NOAA Technical Memorandum NOS CS 42

UPGRADE OF NOS LAKE MICHIGAN AND LAKE HURON OPERATIONAL FORECAST SYSTEMS TO FVCOM: MODEL DEVELOPMENT AND HINDCAST SKILL ASSESSMENT

Silver Spring, Maryland

April 2020

noaa National Oceanic and Atmospheric Administration

U.S. DEPARTMENT OF COMMERCE
National Ocean Service
Coast Survey Development Laboratory

Office of Coast Survey
National Ocean Service
National Oceanic and Atmospheric Administration
U.S. Department of Commerce

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LIST OF ACRONYMS

AGL	Above Ground Level
ASOS	Automated Surface Observing System
AWOS	Automated Weather Observing System
CMMB	Coastal Marine Modeling Branch
C-MAN	Coastal-Marine Automated Network
COARE	The Center for Oceanic Awareness, Research, and Education
CO-OPS	Center for Operational Oceanographic Products and Services
CSDL	Coast Survey Development Laboratory
ECCC	Environment and Climate Change Canada
FVCOM	Finite Volume Community Ocean Model
GLCFS	Great Lakes Coastal Forecast System
GLERL	Great Lakes Environmental Research Laboratory
GLOFS	Great Lakes Operational Forecast System
GLSEA	Great Lakes Surface Environmental Analysis
GRIB2	GRIdded Binary (Version 2)
HRRR	High Resolution Rapid Refresh numerical weather prediction system
HPSS	High Performance Storage System
LBC	Lateral boundary conditions
LEOFS	Lake Erie Operational Forecast System
LHOFS	Lake Huron Operational Forecast System
LMOFS	Lake Michigan Operational Forecast System
LMHOFS	Lake Michigan-Huron Operational Forecast System
NAM	North America Mesoscale Model
NCEP	National Centers for Environmental Prediction
NCO	NCEP Central Operations
NDBC	National Data Buoy Center
NDFD	National Digital Forecast Database
NGDC	National Geophysical Data Center
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
NWLON	National Water Level Observation Network
NWS	National Weather Service
OBC	Open boundary conditions
OCS	Office of Coast Survey
OSU	The Ohio State University
POMGL	Princeton Ocean Model – Great Lakes version
UMASS	University of Massachusetts
USGS	United States Geological Survey
WCOSS	Weather and Climate Operational Supercomputer System
WFO	Weather Forecast Office

WPC	Weather Prediction Center

EXECUTIVE SUMMARY

NOS Lake Michigan-Huron Operational Forecast System (LMHOFS) is a three-dimensional lake forecast modeling system which uses near real-time atmospheric analyses, river observations and numerical weather prediction model forecast guidance to generate hourly nowcasts and forecast guidance out to 120 hours of three-dimensional water temperatures and currents and two-dimensional water levels for Lakes Michigan and Huron. The present operational NOS forecast systems for the two lakes, LMOFS and LHOFS, use the Great Lakes version of the Princeton Ocean Model (POMGL) as its core three-dimensional numerical oceanographic forecast model and have a horizontal resolution of 5 km (3.1 mi) and 20 vertical sigma (terrain-following) levels and provide forecast guidance out to 60 hours.

LMHOFS has been developed using the Finite Volume Community Ocean Model (FVCOM) with a horizontal resolution ranging from 100 m (328 ft) near the shore to 2.5 km (1.6 mi) offshore and with 21 vertical sigma levels. In addition, unlike current LHOFS and LMOFS, this new OFS combined Lake Michigan and Lake Huron together as one model grid domain in order to simulate the flow between the two lakes via the Straits of Mackinac. LMHOFS is another collaborative project among NOAA's Great Lakes Environmental Research Laboratory (GLERL), the National Ocean Service's (NOS) Coast Survey Development Laboratory (CSDL), the Center for Operational Oceanographic Products and Services (CO-OPS), and the FVCOM Development Team at the University of Massachusetts-Dartmouth. NOS' Lake Erie Operational Forecast System (LEOFS) was the first of the Great Lakes Operational Forecast System to be upgraded to FVCOM. LEOFS was implemented operational in 2016.

The accuracy of predictions from LMHOFS was evaluated by thorough NOS comparisons to observations for three NOS skill assessment scenarios: 1) hindcast, 2) the semi-operational nowcast, and 3) the semi-operational forecast guidance. This report describes the results of the hindcast skill assessment. A similar skill assessment report for the semi-operational nowcasts and forecast guidance is being prepared by NOS/CO-OPS.

The main hindcast simulations were conducted for 2015 and 2016 for evaluating time series of water level and surface water temperature predictions. However, hindcasts were conducted for other years to correspond with the sub-surface water temperature observing period in order to evaluate sub-surface temperature predictions. The lateral boundary conditions for the hindcasts, especially the water level lateral boundary conditions (LBCs) were significantly more complicated than LMOFS and LHOFS. The over-lake precipitation, over-lake evaporation and inflow from tributaries, and inflow and outflow of connecting channels are all taken into account in order to simulate LMHOFS lake level. First, the inflows and outflows were estimated through near-real-time discharge observations from USGS gauges in St. Mary's River, St. Clair River, Saginaw River, and Fox River and specified in the FVCOM river discharge file as river forcing. Second, the observed water level change over the previous five days at four NOS CO-OPS gauges (Milwaukee, Ludington, Mackinaw City, and Harbor Beach) were averaged, and used to calculate the unaccounted inflow/outflow due to a combination of inflow from additional tributaries, runoff, and over-lake precipitation and evaporation. This term is then added to the model using FVCOM's formulation for mass addition/subtraction via the precipitation/evaporation forcing file. Finally, to set an open boundary condition (OBC) water level at the St. Joseph Channel of the St. Mary's River, observations were used from the NOS/CO-OPS NWLON gauge at Rock Cut. The difference

between the model's lake level and observed water level at the 3rd inlet will yield a flow across the open boundary to take into account the uncertainties in the prescribed inflow/outflows as well as the uncertainty of lake level estimation.

The water temperatures were specified at three locations in the lakes using hourly temperature observations: USGS gauges in the Fox River and Saginaw River, and the NOS/CO-OPS NWLON station in the St. Mary's River.

Surface meteorological forcing for the LMHOFS hindcasts were provided by 2-hr forecast guidance from the NWS High-Resolution Rapid Refresh (HRRR) analysis and forecast modeling system hourly forecast cycles. HRRR has a horizontal resolution of 3 km (1.86 miles). The specific HRRR meteorological variables used to force FVCOM were the following: surface air temperature (2m Above Ground Level (AGL)), surface dew point temperature (2 m AGL), surface relative humidity (2m AGL), surface wind velocity (7.8 m AGL), mean sea level pressure, cloud/sky cover, downward short-wave radiation, and downward long-wave radiation. Normally, the wind velocity at 10m AGL is used. However, the HRRR developer made a mistake and output the surface winds at 7.8 m AGL instead of at 10m. The mistake was corrected in the operational HRRR.

The hindcasts demonstrated excellent skills for simulating hourly water levels, and surface and subsurface water temperatures during both years and met the NOS acceptance criteria at the majority of stations. The hindcasts were not as good at predicting the water levels in terms of making amplitude and timing predictions of extreme high and low water level events. However, the LMHOFS hindcasts of surface water temperature produced more accurate results than the nowcasts from the present LMOFS and LHOFS, which had unrealistic high frequency fluctuations.

1. INTRODUCTION

NOS' Great Lakes Operational Forecast System (GLOFS) provides hourly nowcasts and short-range forecast guidance of two-dimensional water levels and three-dimensional currents and water temperatures. GLOFS has been operational at NOS for Lakes Erie and Michigan since September 30, 2005 and for Lakes Ontario, Huron, and Superior since March 30, 2006. GLOFS predictions are used by commercial and recreational mariners, NWS marine weather forecasters, and by U.S Coast Guard Search and Rescue Operations.

The original GLOFS used the Great Lakes version of the Princeton Ocean Model (POMGL) (Blumberg and Mellor, 1987) with separate computational grids for each lake. The horizontal grid resolution used for Michigan, Ontario, and Huron is 5 km (3.1 mi) and is 10 km (6.2 mi) for Lake Superior. The number of vertical sigma layers is 20 for the four lakes. GLOFS has four daily nowcast and forecast cycles, which generate forecasts out to 60 hours. The nowcast cycles are forced by surface meteorological analyses of near-real-time meteorological observations from overwater and adjusted overland observing platforms, which are used to provide heat and radiation fluxes and wind stress to POMGL. The forecast cycles were forced by gridded surface wind and air temperature forecasts (2.5 km resolution) from the NWS National Digital Forecast Database. There are no heat or radiation fluxes input during the forecast cycle, only wind forcing.

The present GLOFS nowcasts and forecast guidance of water levels generally meet the NOS acceptance criteria for the amplitudes of hourly water levels and high and low water events. However, GLOFS nowcasts and forecast guidance under predicts water levels at certain locations, which is likely due to a combination of model grid and bathymetric data resolution. Also, GLOFS does not meet the NOS acceptance criteria for timing of extreme water events at most water gauges in the lakes. GLOFS surface water temperature predictions exhibit an unrealistic high frequency oscillation.

In 2013, NOS and NOAA's Great Lakes Environmental Research Laboratory (GLERL) began a project to develop a new version of GLOFS to provide improved lake predictions and guidance out to 120 hours. The Finite Volume Community Ocean Model (FVCOM) was selected as the core ocean model for the new version due to its unstructured grid design that would allow for higher horizontal resolution along the shore and incorporation of predicted heat and radiation fluxes during the forecast cycles. The Lake Erie Operational Forecast System (LEOFS) was migrated to FVCOM and became operational in May 2016. It has spatial grid resolution ranging from 400 m near the shore to 4 km offshore.

This report documents the development and testing of the new forecast modeling system for Lakes Michigan and Huron called the Lake Michigan and Huron Operational Forecast System (LMHOFS) using FVCOM with a single grid and the results of a skill assessment of water level and surface temperature of hindcasts for 2015 and 2016; and subsurface temperature skill assessment of hindcasts for 2014-2017. The skill assessment of the semi-operational nowcasts and forecasts on Weather and Climate Operational Supercomputer System (WCOSS) will be conducted by CO-OPS and its results will be published in a separate CO-OPS technical report. A brief overview of the physical limnology of Lake Michigan-Huron is given first.

2. LAKE MICHIGAN-HURON

Lake Michigan-Huron, referred to in this report as Michigan-Huron, is the combined waters of Lakes Michigan and Huron. The two lakes are joined through the 8.0 km (5 mi) wide, over 60 m (196 ft) deep, open-water Straits of Mackinac. Michigan-Huron are hydrologically a single lake because the flow of water through the straits keeps their water levels in near-equilibrium. When treated as a single entity, Michigan-Huron is the largest freshwater lake by surface area in the world with a surface area of 117,300 km^2 (45,300 mi^2).

Looking at each individually, Lake Michigan is the third largest of the Great Lakes with a water surface of 58,030 km^2 (22,404 mi^2). It has an average depth of 85 m (279 ft) and a maximum depth of 281 m (923 ft). The largest sub-basins or bays in Michigan are Green Bay, Grand Transverse Bay, and Little Transverse Bay. The largest is Green Bay with a surface area of 4,210 km^2 (1,626 mi^2). It is 193 km (120 mi) long with a width ranging from between 16 km (10 mi) to 32 km (20 mi).

Lake Huron is the second largest of the Great Lakes with a water surface area of 59,565 km^2 (23,000 mi^2). It has an average depth of 59 m (195 ft.) with a maximum depth of 229 m (750 ft). The largest sub-basins in Huron are Saginaw Bay, Thunder Bay, and Georgian Bay. The largest is Georgian Bay with a surface area of 2,960 km^2 (1,143 mi^2). It is 190 km (120 mi) long with an average width of 80 km (50 mi).

The Straits of Mackinac has a net eastward flow. However, the water moves in either direction, oscillating on a regular period, depending on regional and local conditions. Anderson and Schwab (2013; 2017) demonstrated with numerical model simulations, that the pumping or Helmholtz mode drives a 3-day barotropic oscillation through the Straits throughout the year while thermal stratification in the summer establishes a bidirectional flow that is governed by a shift from regional-scale to local-scale meteorological conditions.

The largest inflow to Michigan-Huron is from Lake Superior via the connecting channel of the St. Mary's River and the largest outflow is by the connecting channel to Lake Erie via a combination of the St. Clair River, Lake St. Clair and the Detroit River. Smaller inflows to Lake Michigan are from the following rivers: Fox, Grand, Kalamazoo, Menominee, Milwaukee, Muskegon, and St. Joseph. Smaller inflows to Lake Huron are the Au Sable and the Saginaw Rivers and major rivers flowing into Georgian Bay are the French, the Muskoka, the Severn, the Magnetawan, and the Nottawasaga. Smaller outflows are the Trent-Severn Waterway which connects Lake Huron's Georgian Bay to Lake Ontario, running from Port Severn in the southeastern corner of the Bay and the Illinois Waterway which diverts water from Lake Michigan at Chicago to the Mississippi River.

Precipitation and evaporation are important components of the Great Lakes Hydrologic Cycle. Evaporation and precipitation are of the same order of magnitude as runoff of water from the land to the lakes. According to the Great Lakes Commission, the input to Michigan-Huron is estimated to be 38% due to precipitation, 34% due to runoff, and 27% from inflow. Output from Michigan-Huron is 31% due to evaporation, 68% due to outflow and 1% by the Chicago diversion to the Illinois Waterway.

