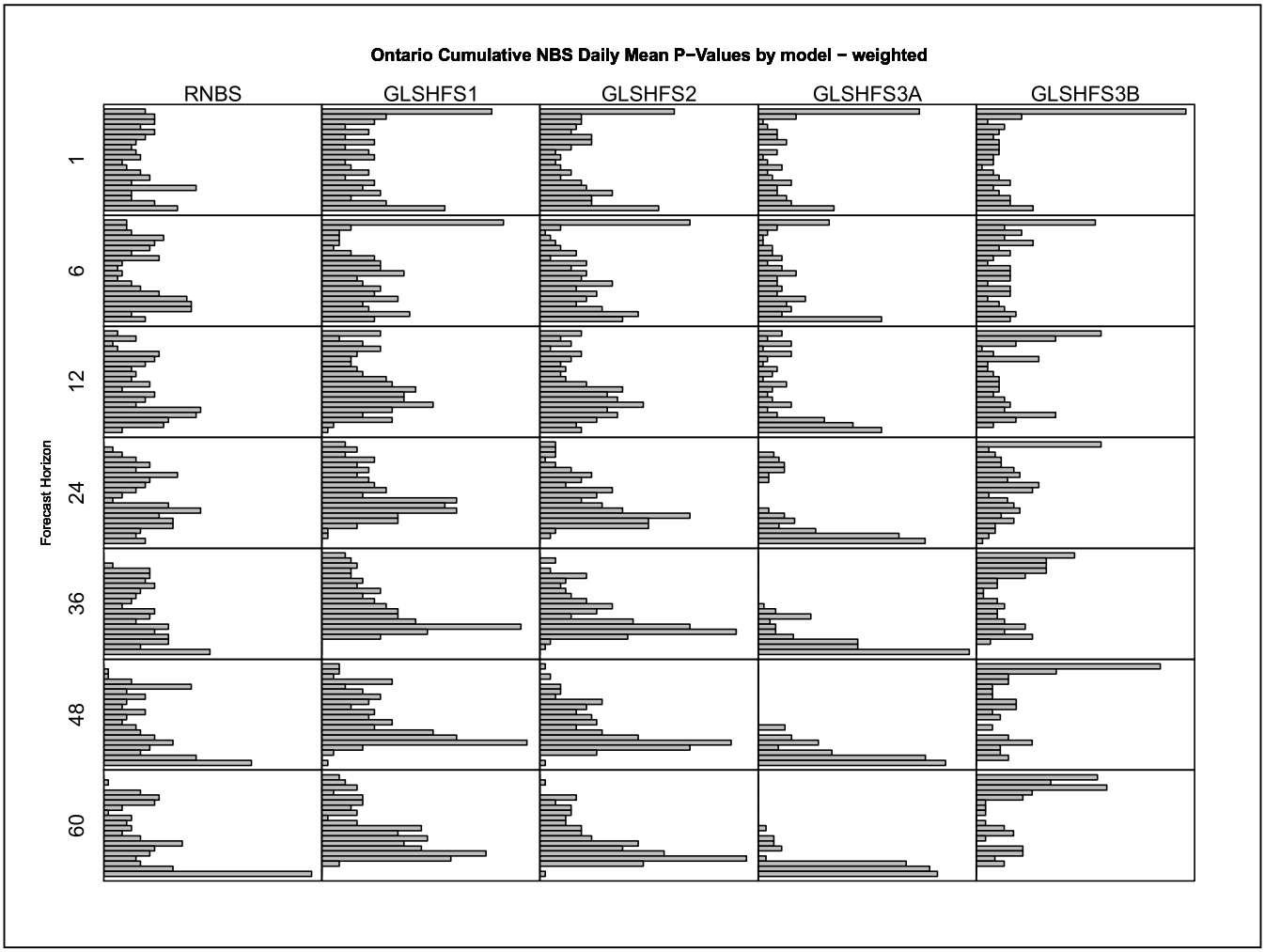
Ontario Cumulative NBS Daily Mean P−Values by model − weighted
RNBS
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GLSHFS2
GLSHFS3A
GLSHFS3B
Forecast Horizon
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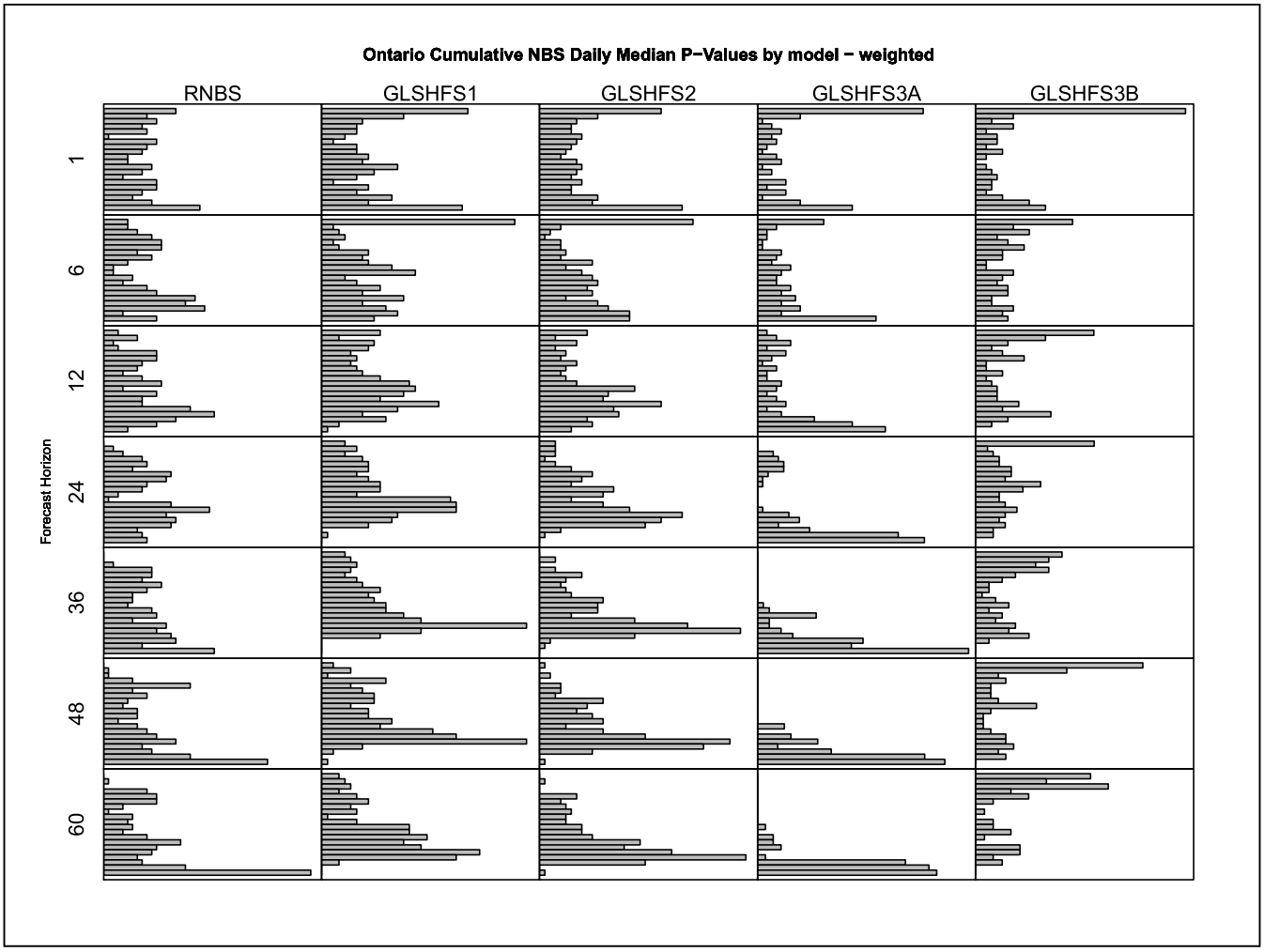
Ontario Cumulative NBS Daily Median P−Values by model − weighted
RNBS
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GLSHFS2
GLSHFS3A
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Forecast Horizon
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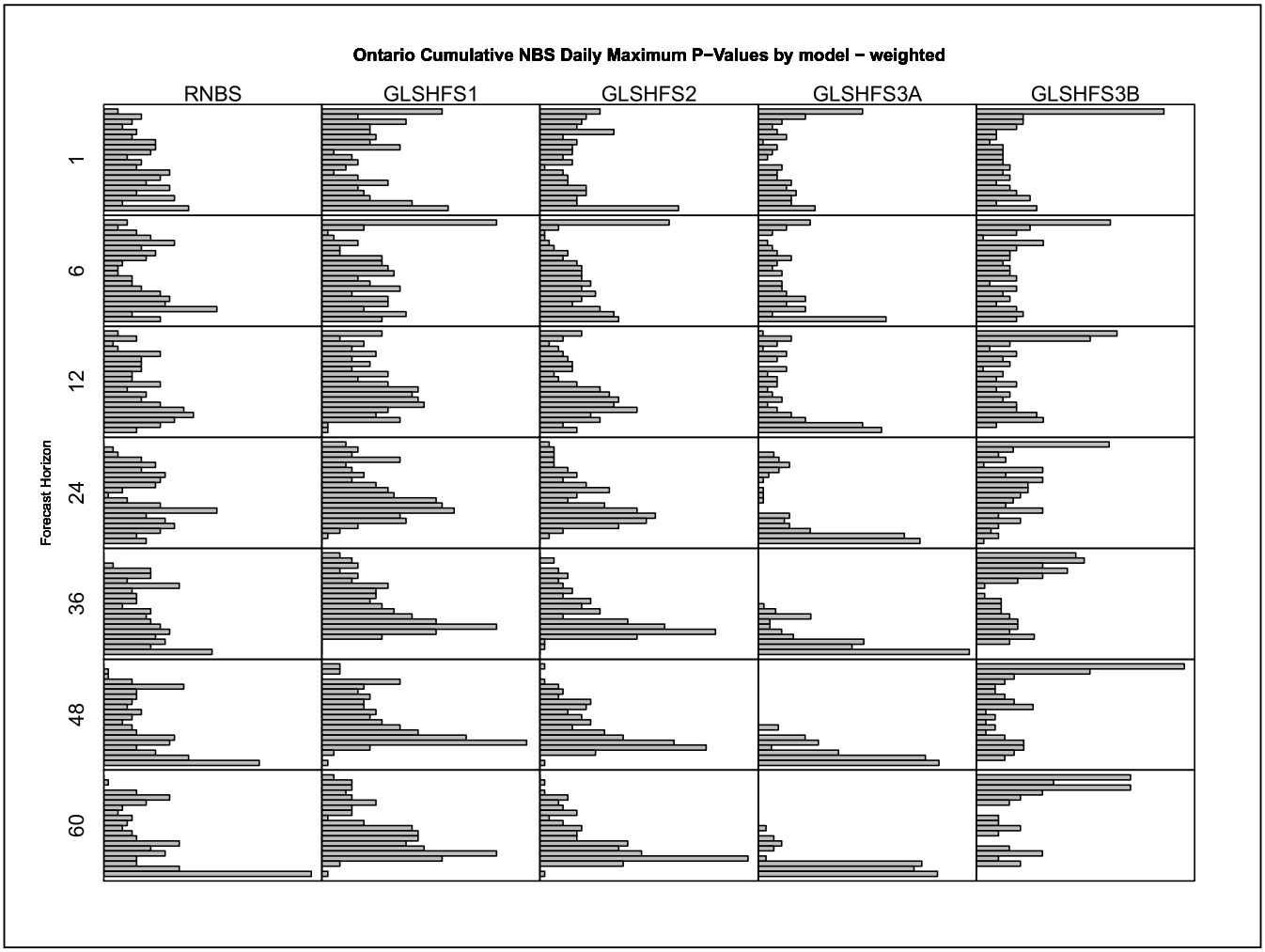
Ontario Cumulative NBS Daily Maximum P−Values by model − weighted
RNBS
GLSHFS1
GLSHFS2
GLSHFS3A
GLSHFS3B
Forecast Horizon
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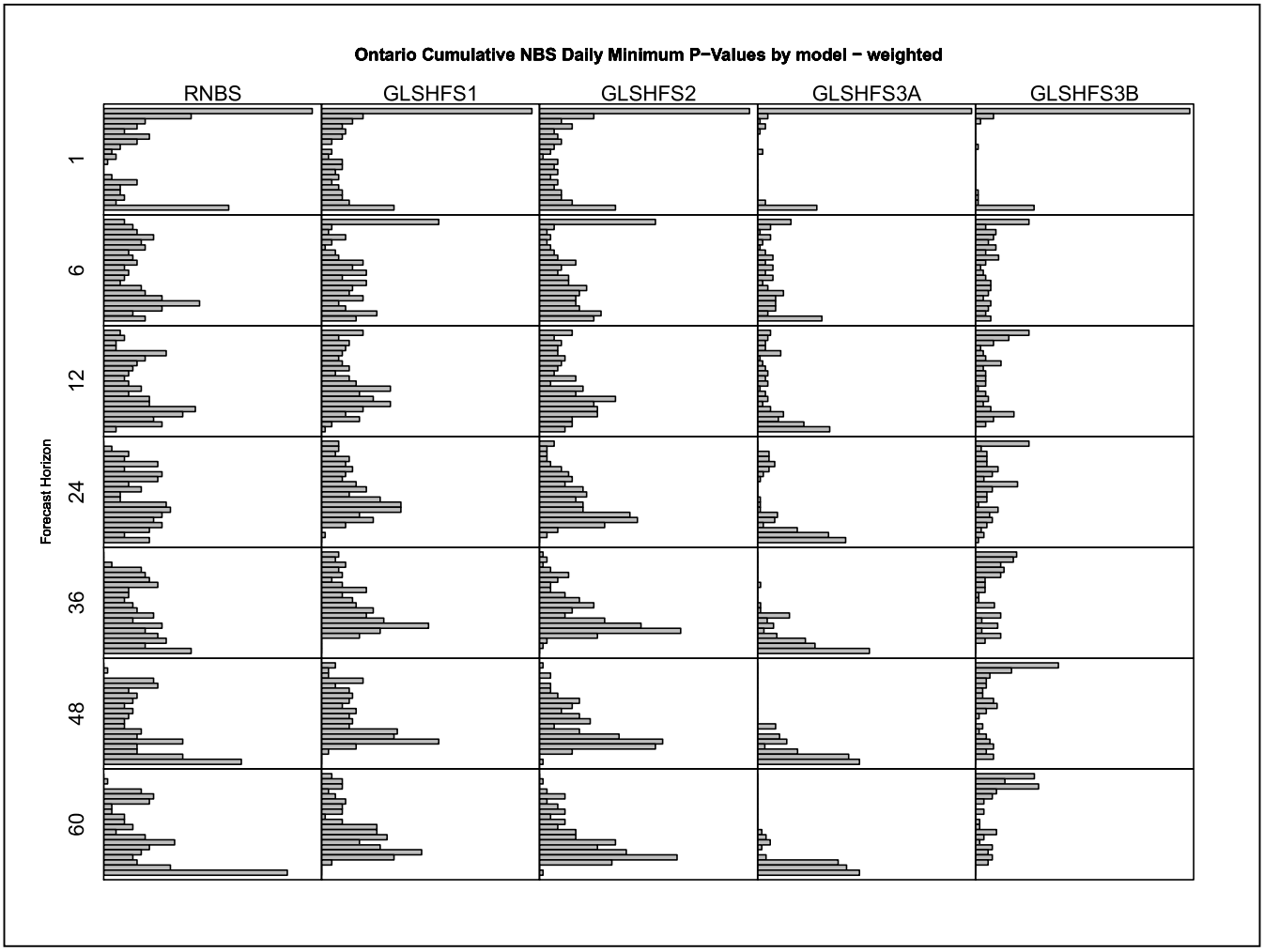
Ontario Cumulative NBS Daily Minimum P−Values by model − weighted
RNBS
GLSHFS1
GLSHFS2
GLSHFS3A
GLSHFS3B
Forecast Horizon
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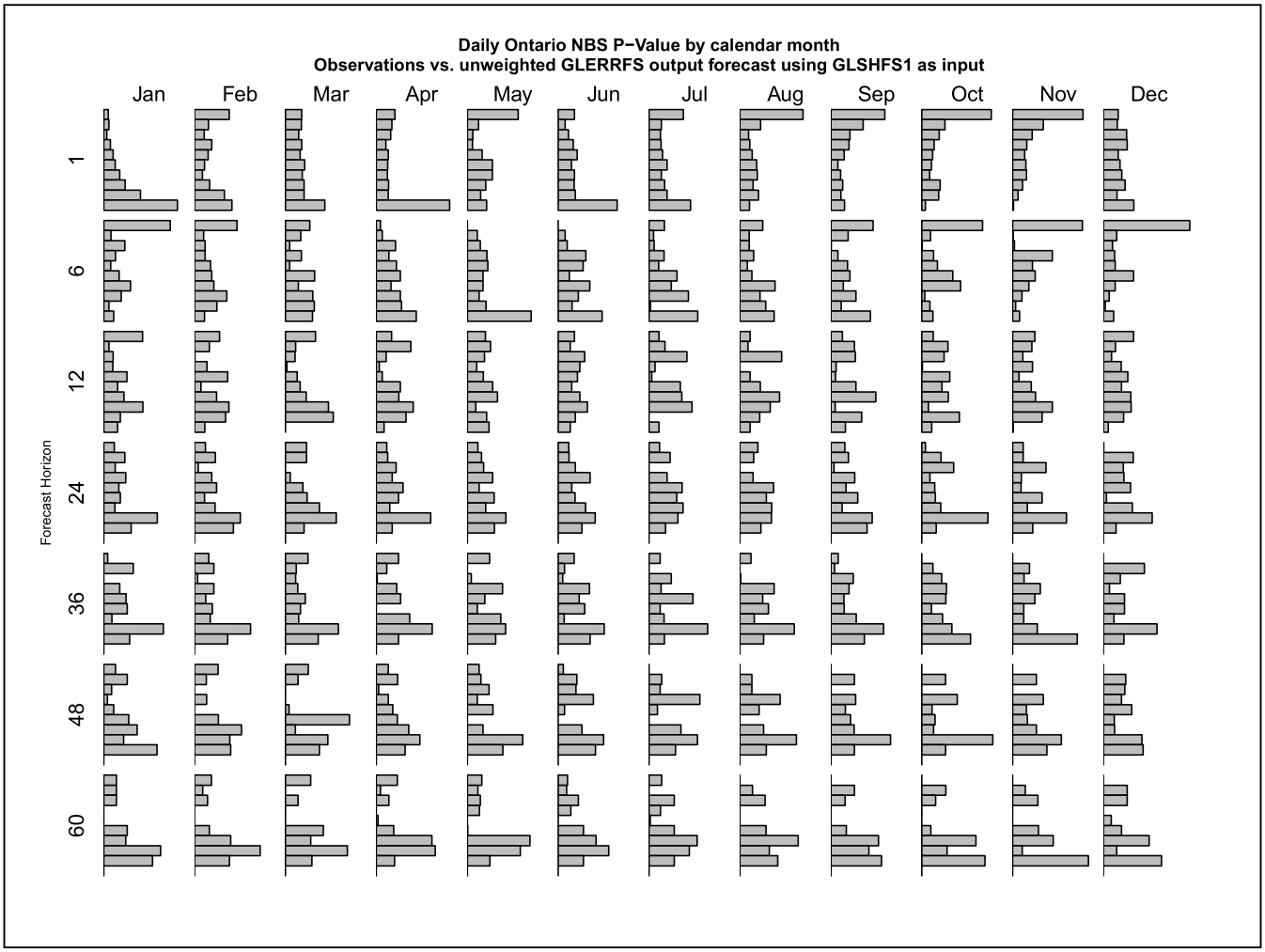
Daily Ontario NBS P−Value by calendar month
Observations vs. unweighted GLERRFS output forecast using GLSHFS1 as input
Jan
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Nov
Dec
Forecast Horizon
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48
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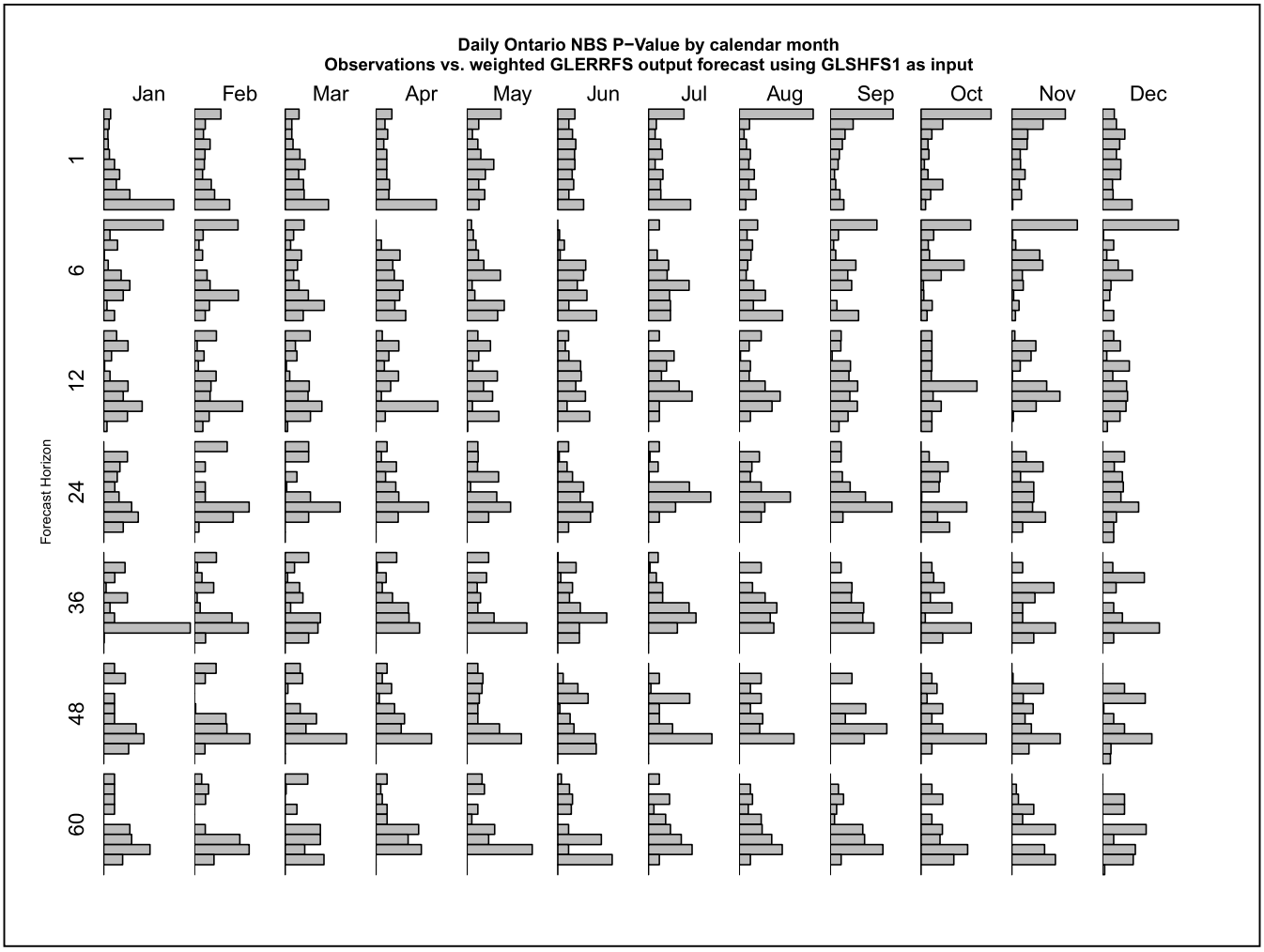
Daily Ontario NBS P−Value by calendar month
Observations vs. weighted GLERRFS output forecast using GLSHFS1 as input
Jan
Feb
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Nov
Dec
Forecast Horizon
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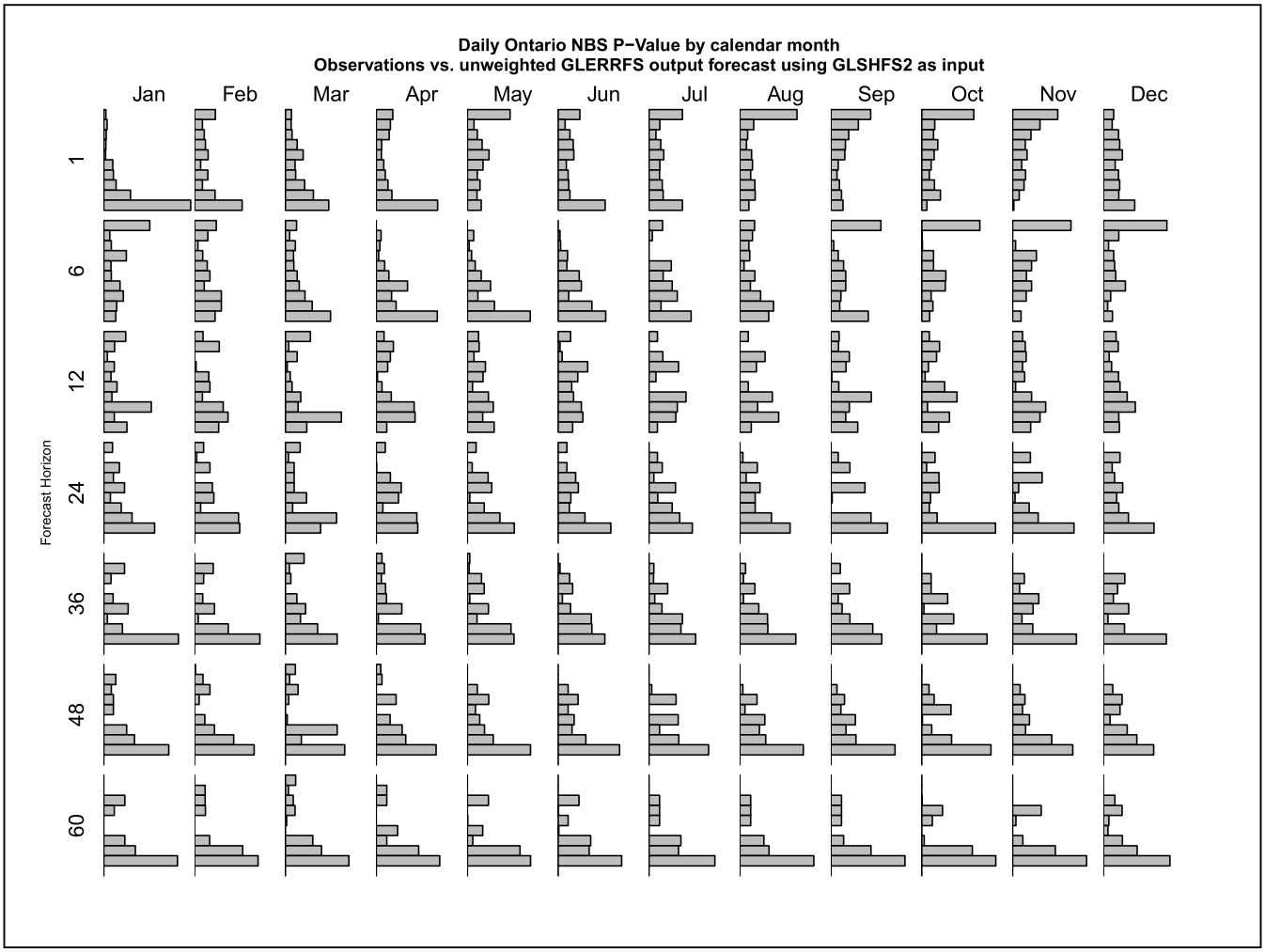
Daily Ontario NBS P−Value by calendar month
Observations vs. unweighted GLERRFS output forecast using GLSHFS2 as input
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Nov
Dec
Forecast Horizon
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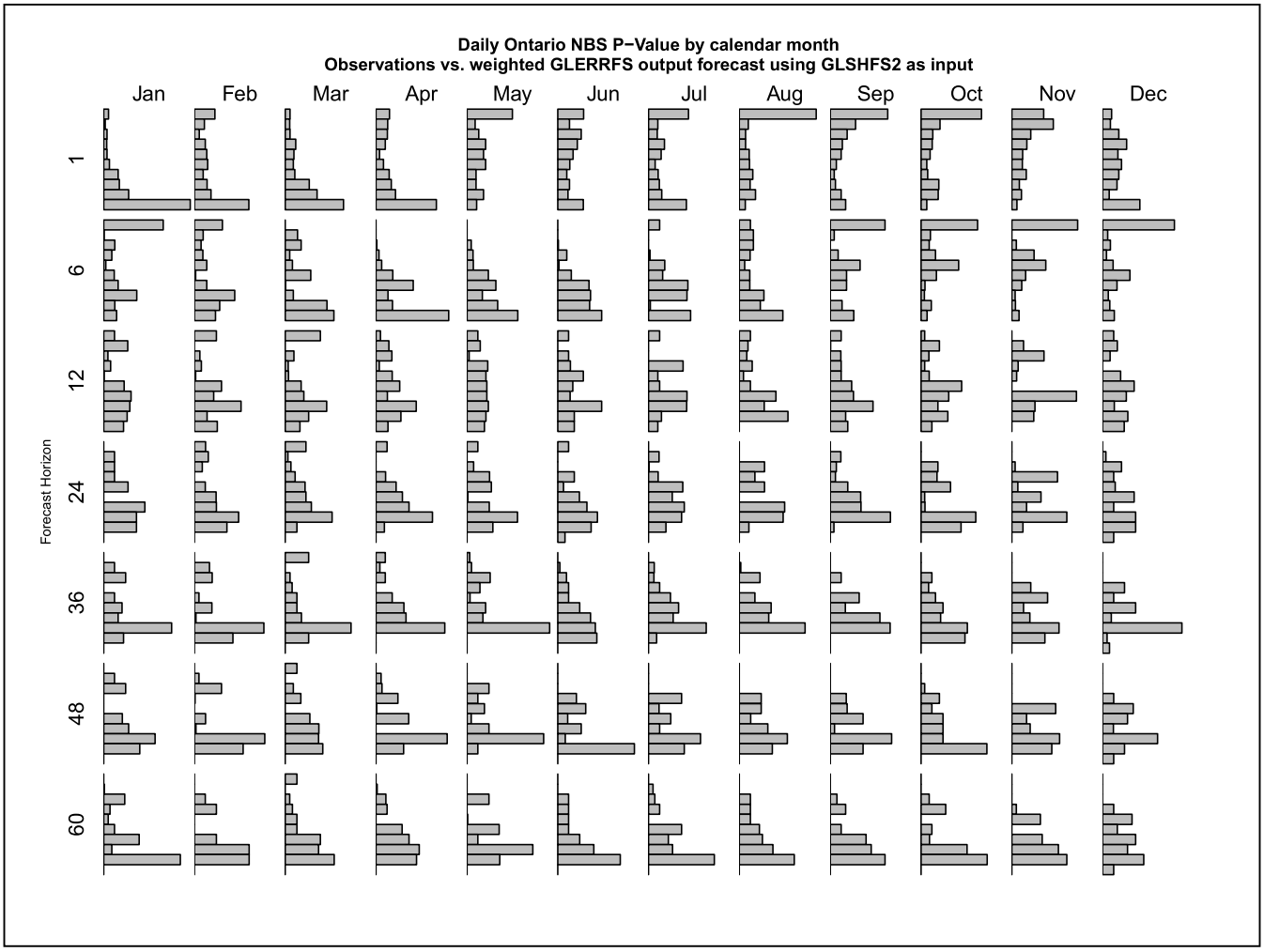
Daily Ontario NBS P−Value by calendar month
Observations vs. weighted GLERRFS output forecast using GLSHFS2 as input
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Sep
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Nov
Dec
Forecast Horizon
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48
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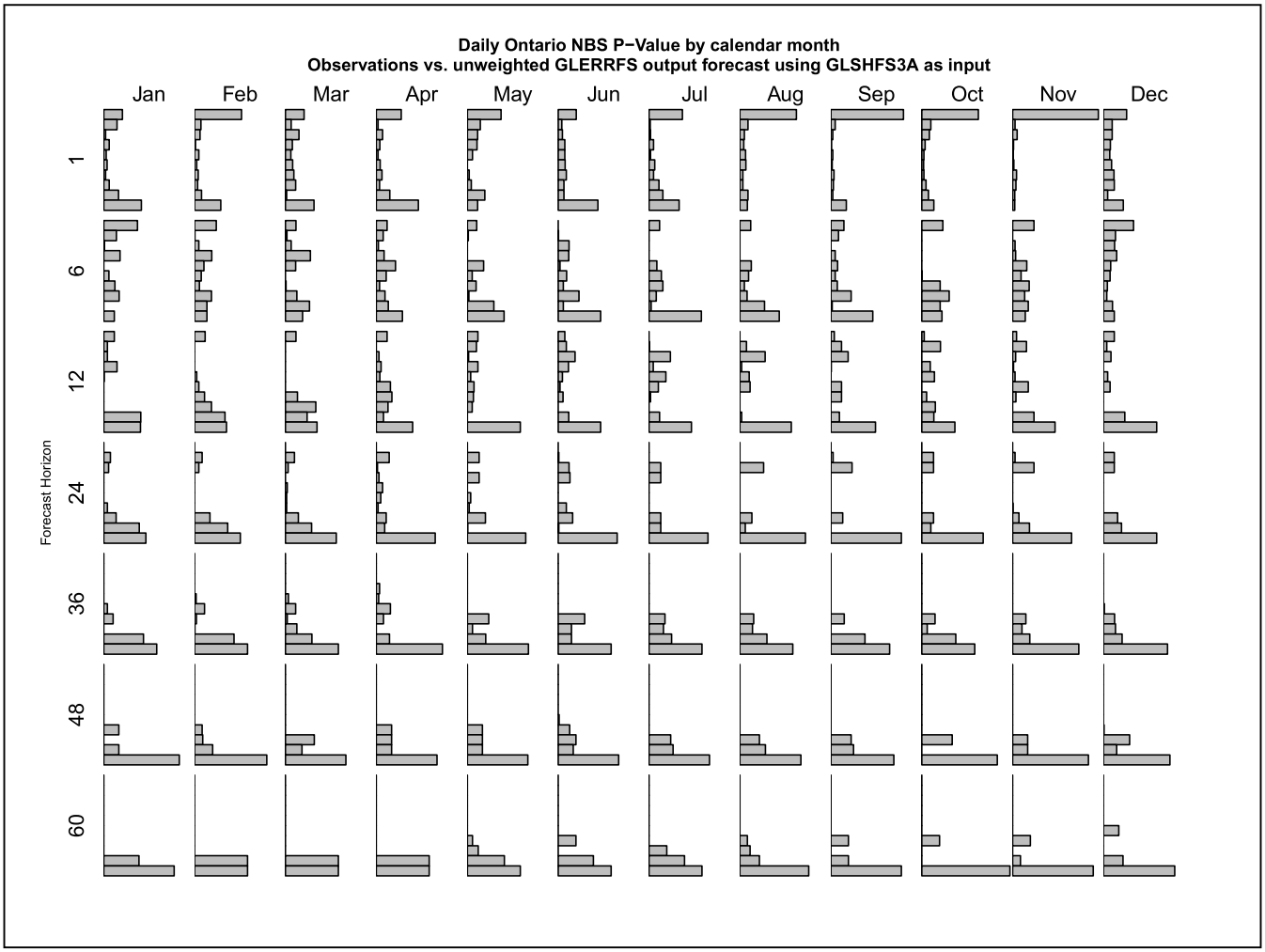
Daily Ontario NBS P−Value by calendar month
Observations vs. unweighted GLERRFS output forecast using GLSHFS3A as input
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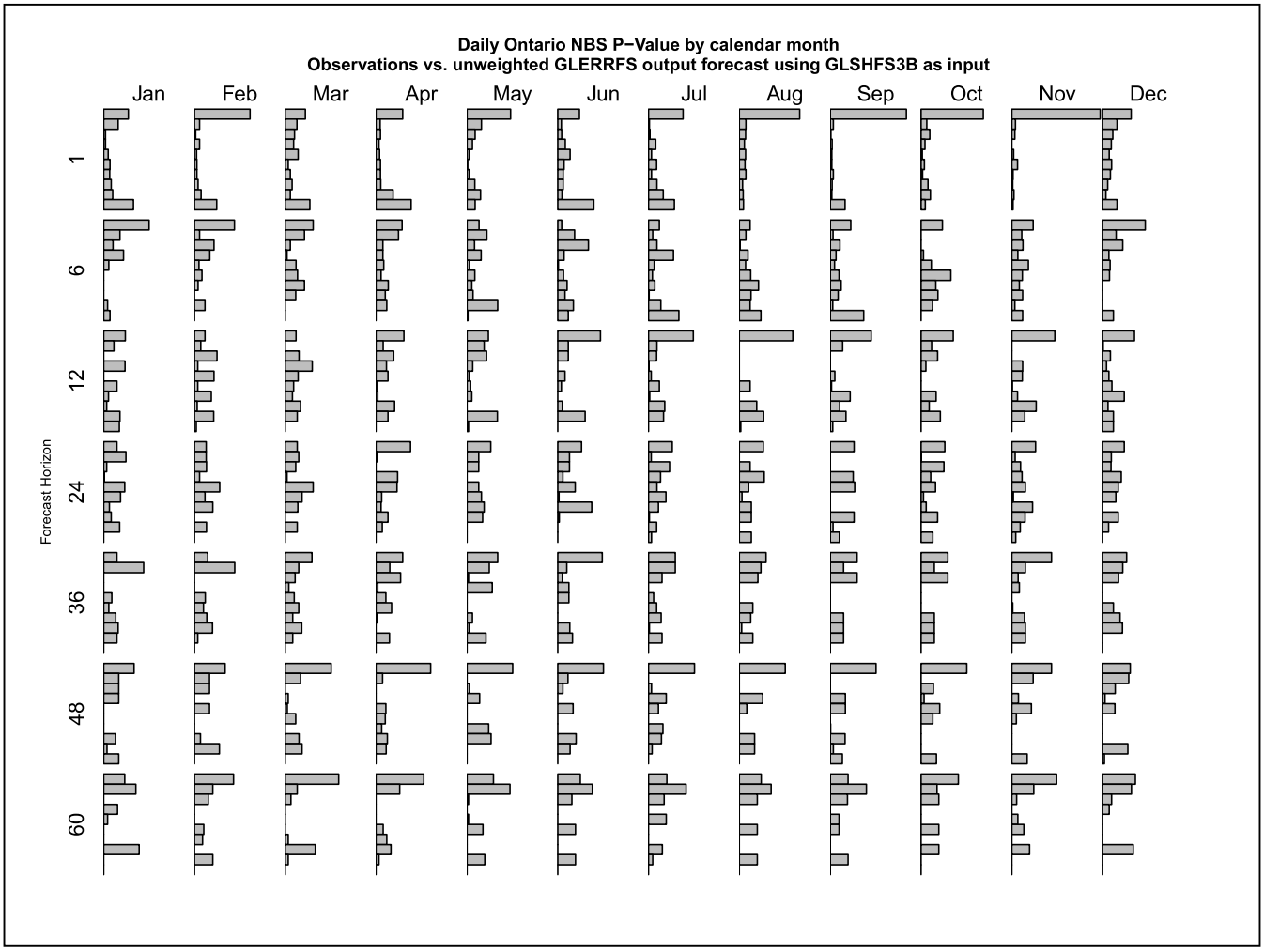
Daily Ontario NBS P−Value by calendar month
Observations vs. unweighted GLERRFS output forecast using GLSHFS3B as input
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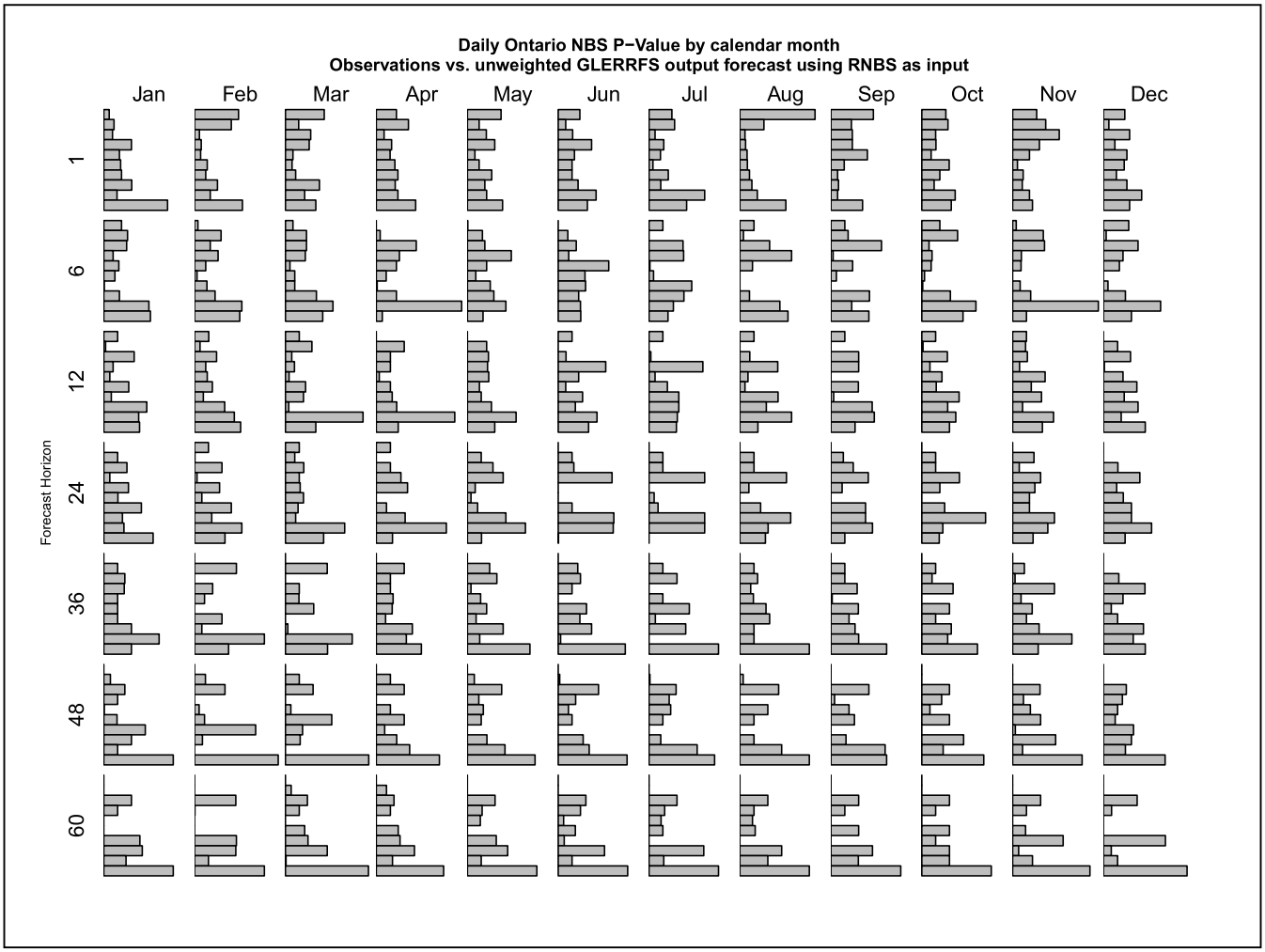
Daily Ontario NBS P−Value by calendar month
Observations vs. unweighted GLERRFS output forecast using RNBS as input
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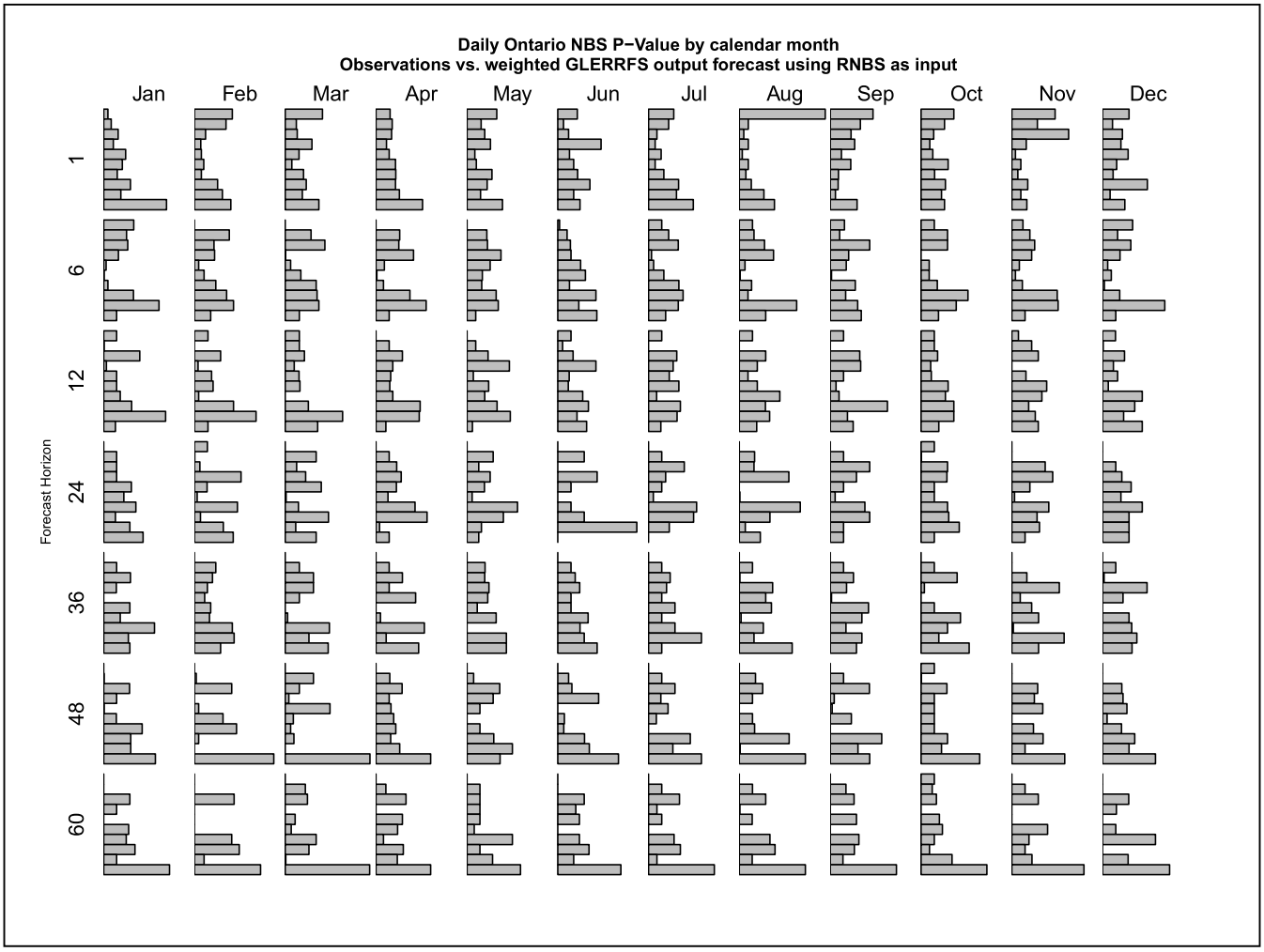
Daily Ontario NBS P−Value by calendar month
Observations vs. weighted GLERRFS output forecast using RNBS as input
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D Project transition plan

Research to Operations Synthesis
USACE-Detroit and NOAA-GLERL

Niagara and St. Lawrence River Forecasting Improvements Project – 2017

1. Purpose/objective

Provide probabilistic seasonal to long term (5-year) forecasts of daily water levels and outflows for the Great Lakes.

