Five-Year Flow Forecast for the Niagara & St. Lawrence Rivers

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1 Background / Introduction

The New York Power Authority (NYPA), which is New York State's biggest electricity producer, operates two power generation projects on the Great Lakes connecting channels: the Niagara Power Project at Niagara Falls and the St. Lawrence-Franklin Delano Roosevelt Power Project on the St. Lawrence River in Massena, NY (Figure 1). Business decisions at NYPA are made on timeframes ranging from days, to months, to several years.

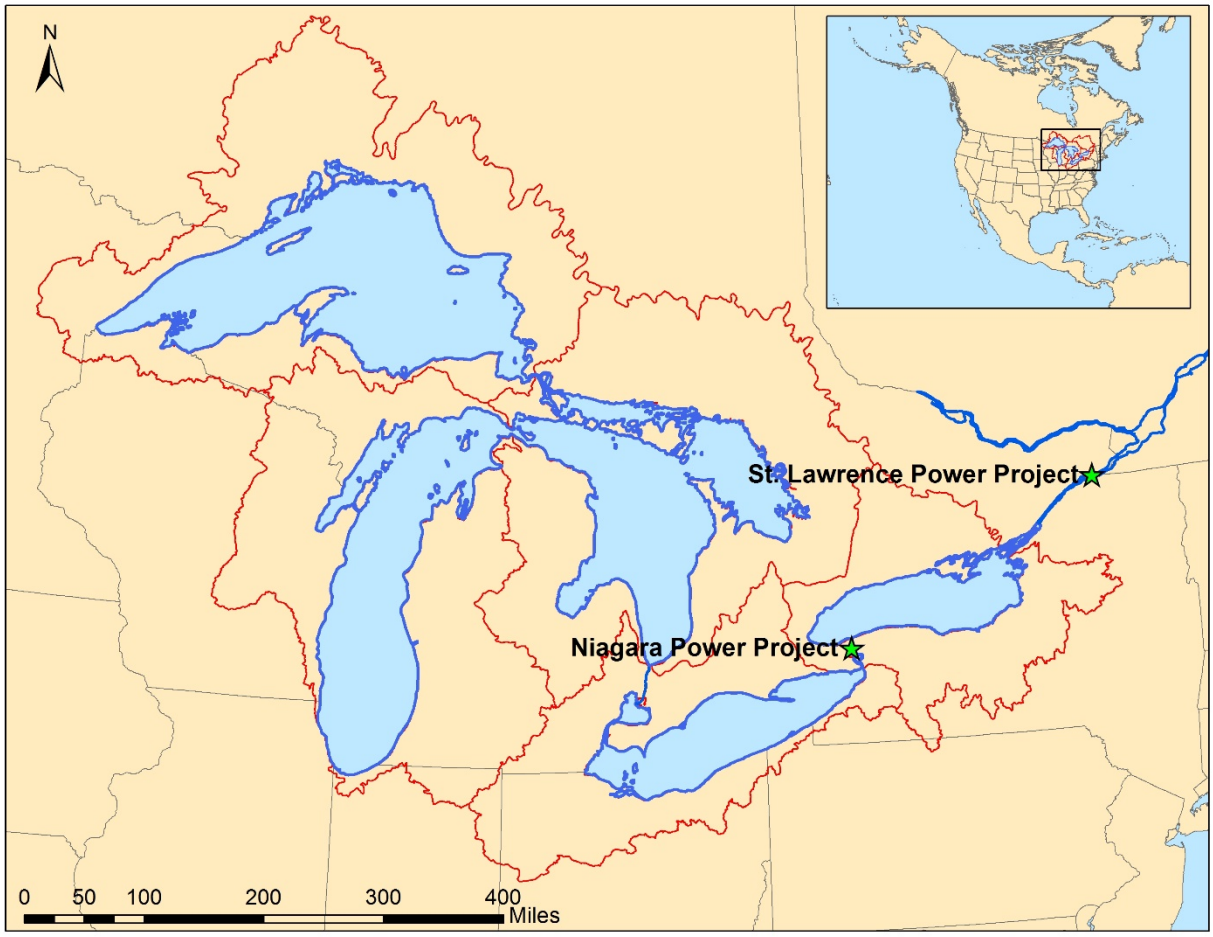


Figure 1. Locations of the NYPA power projects on the Niagara and St. Lawrence Rivers.

USACE-Detroit has a long history of providing seasonal forecasts of Great Lakes water levels in support of Great Lakes water management. The District produces several forecast products at multiple lead times. Forecasts of monthly mean water levels going out 6 months are produced on a monthly basis and coordinated with counterparts in the Great Lakes-St. Lawrence Regulation Office (GLSLRO) of Environment and Climate Change Canada (ECCC). Along with this water level forecast, mean Niagara River and St. Lawrence River flows are forecast and shared with NYPA and OPG engineers. In addition to this 6-month forecast, a forecast of the lakewide average water level one month out is produced each Thursday or Friday. This weekly forecast includes a forecast of channel depths in the connecting

channels over the next 4 weeks. Finally, a 12-month scenario-based water level outlook is produced each month, describing potential water level outcomes under various relevant climate scenarios.

Forecasts of Niagara River and St. Lawrence River flows at time horizons of multiple years are used by hydropower agencies for investigating financial hedging instruments to levelize year-to-year hydropower generation revenue. Insurance premiums guarantee a tolerable minimum level of generation each year, and the cost of these premiums are currently determined based on statistical analysis of the year-to-year change based on historical data, without consideration of the fact that current water levels on the upper lakes have a lasting influence on water levels and outflows of Lake Erie and Lake Ontario. This cost is higher each year out, but could be reduced by millions of dollars with reductions in forecast uncertainty.

In addition to the statistical methods used by re-insurers, NYPA engineers have been running the physically-based Great Lakes Advanced Hydrologic Prediction System (GL-AHPS, developed at NOAA's Great Lakes Environmental Research Laboratory) as additional forecast guidance. The use of this physically-based model with a routing and regulation model adds value beyond statistical models used by the re-insurers, because it allows for more realistic representation of the interplay between regional climate and Great Lakes water levels and flows. After decades of operation, they have found that the accuracy of power generating forecasts that are derived from the probabilistic GL-AHPS Niagara River flow forecast is better than an analysis of the year-to-year change in the historical generating data. However, GL-AHPS forecasts are limited by (1) lack of ability to forecast the Lake Ontario outflow and (2) use of historical meteorology as forcings.

In 2015, following a workshop focused on identifying hydrometeorology research priorities to meet hydropower customer needs, a team composed of representatives from the National Oceanic and Atmospheric Administration (NOAA) Great Lakes Environmental Research Laboratory (GLERL), USACE-Detroit, the Niagara River Control Center (NRCC), NYPA, and Ontario Power Generation (OPG) launched a research project to further develop and improve GL-AHPS for application to forecasting variability of Niagara River and St. Lawrence flows over a 5 year horizon. Specifically, NYPA and OPG were interested in having independent probabilistic forecasts of daily Niagara and St. Lawrence River flows going out 60 months, produced by a trusted operational agency, available on a weekly basis. These forecasts were to be informed by seasonal climate outlooks and longer term climate change projections. USACE-Detroit was identified as the logical operational agency to produce the new forecasts.

Work on this project took place during two phases. From late 2015 to 2017, work was focused on research and development of climate change driven meteorological forcings and a modeling framework that evolved from the GL-AHPS models, but incorporated added flexibility to allow alternative meteorological drivers as well as flexibility to enhance transfer of the modeling framework to USACE-Detroit. Although this funding was not provided through the PAS agreement, a summary of this phase is included in this report as necessary background. This research phase is described in Section 2, describing model development, and Section 4.1, providing a summary of the original assessment results. In FY 2018, a PAS agreement was signed to develop this modeling framework within the operational environment at USACE-Detroit. Work conducted for this project, including operational implementation, assessment of available operational forecasts, and the development of websites used to communicate the forecasts, is described in Sections 3 to 5.

2 Water supply, routing, and regulation models

Flows in the connecting channels of the Great Lakes, which include the Niagara River and St. Lawrence River, depend on water supply generated within each of the Great Lakes basins (i.e. through precipitation over the lakes, evaporation from the lakes, and runoff into the lakes) and hydraulic conditions and regulations that govern the translation of water supply to flow. The research phase of this project addressed both water supply forecasts and translation of forecasted supplies through regulation and routing models. Development of water supply forecasting systems, including the meteorological forcings employed, is described in Section 2.1, and development of an ensemble regulation and routing framework is described in Section 2.2. Sections 2.1 and 2.2 provide an overview description of the modeling systems developed, summarizing details that are found in greater depth in the Project Documentation Report for the Great Lakes seasonal inter-annual water supply forecasting improvements project Phase I: Research and Development (Gronewold et al. 2017).

2.1 Water supply forecasting systems

The ensemble water supply forecast systems developed and tested during the research phase of this project are described in Table 1. All systems result in an ensemble of net basin supply (NBS). NBS represents the amount of water entering (or leaving) a lake, excluding inflows and outflows through connecting channels and diversions. Two methods are used for computing NBS, both of which are derived from the water balance for each lake, described in equation 1.

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

In equation 1, ΔZ is the change in storage (typically calculated as a change in lake surface water elevation); P, R, and E are overlake precipitation, lateral runoff and overlake evaporation; Q_i and Q_o are the inflows and outflows from upstream/downstream lakes and diversions; and ϵ represents the unexplained uncertainty. Equation 1, rearranged, results in two ways of computing the NBS, shown in equation 2.

$$\begin{gathered} P + R - E + \epsilon = \Delta Z - Q_i + Q_o \\ NBS_C = P + R - E \\ NBS_R = \Delta Z - Q_i + Q_o \end{gathered} \tag{2}$$

The water supply forecast systems differ in their configurations, in terms of both the meteorological drivers and the hydrological models used to forecast water supply. Differences in the meteorological drivers are described in Section 2.1.1, and differences in the hydrological models are described in Section 2.1.2. Over time, it is expected that the set of modeling systems will become smaller as differences in skill over long time horizons in the operational environment become apparent.

Table 1. Water supply forecast systems developed and tested for the research phase of the project.

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	CMIP-5	LBRMv2.0	LLTMv2.0
RNBS	None	Historical supply sequences	

GL-AHPS and GLSHyFS are modeling frameworks that compute component NBS (NBS_C) using a lumped conceptual rainfall-runoff model (the Large Basin Runoff Model, LBRM, described in Croley II, 1983) to simulate tributary runoff and the Large Lake Thermodynamics Model (LLTM, described in Croley II, 1989) to simulate evaporation from the lakes. Meteorological forcings are processed to subbasins shown in Figure 2. LBRM simulates runoff from each subbasin, and LLTM simulates evaporation from each lake, designated subbasin zero for each lake basin.

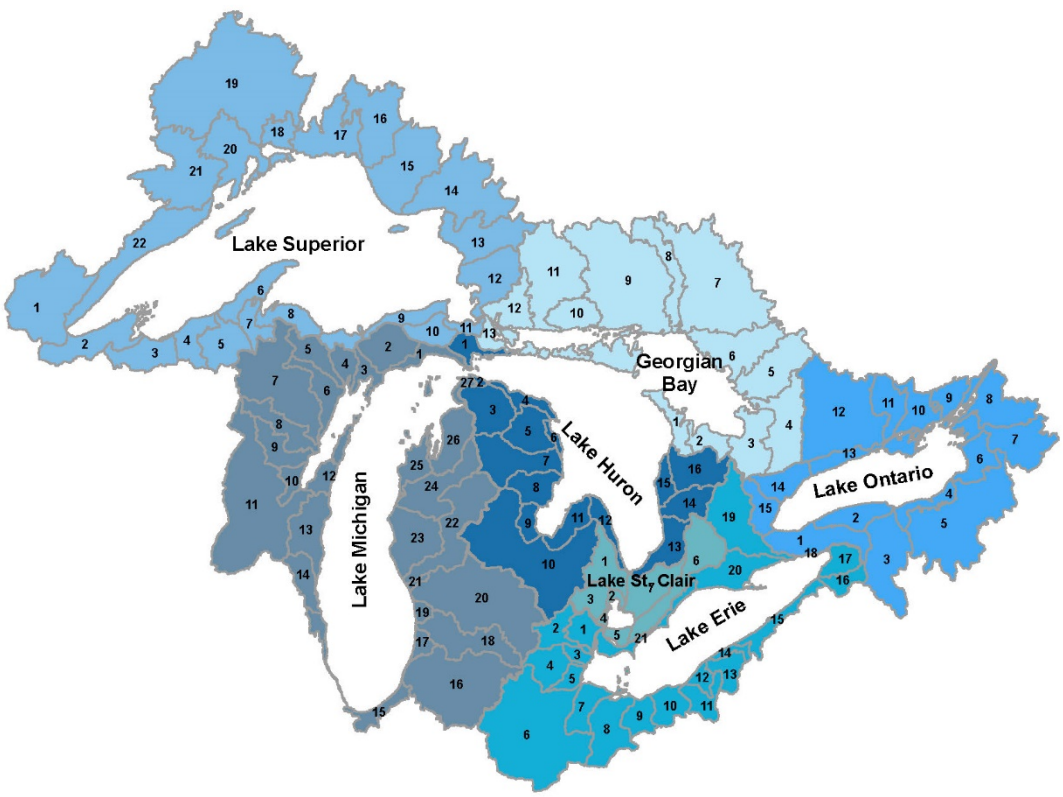


Figure 2. Spatial framework employed by GL-AHPS and GLSHyFS. Meteorological station data is aggregated to each subbasin, LBRM simulates tributary runoff from each of the land subbasins, and LLTM simulates evaporation from the lakes (subbasin zero for each lake basin).

2.1.1 Meteorological forcings

Meteorological data required for GL-AHPS and GLSHyFS include daily maximum, average and minimum air temperature (T_{max}, T_{avg}, and T_{min}), precipitation (P), surface wind speed (U), cloud cover (A_c) and dew point temperature (T_d). Two approaches to developing the meteorological forcings were employed in the water supply forecast systems evaluated for this project. In the first approach, called "climatology" in Table 1, historical meteorological data were used to develop an ensemble of T_{max}, T_{avg}, T_{min}, P, U, A_c, and T_d. In the second approach, meteorological variables simulated by the suite of models in the Couple Model Intercomparison Project (CMIP-5) were downscaled to produce an ensemble of 19 sets of forcings.

Development of the climatology meteorological forcings (used by GL-AHPS, GLSHyFS-1, and GLSHyFS-2) followed methods described by Hunter et al. (2015), in which daily station data are interpolated to subbasin and overlake values using a Thiessen weighting approach.

During the research phase of the project, postdoctoral fellow Lisi Pei (posted at GLERL under the supervision of Andrew Gronewold) developed a suite of meteorological forcings that would represent conditions under a changing climate. Meteorological variables simulated by the suite of models in CMIP-5 were bias corrected using the Quantile Delta Mapping Method (Cannon et al. 2015) for the period of 2006 to 2095. These bias-corrected monthly meteorological fields were disaggregated into daily values for each GLSHyFS/GL-AHPS subbasin to build a set of meteorological forcings for 2006 to 2095. Dr. Pei's work and the resulting dataset is described in detail in the appendix of Gronewold et al. (2017), which can be obtained by request from USACE-Detroit or GLERL.

2.1.2 Hydrological models

In addition to alternative meteorological forcings, the water supply forecasting system configurations described in Table 1 differ in terms of the hydrological models used to simulate NBS. GL-AHPS and all GLSHyFS configurations rely on the Large Basin Runoff Model (LBRM), a lumped conceptual rainfall-runoff model and the Large Lake Thermodynamic Model (LLTM).

The LBRM propagates daily mean air temperature (calculated as an average of daily maximum and minimum temperatures) and daily total precipitation to subbasin runoff. The original version of LBRM (LBRMv1.0) was previously found to significantly over-estimate evapotranspiration (*ET*) due, in part, to its representation of ET as a function of air temperature and solar energy (Lofgren et al., 2011, 2013, Lofgren and Gronewold, 2014). Although the extent to which this misrepresentation impacts forecasts on the inter-annual time horizon is unknown, a new version of LBRM (LBRMv2.0) was developed by GLERL, and it includes a reformulated *ET* algorithm with calibrated model parameters conditioned on temperature-rainfall-runoff relationships. Details on the new *ET* algorithm and model calibration can be found in the appendix of Gronewold et al. (2017).

In GL-AHPS and GLSHyFS, overlake evaporation is modeled using the LLTM. Two versions of the LLTM were included in the development of the ensemble forecast configurations. The first version, LLTMv1.0, is essentially the same as the original version developed by Croley II (1989), but with parameter values that were updated through a joint USACE-Detroit and GLERL project to reflect recent updates to lake surface temperature and ice cover data. The second version, LLTMv2.0, is significantly modified in order to accommodate the CMIP-5 forcings (required for GLSHyFS-3). In LLTMv1.0, cloud cover data is used to estimate radiation, but cloud cover data are not available in the CMIP-5 derived forcings. Accordingly,

LLTMv2.0 uses radiation directly. These modifications are described in the appendix of Gronewold et al. (2017).

The last water supply forcing system listed in Table 1 is the RNBS system. In this system, an ensemble of future NBS is created using an ensemble of historical residual NBS (NBS_R). It is recognized that this is not a true forecast, but is included as both a baseline for comparison and as a forecast scenario in which supplies of the future can be represented by past supplies. For further details, see Gronewold et al. (2017).

2.2 Ensemble Routing and Regulation Models

Translation of NBS to water levels and lake outflows requires simultaneous simulation of flows through all of the connecting channels, which are dependent on lake-to-lake water level differences, channel characteristics (including ice and weed retardation), and regulation of the St. Marys and St. Lawrence River control structures. Regulation and routing models handle this complex simulation. In the case of all but Lake Ontario, simulation is done through the Coordinated Great Lakes Regulation and Routing Model (CGLRRM, described in USACE 2001), which was developed by the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (referred to hereafter as the "Coordinating Committee"). In the case of Lake Ontario regulation and routing, a separate regulation and routing model was required, because although the CGLRRM includes code for simulating Lake Ontario regulation and routing, it has only been rigorously tested for Lakes Superior through Erie (USACE, 2001). Additionally, all previous regulation and routing code within CGLRRM and existing forecast routines at USACE-Detroit ran Lake Ontario code employing Plan 58D. A new Lake Ontario regulation routing script using Plan 2014 was developed in conjunction with this project.

The CGLRRM and the Lake Ontario regulation and routing code are designed to carry out a single simulation. In order to propagate the ensemble forecasts produced by the GL-AHPS, GLSHyFS, and the RNBS water supply forecasting system configurations into an ensemble of water level and outflow forecasts, an ensemble processing procedure was developed. The Great Lakes Ensemble Regulation and Routing Forecasting System (GLERRFS) runs an ensemble of NBS sequences through the CGLRRM and Lake Ontario regulation models, resulting in an ensemble of water level and outflow projections for each of the Great Lakes. GLERRFS also includes a sub-routine that uses user-specified weights to develop weighted probabilistic forecasts for the Great Lakes. This ensemble processing system is shown graphically in Figure 3, and described in greater detail in Gronewold et al. (2017).

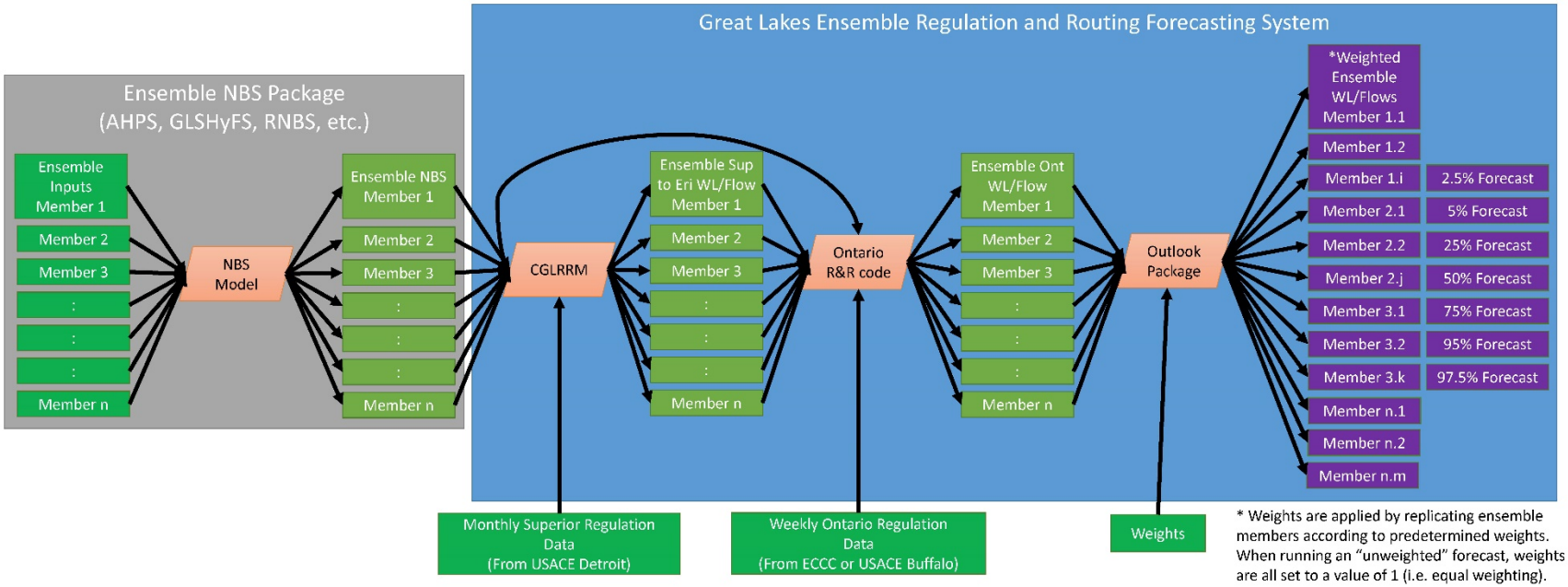


Figure 3. Full graphical description of the ensemble forecasting system implemented in this project.