3. MODEL SYSTEM AND SETUP FOR HINDCASTS

This section provides descriptions of the three-dimensional hydrodynamic (ocean circulation) numerical forecast model, the grid configuration, and how the lateral boundary, surface boundary, and initial conditions were specified for the hindcast runs. The configurations for LMHOFS, when it is run operationally on NOAA's WCOSS, will be different in terms of surface meteorological forcing and lateral boundary conditions for water temperatures and water levels due to decisions by NOS/CO-OPS.

3.1. Description of Model

FVCOM is a prognostic, unstructured-grid, finite-volume, free-surface, three-dimensional primitive equation coastal ocean circulation prediction model developed by the researchers at the UMASS-Dartmouth and Woods Hole Oceanographic Institution (Chen and Beardsley, 2003; Chen et al., 2013). The model consists of momentum, continuity, temperature, salinity and density equations and is closed physically and mathematically using turbulence closure sub-models. The horizontal grid is comprised of unstructured triangular cells. A generalized terrain-following vertical coordinate system is used. Several different turbulent closure schemes (TCS) are available in FVCOM. For LMHOFS, the Mellor Yamada 2.5 TCS was used for the vertical and the Smagorinsky TCS was utilized for the horizontal. FVCOM is solved numerically by a second-order-accurate discrete flux calculation in the integral form of the governing equations over an unstructured triangular grid. According to Chen et al. (2006), this approach combines the best features of finite-element method, which allow for grid flexibility and finite-difference method, which provide for numerical efficiency and code simplicity. The three-dimensional model solution is determined using a mode-splitting technique by which a two-dimensional external mode is updated at frequent intervals while the more slowly evolving internal mode is obtained less frequently. In other words, the free surface, defined as the external mode is integrated by solving vertically averaged equations with a smaller time step and the 3-D momentum and tracer equations, defined as the "internal mode," are integrated with a larger time step. Following every internal time step, an adjustment is made to maintain numerical consistency between the modes (Chen et al., 2006). FVCOM external and internal mode time steps of 5 and 10 seconds were used, respectively.

FVCOM has been successfully applied in several coastal ocean regions to simulate oceanographic conditions. Presently, NOS' Northern Gulf of Mexico Operational Forecast System (Wei et al., 2014; Wei et al., 2015), Lake Erie Operational Forecast System (Kelley et al, 2018), and the San Francisco Operational Forecast System (Peng et al., 2014; Schmalz, 2013) use FVCOM as their core numerical ocean circulation forecast model. For the LMHOFS hindcast runs, FVCOM Version 3.2 was used.

3.2. Grid Configuration

LMHOFS uses a model domain that includes both Lakes Huron and Michigan and the connecting Straits of Mackinac. The grid generation module of the Surface-Water-Modeling System (SMS) software was used by GLERL to generate the unstructured model grid. The grid size distribution

is configured as dependent on the GLERL bathymetry (NOAA NGDC, 3 arc-second). The model bathymetry was obtained by interpolating the GLERL digital bathymetry onto each unstructured FVCOM model grid node, referenced to the Low Water Datum (LWD) or chart datum, which is 176.0 m above the International Great Lakes Datum (IGLD) of 1985. The model bathymetry is shown in Fig. 1.

High resolution NOAA coastline data were applied to delineate the land boundary. The model grid in the horizontal is composed of 171,377 triangular elements and 90,806 nodes. The resolution varies from approximately 100 m (328 ft) near the shore to about 2.5 km (1.6 mi) offshore. The grid is depicted in Fig. 2. The model has 21 uniform sigma levels with distribution referenced to the Great Lakes low water datum of 176 m (577 ft). The sigma levels are the following: 0.0, -0.05, -0.1, -0.15, -0.2, -0.25, -0.3, -0.35, -0.4, -0.45, -0.5, -0.55, -0.6, -0.65, -0.7, -0.75, -0.8, -0.85, -0.9, -0.95, and -1.0.

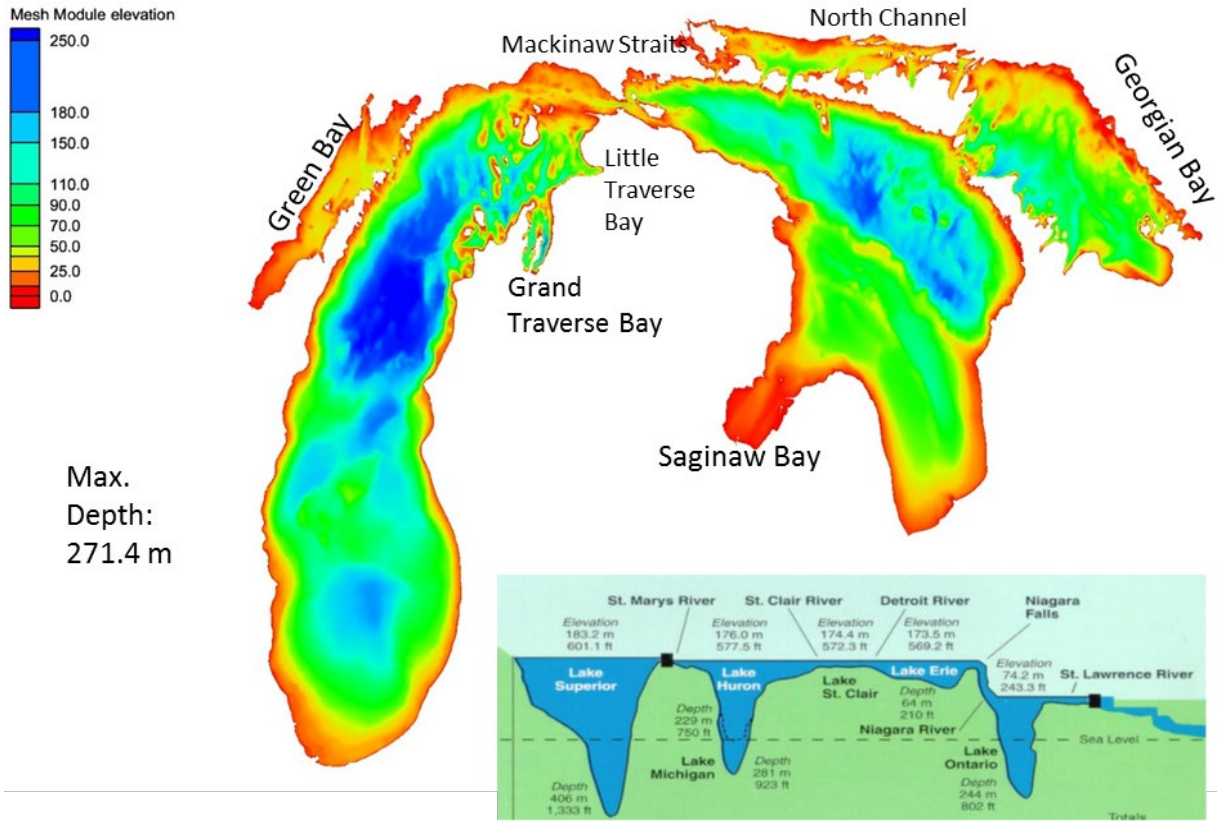

Figure 1. Map of the FVCOM model bathymetry (meters) for LMHOFS, referenced to Low Water Datum (LWD) of 176.0 m (577 ft).

Figure 2. Map depicting the FVCOM grid domain for LMHOFS. The horizontal resolution ranges from 100 m (328 ft) near the shore to 2.5 km (1.6 mi) offshore with 21 vertical levels.

3.3. Lateral Boundary Conditions

The lateral boundary conditions (LBCs) for the hindcasts were prescribed for water temperatures and water levels. The assignment of water level LBCs was the most complicated. Since over-lake precipitation, over-lake evaporation and inflow from tributaries and inflow and outflow of connecting channels are the same order of magnitude for Michigan-Huron, all these components must be estimated for LMHOFS to track low-frequency changes (e.g., seasonal) in lake levels.

The components were estimated in the following equation

$$dV/dt = Q_{\text{St. Marys River}} + Q_{\text{Tributaries}} + P - E - Q_{\text{St. Clair River}}$$

where Q=discharge, P=precipitation rate, E=evaporation rate, and dV=change in lake volume.

Since it is not possible to accurately estimate the over-lake precipitation and evaporation, the water budget is estimated with the equation

$$dV/dt = Q_{\text{St. Marys River}} + Q_{\text{Tributaries}} - Q_{\text{St.Clair River}} + Q_{\text{Residual}}$$

$Q_{St.\ Marys\ River}$ inflow is estimated using near-real-time discharge observations from the USGS gauge, *St. Marys River at Sault Sainte-Marie, MI* (Station ID 04127885) and assigning ½ flow to one inlet (Q1) and ½ to the other inlet (Q2) as depicted in Fig. 3. $Q_{St\ Clair\ River}$ outflow is estimated using near real-time discharge observations from the USGS gauge, *St. Clair River at Port Huron, MI* (Station ID 04159130). The estimation of $Q_{Tributaries}$, the inflow from other tributaries is determined from near-real-time discharge observations from USGS gauges, *Saginaw River at Holland Ave. at Saginaw, WI* (04157005) and *Fox River at Oil Tank Depot at Green Bay, WI* (040851385). These inflows and outflows were specified in the FVCOM river discharge data file, *casename_river.nc*.

The unaccounted inflow/outflow due to a combination of inflow from additional tributaries, runoff, and over-lake precipitation and evaporation is represented in the term, $Q_{Residual}$.

$$Q_{Residual} = dV/dt - (Q_{St.\ Marys\ River} + Q_{Tributaries} - Q_{St.\ Clair\ River})$$

where dV/dt is calculated by multiplying the lake surface area by the average observed water level change over the previous 5 days at the following four NOS/CO-OPS 'Master' Water Level Gauges: 1) Milwaukee, WI (9087057), 2) Ludington, MI (9087023), 3) Mackinaw City, MI (9075080), and 4) Harbor Beach, MI (9075014). GLERL tested different averaging time periods to find the optimal number of days which minimized lags in tracking lake levels while at the same time minimized high frequency variations that may not accurately represent resting lake levels. As a result of this approach, 5 days ending up being the best balance of these two objectives. $Q_{Residual}$ is added to FVCOM using its formulation for mass addition/subtraction via the precipitation/evaporation forcing file, *casename_pre_evap.nc*. Five days were chosen after conducting tests to achieve two objectives: minimize lags in lake level tracking while at the same time minimize high frequency water level variations that may not be accurate measures of 'resting' lake level trends. Five days resulted in providing the best balance of these two objectives.

Finally, to take into account the uncertainties in the prescribed inflow/outflows as well as the uncertainty in estimating lake level, an Open Boundary Water Level Condition was prescribed at the 3rd inlet to Lake Huron. The OBC water level was set at the St. Joseph Channel of the St. Marys River using observations from the NOS/CO-OPS Rock Cut, MI Gauge (9076024) located in the nearby West Neebish Channel (Fig. 4). The difference between the model's lake level and observed water level at the 3rd inlet will yield a flow across the open boundary that can increase or decrease to take into account errors in the prescribed inflows/outflows Q1 and Q2 at inlets #1 and #2, respectively as depicted in Fig. 3.

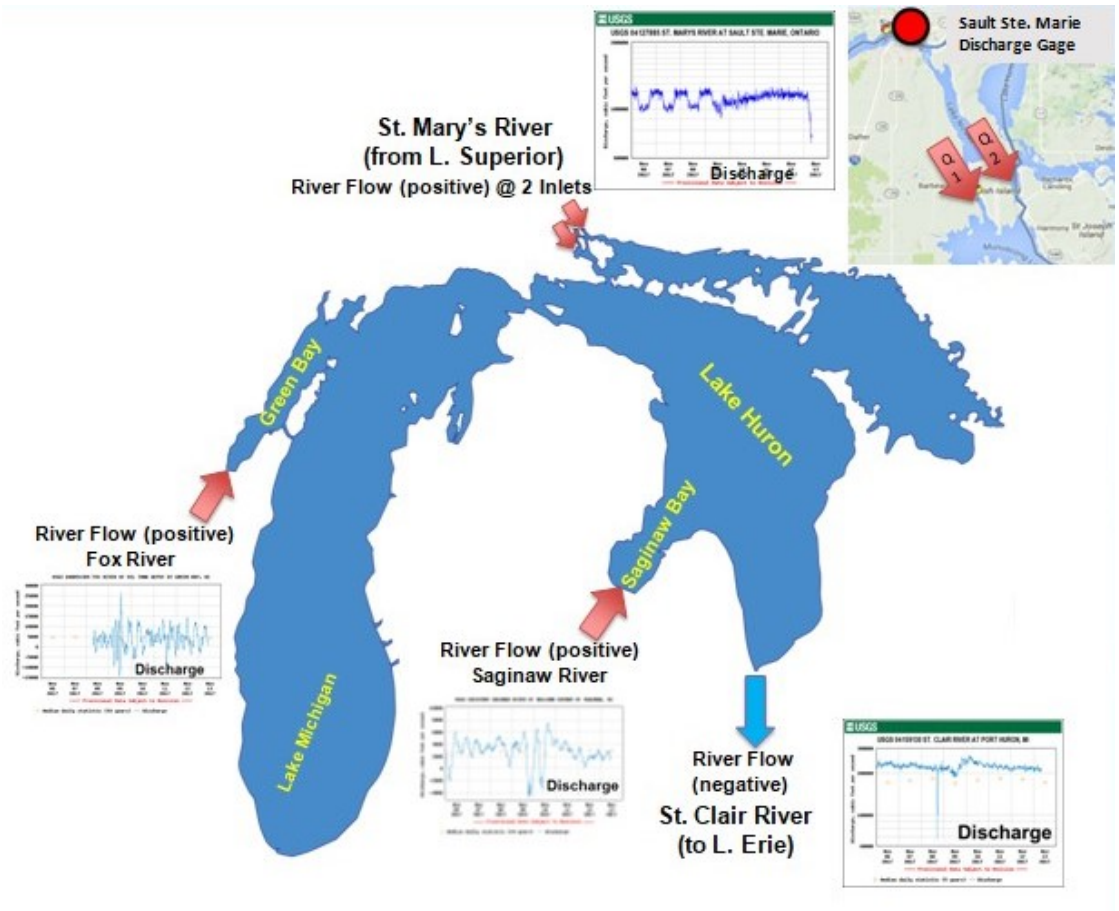

Figure 3. River and interconnecting channels boundary conditions for LMHOFS.