2. Business case
    a. User

The primary user is the hydropower industry, consisting of Ontario Power Generation, New York Power Authority, and the Niagara River Control Center. Additionally, the output will be used by USACE-Detroit as forecast guidance for its contribution to the internationally coordinated 6-month forecast of Great Lakes water levels. This coordinated forecast, which has been published jointly between Canada and the U.S. since the 1960s, is used by a wide variety of stakeholders in the Great Lakes, including the shipping industry, shoreline property owners and homeowners associations, recreational boaters, and water managers. The printed version of the U.S-published coordinated forecast has more than 4,000 subscribers in the U.S. Canada has a similarly wide ranging user base.

    b. User requirements

The fundamental requirement of the hydropower industry is a probabilistic forecast of flows in the Niagara and St. Lawrence Rivers that realistically represents the daily variability and the range of flows to be expected over a 5-year time horizon. The industry's re-insurers typically use statistical models to estimate flows over this time horizon, but engineers in the industry recognize that these models do not account for the inherent "memory" of the Great Lakes system or regulation decisions influencing levels and flows. Accordingly, they require independent, third-party forecasts that incorporate physical processes and reflect regulation decisions and lake-to-lake routing.

    c. Current demonstration system

The current demonstration of the ensemble forecasting suite consists of a suite of alternative forecasts of daily water levels, inflows, and outflows for each of the Great Lakes over a 5-year horizon. These forecasts, which are produced using a combination of a net basin supply (NBS) model, a regulation and routing model, and an outlook package that allows adjustment of the ensemble forecast based on climatic outlooks, are summarized in the first four rows of Table 1. Each alternative forecast consists of a variation in the water supply model used and the use of weighting (or not) to adjust forecasts based on climatic outlooks in the outlook package.

Forecasts are updated each Thursday, consistent with the Lake Ontario regulation cycle. Lake Ontario regulation decisions are made by ECCC and USACE-Buffalo each Thursday, with changes applied the following day. Accordingly, forecasts produced on Thursdays have a Friday start date. Seasonal climate projections are updated by CPC and NMME on the third Thursday of each month. After these are made available, a new weighting scheme is developed for application in the outlook package (when weighting is applied). Forecast data are currently made available to OPG, NYPA, and the USACE-GLERL research team

through an unadvertised website. The forecast data are not currently advertised to the public due to the complexity of interpreting multiple probabilistic forecasts and the need for additional skill assessment. However, they are available to USACE-Detroit forecasters for guidance when preparing seasonal forecasts.

Table 1. Alternative forecast configurations. Configurations in gray represent forecasts alternatives that are currently under development.

Water supply (NBS) model				Routing and Regulation	Outlook package
Name	Meteorology	Runoff	Evaporation		
RNBS	None (ensemble of historical residual NBS is used)			GLERRFS	None
RNBS	None (ensemble of historical residual NBS is used)			GLERRFS	Weighting scheme matching climatology with forecast
AHPS	Ensemble of historical meteorology	(old) LBRM	(old) LLTM	GLERRFS	None
AHPS	Ensemble of historical meteorology	(old) LBRM	(old) LLTM	GLERRFS	Weighting scheme matching climatology with forecast
GLSHyFS 1	Ensemble of historical meteorology	(old) LBRM	(old) LLTM	GLERRFS	None
GLSHyFS 1	Ensemble of historical meteorology	(old) LBRM	(old) LLTM	GLERRFS	Weighting scheme matching climatology with forecast
GLSHyFS 2	Ensemble of historical meteorology	(new) LBRM	(old) LLTM	GLERRFS	None
GLSHyFS 2	Ensemble of historical meteorology	(new) LBRM	(old) LLTM	GLERRFS	Weighting scheme matching climatology with forecast
GLSHyFS 3	Downscaled CMIP5 (19 members)	(new) LBRM	(new) LLTM	GLERRFS	None

d. Justification for transition

The hydropower entities who have funded the development of these forecast systems have clearly requested that forecasts be made available on an operational basis. USACE is the U.S. federal agency that provides technical expertise for regulation of the Great Lakes, maintains coordinated water level, flow, and net basin supply data, and produces operational seasonal water level forecasts. Accordingly, USACE-Detroit is well suited for operationalizing this suite of forecasts.

3. Capabilities and functions
    a. Current capabilities – does this mean our current capabilities (e.g. coordinated 6-month forecast, water level outlook, and weekly forecast) or does this mean current capabilities of the "demonstration system"?
    b. Operational description

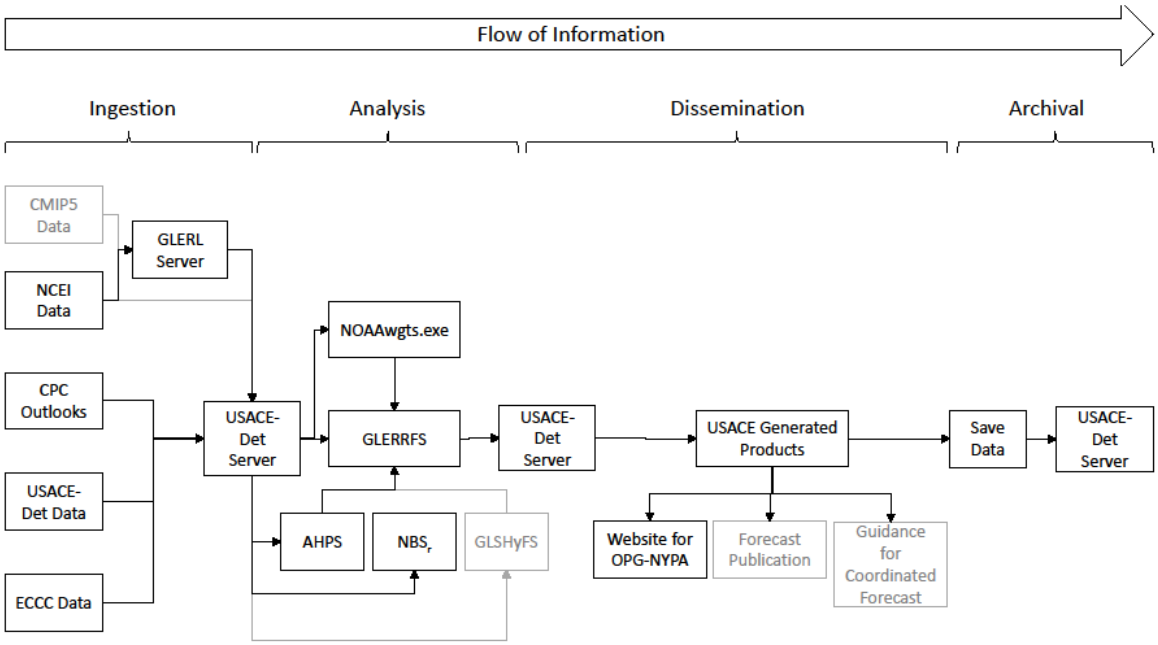


Figure 1. A Conceptual flow of information for the ensemble forecasting infrastructure. Updates and efficiencies achieved during transition may alter this workflow. Gray elements have not yet been incorporated into the demonstration system.

    c. Data collection and management

Table 2. Data required for each model (NBS, regulation and routing, and outlook) employed in the various configurations described in Table 1. The data source represents the primary provider of original data, and the data processer is the entity that is responsible for collecting and managing the data for ingestion into the forecast models.

Model	Data required	Data source	Data processer
AHPS	Daily Tmax, Tmin, Tavg, dew point, wind speed, cloud cover, precip	NCEI	GLERL
RNBS	Historical monthly RNBS	USACE, ECC, CCGLBHHD	USACE-Detroit
GLSHyFS 1	Daily Tmax, Tmin, Tavg, dew point, wind speed, cloud cover, precip	NCEI	USACE-Detroit

GLSHyFS 2	Daily Tmax, Tmin, Tavg, dew point, wind speed, cloud cover, precip	NCEI	USACE-Detroit
GHSHyFS 3	Daily Tmax, Tmin, Tavg, dew point, wind speed, cloud cover, precip Climate projections of Daily Tmax, Tmin, Tavg, dew point, wind speed, incident and net long wave radiation, precip	NCEI CMIP5	USACE-Detroit GLERL
CGLRRM	Superior regulation data	USACE Detroit, ECCC	USACE Detroit
Ontario Regulation and Routing	Ontario regulation data	USACE Buffalo, ECCC	USACE Detroit
Outlook package	Seasonal outlooks	CPC	USACE Detroit

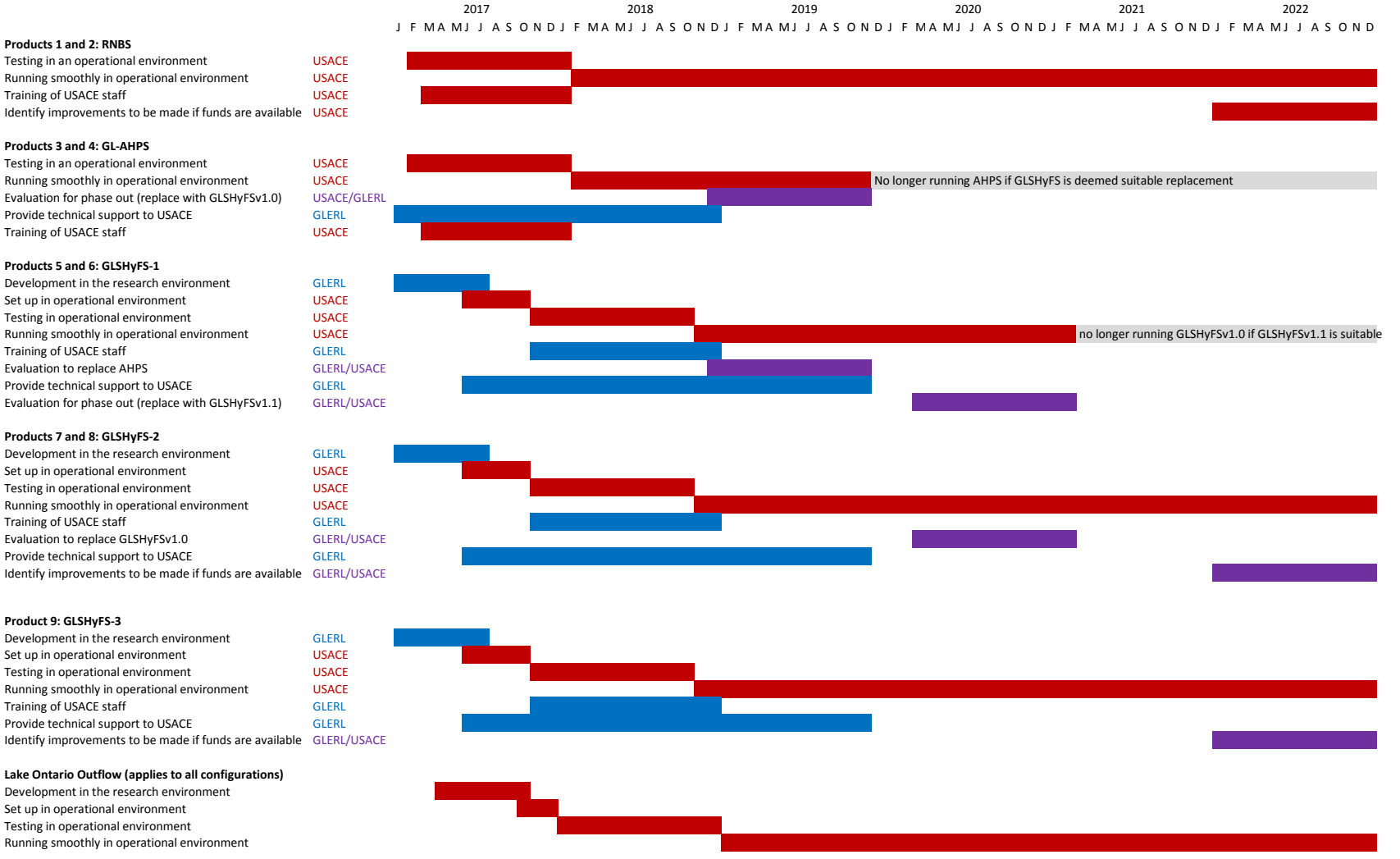
4. Transition schedule of activities

The schedule of transition from research to operation of these products depends on the NBS model on which the product is based. Major milestones for transition are shown in Table 3, as well as responsible agencies. Each product must undergo several common phases: development in the research environment, setup in the operational environment, and running in the operational environment. In the case of weighted and unweighted versions of forecasts derived from residual NBS (products 1 and 2) and AHPS (products 3 and 4), development in the research environment has already been completed, and these products are currently set up and running in testing mode in the operational environment at USACE. Products relying on GLSHyFS for NBS (products 5 through 9) are currently under development in the research environment. Two products (AHPS and GLSHyFSv1) are slated for phasing out during the cycle of this R2O plan. This is because GLSHyFS is meant to be a replacement to AHPS. GLSHyFSv1 is designed to replicate results from AHPS to demonstrate successful model framework mechanics of the GLSHyFS modeling framework, and GLSHyFSv2 incorporates model enhancements that are unavailable for comparison with AHPS. Accordingly, after demonstrating that GLSHyFSv1 produces the same results as AHPS for one year (or identifying problems with AHPS that cause differences), GLSHyFSv1 will replace AHPS. Then, after one year of concurrent forecasts with GLShyFSv2, GLSHyFSv1 will be phased out if the model improvements in v2 result in better forecasts.

In addition to describing the timeline for developing, setting up, and running in the operational environment, Table 3 also provides a timeline for technical support and training of USACE forecasting staff by GLERL staff. It is expected that by the end of this 5-year R2O plan, all forecasting staff at USACE will be trained in running all forecasts and at least one USACE staff will be capable of performing ad-hoc troubleshooting and integrating model enhancements. Finally, for products relying on RNBS (1 and 2) and GLSHyFSv1-2 (7-9), the timeline includes a one-year period of evaluation and planning for future

developments, if necessary, during the 5th full year of the R2O plan. During this period, if potential improvements are identified, funds may be sought to develop and implement these enhancements. Potential developments may include a new downscaled climate forcings package using updated CMIP forcings, recalibration of LBRM or LLTM, and/or integration of an updated coordinated regulation and routing model.

Table 3. [ATTACHED AT END OF THIS DOCUMENT] Schedule of transition of products from research to the operational environment. Products are identified by the NBS model employed. Schedule items that are the responsibility of USACE-Detroit are shown in red; items that are the responsibility of GLERL are shown in blue, and items that are a shared responsibility between GLERL and USACE-Detroit are depicted in purple.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Products 1 and 2: RNBS
Testing in an operational environment USACE
Running smoothly in operational environment USACE
Training of USACE staff USACE
Identify improvements to be made if funds are available USACE
Products 3 and 4: GL-AHPS
Testing in an operational environment USACE
Running smoothly in operational environment USACE
No longer running AHPS if GLSHyFS is deemed suitable replacement
Evaluation for phase out (replace with GLSHyFSv1.0) USACE/GLERL
Provide technical support to USACE GLERL
Training of USACE staff USACE
Products 5 and 6: GLSHyFS-1
Development in the research environment GLERL
Set up in operational environment USACE
Testing in operational environment USACE
Running smoothly in operational environment USACE
no longer running GLSHyFSv1.0 if GLSHyFSv1.1 is suitable
Training of USACE staff GLERL
Evaluation to replace AHPS GLERL/USACE
Provide technical support to USACE GLERL
Evaluation for phase out (replace with GLSHyFSv1.1) GLERL/USACE
Products 7 and 8: GLSHyFS-2
Development in the research environment GLERL
Set up in operational environment USACE
Testing in operational environment USACE
Running smoothly in operational environment USACE
Training of USACE staff GLERL
Evaluation to replace GLSHyFSv1.0 GLERL/USACE
Provide technical support to USACE GLERL
Identify improvements to be made if funds are available GLERL/USACE
Product 9: GLSHyFS-3
Development in the research environment GLERL
Set up in operational environment USACE
Testing in operational environment USACE
Running smoothly in operational environment USACE
Training of USACE staff GLERL
Provide technical support to USACE GLERL
Identify improvements to be made if funds are available GLERL/USACE
Lake Ontario Outflow (applies to all configurations)
Development in the research environment
Set up in operational environment
Testing in operational environment
Running smoothly in operational environment

E Minutes from routine team planning meetings

MEETING PARTICIPANTS:
Drew Gronewold and **Tim Hunter** - NOAA - GLERL
Becky Bolinger and **Lisi Pei** - UCAR
Lauren Fry - USACE - Detroit District

March 21, 2016

Conventional AHPS Hindcasts Tim Hunter has developed the full period of hindcasts for the conventional AHPS model. Lauren Fry has obtained a sample year from him and will be testing the sample set with the latest version of the operational coordinated routing model. Once that is completed, she will run on the entire hindcast period.

Improved AHPS Hindcasts Code has been added to LBRM to improve its evapotranspiration scheme. Now Tim is working on choosing one stable seasonal cycle file per sub-basin. This needs to be done before a recalibration can take place. Becky Bolinger and Tim will be setting up a meeting to discuss methods of recalibration and analyzing the parameters that adjust during a calibration.

Climate Change Model

Lisi Pei is planning to present her progress on statistical downscaling of CMIP5 simulations internally at GLERL to gain feedback on the robustness of her methodology. Results from this presentation can be used to update the documentation.

Lisi has temperature and precipitation simulations ready and available. She still needs to calculate the additional variables that are required for input. She is also currently working on establishing a bias correction method that will hopefully preserve the extremes in the distribution. She currently only has monthly CMIP5 data and will need to disaggregate into daily sequences since AHPS requires a daily resolution of inputs.

Tim describes what he will need to do to "dust off" the Climate Change Simulation Package (CCSP). The CCSP will require new versions of both LBRM and LLTM. CCSP code will need to be updated to accept the new model versions. He will need to update filename structures. He also hopes to update it so that it can run on a Linux box instead of being DOS-based.

Identifying skill criteria and metrics

We have decided to calculate root mean squared error (RMSE) and bias when analyzing the skill of any model's performance compared to observations. Lauren will provide flow observations on the Niagara and St. Lawrence Rivers for analysis. Because routing of the flows on the Niagara River is one of AHPS's functions, Tim will provide the daily outflow forecasts from Lake Erie to compare with the observed Niagara River flows. Since AHPS currently does not forecast flows on the St. Lawrence River, we will wait until Lauren has routed the flows and get those flow forecasts from her.

Another skill metric to keep in mind is relating flows to power gains/losses. This is based on a graphic that Scott Brown (NYPA) shared with Drew Gronewold showing terrawatt hours lost. When flows are underpredicted, this is how their bottom line is affected.

We will be enlisting the help of Joeseph Smith (located at NOAA - GLERL) and his programming resources to handle the different datasets and provide us with skill assessment calculations and graphics.

April 4, 2016

Conventional AHPS and Skill Assessment

Lauren sent historic flow observation data to Tim and he will be making that data available for the skill assessment.

NOAA-GLERL's Advanced Hydrologic Prediction System (AHPS) routes daily NBS sequences through Lake Erie, so the full hindcast that Tim has generated for the conventional AHPS method also contains hindcasts of outflows out of Lake Erie. This would be essentially the same information that Lauren would provide after running the CGLRRM. So, instead of waiting for her to provide hindcast flows for both Niagara and St. Lawrence Rivers, we can begin the skill assessment on just Niagara River flows with the hindcast that Tim has. Tim will make the hindcast flows available for the skill assessment, and will also send it to Lauren so she can verify format and maintain consistency.

Improved AHPS and LBRM Calibration

Tim, Becky, and Drew have met to discuss the recalibration of LBRM. There are multiple goals for the recalibration - 1) to include the improved ET scheme, 2) to update the calibration time period, and 3) to possibly use an improved optimization algorithm. The next step agreed upon is to use the improved optimization algorithm (provided by Bryan Tolson at the University of Waterloo) to test the calibration of several sub-basins in the Ontario basin. The calibration will generate a set of parameter values that will be analyzed by the group. Becky will be working on this calibration test and will be presenting results of the calibration during the April 18 meeting. **note: this ended up being changed to April 25, as April 18 would be a shortened meeting.*

Climate Change Model

Tim has decided that for now, it would be a better idea to focus on altering AHPS to take Lisi's climate change forcings, as opposed to spending time preparing the Climate Change Simulation Package. His main reason for this is because there would be more front-end work to prepare the CCSP, and the timeline for the deliverables may not allow for that much preparation time. Developing an adjusted AHPS will take much less time.

Lisi is almost done with the bias correction method and will then begin verification. She should be ready to present initial results to the other GLERL scientists within the next couple of weeks.

April 11, 2016

No meeting notes available from this meeting.

April 18, 2016

Conventional AHPS

Lauren has discovered a bug in the routing code when running the sample dataset she got from Tim. Once the bug is fixed, she should be able to get routes sequences soon after. She thinks the end of April may be a little too optimistic, but is shooting for early May.

The question has been raised about daily vs. monthly issues when updating the coordinated routing model for operational forecasting. The most simplified option would be to route the daily sequences, but only update it monthly.

Climate Change Model

Lisi plans to give an internal GLERL presentation on her statistical downscaling methods within the next week. She will also get additional feedback on the robustness of her methods from her former adviser at Michigan State and from Lisa Goddard (chair of the PACE program).

April 25, 2016

LBRM Calibration

Becky presented initial results for 8 Ontario sub-basins, comparing old LBRM calibrations with the new ones provided by Bryan Tolson's Ostrich. The group analyzed parameter values that different optimization methods chose during calibration. Sometimes both the optimization methods pick values that align well with neighboring sub-basins, and sometimes there's a lot of discontinuity that should be addressed for a proper calibration. Next steps would be to decide how to replace "outlier" parameter values during the calibration process.

Skill Assessment

Joe Smith has provided the group with initial skill assessment results for the Niagara River. The group briefly looked over the results together, noting that RMSE and the magnitude of bias both increase with increasing forecast horizons. For long forecast horizons (longer than 2 years), there is a consistent over-prediction of flows (positive bias). These results will need to be analyzed further.

May 2, 2016

Conventional AHPS

Lauren was able to successfully run the routing model on the sample year she received from Tim. She is currently working on post-processing. One current hold-up in her progress is getting all the Ontario quarter month regulation data for the entire hindcast. The data are straight-forward from 2012 to present. But prior to 2012 there are no digital archives. So it is more time consuming to gather that data.

Once routing is completed, the hindcast flows are unweighted (i.e., a probabilistic forecast in AHPS is based on historic meteorology extending back to 1948, and all years are given equal weighting when developing the probabilistic distribution). The question was raised as to who will apply the weighting scheme to the full hindcast (note: the weighting scheme weights the historic meteorology based on how closely certain years align with the seasonal climate forecast). In operations, USACE will likely be generating the weights files. But for the hindcast, Tim already has all the weights files, so he will send those to Lauren so that she can apply the scheme to get a weighted hindcast.

Improved AHPS and LBRM Calibration

Tim has successfully implemented the new LBRM into his "operational" version of AHPS. He's updated the code so that AHPS will run whether the improved ET parameters are included in the parameter files or not. Therefore, if old parameter files are used, AHPS will run like it always has. If the parameter files include the new ET parameters (used by the improved LBRM), it will also run under the improved conditions.

We discussed the LBRM calibration using Ostrich. Ostrich currently contains the old LBRM. The question needs to be answered if Ostrich can easily incorporate the new LBRM before the full recalibration can begin. If not, it may make more sense to recalibrate LBRM without Ostrich in order to meet deadlines, and then work to incorporate Ostrich at a later date.

Climate Change Model

Lisi is redoing some of her initial work. She is now generating 30-yr historical runs. The historic run is defined as 1979 - 2005. The 30-yr future run begins in 2006. The first part of the future run, 2006 - 2015, will be used for validation with observations.

Lisi analyzed the results from two different scenarios (the amount of CO2 added to the atmosphere is different). Results from both the rcp4.5 and rcp8.5 scenario showed virtually no difference in results in the near future. Changes are really only evident at much longer time scales (i.e., 50 to 100 years).

More work needs to be done on the precipitation bias correction. But Lisi is still working toward having all the forcing files to Tim by end of September.

Tim gave more details on creating a modified version of AHPS that will take Lisi's climate change simulations. Essentially what he will do is define the new climate change years as older years. Then those years will be weighted, and all the historic years will be given a weight of zero so they won't be considered at all. Only the climate change years will be weighted to generate the probabilistic distribution of forecasts. In order to do this he will be updating the climate files that AHPS requires as inputs and will create the new weights files.

Transition to Operations

These meetings have primarily been dedicated to discussing the portion of the timeline that involves generating the suite of models that will be used and assessing the skill of the various models. However, it is important that we begin the discussion of how we will officially transition this suite of models from test mode and into operational framework at USACE.

Lauren feels the process will be fairly simple and seamless. The bulk of the work will be the transfer of data and files from Tim to Lauren. Lauren would then add all updated files and code to USACE's current file structure and create a new location to run the climate change model.

Other questions that need to be answered: Where will the forecasts be located? Where will archived forecasts be stored? Becky has added this section to our project timeline to be discussed in more detail.

May 9, 2016

No meeting this week.

May 16, 2016

Some of this meeting, the group went over the email Peter Kowalski sent regarding the timeline for the long-term forecasting project. Since there seemed to be a bit of confusion about when the long-term forecasts would be operational, Drew asked Peter for clarification on that timeline, including the exact documentation that refers to the correct timeline. After going over Peter's response, we have agreed that the suite of models used to provide long-term forecasts will be operational and providing forecasts to NYPA and OPG by the end of 2016 (December 31, 2016). Any further improvements made after that time (e.g., new climate change information, climate change simulation package, etc.) can be seamlessly incorporated into the operational framework without interruption of service.

Conventional AHPS

Tim is updating the climate files to include historical meteorology through 2015. This will be available for both the conventional and improved AHPS forecasts.

Lauren is working through routing the hindcast NBS sequences to finish the creation of the full hindcast of flows at Niagara and St. Lawrence Rivers. She has gotten some erroneous results while working on this and is currently trying to troubleshoot the problem. Once she has figured that out, it will be very quick to finish generating the full hindcast of unweighted flows.

Climate Change Model

Lisi has finished the bias correction on all 11 variables that Tim will need to input into the modified AHPS. She now has monthly simulations, and now is working to downscale the simulations to a daily timestep.

Skill Assessment

While we briefly looked over the skill assessment results that Joe provided us, we still need to dedicate some time to analyze and interpret the results. We've decided it would be best to set a separate meeting time to do this. Becky will work with Tim and Lauren to determine a time to get together and go over the results in more depth within the next couple of weeks.

May 23, 2016

Conventional AHPS

Lauren has the procedure in place to successfully run the routing model. However, there is an issue with Lake Erie levels. She plans on spending some time talking to Tim about it after this meeting.

Tim has had to update the code that creates the weights files. Previous code did not take into account a five-year sequence. So he has to adjust the code specifically for this project so that it works with five-year sequences. He has updated the code and will now be transferring those weights files to Lauren.

Lauren will need to write new scripts to adjust how the weighting procedure is run by AHPS. For now, she thinks that can be done by the end of July.

Skill Assessment

Becky, Tim, Lauren, and Lisi took time after the meeting to analyze the results of the skill assessment. Upon further analysis, they discovered that large biases were showing in the skill assessment that were very similar to the errors Lauren found in her simulations of Lake Erie levels. These large biases begin to show up after 24 month forecast horizon where the hindcast flows are much higher than the observed flows. Further investigation appears to point to a possible coding issue, not an issue with a bad forecast. Both Tim and Lauren will be looking into the routing model and AHPS to determine where the problem is located.

Transition: Research to Operations

The main step of transitioning models from research (NOAA - GLERL) to operations (USACE - Detroit District) will be Tim sending Lauren the new AHPS package. According to Tim, it is all ready to be sent. His current "experimental" version is AHPS1.3, and the new version (which includes the new LBRM) is AHPS1.5. The transfer can take place soon so that Lauren can run it in test mode (hopefully by mid-June).

Tim is generating new climate files and over-lake files, 1948 - 2015. Those will also have to be transferred to Lauren. He's hoping to have that completed by the end of July.

Lauren doesn't know the logistics yet of making the forecasts available via FTP. But that is on her task list to investigate. She will look into figuring out the logistics for archiving forecasts as well.

May 30, 2016

Holiday, no meeting this week.

June 6, 2016

Several members were on travel this week and unable to attend the meeting. Tim and Becky had a quick meeting and updated each other on progress.

Conventional AHPS

Tim is narrowing down where the main issue in the hindcast is, first discovered by Lauren (as large biases on Lake Erie levels) and then again identified during the analysis of the skill assessment. After investigating the coordinated routing model, it was determined that there were no issues there. There are also no issues when running the new LBRM versus the old LBRM. Precipitation and evaporation estimates appear okay. The issue appears to be isolated to runoff, but since it's not within LBRM, there is likely an issue within how AHPS runs LBRM. Tim believes he will be able to successfully isolate the issue within a couple of days. As long as it is an easy fix, he will be able to re-generate the full hindcast within two weeks. All skill assessment of the previously generated hindcast has been ceased until the problem is fixed.

Improved AHPS

Becky is still working on getting all the files and folders prepped and ready for the recalibration runs. Folders for each lake sub-basin have been created, and configuration and boundary condition files have been added to the folders. This work has also included the preparation of all the updated parameter files that will be used by the new LBRM. This needs to be done for all 121 sub-basins within the Great Lakes basin.

June 13, 2016

Conventional AHPS

Tim has identified an issue with bad values of air temperature data that are impacting the flow forecasts and ultimately leading to too much water in the system. He isolated the issue to his latest run of station data processing. This recent processing was done specifically for the NYPA-OPG project and is not a factor in current operational forecasts released by AHPS. Now, Tim is reprocessing the station data. The process has been completed for Lake Superior, and his analysis of net basin supplies look good. Reprocessing will continue for the rest of the lake basins. After that, he can begin generating a new hindcast dataset. He's estimating he will be completed and can have a corrected hindcast to Lauren in approximately 2 to 3 weeks.

Drew pointed out that the work plan document should contain a detailed methodology on the generation of the historical meteorological dataset used by AHPS. It would also be beneficial to bring up how others in the region do this and other possible existing datasets.

Improved AHPS

Becky has generated parameter files for all 121 sub-basins within the Great Lakes basin. She is now working on code that will create the 121 template files that Ostrich needs for the calibration of each sub-basin. She won't work on creating the meteorology input files until Tim has reprocessed all the meteorological data.

Skill Assessment

Skill assessment is currently on hold until the new corrected hindcasts have been generated. However, the team has determined that the first part of the skill assessment has successfully achieved its purpose, which is to isolate any possible issues and remove those issues before operationalization of the models. The second part of the skill assessment of the conventional AHPS model is to simply provide an overall picture of how well the model's hindcast does at simulating flows on the Niagara and St. Lawrence Rivers.

Lauren is currently preparing code for the skill assessment plots so when the hindcasts are all ready to go, she can easily plot the results.

Transition: Research to Operations

Lauren is making progress on generating operational runs that combine AHPS with the full routing model. She still has to work on the code that will apply the weighting scheme.

June 20, 2016

Conventional AHPS

All new meteorological datasets have been created as of last Friday. Tim has now started rerunning AHPS to generate the hindcasts and has finished one year of that. Hindcast water levels did go down a bit, but he's concerned that they haven't come down enough. He will be sending the one completed hindcast year to Lauren so that she can plot and analyze the results and verify that there are no more issues.

Tim raised the question if it would be necessary to continue the plan of weighting the historical sequences. Weights files are created from analysis of the CPC's seasonal temperature and precipitation outlooks. Typically he can only match to the first three months anyway, so any information beyond that is not applicable to longer timescales. Using the first three months to match and then using that information to try to match information from 12 - 60 months is not scientifically defensible. It is not reasonable to assume that because the first three months of Year X matches the first three months of Year Y, then Year X+5 will match Year Y+5 (and this is what the weighting scheme assumes). Additionally, Tim pointed to previous research by conducted by Tom Croley that showed beyond 2 years the model would converge upon a similar solution regardless of initial weighting. Therefore, the team has agreed that weighting the sequences for this project is not applicable and that time will be saved by removing it from the timeline. The team also agrees that the weighting is still important for seasonal prediction and that it would be beneficial for Lauren et al. (at USACE) to incorporate the seasonal flow predictions (for the first 6 out of 60 months) as part of the output product to NYPA and OPG.

Climate Change Model

After a Great Lakes binational hydrologic workshop, Lisi has gained some important information about precipitation datasets in the region. She is currently working to analyze more precipitation datasets. The current precipitation dataset she is using for her bias correction methods has some clear problems, and she is hoping she can address these issues by utilizing other data sources.

As of now, she has successfully bias corrected all other meteorological variables needed to force AHPS. She is hoping that her analysis will lead to a better precipitation dataset for use in bias correction of precipitation. She has also started working with the disaggregation of monthly variables into daily variables so that it is suitable for input into AHPS.

There was some conversation about what specifically Lisi will be handing over to Tim when she is completed with her statistical downscaling of CMIP5 projections. She will be giving Tim 19 different models/members of climate projections. Tim's plan is to include all 19 members within one climate file to be read by AHPS. Another important question that has been raised is regarding the methodology of input projection sequences. In current AHPS versions, each year is run as an individual sequence (e.g., 1948-1952 is one five-year sequence that forces AHPS, 1949 - 1953 is one five-year sequence that forces AHPS, etc.). Lisi does not think this is an appropriate methodology to use for future projections. So instead of using any and all five-year sequences to generate the probabilistic projection, Lisi suggests only using the matching year sequences (e.g., in 2017, only use the 2017-2021 sequence projected by the 19 different members). The team will be having further discussions to consider both options and agree upon which one is better for this project.

Transition: Research to Operations

Lauren has completed the set up of AHPS and the routing model to run in operational mode. She has now started testing to make sure that all parts are working.

Lauren brought up the question of storing and archiving forecasts. Becky reiterated that the group will be archiving flow forecasts on the Niagara and St. Lawrence rivers. But the question was raised as to what specific forecasts will be archived – will there be an archive of just the probabilistic forecast distribution (e.g., 5th percentile, 50th percentile, 95th percentile, etc.) or will all sequence years used to generate the probability distribution be archived? The group agreed that this question needs to be addressed and plans to bring it up during the Roadmap to Rollout meeting at USACE at the end of the month.

Lauren also brought up the question of operational skill assessment. The group has agreed upon skill assessment metrics and criteria for analysis of the hindcasts. But the group has not yet discussed how ongoing skill assessments and verification of operational forecasts will take place. The group agreed that this question needs to be addressed, moving forward.

June 27, 2016

Meeting dedicated to preparation of talking points and agenda for the Long Term Flow Forecasting meeting to take place on June 28-29 in Detroit at the U.S. Army Corps of Engineers office.

July 4, 2016

Holiday, no meeting this week.

July 11, 2016

Conventional AHPS

Tim is still working on recreating the hindcast. He ran into an issue where AHPS stopped running in 2005. He's had to switch compilers for AHPS to work, but he is not able to debug issues with this new compiler. So, he can't figure what is causing the issue. He's therefore decided that it's important at this time to develop a pure Fortran version of AHPS. This version will run directly from the command line, will not have a GUI, and will be easier to debug and troubleshoot whenever there is an issue. He's expecting that this will take him a couple of weeks to complete before he can resume and complete the hindcast.

Improved AHPS

Becky has completed building all the folder and file structures needed to begin the recalibration. Calibration requires parameter files, parameter templates, meteorology files, flow files, configuration files, and boundary condition files for all 121 sub-basins. Now that they're all prepared, calibration with Ostrich can begin. Assuming there are no unforeseen issues, the calibration should move fairly quickly now.

Climate Change Model

Lisi is currently working on incorporating the Canadian Precipitation Analysis (CaPA) dataset into her precipitation observations data used for bias correcting the CMIP5 precipitation simulations. She has to use a combination of datasets because the CaPA dataset does not have a long enough time period to be solely used. So, she needs to interpolate the CaPA data to be at a similar gridded resolution as the NLDAS precipitation she was already using. Then she'll have to compare the two to make sure there is continuity between the datasets, so that there is smooth transition from one to the other when going through time.

She is estimating that this process may take a few weeks. Once completed, she can go back to the bias correcting and statistical downscaling of the CMIP5 projections. She still plans on completing and providing daily forcing files to Tim by the end of September.

Transition: Research to Operations

Lauren has no updates on transitioning the models to operations. However, on her immediate to-do list (i.e., high priority) is to investigate what specifically needs to happen in order to implement a weekly update of the operational forecasts (which are currently updated monthly). This is in direct response to the meeting at the Army Corps on June 28-29, where it was agreed upon that a weekly update to the forecasts was doable by USACE and desired by both NYPA and OPG.

July 18, 2016

Conventional AHPS

Tim is still working on the coding of a pure Fortran version of AHPS. It is a lot of code translation from Pascal to Fortran, and he's also having to build utility routines to do things in Fortran that Pascal had built in. Making progress, but not complete yet.

Improved AHPS

Becky has completed the recalibration of most of the Superior and Huron sub-basins. There are a few sub-basins with no gaged flow data that will need to be dealt with (in terms of how to choose parameters, or what flow data to use to generate the parameters). Also, some sub-basins will need a new calibration period chosen because they don't have complete data in the already chosen calibration time period. Otherwise, calibration is going smoothly.

Climate Change Model

Lisi is still working on the CaPA dataset and getting it incorporated into the historical observational data pool for the statistical downscaling. The data processing includes fixing missing data, converting them from daily to monthly, truncating them from originally 12 UTC to the 00 UTC, regridding, comparing it with NLDAS2 to confirm consistency, incorporating them into the NLDAS2, and eventually redoing the statistical downscaling by using this new data and checking to see if there are improvements.

Transition: Research to Operations

Lauren is working on coding for weekly operational forecast updates. Because this would involve a lot of creative coding with the current code, which is based on quarter-month regulation (incidentally, Cornwall computes quarter-month regulation data just for this purpose, as Ontario regulation is done weekly, in practice), she decided to start fresh with weekly regulation and routing rather than adapt our quarter-month regulation and routing code. Fortunately, the USACE weekly forecast process is based on some translated fortran code that actually does weekly regulation and routing, so there are a limited number of changes that need to be made to make that work within this process:

1. Read Niagara River flow from CGLRRM output rather than the regulation data USACE gets for the weekly forecast.
2. Output weekly data.
3. Extend the length of the forecast period.
4. Figure out how to deal with the hindcasts, which were run to start from the first of a month rather than the start of a regulation period. This one is the trickiest. In practice, the weekly runs estimate starting levels for Friday on every Thursday. Not really a big deal. But for the hindcast runs, the start may be mid-week, so there could be significant change in water levels before the next regulation period. Lauren asked Tim if there was any way the hindcasts could be changed to all start on Fridays. Tim said this would put a lot of work back on his plate, and there would be additional issues with doing that. For now, no solution has been agreed upon to address this issue, but it is something that will need to be addressed and worked on.