3 Operational Implementation

As model configurations were developed, simultaneously, work was underway to transition completed configurations to an experimental operational environment. By the end of FY2017, configurations based on GL-AHPS and RNBS were implemented and running in an experimental mode on a forecaster's desktop machine at USACE-Detroit, resulting in forecasts for Lakes Superior through Erie. At the end of the model development phase, a project closeout meeting was held with the GLERL-USACE team and OPG, NYPA, and NRCC representatives to provide results and set the stage for future work to fully operationalize the new modeling frameworks. A research-to-operations (R2O) timeline, depicted in Figure 4, was proposed, and is the basis for work conducted for this PAS agreement. Accordingly, the majority of effort for this phase of the project was focused on implementing GLSHyFS and new Lake Ontario regulation and routing code within this new operational environment, improving the automated operational procedures that run the forecast system, assessing the forecasting systems, and developing products to communicate the forecast.

In addition to forecasts of Lake Erie outflow and St. Lawrence River flows, it was also determined that further work was needed to develop a post-processing procedure to translate Lake Erie water level (or outflow) forecasts to flows at the Chippewa Grass Island Pool, the location on the Niagara River of most importance to hydropower decisions.

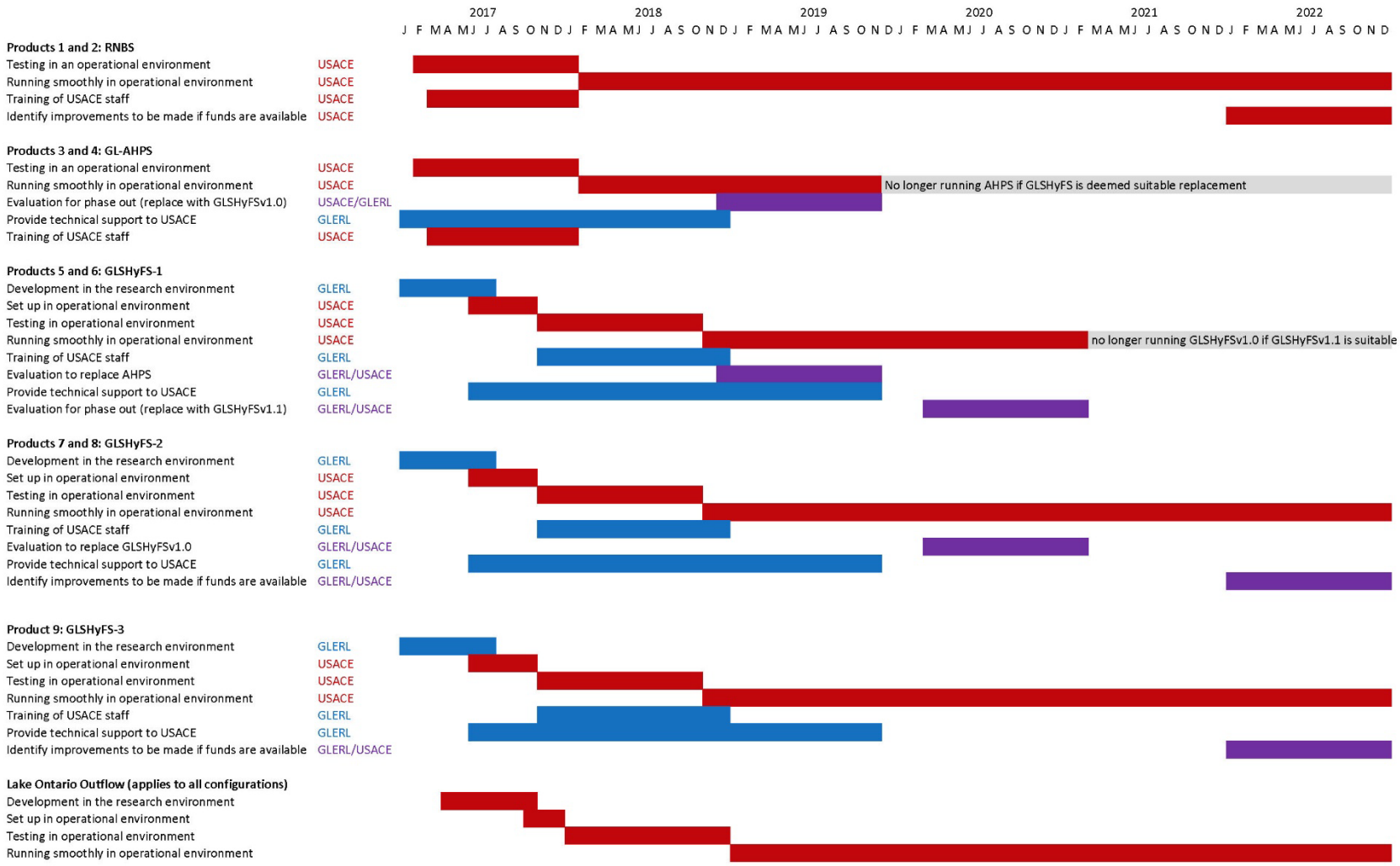


Figure 4. Timeline for transition from research to operations.

3.1 Data flow

Figure 5 shows the general flow of information for each forecast system, with emphasis on where data are coming from and where model software is run. There are some differences in the flow of information among the forecast systems that are worth pointing out. First, GL-AHPS water supply forecasts are implemented in much the same way that these water supply forecasts have been run at USACE since 2007. The main advancement over previous GL-AHPS implementation is that it is now being run through GLERRFS. Previously, the median GL-AHPS NBS forecast was used as a deterministic input to the 6-month water level forecast. Notably, operation of GL-AHPS was never truly transitioned from GLERL to USACE; USACE GL-AHPS forecasts continue to rely on the GLERL server to gather and preprocess meteorological station data from the National Center for Environmental Information (NCEI) into an appropriately formatted input file. One major advancement of the GLSHyFS system over GL-AHPS is the inclusion of meteorological station data downloading and preprocessing routines, allowing USACE-Detroit to fully operate the system. The CMIP-5 implementation of GLSHyFS (GLSHyFS-3) is shown separately, with the main distinction being that the CMIP-5 forcings for the forecast period have already been prepared on GLERL servers. The resulting forcings have been transferred to USACE servers, but any future development of similar forcings (for example, when new versions of CMIP are released) would likely involve an effort by the GLERL team. Finally, the RNBS system is run entirely at USACE-Detroit.

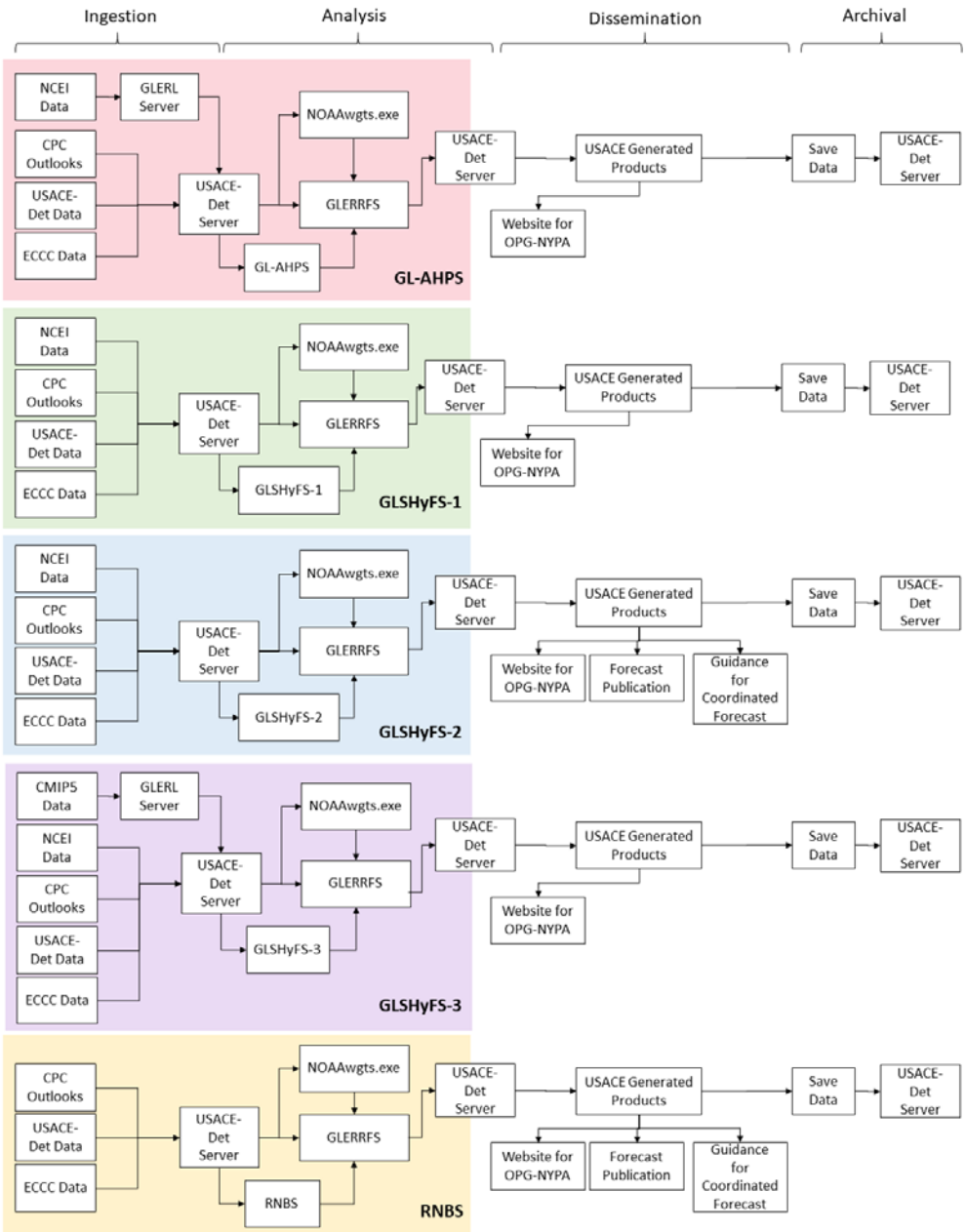


Figure 5. Flow of information for the operational setup of forecasting systems described in this report. Each colored box represents a different NBS forecasting system. Note that for the GLSHyFS-3 system, the CMIP5 data was processed at the GLERL server during the research phase of this project and transferred as a static dataset to USACE-Detroit. Subsequent to this transfer, the GLERL server is no longer involved in operational forecasts using GLSHyFS-3.

3.2 GLSHyFS Implementation at USACE-Detroit

The GLSHyFS executable was developed and is currently maintained by Tim Hunter at GLERL. In addition to the modeling software, Mr. Hunter included with GLSHyFS a procedure for updating meteorological station data. During the PAS funded project, USACE-Detroit staff worked to develop a batch process that

runs the meteorological data updating procedure and then runs GLSHyFS-1, -2, and -3. These processes are run on a Windows machine that is dedicated for automated forecasting tasks. Details for each procedure are described here.

3.2.1 Meteorological data updating procedure

All versions of GLSHyFS require station data to simulate hydrologic conditions for a historical period, which ends at the forecast start date. In the case of GLSHyFS-1 and -2, the ensemble meteorology used to forecast future water supply is also drawn from this historical station data, whereas GLSHyFS-3 uses CMIP-5 derived forcings during the forecast period. The meteorological data updating procedure (hereafter called MakeMet) retrieves and unpacks data from the Integrated Surface Hourly Data Base maintained by the National Center for Environmental Information. Each January, data for a larger set of stations are retrieved and unpacked to create a robust "banked" set of station data files. Data are retrieved and unpacked for 941 stations, shown as large dark red dots in Figure 6, for the period of 1940 to the end of the previous year. On a daily basis, data for a subset of 256 of these stations are retrieved for a "provisional" period starting at the end of the "banked" period. This smaller set of stations is used on a daily basis, because of the time required to download and unpack station data.

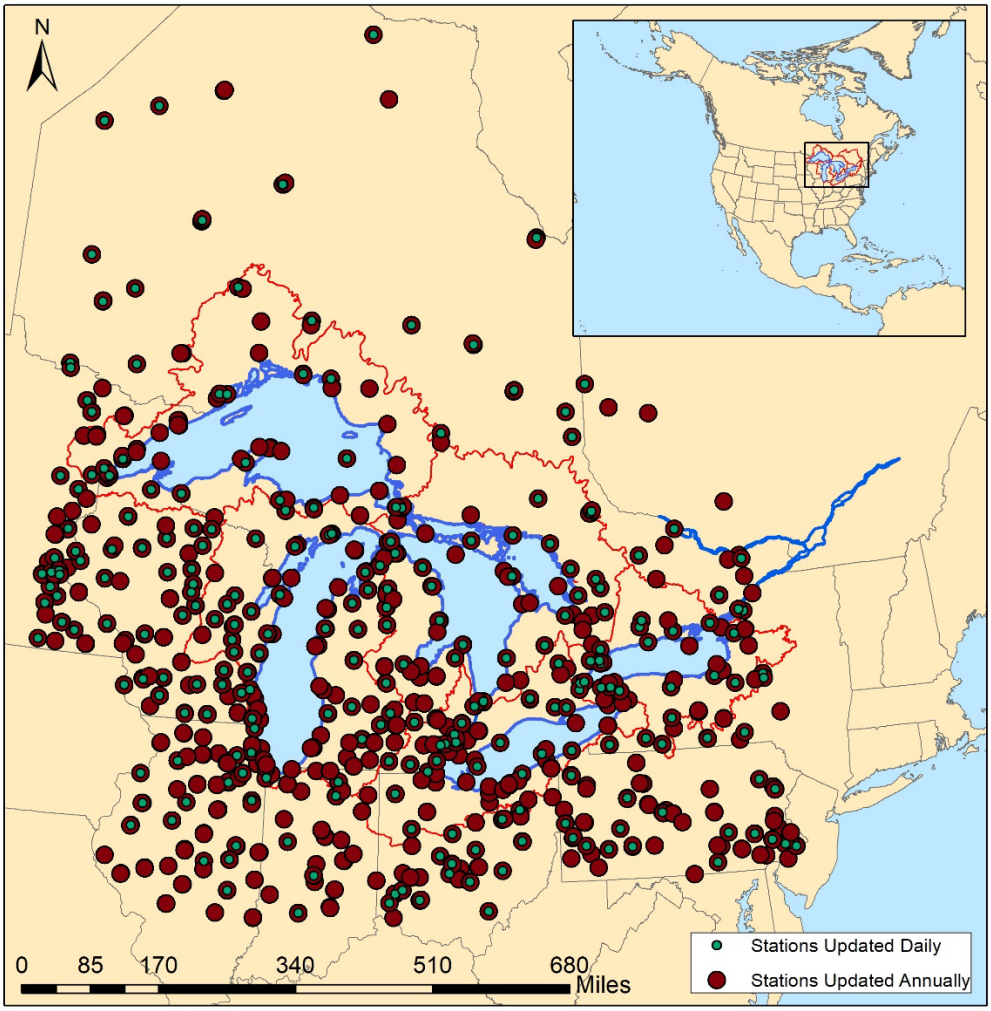


Figure 6. Meteorological Stations used by GLSHyFS.

3.2.2 Running GLSHyFS

GLSHyFS is run on a daily basis from Monday to Friday, except on days when the ensemble water level and outflow forecast is being run (typically Thursdays). It is run on the forecasting Windows 10 machine via a batch file. This batch process starts by running the MakeMet procedure described above to update the station data. Then, configuration files are created for the GLSHyFS-1 and GLSHyFS-2 forecasts. Example configuration files for operational runs of GLSHyFS-1, -2, and -3 are shown in Figure 7, Figure 8, and Figure 9, respectively. The only line that changes in this file from run to run for GLSHyFS-1 and -2 is the line giving the scenario names. This is because the scenario names (i.e. ensemble members to include in the run) must be the same as the scenario names included in the weighting file that is used to create the weighted version of the forecast. A new configuration file is not created for each run of GLSHyFS-3, because the same 19 CMIP-5 scenarios are to be run with each forecast.

Lines 2-5 of the configuration file describe the four procedures that GLSHyFS will execute. The first step, “AddStationData” in the configuration file, gets meteorological station files (that were previously downloaded during the MakeMet procedure), removes unreasonable values, and updates master meteorological files in GLSHyFS. Data are updated starting from the earliest date of a new (or changed) data value in the station data files. In the second step, “BuildSubbasinMet” in the configuration file, station data are used to compute subbasin averages (see Figure 2 for a map of subbasins) using a Thiessen weighting methodology. The third step, “UpdateHistorical” in the configuration file, simulates runoff using LBRM and evaporation using LLTM for a historical period, ending at the end of the provisional station data. This step results in an initial condition for the forecast start. The final step run by GLSHyFS, “RunForecasts” in the configuration file, runs LBRM and LLTM using meteorological forcings defined by the ensemble members listed in the “ScenarioNames” line of the configuration file. In the operational procedure, all four steps outlined above are run for the GLSHyFS-1 and -2 forecasts. Because the GLSHyFS-3 forecast requires initial conditions derived from a historical run of LBRMv2.0 and LLTMv1.0, GLSHyFS-3 is run using the updated historical data from the latest run of GLSHyFS-2. Only the last step in the process (“RunForecasts”) is required for GLSHyFS-3.

cfg_daily_lbrm1.txt - Notepad

File Edit Format View Help

```
cfgname = daily_lbrm1
AddStationData   = Yes
BuildSubbasinMet = Yes
UpdateHistorical = Yes
RunForecasts     = Yes
basedir = c:\GLSHFS_DLY\glshfs1\data
prgdir  = c:\GLSHFS_DLY\glshfs1
stndir  = c:\GLSHFS_DLY\met_stn
BasinBuffer = 50
LbrmMethodET = 1982
LltmMethodRadiationHist = 1
LltmMethodRadiationFcst = 1
LltmApplyDataCorrectionsHist = TRUE
LltmApplyDataCorrectionsFcst = TRUE
ForecastName = dlyfcst
ForecastStart = endofhistdata
ForecastLength  = 61
ForecastMetSource = extractfromhist
ScenarioNames =
1948,1949,1950,1951,1952,1953,1954,1955,1956,1957,1958,1959,1960,1961,1962,19
63,1964,1965,1966,1967,1968,1969,1970,1971,1972,1973,1974,1975,1976,1977,1978
,1979,1980,1981,1982,1983,1984,1985,1986,1987,1988,1989,1990,1991,1992,1993,1
994,1995,1996,1997,1998,1999,2000,2001,2002,2003,2004,2005,2006
MissingValueString = NA
```

Figure 7. Example configuration file for GLSHyFS-1, which uses the climatology approach for meteorological forcings, LBRMv1.0, and LLTMv1.0.

cfg_daily_lbrm2.txt - Notepad

File Edit Format View Help

```
cfgname = daily_lbrm2
AddStationData   = Yes
BuildSubbasinMet = Yes
UpdateHistorical = Yes
RunForecasts     = Yes
basedir = c:\GLSHFS_DLY\glshfs2\data
prgdir  = c:\GLSHFS_DLY\glshfs2
stndir  = c:\GLSHFS_DLY\met_stn
BasinBuffer = 50
LbrmMethodET = 2016
LltmMethodRadiationHist = 1
LltmMethodRadiationFcst = 1
LltmApplyDataCorrectionsHist = TRUE
LltmApplyDataCorrectionsFcst = TRUE
ForecastName = dlyfcst
ForecastStart = endofhistdata
ForecastLength  = 61
ForecastMetSource = extractfromhist
ScenarioNames =
1948,1949,1950,1951,1952,1953,1954,1955,1956,1957,1958,1959,1960,1961,1962,19
63,1964,1965,1966,1967,1968,1969,1970,1971,1972,1973,1974,1975,1976,1977,1978
,1979,1980,1981,1982,1983,1984,1985,1986,1987,1988,1989,1990,1991,1992,1993,1
994,1995,1996,1997,1998,1999,2000,2001,2002,2003,2004,2005,2006
MissingValueString = NA
```

Figure 8. Example configuration for GLSHyFS-2, which uses the climatology approach for meteorological forcings, LBRMv2.0, and LLTMv1.0.

cfg_daily_cmip.txt - Notepad

File Edit Format View Help

```
cfgname = daily_cmip
AddStationData   = No
BuildSubbasinMet = No
UpdateHistorical = No
RunForecasts     = Yes
basedir = c:\GLSHFS_DLY\glshfs2\data
prgdir  = c:\GLSHFS_DLY\glshfs2
stndir  = c:\GLSHFS_DLY\met_stn
BasinBuffer = 50
LbrmMethodET = 2016
LltmMethodRadiationHist = 1
LltmMethodRadiationFcst = 2
LltmApplyDataCorrectionsHist = TRUE
LltmApplyDataCorrectionsFcst = FALSE
ForecastName = dlycmip
ForecastStart = endofhistdata
ForecastLength  = 61
ForecastMetSource = usersupplied
UserMetLocation = c:\GLSHFS_DLY\met_cmip
ScenarioNames =
bccc,caes,ccs4,cnr5,csir,gcm3,ge2g,ge2m,gie2,hgcc,hges,inm4,iplr,ipmr,mir5,mi
re,mpim,mric,ne1m
MissingValueString = NA
```

Figure 9. Example configuration file for GLSHyFS-3, which uses CMIP-5 derived forcings, LBRMv2.0, and LLTMv2.0.