Figure 4. Map depicting the location where open boundary conditions were prescribed to take into account uncertainties in estimating inflow/outflow.

The temperature of waters flowing into Michigan-Huron were specified at three locations (Fig. 5). The temperature of water entering into Michigan's Green Bay from the Fox River was specified with hourly water temperatures from the USGS gauge at *Fox River at Oil Tank Depot* (040851385). The temperature of water flowing into Lake Huron's Saginaw Bay from the Saginaw River was specified with hourly water temperature observations from the USGS gauge at *Saginaw River at Hollard Ave. at Saginaw, WI* (04157005). The temperature of water entering the St. Marys River, which is split into two inlets and depicted in Figure 4, was specified with hourly water temperatures from the NOS/CO-OPS *S.W. Pier* gauge (9076070). The water temperatures are specified for these locations in the *casename_river.nc* file.

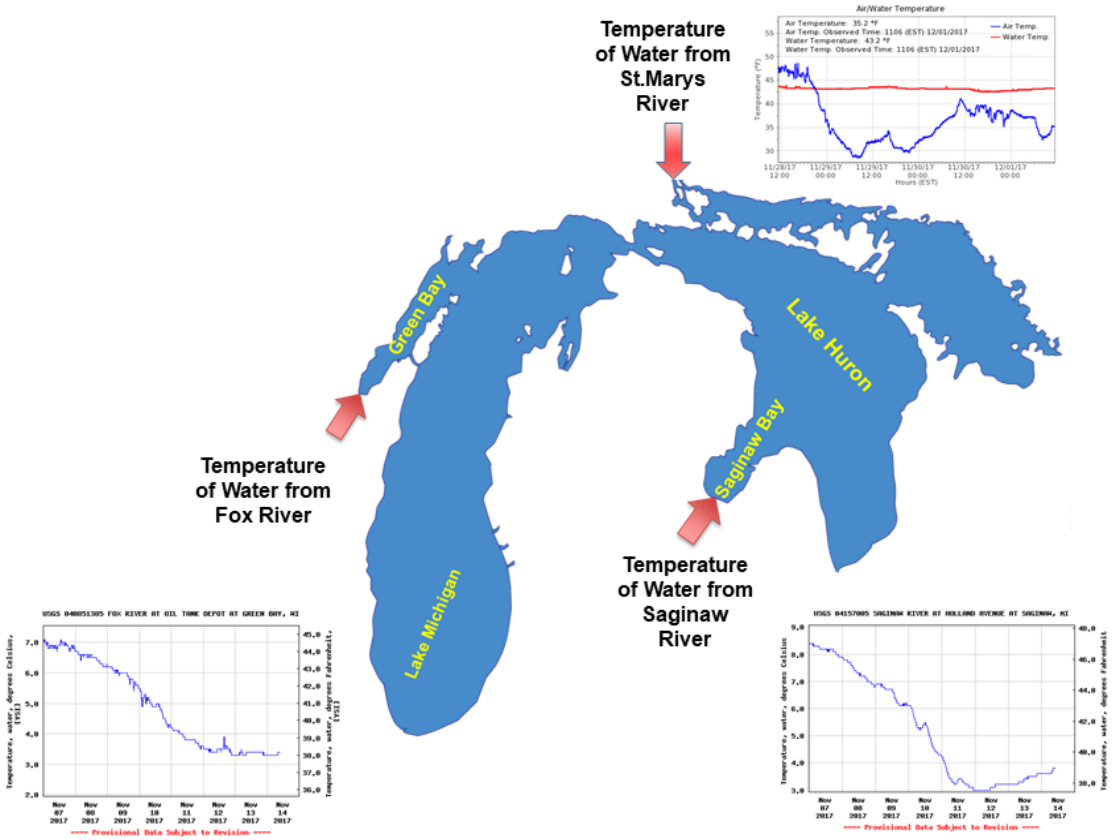

Figure 5. Locations where surface water temperatures are specified on the lateral boundaries of LMHOFS.

3.4. Surface Boundary Forcing

The surface meteorological forcing for the hindcasts was supplied using very-short range forecast guidance from the hourly forecast cycles of the NWS High-Resolution Rapid Refresh (HRRR), a 3-D numerical weather prediction analysis and forecast modeling system (Benjamin et al., 2016). HRRR provides analyses and forecast guidance out to 18 hours at a horizontal resolution of 3 km (1.86 mi). HRRR runs on WCOSS. The HRRR variables used to force

FVCOM are the following: 1) surface air temperature (2m AGL), 2) surface dew point temperature (2 m AGL), 3) mean sea level pressure (2 m AGL), 4) cloud/sky cover, 5) u- and v-wind components (~7.8 m AGL), 6) net downward short-wave radiation, and 7) downward long-wave radiation. All variables were obtained from the 2-hr forecast of the HRRR. The HRRR analyses (0-hr) and the 1-hr forecast guidance were not used because of artificially sharp gradients, artifacts from the HRRR's assimilation system (Stan Benjamin, personal communication).

Output from HRRR Version 1 was used for forcing the hindcasts from Jan. 1, 2015 to Aug. 30, 2016 and HRRR Version 2 was used for Sept. 23, 2016 to June 30, 2017. The HRRR output was obtained from the NOAA High Performance Storage System (HPSS) runtime history archives, the required variables were extracted, and subsetted for the Great Lakes Region by CSDL personnel. The processed HRRR output was then provided to GLERL researchers. The latent and sensible heat fluxes were calculated from several of the meteorological variables using COARE 2.6, Bulk Air Sea Flux Algorithm (Fairall et al., 2003), using the freshwater version of the COARE algorithm of FVCOM (HEATING_CALCULATED_GL).

3.5. Initial Conditions

LMHOFS required initial three-dimensional conditions including surface elevation field and three-dimensional velocity and water temperature fields at the beginning of the hindcasts. The model was initialized one year prior to the start of the hindcast period with surface temperatures derived from NOAA AVHRR imagery obtained through the Great Lakes CoastWatch program and prescribed from the NOAA Great Lakes Surface Environmental Analysis (GLSEA) and subsurface temperatures below 10 m set to a uniform water temperature of 2 ºC, 0.0 m elevation (relative to LWD), and 0 m/s currents. The GLSEA is valid at an approximate depth of 10 μm or 1 x 10^{-6} m (Songzhi Liu, Personal Communication). The model was continuously forced with observed LBCs and surface meteorological analyses of near-real-time adjusted overland and overwater weather observations. The restart file after the one-year run was used as the initial conditions for the start of the hindcasts. The dates for the hindcast periods are given in the next section.

4. DESCRIPTION OF HINDCAST PERIODS

Three hindcast model simulations using LMHOFS were conducted by GLERL on their Linux cluster in Ann Arbor, MI. Hindcast #1 covered the period from Jan. 1, 2015 to Dec. 31, 2015; Hindcast #2 was for the period Jan. 1, 2016 to Dec. 31, 2016; and extended hindcast from Jan.1, 2014 to Jan. 1, 2018 for evaluating subsurface water temperatures.

5. METHOD OF EVALUATION

LMHOFS's hourly hindcasts of water levels and water temperatures for 2015 and 2016 were compared to hourly observations from coastal and offshore observing platforms in Lakes Huron and Michigan. For 2016, the LMHOFS hindcasts were also compared to nowcasts from the operational LMOFS and LHOFS at locations where nowcasts were available in archived LMOFS and LHOFS station netCDF output files. The hindcasts and nowcasts are similar since both are forced by 'observed' conditions.

The evaluation used the standard NOS suite of skill assessment statistics. These statistics included Error, or more commonly referred to as Mean Algebraic Error (MAE), Root Mean Squared Error (RMSE), Central Frequency (CF), Positive Outlier Frequency (POF), Negative Outlier Frequency (NOF), Maximum Duration of Positive Outliers (MDPO), and Maximum Duration of Negative Outliers (MDNO). These statistics are described briefly in Table 1 while more detailed descriptions can be found in Hess et al. (2003). The comparisons were done using the NOS standard skill assessment software (Zhang et al., 2010 and Zhang et al., 2013).

The calculation of the target frequency of occurrence skill statistics, CF, POF, MDPO and MDNO, required the assignment of 1) acceptable magnitude errors for water level and water temperature amplitudes, 2) acceptable timing error for water levels, and 3) maximum allowable time durations for consecutive positive and negative water level outliers. The same acceptable errors and maximum allowable time duration used to evaluate GLOFS, when it was first implementation operationally at NOS, were employed in evaluating these hindcasts (see last column in Table 1). These specific values for the water level and temperature skill assessments will be discussed in the Sections 5.1 and 5.2, respectively.

The standard skill assessment code has a coarse quality assurance function that is applied to all downloaded CO-OPS and National Data Buoy Center (NDBC) buoy observational data. It calculates a "quality control range" first; any data that is out of this range will be regarded as unrealistic and will then be deleted. The quality-control-range is calculated in the subroutine *refwl.f*. The code in the subroutine calculates average and standard deviation for the whole data set, and uses average +/- 5 times standard deviation as upper and lower boundaries and writes out data that are within this range. This +/- 5 SD QA check erroneously removed several high amplitude water level events at NOS/CO-OPS in the Great Lakes. This QA check was commented out in order to include all high amplitude water level and water temperature events when assessing the hindcasts' performance skills. However, both the water level and water temperature observational data were plotted and obvious erroneous spikes were manually deleted from the data prior to running the skill assessment program.

Extreme high or low water events were selected from the observed data and hindcasts using the equations hupper=mean+factor*SD and hlower=mean-factor*SD where the value for factor was set to 2.0 (Zhang et al., 2013).

The resulting values for each statistic were then judged against the NOS Acceptance Criteria (Table 1) for that statistic. These critieria include target frequencies of occurrence for CF, NOF, and POF and limits on the duration of errors (i.e. maximum length of time of consecutive occurrences) for MDPO and MDNO. Any new or upgraded NOS operational oceanographic

modeling system is expected to meet or exceed most of the NOS Acceptance Criteria (targets) in order to be implemented operationally.

Table 1. Description of NOS skill assessment statistics (Modified from Hess et al., 2003) along with NOS Acceptance Criterion (targets) used to evaluate LMFOFS hindcasts.

Statistic	Units	Description	NOS Acceptance Criterion
Mean Algebraic Error (MAE)	Meters or Hours	The error is defined as the predicted value, p, minus the reference (observed value)	NA
SD	Meters or Hours	Standard Deviation	NA
RMSE	Meters or Hours	Root Mean Square Error	NA
SM	Meters or Hours	Series Mean. The mean value of a series y	NA
CF(X)	%	Central Frequency. Fraction (percentage) of errors that lie within the limits $\pm$X.	=> 90%
POF(X)	%	Positive Outlier Frequency. Fraction (percentage) of errors that are greater than X.	<= 1%
NOF(X)	%	Negative Outlier Frequency. Fraction (percentage) of errors that are less than -X.	<= 1%
MDPO(2X)	Hours	Maximum Duration of Positive Outliers. A positive outlier event is two or more consecutive occurrences of an error greater than +2X. MDPO is the length of time in hours (based on the number of consecutive occurrences) of the longest positive outlier event.	<= L
MDNO(2X)	Hours	Maximum Duration of Negative Outliers. A negative outlier event is two or more consecutive occurrences of an error less than -2X. MDNO is the length of time in hours (based on the number of consecutive occurrences) of the negative outlier longest event.	<= L
NOS Standard Criteria		where X=acceptable error magnitude (cm or minutes) X = +- 15cm for water level amplitude errors X = +- 1.5 hours (90 minutes) for water level timing errors X = +- 3.0^{o}C for water temperature amplitude errors	where L=time limit or max. allowable duration L=24 hours

5.1. Evaluation of Water Level Hindcasts

The evaluation of hourly water levels was based on comparisons of time series from the hindcasts to observations and also on comparisons to nowcasts from LMOFS and LHOFS during 2016. The comparison of time series from 2015 and 2016 water level hindcasts used the statistics SM, RMSE, SD, NOF, POF, MDPO, and MDNO as described in the previous section. The assessment evaluated the ability of the hindcasts to predict hourly water levels and also extreme high and low water events. The identification of extreme high and low water events during the hindcast periods in the Great Lakes was accomplished using the method described in Chu et al. (2007).

The acceptable magnitude errors for water levels was set at +/- 15 cm (0.5 ft) and the acceptable timing error was set at +/- 1.5 hours. In addition, for the calculation for the MDPO and MDNO statistics, a maximum allowable time duration of consecutive occurrences with an error greater than the acceptable amplitude or timing error was specified at 24 hours.