Once the Ontario code is set up, Lauren will have some tweaks to do on the ensemble routing code to write input data files from CGLRRM output and post-processing weekly rather than quarter-monthly Ontario output data.

July 25, 2016

No meeting minutes available.

August 1, 2016

Drew and Tim update what was discussed at the previous week's meeting: Tim talked about his reworking of the modeling code. Drew asked how it will impact the project timeline. Becky agrees that the project timeline should be updated to reflect that much of the work that had been marked as completed needs to be redone. Update the whole timeline based on that fact. The original parts of the timeline will be left marked completed, but marked in red (to show first runs) and new lines added to show that these steps need to be done again after Tim reworks the modeling code.

Conventional AHPS

Tim is still working on coding. found a few more bugs in the code that would flag problems when introducing CMIP5 simulations. He expects maybe a couple more weeks on coding.

Improved AHPS

While Becky is still making progress on the calibration of LBRM, one question raise was regarding ungaged basins that can't be calibrated. Possibilities are either to come up with a daily flow estimate from the average of the flows of the other sub-basins, or to use parameter estimates from a nearby, similar sub-basin. Is there a pattern in the parameters around the ungaged basin? Is it obvious what parameters to use based on spatial patterns? Caveat: a couple of the parameters may be tied to the area of the basin. So they can't be easily transferred but may need to be transformed. These are problems that will need to be addressed when the calibration is completed and before Becky gives the parameter files to Tim.

Transition: Research to Operations

Lauren is taking old fortran code and adjusting it so it can be run as a weekly update. Making progress. She came across a new problem which may be applicable to the hindcast. In order to update weekly for forecasts that are not performed on a Friday, need to fill in some data, bring it up to the current week, and run regulation starting on a Friday. AHPS output - use NBS forecasts up until regulation day, but the output isn't coming up right. So she's working through that.

Lauren and Drew also met last week to discuss, in-depth, how to handle weighting and how to handle a probabilistic interpretation of ensemble members. They will be doing more research on the methods behind that and hopefully generate a full probability distribution function (PDF) from Lisi's 19 climate projection ensemble members, which Drew thinks will be the best method for delivering a probabilistic forecast to NYPA and OPG.

August 8, 2016

Becky updated the project timeline and shared with the group. Lines in a red font color were previously completed task items that will now have to be redone because of the errors and issues that popped up in AHPS. New lines have been added with estimated timelines for when the group is ready to perform the tasks again. Becky made a rather aggressive timeline for the new tasks and sought feedback from the group on if these projected times were doable.

Conventional AHPS

Tim was not at the meeting to give an update, but Lauren had an update related to the AHPS hindcasts that he will be generating, and related to Becky's question about the timeline of completing the hindcast and routing again. She is questioning whether to run the hindcast through the weekly routing model. She still doesn't have the weekly routing code ready, so it may not be easy or straightforward to route the hindcast sequences once those are ready. Would it be more beneficial to route the model quarter monthly as has previously been done? It was decided among the group that it would be better to run the quarter monthly routing for immediate skill assessment, and run the weekly routing code on hindcasts when it's ready.

Improved AHPS Becky's recalibration of LBRM is ongoing, making progress. Should be done with the gaged basins within the next week.

Climate Change Model

Lisi working on bias correction for monthly precipitation. Should be done in 2-3 days and will be able to do an analysis on that. Based on current results, precipitation is still very difficult to simulate. Will next work to downscale to daily time step.

Transition: Research to Operations

Drew and Lauren came up with a methodology to generate a probabilistic sequence from either Lisi's 19 climate projection ensemble members, or from Tim's 60 years historic sequences. Working with monthly data currently, but need to come up with a methodology for daily. Lauren's challenge is that the routing model needs input files and output files for every sequence in the probability distribution. For 19 members or 60 years, it runs pretty quickly. But if 1000 iterations are created to generate a PDF of NBS, it takes the routing model a very long time to get through all of those. She needs to investigate more efficient methods, or fewer iterations.

Lauren didn't work as much on the code to provide weekly updates to the forecast. Most of her focus right now is generating the probability distribution sequences.

August 15, 2016

Conventional AHPS

Tim's transfer of AHPS to fortran is going slower than he hoped, and he's been running into some issues. The code was crashing if he tried to do a forecast longer than 48 months. He found the issue and fixed that. Now he's working on getting LBRM to work correctly. Not likely that it will be done in the next week. But he should be able to run the hindcast relatively quickly. He can start feeding them to Lauren, by year, when they're ready.

Improved AHPS

Becky is mostly finished with the calibration of the gaged sub-basins. There are about 25% of the basins that couldn't be calibrated because either a) they were ungaged, or b) they were missing flows during the time period with which the group chose to calibrate the model. She has plotted up all of the simulated outputs for the group to view. The group will need to go through all of these to verify that the model is correctly capturing the hydrology of each sub-basin.

Drew emphasized that this is important hydrological work... analyzing the output from the LBRM calibration. He also requested that Becky plot the precipitation and temperature for all sub-basins. When there is an issue with the hydrological output, then the group can easily see if it's an issue with the precipitation or temperature that was used for the calibration.

Climate Change Model

Lisi has completed the precipitation improvement method and is moving forward with this current method for precipitation. She is now working on downscaling to daily, which may take 3 weeks to finish this step of the process. She then still needs to do a spatial downscaling after the temporal downscaling is completed.

Transition: Research to Operations

Lauren is still working on the method for building NBS probabilistic sequences. She's written the code for that and finished the file process for implementing that and is currently processing it. It's running right now. This method will increase the runtime of the model substantially, but can get it to run within several hours. She did reduce the sample size from 1000 to 300. She's also still working on the coding for weekly updates of the model runs.

August 22, 2016

Only Tim and Becky were on the call for the day, so updates are minimal.

Conventional AHPS

Tim's still working on the transfer. But so many things are different that he's encountering. Most of his issues are when he comes across a section from the original AHPS that has no comparable coding options for Fortran, and he's having to decide on how to deal with those. This is turning into a much bigger project than originally anticipated, but is a necessary step for the project. He's tentatively hoping to be complete with the transfer by the end of September, and is anticipating that generating the hindcasts will go relatively quickly and smoothly after that.

Improved AHPS

Becky and Drew have gone over some of the results from the LBRM recalibration. They are confident that the time period chosen for the calibration period is a good time period to stick with, even though about 25% of the sub-basins couldn't be calibrated. After analyzing the Superior sub-basin outputs and inputs, they've decided that a good next step will be to pick representative "global" values for each of the parameters and run LBRM on all sub-basins using those values. If the output looks reasonable, this could be how the group chooses parameter values for the sub-basins that are ungaged or with missing data during the calibration period.

August 29, 2016

Conventional AHPS Tim has made a lot of progress and rewrote around a thousand of lines of code last week. There is still a lot of work to be done.

Improved AHPS

Drew is going to enlist Joe Smith's help at analyzing the precipitation data for the sub-basins. He's interested in finding relationships between precipitation events in neighboring sub-basins and the correlation between those sub-basins' precipitation events. He also wants to look at the daily statistics of precipitation, dry days versus days with precip, length of time between dry days, and the frequency distribution. These statistics may help us better understand the hydrologic response of a sub-basin's LBRM output to the precipitation input.

Meanwhile, Becky is working to pick "global" parameter values for the Superior sub-basins. She's also going to be doing a sensitivity analysis for sub-basins with anomalous parameter values to determine how the output simulations change when an anomalous parameter value is replaced to more closely match the other sub-basins' parameter values.

Climate Change Model

Lisi is working on downscaling monthly CMIP5 projections to daily. Making progress, but no results to share yet. She's having issues with the cloud cover term and has checked with Tim to see if LLTM can use the shortwave radiation directly so that cloud cover does not have to be calculated. This is because Lisi is having challenges in downscaling monthly radiation values from CMIP5 to daily cloud cover that LLTM needs as input. But, LLTM uses the cloud cover to calculate

radiation, so Tim needs to investigate if there is a way to cut out that redundant step that is not needed when CMIP5 data are being used. Tim has recommended that the project timeline be adjusted with a new line added to develop a new LLTM that uses radiation directly and recalibrate LLTM.

Transition: Research to Operations

Lauren and Drew worked more on the PDF development and analysis last week and are making progress on that methodology. Daily NBS is not normally distributed, so Lauren is working on that aspect.

Most of her work this past week has been on the coding for weekly updates. Made a lot of progress on that. She now has what she thinks is a working weekly Ontario regulation and forecasting code and is working it into her ensemble framework. Working on pre-processing and post-processing data with that to see how it works. Basically, development is done, and now she's in the process of implementation.

September 5, 2016

No meeting, holiday.

September 12, 2016

Conventional AHPS

Tim is still working on transitioning AHPS to Fortran, and may be possibly getting close to a clean compile. He has encountered several different issues that he can temporarily "patch" for now, but are in desperate need of further attention in the future. These temporary fixes will be necessary to finish the transition so that an operational forecast product can be delivered to NYPA and OPG by the end of the year. However, for a true transition to operations at USACE to actually occur, there are some bigger fixes that need to be addressed and will take a longer amount of time. But when Tim finishes those big fixes, AHPS will be a much more versatile framework and can truly be solely operational at USACE, without Tim needing to always troubleshoot issues.

One issue that Tim will need to address immediately is how to incorporate Lisi's forcing files into AHPS. The issue is that Lisi will be delivering radiation forcings, not cloud cover information. At this time, neither AHPS, nor LLTM itself, is set up to read in that information from a file. It should be relatively simple to adjust LLTM to read in that information instead of calculating the information (which is what it currently does). But the bigger issue, which will take a bit longer, is to changes AHPS and how it reads in files. There is not a quick "patch" for this, and Tim will need to work on this before the climate change product can become operational.

Transition: Research to Operations

Lauren has successfully compiled the weekly update of routing. She has now implemented it into the ensemble forecasting code. She hasn't yet really dug into the output to verify that it is running correctly. But she will soon do a quick check to make sure the output looks realistic. A more robust assessment will still have to be done.

Lauren and Drew are still working on PDF development methodology. She has written some code to use the weighting file to weight the ensemble members and incorporate that into the PDF. But the PDF development is more complicated than they first anticipated. The issue is that the different meteorological variables are not completely independent of one another, and all the variables that the model outputs (or receives as input) are correlated with each other, so a PDF needs to take that into consideration. They've started looking into copula functions - a multivariate PDF that maintains the temporal correlation between variables. There are several ways to do this. The best way would be to come up with the function on the pre-processed input meteorological data and run AHPS with that full distribution then. But the ideal way for this project may be to come up with the function on the various components of NBS and develop the full distribution of NBS values that will then feed into the routing model. Lauren and Drew will continue working on this.

September 19, 2016

The primary focus of this meeting was on updating the project timeline. Last week, Tim updated the entire group (during the monthly call with NYPA, OPG, and NRCC) about transitioning AHPS to a Fortran version and that some bigger changes would become eventually necessary. It was agreed upon that it would be better to address those issues immediately and delay the timeline. Therefore, the project timeline will need to be redone to reflect the necessary changes that will be taking place.

For finishing the coding of AHPS in Fortran, Tim wants internal target date set for the end of January, 2017. Concurrently, a line will be added for LLTM updates, also to be completed by the end of January. LLTM updates will include updating the model to read in radiation data, recalibrating the model, and analyzing the calibration parameters.

Once the coding of AHPS (and updating of LLTM) is finished, the conventional, improved, and climate change AHPS will need to be run to generate a full hindcast of NBS sequences that will be routed through CGLRRM and assessed for skill. The new AHPS package will also be transitioned by Tim from GLERL to Lauren at USACE. Based on the additional time needed for these various components, we estimated that the new AHPS package (for conventional, improved, and climate change) will be operational at USACE by the end of March, 2017.

September 26, 2016

General Updates

Becky is working to the update the project timeline but has encountered some obstacles. As she transitions to her new job, she is working on accessing an editor for the project timeline files that were created by Microsoft Project. There are open source applications out there that can be used to edit the files, but they look significantly different, so there is a bit of a learning curve. So, the creation of a newly updated project timeline is a bit delayed.

In the meantime, Becky proposed completion dates and organization for several different aspects of the project timeline to Lauren and Tim, which were agreed upon. Lauren wanted to point out that the development of the PDFs that she's been working on with Drew may be a better task item to mark as "ongoing" as it may not be completed before operationalization

of the forecasts. It's not a necessary step to provide deliverables of 0-60 month forecasts, so it won't delay the completion of that part of the project, but will still be an important step in providing a true probabilistic ensemble forecast.

AHPS Transition

Programming is progressing. Tim has some of the basic data storage structure stuff built and it seems to be working well in the testing so far. He's now working on file structures and looking at the first "real" program on Friday. He's taking advantage of Fortran 2003/2008 object-oriented programming additions that allow for a much cleaner implementation in the code.

Transition: Research to Operations

Lauren has been working to add a functionality to optionally route historical NBS sequences through the ensemble framework. This is really for the purpose of evaluating the effects of biases in NBS on water levels, but it will be handy for other uses. Next step will be to add functionality to change the starting levels (trickier than it seemed on the surface, due to the need to change the regulation data so that it makes sense with the starting levels).

October 3, 2016

Lisi - recalibrating WRF-Hydro using DDS. Working with a team of about 12 scientists at NCAR to get it recalibrated in the next two weeks. They're giving her all the R programs she needs to run the calibration. Can use these results to compare to LBRM calibration results on similar watersheds.

October 11, 2016

The group went over the new project timeline that Becky developed. There was general agreement with the layout of the timeline and when tasks are due. However, Lauren was unable to attend the meeting, so her input will be needed to update certain tasks on the timeline to more accurately reflect when she will be able to finish things.

Tim stated that he needs radiation simulations to test with new LLTM and calibration. A line will be added to the project timeline to reflect this delivery of radiation data from Lisi to Tim, separate from the delivery of the rest of the forcing files.

Tim's work on the transition of AHPS to Fortran is progressing. Based on the new timeline and major transition, the group is considering the renaming of AHPS (partially because the National Weather Service has its own product that uses the same acronym, so renaming ours would reduce confusion). Current acronym under consideration is GLSHFS (Great Lakes Surface Hydrologic Forecasting System).

Lisi's goal right now is to get forcing files to Tim by the end of this month. Then she will be starting the documentation phase (with the goal of providing the NYPA and OPG folks this fall with supporting documents on the bias correction and statistical downscaling methods that she used for this project) and writing a paper.

October 17, 2016

Lauren went over results of analyzing the next five years of forecasts of AHPS NBS and flows (based on component NBS) compared to USACE NBS and flows (based on residual NBS). These results do show a slight positive systematic bias in the AHPS product, ranging from no bias at all on Lake Erie, to a very minor bias on Lake Superior, and larger biases on Michigan-Huron and Ontario. Drew wants to make sure we take note so that these don't get put too far on the backburner.

Tim is working on map stuff now. Error checking part is done. He went over formats and data structure stuff, changed some file formatting. Things are progressing smoothly right now.

Lisi is going to try to get a daily sequence done by the monthly meeting on Thursday. Bias correction on the interpolation from coarse to finer resolution is what she's working on. How big is the difference if she doesn't bias correct for that interpolation over the 10 years she has observations? Hoping to have this next step done by the end of this month and have the data sequence ready. Considering how to handle future biases.

The group briefly discussed that archival of forecasts would likely take place at both USACE and GLERL. It is still being discussed where archives will be located, how many forecasts will be saved, and for how long they'll be saved. Documentation and/or communication will likely be needed to advertise these forecast archives for operational and research purposes.

October 24, 2016

Meeting canceled.

October 31, 2016

Tim fixed some memory leaks after program was crashing during tests last week. Now there is an issue with reading station data that he is working on fixing. Still working toward goal of finishing transition by the end of January.

Lisi is done prepping the radiation simulations to give to Tim. She is still working on the daily max and min temperature simulations, but all other variables are completed. She is also completing writing documentation. She has created a detailed technical report on her methodologies for downscaling and bias correcting the CMIP5 simulations for use in the GLSHFS. Once completed, this technical report will be sent to Peter Kowalski and NYPA and OPG. It is also an important major step toward a peer-reviewed manuscript. She should be completed with this document before the end of the week. Much of this documentation will also be included in the work plan document for the long-term forecast project.

Lauren suggested adding to the project timeline: work on coding to apply weighting. Weights based on CPC outlooks, but applying it to only the first 3 months. Equal weighting will be given to all sequences from 4 months to 60 months. Drew said in Tom Croley's code, there was a toggle switch that you could use to determine how many months would be weighted by CPC outlooks. What Lauren is doing is similar, but in the post-processing code. Drew brought up that there are some limitations with the CPC products. Another idea for phase 2 of the project is to incorporate NMME probabilistic predictions into the weighting scheme.

Based on the fact that Drew and Lauren have had several conversations outside of the Monday morning meetings, Lauren also brought up the importance of documenting what was talked about. It was decided that important points from these conversations could either be included in the meeting minutes or in the work plan document. Either way, it is important that there is some sort of digital trail that we can all refer to, so we don't forget some of these ideas that can't be addressed right away.

November 7, 2016

Short meeting. Tim is deeply entrenched in coding and Lisi has finished the bulk of the work needed to deliver climate change information to the operational long-term forecasting project. With Tim unable to give us specific updates (except "I'm still working on coding") and Lisi beginning work on a peer-reviewed paper of her work, the group decided it may be beneficial to reduce the frequency of these meetings through the holiday season. This will give us all the opportunity to focus on our work and give more useful and detailed updates when the next meeting comes.

December 5, 2016

Tim is trying to figure out a way of giving us an idea of where he is. He's still working, but it is going slower than expected. Working on code that will read and write all of the file formats that are used. Next step is working on the Thiessen polygon calculations and converting into what LBRM and LLTM reads.

Becky has finished preparing all of the parameter files that Tim will need to run the improved LBRM. She's delivered those to Tim. Parameter files were created for ungaged basins by using parameter files from other basins that had the highest correlation in daily precipitation.

Lisi has completed work on every variable for all 19 models in CMIP5 for January 2017 to January 2026, daily forcings and spatially downscaled. Need to test and validate. Working on documenting this work and developing a poster presentation.

Lauren has been working on cleaning up code on making data flow diagrams. Made a "big picture" diagram, and now working on more specific steps flow diagrams to help with programming in the USACE office. Looking where she can make some improvements in efficiency in the future. She's also working on coding for weighting of forecasts. Implemented a weighting code that takes water levels and flows and total supplies from the routing model output and applies the weights. She's thinking about ways to apply that to the early part of the period (i.e., apply it only to the first 3 months) and coming up with a smooth and continuous forecast (i.e., with no jumps between the weighted and unweighted periods). Talked with Drew and developed a hypothesis that they should be able to apply weighting to the whole period, because the probabilistic ensemble will still capture the uncertainty in a subset of weighted years (assuming that some years will get a weight of zero and not be utilized). Lauren is testing this hypothesis now. Positive results would mean an easier time with coding for weighting and not having discontinuous jumps.

During the last large NYPA-OPG meeting, Becky agreed to develop a schematic flow diagram for the long-term forecasting process. Lauren has provided her with helpful documentation to start off. This is a good first step in developing the User's Guide that Becky and Lauren will work on and provide to NYPA-OPG upon delivery of the first forecasts. Tim pointed out that there will be several documents that need to be worked on. First would be a general User's Guide - this is how you run the forecast models. Then there would be a technical programmer's guide - this is how you go in and fix portions of code, this is how you recalibrate, file structures, etc. Becky also mentioned that there should be documentation that is simply for the forecast output - a sort of readme for what's in the output files and how the output files were generated (information used from the flow diagram).

December 12, 2016

Last week Lisi and Tim worked on transferring data into the format needed for LBRM to begin a validation of LBRM with CMIP5 projections. Tim's been working on coding to grab the gridded data and interpolating it into sub-basin scale inputs.

Lauren has run some experiments, testing her hypothesis that they can use the weights for the whole period and still have representative results. Tim had suggested that a small weighting be used, even for years that would not be typically used. So Lauren is including that in her methodology. She has results, and Drew and she will analyze the results at their next meeting.

The group discussed some of the "bigger picture" plans for this project, as a way to refocus efforts and make sure we're on the right track. One of the fundamental motivations of this project was to incorporate climate change into the flow forecasts. But the question remains: is there a climate change signal in the daily forcings that will drive the hydrologic models? While waiting for Tim to finish the coding of GLSHFS in Fortran, it seems pertinent to do some analysis on the CMIP5 projections, how they differ from current observations, and how the hydrologic response changes when using those projections as opposed to historic sequences. Since Lisi is already working on a lot of this in preparation for her AMS poster presentation in January, hopefully there will be results to present within the next month.

January 9, 2017

Tim: Completed the work for Lisi that she needed. CMIP5 projections are now at a sub-basin scale. He is getting back into the transition of GLSHFS to run in Fortran. He's still in the earlier stages of setting up the framework. But once that is set up, things should be able to move faster and he'll soon be able to incorporate the models in the framework.

Lisi will be spending the next couple of weeks preparing for the AMS meeting, which includes testing LBRM results with the CMIP5 projections.

Lauren: results from her experiments were analyzed. She ran weighting procedures where she took the 30 wettest years and gave them a weight, then compared when she gave all the years equal weighting. She did the same thing for the 30 driest years. As expected, the NBS was shifted upward during the earlier months. The assumption was that the full range

of variability would be accounted for in the later months and the weights wouldn't affect the later months. What actually happened was that the bounds were broadened, introducing more uncertainty, because fewer ensemble members were being weighted.

Drew pointed out that maybe it's not realistic to give any years a zero weighting. But this problem may be more appropriately addressed in phase 2 of this project.

Becky is working on the schematic flow diagram requested by Peter Kowalski. She has started with the flow diagram from Drew's paper on the appraisal of AHPS and plans to include additional specifics to this project, such as the different forcings and outputs. Becky also suggested working on a "to do" list of phase 2 ideas. So many ideas and plans have been discussed as part of phase 2. She would like to go through all these meeting minutes, the work plan document, and Peter's spreadsheets of meeting minutes to document everything that was suggested for a phase 2. This will help in the organization for next steps once the forecasts are operational.

Drew met with Peter recently to go over updates on the short-term and long-term projects and touch base with him on the management of the project, and everything seems to be going well. Drew also wants to address a formal transition plan for the project as it goes from research to operations. The GLERL office has begun a protocol for an official formal transition document with projects that go from research to operations. This document should be straight forward and can pull from the work plan document and the project timeline. It will include signatures from parties at the U.S. Army Corps and should help with organization and management.

Lauren wanted to bring up the Ontario regulation: Plan 2014 was adopted, which is good news, but complicates the forecasting procedure. USACE is currently using the forecast from Cornwall for their operational 6 month forecasts. Right now, they don't have their own forecasting code, but it is being developed right now. For this project, this means that there is currently no St. Lawrence River forecast. Lauren is unsure when this will change, so this is something that USACE folks plan to bring up with NYPA and OPG soon.

January 30, 2017

Tim: Not much further. Written a lot more code, hoping to be at a milestone, but not there yet. Dealing with various issues, making progress, just going slower than he had hoped.

Need to start discussing a contingency plan. Tim will still try to finish updating the model by the end of March, but there will still need to be some time dedicated to transferring that, getting it running at USACE, and testing it. That will definitely not be done by the proposed timeline we were initially following. Hence the need for a contingency plan - what can be provided as a deliverable until the GLSHFS is operational? Tim will be looking over the old version of AHPS to see what can be done to have it run forecasts in the interim. The group will also plan to have a separate phone conference with NYPA, OPG, and NRCC to prepare them with this information. Becky will set up the meeting, with the plan that it will occur after the monthly NYPA-OPG conference call that will take place on February 16.

February 6, 2017

Tim: Finished a certain piece of GLSHFS that wasn't working. It can now do all the Thiessen weighting and transitions individual station files into sub-basin files and mapping. He also went back and looked at AHPS to see if he could run it for a contingency plan. He discovered that his executable is very sensitive to the version of Windows that he's running. AHPS is now experiencing a hard crash at the same spot (a different spot than the last time he was running it). Based on his current version of Windows, it is nearly impossible to diagnose the issue and fix. He strongly feels that he should not be spending his time trying to get AHPS to work at this point.

What does this mean for a contingency plan? Lauren has, in her hands, an operable 6-10 month AHPS forecast. Beyond that, she has historical NBS sequences that she can route out to 5 years for a statistical probabilistic sequence. This is the best option on the table for providing NYPA and OPG a deliverable before GLSHFS is ready to go out.

Since we won't hit the delivery date for all the deliverables related to GLSHFS, we should suggest to NYPA/OPG a phased rollout. As a model becomes available to USACE and they begin testing it, NYPA and OPG will also get to use it. Instead of waiting for all of them being available at once, each individual one will be available as USACE begins to test and implement it.

As Tim works to get GLSHFS up and running, we could still run experiments with LBRM, checking calibration and boundary conditions, and researching the physical properties and how they respond. May check with Joe again about visualizing the calibration results. And it may be prudent to have another meeting where we discuss the results of the LBRM re-calibration.

Lisi is working on the methodology of downscaling Tmax and Tmin from monthly to daily time steps, with quality controlling methods to check the validity of the Tmax and Tmin daily values. Occasionally, the daily Tmax value would be less than the daily Tmin value, because the downscaling was run independently on the two separate variables. Lisi has now fixed this issue.

February 13, 2017

Get a quick update from Tim about where he is in the process. Final plans on how to deliver message to NYPA and OPG.

Tim's update: all the station processing is now working correctly. But it takes a very long time. Running the entire time period, 1948 - 2015 took about 24 hours. He knows of several areas where optimization can be added to make the processing faster. He is now working on incorporating LBRM into GLSHFS.

Inventory of forecast deliverables: 1. GLSHFS with old LBRM, old LLTM, 5 year forecasting with historic sequences of meteorology as forcings. NBS is routed through CGLRRM from Superior through Erie, with an updated Ontario regulation model. Updates are currently underway on getting GLSHFS running through Fortran (see Tim's updates) and a completed update of the Ontario regulation model that is currently being undertaken by Buffalo and Cornwall USACE offices. 2.

GLSHFS with new LBRM (recalibrated), old LLTM, 5 year forecasting with historic sequences of meteorology as forcings. NBS is routed the same way as 1. 3. GLSHFS with new LBRM, new LLTM (updated solar radiation), CMIP5 projections as forcings. NBS is routed the same way as 1. 4. Residual NBS, historical sequences, weighted using the outlook mechanisms (CPC outlooks) that are used by AHPS and GLSHFS, but run independently of AHPS or GLSHFS. NBS is routed the same way as 1. 5. Old AHPS, old LBRM, old LLTM, can run out 5 years at USACE. But it has issues, and nobody is confident in releasing those forecasts to NYPA and OPG.

Should be updating the group based on water supply component and routing component. Example: Model 5, water supply component comes from old AHPS, historical forcings, 5 year forecasts of NBS. Routing component comes from....

Have a table and schematic flow diagram ready for the meeting to refer to. Start with a clear description of each model. Then move to status of each model - status of improvements and details of transition to operations.

March 20, 2017

Since this is Becky's last couple of weeks on the project, the group went over everything that they would need from her. All of the LBRM calibration stuff that she did is located on a shared Google Drive folder with the group, under "LBRM". Inside the LBRM folder is a folder titled "Calibration Information" which contains scripts for calibration, and a readme.docx file that Becky wrote, detailing all the steps of an LBRM calibration using Ostrich. There is also a shared Google Drive folder called `NYPA/OPG_bolinger` which contains management documentation, i.e., the original work plan document and the meeting minutes document (this document). At this point, it appears the group has everything they need from Becky, so this is likely to be her last call in to the Monday morning meetings.

Lauren is making forecasts available (but not public) for NYPA and OPG to grab with the old version of AHPS that USACE has. She also got the Plan2014 forecast code. It's going to be a pretty big job to integrate it into their operations because it's in an unfamiliar programming language. But she's working on it now.

Tim has been working on LLTM (after finishing integrating LBRM into GLSFHS). Getting pretty close with integrating it in. That also includes the coding that directly calculates radiation instead of using cloud cover. Unfortunately processing data is still going very slow. But GLSHFS runtime should be similar to AHPS.

F Slides from Phase I (R&D) project closeout meeting

This section includes slides (modified for this summary report) presented during the September 2017 meeting held in Ann Arbor, MI, for the close-out of the research & development phase of the project.

NYPA/OPG/NRCC Forecasting Improvements Project

Phase I close-out

September 2017
Ann Arbor, Michigan

Outline

- Goals
- Background
- Model development
  - Meteorological forcings
  - Hydrological models
  - Water supply forecasting systems
  - Routing and regulation models
  - Ensemble processing
- Skill assessment
- Operational implementation
- Future work

System name	Meteorology	Hydrology	
		Tributary inflows	Lake evaporation
GL-AHPS	Climatology	LBRMv1.0	LLTMv1.0
GLSHyFS-1	Climatology	LBRMv1.0	LLTMv1.0
GLSHyFS-2	Climatology	LBRMv2.0	LLTMv1.0
GLSHyFS-3	CMIP5	LBRMv2.0	LLTMv2.0
NBSr	None	Historical supply sequences	

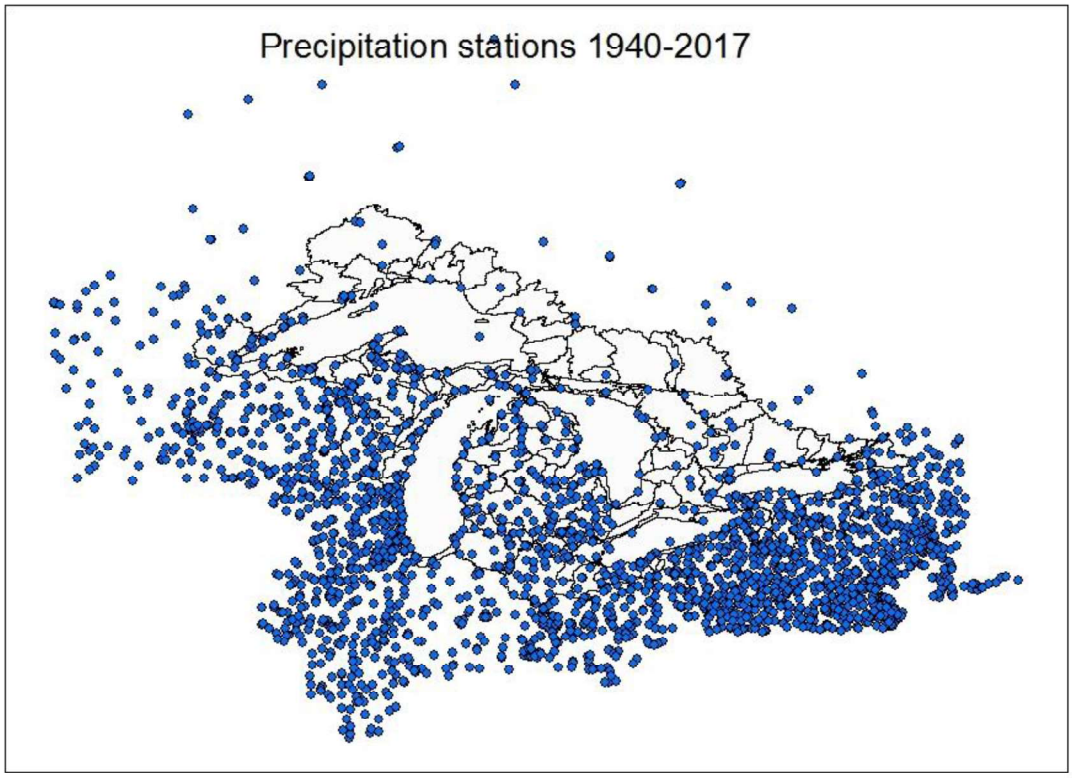
Data requirements driven by the models

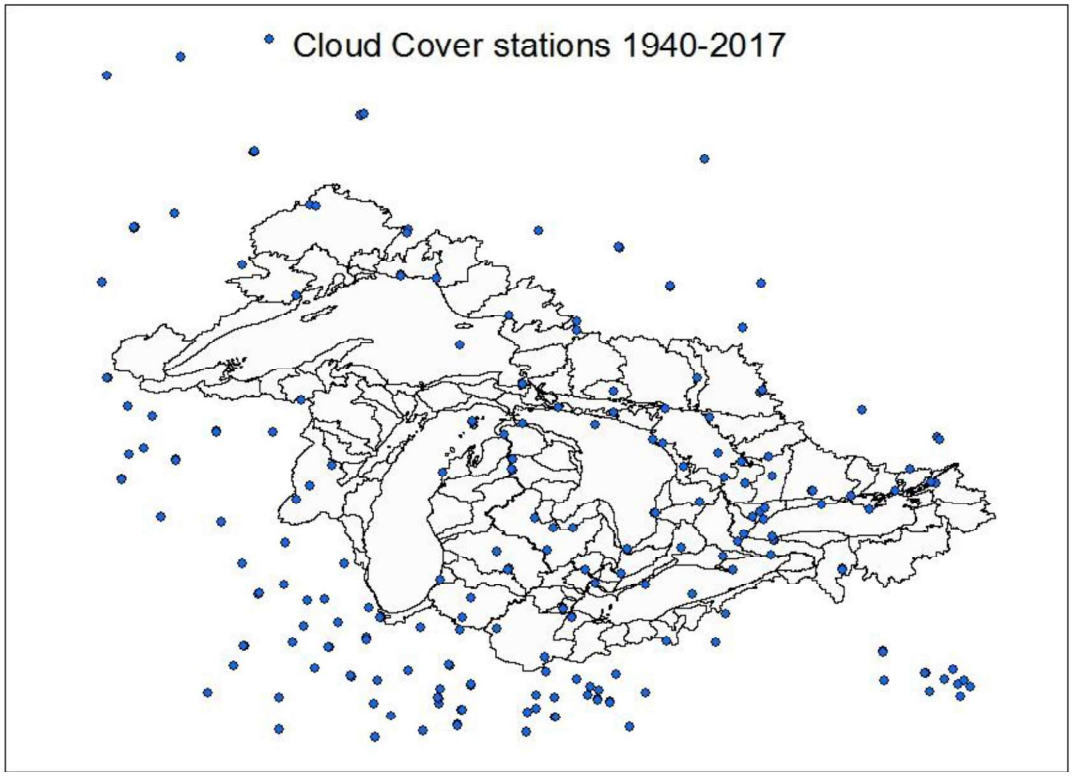
Large Basin Runoff Model (LBRM)

- Minimum daily air temperature over land area
- Maximum daily air temperature over land area
- Daily total precipitation over land area

Large Lake Thermodynamics Model (LLTM)

- Mean daily air temperature over lake surface
- Mean daily humidity (dewpoint) over lake surface
- Mean daily windspeed over lake surface
- Mean daily cloud cover over lake surface
- Total daily net longwave radiation over lake surface
- Total daily incident radiation over lake surface


Precipitation stations 1940-2017


Cloud Cover stations 1940-2017

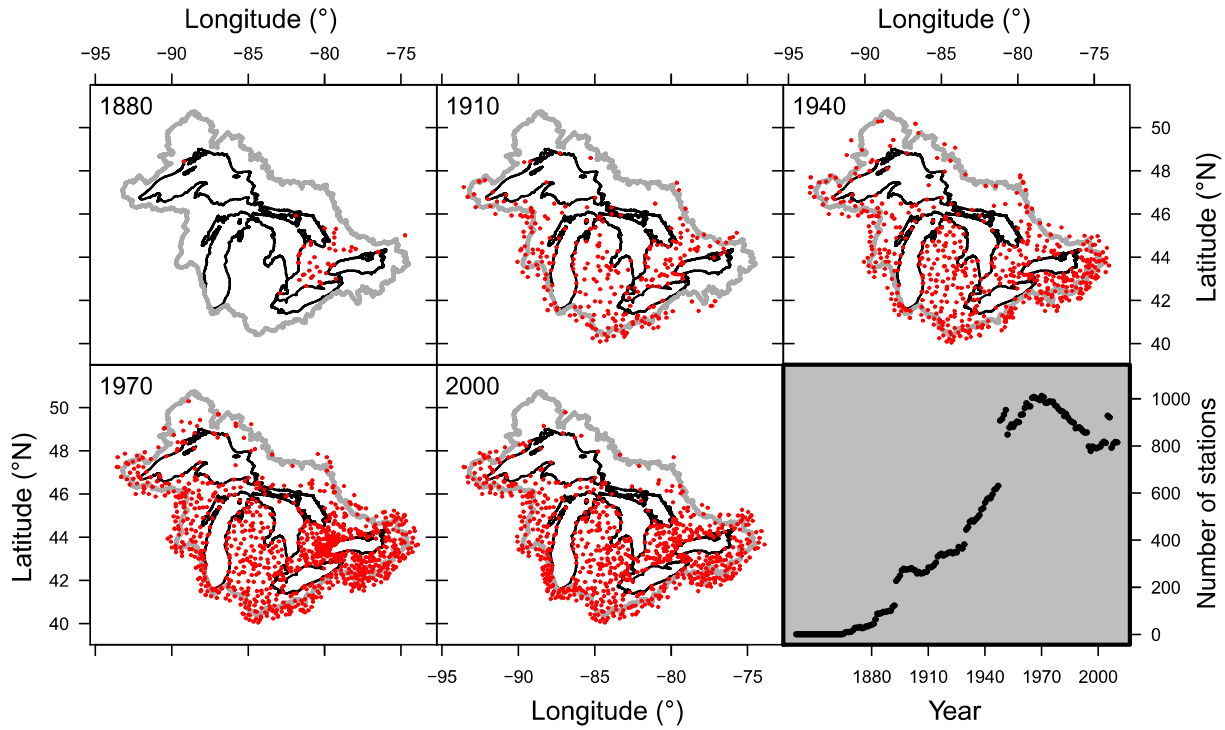


Fig. 2. Spatial distribution of meteorological stations within the Great Lakes basin (boundary represented by gray line), and outside but within 50 km of the Great Lakes basin, reporting daily precipitation totals in 1880, 1910, 1940, 1970, and 2000. Bottom right-hand panel indicates total number of corresponding meteorological stations from 1840 to present.

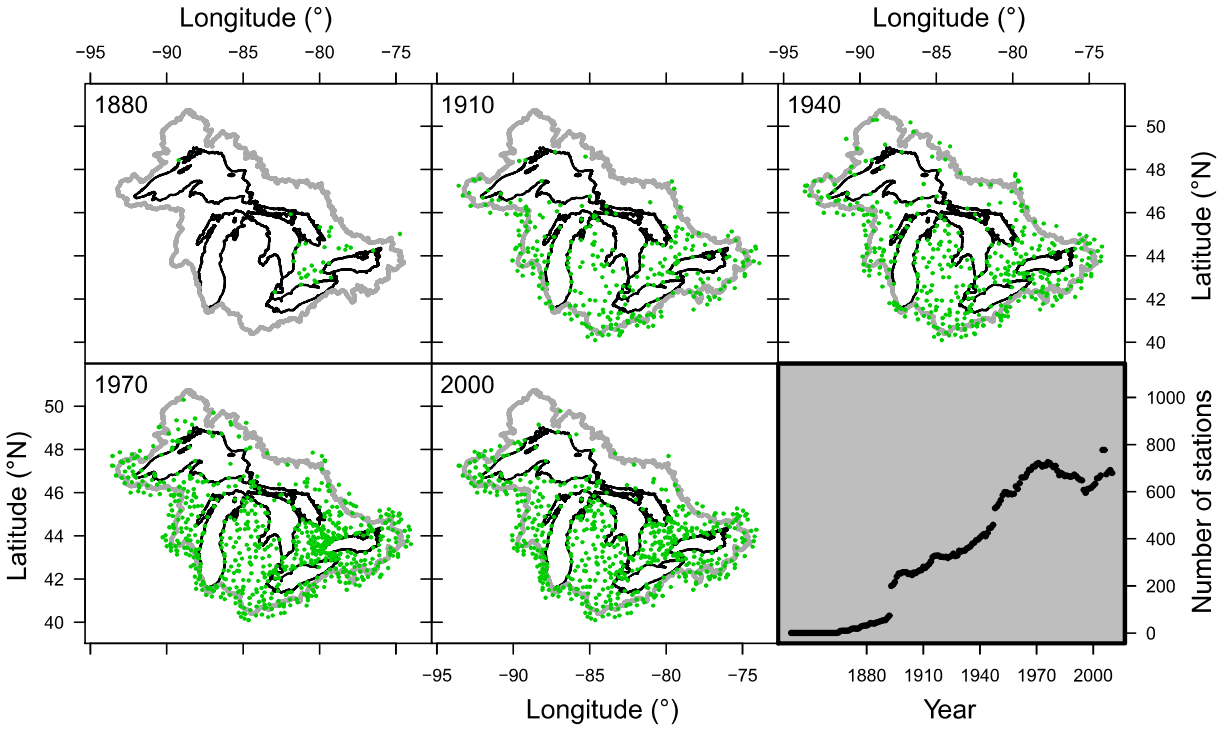


Fig. 3. Spatial distribution of meteorological stations within the Great Lakes basin (boundary represented by gray line), and outside but within 25 km of the Great Lakes basin, reporting maximum, or minimum, or both maximum and minimum daily air temperatures in 1880, 1910, 1940, 1970, and 2000. Bottom right-hand panel indicates total number of corresponding stations from 1840 to present.