After each GLSHyFS configuration is run, output is archived for later use by GLERRFS. In addition to archiving output, steps are taken to archive files, such as the configuration files, that would be required to reproduce a forecast, should the need arise.

3.3 USACE-Detroit Lake Ontario Regulation Plan 2014 Forecast Code

Previous forecasts run by USACE-Detroit relied on Lake Ontario forecast code employing regulation Plan 58D. When Plan 2014 was approved for regulation of Lake Ontario in 2017, USACE-Detroit had no Plan 2014 forecast code available. In existing operational forecasts (e.g. the Coordinated 6-month forecast and the Weekly Update), Lake Ontario forecasts provided by counterparts in the Great Lakes and St. Lawrence Regulation Office of Environment and Climate Change Canada (GLSLRO) are currently used. As part of this PAS-funded project, new Lake Ontario regulation and routing code was developed for use in the 5-year forecast.

The new Plan 2014 forecast code was initially based on weekly regulation code supplied by GLSLRO. The supplied code was in Fortran, and was designed to be run in a user interface designed specifically for GLSLRO regulation procedures. This regulation code was translated to the R programming language for consistency with other forecasting software at USACE-Detroit, and a forecasting wrapper script was developed to run the regulation code on an iterative basis.

A single Lake Ontario forecast, which is run by a Windows batch file, begins by preparing input data from files on the USACE-Detroit server. Some of these data files require inputs from regulation data that are summarized in the regulation process that is coordinated between GLSLRO and USACE- Buffalo. This regulation process takes place each Thursday. After input data are prepared, the Plan 2014 forecast code is run. This forecast code iteratively uses Plan 2014 regulation code to determine the regulated outflow for the coming week and compute the actual ending levels given the forecasted Lake Erie

outflow (output from CGLRRM) and forecasted NBS (forecasted by GL-AHPS, GLSHyFS, or RNBS) for the week.

Operationally, the Lake Ontario forecast code is called for each ensemble member from within GLERRFS after all ensemble members have been routed through the upper lakes using CGLRRM. The inclusion of Lake Ontario forecasts began with GLERRFS version 1.1, created in January 2018, and improvements to the Lake Ontario forecast continued throughout 2018 as it was tested in the operational environment. A major bug that resulted in very high flows during some periods was found and fixed on 4 April 2018, and subsequent bug fixes have been minor. Prior to the 6 April 2018 forecast, the Lake Ontario outflows were too high and water levels too low, so the adjustment resulted in higher water level forecasts over the long term.

3.4 Predicting Chippewa Grass Island Pool Flows

As mentioned earlier in the report, the Chippewa Grass Island Pool (CGIP) flows are of particular interest to hydropower engineers and professionals. CGIP flows can be calculated as a function of the Lake Erie water level, with the appropriate river translation factor applied to Lake Erie outflow computed using a rating equation. The river translation represents the difference in flow between the Chippewa Grass Island Pool and the Lake Erie outlet (identified by yellow stars in Figure 10).

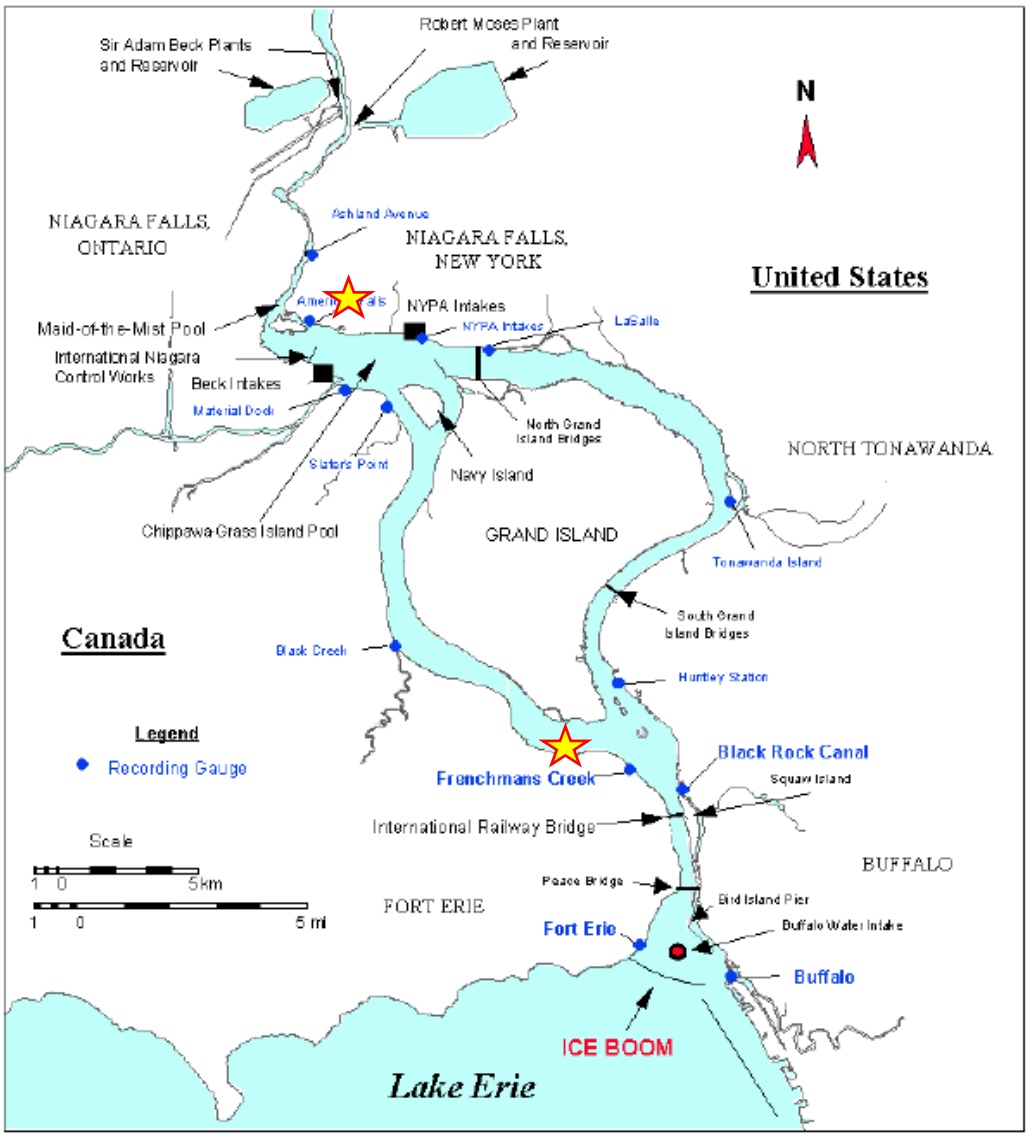


Figure 10. Map of the Niagara River. Buffalo and CGIP locations are indicated by yellow stars. Adapted from Quinn and Noorbakhsh (2001).

The Niagara River flows from Buffalo, downstream (north) around the Grand Island, through the Chippewa-Grass Island Pool, over the Niagara River Falls, past the Maid-of-the-Mist Pool, Ashland Avenue, the power plant Reservoirs, and into Lake Ontario. Accordingly, it can be assumed that the flow at the CGIP, Q_{cgip}, is the sum of the flow at Buffalo, Q_{buff}, plus some additional flow that would account for local inflows, Q_{local}, that occurs between Buffalo and CGIP:

$$Q_{cgip} = Q_{buff} + Q_{local} \tag{3}$$

Typically, flow at Buffalo is calculated using the appropriate rating equation with ice and weed retardation, the general form of which is shown in equation 4.

$$Q_{buff} = k(Z - y_m)^a - R \tag{4}$$

In equation 4, k, y_m, and a are calibrated rating coefficients, Z is the water level at Buffalo, and R is an ice and weed retardation value. In forecasting applications, the lakewide average water level, Z_{Erie}, is typically used as a proxy for the water level at Buffalo. Substitution of the Buffalo flow computed using the rating equation (equation 4) into equation 3 results in an alternative expression of flow at CGIP (equation 5):

$$Q_{cgip} = k(Z_{Erie} - y_m)^a - R + Q_{local} \qquad (5)$$
$$Q_{cgip} = k(Z_{Erie} - y_m)^a - (R - Q_{local})$$

In equation 5, the ice and weed retardation, R, and local inflows, Q_{local} can be lumped together and classified as "River Translation" or RT, resulting in equation 6.

$$Q_{cgip} = k(Z_{Erie} - y_m)^a - RT \qquad (6)$$

Rearranging equation 6 gives an expression of river translation:

$$RT = k(Z_{Erie} - y_m)^a - Q_{cgip} \qquad (7)$$

By intuition, and the mere fact that CGIP is downstream of Buffalo, one may hypothesize that the quantity '$-RT$' would be positive when considering general watershed principles that flow downstream is upstream flow plus additional inflow. However, the ice and weed retardation values of this system are of a larger magnitude than known local inflows.

3.4.1 Historical River Translation Analysis

Average monthly values of river translation (RT, as computed by equation 7) are used to translate forecasts of Lake Erie water levels to flows at CGIP. These average monthly values of RT were computed using historical CGIP flows and historical ice and weed free Buffalo flows. For this analysis, monthly CGIP flow time series were calculated by summing the flows at the Maid of the Mist with the diversions at the NYPA and OPG intakes. These data were provided by Frank Seglenieks of Environment and Climate Change Canada. Monthly Buffalo flow time series were calculated using historical rating equations with historical lakewide average Lake Erie water levels. Over that period of record, various rating equations have been applied. For this analysis the following two rating equations were used for two different period of records. The first is applied to 1948 – 1973 and the second is applied to 1974—2011.

$$Q_{Buff} = 616.78 * (Z_{Erie} - 169.75)^{1.5}$$

$$Q_{Buff} = 699.4 * (Z_{Erie} - 170.043)^{1.5}$$

The resulting flows at CGIP and Buffalo are shown in Figure 11. The period of overlap between these two time series is from 1952 through 2008. The resulting time series for the difference (Q_{buff} - Q_{cgip}) is shown as the light blue line in Figure 12. The time series that results is therefore RT.

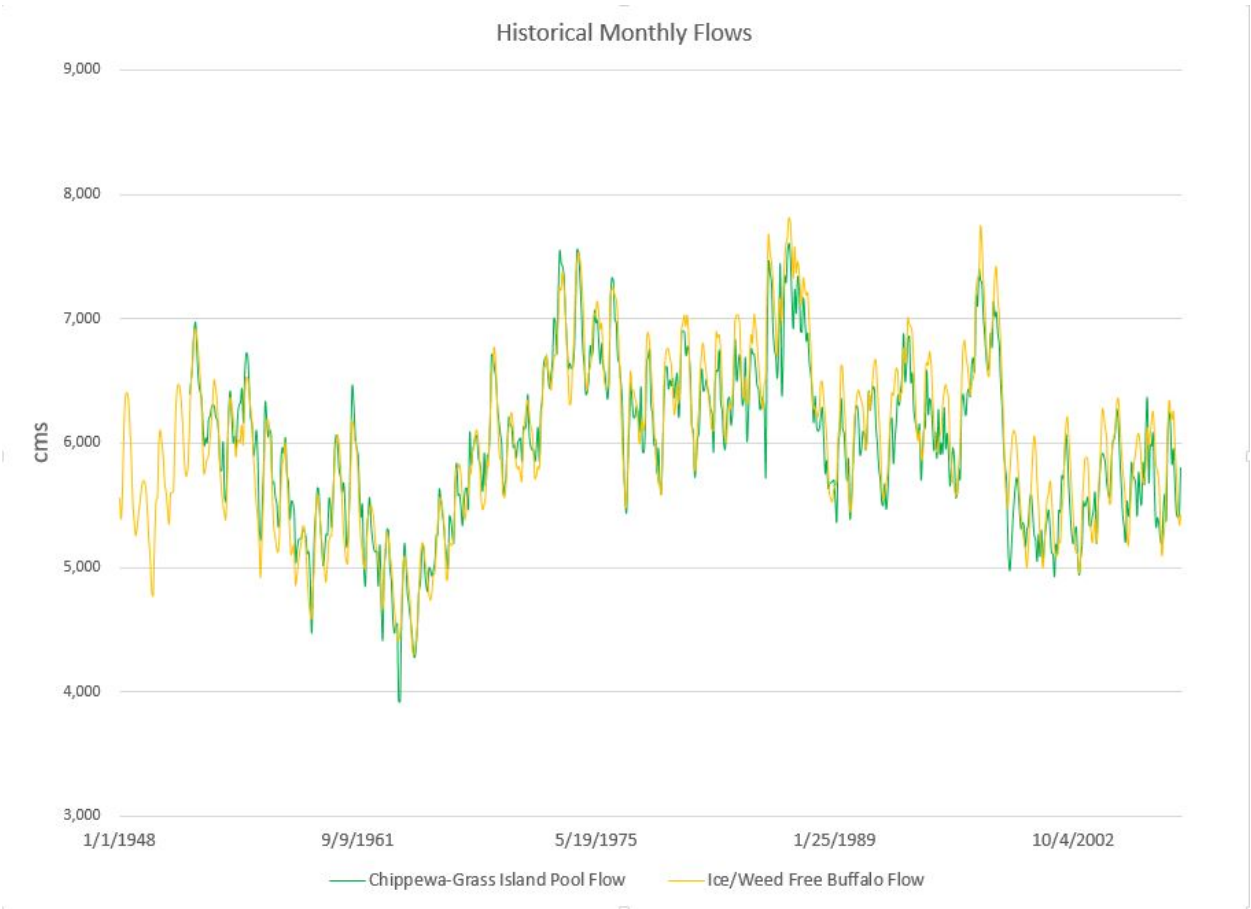


Figure 11. Historical monthly Chippewa-Grass Island Pool and Ice/Weed Free Buffalo Flow for 1948 – 2008 and 1952 –2008, respectively.

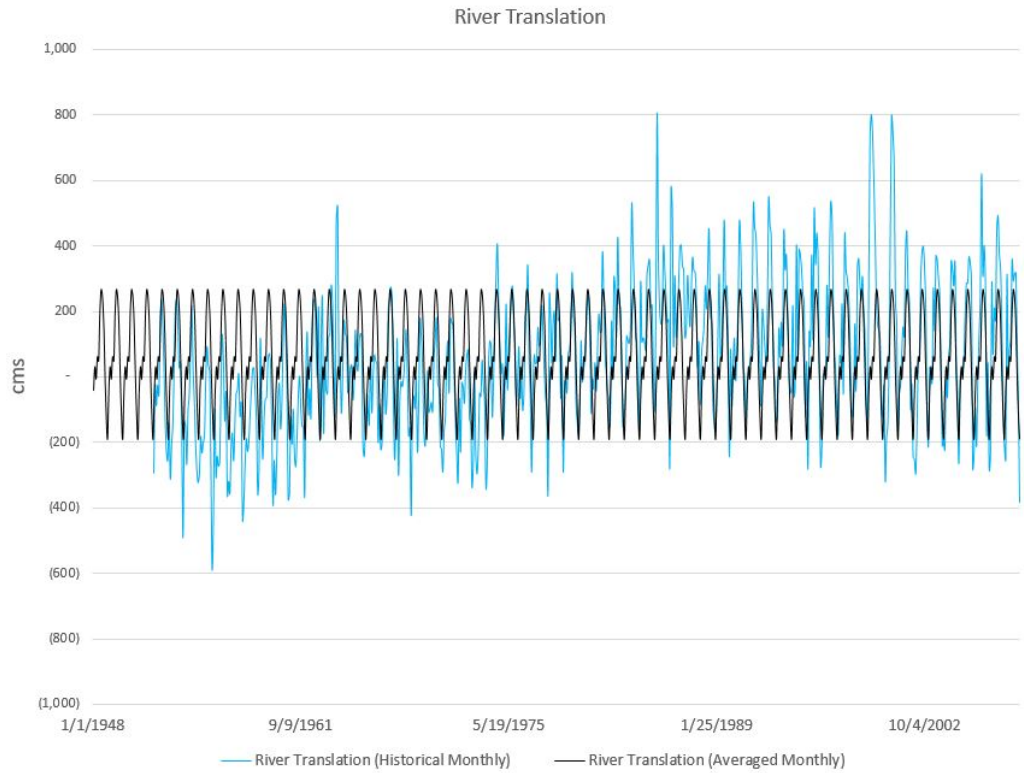


Figure 12. Historical and average monthly river translation.The historical monthly time series, shown in light blue, is derived by subtracting monthly Buffalo flow from monthly Chippewa-Grass Island Pool flow for 1952 – 2008. The black line shows the average monthly river translation, which is the result of averaging the historical monthly values for each calendar month.

The derived historical river translation for 1952 to 2008, shown as the light blue line in Figure 12 was used to calculate monthly constants which are used in the post processing steps for the five year forecast, in conjunction with the Buffalo rating equation coefficients. These monthly constants are shown as a repeating series by the black line in Figure 12, and the final *RT* values are summarized in Table 2.

Table 2. River Translation (cms) for equation 6

Monthly Values for River Translation: to be used in equation 6.											
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
-41	32	-7	62	49	197	267	244	162	9	-117	-189

3.4.2 Verification of River Translation Values

The analysis described above resulted in 12 average monthly values of river translation (Table 2) that are applied to forecasts of Lake Erie water levels. The aggregation to *long term average monthly* values will have some impact on the skill of forecasts at accurately representing the *interannual* and *daily* variability of flows at CGIP. However, limitations of operational forecasting make using average monthly values more practical. For example, the historical record is limited to a period that does not correspond with the length of record required for ensemble forecasts using the climatology approach (e.g. the GL-AHPS, GLSHyFS-1, and GLSHyFS-2 based forecasting systems), there is no corresponding “historical” record to

accompany forecast output from CMIP-5 derived forecasts (i.e. the GLSHyFS-3 based forecast system), and the readily accessible record of daily flows is not available for earlier time periods.

Daily river translation values computed from daily ice and weed free flows at Buffalo and daily flows at CGIP are compared with the historical monthly river translation values in Figure 13. Limited data were available for daily CGIP and Buffalo flow (1998-2008), however, from these time series a short daily historical river translation could be built for a short period of record. Figure 13 shows that the monthly values follow the same pattern and cycle as daily values, but some variability is lost in the monthly representation. However, the variability *among* ensemble members in the probabilistic forecasts going out 5 years is likely large relative to the variability *within* an individual ensemble member that is lost due to the monthly approach.

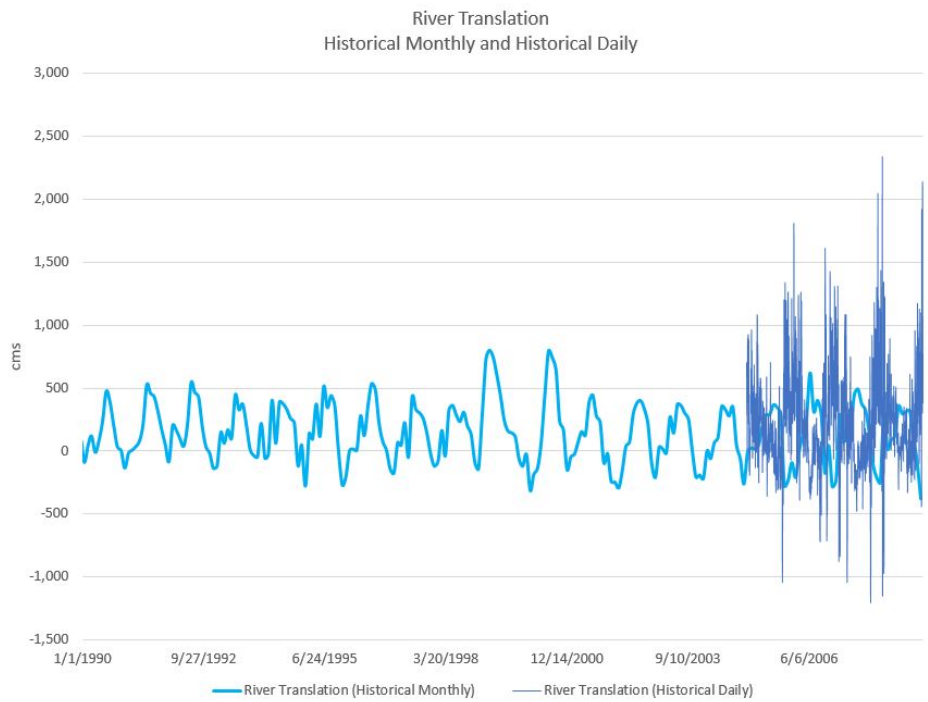


Figure 13 Comparison of Monthly and Daily River Translations.

Finally, an analysis was done to evaluate the impact of applying the 12-month constant values, relative to application of historical monthly *RT* values. The historical monthly river translation was applied to a GLSHyFS-2 forecast, with the ensemble paired down to the ensemble members for which historical monthly values of *RT* were available (i.e. beginning in 1952). The 12 average monthly river translation values in Table 2 were also applied to the same ensemble members. The resulting ensemble forecasts of CGIP flows are shown in Figure 14. Comparing these two forecasts visually does suggest that some variability is lost in the aggregation to average monthly. However, an analysis of the Komogolov-Smirnov (KS) statistic comparing the two ensembles over the forecast horizon shows that the statistic improves over the forecast horizon. This suggests that over time, the ensemble members are essentially drawn from the same distribution. Figure 15 shows the KS statistic and p-value comparing the ensemble forecast for each day of the forecast horizon. In Figure 15, the statistic represents the maximum distance between the cumulative distribution function of the two ensembles, and p-values approaching

one over the forecast horizon suggest acceptance of the null hypothesis that the two ensembles were drawn from the same distribution.