The water level time series from hourly hindcasts were compared to observed hourly water levels recorded at NOS/CO-OPS NWLON and Canadian Hydrographic Service (CHS) stations along the shores of Lakes Michigan-Huron. (Fig. 6). Information about these stations is given in Table 2. The hourly water level observations from the NOS NWLON gauges were obtained from CO-OPS online archives at http://tidesandcurrents.noaa.gov. The hourly water levels from the CHS gauges were obtained from Canada's Dept. of Fisheries and Oceans online archives at http://www.meds-sdmm.dfo-mpo.gc.ca/isdm-gdsi/twl-mne/inventory-inventaire/list-liste-eng.asp?user=isdm-gdsi&region=CA&tst=1. All observations were plotted as time series and visually inspected for erroneous data. Any erroneous data was removed prior to conducting the skill assessment.

Figure 6. Locations of water level verification sites for LMHOFS.

Table 2. Information on NOAA/NOS/CO-OPS NWLON and CHS stations whose observations were used to evaluate the LMHOFS hindcasts. N/A indicates that an official NWS station ID has not been assigned to the station yet or not available since it is a Canadian station.

Station Name	State or Prov.	NOS or CHS Station ID	NWS Station ID	Coordinates	
				Lat. (deg N)	Lon. (deg W)
Fort Gratiot	MI	9014098	FTGM4	43.007	82.422
Lakeport	MI	9075002	N/A	43.142	82.493
Harbor Beach	MI	9075014	HRBM4	43.847	82.643
Essexville	MI	9075035	N/A	43.640	83.847
Alpena	MI	9075065	LPNM4	45.063	83.428
Mackinaw City	MI	9075080	MACM4	45.778	84.720
De Tour Village	MI	9075099	DTLM4	45.990	83.900
Rock Cut	MI	9076024	RCKM4	46.265	84.192
Ludington	MI	9087023	LDTM4	43.946	86.441
Holland	MI	9087031	HLNM4	42.768	86.201
Calumet Harbor	IL	9087044	CMTI2	41.730	87.538
Milwaukee	WI	9087057	N/A	43.001	87.886
Kewaunee	WI	9087068	N/A	44.463	87.500
Sturgeon Bay Canal	WI	9087072	N/A	44.795	87.313
Green Bay	WI	9087079	N/A	44.542	88.007
Menominee	MI	9087088	MNMM4	45.097	87.590
Port Inland	MI	9087096	PNLM4	45.970	85.871
Thessalon	ON	C11070	NA	46.25	83.55
Little Current	ON	C11195	NA	45.98	81.93
Midland	ON	C11445	NA	44.75	79.85
Collingwood	ON	C11500	NA	44.50	80.22
Tobermory	ON	C11690	NA	45.25	81.67
Goderich	ON	C11860	NA	43.75	81.73

5.2. Evaluation of Surface Water Temperature Hindcasts

The evaluation of hourly hindcasts of surface water temperatures was based on comparisons of time series from the hindcasts to observations at both offshore and coastal locations in Lake Michigan-Huron (Fig. 7) and also on comparisons to operational nowcasts from LMOFS and LHOFS during 2016. The comparisons were done using SM, RMSE, SD, NOF, POF, MDPO, and MDNO. In evaluating predicted water temperature in tidal regions, NOS sets an acceptable error of 7.7 ºC to meet the acceptable error of draft of 7.5 cm (3 inches), as water density is a function of temperature and salinity. However, since the Great Lakes are considered fresh water and non-tidal, there is no preset standard for lake temperature prediction. Based on ten years of experience in running the Great Lakes Forecasting System and input from the Great Lakes user community, Dr. David Schwab of NOAA/GLERL suggested a 3 ºC criteria for water temperature skill assessment in the Great Lakes region (personal communication). Thus a 3 ºC criteria for water temperature was assigned, the same criteria used in earlier evaluations of GLOFS (Chu et al., 2007; Kelley et al., 2018).

Hindcasts at nearshore and offshore locations were compared to observations at twenty-four fixed buoys in the lakes. The buoys are operated by the NOAA/NWS/National Data Buoy Center (NDBC) or ECCC. The point evaluations were conducted by comparing surface (highest sigma layer) temperature hindcasts at the nearest grid points to the buoys. Geographic information for the twenty-four buoys is given in Table 3.

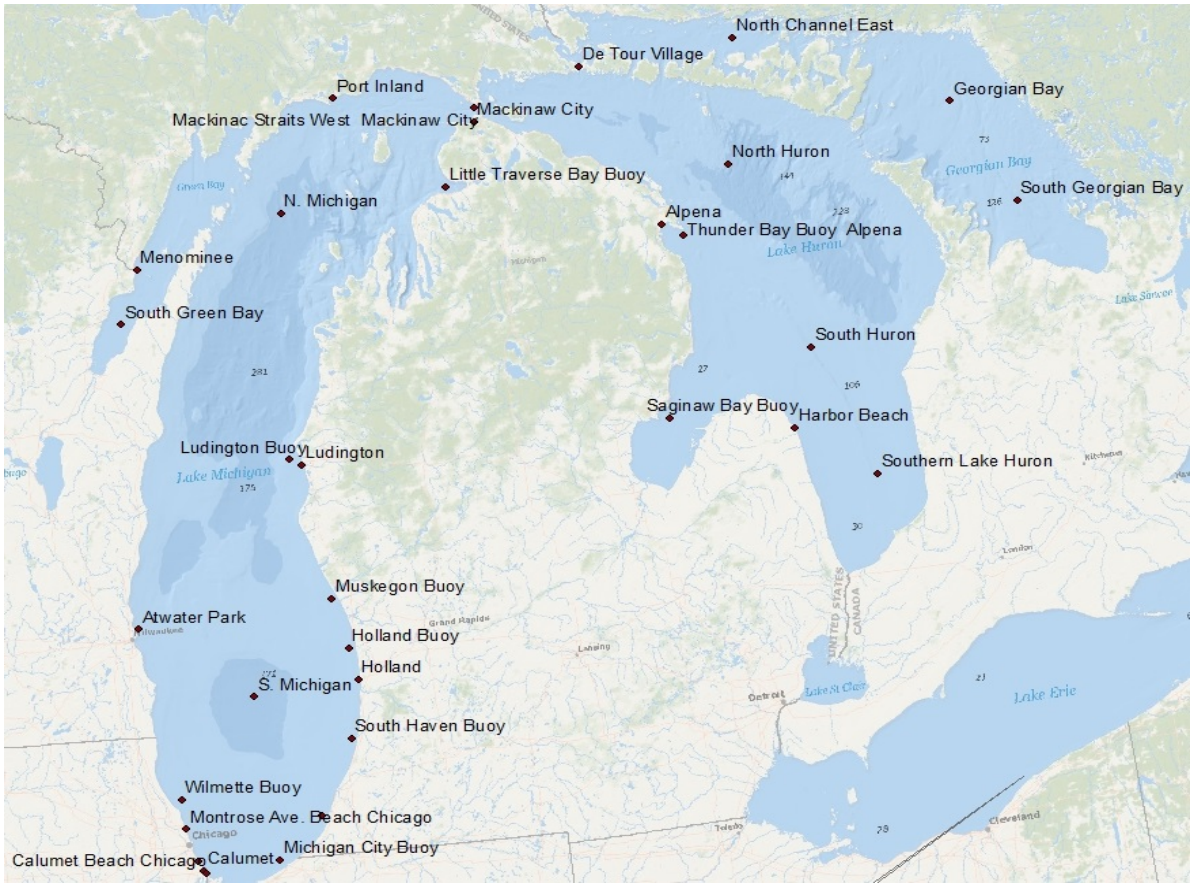

Figure 7. Locations of water temperature observing stations used to verify LMHOFS.

Table 3. Information about NWS/NDBC and ECCC fixed buoys whose surface water temperature observations were used to evaluate the LMHOFS hindcasts offshore.

Buoy Name	Agency	Prov. or State	NWS Buoy Platform ID	Coordinates	
				Latitude (deg N)	Longitude (deg W)
N. Michigan	NWS/NDBC	MI	45002	45.344	86.411
North Huron	NWS/NDBC	MI	45003	45.351	82.840
S. Michigan	NWS/NDBC	WI	45007	42.674	87.026
South Huron	NWS/NDBC	MI	45008	44.283	82.416
Atwater Park	NWS/NDBC	WI	45013	43.100	87.850
South Green Bay	NWS/NDBC	WI	45014	44.800	87.760
Calumet Beach	NWS/NDBC	IL	45015	41.714	87.527
Sixth-third St. Beach	NWS/NDBC	IL	45016	41.783	87.573
Montrose Ave. Beach	NWS/NDBC	IL	45018	41.968	87.637
Little Traverse Bay Buoy	NWS/NDBC	MI	45022	45.403	85.088
Ludington Buoy	NWS/NDBC	MI	45024	43.973	86.556
Cook Nuclear Plant Buoy	NWS/NDBC	MI	45026	41.983	86.617
Holland Buoy	NWS/NDBC	MI	45029	42.900	86.272
Georgian Bay	Envir. Canada	ON	45137	45.540	81.010
South Georgian Bay	Envir. Canada	ON	45143	44.940	80.627
Southern Lake Huron	Envir. Canada	ON	45149	43.540	82.070
North Channel East	Envir. Canada	ON	45154	46.050	82.640
Muskegon Buoy	NWS/NDBC	MI	45161	43.179	86.357
Thunder Bay Buoy	NWS/NDBC	MI	45162	44.988	83.271
Saginaw Bay Buoy	NWS/NDBC	MI	45163	43.986	83.595
South Haven Buoy	NWS/NDBC	MI	45168	42.397	86.331
Michigan City Buoy	NWS/NDBC	IN	45170	41.755	86.968
Wilmette Buoy	NWS/NDBC	IL	45174	42.135	87.655
Mackinac Straits West	NWS/NDBC	MI	45175	45.825	84.772

Hindcasts at coastal locations were compared to observations at seven NOS/CO-OPS NWLON stations (Table 4). The water temperature sensors at the NWLON stations are located approximately 1.5 m below the low water datum (LWD) for the Great Lakes. According to Grodsky (personal communication, 2014), the sensors are located fairly close to the shore structure that the water level gauges are mounted to.

Table 4. Information about NOS/CO-OPS NWLON stations whose water temperature observations were used to evaluate the LMHOFS hindcasts along the coast.

Station Name	State	NOS Station ID	NWS Station ID	Coordinates	
				Latitude (deg N)	Longitude (deg W)
Harbor Beach	MI	9075014	HRBM4	43.847	82.643
Alpena	MI	9075065	LPNM4	45.063	83.428
Mackinaw City	MI	9075080	MACM4	45.778	84.720
De Tour Village	MI	9075099	DTLM4	45.990	83.900
Holland	MI	9087031	HLNM4	42.768	86.201
Menominee	MI	9087088	MNMM4	45.097	87.590
Port Inland	MI	9087096	PNLM4	45.970	85.871

5.3. Evaluation of Sub-Surface Water Temperature Hindcasts

The evaluation of hourly hindcasts of sub-surface water temperatures was based on comparisons of time series from the hindcasts to observations at three thermistor-chain locations in Lake Michigan-Huron. The duration of available observations varied at the three locations. The comparisons were done using RMSE. Similar to surface temperature skill assessment for the Great Lakes, a 3^{o}C criteria for subsurface water temperature was assigned, the same criteria used in earlier evaluations of GLOFS (Chu et al., 2007; Kelley et al., 2008).

The thermistors were deployed by GLERL in southern Lake Michigan near NDBC buoy 45007, the Straits of Mackinac, and mid Lake Huron (Fig. 8). The point evaluations were conducted by comparing modeled temperature hindcasts at the nearest grid points to the thermistor locations, and then by interpolating modeled temperatures from the nearest sigma layer (e.g., depth) to the depth locations of the thermistors. Geographic information for the three thermistor chains is given in Table 5.