Journal of Great Lakes Research 41 (2015) 65–77

Contents lists available at ScienceDirect

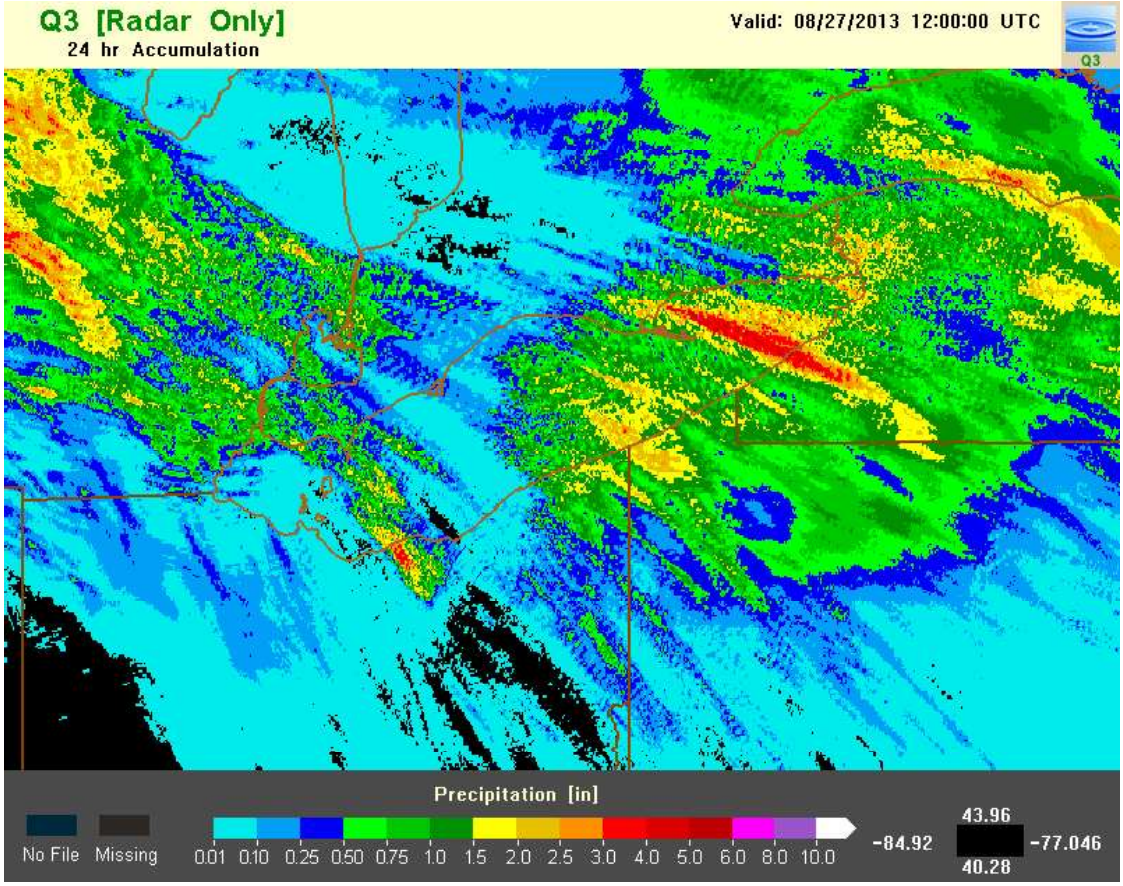
Journal of Great Lakes Research

journal homepage: www.elsevier.com/locate/jglr

Development and application of a North American Great Lakes hydrometeorological database — Part I: Precipitation, evaporation, runoff, and air temperature

Timothy S. Hunter [a], Anne H. Clites [a], Kent B. Campbell [a,b], Andrew D. Gronewold [a,*]

[a] Great Lakes Environmental Research Laboratory, National Oceanic and Atmospheric Administration, Ann Arbor, MI 48108, USA
[b] Cooperative Institute for Limnology and Ecosystems Research, University of Michigan, Ann Arbor, MI 48109, USA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24 hr Accumulation
Valid: 08/27/2013 12:00:00 UTC
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Precipitation [in]
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Missing
0.01 0.10 0.25 0.50 0.75 1.0 1.5 2.0 2.5 3.0 4.0 5.0 6.0 8.0 10.0
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43.96
40.28
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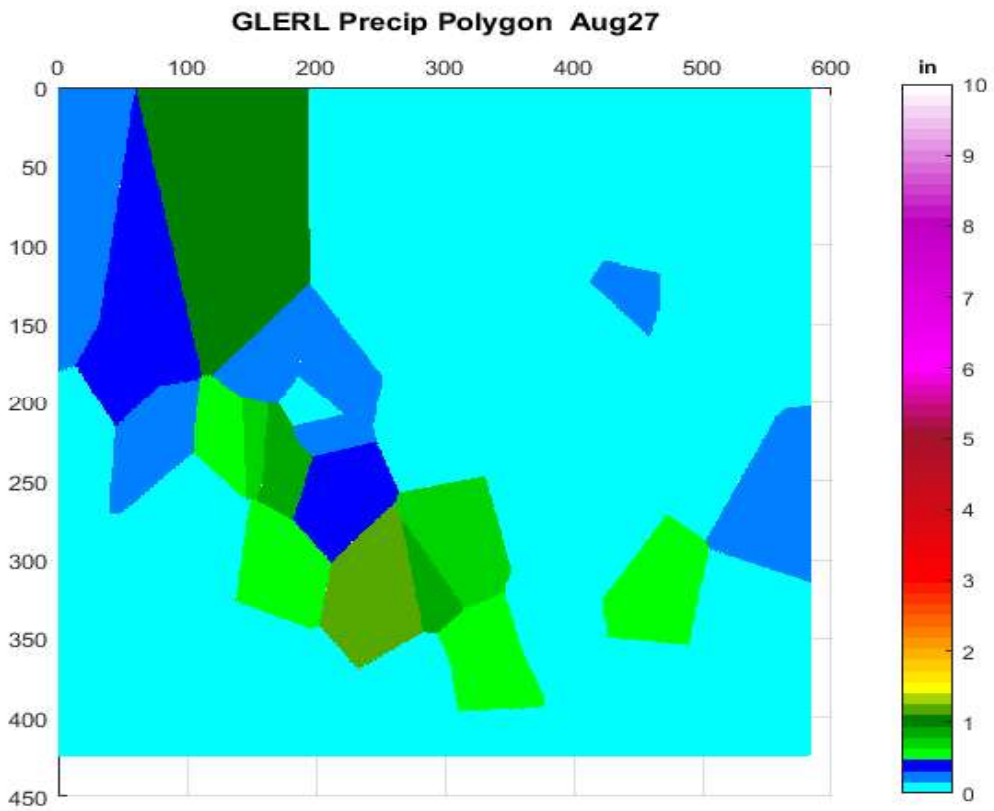
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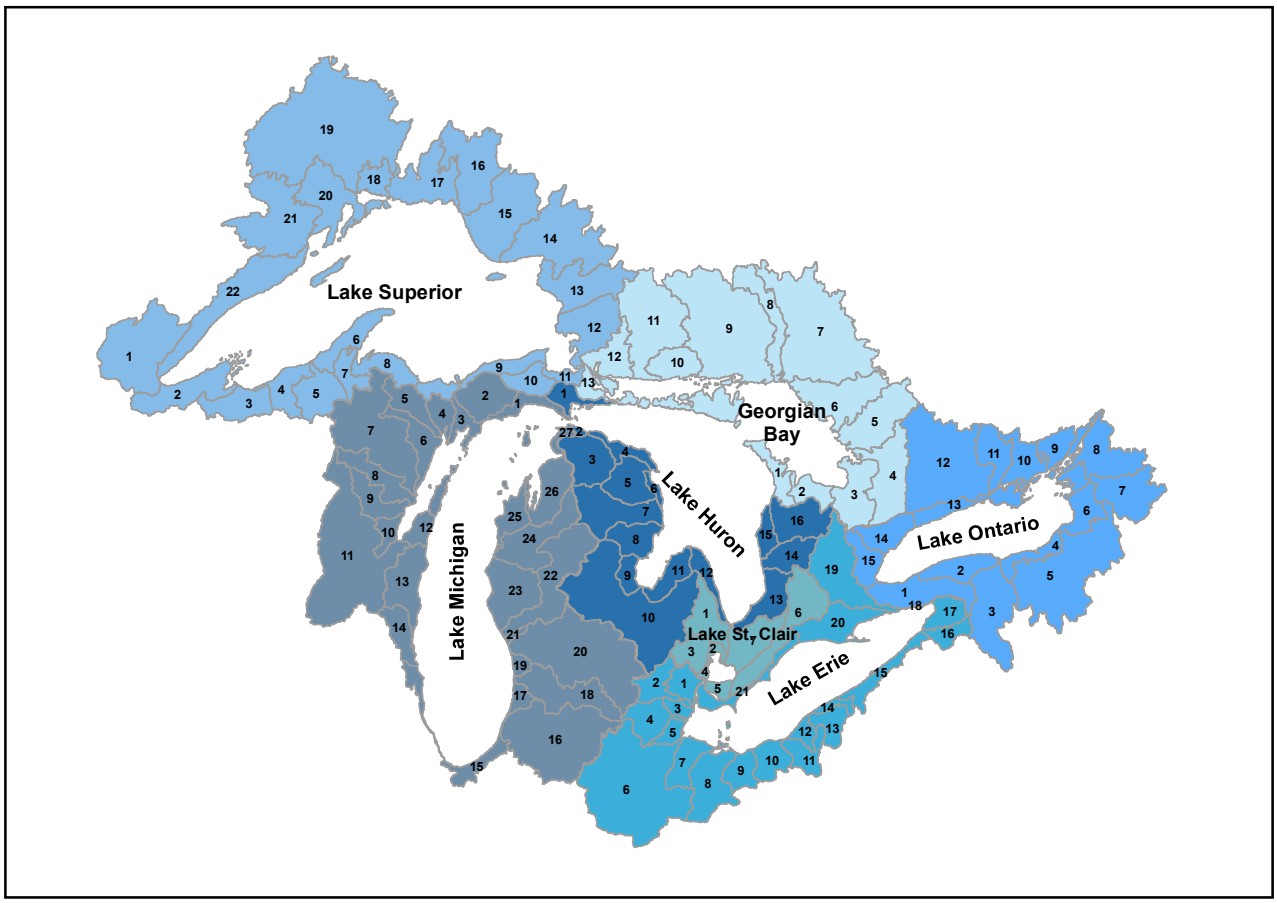
0 50 100 150 200 250 300 350 400 450
in
10 9 8 7 6 5 4 3 2 1 0



System name	Meteorology	Hydrology	
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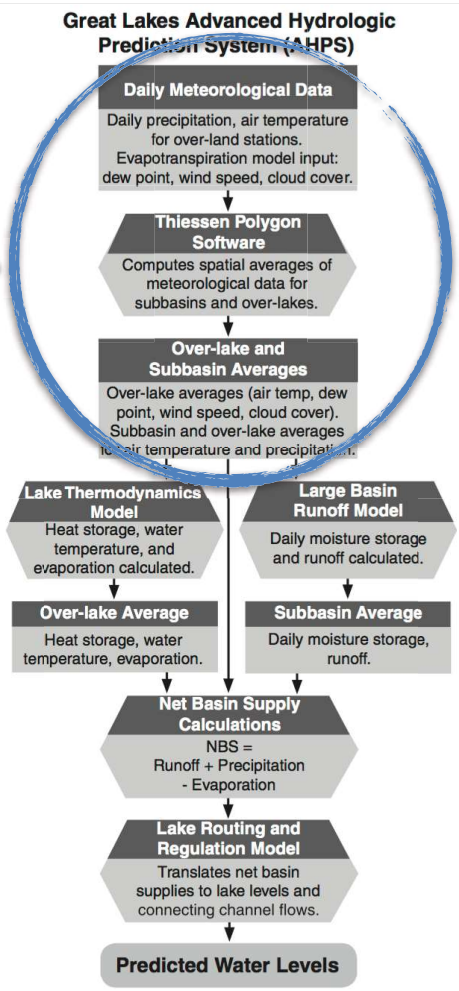
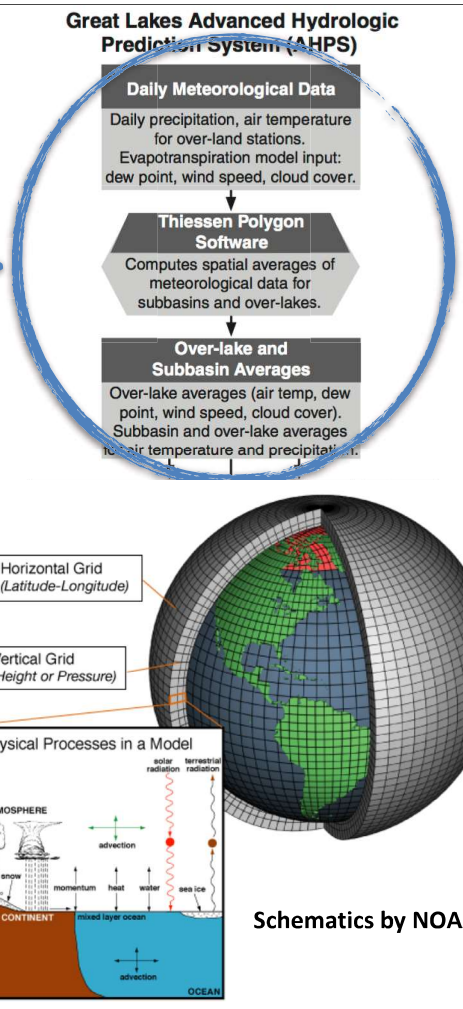
GLSHyFS-1	Climatology	LBRMv1.0	LLTMv1.0
GLSHyFS-2	Climatology	LBRMv2.0	LLTMv1.0
GLSHyFS-3	CMIP5	LBRMv2.0	LLTMv2.0
NBSr	None	Historical supply sequences	

Historical meteorological sequences



(Gronewold et al. 2011)

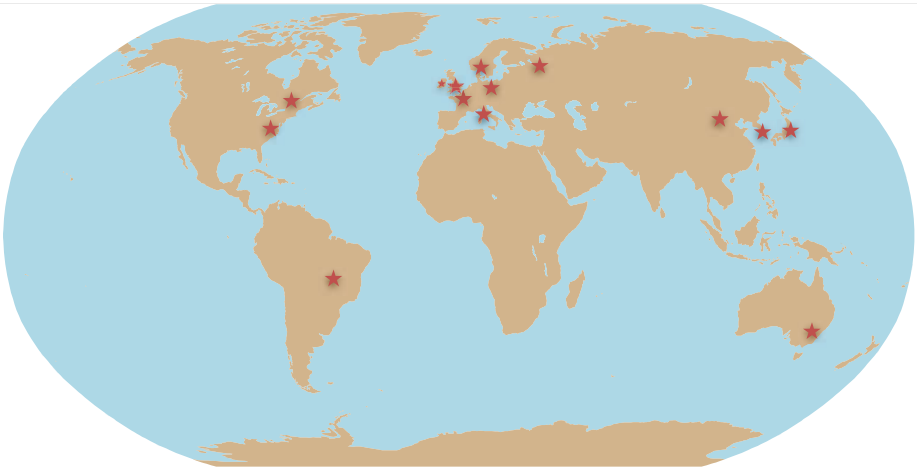
CMIP5 (*Coupled Model Intercomparison Project Phase 5*)



(Gronewold et al. 2011)

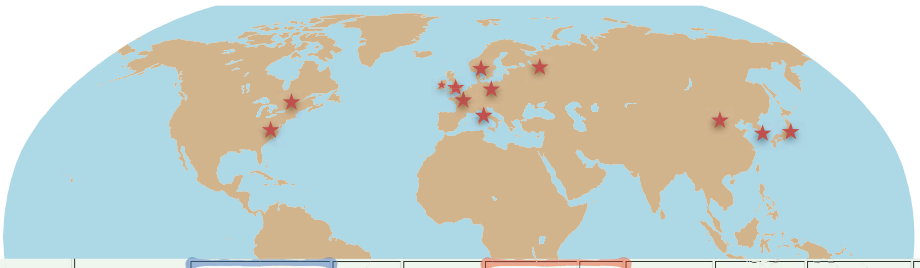
Schematics by NOAA

CMIP5



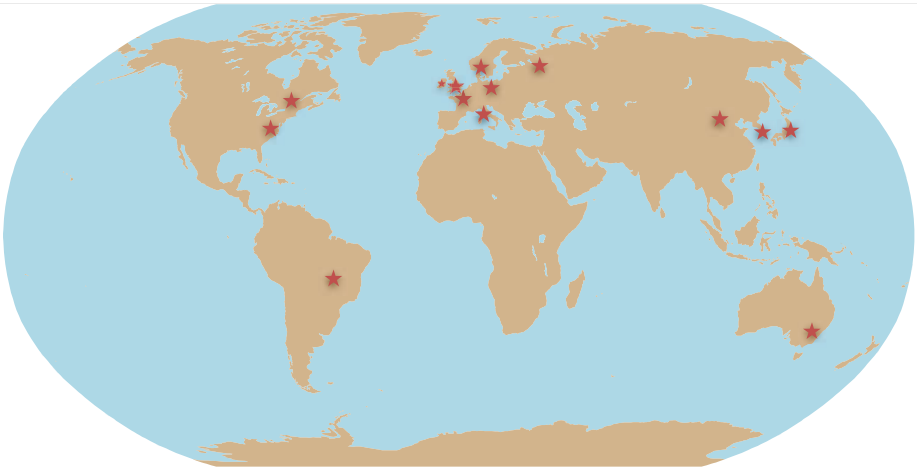
http://www.ipcc-data.org/sim/gcm_monthly/AR5/Reference-Archive.html

CMIP5



NASA/GISS (Goddard Institute for Space Studies) **USA**	NASA-GISS	GISS-E2-H-CC	piControl	-	historical	rcp45	-	esmFdbk2 esmFixClim2	-	-
		GISS-E2-R	piControl	amip	historical historicalExt historicalGHG historicalMisc historicalNat	rcp26 rcp45 rcp60 rcp85	abrupt4xCO2 1pctCO2	-	-	lgm midHolocene past1000
		GISS-E2-R-CC	piControl	-	historical	rcp45	-	esmFdbk2 esmFixClim2	-	-
National Center for Atmospheric Research **USA**	NCAR NSF-DOE-NCAR	CCSM4 (Journal)	piControl	amip amip4K amip4xCO2 amipFuture	historical historicalGHG historicalMisc historicalNat	rcp26 rcp45 rcp60 rcp85	abrupt4xCO2 1pctCO2	-	sstClim sstClim4xCO2	lgm midHolocene past1000
		CESM1(BGC) (Journal)	piControl	-	historical	rcp45 rcp85	1pctCO2	esmControl esmFdbk1 esmFdbk2 esmFixClim1 esmFixClim2 esmHistorical esmrcp85	-	-
		CESM1(CAM5) (Journal)	piControl	amip amip4xCO2 amipFuture	historical	rcp26 rcp45 rcp60 rcp85	1pctCO2	-	-	-
		CESM1(CAM5.1,FV2) (Journal)	piControl	-	historical historicalGHG historicalMisc historicalNat	-	abrupt4xCO2 1pctCO2	-	-	-
		CESM1(FASTCHEM)	piControl	-	historical	-	-	-	-	-
		CESM1(WACCM) (Journal)	piControl	-	historical	rcp26 rcp45 rcp85	-	-	-	-
Bjerknes Centre for Climate Research, Norwegian Meteorological Institute **Norway**	NCC, NMI	NorESM1-M	piControl	amip amip4xCO2	historical historicalExt historicalGHG historicalMisc historicalNat	rcp26 rcp45 rcp60 rcp85	abrupt4xCO2 1pctCO2	-	sst2030 sstClim sstClim4xCO2 sstClimAerosol	-
		NorESM1-ME	piControl	-	historical	rcp26 rcp45 rcp60	1pctCO2	esmControl esmFdbk1 esmFixClim1	-	-

CMIP5



Scenarios

Historical (1850->2005)

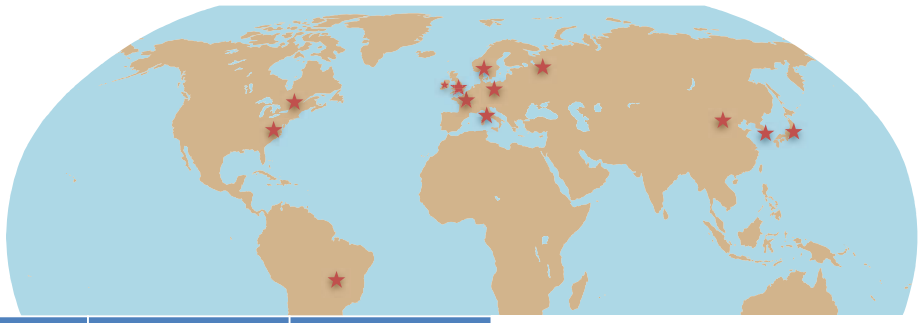
Future Projections (2006->2300)

Representative Concentration Pathway:

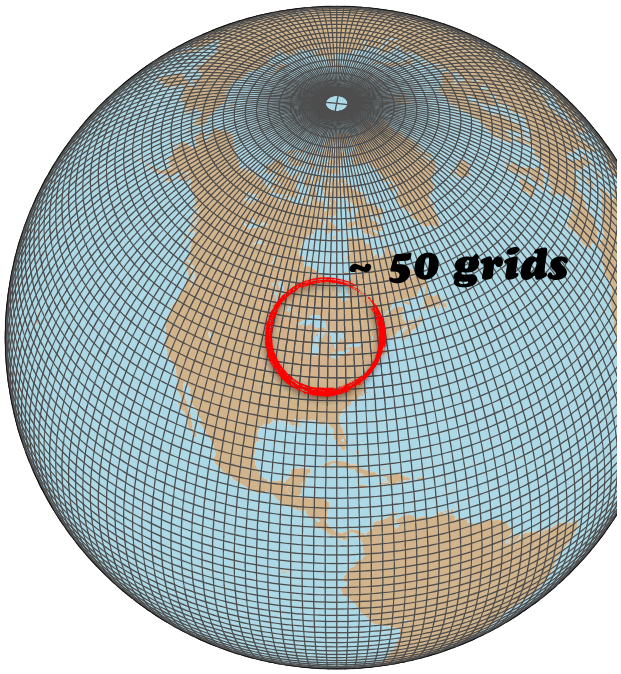
RCP2.6; RCP4.5; RCP6.0; RCP8.5

(The four RCPs, RCP2.6, RCP4.5, RCP6, and RCP8.5, are named after a possible range of radiative forcing values in the year 2100 relative to pre-industrial values (+2.6, +4.5, +6.0, and +8.5 W/m^2, respectively)

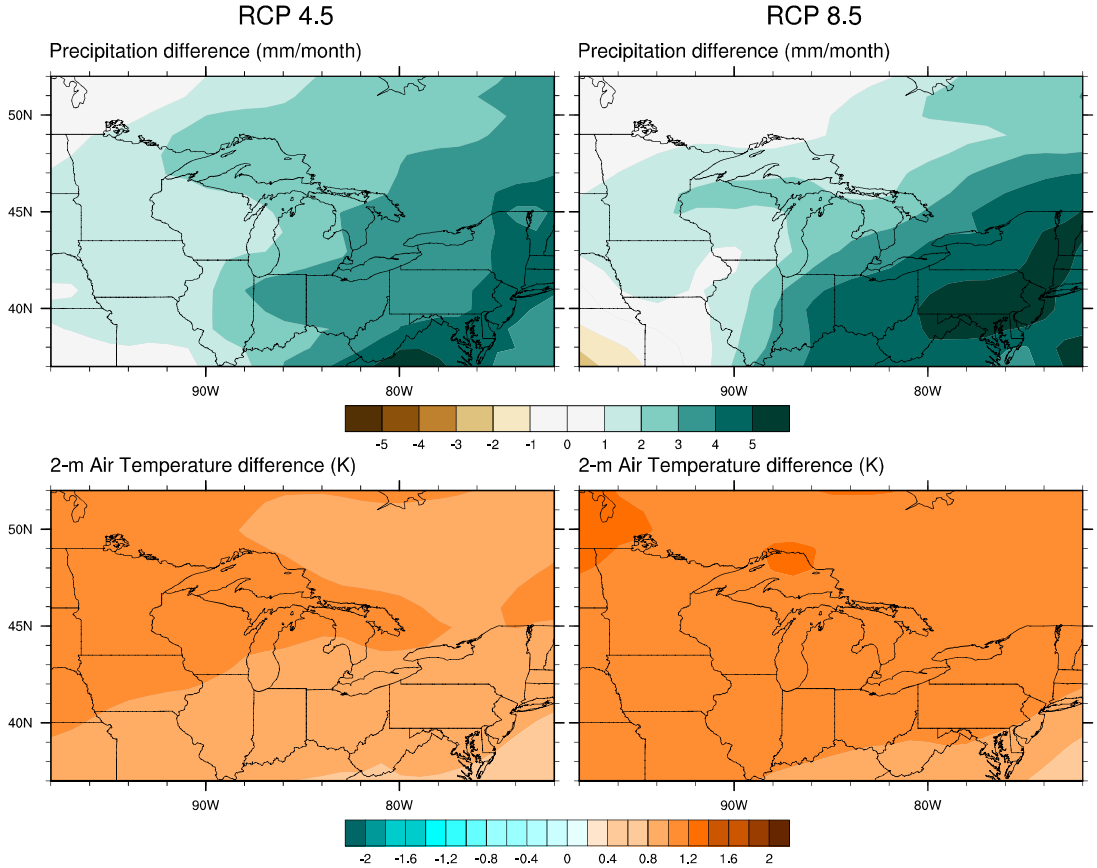
CMIP5



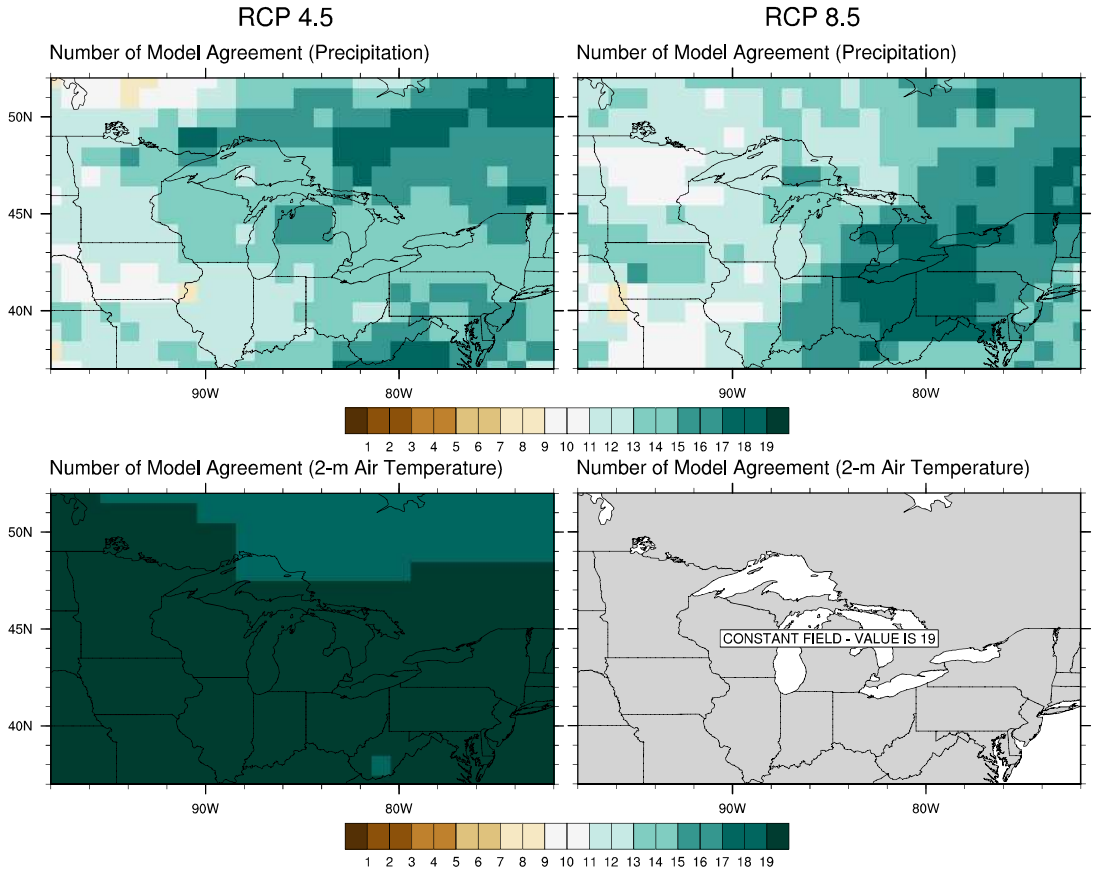
Model	Lat x Lon	km x km
Bcc-CSM1.1	2.8 x 2.8	~ 300
CanESM2	2.8 x 2.8	~ 300
CCSM4	1.25 x 0.94	~ 120
CNRM-CM5	1.4 x 1.4	~ 150
CSIRO-MK3.6	1.8 x 1.8	~ 190
GFDL-CM3	2.5 x 2.0	~ 240
GFDL-ESM2G	2.5 x 2.0	~ 240
GFDL-ESM2M	2.5 x 2.0	~ 240
GISS-E2R	2.5 x 2.0	~ 240
HADGEM2-CC	1.875 x 1.25	~ 170
HADGEM2-ES	1.875 x 1.25	~ 170
INM-CM4	2.0 x 1.5	~ 190
IPSL-CM5A-LR	3.75 x 1.8	~ 300
IPSL-CM5A-MR	2.5 x 1.25	~ 200
MIROC5	1.4 x 1.4	~ 150
MIROC-ESM	2.8 x 2.8	~ 300
MPI-ESM-LR	1.9 x 1.9	~ 205
MRI-CGCM3	1.1 x 1.1	~ 120
NorESM1-M	2.5 x 1.9	~ 240



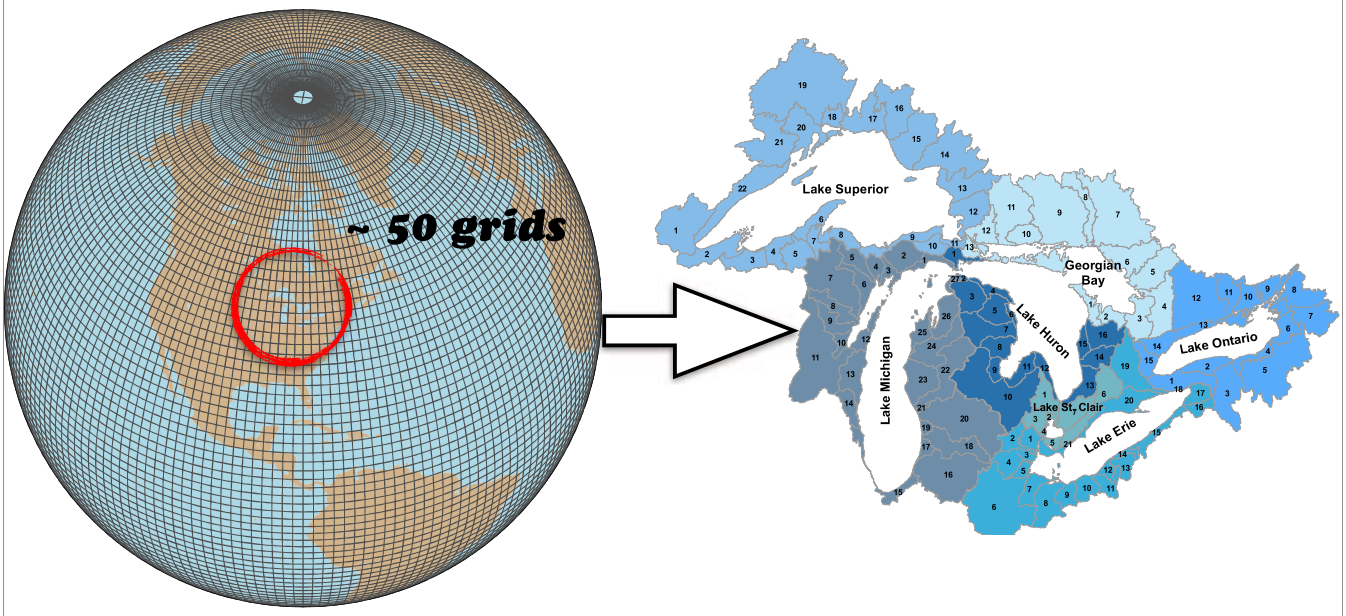
CMIP5 19 Model Ensembles: 2018-2027 minus 1979-2013
Projected Changes



CMIP5 19 Model Ensembles: 2018-2027 minus 1979-2013
Model Agreement on Projected Changes



CMIP5 GLSHyFS



Spatial Downscaling **Temporal Disaggregation** **Bias Correction**

GLSHyFS-CMIP5

Monthly Raw CMIP5
Monthly Observation
(1° x 1°)

Bias Correction → Quantile Delta Mapping

Monthly Bias-Corrected CMIP5
(1° x 1°)

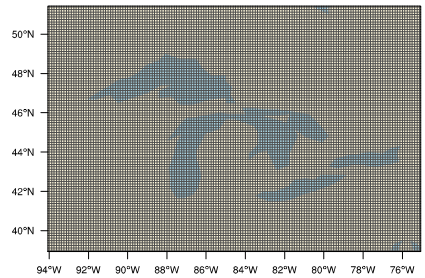
Spatial Interpolation

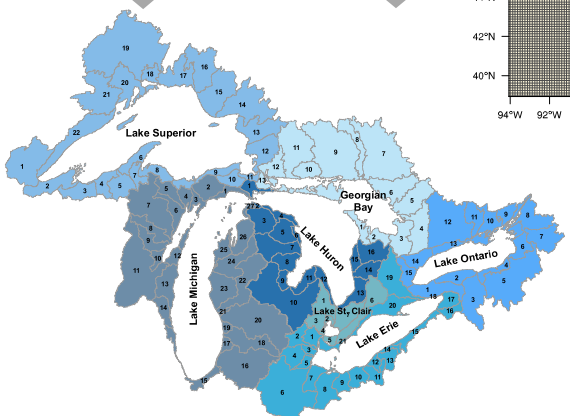
Monthly Bias-Corrected CMIP5
(0.125° x 0.125°) → Resolution of gridded historical reference data

Temporal Disaggregation ← Employing Historical Daily Patterns

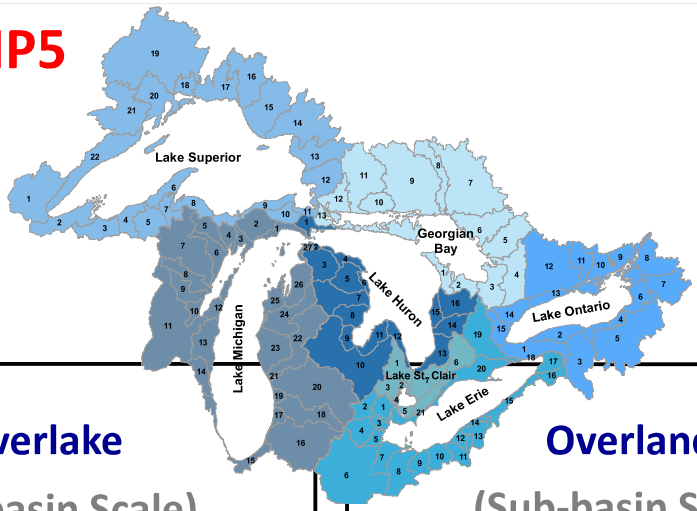
Daily Bias-Corrected CMIP5
(0.125° x 0.125°)

Thiessen Polygon Interpolation





GLSHyFS-CMIP5



Overlake

(Sub-basin Scale)

Bias-Corrected Daily CMIP5

Precipitation, Tmean, Wind, Dew point T, Cloud Cover

Overland

(Sub-basin Scale)

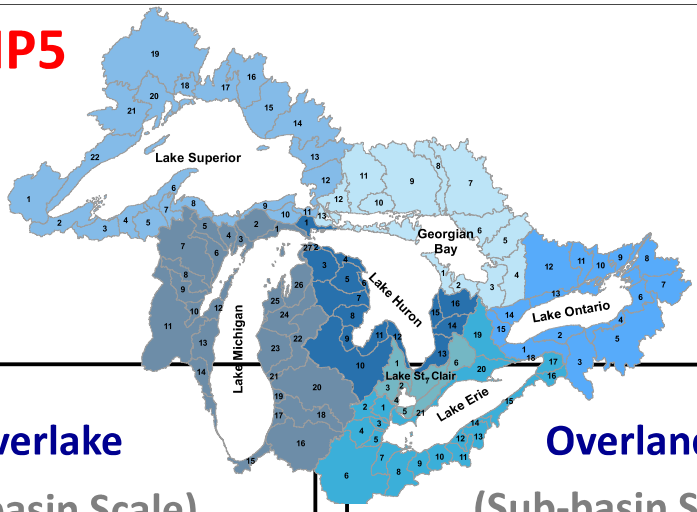
Bias-Corrected Daily CMIP5

Precipitation, Tmin, Tmax

Large Lake Thermodynamic Model → Evaporation

Large Basin Runoff Model → Runoff

GLSHyFS-CMIP5



Overlake

(Sub-basin Scale)

Bias-Corrected Daily CMIP5

Precipitation, Tmean, Wind, Dew point T, Radiation

Surface Pressure
Tmean
Specific Humidity

Overland

(Sub-basin Scale)

Bias-Corrected Daily CMIP5

Precipitation, Tmin, Tmax

Large Lake Thermodynamic Model → Evaporation

Large Basin Runoff Model → Runoff

GLSHyFS-CMIP5

Monthly Raw CMIP5
Monthly Observation
(1° x 1°)

Bias Correction → Quantile Delta Mapping

Monthly Bias-Corrected CMIP5
(1° x 1°)

Spatial Interpolation

Monthly Bias-Corrected CMIP5
(0.125° x 0.125°) → Resolution of gridded historical reference data

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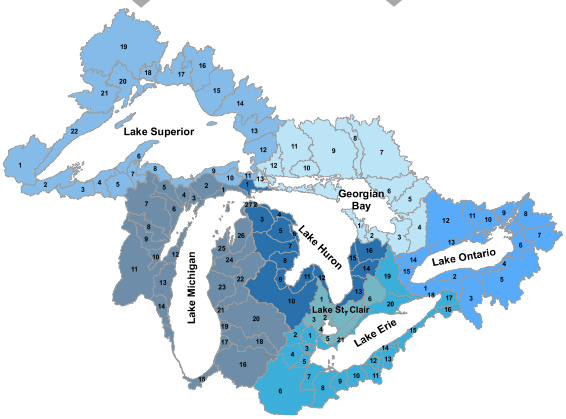
(0.125° x 0.125°)

Thiessen Polygon Interpolation



GLSHyFS-CMIP5

Monthly Raw CMIP5
Monthly Observation
(1° x 1°)

Bias Correction → Quantile Delta Mapping

Monthly Bias-Corrected CMIP5
(1° x 1°)

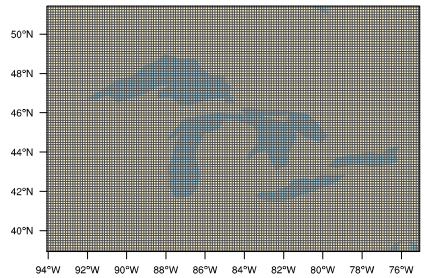
Spatial Interpolation

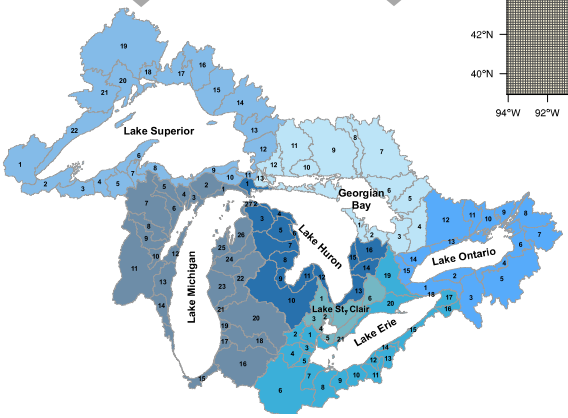
Monthly Bias-Corrected CMIP5
(0.125° x 0.125°) → Resolution of gridded historical reference data

Temporal Disaggregation ← Employing Historical Daily Patterns

Daily Bias-Corrected CMIP5
(0.125° x 0.125°)