Figure 14. Ensemble forecasts resulting from applying historical monthly river translation values (left) and average monthly river translation values (right).

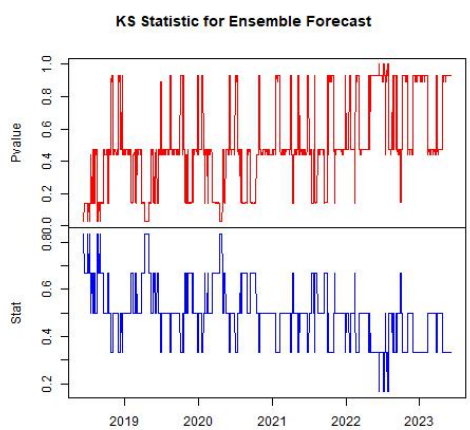
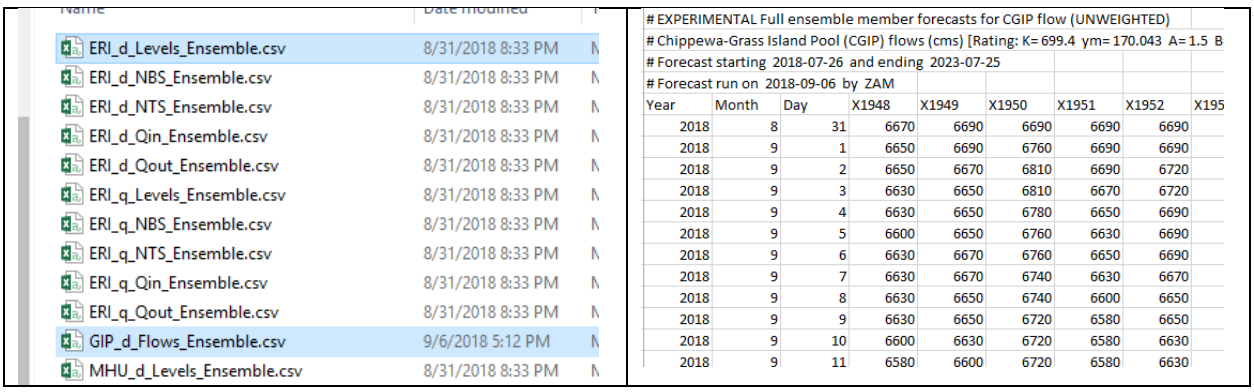


Figure 15 Komogolov-Statistic for comparing the use of historical monthly River Translation ensembles and 12-month constant values.

In consideration of the analysis described here, the recommended approach for translation of ensemble forecasts of Lake Erie water levels to flows at the Chippewa Grass Island Pool is to apply the 12 monthly values of river translation in Table 2 to Lake Erie water levels using equation 6. In forecast mode, equation 6 should be applied using the latest calibration coefficients for the Buffalo rating equation.

3.4.3 Post-Processing in Operational Forecast

The operational forecast now includes ensemble forecasts of the resulting CGIP flows that are calculated using equation 6, using the forecast Lake Erie lake levels and average monthly river translation values in Table 2 as inputs. Results are output in the same csv format as the other forecasted lake level and outflows that are provided (an example is shown in Figure 16). Both unweighted and weighted CGIP flows are compiled during post-processing.



Name	Date modified
ERI_d_Levels_Ensemble.csv	8/31/2018 8:33 PM
ERI_d_NBS_Ensemble.csv	8/31/2018 8:33 PM
ERI_d_NTS_Ensemble.csv	8/31/2018 8:33 PM
ERI_d_Qin_Ensemble.csv	8/31/2018 8:33 PM
ERI_d_Qout_Ensemble.csv	8/31/2018 8:33 PM
ERI_q_Levels_Ensemble.csv	8/31/2018 8:33 PM
ERI_q_NBS_Ensemble.csv	8/31/2018 8:33 PM
ERI_q_NTS_Ensemble.csv	8/31/2018 8:33 PM
ERI_q_Qin_Ensemble.csv	8/31/2018 8:33 PM
ERI_q_Qout_Ensemble.csv	8/31/2018 8:33 PM
GIP_d_Flows_Ensemble.csv	9/6/2018 5:12 PM
MHU_d_Levels_Ensemble.csv	8/31/2018 8:33 PM

EXPERIMENTAL Full ensemble member forecasts for CGIP flow (UNWEIGHTED)
Chippewa-Grass Island Pool (CGIP) flows (cms) [Rating: K= 699.4 ym= 170.043 A= 1.5 B
Forecast starting 2018-07-26 and ending 2023-07-25
Forecast run on 2018-09-06 by ZAM

Year	Month	Day	X1948	X1949	X1950	X1951	X1952	X195
2018	8	31	6670	6690	6690	6690	6690	
2018	9	1	6650	6690	6760	6690	6690	
2018	9	2	6650	6670	6810	6690	6720	
2018	9	3	6630	6650	6810	6670	6720	
2018	9	4	6630	6650	6780	6650	6690	
2018	9	5	6600	6650	6760	6630	6690	
2018	9	6	6630	6670	6760	6650	6690	
2018	9	7	6630	6670	6740	6630	6670	
2018	9	8	6630	6650	6740	6600	6650	
2018	9	9	6630	6650	6720	6580	6650	
2018	9	10	6600	6630	6720	6580	6630	
2018	9	11	6580	6600	6720	6580	6630	

Figure 16. Sample of Chippewa-Grass Island Pool outflow files.

3.5 Improved Operational Procedures

The implementation of GL-AHPS, GLSHyFS, and RNBS derived water level and outflow forecasts has resulted in a number of automated operational and manual procedures to be run by staff at USACE-Detroit. These are described in Table 3. New automated procedures that have been developed and implemented during the PAS project include all processes used to run GLSHyFS, procedures within GLERRFS to run and postprocess the Lake Ontario Plan 2014 forecast code, and a procedure to build a "banked" set of meteorological station data for GLSHyFS.

Table 3. New operational procedures to be run by USACE-Detroit in order to produce the 5-year ensemble forecast.

Daily	Run GLSHyFS batch process, (MakeMet, GLSHyFS-1, -2, and -3)
Weekly (Thursdays)	Run all ensemble water level and outflow forecasts
Monthly (after 3rd Thursday)	Create new weights file using latest CPC seasonal outlooks
Monthly (after last day)	Create new weights file, if CPC changed 1st month outlook significantly
Annually (January)	Run MakeMet to update the "banked" station data for GLSHyFS

Upon development of each new process, it was transitioned to the forecasting Windows machine to be tested in the operational setting. Over the life of this project (FY2018), the Lake Ontario forecast code and GLSHyFS-1, -2, and -3 have been tested in this operational environment, and procedures have been incrementally improved such that by the end of September, all forecasts are running smoothly on a weekly basis. In addition to changes made to debug software or enhance the procedural flow of the

forecasts, efforts have been made to improve error handling and reporting, as well as logging critical information while software is running. All changes, major and minor, are tracked for each automated process using a version control spreadsheet that is maintained by USACE-Detroit staff supporting this effort.

In addition to improving the automated procedures used to produce the forecasts, standard operating procedures have been developed for each process, and key forecasting staff have been trained to run GLSHyFS daily runs and the weekly 5-year ensemble forecasts. As of the writing of this report, four forecasters can run these daily and weekly operational processes.

4 Assessment of Forecast Systems

4.1 Results from initial assessment

Considerable assessment was conducted during the model development phase of this project, including evaluation of hindcasts for forecast start dates from 1998 to 2015. In that assessment, it was noted that all of the forecasting systems reflected seasonality appropriately, but dramatic changes were only reflected in one-month-ahead forecasts. Predictive p-values (Elmore, 2005) for 1- and 6-month forecasts of Lake Erie monthly outflow indicated significant underdispersion across all forecasting system. Over longer horizons, uncertainty bounds appeared to reflect the variability of observations; however the RNBS-based forecast appeared to be biased over long horizons, and the GLSHyFS-3 forecasts, which are driven by CMIP-5 forcings appeared to be significantly biased. Assessment of Lake Ontario forecasts was conducted only on cumulative NBS (as a proxy for St. Lawrence River flows), because the routing and regulation code had not yet been developed. This analysis showed that the RNBS-derived forecasts had the most consistently unbiased forecasts across the entire range of forecasting horizons. For details on analysis methods and results, see Gronewold et al. (2017).

4.2 Assessment of operational forecasts

The transition of forecast software to the operational environment included the development of archiving routines to save all necessary inputs and outputs to the USACE-Detroit network. As of the writing of this report, there are 65 archived forecasts with start dates from February 2017 to present. During the transition to operations, the convention for archiving output changed to accommodate all forecasting systems, so for this analysis, the consistent archiving period from 9 June 2017 to present is evaluated. Table 4 shows the date of implementation of each forecast system and the number of archived forecasts that are included in the assessment of operational forecasts. Although none of these forecasts have been verified through their entire 5-year horizon, the comparison among the forecast output offers some insight into potential relative skill.

Table 4. Archived forecasts evaluated for the analysis at the end of the PAS-funded project.

Forecasting System	Date of Implementation	Number of archived forecasts considered in assessment
AHPS	10 February 2017	65
GLSHyFS-1	24 November 2017	40
GLSHyFS-2	24 November 2017	40
GLSHyFS-3	19 January 2018	32
RNBS	10 February 2017	65

The median forecast from each ensemble forecasts (unweighted versions only) of Lake Erie and Lake Ontario water levels and outflows are shown in Figure 17 to Figure 20. While these plots do not show the overall variability of each model, they do offer a means of comparing the bias of models relative to one another. The most striking difference is between the GLSHyFS-3 forecasting system and the rest of the forecasting systems. Since they were first implemented in January 2018, all GLSHyFS-3 forecasts have shown a strong bias toward higher water levels and outflows relative to other models. The ensemble NBS component forecasts (i.e. precipitation, runoff, and evaporation) are tracked on an operational basis. Typical density plots of these components are shown in Figure 21. Based on evaluation of Figure 21 and similar plots produced with every forecast run, it appears that the bias in GLSHyFS-3 (relative to the other models) is primarily a result of very low evaporation rates.

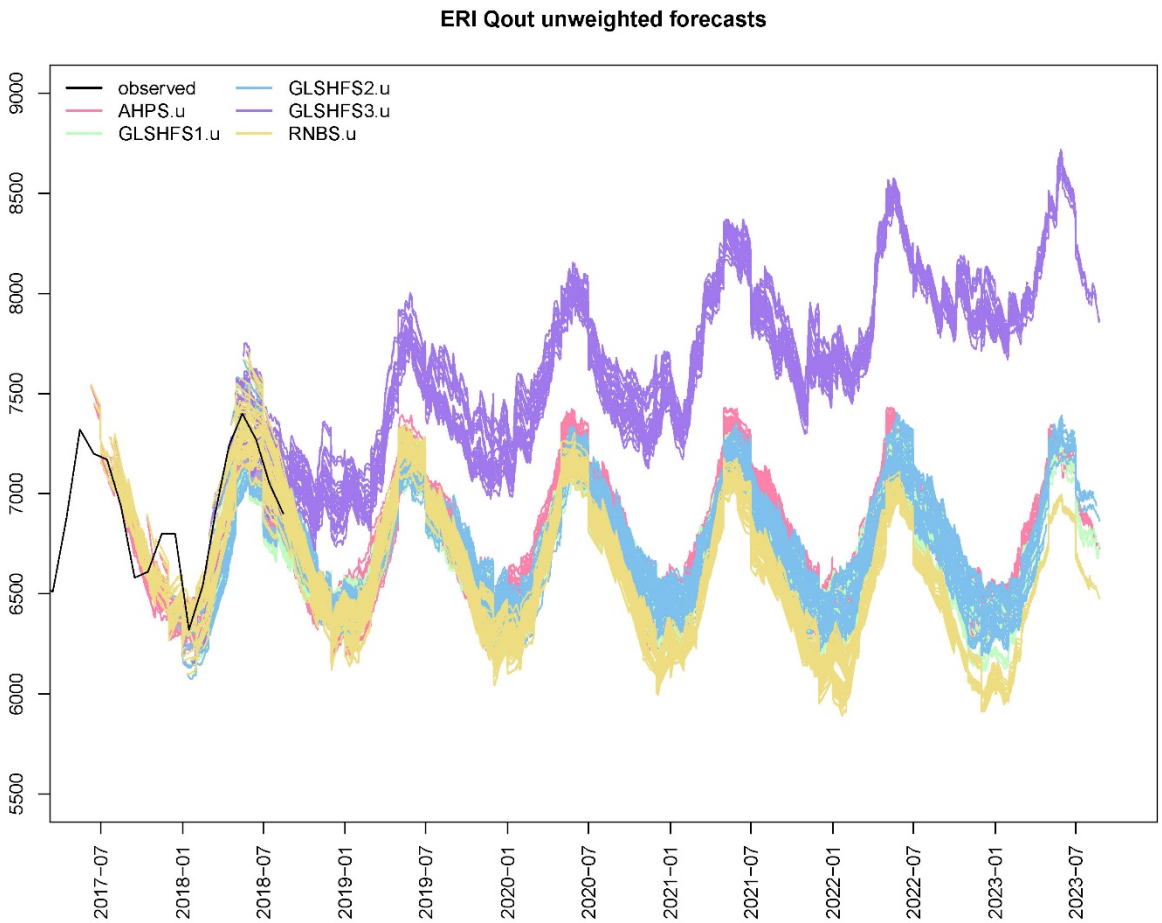


Figure 17. Ensemble median Lake Erie outflow for each archived forecast starting in June 2017. Each line represents the median of an individual ensemble forecast. Note that forecasts depict daily Lake Erie outflow, while the black observed line depicts a monthly mean outflow.

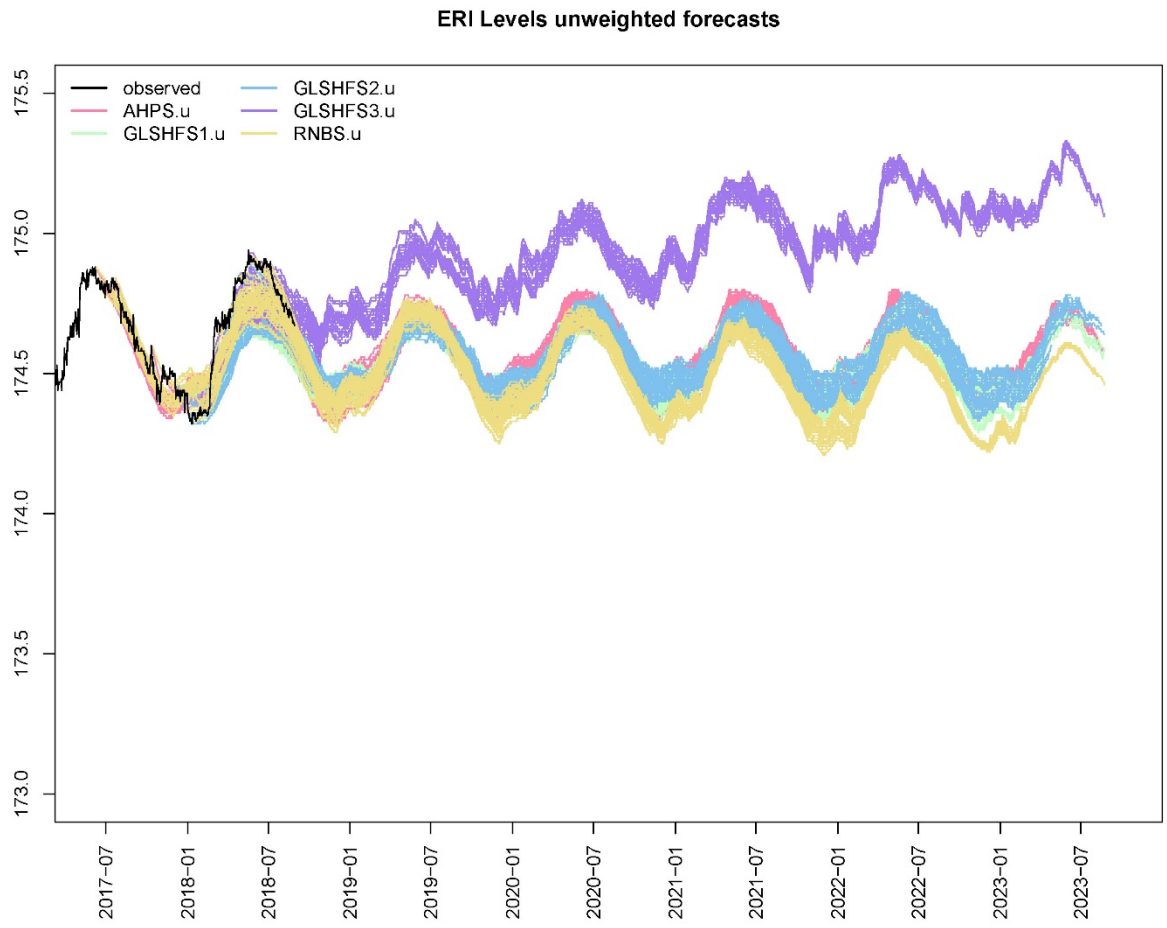


Figure 18. Ensemble median Lake Erie water levels for each archived forecast starting in June 2017. Each line represents the median of an individual ensemble forecast.

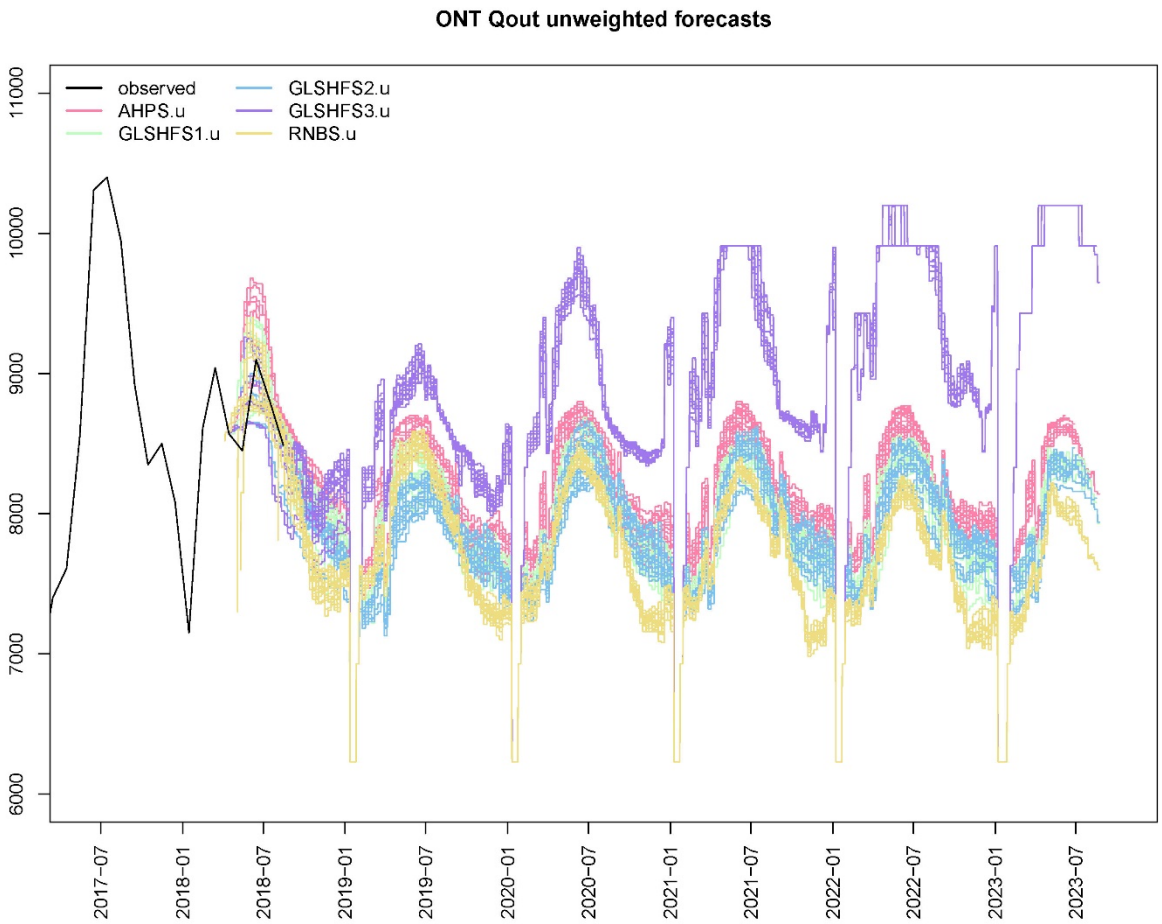


Figure 19. Ensemble median Lake Ontario outflow for each archived forecast starting in April 2018. Each line represents the median of an individual ensemble forecast. Note that forecasts depict daily Lake Ontario outflow, while the black observed line depicts a monthly mean outflow. Also note that there was a significant version change at the beginning of April 2018, when a bug was discovered that resulted in setting the applied limit to 9999 cms when negative flow change was less than the change limit. Accordingly, this plot shows forecast starting with 6 April 2018.