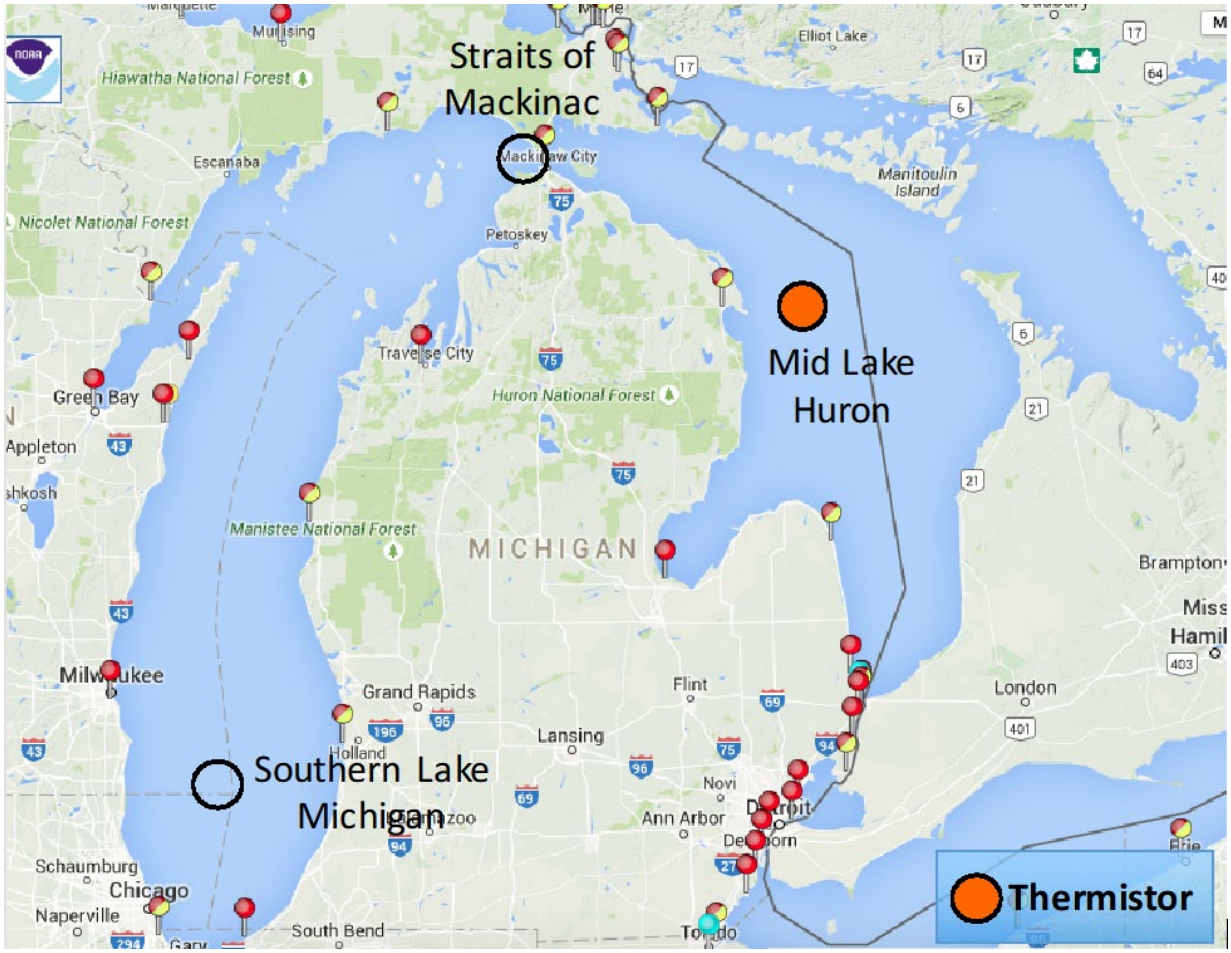

Figure 8. Locations of the three sub-surface water temperature moorings used to verify LMHOFS hindcasts.

Table 5. Information about GLERL thermistor chain stations whose sub-surface water temperature observations were used to evaluate the LMHOFS hindcasts of the vertical thermal structure.

Station Name	Depth (m)	Coordinates	
		Latitude (deg N)	Longitude (deg W)
Southern Lake Michigan	153	42.67	87.03
Straits of Mackinac	36	45.815	84.822
Mid-Lake Huron	209	45.158	82.583

6. HINDCAST SKILL ASSESSMENT RESULTS

Although Lake Michigan-Huron is hydrologically a single lake, the Straits of Mackinac create a pronounced constriction that creates two distinct basins. As both basins span more than 482 km (300 mi) from west to east, and 531 km (330 mi) from north to south, and with differing weather conditions over each basin, assessments of water levels and temperatures will be discussed by the following geographic regions. The results of the water level assessment will be given first followed by a discussion of the water temperature evaluation results.

6.1. Assessment of Water Level Hindcasts

The standard suite of skill assessment statistics evaluated the ability of the hindcasts to predict hourly and extreme high and low water levels at NOS and CHS gauges during 2015 and 2016. The results of the assessment of the hourly hindcasts are described in Section 6.1.1 and the assessment results of extreme high and low water events are given in Section 6.1.2. The results are given for the following basins: Lake Huron's Georgian Bay, the main stem of Lake Huron, Northern Lake Michigan, and Southern Lake Michigan.

6.1.1. Hourly Water Levels

The snapshot of hourly water level time series plots at different regions of 2015 and 2016 are shown from Figures 9-14. The mean algebraic error (MAE) and RMSE of hindcast were highlighted on all 2015 hindcast plots. The 2016 time series plots contain both hindcasts and operational nowcasts (if station output is available) of hourly water levels as well as MAE and RMSE from both LMHOFS and LMOFS and/or LHOFS. Full statistic tables are available from Table 6 to Table 13.

6.1.1.1. Georgian Bay – Lake Huron

Often referred to as the sixth Great Lake, Georgian Bay is the largest bay of Lake Huron, located entirely within Ontario, Canada. Therefore, all hourly water level observations at Georgian Bay came from CHS. Geographic locations of CHS stations are labeled from 1 to 4 on the regional map as well as corresponding water level time series plots in Figure 9.

The skill statistics assessing the ability of the hindcasts to predict hourly water levels at CHS gauges in 2015 are given in Table 6. A similar table for 2016 is given in Table 7, but also includes comparable statistical assessment of operational nowcasts from LHOFS (if data were available). The MAE during 2015 at Georgian Bay stations ranged between 4.2 and 6.8 cm; and the RMSE ranged between 5.9 and 9.5 cm. For 2016, the hindcast MAEs ranged from 2.9 to 5.9 cm and the RMSE ranged from 5.4 to 8.9 cm. The LHOFS MAEs ranged from 3.1 to 6.3 cm and the RMSE ranged from 8.4 to 13.0 cm. The smallest MAEs during 2015 and 2016 were at Station #4, Collingwood. Both LMHOFS and LHOFS gave better predictions of water level at this station than at other locations. The hindcasts for 2015 and 2016 passed all the NOS Acceptance Criteria at all Georgian Bay CHS stations. Compared to LHOFS, LMHOFS performs better in terms of POF and CF at Station #2, Little Current, during 2016. CF and POF

of LHOFS at Little Current during 2016 are 79.6 and 2.1 respectively, which are out of NOS Acceptance Criteria. The corresponding CF and POF of LMHOFS are improved to 97.6 and 0.0.

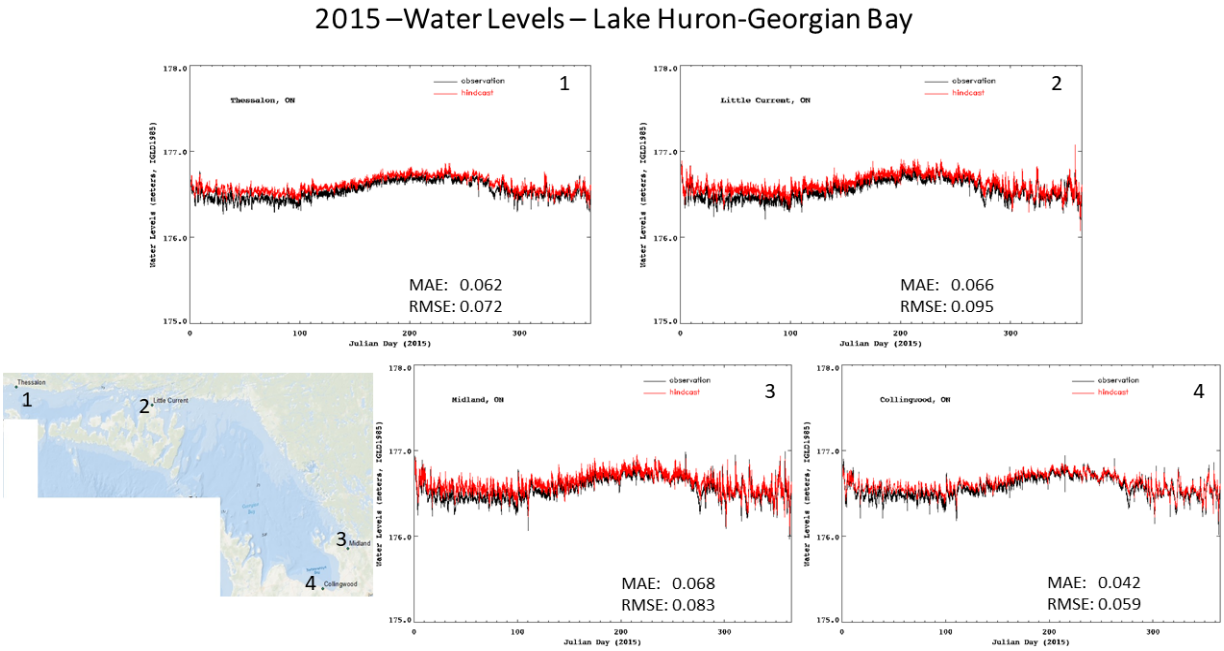

Figure 9. Time series plots of hourly hindcasts of water level (red) vs. observations (black) at CHS gauges (1. Thessalon, ON, 2. Little Current, ON, 3. Midland, ON, and 4. Collingwood, ON) at Georgian Bay, Lake Huron during 2015. MAE and RMSE (m) at each station are shown individually on each panel.

Table 6. Summary of skill assessment statistics evaluating the ability of the LMHOFS hindcasts to predict hourly water levels at CHS gauges in Georgian Bay, Lake Huron for 2015. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	C11070 Thessalon	C11195 Little Current	C11445 Midland	C11500 Collingwood
N	8753	8760	8754	8760
Mean Alg. Error (m)	0.062	0.068	0.066	0.042
RMSE (m)	0.072	0.083	0.095	0.059
SD (m)	0.036	0.047	0.069	0.041
NOF [2x15 cm] (%)	0.0	0.0	0.1	0.0
CF [15 cm] (%)	98.8	95.6	90.0	99.2
POF [2x15 cm] (%)	0.0	0.0	0.1	0.0
MDNO [2x15 cm] (hr)	0.0	0.0	1.0	0.0
MDPO [2x15 cm] (hr)	0.0	0.0	1.0	0.0

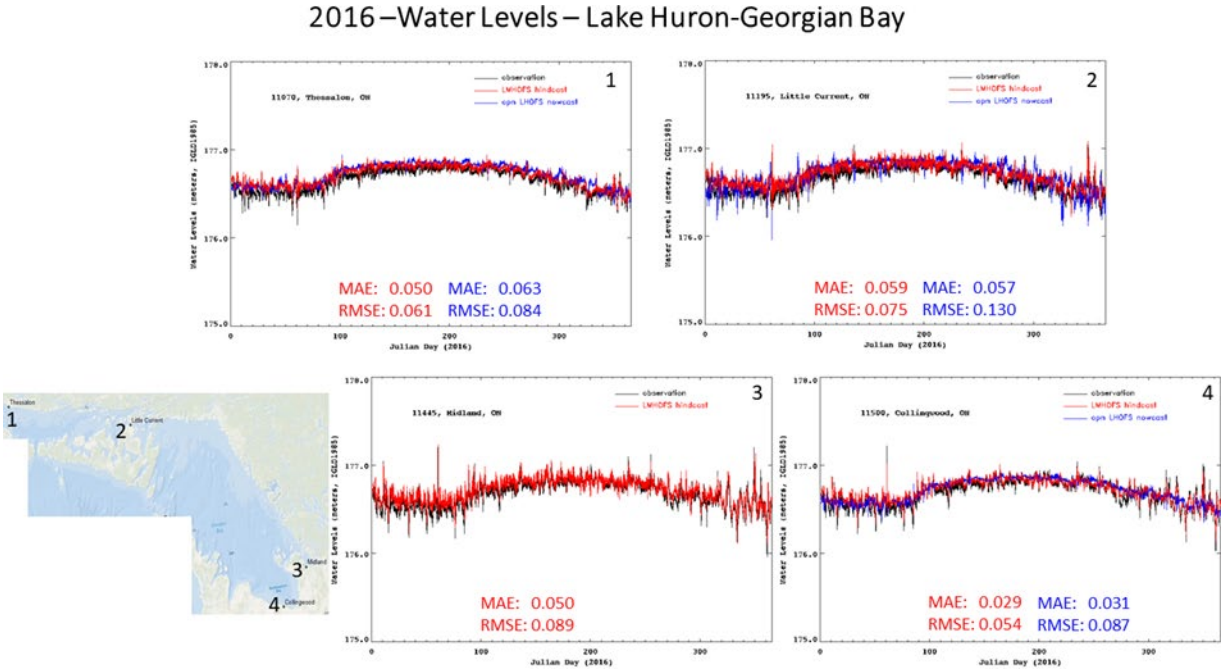

Figure 10. Same as Figure 9 except includes operational nowcasts from LHOFS for 2016.

Table 7. Summary of skill assessment statistics evaluating the ability of the LMHOFS hindcasts to predict hourly water levels at Canadian Hydrographic stations in Georgian Bay, Lake Huron for 2016. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	C11070 Thessalon		C11195 Little Current		C11445 Midland		C11500 Collingwood	
	LMHOFS	LHOFS	LMHOFS	LHOFS	LMHOFS	LHOFS	LMHOFS	LHOFS
N	8754	8679	8760	8682	8760	N/A	8487	8407
Mean Alg. Error (m)	0.050	0.063	0.059	0.057	0.050	N/A	0.029	0.031
RMSE (m)	0.061	0.084	0.075	0.130	0.089	N/A	0.054	0.087
SD (m)	0.035	0.055	0.046	0.117	0.073	N/A	0.045	0.081
NOF [2x15 cm] (%)	0.0	0.0	0.0	0.9	0.2	N/A	0.0	0.2
CF [15 cm] (%)	99.5	94.9	97.6	79.6	92.7	N/A	99.6	92.6
POF [2x15 cm] (%)	0.0	0.0	0.0	2.1	0.2	N/A	0.0	0.2
MDNO [2x15 cm] (hr)	0.0	0.0	0.0	6.0	2.0	N/A	0.0	4.0
MDPO [2x15 cm] (hr)	0.0	0.0	0.0	23.0	2.0	N/A	0.0	7.0

6.1.1.2. Lake Huron – Main Stem

Lake Huron is bounded on the north and east by the Canadian province of Ontario and on the south and west by the State of Michigan. Manitoulin Island separates the North Channel and Georgian Bay from Lake Huron's main body of water. Observations from six CO-OPS NWLON and two CHS water level gauges along Saginaw Bay and Lake Huron proper were examined for hindcast period 2015 and 2016. Locations and time series plots as well as MAEs and RMSEs of these eight stations are shown on Figure 11 and Figure 12. The range of hindcast MAEs at this region vary from -6.8 to 5.0 cm in 2015 (Table 8) and from -7.1 to 3.7 cm in 2016 (Table 9). In both hindcasts, all three stations located in the northern half of Lake Huron Proper have positive MAEs, and the MAEs of four stations in the southern half are all negative. The hindcasts for 2015 and 2016 passed all the NOS Acceptance Criteria at all NWLON and CHS gauges located in the main stem of Lake Huron. The RMSE was less for the LMHOFS hindcasts than for LHOFS nowcasts at seven of the eight gauges in 2016.