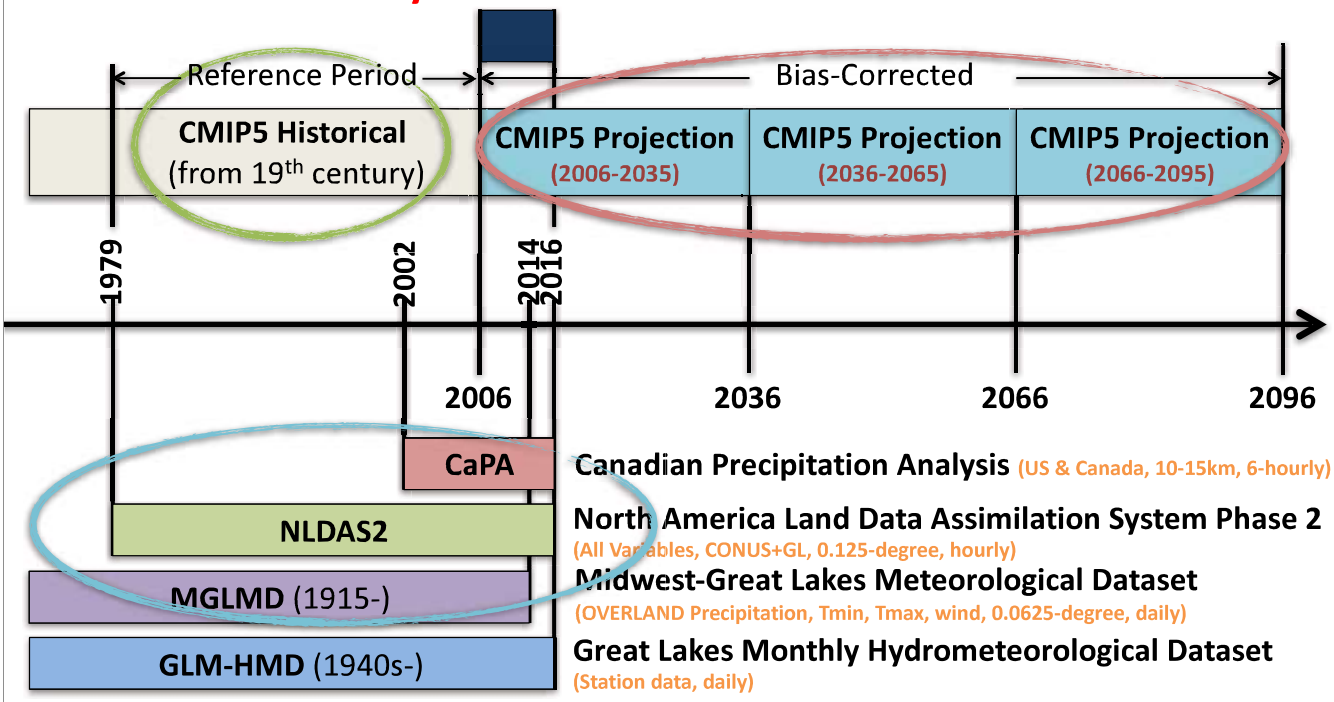
Thiessen Polygon Interpolation





For each grid at 1-degree resolution
For all the variables at monthly timestep

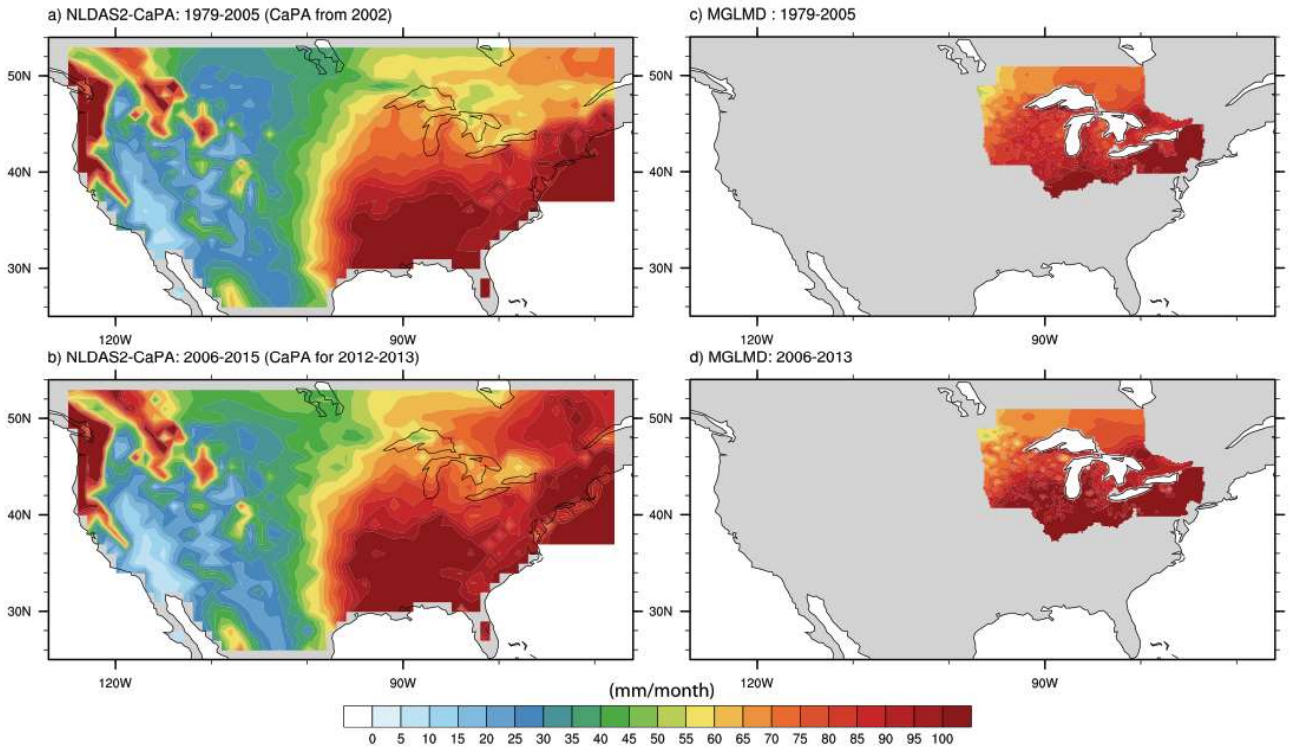
10-year Validation



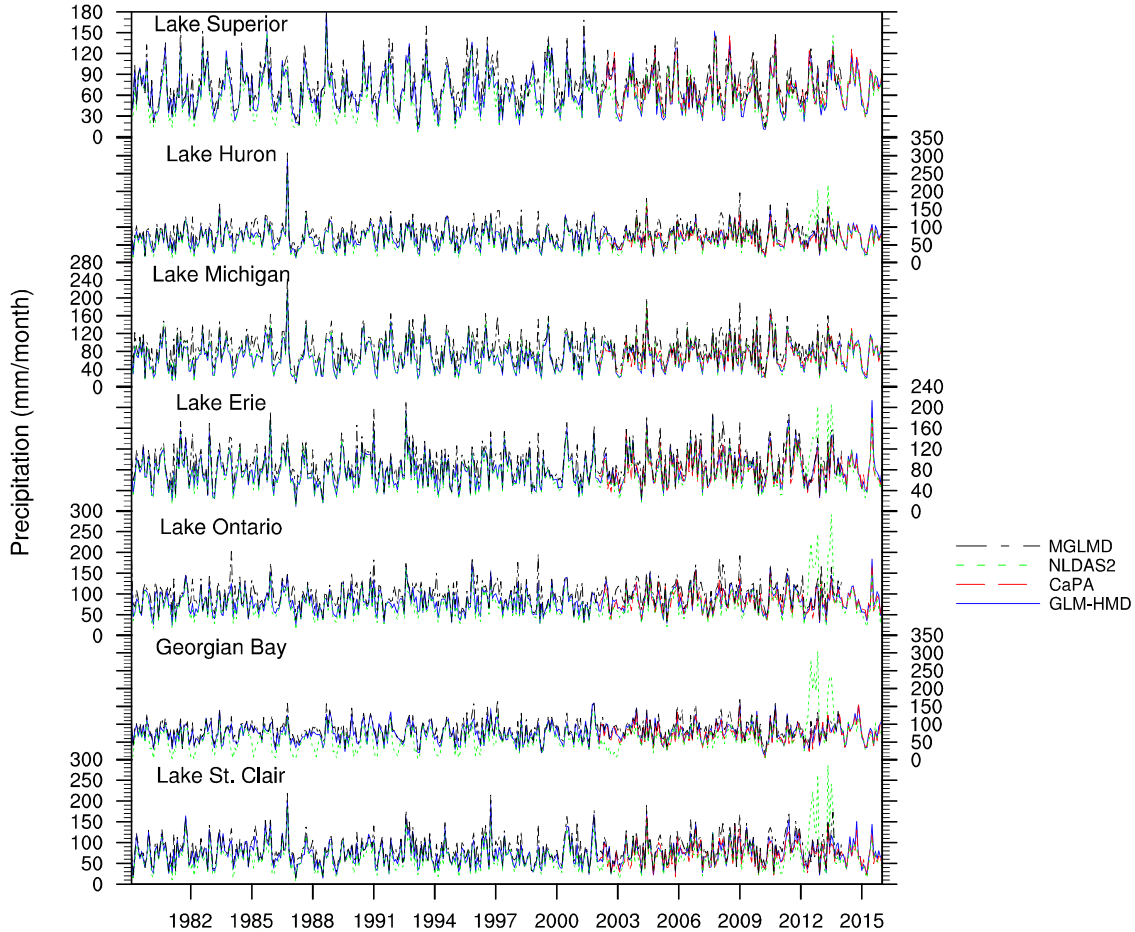
Precipitation

NLDAS2-CaPA

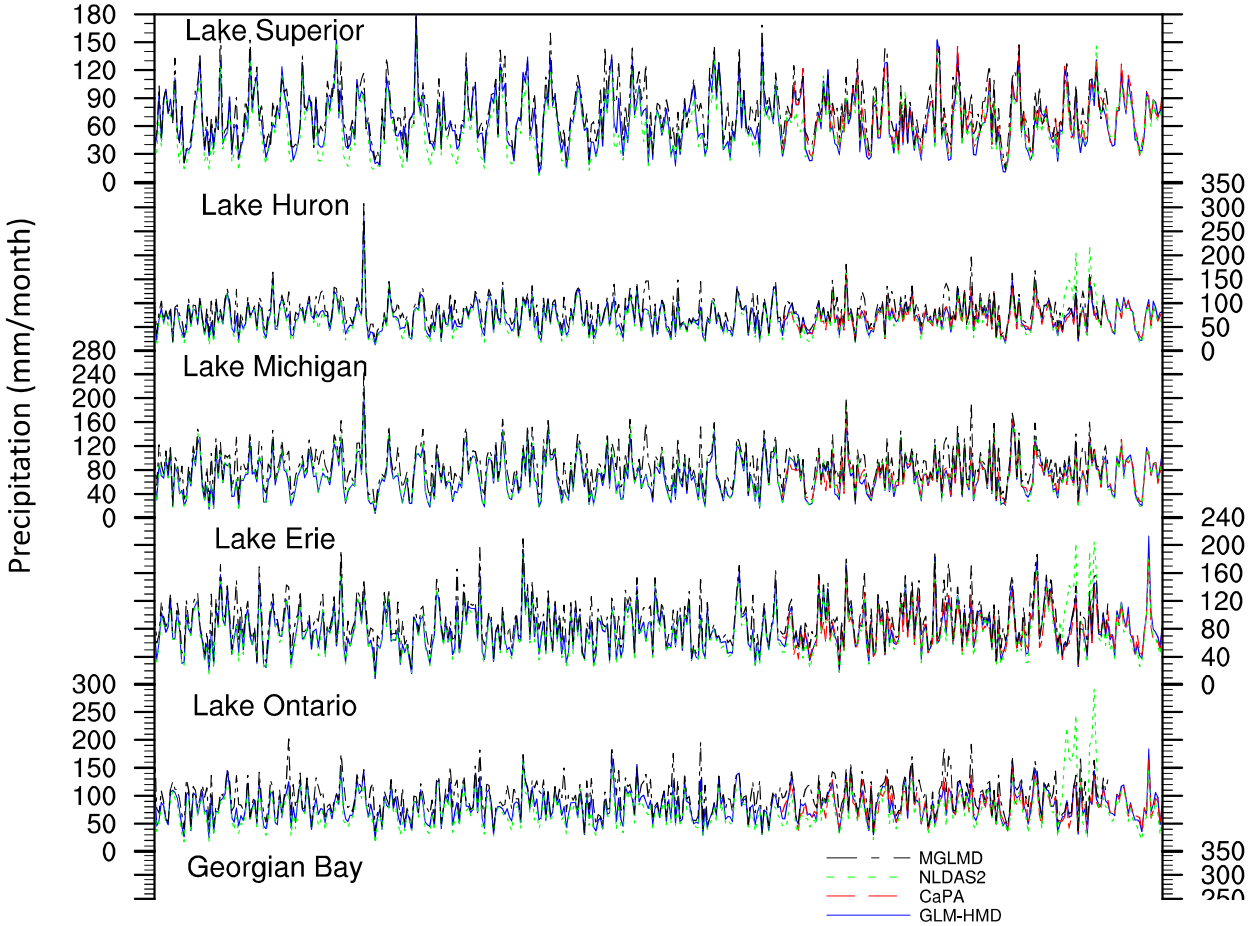
MGLMD



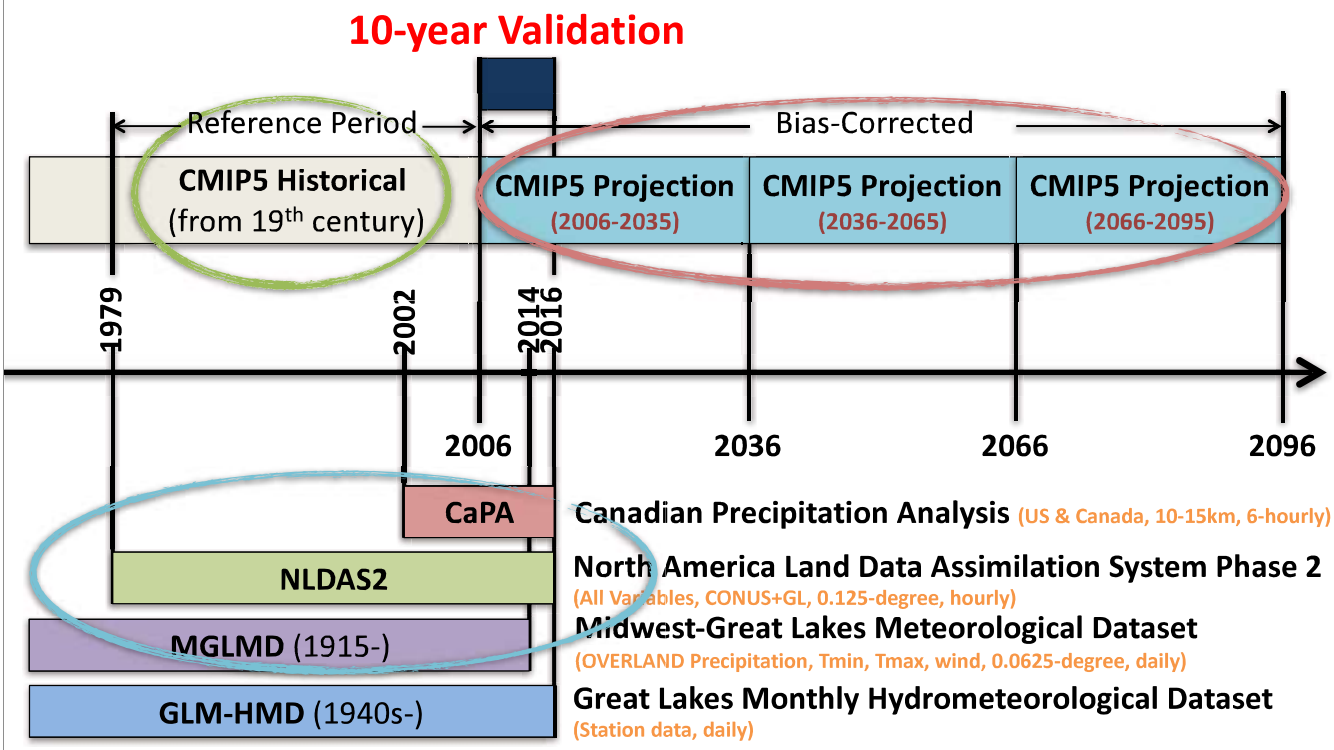
1979-2015 Precipitation: CaPA, NLDAS2, MGLMD, GLM-HMD



1979-2015 Precipitation: CaPA, NLDAS2, MGLMD, GLM-HMD



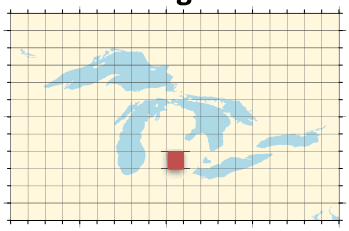
For each grid at 1-degree resolution
For all the variables at monthly timestep



Bias-Correction

Quantile Delta Mapping (Cannon et al. 2015)

1-degree



Monthly: Precipitation
Temperature
Radiation
Wind
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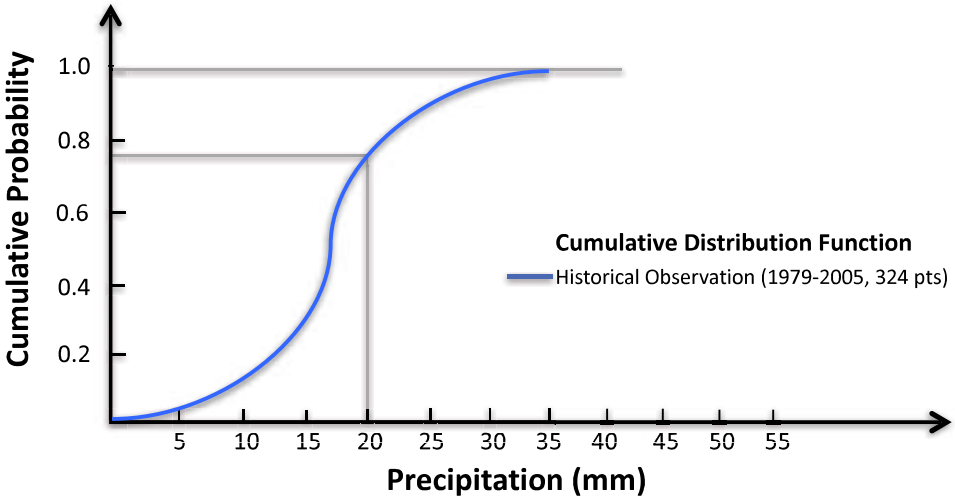
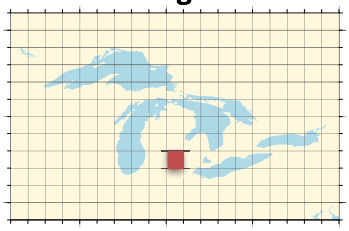


Bias-Correction

Quantile Delta Mapping (Cannon et al. 2015)

1-degree



Monthly: Precipitation
Temperature
Radiation
Wind
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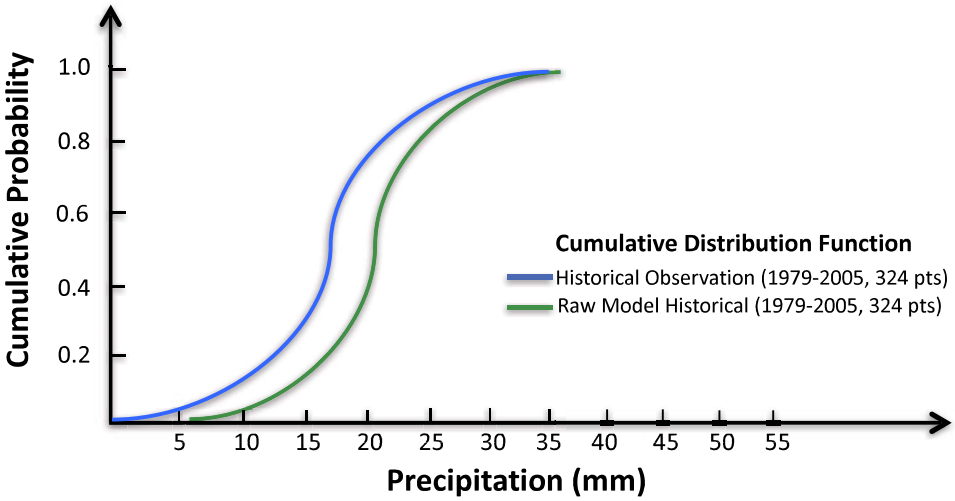
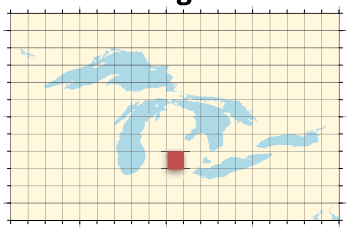


Bias-Correction

Quantile Delta Mapping (Cannon et al. 2015)

1-degree



Monthly: Precipitation
Temperature
Radiation
Wind
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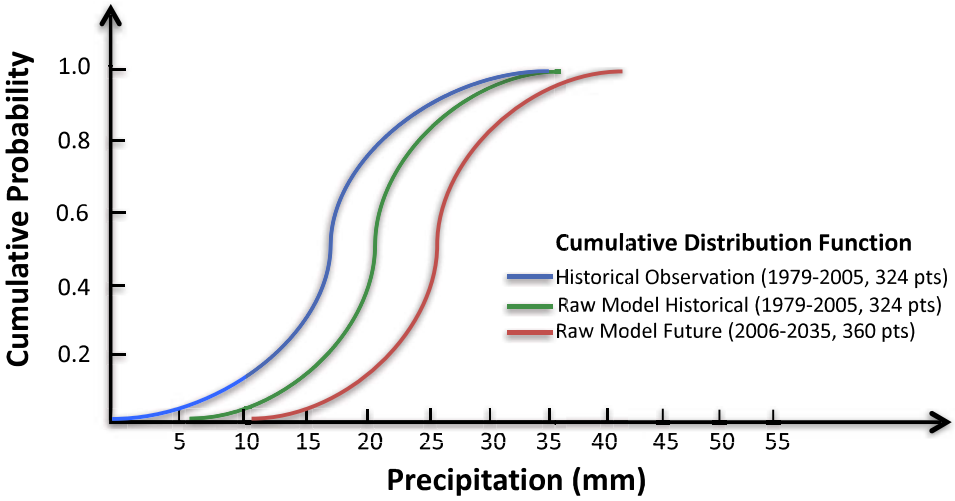
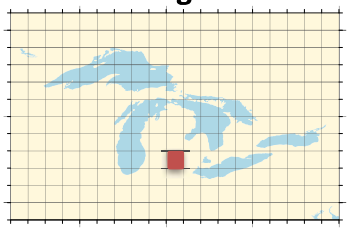


Bias-Correction

Quantile Delta Mapping (Cannon et al. 2015)

1-degree



Monthly: Precipitation
Temperature
Radiation
Wind
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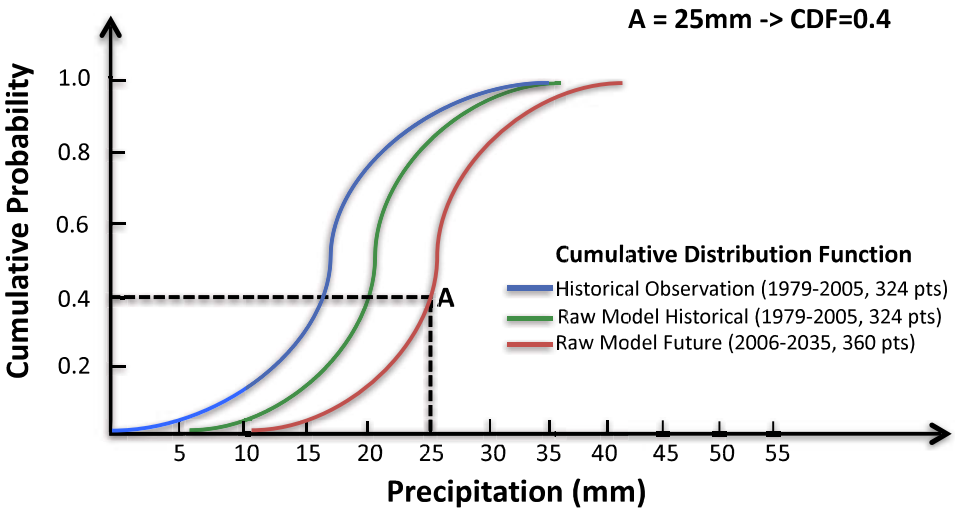
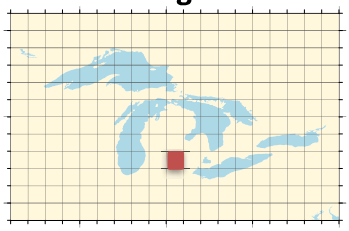


Bias-Correction

Quantile Delta Mapping (Cannon et al. 2015)

1-degree



Monthly: Precipitation
Temperature
Radiation
Wind
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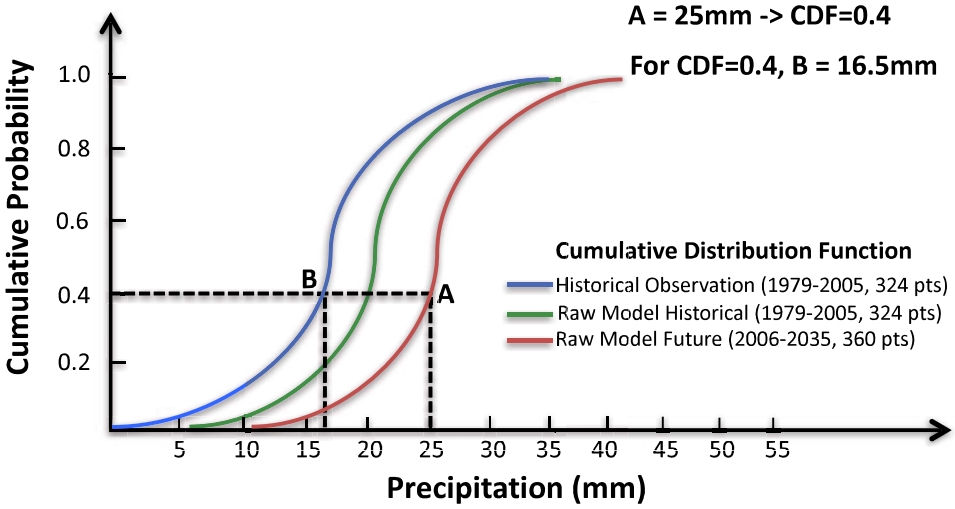
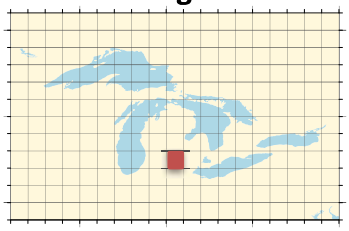


Bias-Correction

Quantile Delta Mapping (Cannon et al. 2015)

1-degree



Monthly: Precipitation
Temperature
Radiation
Wind
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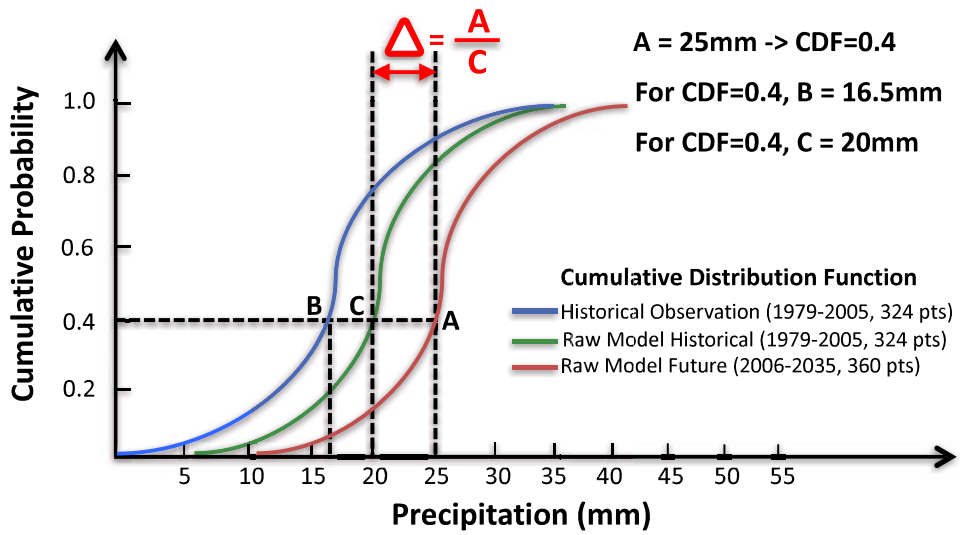
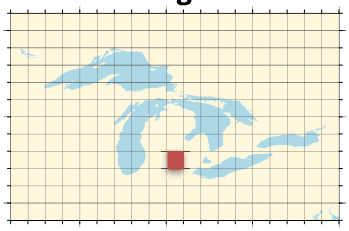


Bias-Correction

Quantile Delta Mapping (Cannon et al. 2015)

1-degree



Monthly: Precipitation
Temperature
Radiation
Wind
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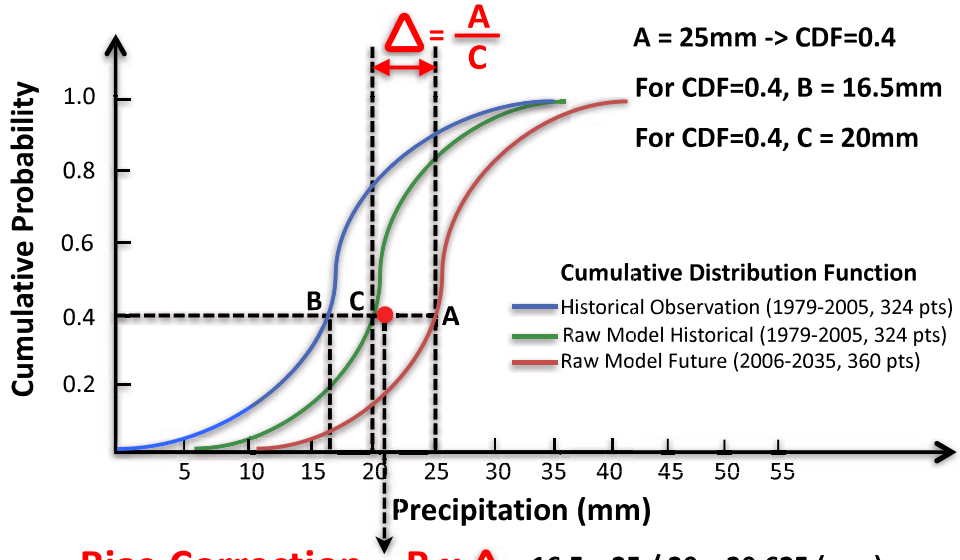


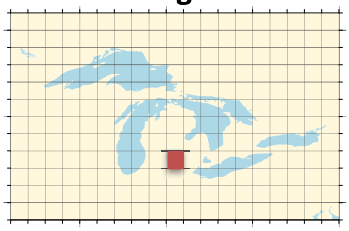
Bias-Correction = B x Δ = 16.5 x 25 / 20 = 20.625 (mm)

Applying to: Precipitation
Temperature (mean, minimum and maximum, Δ = A-C)
Radiation (longwave, shortwave)
Wind speed
Surface pressure
Specific humidity

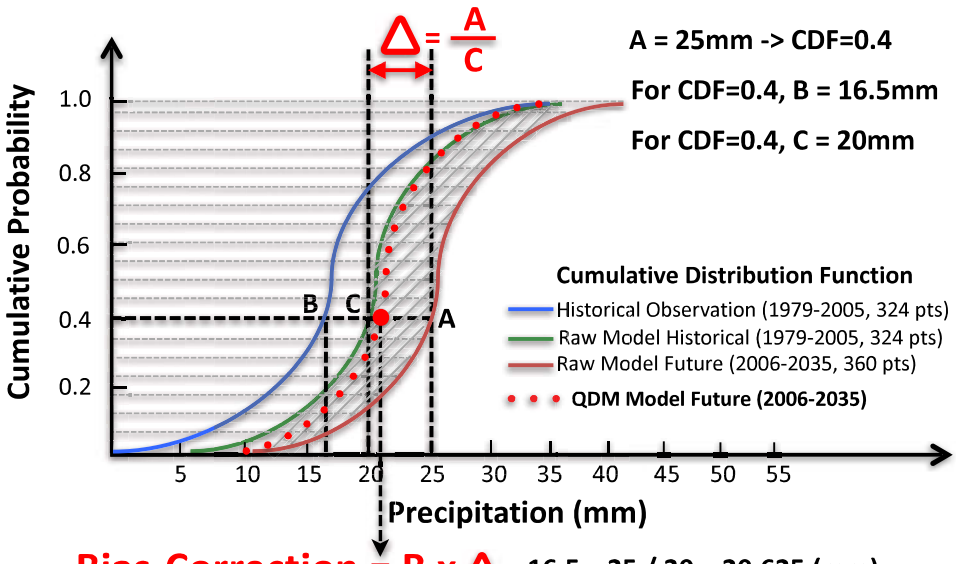
Bias-Correction

Quantile Delta Mapping (Cannon et al. 2015)

1-degree



Monthly: Precipitation
Temperature
Radiation
Wind
.
.
.



Bias-Correction = B x Δ = 16.5 x 25 / 20 = 20.625 (mm)

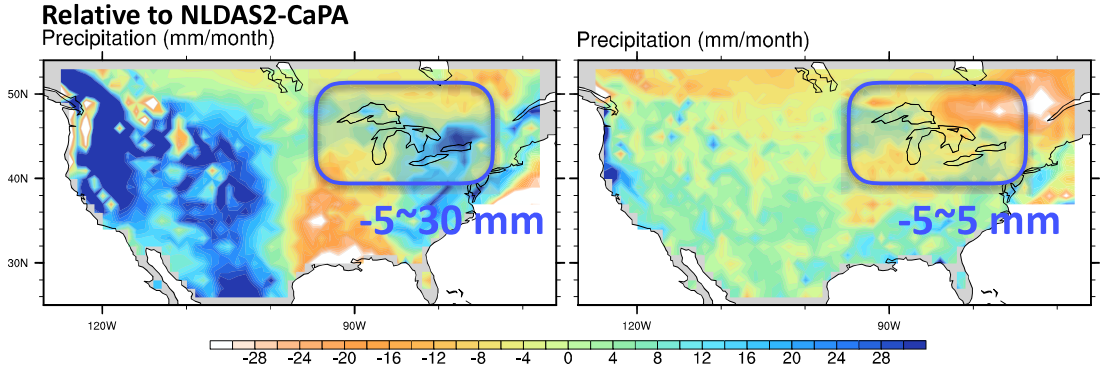
Applying to: Precipitation
Temperature (mean, minimum and maximum, Δ = A-C)
Radiation (longwave, shortwave)
Wind speed
Surface pressure
Specific humidity

Precipitation: 2006-2015

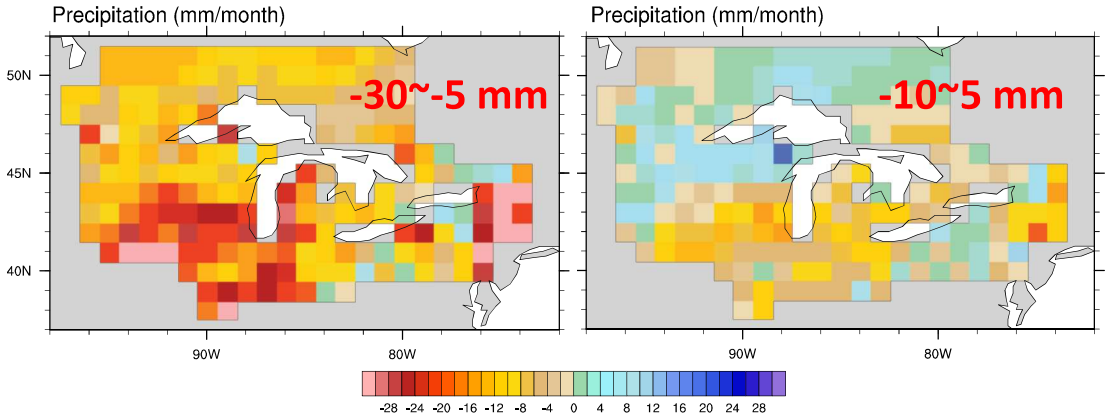
Raw Bias

QDM Bias

Relative to NLDAS2-CaPA



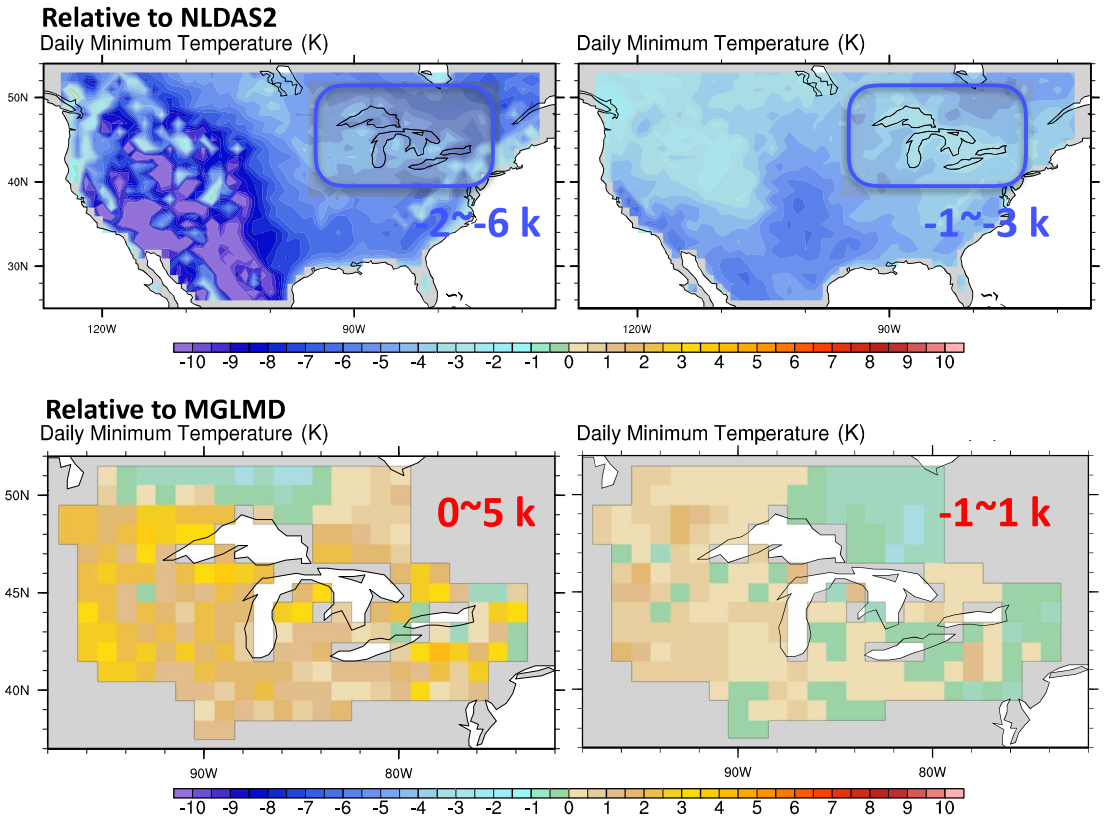
Relative to MGLMD



Daily Minimum Temperature: 2006-2015

Raw Bias

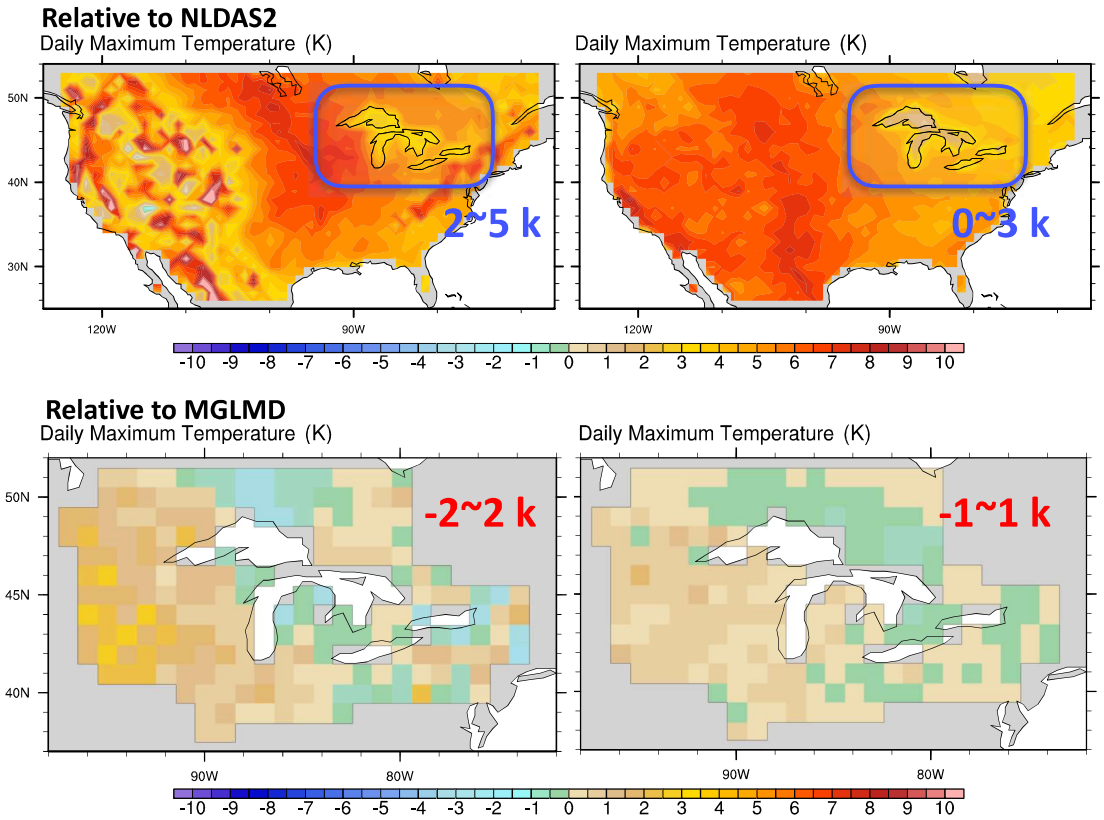
QDM Bias



Daily Maximum Temperature: 2006-2015

Raw Bias

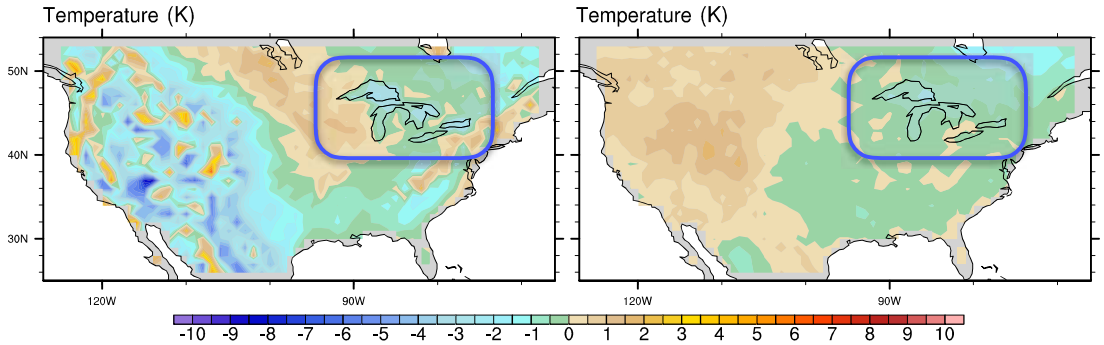
QDM Bias



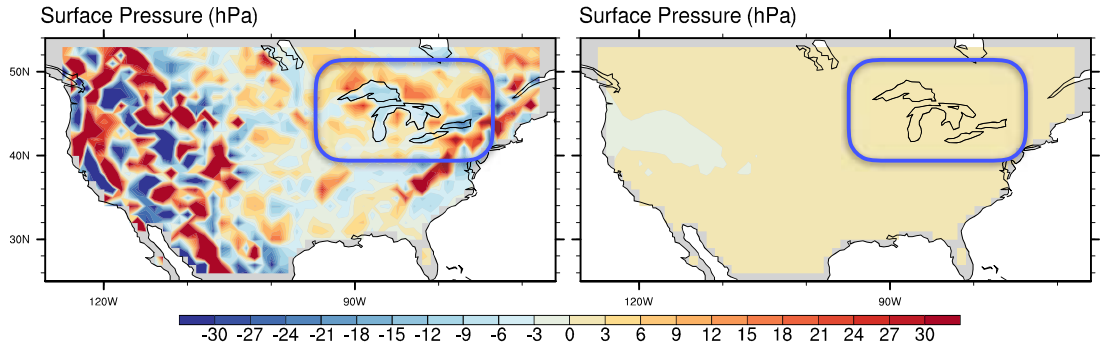
Temperature and Surface Pressure: 2006-2015

Raw Bias | QDM Bias

Relative to NLDAS2



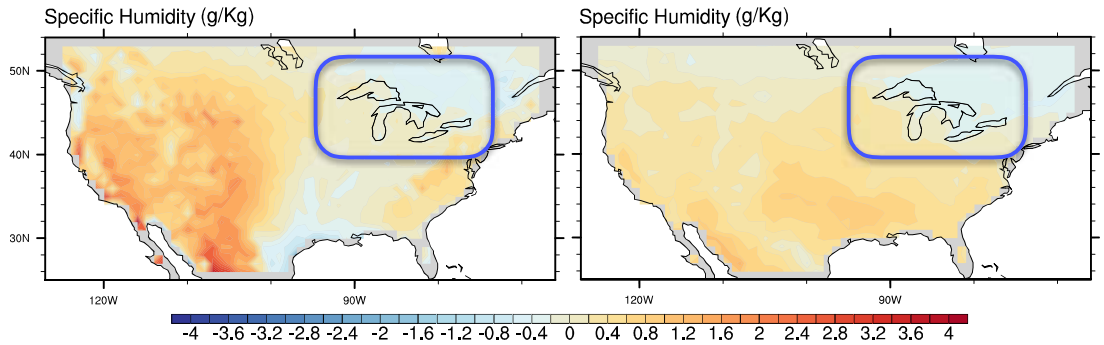
Relative to NLDAS2



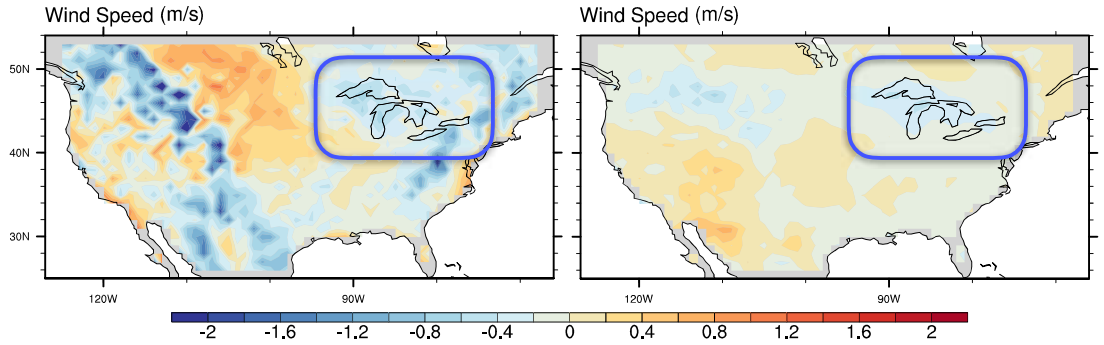
Specific Humidity and Wind Speed: 2006-2015