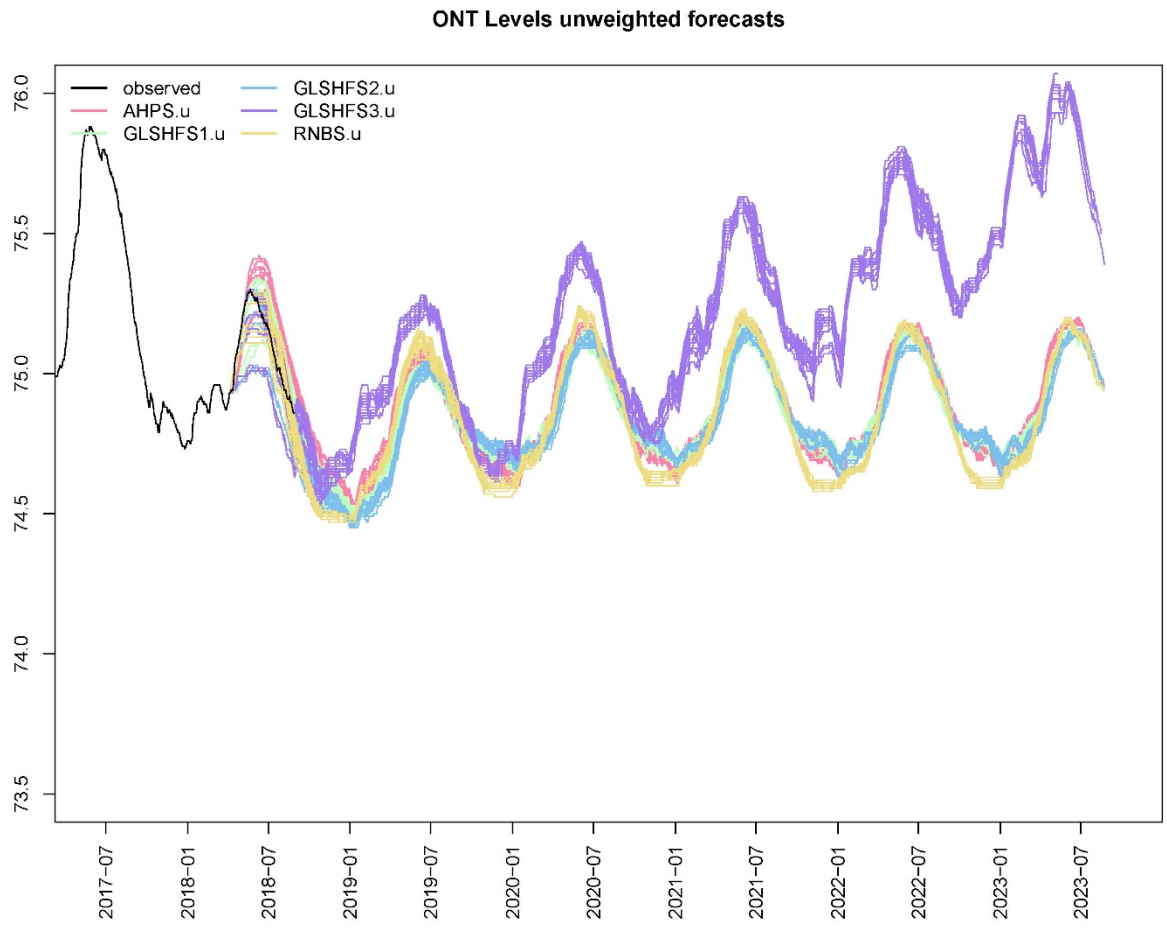


Figure 20. Ensemble median Lake Ontario levels for each archived forecast starting in April 2018. Each line represents the median of an individual ensemble forecast. Note that there was a significant version change at the beginning of April 2018, when a bug was discovered that resulted in setting the applied limit to 9999 cms when negative flow change was less than the change limit. Accordingly, this plot shows forecast starting with 6 April 2018.

Figure 21. Density plots of ensemble forecasts of the NBS and NBS components produced by each (unweighted) forecasting system. Although this graphic shows data for the 11 May 2018 forecasts, the result is similar for other forecasts.

The LLTM forcings used by GLSHyFS-2 (climatology) and GLSHyFS-3 (CMIP-5) are summarized in Figure 22 to Figure 27, and show that the wind speed derived from the CMIP-5 output is biased much lower than the climatology (station-derived) forcings. It has been shown previously that models assimilating land-based gage information (such as NARR, which was the basis for downscaling CMIP-5 wind speeds) result in estimates of overwater wind speeds that are biased low relative to overwater wind speeds estimated through interpolation from land-based gages with empirical adjustments (as is done in the climatology setup of GLSHyFS) (Rowe et al., 2015). The large difference between the two wind forcings could be an explanation for the very low evaporation, and thus the very high water levels and outflows that are forecast by GLSHyFS-3.

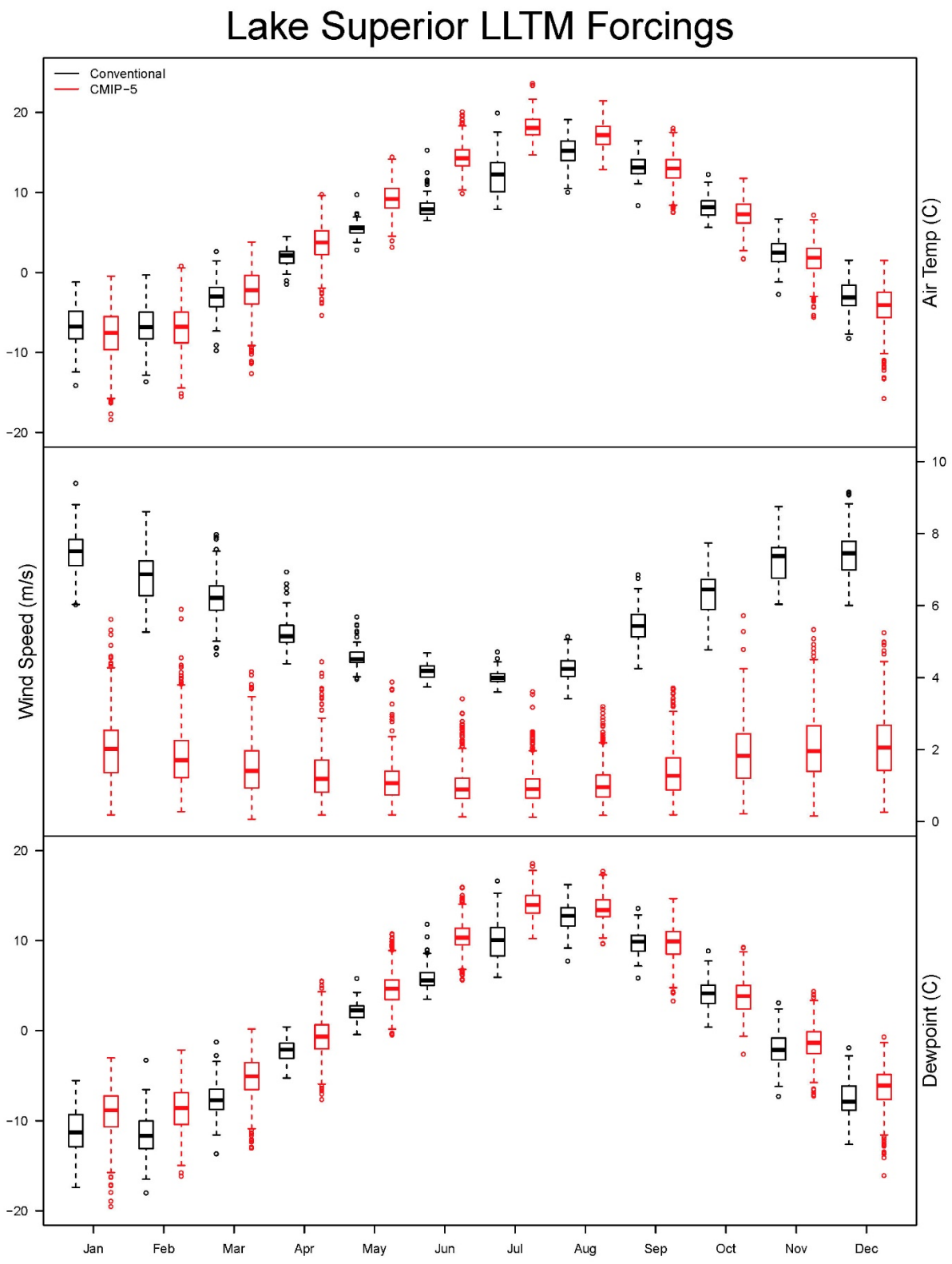


Figure 22. LLTM meteorological forcings, summarized by month, used by GLSHyFS-2 (climatology) and GLSHyFS-3 (CMIP-5) for Lake Superior NBS forecasts.

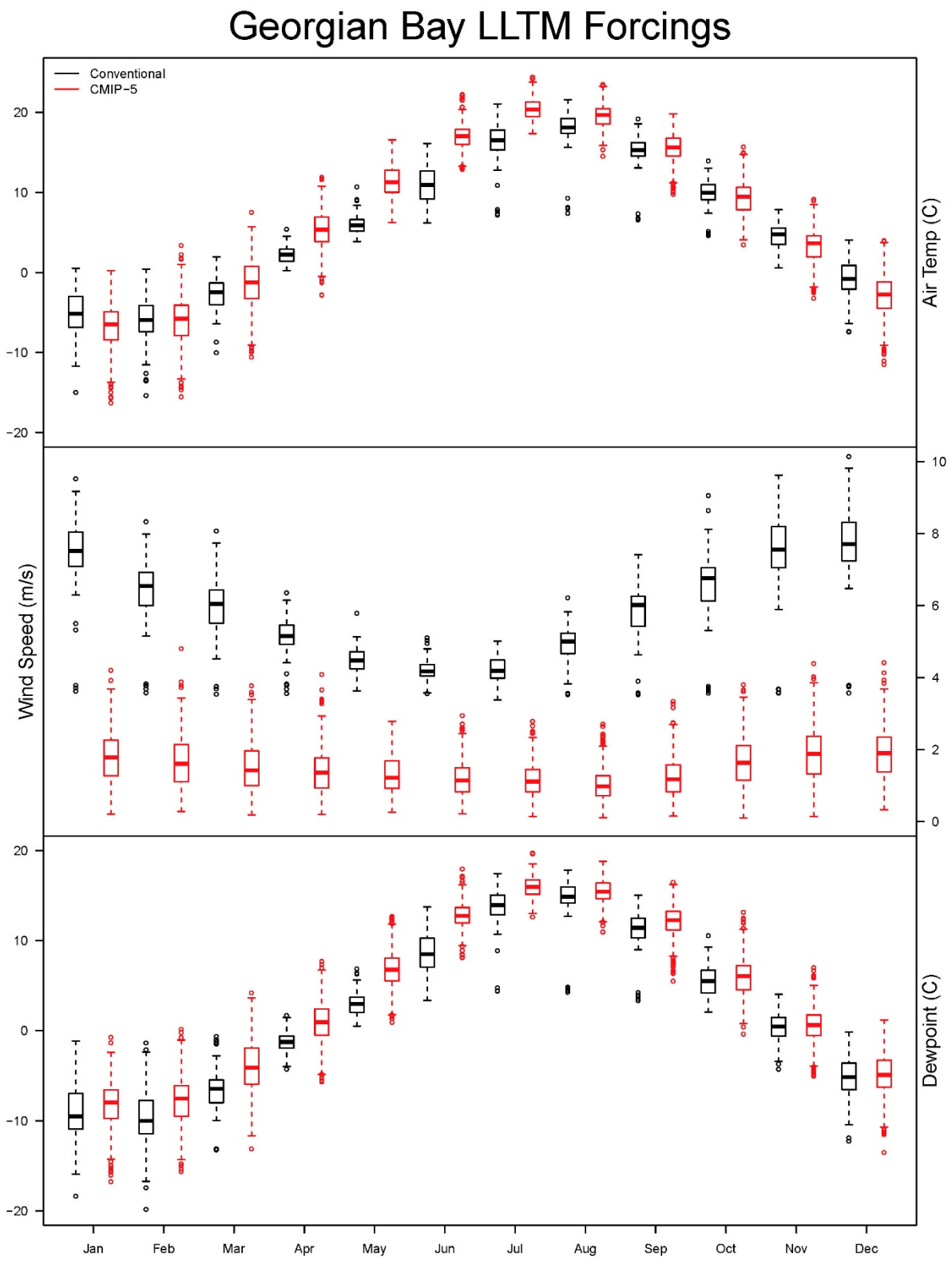


Figure 23. LLTM meteorological forcings, summarized by month, used by GLSHyFS-2 (climatology) and GLSHyFS-3 (CMIP-5) for Georgian Bay NBS forecasts.

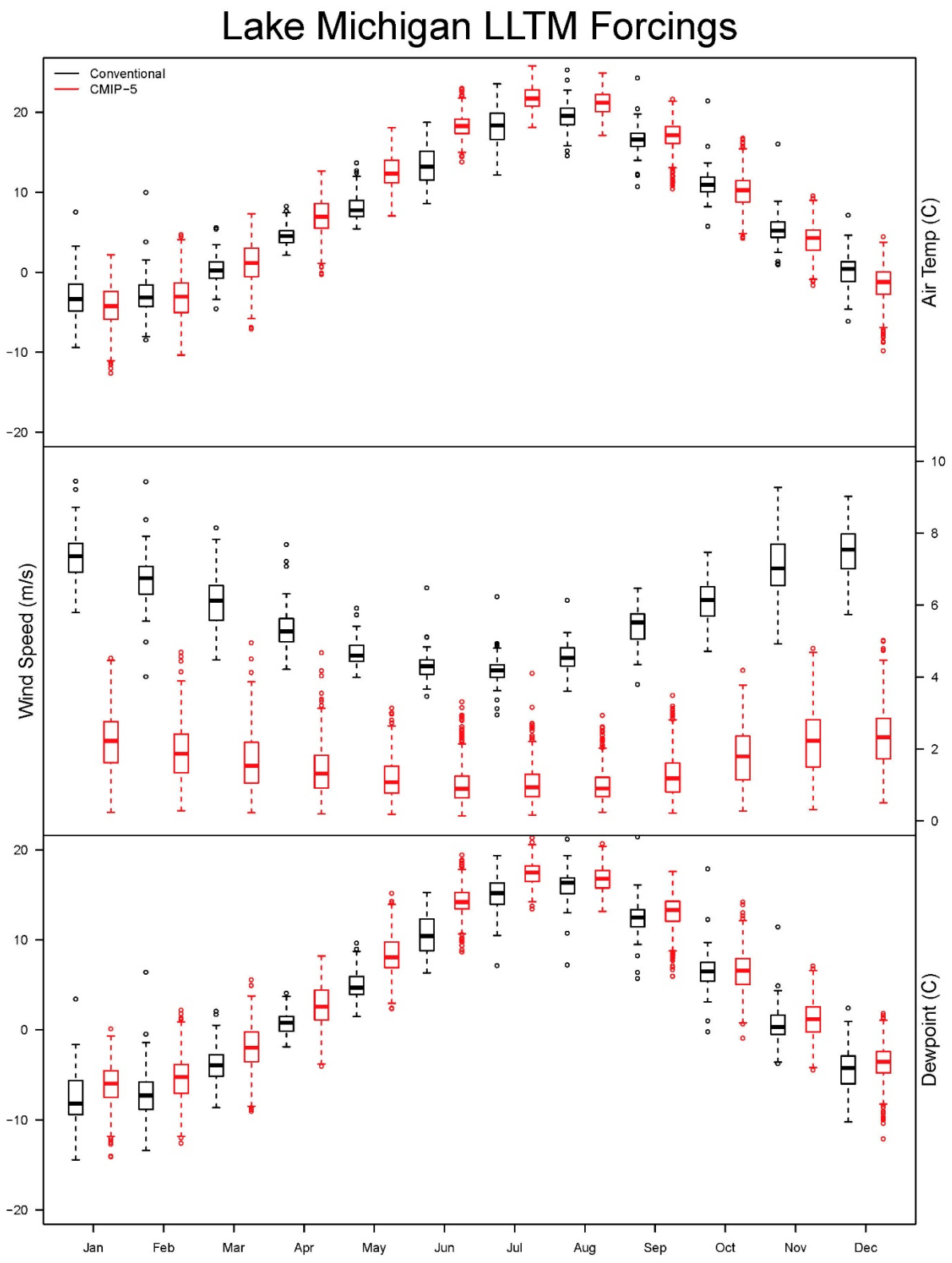


Figure 24. LLTM meteorological forcings, summarized by month, used by GLSHyFS-2 (climatology) and GLSHyFS-3 (CMIP-5) for Lake Michigan NBS forecasts.

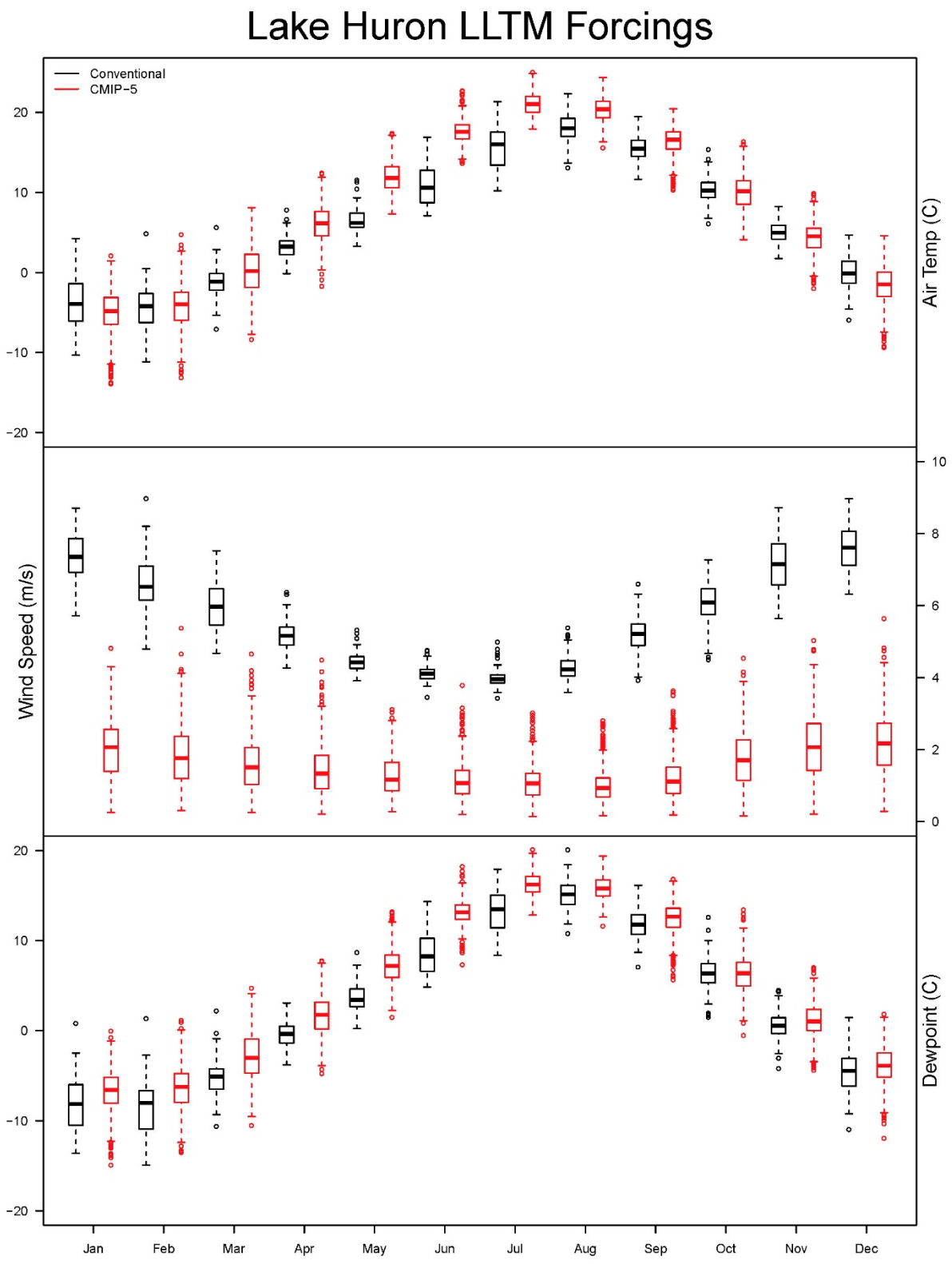


Figure 25. LLTM meteorological forcings, summarized by month, used by GLSHyFS-2 (climatology) and GLSHyFS-3 (CMIP-5) for Lake Huron NBS forecasts.