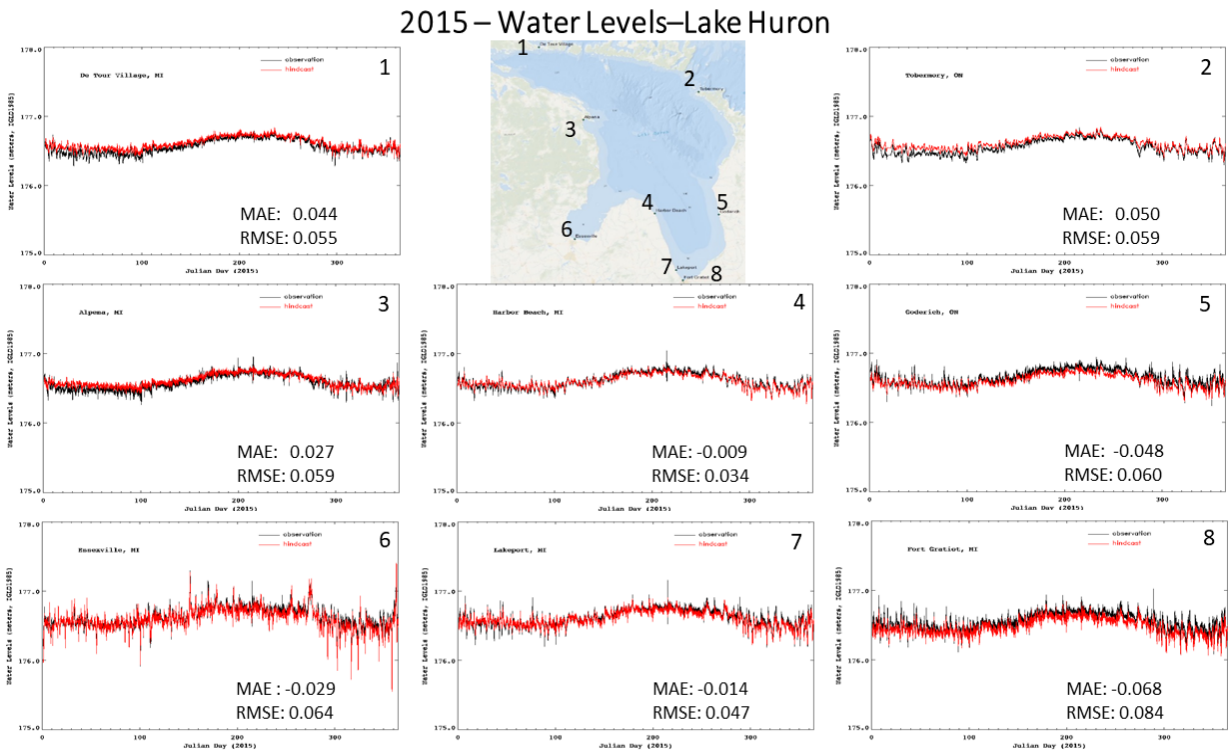

Figure 11. Time series plots of hourly LMHOFS hindcasts of water level (red) vs. observations (black) at CO-OPS NWLON and CHS gauges (1. De Tour Village, MI, 2. Tobermory, ON, 3. Alpena, MI, 4. Harbor Beach, MI, 5. Goderich, ON, 6. Essexville, MI, 7. Lakeport, MI, and 8. Fort Gratiot, MI) in Lake Huron during 2015. MAE and RMSE (m) at each station are shown individually on each panel.

Table 8. Summary of skill assessment statistics of LMHOFS hindcasts of hourly water levels at NOS NWLON and CHS gauges in Lake Huron for 2015. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9076024 Rock Cut	9075099 De Tour Village	C11690 Tobermory	9075065 Alpena	9075014 Harbor Beach
N	8761	8761	8670	8761	8761
Mean Alg. Error (m)	0.049	0.044	0.050	0.027	-0.009
RMSE (m)	0.068	0.055	0.059	0.050	0.034
SD (m)	0.047	0.033	0.031	0.043	0.032
NOF [2x15 cm] (%)	0.0	0.0	0.0	0.0	0.0
CF [15 cm] (%)	98.3	99.6	99.9	99.5	100.0
POF [2x15 cm] (%)	0.0	0.0	0.0	0.0	0.0
MDNO [2x15 cm] (hr)	0.0	0.0	0.0	0.0	0.0
MDPO [2x15 cm] (hr)	0.0	0.0	0.0	0.0	0.0

C11860 Goderich	9075035 Essexville	9075002 Lakeport	9014098 Fort Gratiot
8701	8761	8761	8761
-0.048	-0.029	-0.014	-0.068
0.060	0.064	0.047	0.084
0.036	0.057	0.045	0.049
0.0	0.1	0.0	0.0
99.5	97.8	99.5	95.5
0.0	0.0	0.0	0.0
0.0	1.0	0.0	0.0
0.0	1.0	0.0	0.0

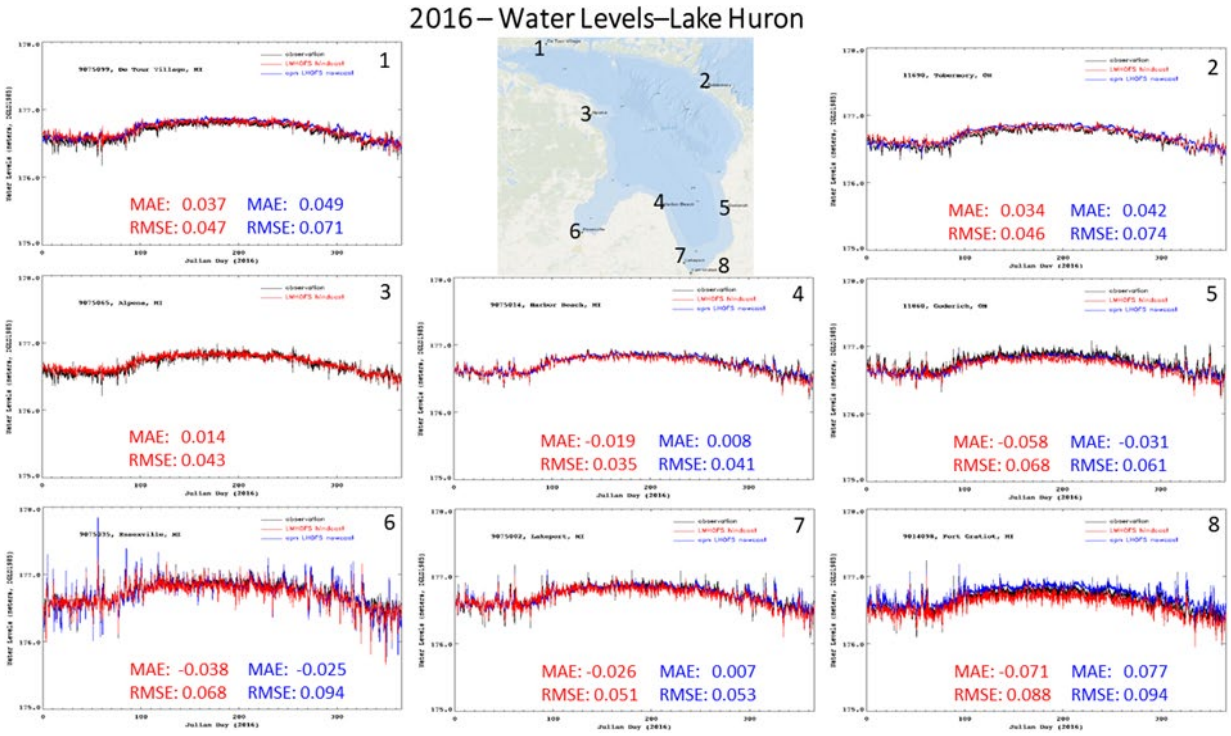

Figure 12. Same as Figure 11 except includes operational LHOFS data for 2016.

Table 9. Summary of skill assessment statistics of LMHOFS hindcasts and LHOFS nowcasts of hourly water levels at NOS NWLON and CHS gauges in Lake Huron for 2016. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9076024 Rock Cut		9075099 De Tour Village		C11690 Tobermory		9075065 Alpena	
	LMHOFS	LHOFS	LMHOFS	LHOFS	LMHOFS	LHOFS	LMHOFS	LHOFS
N	8760	8685	8760	8685	8711	8632	8691	N/A
Mean Alg. Error (m)	0.050	0.014	0.037	0.049	0.034	0.042	0.014	N/A
RMSE (m)	0.069	0.082	0.047	0.071	0.046	0.074	0.043	N/A
SD (m)	0.047	0.080	0.029	0.051	0.030	0.062	0.040	N/A
NOF [2x15 cm] (%)	0.0	0.1	0.0	0.0	0.0	0.0	0.0	N/A
CF [15 cm] (%)	98.3	93.6	99.9	97.2	100.0	96.3	99.7	N/A
POF [2x15 cm] (%)	0.0	0.1	0.0	0.0	0.0	0.0	0.0	N/A
MDNO [2x15 cm] (hr)	0.0	3.0	0.0	0.0	0.0	0.0	0.0	N/A
MDPO [2x15 cm] (hr)	0.0	2.0	0.0	0.0	0.0	0.0	0.0	N/A

Table 9. Continued

9075014 Harbor Beach		C11860 Goderich		9075035 Essexville		9075002 Lakeport		9014098 Fort Gratiot	
LMHOFS	LHOFS	LMHOFS	LHOFS	LMHOFS	LHOFS	LMHOFS	LHOFS	LMHOFS	LHOFS
8760	8685	8760	8679	8760	8685	8760	8685	8664	8565
-0.019	0.008	-0.058	-0.031	-0.038	-0.025	-0.026	0.007	-0.071	0.077
0.035	0.041	0.068	0.061	0.068	0.094	0.051	0.053	0.088	0.094
0.030	0.041	0.037	0.053	0.056	0.091	0.044	0.052	0.051	0.055
0.0	0.0	0.0	0.0	0.1	1.0	0.0	0.0	0.1	0.0
100.0	99.7	98.7	98.1	97.5	90.8	99.1	98.6	94.7	91.5
0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.2
0.0	0.0	0.0	0.0	1.0	21.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	1.0	19.0	0.0	0.0	0.0	3.0

6.1.1.3. Northern Lake Michigan

Lake Michigan is bounded, from west to east, by the States of Wisconsin, Illinois, Indiana, and Michigan. There are six NOS NWLON stations in northern Lake Michigan; three in Wisconsin, and three in Michigan. Locations of these six stations are shown on the maps of Figures 13 and 14. The time series plots of each station as well as their MAEs and RMSEs are also included on both figures. The range of hindcast MAEs for northern Lake Michigan varied from -4.1 to 6.2 cm in 2015 (Table 10) and from -4.6 to 4.9 cm in 2016 (Table 11). In both hindcasts, stations Port Inland and Mackinaw City, which are located in far northern part of Lake Michigan, have positive MAEs, while the MAEs for the rest stations were all negative. Both 2015 and 2016 water level hindcasts passed all the NOS Acceptance Criteria at all stations except the CF at the station Green Bay in both 2015 and 2016. The Mackinaw City station, which is located close to the Mackinac Bridge, is covered not only by LMHOFS but also by both LMOFS and LHOFS. Therefore, year-long water level statistics at this station for – LMOFS, LHOFS and LMOFS are shown in Table 11. The RMSEs were less for LMHOFS than for LMOFS at four of the six gauges by 0.8 to 2.7 cm and about the same at the other two gauges. For Mackinaw City, the RMSE for the LMHOFS hindcasts were less than for nowcasts from both LMOFS and LHOFS.