Raw Bias | QDM Bias

Relative to NLDAS2



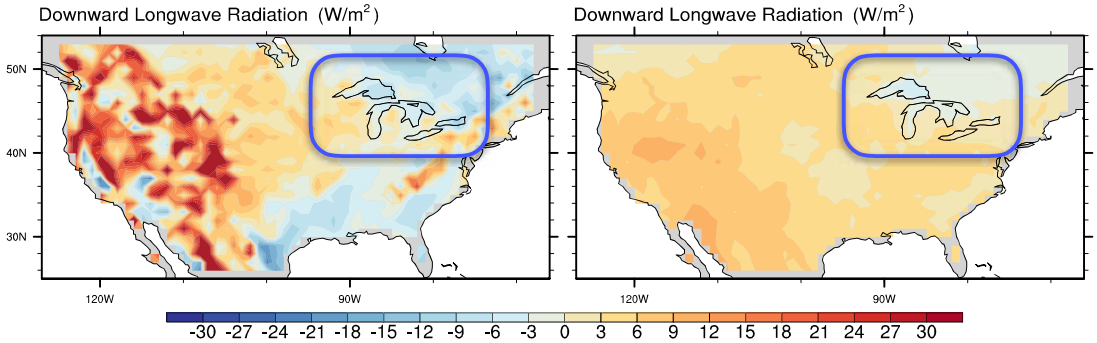
Relative to NLDAS2



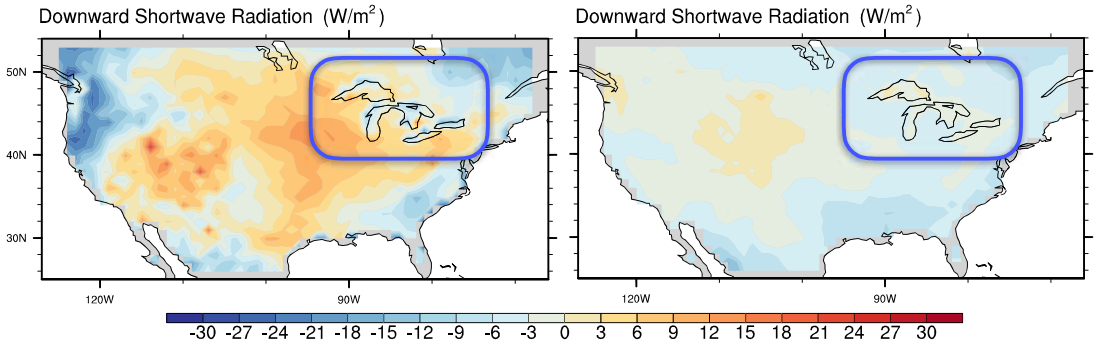
Downward Longwave/Shortwave Radiation: 2006-2015

Raw Bias | QDM Bias

Relative to NLDAS2

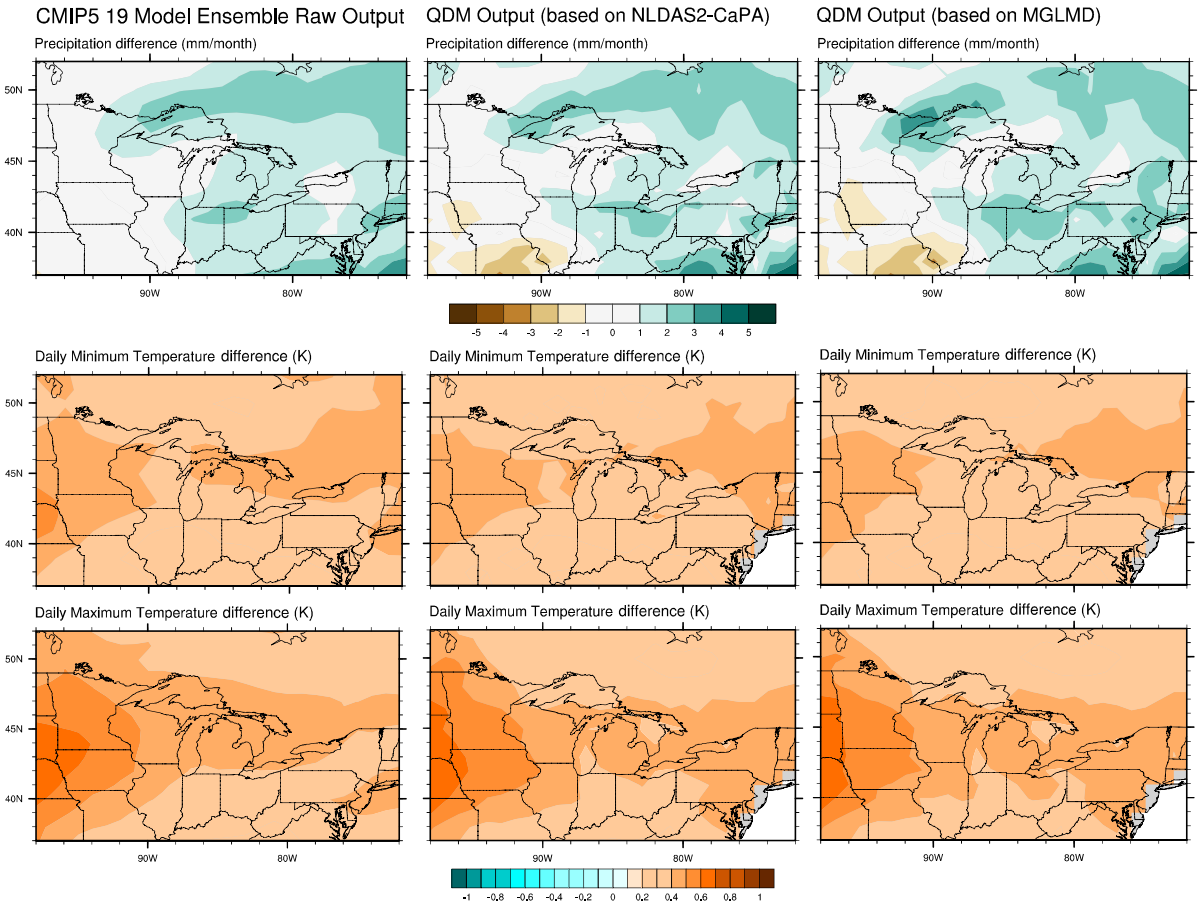


Relative to NLDAS2

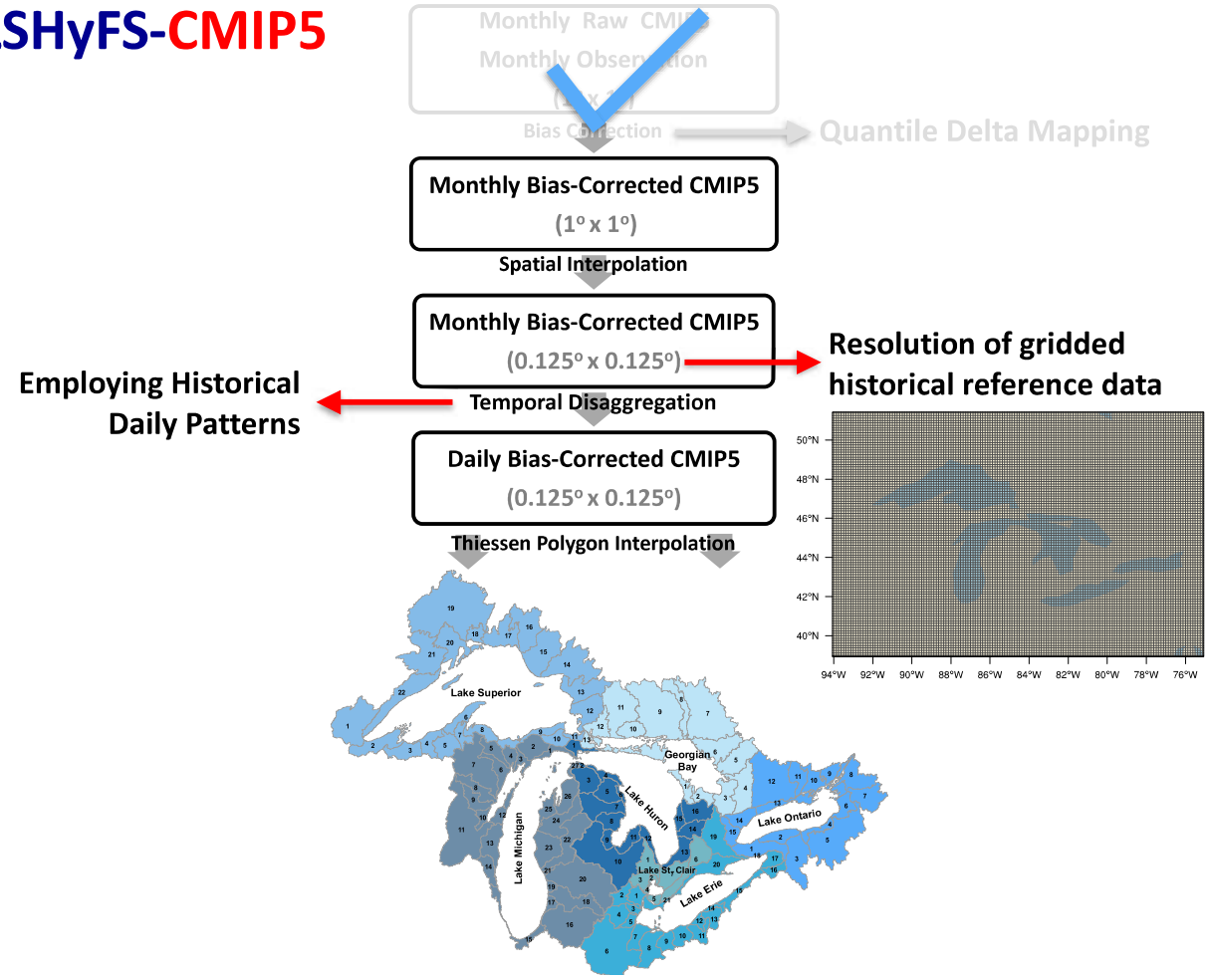


How well have the climate change signals been preserved?

Mean of 2018-2027 minus Mean of 2008-2017

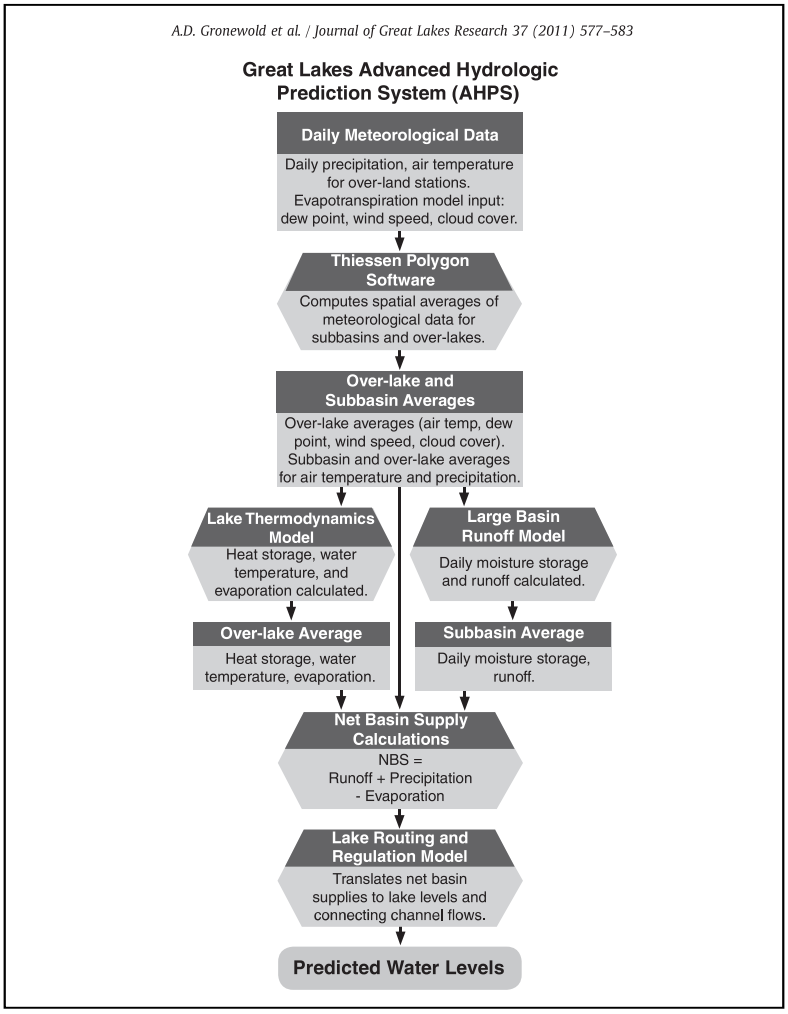


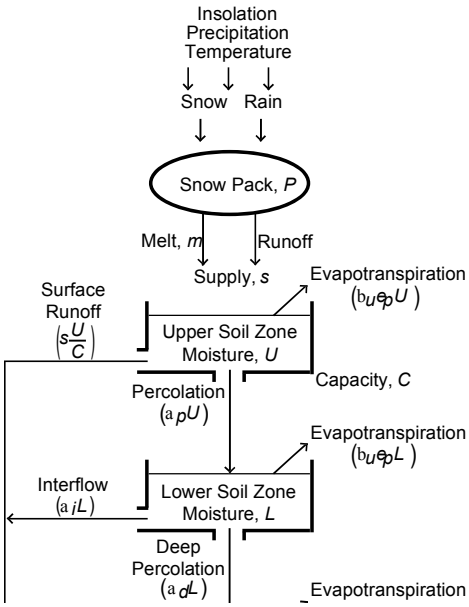
GLSHyFS-CMIP5



Outline

- Goals
- Background
- Model development
  - Meteorological forcings
  - Hydrological models
  - Water supply forecasting systems
  - Routing and regulation models
  - Ensemble processing
- Skill assessment
- Operational implementation
- Future work


Great Lakes Advanced Hydrologic Prediction System (AHPS)
Daily Meteorological Data
Daily precipitation, air temperature for over-land stations. Evapotranspiration model input: dew point, wind speed, cloud cover.
Thiessen Polygon Software
Computes spatial averages of meteorological data for subbasins and over-lakes.
Over-lake and Subbasin Averages
Over-lake averages (air temp, dew point, wind speed, cloud cover). Subbasin and over-lake averages for air temperature and precipitation.
Lake Thermodynamics Model
Heat storage, water temperature, and evaporation calculated.
Large Basin Runoff Model
Daily moisture storage and runoff calculated.
Over-lake Average
Heat storage, water temperature, evaporation.
Subbasin Average
Daily moisture storage, runoff.
Net Basin Supply Calculations
NBS = Runoff + Precipitation - Evaporation
Lake Routing and Regulation Model
Translates net basin supplies to lake levels and connecting channel flows.
Predicted Water Levels


Insolation
Precipitation
Temperature
Snow
Rain
Snow Pack, P
Melt, m
Runoff
Supply, s
Evapotranspiration
Surface Runoff
Upper Soil Zone Moisture, U
Capacity, C
Percolation
Evapotranspiration
Interflow
Lower Soil Zone Moisture, L
Deep Percolation
Evapotranspiration

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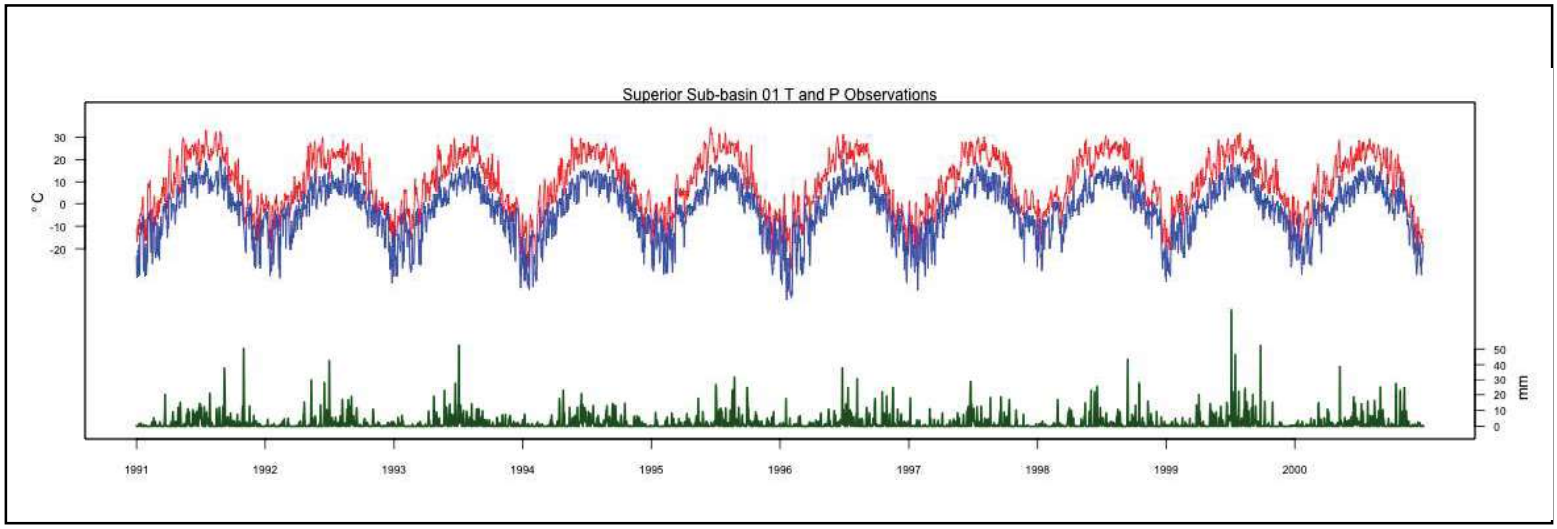
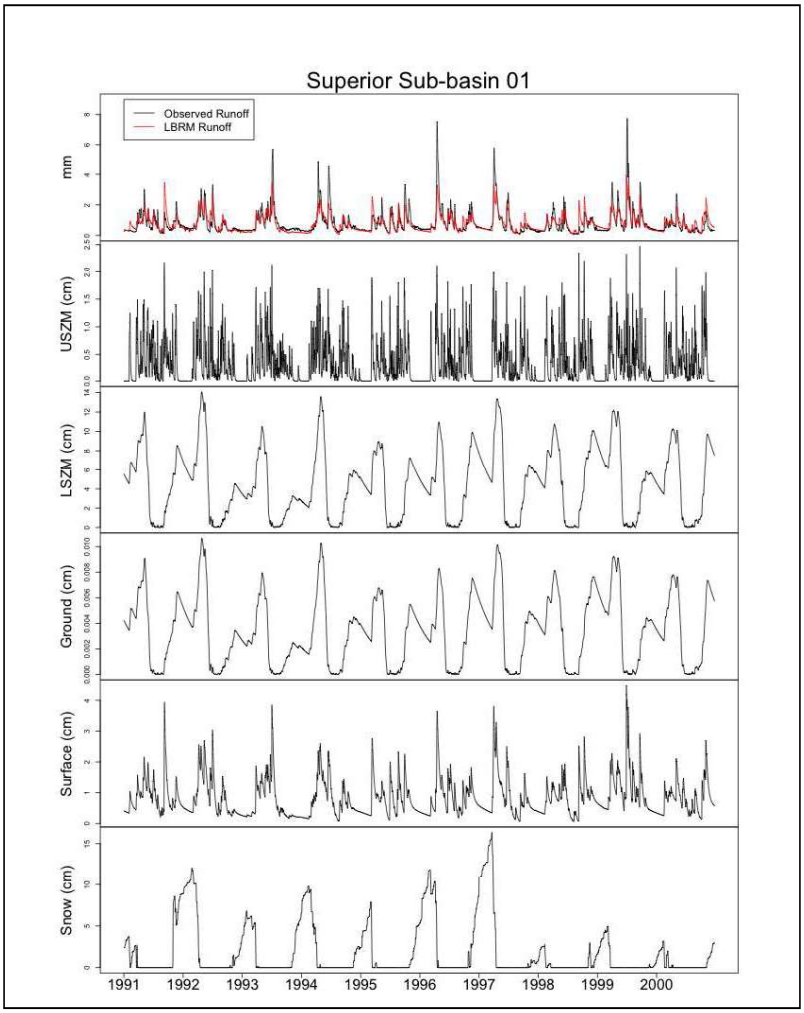
Effects of using air temperature as a proxy for potential evapotranspiration in climate change scenarios of Great Lakes basin hydrology

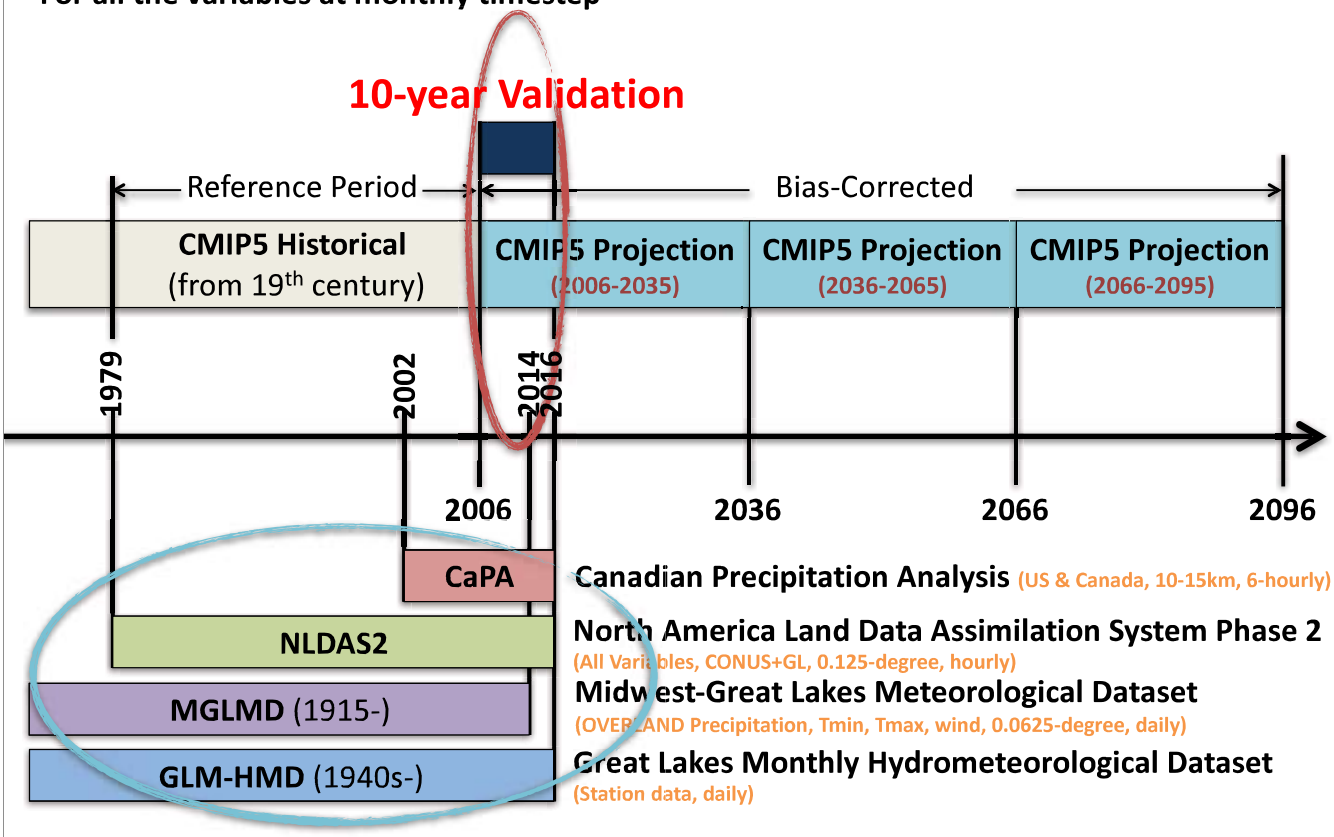
Brent M. Lofgren [a,*], Timothy S. Hunter [a,1], Jessica Wilbarger [b,2]

[a] NOAA/Great Lakes Environmental Research Laboratory, 4840 S. State Rd., Ann Arbor, MI 48108, USA
[b] Cooperative Institute for Limnology and Ecosystems Research, University of Michigan, Ann Arbor, MI, USA


Superior Sub-basin 01 T and P Observations
°C
mm
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000

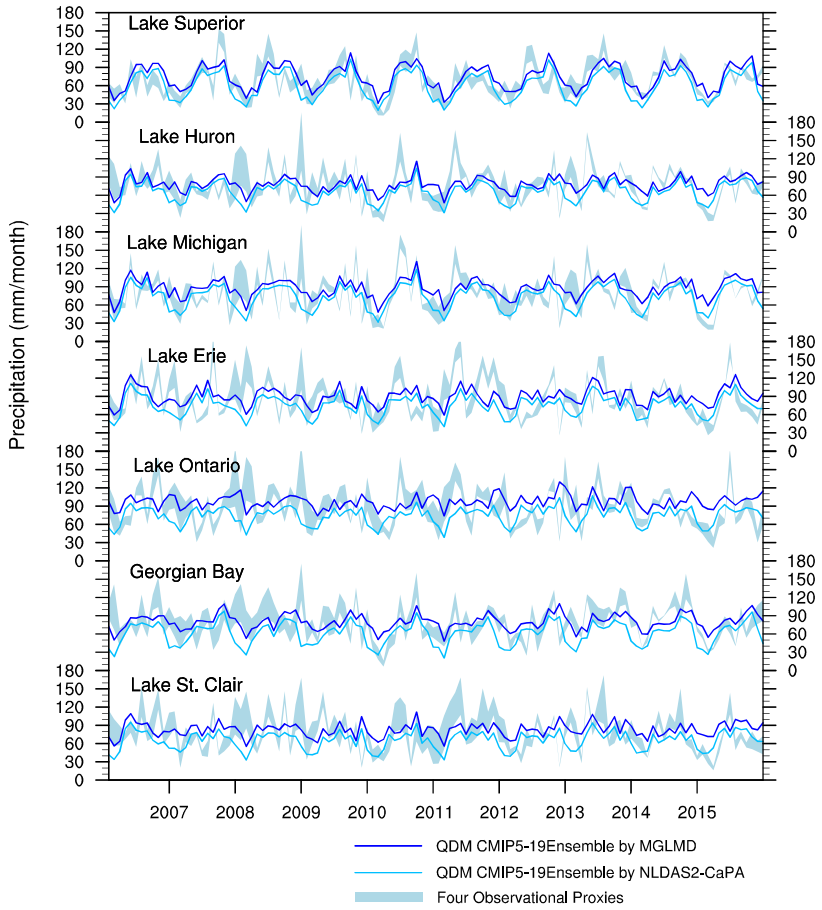

Superior Sub-basin 01
Observed Runoff
LBRM Runoff
mm
USZM (cm)
LSZM (cm)
Ground (cm)
Surface (cm)
Snow (cm)
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000

For each grid at 1-degree resolution
For all the variables at monthly timestep



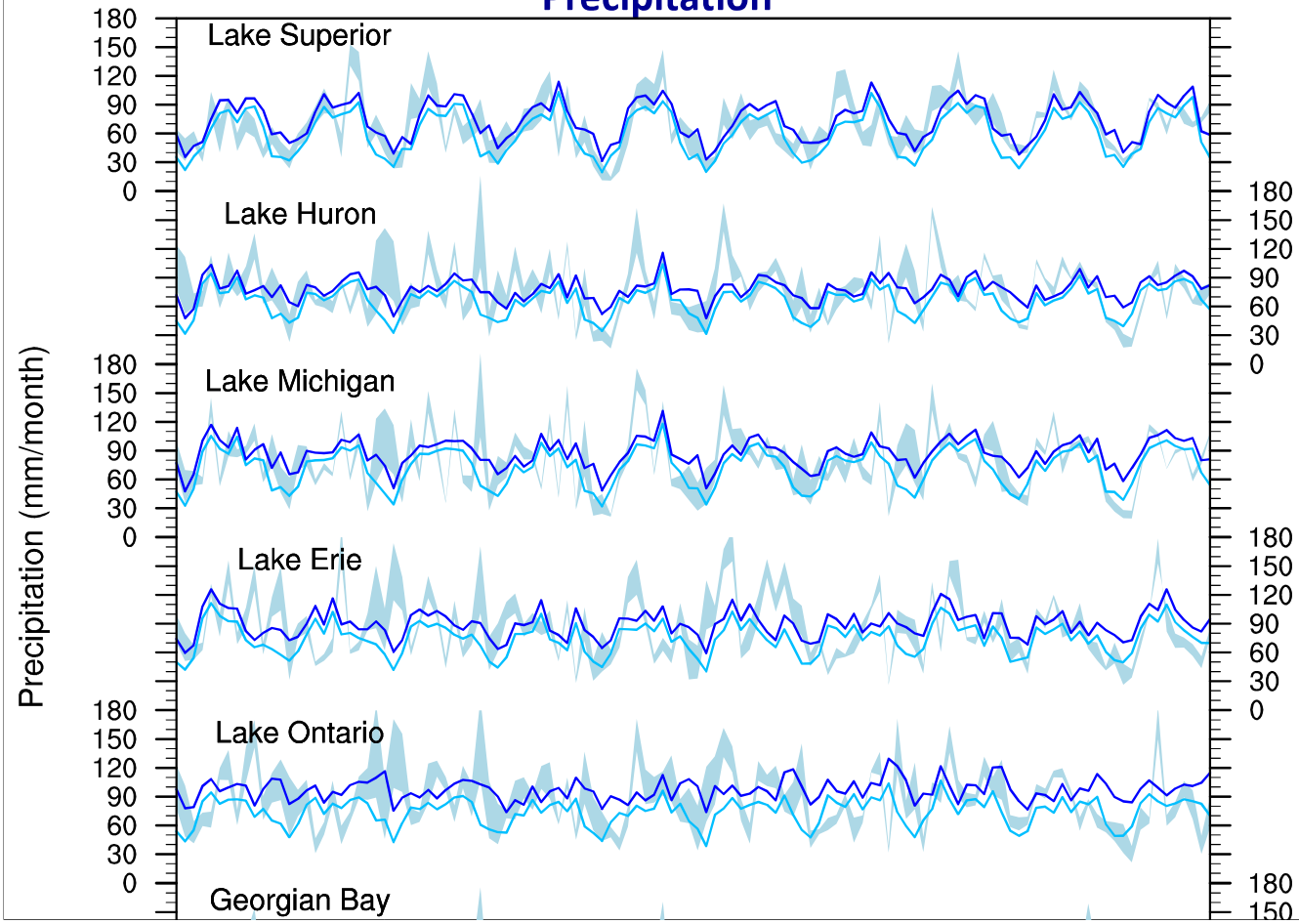
LBRM: 2006-2015

Precipitation



LBRM: 2006-2015

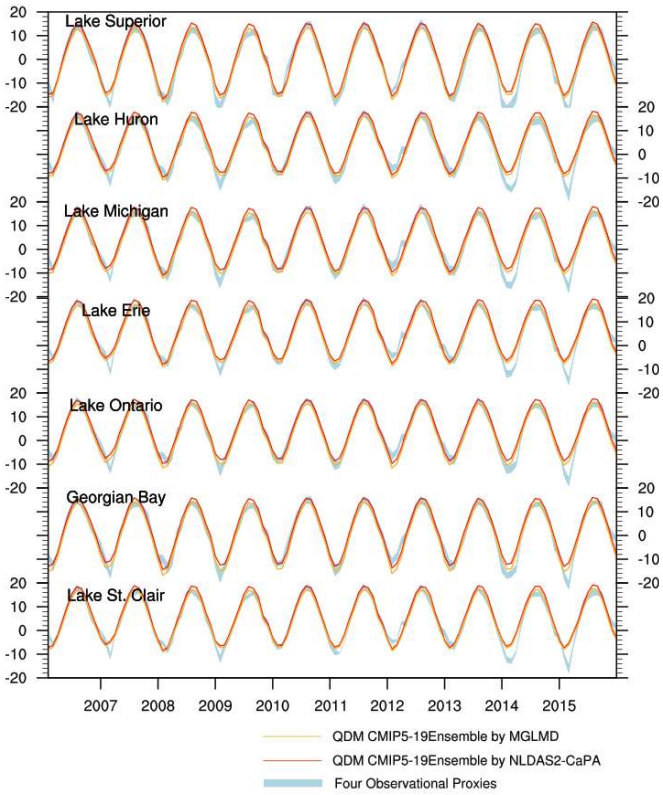
Precipitation



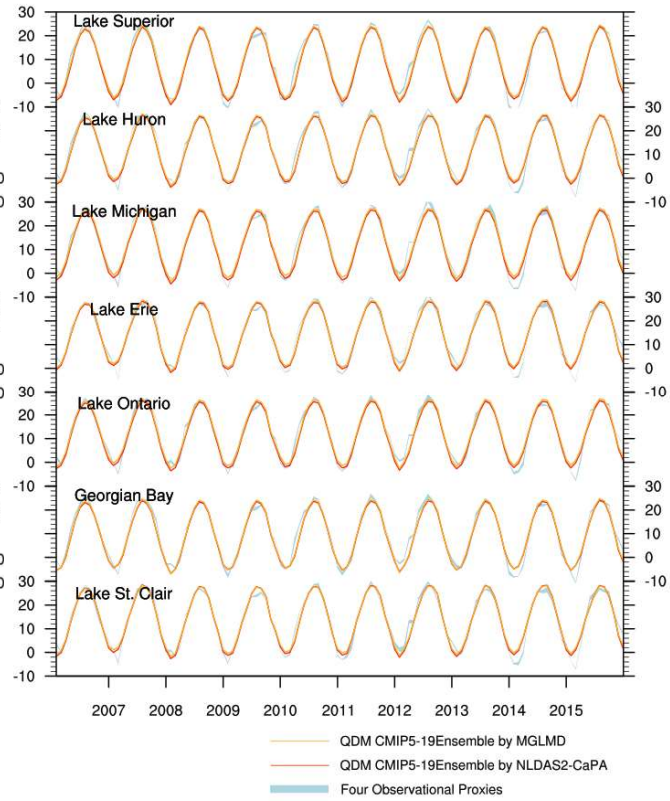
LBRM: 2006-2015

Temperature

Minimum Temperature

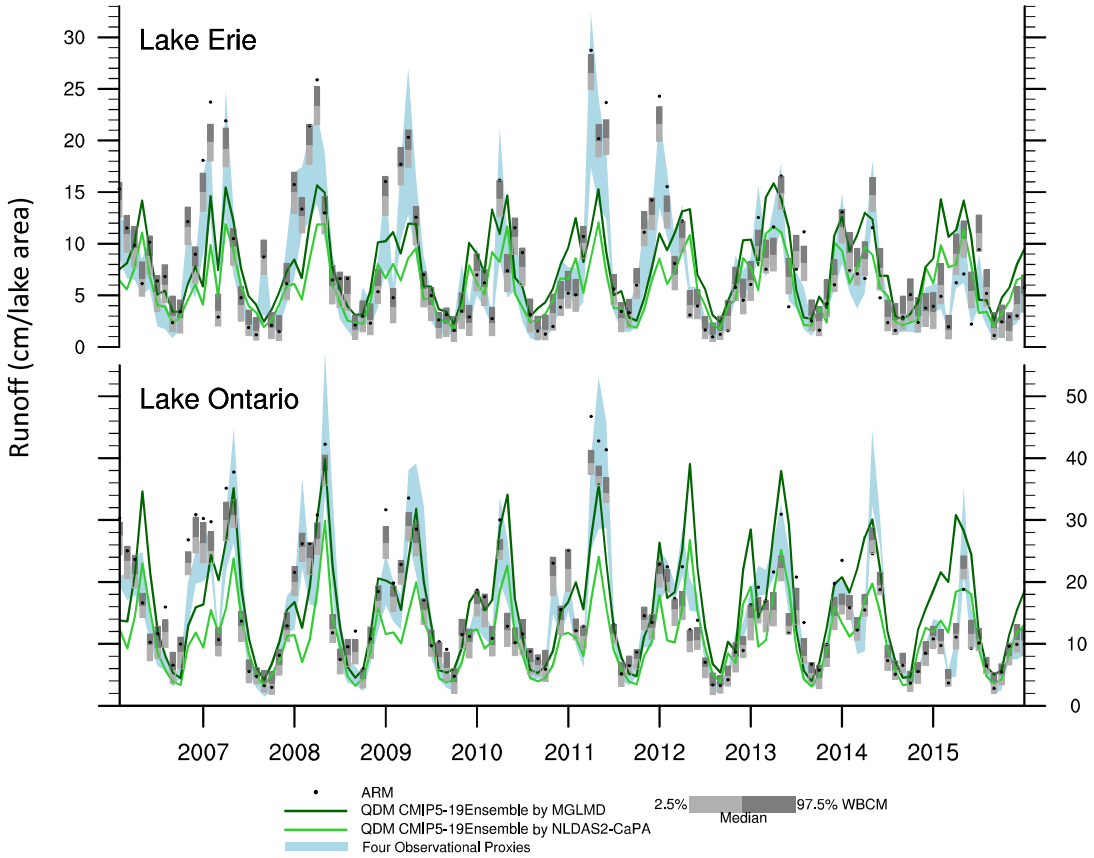


Maximum Temperature



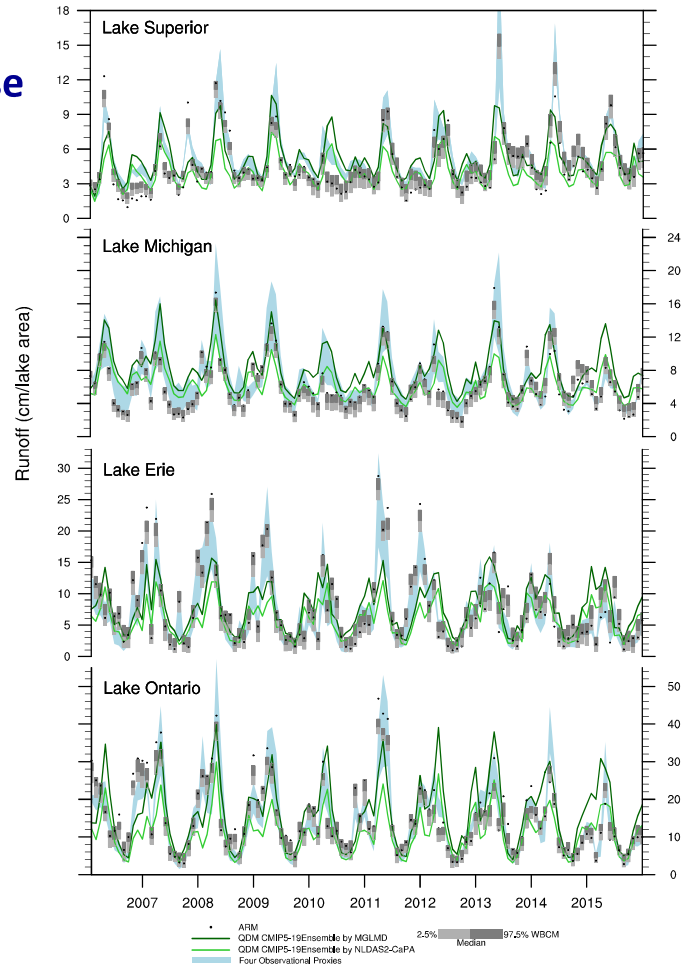
LBRM: 2006-2015

Runoff Response



LBRM: 2006-2015

Runoff Response



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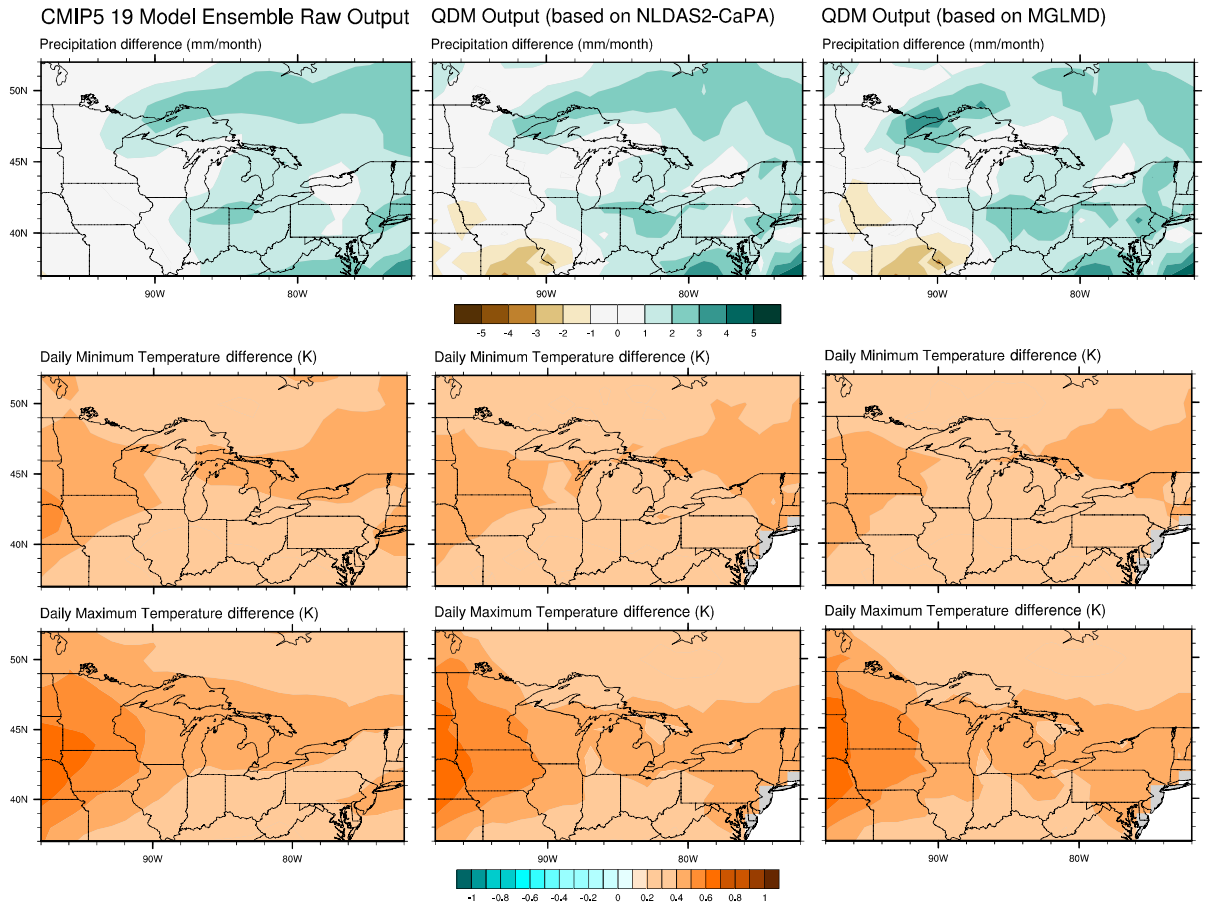
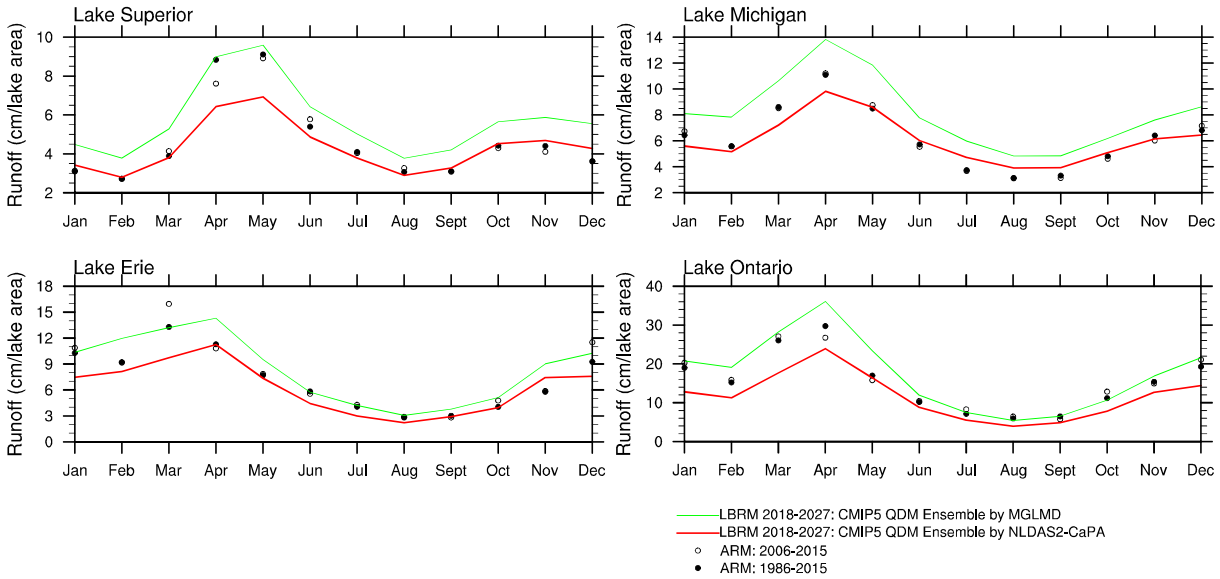
Mean of 2018-2027 minus Mean of 2008-2017