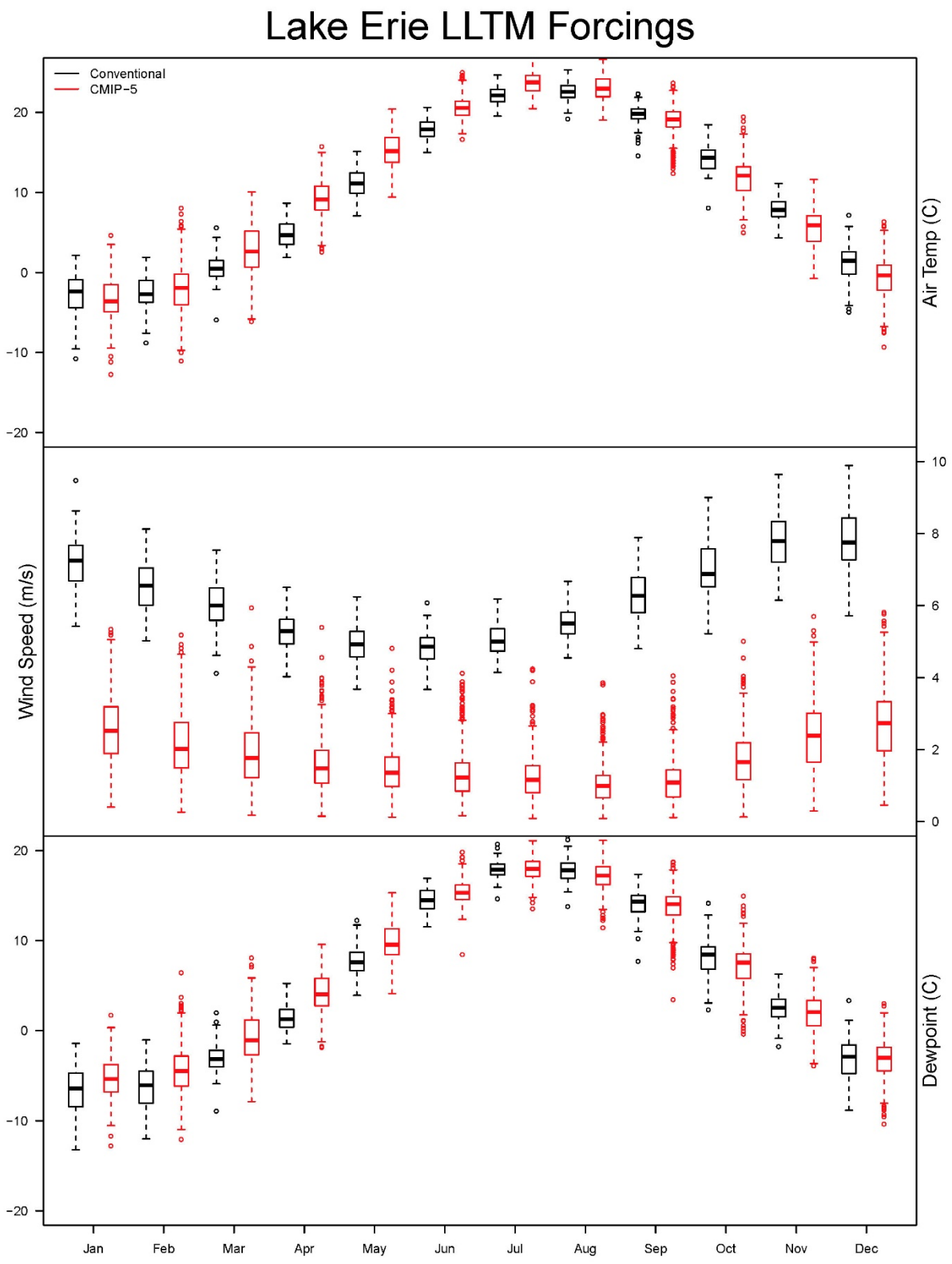


Figure 26. LLTM meteorological forcings, summarized by month, used by GLSHyFS-2 (climatology) and GLSHyFS-3 (CMIP-5) for Lake Erie NBS forecasts.

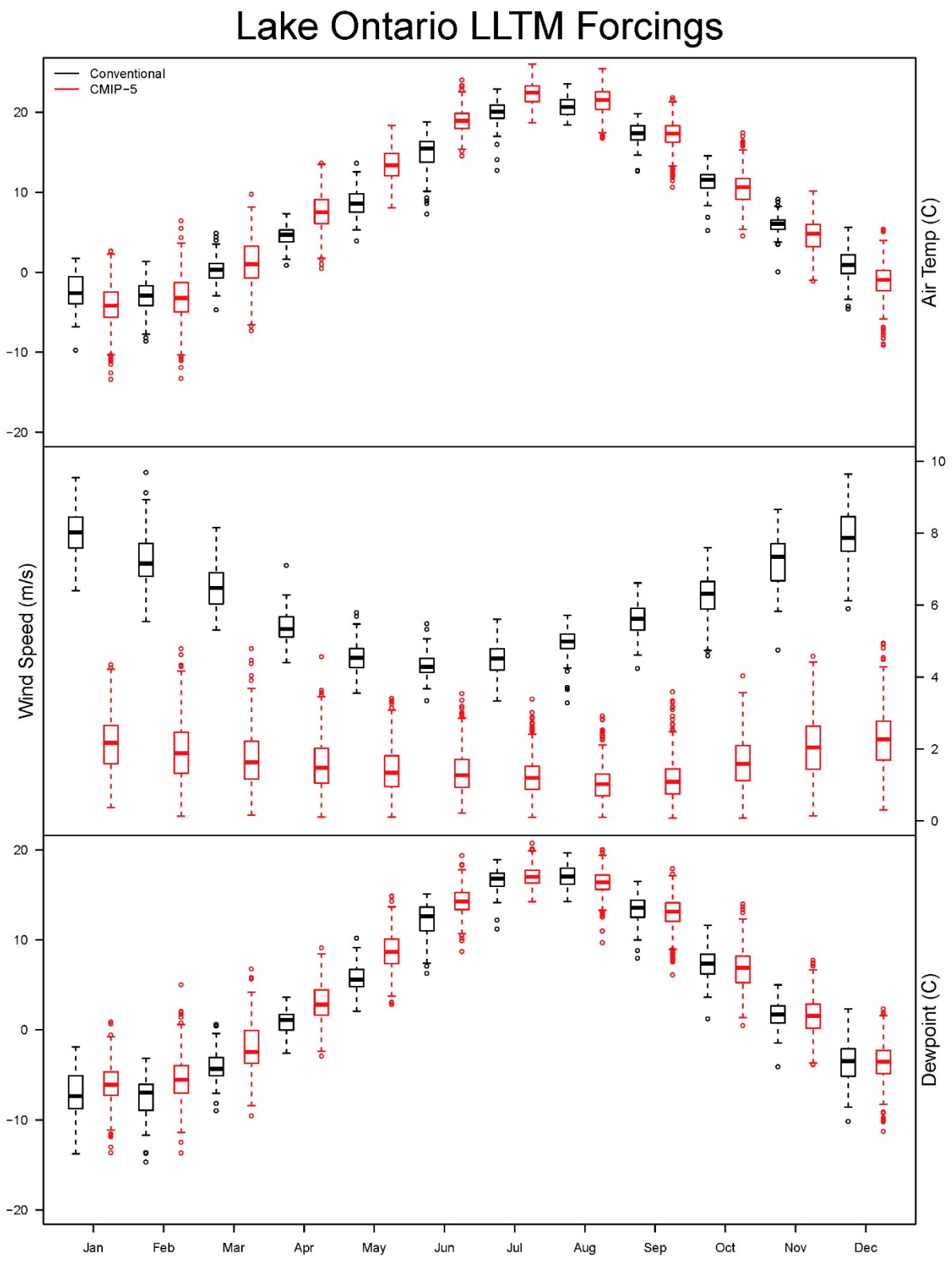


Figure 27. LLTM meteorological forcings, summarized by month, used by GLSHyFS-2 (climatology) and GLSHyFS-3 (CMIP-5) for Lake Ontario NBS forecasts.

Although the overlapping period of operational implementation of GL-AHPS and GLSHyFS-1 is too short for a rigorous comparison of skill, ultimately, the aim is to demonstrate that GLSHyFS-1 has as good or better skill than GL-AHPS. Lake Erie and Lake Ontario outflow forecasts from the unweighted versions of GL-AHPS and GLSHyFS-1 forecasting systems are shown in Figure 28 and Figure 29. Based on this comparison of 8 months of archived weekly forecasts, it appears that forecasts from the GLSHyFS-1 forecasting system are somewhat lower than the GL-AHPS derived forecasts. In Figure 21, GL-AHPS does predict higher NBS for Lake Superior (which is propagated to higher levels and outflows on the lower lakes) and Lake Ontario. The higher NBS appears to be a result of higher overlake precipitation in the GL-AHPS system for Lakes Superior and Ontario. Over the coming year, work will be conducted to more rigorously compare these two forecasting systems in order to phase out GL-AHPS. Figure 21 also suggests that an upgrade from GL-AHPS to GLSHyFS-1 will have a larger impact than an upgrade from GLSHyFS-1 to GLSHyFS-2, and this is at least preliminarily confirmed by outflow forecasts shown in Figure 30 and Figure 31, which show Lake Erie and Lake Ontario outflow forecasts from GLSHyFS-1 and GLSHyFS-2.

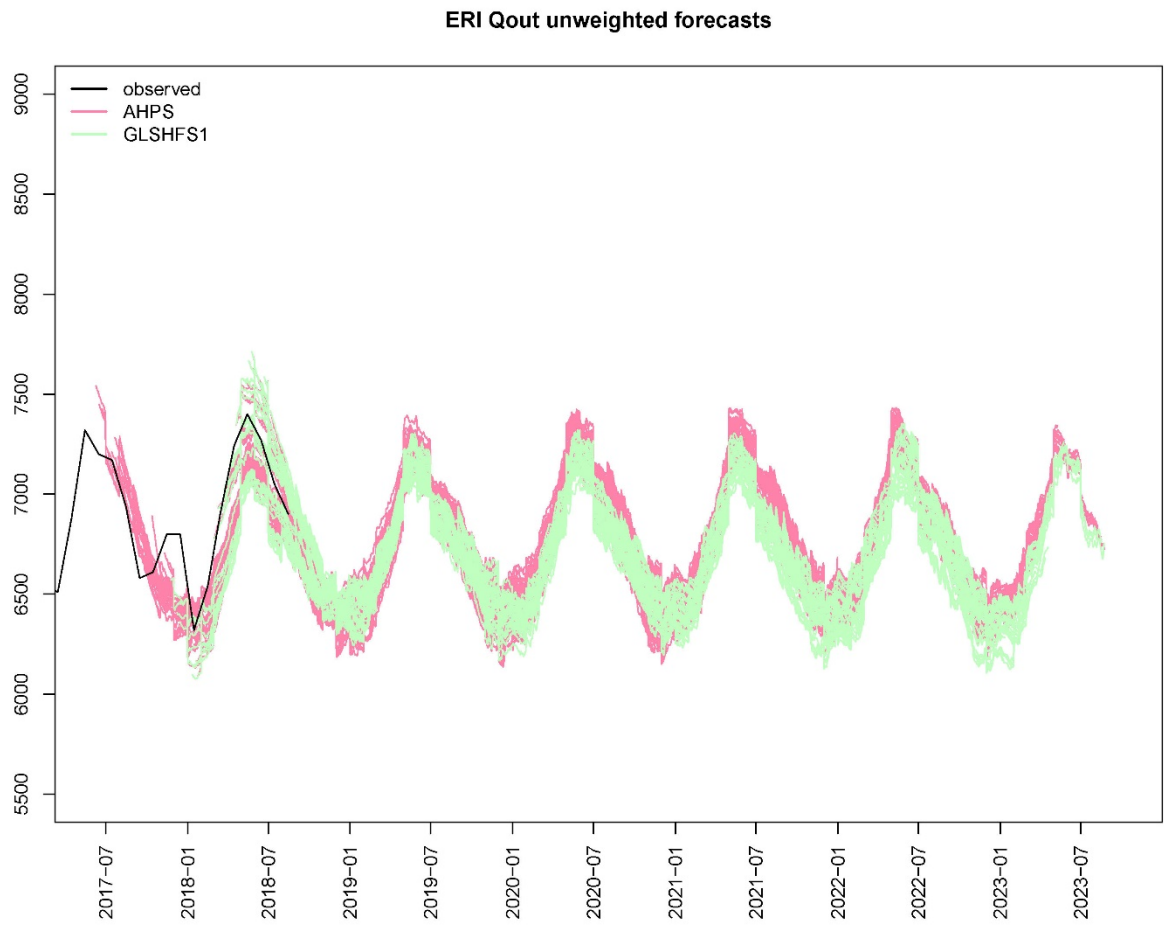


Figure 28. Comparison of median GL-AHPS and GLSHyFS-1 Lake Erie outflow forecasts.

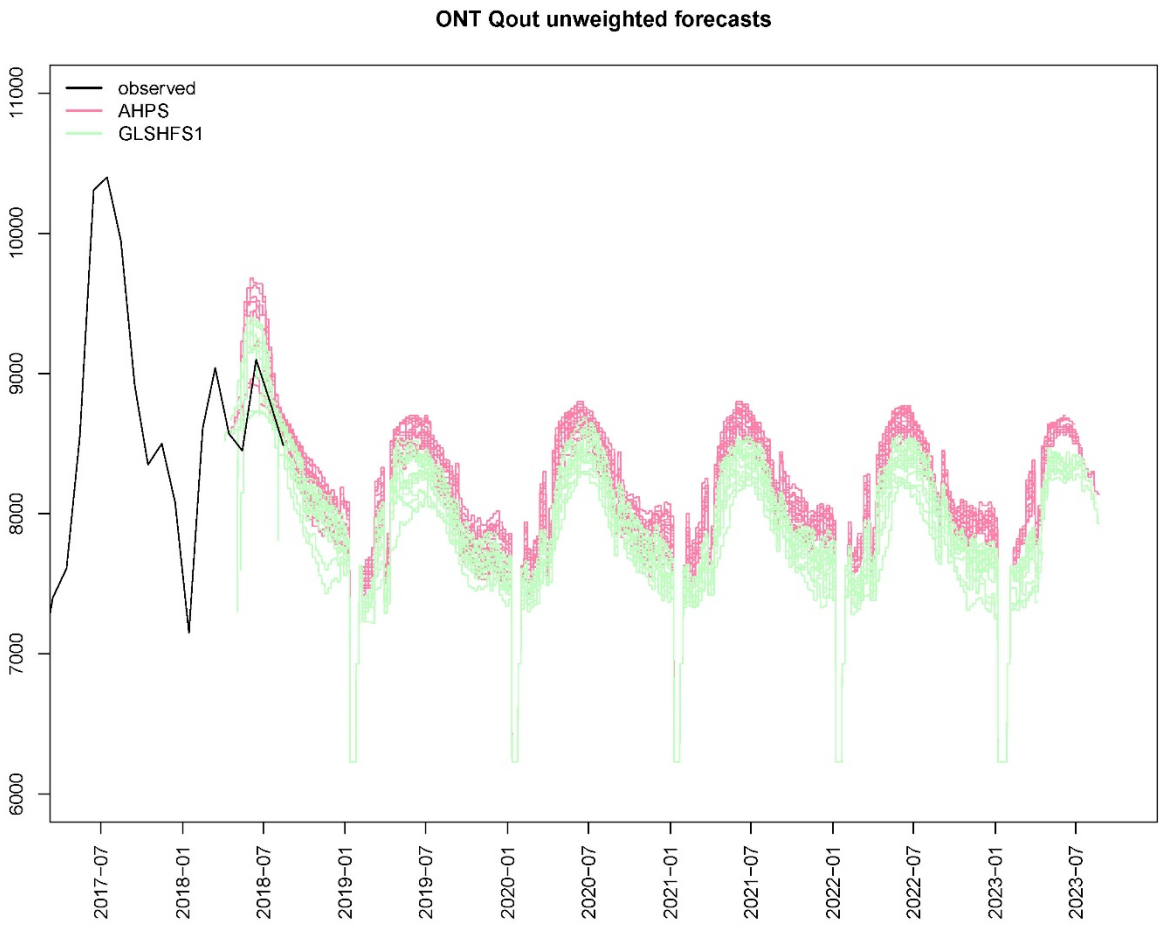


Figure 29. Comparison of GL-AHPS and GLSHyFS-1 Lake Ontario outflow forecasts.

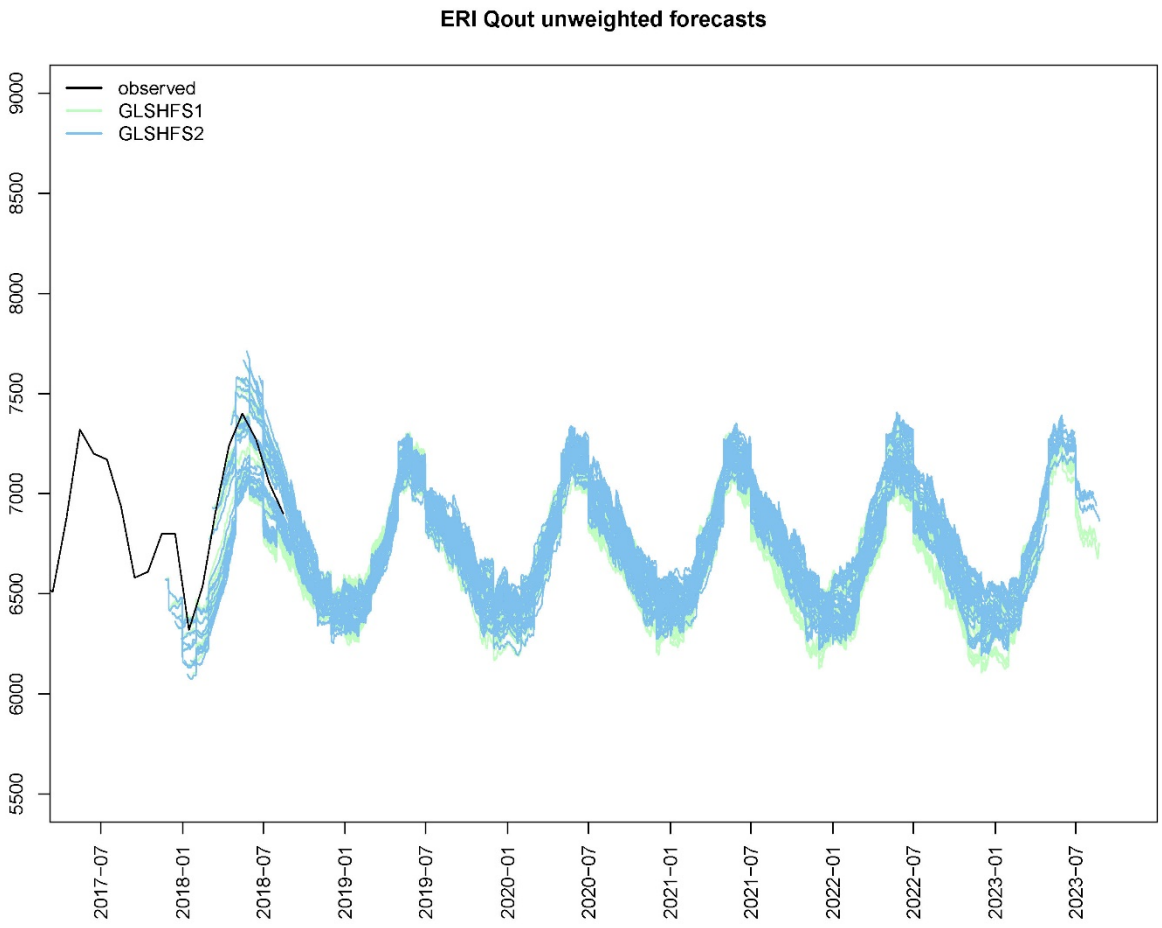


Figure 30. Comparison between GLSHyFS-1 and GLSHyFS-2 Lake Erie outflow forecasts.

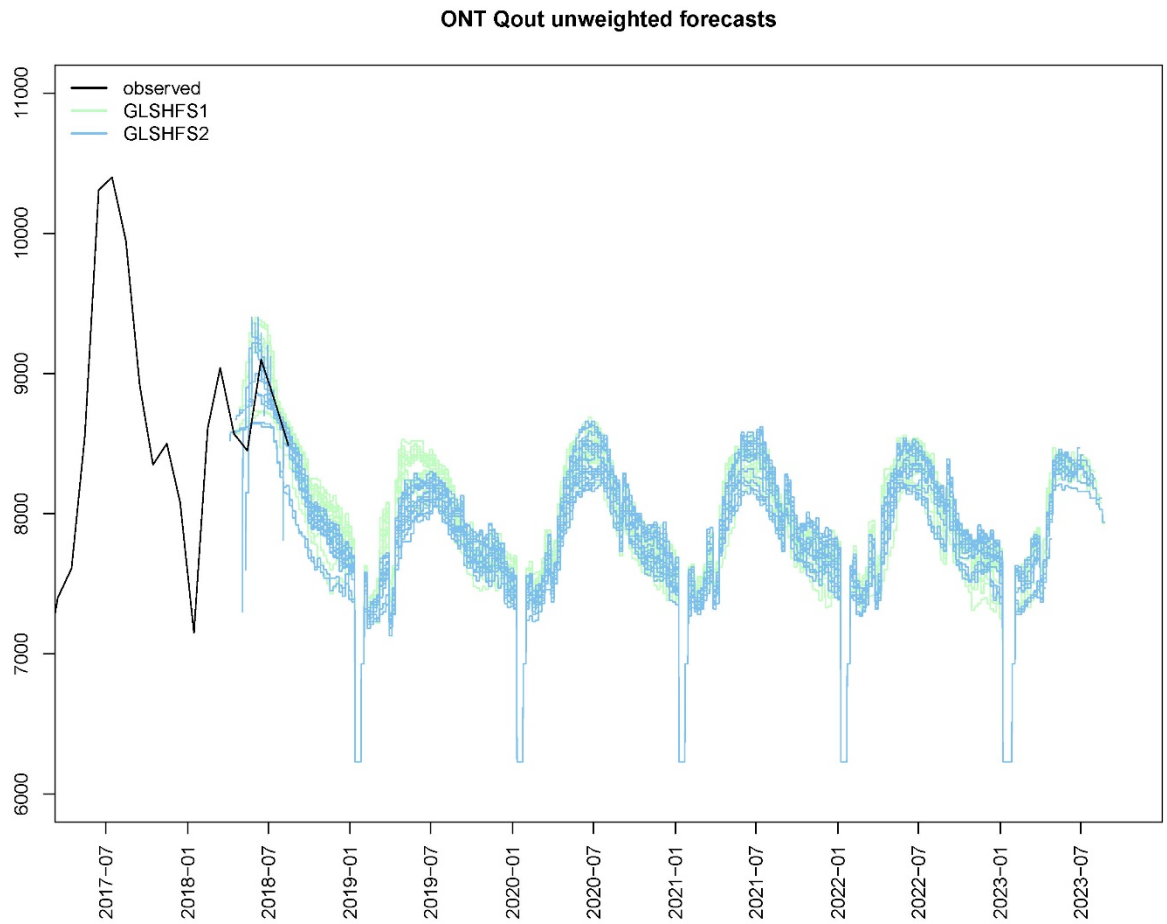


Figure 31. Comparison between GLSHyFS-1 and GLSHyFS-2 Lake Ontario outflow forecasts.