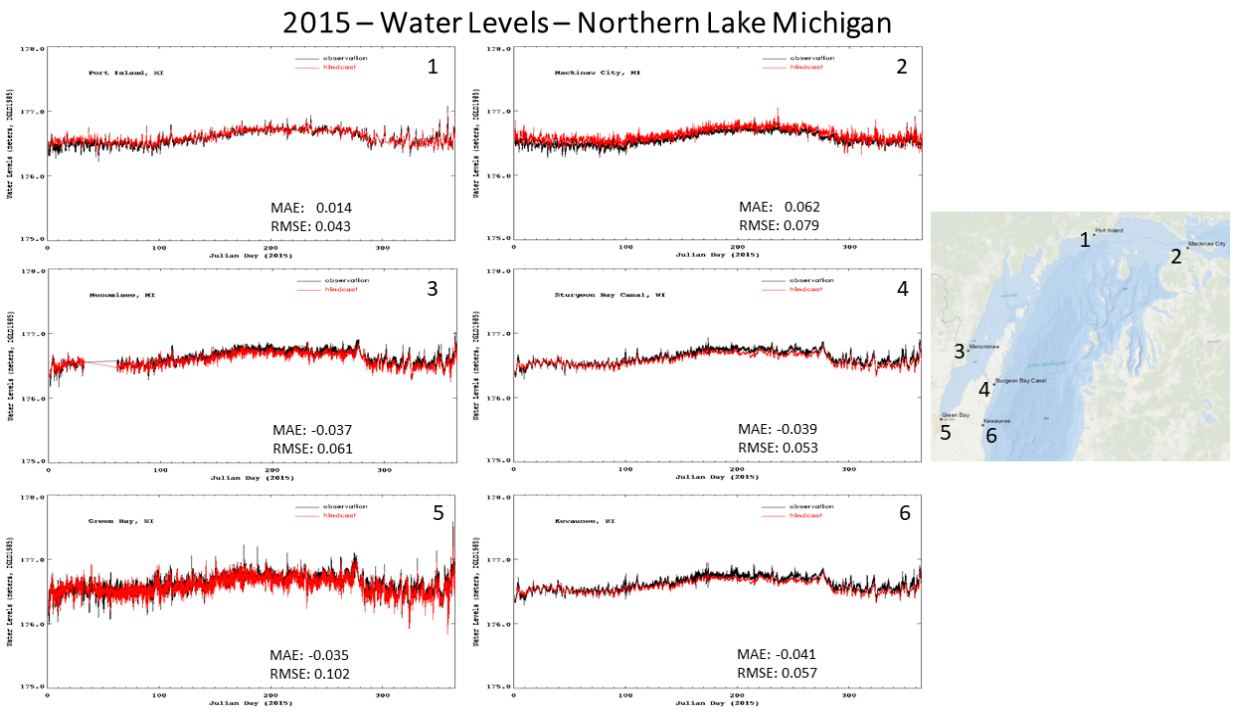

Figure 13. Time series plots of hourly hindcasts of water level (red) vs. observations (black) at CO-OPS NWLON gauges (1. Port Inland, MI, 2. Mackinaw City, MI, 3. Menominee, MI, 4. Sturgeon Bay Canal, WI, 5. Green Bay, WI, and 6. Kewaunee, WI) at northern Lake Michigan during 2015. MAE and RMSE (m) at each station are shown individually on each panel.

Table 10. Summary of skill assessment statistics of LMHOFS hindcasts of hourly water levels at NOS NWLON stations in northern Lake Michigan for 2015. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9087096 Port Inland	9075080 Mackinaw City	9087088 Menominee	9087072 Sturgeon Bay Canal	9087079 Green Bay	9087068 Kewaunee
N	8446	8761	8065	8761	8761	8761
Mean Alg. Error (m)	0.014	0.062	-0.037	-0.039	-0.035	-0.041
RMSE (m)	0.043	0.079	0.061	0.053	0.102	0.057
SD (m)	0.041	0.049	0.048	0.037	0.096	0.040
NOF [2x15 cm] (%)	0.0	0.0	0.0	0.0	0.3	0.0
CF [15 cm] (%)	99.8	96.7	98.9	99.8	86.6	99.3
POF [2x15 cm] (%)	0.0	0.0	0.0	0.0	0.1	0.0
MDNO [2x15 cm] (hr)	0.0	0.0	0.0	0.0	1.0	0.0
MDPO [2x15 cm] (hr)	0.0	0.0	0.0	0.0	3.0	0.0

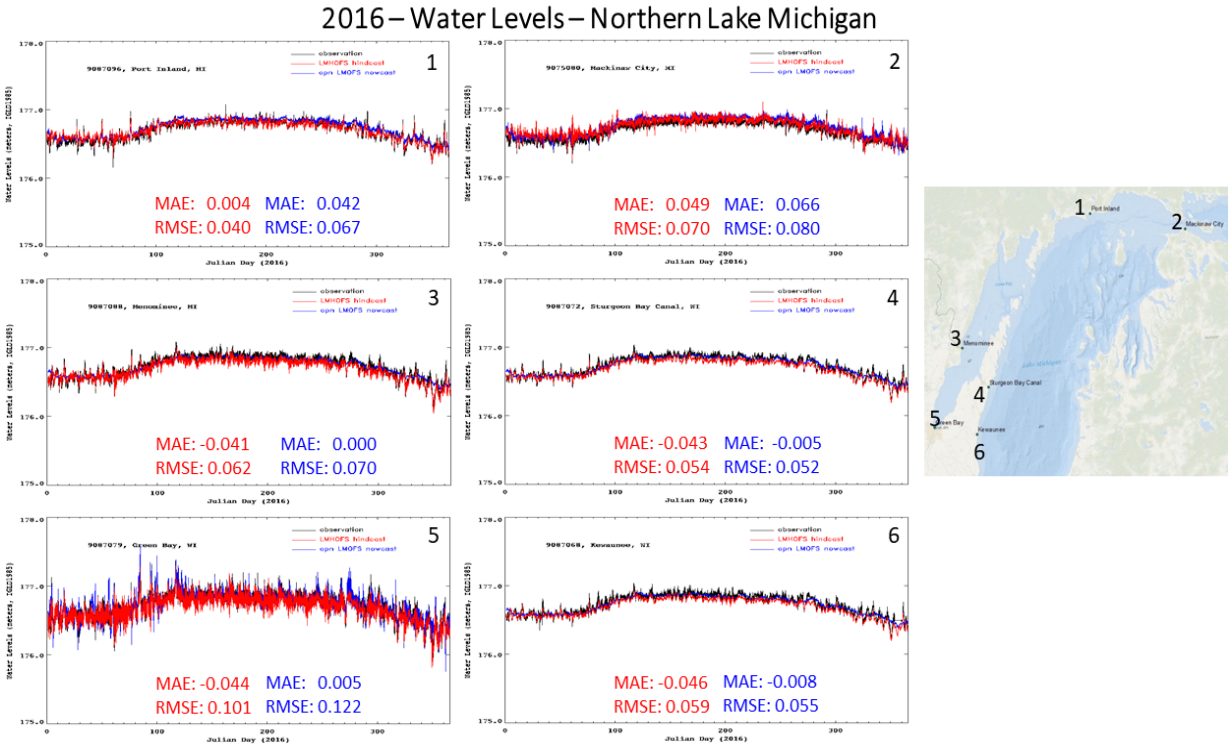

Figure 14. Same as Figure 13 except includes operational nowcasts from LMOFS for 2016.

Table 11. Summary of skill assessment statistics of LMHOFS hindcasts and LMOFS nowcasts of hourly water levels at NOS NWLON stations in northern Lake Michigan for 2016. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9087096 Port Inland		9075080 Mackinaw City			9087088 Menominee	
	LMHOFS	**LMOFS**	**LMHOFS**	**LMOFS**	**LHOFS**	**LMHOFS**	**LMOFS**
N	8760	8685	8760	8685	8685	8754	8679
Mean Alg. Error (m)	0.004	0.042	0.049	0.066	0.040	-0.041	0.000
RMSE (m)	0.040	0.067	0.070	0.080	0.073	0.062	0.070
SD (m)	0.040	0.053	0.050	0.045	0.061	0.046	0.070
NOF [2x15 cm] (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.1
CF [15 cm] (%)	99.8	97.7	97.6	97.2	96.0	99.3	95.4
POF [2x15 cm] (%)	0.0	0.0	0.1	0.0	0.0	0.0	0.2
MDNO [2x15 cm] (hr)	0.0	0.0	0.0	0.0	0.0	0.0	2.0
MDPO [2x15 cm] (hr)	0.0	0.0	2.0	0.0	0.0	0.0	7.0

Table 11. Continued

9087072 Sturgeon Bay Canal		9087079 Green Bay		9087068 Kewaunee	
LMHOFS	**LMOFS**	**LMHOFS**	**LMOFS**	**LMHOFS**	**LMOFS**
8760	8685	8760	8685	8732	8657
-0.043	-0.005	-0.044	0.005	-0.046	-0.008
0.054	0.052	0.101	0.122	0.059	0.055
0.032	0.052	0.091	0.122	0.037	0.054
0.0	0.0	0.5	0.8	0.0	0.0
100.0	98.4	87.0	82.0	99.2	98.5
0.0	0.0	0.0	1.8	0.0	0.0
0.0	0.0	2.0	5.0	0.0	1.0
0.0	0.0	0.0	9.0	0.0	0.0

6.1.1.4. Southern Lake Michigan

Four NOS NWLON stations were used to evaluate the LMHOFS predictions in the southern part of Lake Michigan. The locations of these four stations are shown on the maps of Figures 15 and 16. The time series plots of predictions for each station as well as their MAEs and RMSEs are also given on the figures. Both 2015 and 2016 hindcasts, as well as LMOFS nowcasts for 2016 showed negative MAEs at all four stations. The MAEs of the LMHOFS hindcasts ranged from -6.8 to -5.4 cm in 2015, and -7.0 to -5.8 cm in 2016. The MAEs of LMOFS were from -2.0 to 0.8 cm in 2016. Detailed skill statistics are given in Tables 12 and 13. Both the 2015 and 2016 hindcasts passed all the acceptance criteria at all four stations. The RMSEs were larger for LMHOFS than LMOFS by 0.8 to 1.7 cm.

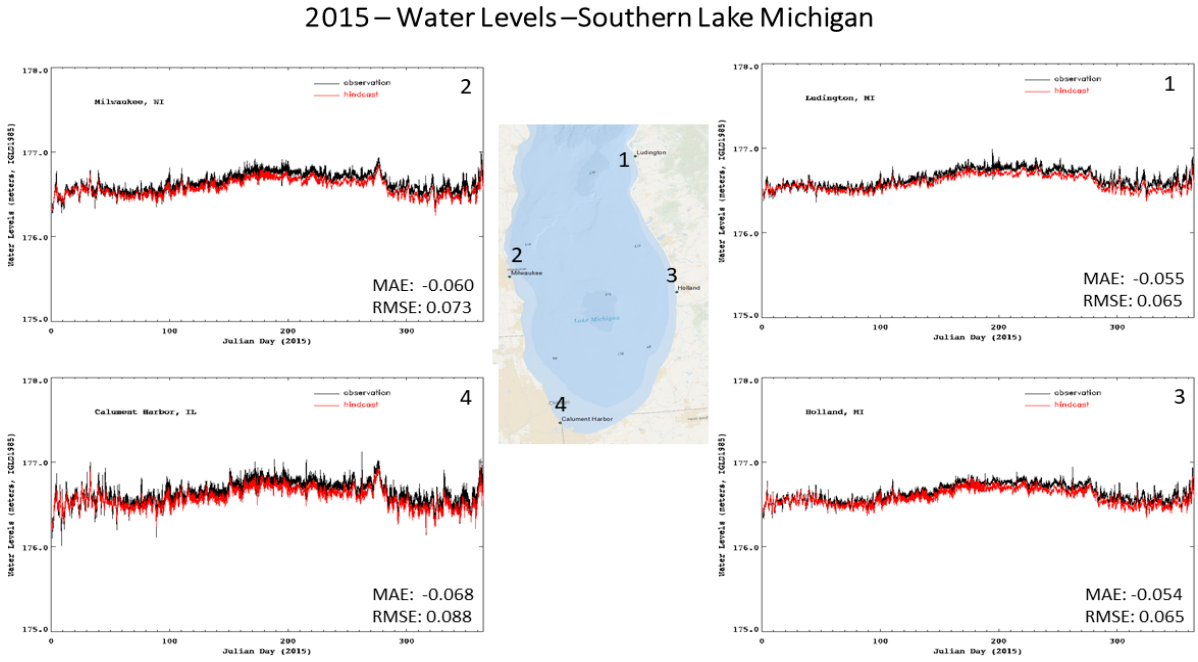

Figure 15. Time series plots of hourly hindcasts of water level (red) vs. observations (black) at NOS NWLON gauges (1. Ludington, MI, 2. Milwaukee, WI, 3. Holland, MI, 4. Calumet Harbor, IL) at southern Lake Michigan during 2015. MAE and RMSE (m) at each station are shown individually on each panel.