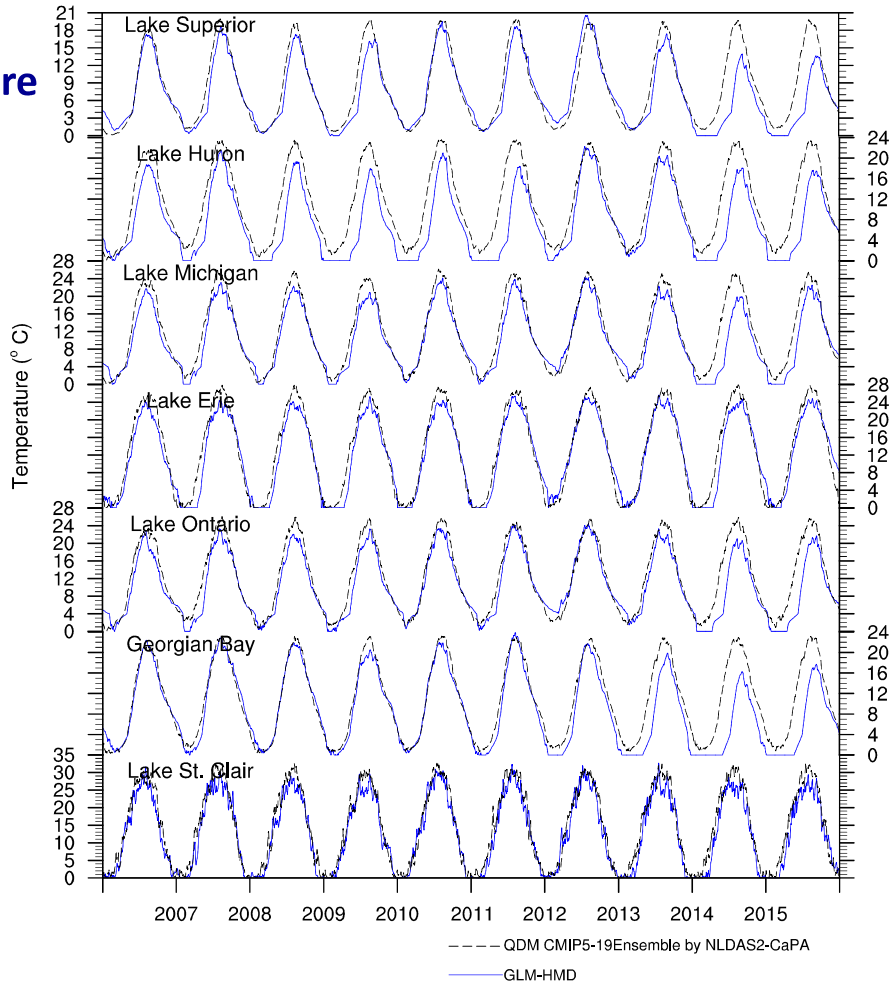


LBRM: Future Projection

Projected 2018-2027 Runoffs Comparing to Historical Records



LLTM: 2006-2015 Water Temperature



Outline

- Goals
- Background
- Model development
  - Meteorological forcings
  - Hydrological models
  - Water supply forecasting systems
  - Routing and regulation models
  - Ensemble processing
- Skill assessment
- Operational implementation
- Future work

GLSHyFS

Great Lakes Seasonal Hydrology Forecasting System

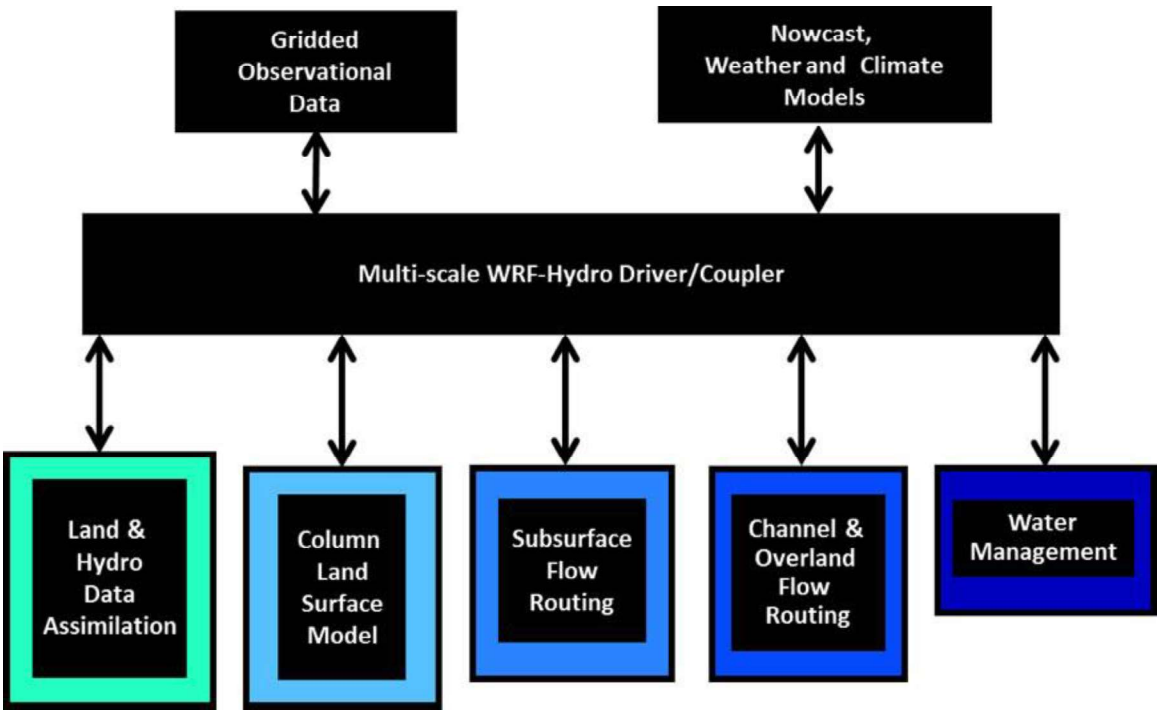
(aka GLSHyFS, or G. L. Shiffs)

GL-AHPS (Advanced Hydrologic Prediction System)

The predecessor to GLSHyFS was GL-AHPS.

Tim announced in February, 2015 that GL-AHPS was being phased-out / retired in favor of WRF and WRF-Hydro, because that is the future of forecasting in NOAA.

WRF-Hydro



GL-AHPS (Advanced Hydrologic Prediction System)

We said that GLERL would continue to use and support GL-AHPS as an interim solution, but no major effort was planned. Specifically, we said…

Things we **WILL** do for AHPS

- Updated data sets
- New parameter sets for LBRM
- Updated methods for gathering input meteorology (station data)
- Include the latest version of CGLRRM
- User manual
- Updated digital maps (?)
- Inclusion of snow observations (?)

Things we **WILL NOT** do for AHPS

- Standardized file formats
- Simplified data organization
- Cross-platform code base
- Seamless integration of all pieces (data acquisition and CGLRRM)
- New graphical output options
- Alternate methods for forecast meteorology
- Alternate models

GL-AHPS (Advanced Hydrologic Prediction System)

However… When this project started, it was immediately clear that we could not wait for WRF-Hydro (will not be ready for a few years, at best) and that GL-AHPS was going to be the tool we needed for doing NBS (water supply) forecasts.

GL-AHPS (Advanced Hydrologic Prediction System)

For computing NBS, we need:

- Meteorology data (Precipitation)
  - Station-derived
  - Gridded (CMIP5)
- Runoff
- Evaporation

Regulation/routing to get channel flows is a second step, not part of GL-AHPS.

GL-AHPS (Advanced Hydrologic Prediction System)

Changing to 5-year forecast horizon revealed issues in GL-AHPS *(hindcasts at GLERL)*. As we dug deeper, we ran into several issues:

- Software architecture problems/annoyances:
  - Obsolete development tools (compilers, libraries)
  - Pascal & Fortran interfacing (messy)
  - MS-Windows only
- No means for handling gridded data
- Could not be updated for new models

These issues made AHPS unusable.

GLSHyFS

- Development began in August, 2016
- Took a lot longer than estimated
  - Tim is a bad estimator
  - Feature creep (necessary). We implemented a number of items from the old GL-AHPS wish-list, which added development time
- Eliminated some options from GL-AHPS that were never used and just added complexity
- Goal was to make it more “model neutral”, but that turned out to be impractical at this time.

Things we **WILL** do for AHPS

- Updated data sets
- New parameter sets for LBRM
- Updated methods for gathering input meteorology (station data)
- Include the latest version of CGLRRM
- User manual
- Updated digital maps (still planned)
- Inclusion of snow observations (code is improved)

Things we **WILL NOT** do for AHPS

- Standardized file formats
- Simplified data organization
- Cross-platform code base
- Seamless integration of all pieces (data acquisition and CGLRRM)
- New graphical output options
- Alternate methods for forecast meteorology
- Alternate models

GLSHyFS

- Code base completely revamped (~90% of code is new). Needed due to file format changes.
- 100% Fortran
- Approximately 20,000 lines of code
- Compiles and runs on Windows and linux
- Removed the data period duality
- Far easier for the user to update station data
- All files are now text format (most are CSV)
  - User can directly examine data
  - Easier to use in other processes/software

GLSHyFS

- Newly coded version of LBRM
  - Same processes except for heat index computation
  - Single model; parameter file determines PET method
- Newly coded version of LLTM
  - Single model with option to use direct radiation forcings in place of cloud cover proxy (allowing use of CMIP data)
  - Radiation source is specified in config file

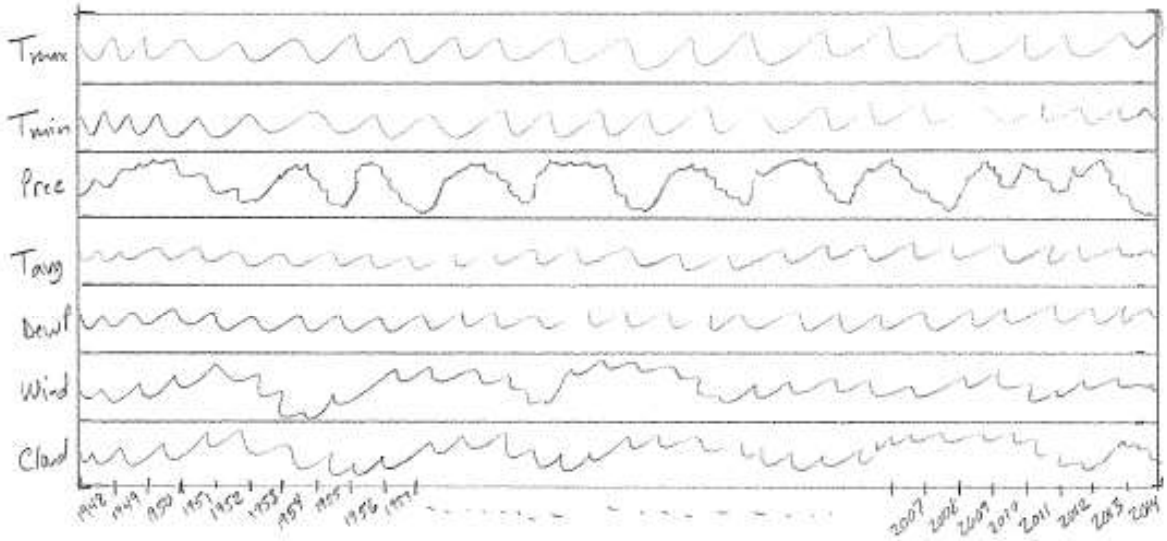
GLSHyFS

Result of recoding work:

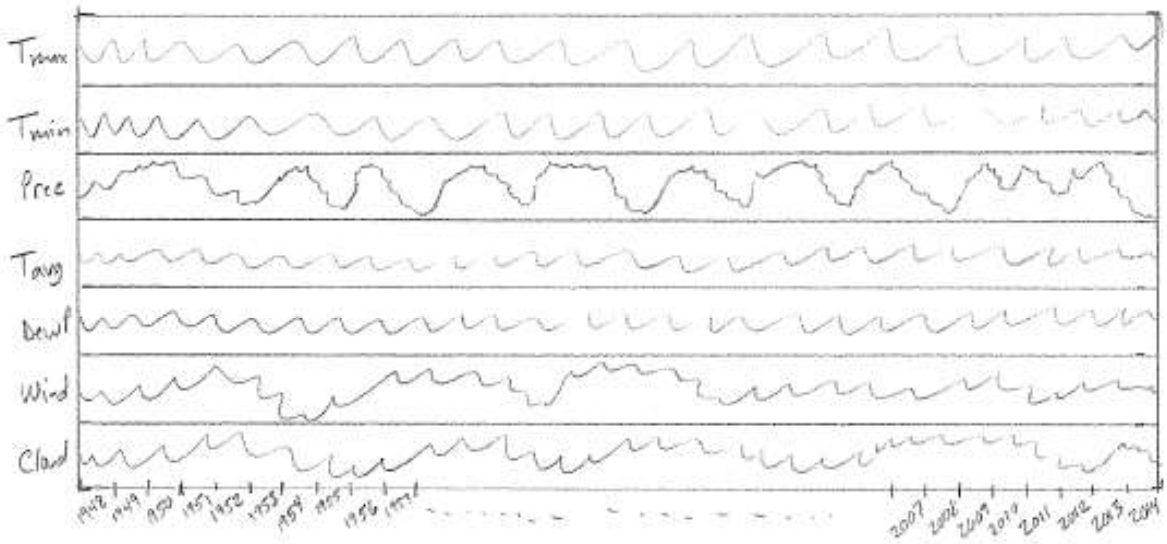
- Much easier to debug/maintain the code
- Much easier to use the data (both input and output)
- Results will show that we seem to have fixed bias problems with GL-AHPS (though we don't know exactly how/why, since we can't debug the old code)

How do we use meteorology to generate NBS sequences?

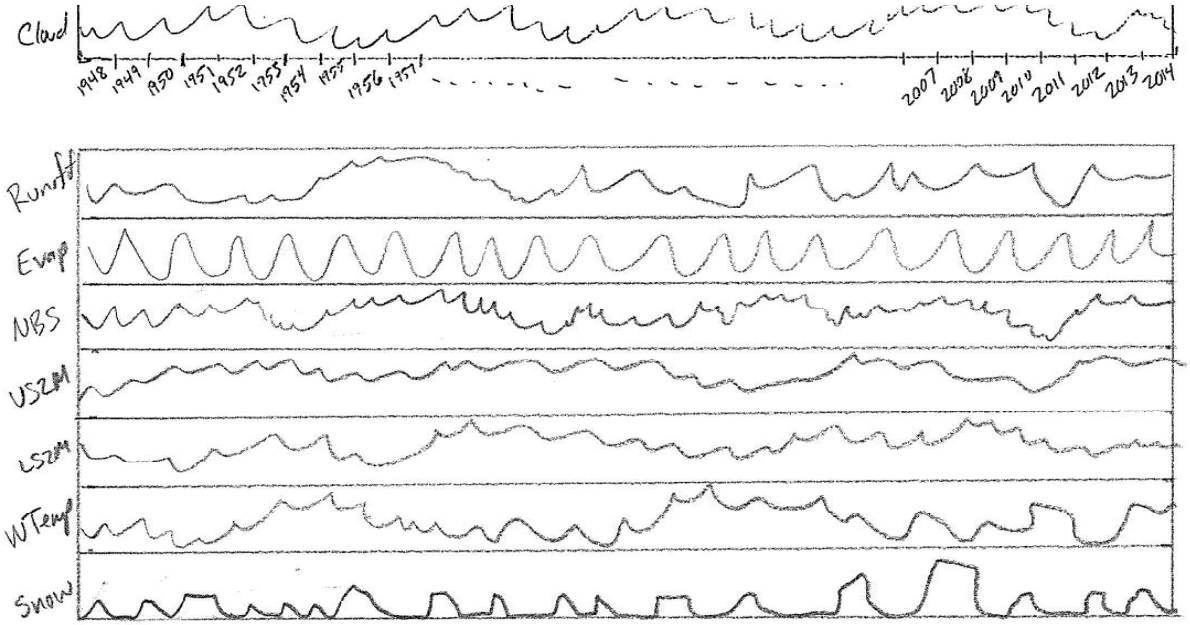
Assuming this meteorology for 1948-2014…



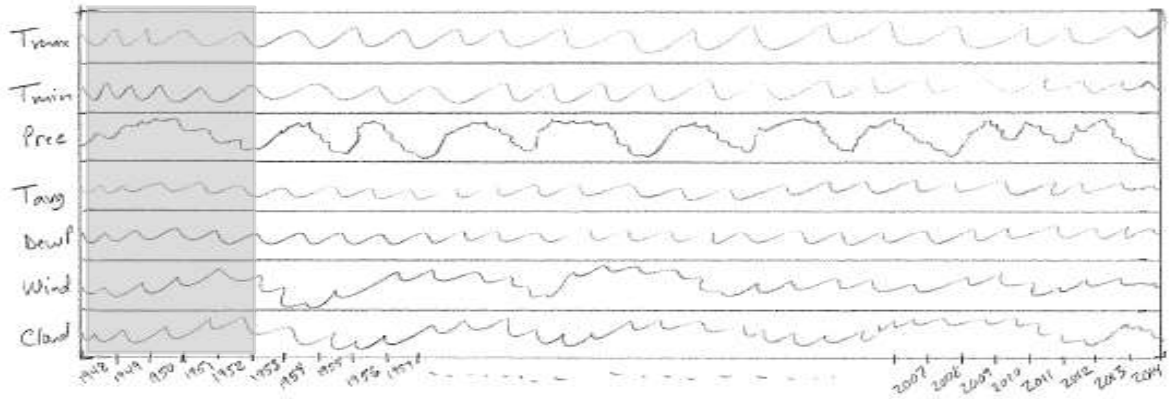
When we wish to run a forecast, we update provisional subbasin meteorology through **<u>at least</u>** the day before the forecast start date by incorporating station observations.



The models are then run so that the stored time-series of model output reflect the updated station data. We can then get initial conditions for the forecast.



Now we can run forecast scenarios using daily meteorology for those seven necessary input variables. The source of that input meteorology could be ANYTHING. Standard procedure has been to use sequences from the past, using the same time period for each lake basin.



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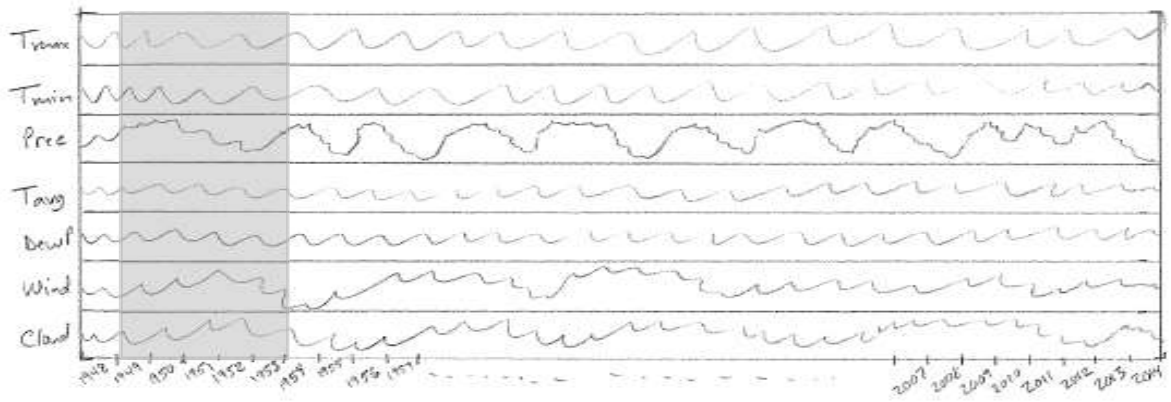

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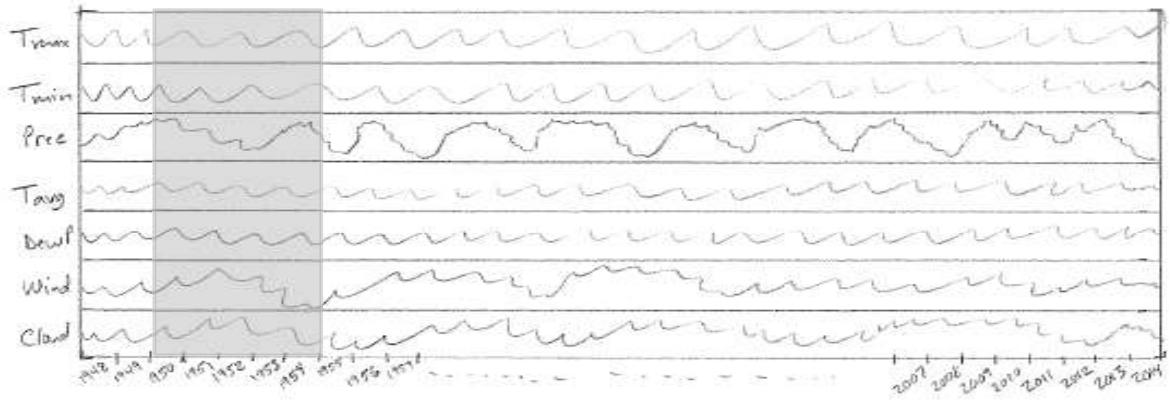

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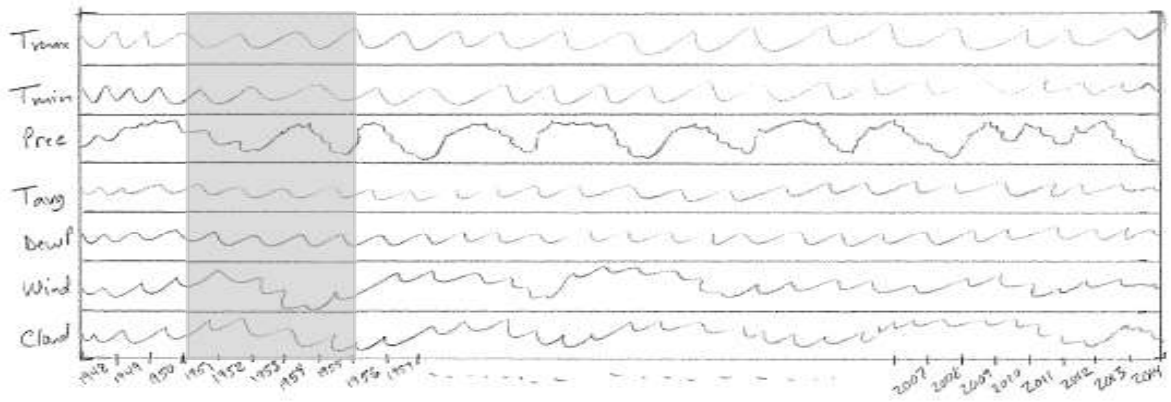
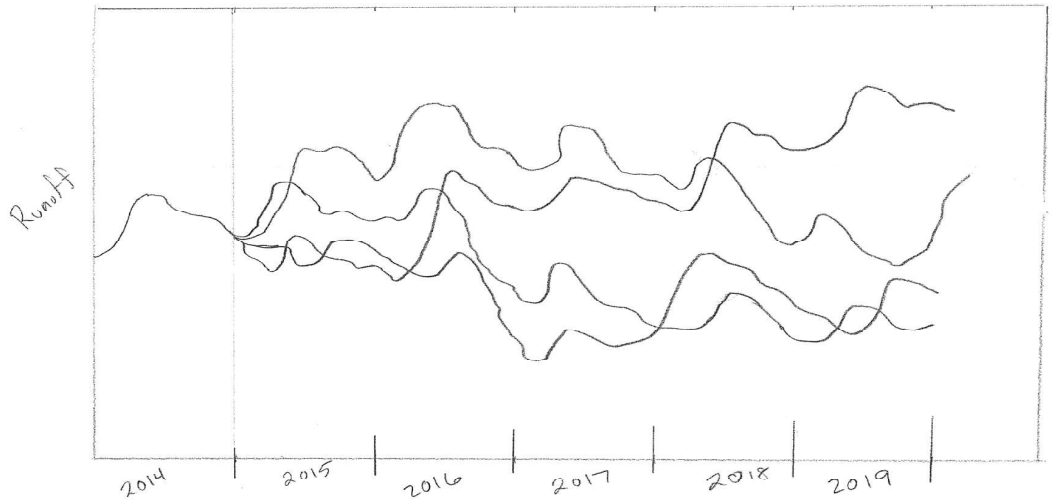
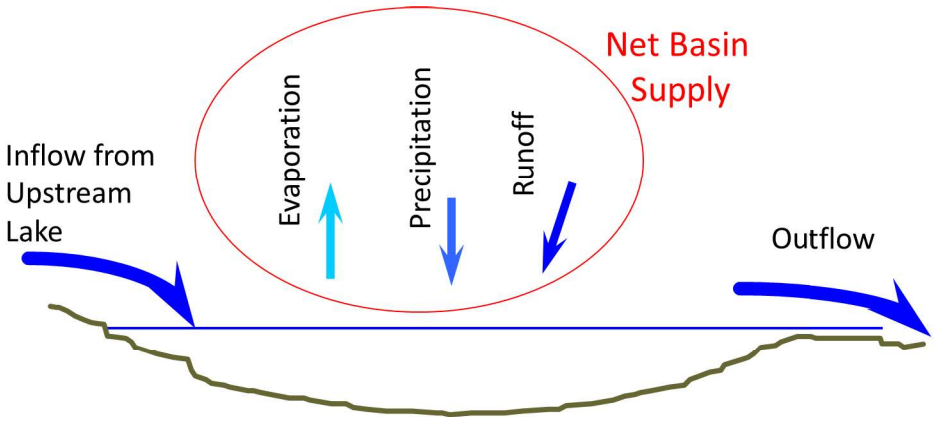


The result is an ensemble of outputs, each corresponding to one of the input sequences. These can then be used to produce a probabilistic outlook via some user-selected methodology (weighting optional).

In our process, CMIP5 data is used somewhat similarly to extracted met sequences.
[Discuss CMIP ensembles vs super-ensembles]



Residual Net Basin Supply System



$$\Delta Z = P + R + E + Q_i - Q_o + \epsilon$$

$$P + R + E = \Delta Z - Q_i + Q_o$$

$$NBS_r = \Delta Z - Q_i + Q_o$$

Residual Net Basin Supply System

- Build an ensemble using historical residual NBS. For example, forecast starting 22 Sep 2017, the ensemble is:

$$\begin{aligned}
1948:&\quad NBS_{Sep1948}, NBS_{Oct1948}, \cdots, NBS_{Sep1953}\\
1949:&\quad NBS_{Sep1949}, NBS_{Oct1949}, \cdots, NBS_{Sep1954}\\
1950:&\quad NBS_{Sep1950}, NBS_{Oct1950}, \cdots, NBS_{Sep1955}\\
&\quad\vdots\\
&\quad\vdots\\
2006:&\quad NBS_{Sep2006}, NBS_{Oct2006}, \cdots, NBS_{Sep2006}
\end{aligned}$$

- NBS_r is *monthly*, so daily NBS is constant throughout month.
- New product developed to work within 5-year forecasting system: “Build Ensemble Residual NBS System (BERNS)”

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Routing and Regulation Models

- Coordinated Great Lakes Regulation and Routing Model (CGLRRM)
- Lake Ontario Regulation and Routing Model

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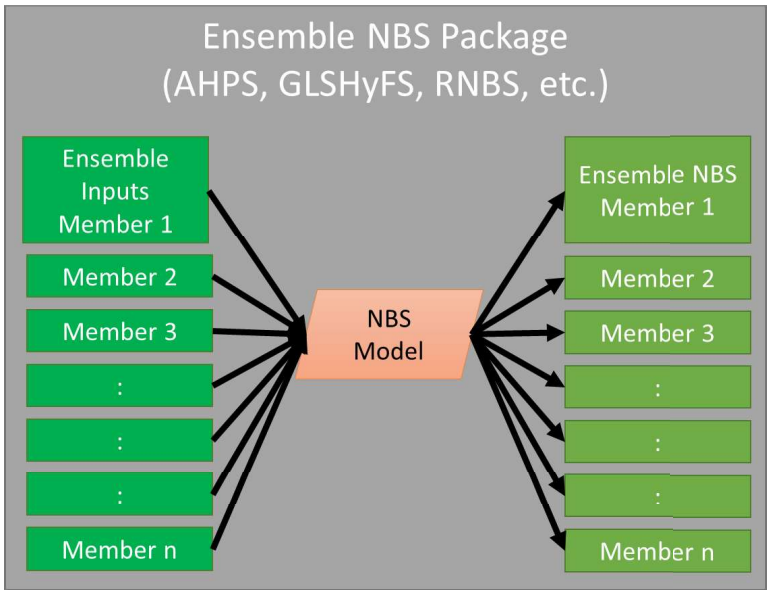
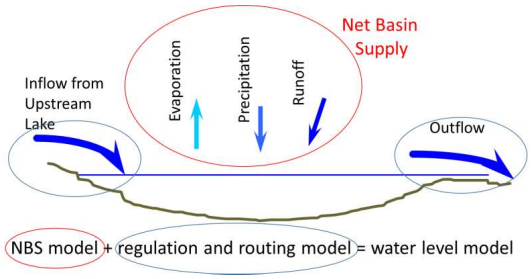
Great Lakes Ensemble Regulation and Routing Forecasting System (GLERRFS)





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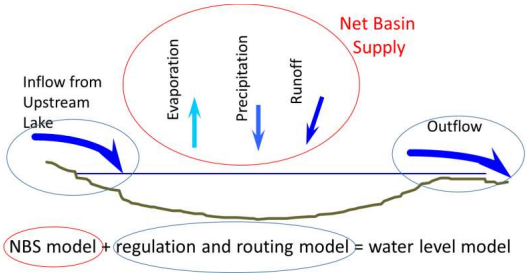

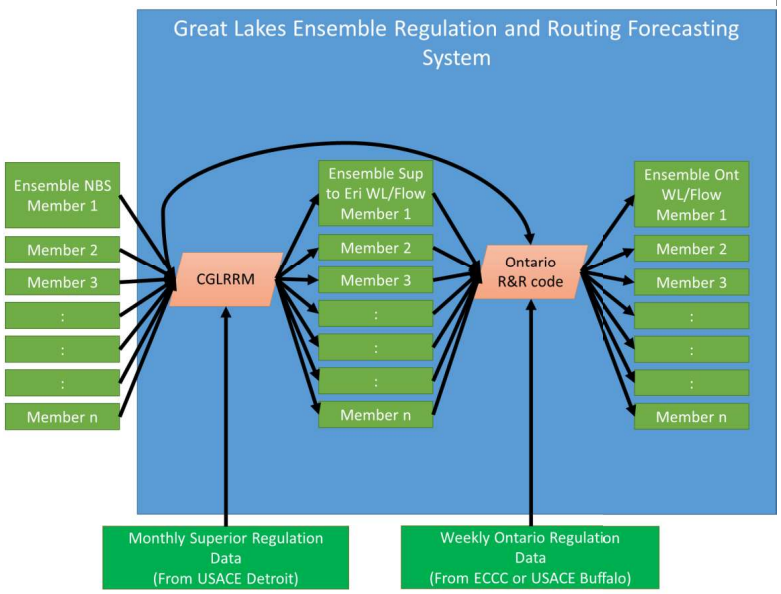

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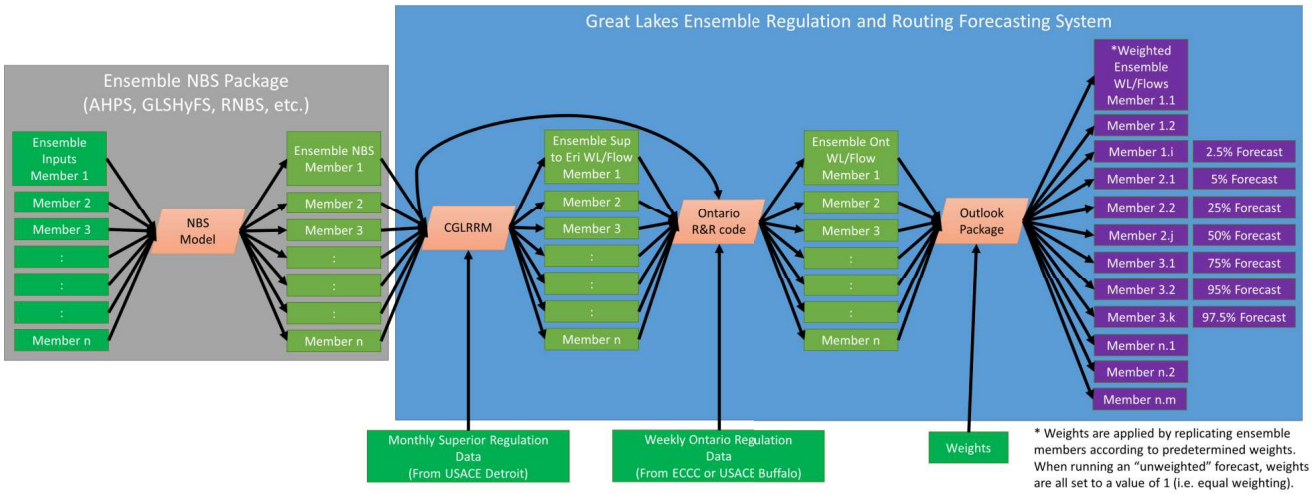

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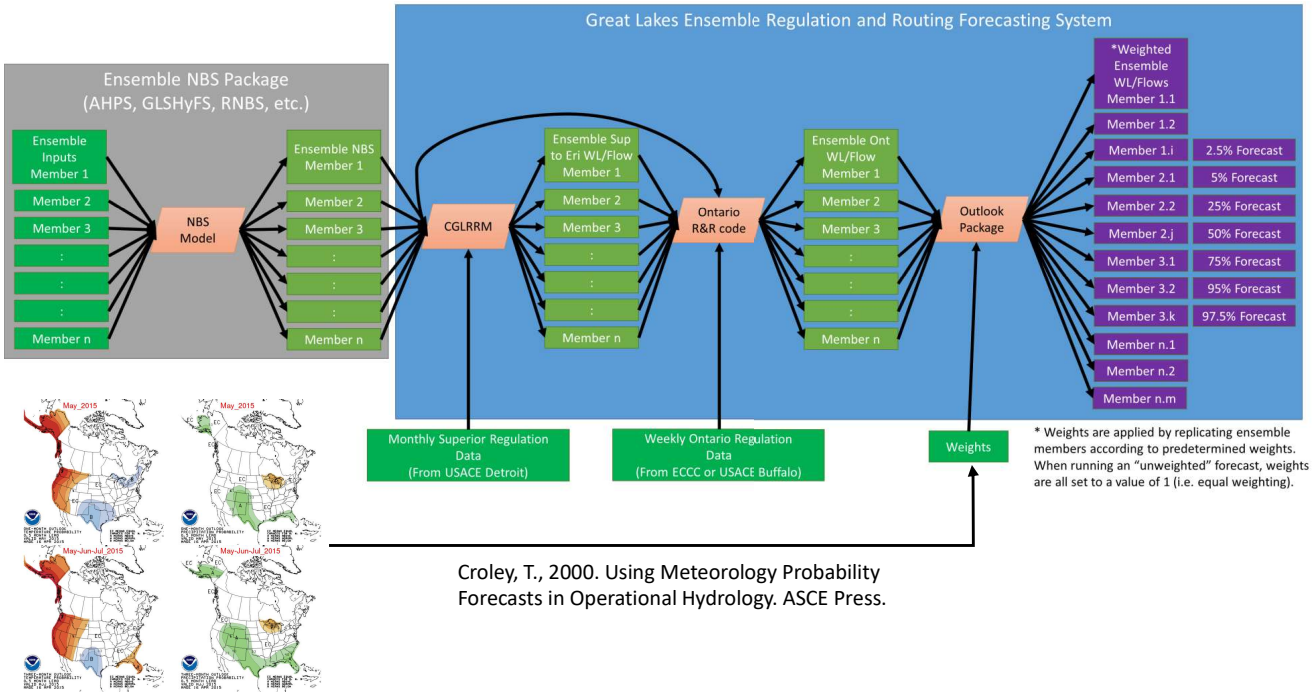

Croley, T., 2000. Using Meteorology Probability Forecasts in Operational Hydrology. ASCE Press.

Great Lakes Ensemble Regulation and Routing Forecasting System (GLERRFS)

Outlook weighting based on methods developed by Croley (2002) for AHPS.