4.3 Lake Ontario forecast skill

Because existing operational forecasts were encoded with Plan 58D regulation logic, a new in-house version of code for Plan 2014 was developed, in part, to support this project. To test this new forecast code, hindcasts were run for weekly forecast dates starting in March 2017 and ending in March 2018. These hindcasts were run using the RNBS ensemble, which is similar to the methodology used in the forecasts produced for the International Lake Ontario – St. Lawrence River Board of Control by the GLSLRO in order to compare output (see Figure 32 and Figure 33). In general, forecasts compare reasonably well, with some discrepancies that appear to be related to input data used to initiate the forecasts (for example, the ice indicator). Work is currently underway to develop procedures to track and better coordinate inputs used by both forecast offices.

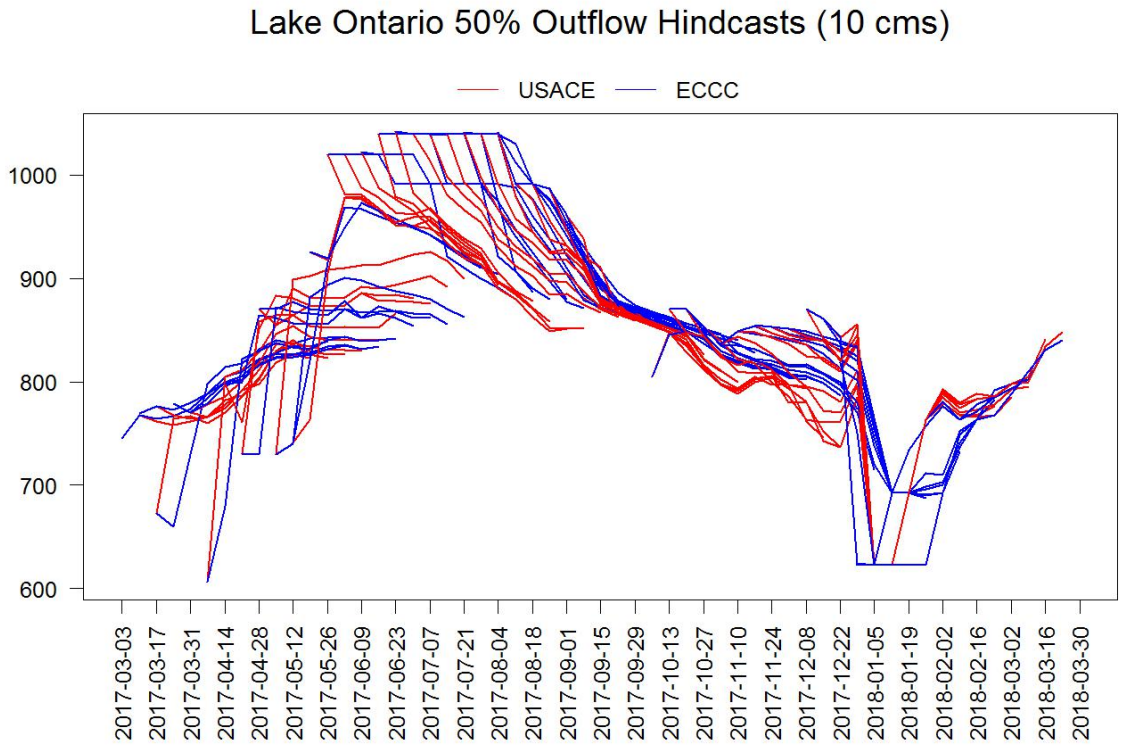


Figure 32. Median Lake Ontario outflow forecasts produced by new Plan 2014 regulation and routing code, compared with median forecasts produced by GLSLRO for the International Lake Ontario – St. Lawrence River Board.

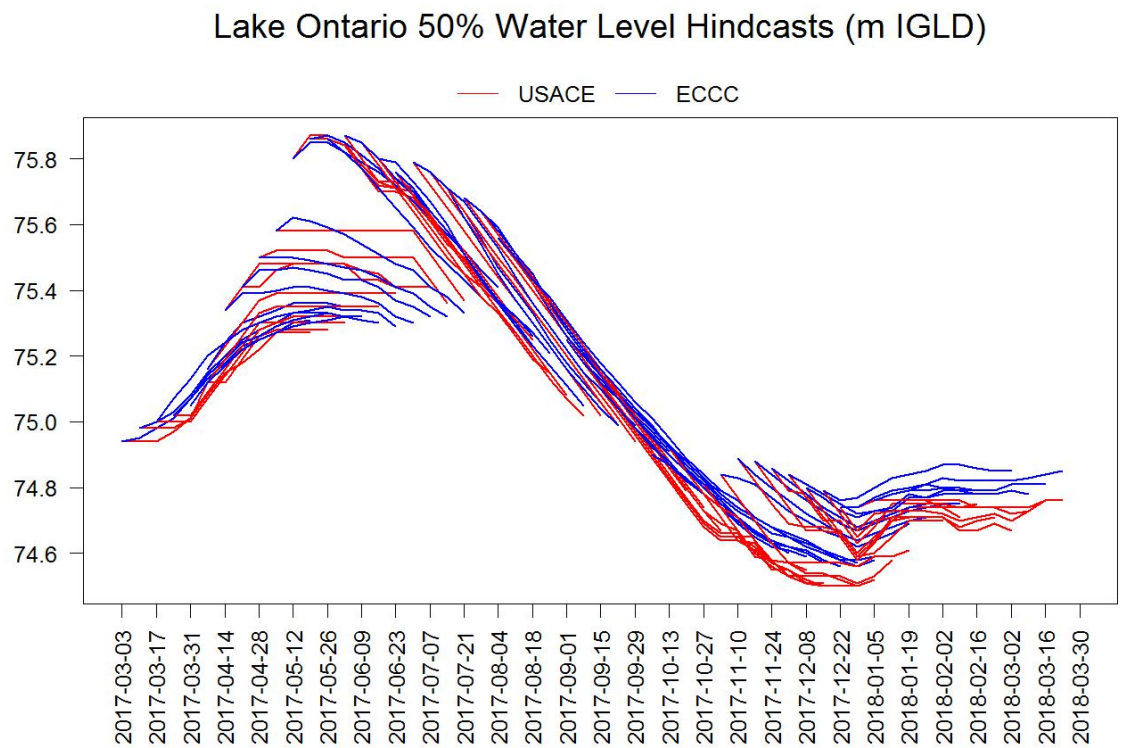


Figure 33. Median Lake Ontario water level forecasts produced by new Plan 2014 regulation and routing code, compared with median forecasts produced by GLSLRO for the International Lake Ontario – St. Lawrence River Board.

5 Communication of Forecasts

Two websites were developed for this project: an unadvertised webpage used to share the full suite of output from all ensemble forecasts with hydropower users, and a public facing website showing forecasts of monthly mean water levels resulting from the GLSHyFS-2 and RNBS derived forecasting systems.

The data sharing website for hydropower customers is found at: http://lre-wm.usace.army.mil/ForecastData/OPG_NYPA_5yrForecast/. This website includes the most recent thirty forecasts resulting from GL-AHPS, GLSHyFS-1, -2, and -3, and RNBS based forecasting systems. No discussion is included on this webpage, as it is assumed that hydropower users have a basic understanding of each of each forecasting system, and will have access to this report as a reference. Graphics depicting the variability in daily Lake Erie and Lake Ontario outflows from the most recent forecast from the GLSHyFS-2 (weighted), GLSHyFS-3, and RNBS (unweighted) systems are included as a "first glance", but it is understood that NYPA engineers will use the data to produce their own products necessary to communicate forecasts within their agency. Examples of these graphics are shown in Figure 34 and Figure 35. Each graphic has 5 panels. The largest and furthest left panel depicts the 95% prediction interval (shaded areas) and median forecast (lines) of daily outflows that are projected for the next 12 months using the GLSHyFS-2 (weighted), GLSHyFS-3, and RNBS (unweighted) forecasting systems. The four narrow panels to the right depict the range of variability (shown as shaded vertical lines) of daily outflows within the subsequent two to four 12-month periods of the forecast horizon, as well as the annual mean outflow predicted for those 12 month periods (shown as large dark points).

Plots of all forecasts for all variables are available in the compressed forecast output that can be downloaded from the website.

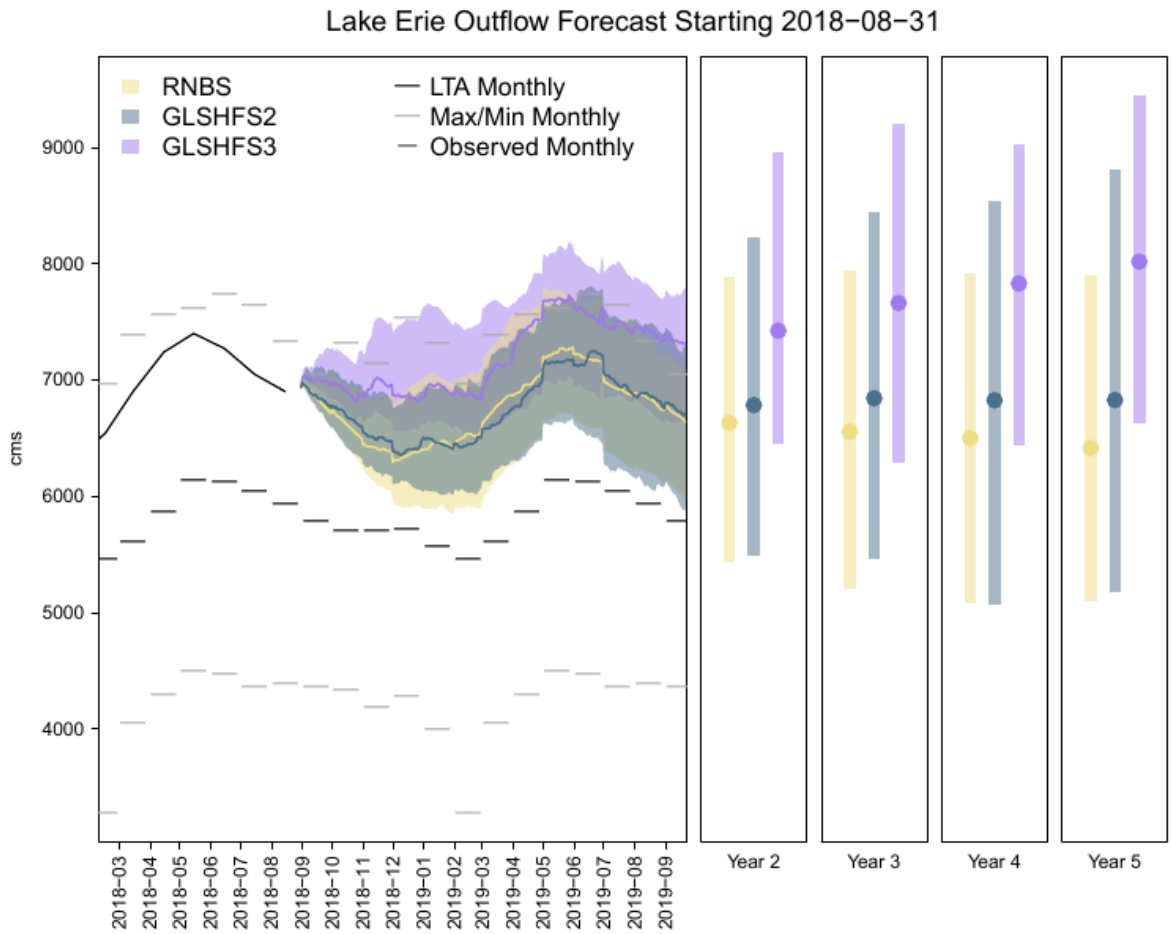


Figure 34. Example graphic of Lake Erie outflow forecast to be included on the unadvertised data sharing website as a first look for hydropower customers. The largest and furthest left panel depicts the 95% prediction interval (shaded areas) and median forecast (lines) of daily outflows that are projected for the next 12 months using the GLSHyFS-2 (weighted), GLSHyFS-3, and RNBS (unweighted) forecasting systems. The four narrow panels to the right depict the range of variability (shown as shaded vertical lines) of daily outflows within the subsequent two to four 12-month periods of the forecast horizon, as well as the annual mean outflow predicted for those 12 month periods (shown as large dark points).

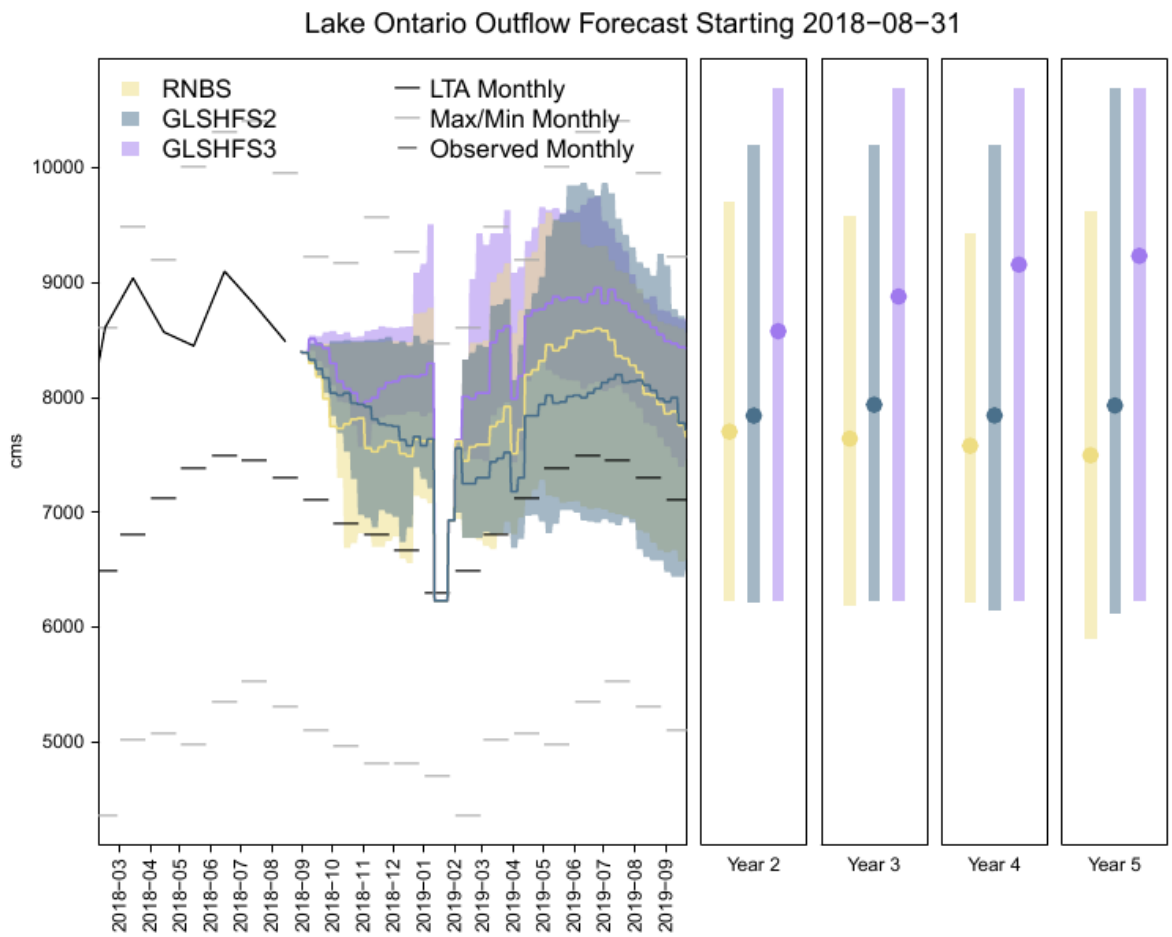


Figure 35. Example graphic of Lake Ontario outflow forecast to be included on the unadvertised data sharing website as a first look for hydropower customers. The largest and furthest left panel depicts the 95% prediction interval (shaded areas) and median forecast (lines) of daily outflows that are projected for the next 12 months using the GLSHyFS-2 (weighted), GLSHyFS-3, and RNBS (unweighted) forecasting systems. The four narrow panels to the right depict the range of variability (shown as shaded vertical lines) of daily outflows within the subsequent two to four 12-month periods of the forecast horizon, as well as the annual mean outflow predicted for those 12 month periods (shown as large dark points).

The public facing website is found at: https://lre.usace.army.mil/Missions/Great-Lakes-Information/Great-Lakes-Water-Levels/Water-Level-Forecast/Long-Term-Forecast/. This website includes graphics depicting the monthly mean water levels that are forecast by the weighted version of the GLSHyFS-2 based forecast and the unweighted version of the RNBS derived forecast. Some discussion is included on this website to help users interpret the forecast plots. Example plots are shown in Figure 36 to Figure 40.

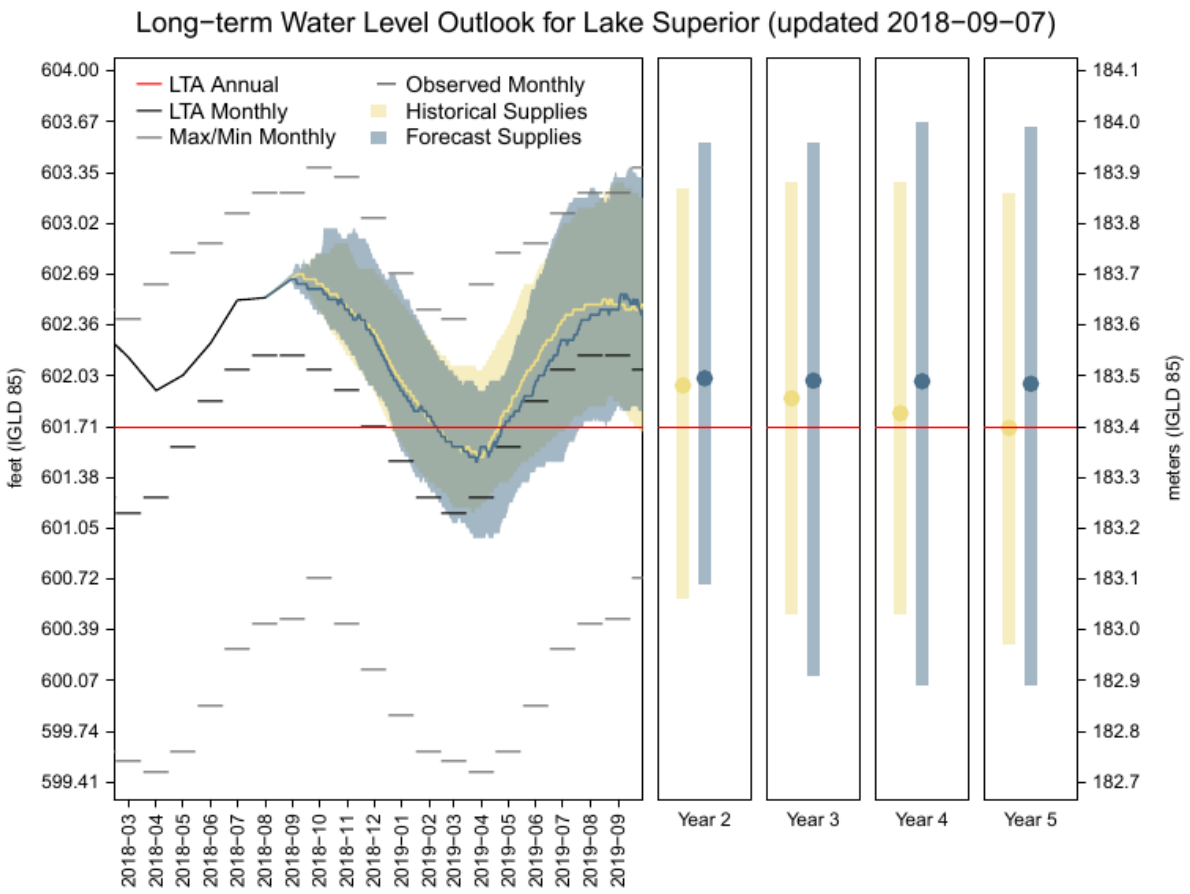


Figure 36. Example graphic of monthly mean Lake Superior water level forecast to be included on the public facing website. The largest and furthest left panel depicts the 95% prediction interval (shaded areas) and median forecast (lines) of monthly mean water levels that are projected for the next 12 months using the GLSHyFS-2 (weighted) and RNBS (unweighted) forecasting systems, described as "Forecast Supplies" and "Historical Supplies", respectively. The four narrow panels to the right depict the range of variability (shown as shaded vertical lines) of monthly mean water levels within the subsequent two to four 12-month periods of the forecast horizon, as well as the annual mean water level predicted for those 12 month periods (shown as large dark points).