Ensemble member	Value	Weight	Replications
A	5	0	
B	10	0.5	10
C	15	2.0	15, 15, 15, 15
D	20	1.5	20, 20, 20
Ensemble Average	12.5		
Weighted Ensemble Average			16.25

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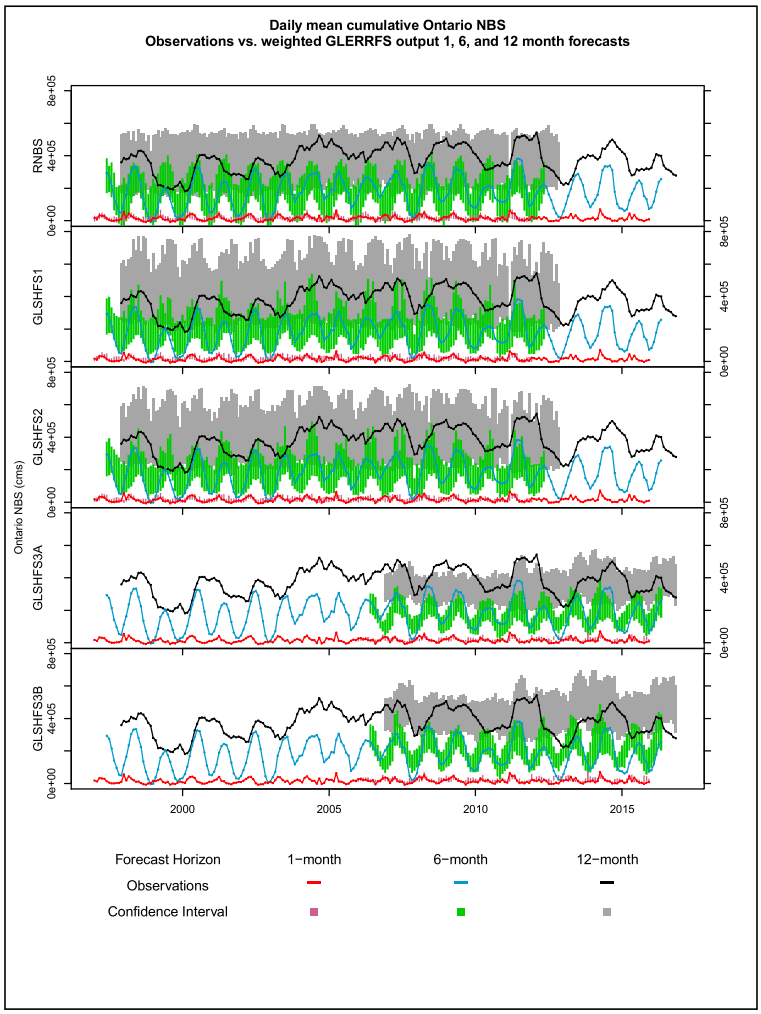
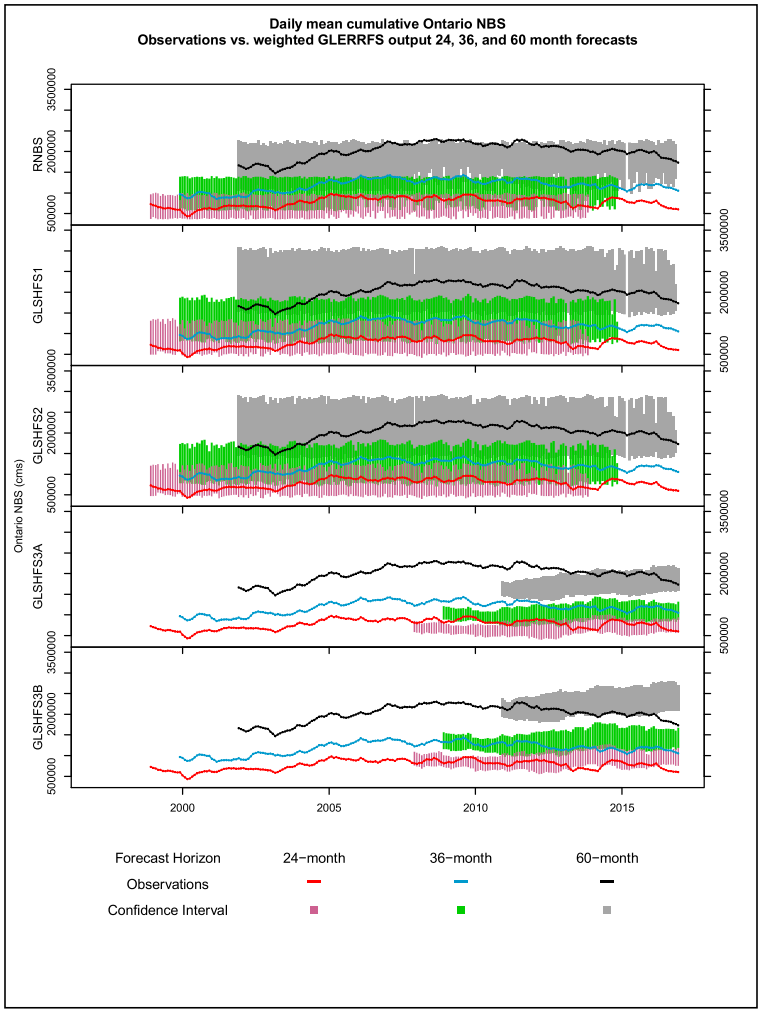
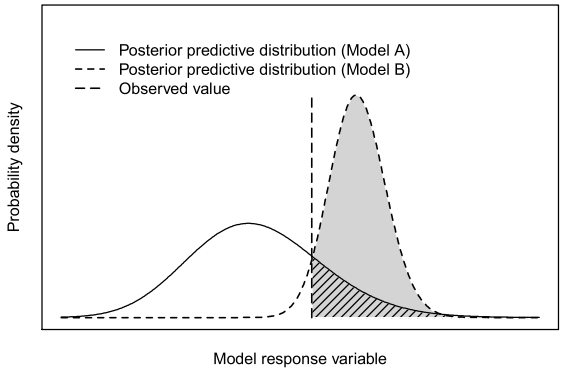




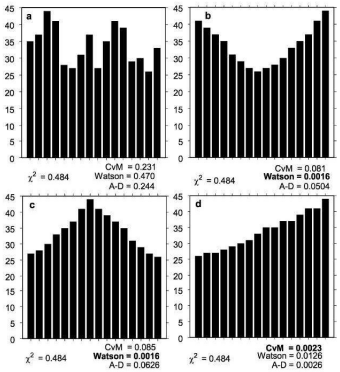
Assessing predictive performance



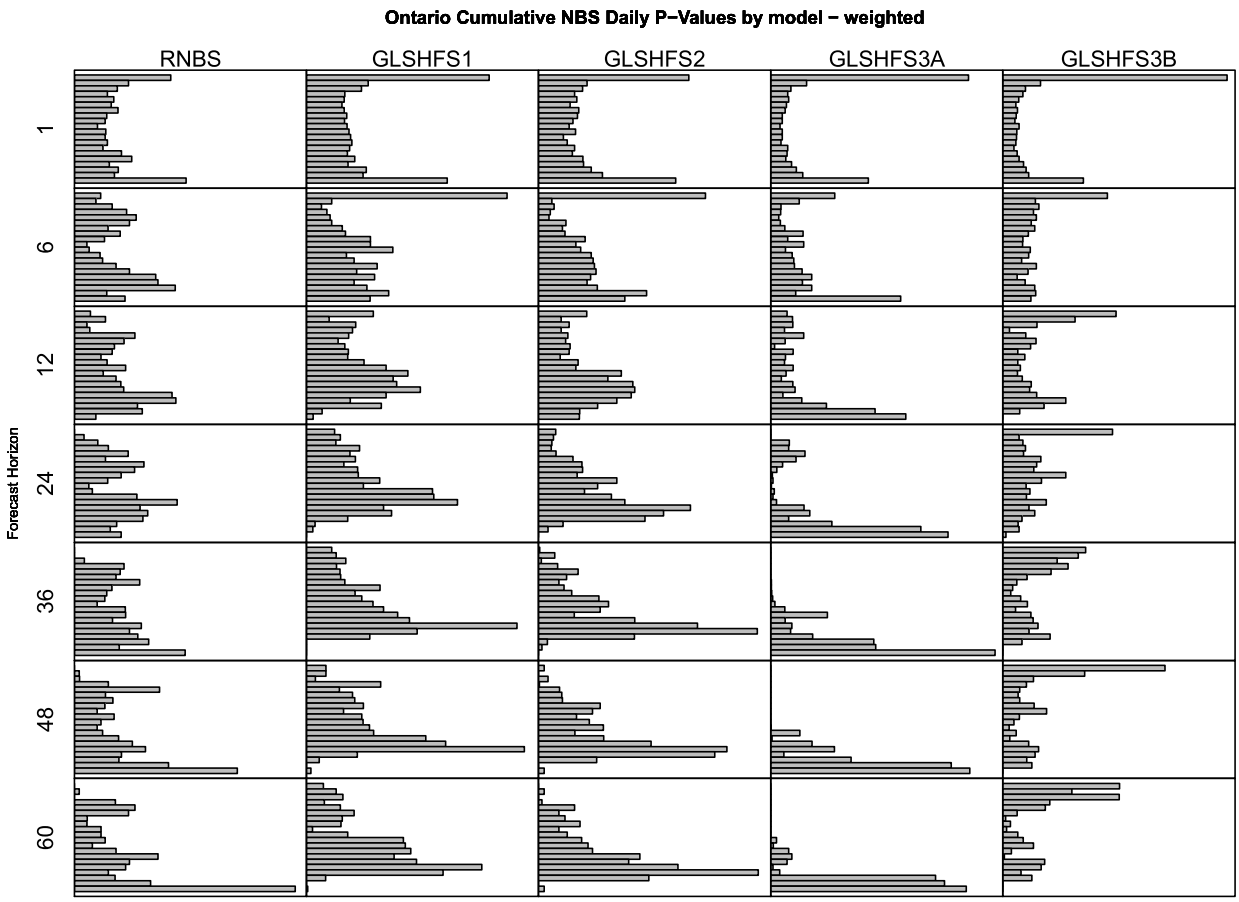
A. Gelman, J. Carlin, H. Stern, D. Rubin, *Bayesian Data Analysis*, 2004. pp 163.

A. Gronewold, S. Qian, K. Reckhow, R. Wolpert, *Water Research*, **43**, 2009

Assessing predictive performance

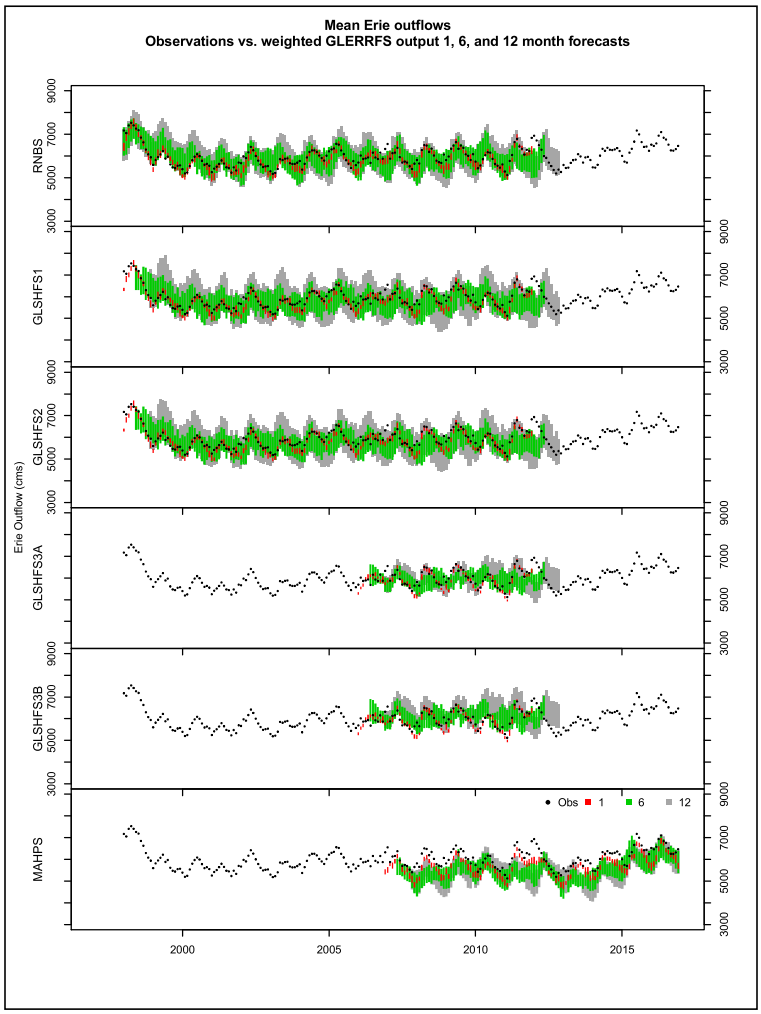


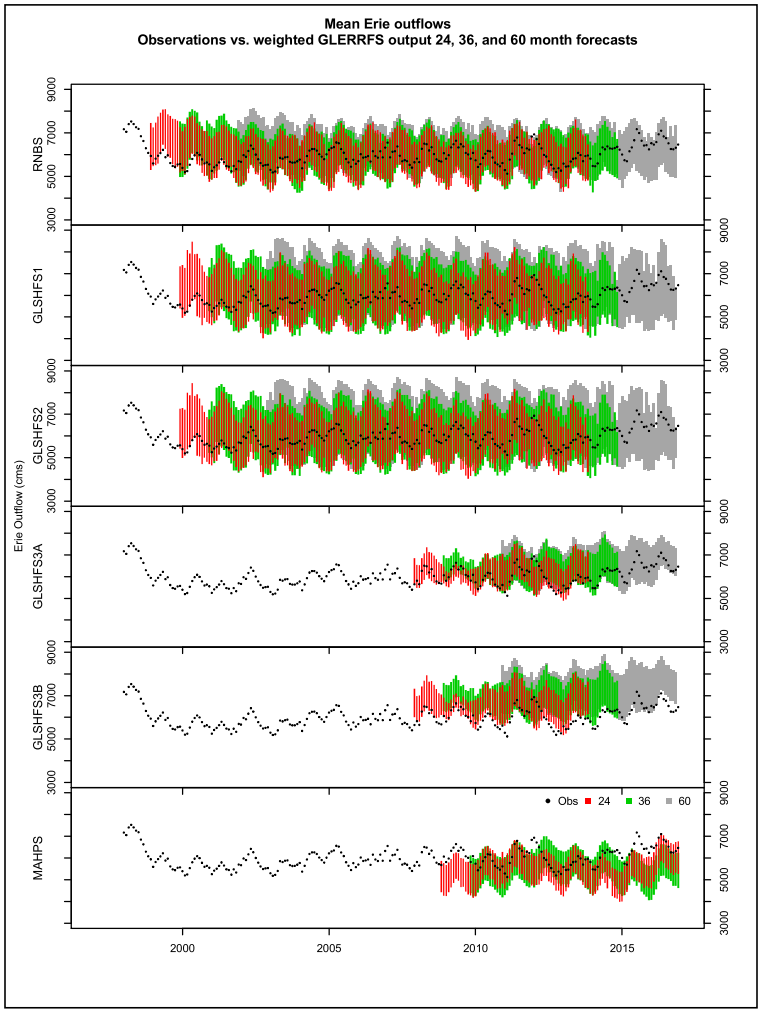
K. Elmore, *Weather and Forecasting*, **20**(5), 2005.

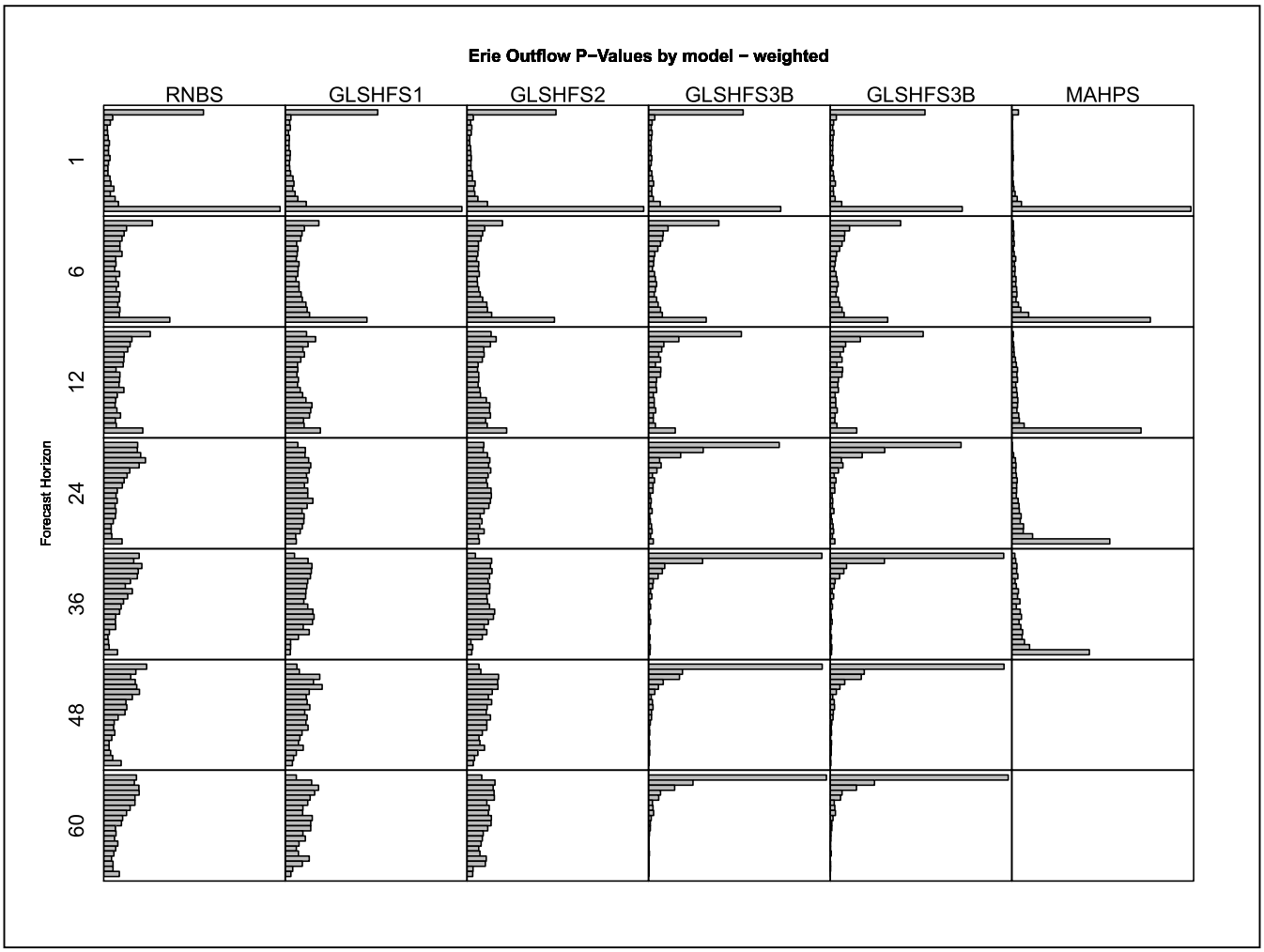


Lake Ontario cumulative NBS forecasts

- NBSr has most consistent skill
- All models indicate underdispersion at 1-month
- Nearly all models indicate negative bias across longer forecast horizons
- No noticeable difference via weighting




Mean Erie outflows
Observations vs. weighted GLERRFS output 24, 36, and 60 month forecasts
Erie Outflow (cms)
RNBS
GLSHFS1
GLSHFS2
GLSHFS3A
GLSHFS3B
MAHPS
Obs
24
36
60
3000
5000
7000
9000
2000
2005
2010
2015


Erie Outflow P−Values by model − weighted
RNBS
GLSHFS1
GLSHFS2
GLSHFS3B
GLSHFS3B
MAHPS
Forecast Horizon
1
6
12
24
36
48
60

Lake Erie outflow forecasts

- For all models, short-term (1-6 months) forecasts underestimate variability of average flows
- GLSHyFS-1 -2 capture observed variability well in 2-5 year horizon; NBSr also captures variability, but with a slight positive bias
- GLSHyFS-CMIP5 has chronic positive bias
- Legacy GLAHPS (via archived 3-year forecasts) has strong negative bias
- No noticeable difference via weighting

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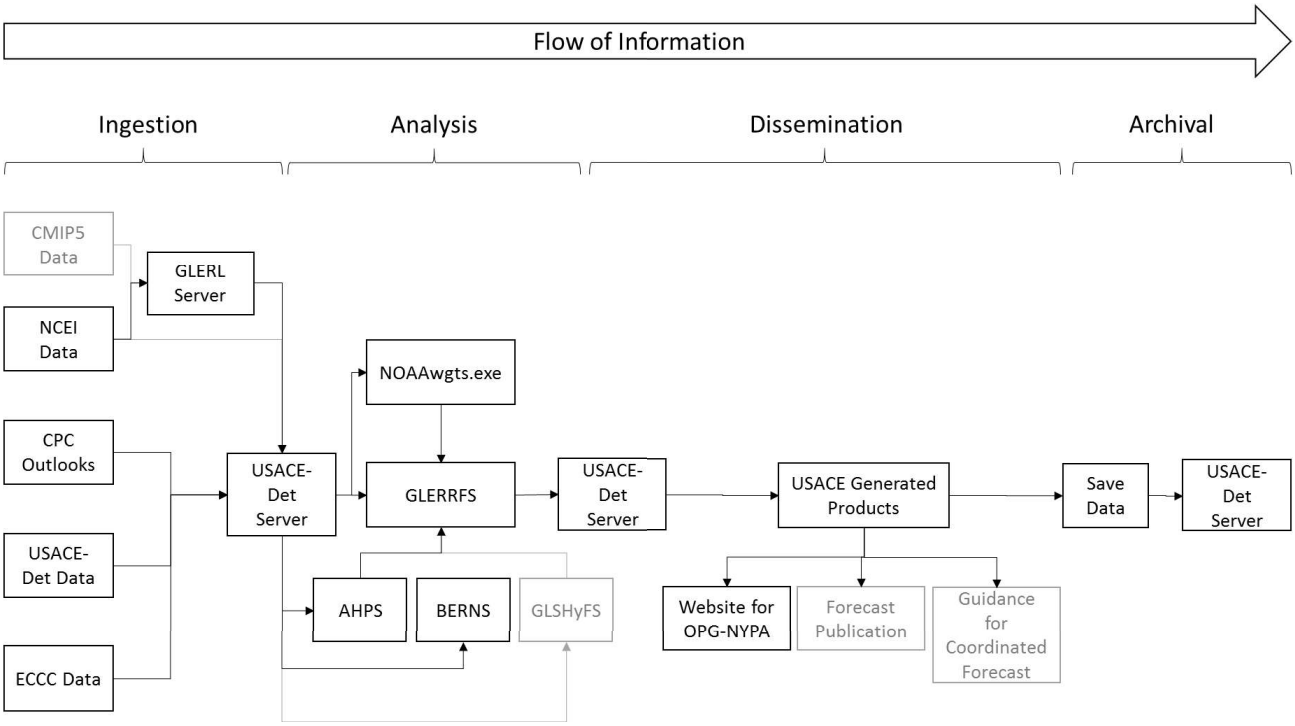
Operational Implementation



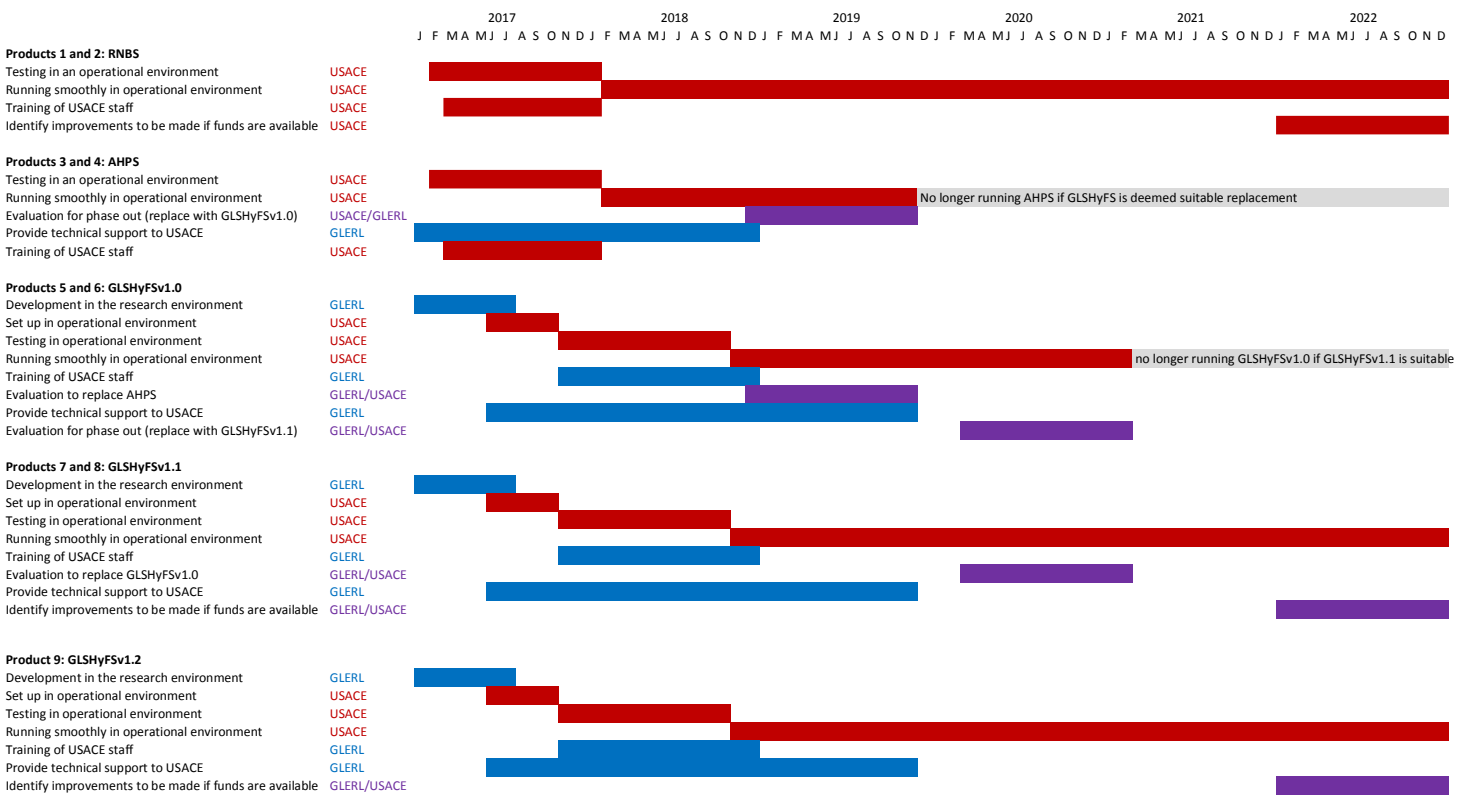
http://lre-wm.usace.army.mil/ForecastData/OPG_NYPA_5yrForecast/

Status of model installation and execution

System name	Meteorology Source	Hydrology		GLERRFS Configuration
		Tributary inflows	Lake evaporation	
GL-AHPS	Climatology	LBRMv1.0	LLTMv1.0	Unweighted
				Weighted
GLSHyFS-1	Climatology	LBRMv1.0	LLTMv1.0	Unweighted
				Weighted
GLSHyFS-2	Climatology	LBRMv2.0	LLTMv1.0	Unweighted
				Weighted
GLSHyFS-3	CMIP5	LBRMv2.0	LLTMv2.0	Unweighted
NBS_r	None	Historical supply sequences		Unweighted
				Weighted

Status of model installation and execution

- NBS_r and AHPS forecasts running in operational environment since February (testing period)
- GLSHyFS implementation is still in progress (work continues with GLERL to test versions in operational environment).
- Lake Ontario Plan 2014 code has been developed. Working to wrap it into GLERRFS (and other USACE forecasting systems)
- Programming staff has been hired to assist in transition all systems to full operational status over the coming year.

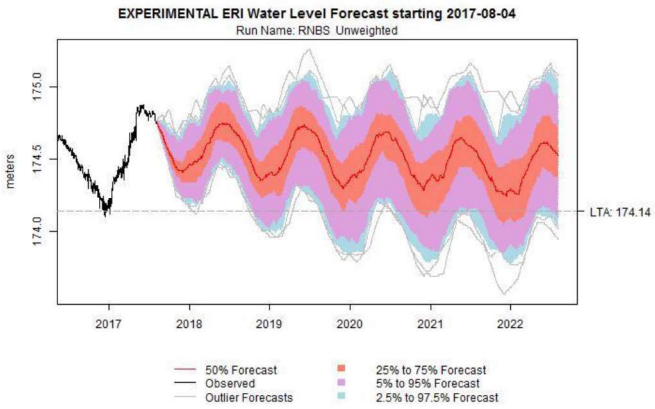


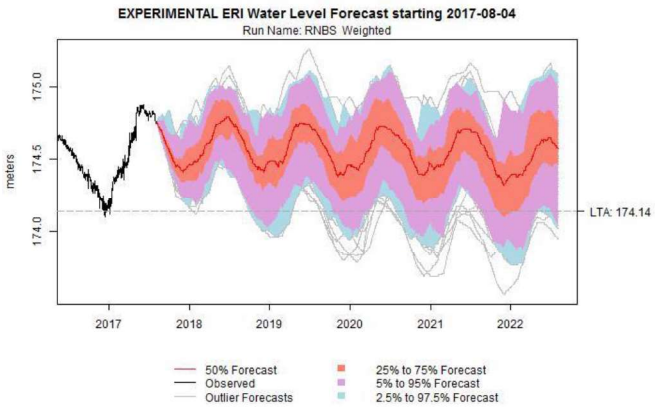
Operational Forecasts

- Provided on web interface:
  - Water levels, inflows, outflows, NBS, and NTS for last 30 forecasts
    - Full ensemble output
    - Probabilistic outlook
    - Forecast plots
- Archived on USACE server
  - Water levels, inflows, outflows, NBS, and NTS
    - Full ensemble output
    - Probabilistic outlook
    - Forecast plots

http://lre-wm.usace.army.mil/ForecastData/OPG_NYPA_5yrForecast/

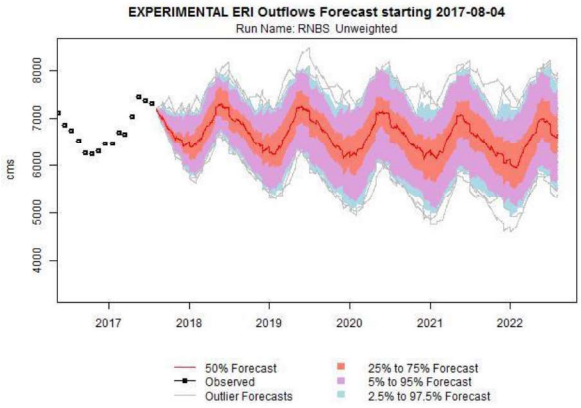
Example Forecast Plots (Erie Levels)

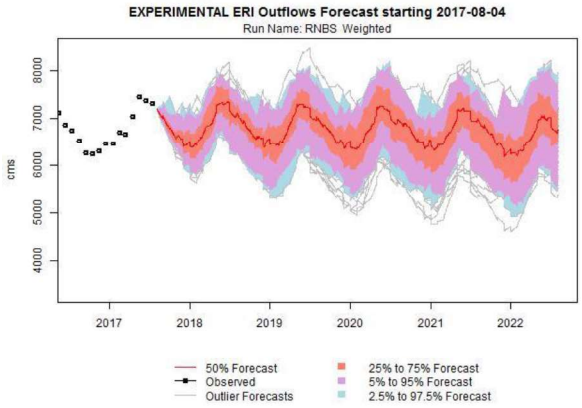




http://lre-wm.usace.army.mil/ForecastData/OPG_NYPA_5yrForecast/

Example Forecast Plots (Erie Outflow)





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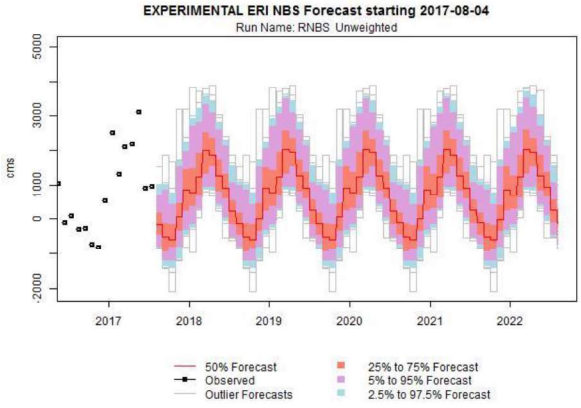
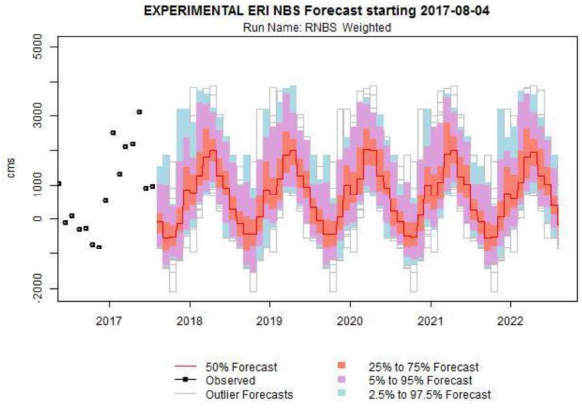
Example Forecast Plots (Erie NBS)





http://lre-wm.usace.army.mil/ForecastData/OPG_NYPA_5yrForecast/

Schedule of Operational Forecasts

- Every Thursday
  - Conducted alongside regular weekly forecasting operations
  - Initiated when starting levels are determined (typically after 11:00, sometimes later)
  - Run time for current operational installation is about 2 hours. Expect longer time for GLSHyFS configurations.
- Mid-month
  - Develop new outlook weights using CPC Climate Outlook maps
- End-of-month
  - Develop new outlook weights using updated CPC Climate Outlook maps, if necessary

http://lre-wm.usace.army.mil/ForecastData/OPG_NYPA_5yrForecast/

Considerations for Operational Implementation

- Infrastructure
  - Operation on Windows 7 and Windows 10 PCs
  - Potential to implement GLSHyFS and download/pre-processing of met data on Linux server
- Personnel
  - Three dedicated Great Lakes forecasting staff
  - Multiple staff rotating into forecasting duties
  - Newly hired programmer (thank you!)
- Data storage
  - Detroit District archives all forecast output and any input required to reproduce forecasts
- Forecast dissemination
  - Website, primarily

http://lre-wm.usace.army.mil/ForecastData/OPG_NYPA_5yrForecast/

FY18 Operational Implementation Plan

- Transition GLSHyFS to operational environment
  - Final, working version of executable
  - Wrap into automated forecasting procedures
  - Documentation
  - Training (operation and coding)
- Implement Plan 2014
  - Wrap regulation and routing code into GLERRFS
- Build operational assessment/verification procedures
- Establish methodology for reconciling forecasts
- Parallel development with updated routing and regulation model
- Incorporate into other USACE forecasting operations and develop new products

Outline

- Goals
- Background
- Model development
  - Meteorological forcings
  - Hydrological models
  - Water supply forecasting systems
  - Routing and regulation models
  - Ensemble processing
- Skill assessment
- Operational implementation
- Future work

The End

G Response to comments on draft documentation report

This appendix includes comments on the August 2017 draft version of the project documentation plan, and responses to those comments.

Comments from: Rich Mueller

1. Acknowledgements (page 2): NRCC is not a funding source. You can remove the reference to NRCC, leaving OPG and NYPA as the funding sources.

   Correction made.

2. 3.1.1 Calculation of observed Niagara River Flows It is not mentioned how you estimated the value of "local inflows" Q_l in equation 4.

   We have modified the report text (near equation 4), and added a historical reference, to more clearly indicate the basis for calculating local inflows.

3. 3.1.2 Comparison to flow forecasts (I see the skill assessment is a work in progress... but that you have some preliminary results for Lake Erie outflows and Lake Ontario NBS. I look forward to seeing completion of Appendix C)

   Appendix C now includes a comprehensive array of results, though Lake Ontario water level and St. Lawrence flow simulations are not included in this (R&D phase closeout) report; we anticipate these both being available during the operational implementation phase.

   (a) Is your skill assessment based on weighted or unweighted ensembles? Which weighting method did you use? Furthermore, it would be interesting and useful to know if the weighted forecast is significantly better than the unweighted forecast for the 1, 6, 12, 24, 36 and 60 month forecasts.

   The skill assessment results in Section 3 of the report are based primarily on weighted forecasts. In the Appendix, however, we have included comparisons of weighted and unweighted forecasts, as well as posterior predictive p-values of both. Weighting is based on the conventional procedures from the original AHPS package. We found, in preliminary tests, that the primary impact of this weighting procedure was on the range of forecast uncertainty. If, for example, relatively few ensemble members met the weighting criteria (and were therefore eliminated from the ensemble), the uncertainty in the forecast increased.

   (b) You mentioned NBSr and CMIP5 forecast systems have a Lake Erie outflow bias. Does that mean the other forecast systems are unbiased? Will you make that clearer?

   For the purposes of this report, we are going to refrain from further interpretation of results, particularly with respect to bias. We believe that the new results in Appendix C provide insight into multiple potential skill evaluations.

(c) It was good to see the 12, 14, 36, and 60 month Lake Erie outflow forecast ensembles from the NBSr, GLSHyFS-1 and GLSHyFS-2 systems are neither overdispersed or underdispersed, as those are the timeframes for NYPA's hedging low generation. For the 1 and 6 month forecasts, model/parameter calibration error may be as large as the variability of the weather driven ensemble. The underdispersion of the 1 and 6 month forecasts may be caused by model/parameter calibration errors not reintroduced back into the ensembles. I use Monte Carlo simulation to reintroduce model errors in my flow-to-gen model, but this makes the ensembles change whenever the ensembles are recalculated, which is annoying.

We agree that model parameter uncertainty could certainly be a factor in the underdispersion of sub-seasonal forecasts; explicitly quantifying parameter uncertainty has been a long-term goal of regional forecasting improvements, but unfortunately has not yet been implemented.

(d) The cumulative Lake Ontario NBS p-values show quite a mixture of results. In the GLSHFS models, I see underdispersion in the 1 month forecast, then overdispersion and possible bias for the longer forecasts. I wonder if the Lake Ontario outflows will mimic this?

As we mentioned earlier, given the complexities of encoding the latest Lake Ontario regulation plan, we anticipate Lake Ontario outflow results being available during the operational implementation phase of the project.

(e) The observed "daily" min and max Erie outflows are influenced by seiche events. The forecast systems use flat level lake routing. This causes the bias displayed in the figures.

We appreciate this observation, though we have not made modifications to the report text.

4. My preliminary recommendation for operational use at NYPA - NYPA will probably use unweighted forecast ensembles to make a probabilistic hydro generation forecast. The 59 ensemble members for Erie will be paired with the corresponding 59 members for Ontario. The positive spatial and temporal correlations between these two ensembles have a significant effect on the combined Niagara and St. Lawrence hydro generation.

This recommendation has been recorded and will be evaluated during model implementation in the operational environment at USACE-Detroit.

Comments from: Laci Farczadi

1. 2 - Model development

   - consider streamlining water supply forecasting system component names listed in Table 1 with model/product names used in the "Research to Operations Synthesis" appendix (e.g. NBSr vs. RNBS, GLSHyFS-3 vs. GLSHyFSv1.2)

     The documentation report has been modified to ensure consistency. We now use the term RNBS to refer to the residual net basin supply system, and alternate versions of GLSHyFS are now identified as v1, v2, and v3.

2. 2.2.2 - LLTM

   - is there any conceptual upgrade from v1.1 to v2.0 other than those associated with the accommodation of the CMIP5 forcing as described in 2.3.2?

     There is no other change than that associated with accommodation of CMIP5 forcings.

   - is there any noticeable impact on model performance from using radiative forcing (from CMIP5) instead of the cloud cover proxy (from traditional climatology)?

     This is an important question, and one we have not fully evaluated at this point in the project. We hope to do so in follow-on studies in partnership with Dr. Tyler Smith.

3. 2.3.1 - GL-AHPS is used to generate longer than 12-month forecasts

   - only NYPA is mentioned to be using AHPS for longer than 12-month forecasts (I believe, 18-month on a regular basis, and longer horizon only on an annual basis), whereas OPG has been using AHPS to generate 24-month horizon forecasts on a regular monthly basis

     We have modified the text to more accurately reflect OPG operational procedures.

4. 2.4.1 - CGLRRM

   - has been updated with the new Lake Superior regulation plan? If not, can include an expected timeline in the 5-yr R20 plan mentioned in the "Research to Operations Synthesis" appendix (specifically Table 3)

     We have modified the timeline to reflect anticipated updates to the Lake Superior and Ontario regulation plans.

5. 3.1.1 - Calculation of observed Niagara River flow

   - what was the source for the Welland River flow and local inflow series?

- any ice/weed corrections?

  Estimates of inflow from the Welland River are provided to USACE Detroit by Seaway. Local inflow information has been included in the report (per response to earlier comment from Rich). Ice and weed retardation are not factored into the computation because of the way that the outflow is computed. In equation 4, the flow at Buffalo is computed as the flow over the falls plus the flow through the power plants plus the NYSBC flow (which is very small) minus inflows that come in between Buffalo and the falls (i.e. inflow from Welland River and local inflows).

6. 3.1.2 - Comparison to forecasts

   - would be useful to see some simple quantitative stats possible to compare with existing records, such as Jan through Dec monthly max, avg, min 50% forecast errors (even if they will not end up being included in the final report).

   - daily variability in LE outflow is of special interest to OPG due to its lower diversion capability (a user requirement properly documented in the Research to Operations Synthesis appendix) - is there any interest/possibility for future improvement on the corresponding (monthly min/max daily flow) forecast skill?

     It is our understanding that the first bullet above represents a request for operational forecasts to include a comparison between future (anticipated) statistics, and historical statistics. Including these as part of the new operational protocol will be discussed during the implementation phase. The second bullet point reflects an interest in improving forecasting skill. There are no immediate plans for model changes that explicitly target improvements in these skill metrics, however we believe it is inherent in the USACE-NOAA R2O partnership that skill deficiencies will be identified and addressed over time.

7. 4 - Operational deployment

   - dissemination and future model selection are limited to OPG and NYPA (see last comment further down)

     Change made.

   - "station data" updates for current GL-AHPS operation will continue to be made available to OPG/NYPA until appropriate to replace with the next model (as explained in the appendix D), isnt it?

     Yes. Until AHPS is formally retired (and replaced by operational implementation of GLSHyFS and RNBS) NOAA-GLERL will continue to provide station updates for the legacy GL-AHPS.

8. Appendix A (3.1.3) - verification of precip forcing for LBRM

   - figure 31 shows monthly precip from CMIP5 QDM output to be underdispersal relative to the corresponding observational proxies - is this a concern for subsequent underdispersion of monthly forecast flows?

     The representation of CMIP5 precipitation is an average of the 19-member ensemble, and is therefore not a particularly valid comparison to the historical observation ensemble. A more

robust comparison would be based on precipitation statistics (including event duration and intensity) of the CMIP5 models, and those of the historical records and historical reconstructions. It is uncertain if this analysis will be included in the documentation report, however we believe it would be an important element of the more detailed follow up studies we anticipate evolving out of this project.

9. **Appendix - Research to operations synthesis**

- Business case: NRCC is not a user (by itself) of the long term forecast - for OPG business purposes, NRCC is using the official OPG forecast (derived using the GL-AHPS, but not identical with, as subject to additional adjustments)

  Changes made to reflect this point.

Comments from: Scott Brown

1. Up front it would be helpful to state that this report is prepared by an independent entity who has no commercial interests in its use. Many times I'll read a report by a consultant taking a position, then later learn the consultant was hired by that firm. Stressing the independence up front would be helpful.

   We have added a preliminary comment to the report (under 'notes') clarifying the independent roles of NOAA, USACE, and UCAR.

2. Also, upfront it might be helpful to give a short description of the various parties. GLERL, USACOE, NRCC, OPG, NYPA, NOAA, etc. Who they are & what they do. For example, NYPA owns and operates two large hydroelectric power projects, one on the Niagara river and the other on the St. Lawrence river, hence our interest in forecasting.

   We have added a section to the beginning of the report providing a brief description of the parties involved in this project.

3. On page 6, the third paragraph (starting with "It is informative. . . "). Might that be better placed toward the end of the report? In first reading, the conclusion is that there are many changes & advancements occurring which may lead a reader to want to sit & wait till that point in time.

   We agree, and have moved this statement into the final section ('additional considerations for operational deployment').

4. Section 2.3. Might it be helpful to list what are the sources of risk (precip, evap, run-off. . .) along with their magnitude? 30% of the deviation with +/- of 15%, for example. Does one introduce more risk than another?

   It is our understanding that this comment relates to uncertainties in forecasts for each water cycle component. Propagating uncertainty in each of those components into overall uncertainty in Niagara and St. Lawrence River flow forecasts is challenging and is not something we have addressed in this documentation report.

5. Page 10, references 1950 - 2011. Is there data available before that, and why not till 2016? For NBS, was there interaction with Environment Canada and was there an improvement in any of the processes as a result of that. If so, state it & take credit for that improvement.

   NBS results are available prior to 1950, however current operational protocols rely on weighting members of a probabilistic ensemble, and those weights are derived from meteorological records that are only developed (for the purposes of operational forecasting) back to 1950. The report text has been modified to clarify this point. Also, NBS values are derived from a binational coordination process that involves Environment and Climate Change Canada, USACE, and other agencies.

6. Page 30, 2nd bullet. Is there any value to updating the forecast more than once a month?

   There may be some benefit to weekly updates, most notably during the early portion of the forecast when initial conditions are important. To address this potential improvement and other needs of this project, forecasts are being updated weekly (rather than monthly) moving forward.

7. Would it be possible to have a 1 or 2 page summary of acronyms? I found myself reading and having to go back.

   We have included a summary of acronyms in the beginning of the report.

END OF REPORT