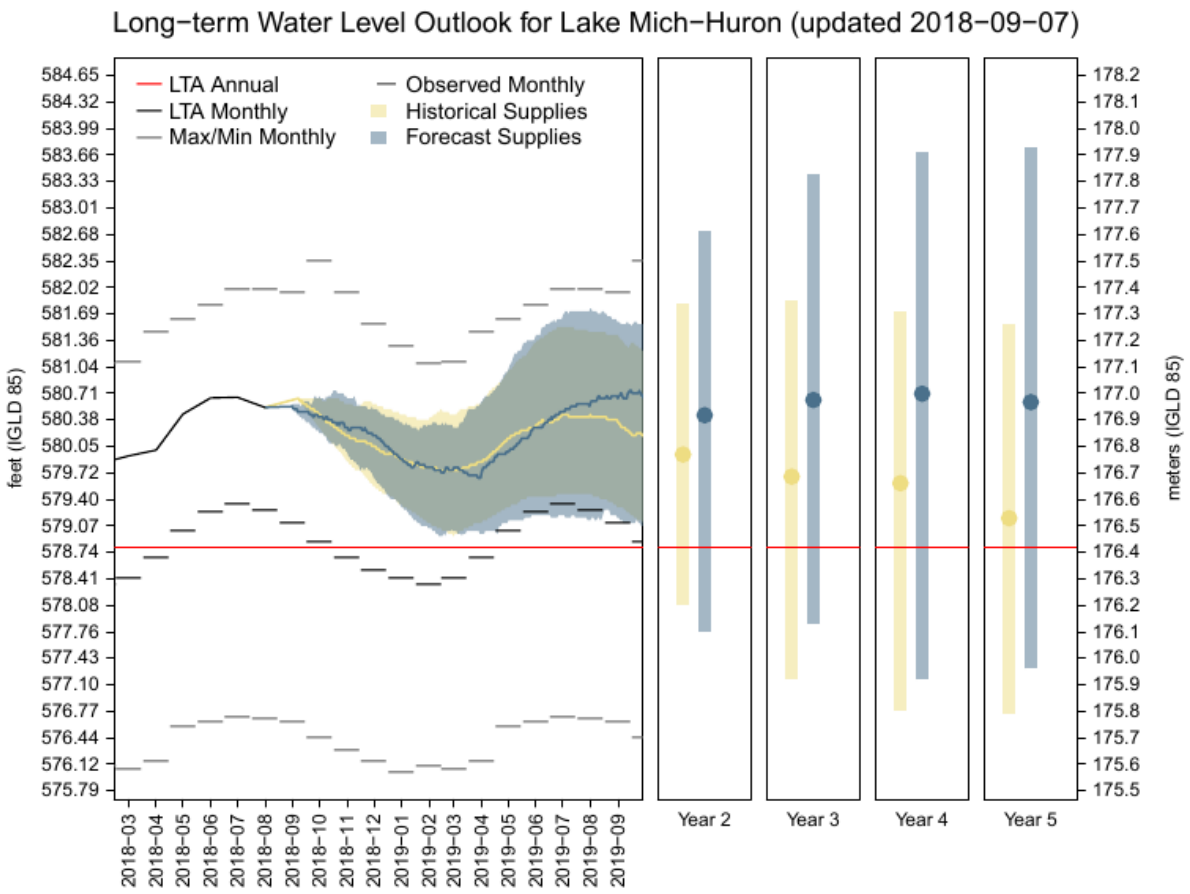


Figure 37. Example graphic of monthly mean Lake Michigan-Huron water level forecast to be included on the public facing website. The largest and furthest left panel depicts the 95% prediction interval (shaded areas) and median forecast (lines) of monthly mean water levels that are projected for the next 12 months using the GLSHyFS-2 (weighted) and RNBS (unweighted) forecasting systems, described as "Forecast Supplies" and "Historical Supplies", respectively. The four narrow panels to the right depict the range of variability (shown as shaded vertical lines) of monthly mean water levels within the subsequent two to four 12-month periods of the forecast horizon, as well as the annual mean water level predicted for those 12 month periods (shown as large dark points).

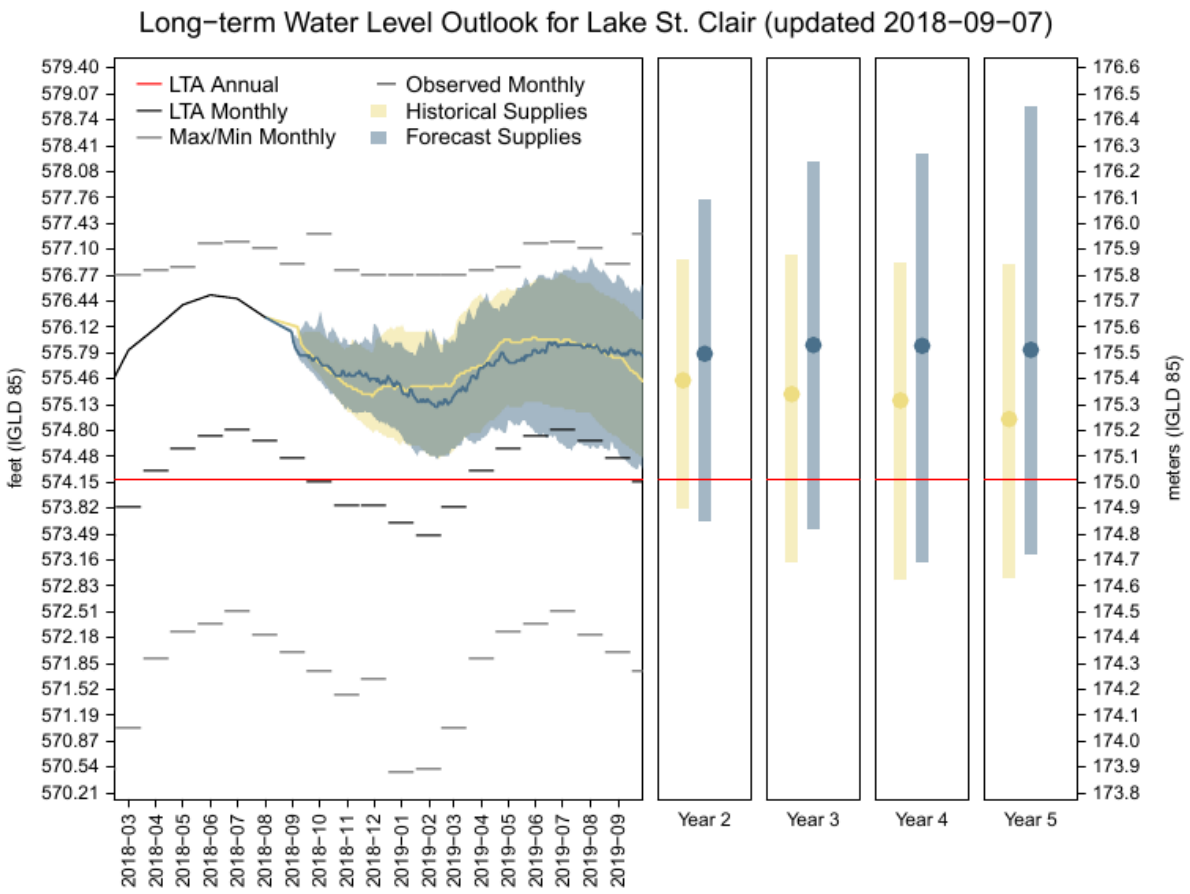


Figure 38. Example graphic of monthly mean Lake St. Clair water level forecast to be included on the public facing website. The largest and furthest left panel depicts the 95% prediction interval (shaded areas) and median forecast (lines) of monthly mean water levels that are projected for the next 12 months using the GLSHyFS-2 (weighted) and RNBS (unweighted) forecasting systems, described as "Forecast Supplies" and "Historical Supplies", respectively. The four narrow panels to the right depict the range of variability (shown as shaded vertical lines) of monthly mean water levels within the subsequent two to four 12-month periods of the forecast horizon, as well as the annual mean water level predicted for those 12 month periods (shown as large dark points).

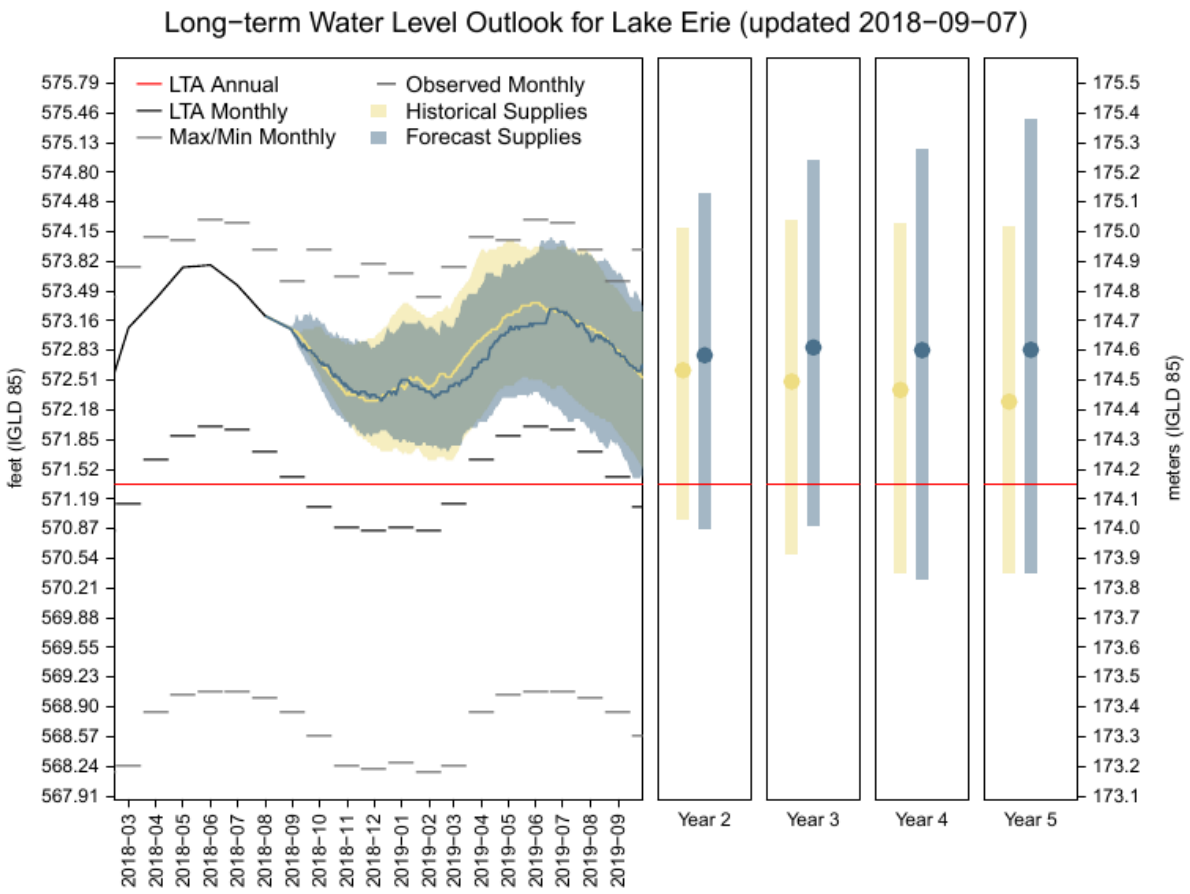


Figure 39. Example graphic of monthly mean Lake Erie water level forecast to be included on the public facing website. The largest and furthest left panel depicts the 95% prediction interval (shaded areas) and median forecast (lines) of monthly mean water levels that are projected for the next 12 months using the GLSHyFS-2 (weighted) and RNBS (unweighted) forecasting systems, described as "Forecast Supplies" and "Historical Supplies", respectively. The four narrow panels to the right depict the range of variability (shown as shaded vertical lines) of monthly mean water levels within the subsequent two to four 12-month periods of the forecast horizon, as well as the annual mean water level predicted for those 12 month periods (shown as large dark points).

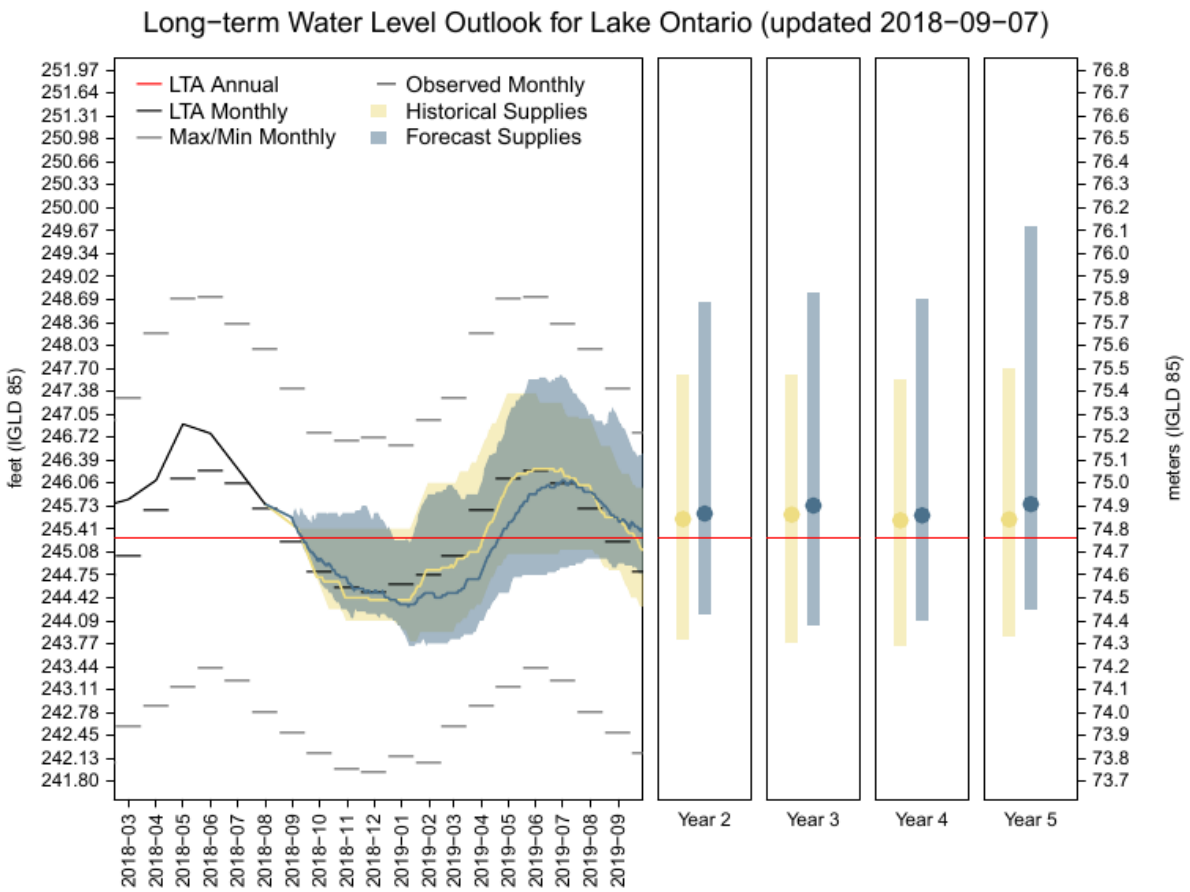


Figure 40. Example graphic of monthly mean Lake Ontario water level forecast to be included on the public facing website. The largest and furthest left panel depicts the 95% prediction interval (shaded areas) and median forecast (lines) of monthly mean water levels that are projected for the next 12 months using the GLSHyFS-2 (weighted) and RNBS (unweighted) forecasting systems, described as "Forecast Supplies" and "Historical Supplies", respectively. The four narrow panels to the right depict the range of variability (shown as shaded vertical lines) of monthly mean water levels within the subsequent two to four 12-month periods of the forecast horizon, as well as the annual mean water level predicted for those 12 month periods (shown as large dark points).

6 Future work

As depicted in Figure 4, it is anticipated that all forecast configurations will continue to be run in parallel for one more year in order to provide a basis for comparison. After 2019, it is expected that GL-AHPS will be phased out, in favor of GLSHyFS-1, assuming that performance of GLSHyFS-1 is deemed to be equal to or better than GL-AHPS. Then, after another year to compare GLSHyFS-1 and -2, it is likely that GLSHyFS-1 will be retired in favor of GLSHyFS-2, assuming that the upgraded LBRM algorithm of GLSHyFS-2 outperforms the LBRM algorithm in GLSHyFS-1. The final suite of operational models will include RNBS, GLSHyFS-2, and GLSHyFS-3. Because GLSHyFS-3 appears to have bias resulting from downscaled wind from CMIP-5 forcings (see Section 4.1), USACE-Detroit will continue to provide this forecast only on the data sharing site for hydropower customers, and not on the public facing website, until either the bias is reduced or it is found that the biases are reflective of actual changes, as verified by future observations.

The forecasting systems that have been operationalized as a result of this project were developed and implemented for the purpose of providing forecast guidance to hydropower customers. However, the significant advancements in modeling and operational framework design offer an opportunity to improve existing operational forecast products produced by USACE-Detroit. The ensemble routing framework (GLERRFS) has already been implemented within the forecasting tool used in Lake Superior regulation procedures and the Great Lakes Water Level Outlook (for Superior through Erie) to perform ensemble routing of historical RNBS sequences. Tools to implement the new forecasting systems into weekly and monthly forecasts are also under development.

Additionally, at some point in the future, it will be necessary to accommodate changes in the regulation and routing models that are employed in GLERRFS (i.e. CGLRRM and the Lake Ontario Regulation and Routing Model). These changes will result from either changes to regulation plans or upgrades to regulation and routing model software. While no known regulation plan change is on the immediate horizon, an upgrade to CGLRRM (including Lake Ontario regulation and routing modules) is under development. When this upgrade is complete, work will be required to adjust pre- and post-processing scripts used to run the routing and regulation models within GLERRFS.

7 References

Gronewold, A.D., T.S. Hunter, J. Allis, L. Fry, K. Kompoltowicz, R. Bolinger, and L. Pei. (2017). Project Documentation Report for Great Lakes seasonal and inter-annual water supply forecasting improvements project Phase I: Research and Development.

Cannon, A.J., S.R. Sobie, and T.Q. Murdock. (2015). Bias correction of GCM precipitation by quantile mapping: how well do methods preserve changes in quantiles and extremes? *Journal of Climate*, 28(17): 6938-6959.

Croley II, T.E. (1983). Great Lakes basins (USA-Canada) runoff modeling. *Journal of Hydrology*, 64(1):135-158.

Croley II, T.E. (1989). Verifiable evaporation modeling on the Laurentian Great Lakes. *Water Resources Research*, 25(5):781-792.

Elmore, K.L. (2005). Alternatives to the chi-square test for evaluating rank histograms from ensemble forecasts. *Weather and Forecasting*, 20(5): 789-795.

Hunter, T.S., A.H. Clites, K.B. Campbell, and A.D. Gronewold. (2015). Development and application of a monthly hydrometeorological database for the North American Great Lakes – Part I: precipitation, evaporation, runoff, and air temperature. *Journal of Great Lakes Research*, 41(1): 65-77.

Lofgren, B.M., and A.D. Gronewold. (2014). Water Resources. In: Winkler, J.A., J.A. Andresen, J.L. Hatfield, D. Bidwell, and D. Brown (Eds), *Climate Change in the Midwest: A Synthesis Report for the National Climate Assessment.* Island Press, Washington, DC, Ch. Water Reso, pp. 224-237.

Lofgren, B.M., A.D. Gronewold, A. Acciaioli, J. Cherry, A.L. Steiner, and D.W. Watkins. (2013). Methodological approaches to projecting the hydrologic impacts of climate change. *Earth Interactions*, 17(22): 1-19.

Lofgren, B.M., T.S. Hunter, and J.Wilbarger. (2011). Effects of using air temperature as a proxy for potential evapotranspiration in climate change scenarios of Great Lakes basin hydrology. *Journal of Great Lakes Research*, 37(4):744-752.

Quinn, F. and N. Noorbakhsh (2001). Niagara River Rating Equations for the Post-1973 Directive Period. Report to the Coordinating Committee for Great Lakes Basic Hydraulic and Hydrologic Data.

Rowe, M.D., E.J. Anderson, J. Wang, and H.A. Vanderploeg. (2015). Modeling the effect of invasive quagga mussels on the spring phytoplankton bloom in Lake Michigan. *Journal of Great Lakes Research* (2015), http://dx.doi.org/10.1016/j.jglr.2014.12.018.

U.S. Army Corps of Engineers (USACE). (2001). Verification of the Coordinated Great Lakes Regulation and Routing Model for Lake Superior Regulation Results.

U.S. Army Corps of Engineers (USACE). (2013). Review of 2001 Buffalo Rating Equation for Niagara River Flows and Discharge Measurements Made Near the International Railway Bridge.