Table 12. Summary of skill assessment statistics of LMHOFS hindcasts of hourly water levels at NOS NWLON stations in southern Lake Michigan for 2015. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9087023 Ludington	9087057 Milwaukee	9087031 Holland	9087044 Calumet Harbor
N	8737	8761	8750	8761
Mean Alg. Error (m)	-0.055	-0.060	-0.054	-0.068
RMSE (m)	0.065	0.073	0.065	0.088
SD (m)	0.035	0.041	0.037	0.056
NOF [2x15 cm] (%)	0.0	0.0	0.0	0.1
CF [15 cm] (%)	99.4	98.8	99.7	93.9
POF [2x15 cm] (%)	0.0	0.0	0.0	0.0
MDNO [2x15 cm] (hr)	0.0	0.0	0.0	0.0
MDPO [2x15 cm] (hr)	0.0	0.0	0.0	0.0

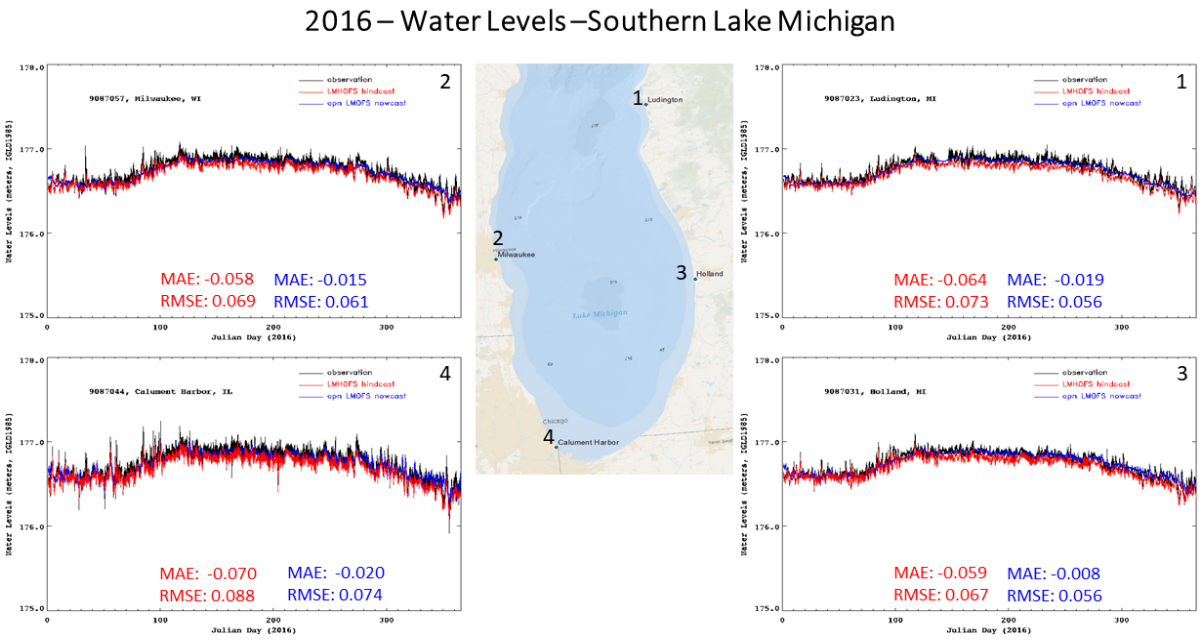

Figure 16. Same as Figure 15 except includes operational nowcasts from LMOFS data for 2016.

Table 13. Summary of skill assessment statistics of LMHOFS hindcasts and LMOFS nowcasts of hourly water levels at NOS NWLON stations in southern Lake Michigan for 2016. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9087023 Ludington		9087057 Milwaukee		9087031 Holland		9087044 Calumet Harbor	
	LMHOFS	LMOFS	LMHOFS	LMOFS	LMHOFS	LMOFS	LMHOFS	LMOFS
N	8353	8278	8760	8685	8699	8624	8760	8685
Mean Alg. Error (m)	-0.064	-0.019	-0.058	-0.015	-0.059	-0.008	-0.070	-0.020
RMSE (m)	0.073	0.056	0.069	0.061	0.067	0.056	0.088	0.074
SD (m)	0.035	0.052	0.037	0.059	0.033	0.056	0.052	0.072
NOF [2x15 cm] (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
CF [15 cm] (%)	98.7	98.1	99.1	97.3	99.6	97.8	94.2	94.8
POF [2x15 cm] (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MDNO [2x15 cm] (hr)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0
MDPO [2x15 cm] (hr)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

6.1.2. Extreme High Water Level Events

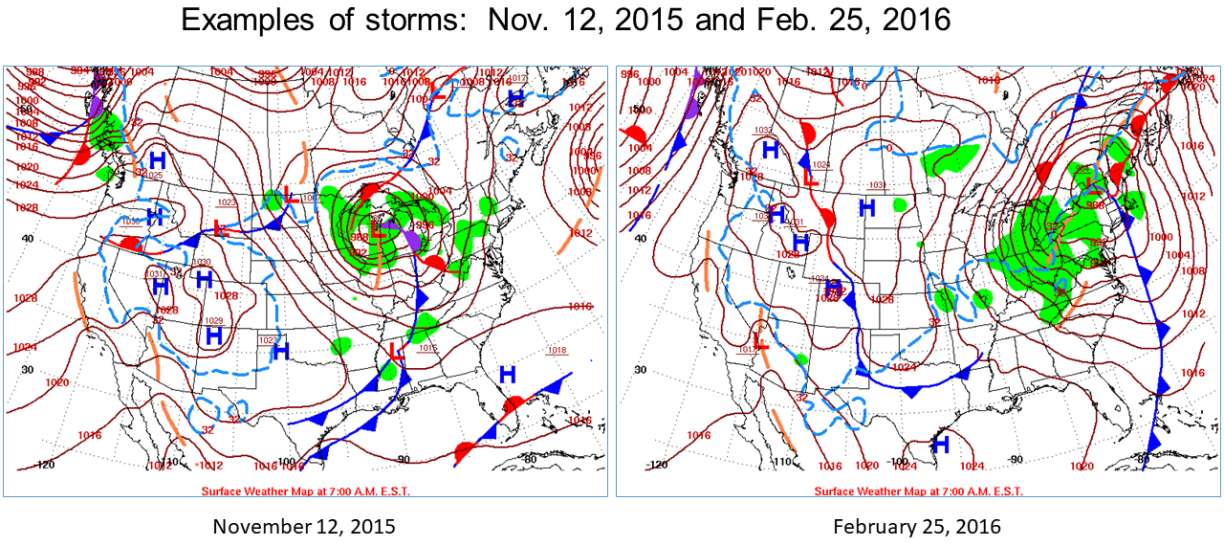

Figure 17. U.S. Daily Weather Maps on Nov. 12, 2015 and Feb. 25, 2016 (From NWS/NCEP WPC).

There were few significant extra-tropical cyclones over Lakes Michigan and Huron in 2015 and 2016. Two relatively important storms were picked for each hindcast period. One influenced mainly Lakes Michigan and Huron on November 12, 2015. The other one occurred from February 24 to 25, 2016 and affected Lake Huron and southern Lake Michigan.

Figure 18 shows the location of Essexville, MI gauge along with water level time series during these two storms. The storm during 2015 is also a good case of extreme low water level for Lake Huron region. When the weather system started to move over the Great Lakes, the west wind caused a water level to drop at Essexville at the beginning. Then the water level rose as the wind direction changed from west to northwest.

The 2015 LMHOFS hindcasts successfully captured the amplitude and timing of the water level peaks caused by the November 12th extra-tropical cyclone. Compared with LHOFS, LMHOFS hindcasts better predicted the peak water level during the 25 February 2016 event. However, there was a small peak afterward that was not seen in the observations.

Skill assessment tables for all extreme high water levels during 2015 and 2016 will be discussed in detail by geographic regions in the next section.

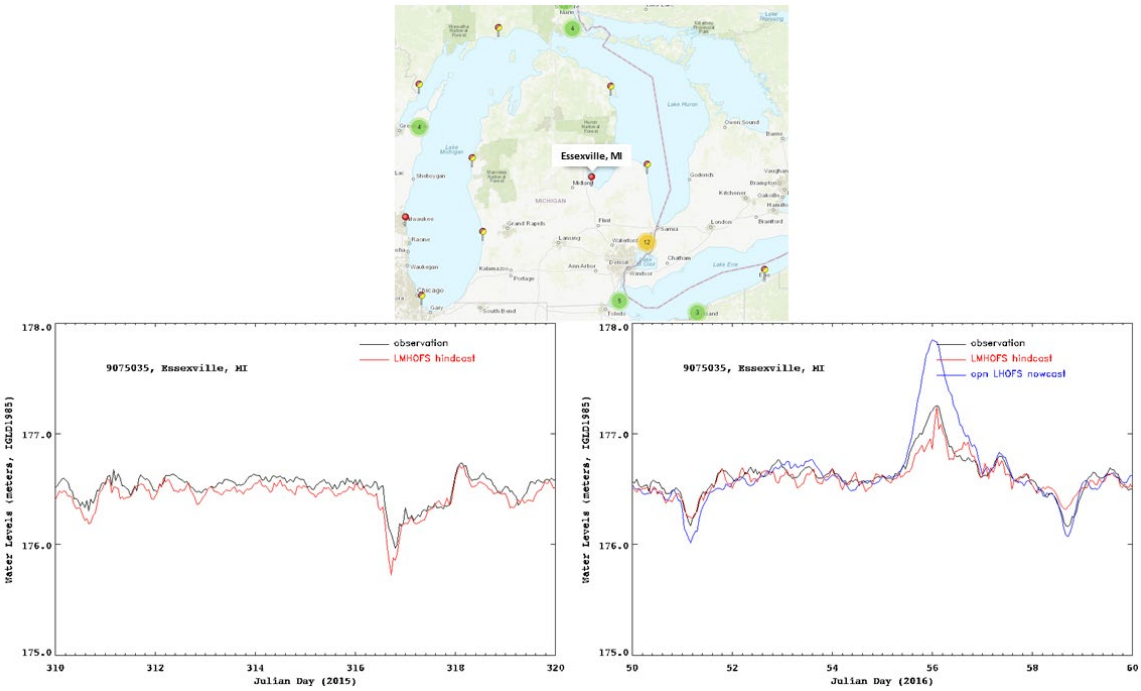

Figure 18. Detailed water level time series at NOS NWLON Essexville, MI gauge during the significant storms in 2015 (a) and 2016 (b). (Black: hourly observation, Red: LMHOFS, and Blue: LHOFS)

6.1.2.1. Georgian Bay – Lake Huron

There were up to four (depending on the location) extreme high water level events at different CHS gauges in Georgian Bay in 2015. LMHOFS performed excellently in terms of amplitude and time forecast, except at station Midland, ON (Table 14). The NOF and CF of amplitudes at this station were significantly poorer than the other Georgian Bay locations. The amplitude MAEs ranged from -13.9 to 0.5 cm and the RMSEs ranged from 1.8 to 18.6 cm. The ranges of time MAEs and RMSEs were 0.25 to 0.5 hours, and 0.5 to 0.87 hours, respectively.

The skill statistics table for 2016 extreme high water level at three CHS gauges in Georgian Bay (Table 15) showed satisfactory results between LMHOFS hindcasts and observations. Except for CF of time at station Little Current, the 2016 hindcasts of extreme high water levels passed all the NOS Acceptance Criteria at all CHS stations.

The results indicated that all the amplitude MAEs of LMHOFS and LHOFS were negative, meaning both forecast systems underestimated the peak water levels during the events. However, compared to LHOFS, LMHOFS was able to predict the extreme high water level events more accurately in the Georgian Bay region.

Table 14. Summary of skill assessment statistics evaluating the ability of the LMHOFS hindcasts to predict extreme high water level events at CHS gauges in Lake Huron's Georgian Bay during 2015. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	C11070 Thessalon **LMHOFS** N=2		C11195 Little Current **LMHOFS** N=4		C11445 Midland **LMHOFS** N=4		C11500 Collingwood **LMHOFS** N=3	
	Amp.	Time	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	0.005	0.500	0.005	0.250	-0.139	0.250	0.001	0.333
RMSE (m) (hr)	0.043	0.707	0.018	0.866	0.186	0.500	0.049	0.577
SD (m) (hr)	0.060	0.707	0.020	0.957	0.143	0.500	0.060	0.577
NOF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0	25.0	0.0	0.0	0.0
CF [15 cm or 90 min] (%)	100.0	100.0	100.0	100.0	50.0	100.0	100.0	100.0
POF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MDNO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MDPO [2x15 cm or 90min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 15. Summary of skill assessment statistics evaluating the ability of the LMHOFS hindcasts and LHOFS nowcasts to predict extreme high water level events at CHS stations in Lake Huron's Georgian Bay during 2016. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	C11195 Little Current				C11445 Midland		
	LMHOFS N=9		**LHOFS** N=3		**LMHOFS** N=4		**LHOFS** N/A
	Amp.	Time	Amp.	Time	Amp.	Time	
Mean Alg. Error (m) (hr)	-0.030	0.444	-0.104	-1.333	-0.011	-0.250	
RMSE (m) (hr)	0.057	1.054	0.106	1.414	0.064	0.866	
SD (m) (hr)	0.052	1.014	0.024	0.577	0.073	0.957	
NOF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0	0.0	0.0	
CF [15 cm or 90 min] (%)	100.0	88.9	100.0	66.7	100.0	100.0	
POF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0	0.0	0.0	
MDNO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0	
MDPO [2x15 cm or 90min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0	

C11500 Collingwood			
LMHOFS N=3		**LHOFS** N=3	
Amp.	Time	Amp.	Time
-0.050	0.000	-0.151	-0.333
0.069	0.816	0.185	1.000
0.057	1.000	0.132	1.000
0.0	0.0	0.0	1.155
100.0	100.0	33.3	100.0
0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0

6.1.2.2. Lake Huron – Main Stem

During 2015, the hindcasts under-predicted the extreme high events at all stations, which included one CHS and six NWLON stations in the main stem of Huron (Table 16). MAEs ranged from -15.7 cm at Fort Gratiot to -0.6 cm at De Tour Village. The RMSEs ranged from 2.7 to 18.4 cm. The MAEs for timing ranged from -0.8 hours at Essexville to +0.3 hours at De Tour Village and Alpena. The RMSEs ranged between 0.0 and 1.4 hours. The hindcasts of extreme high events passed all the NOS acceptance criteria for amplitude and time at De Tour Village, Alpena, Harbor Beach, and Lakeport stations. The CFs for amplitude and time at Goderich, Essexville, and Fort Gratiot did not meet the acceptance criteria.

For 2016, the hindcasts underpredicted the amplitude at five of the six stations. At the five stations, the MAEs ranged from –15.8 cm to -2.9 cm (Table 17). However, at De Tour Village, LMHOFS overpredicted by 2.4 cm. This was the same station where the 2015 hindcasts had the smallest MAE (-0.6 cm) and RMSE (2.7 cm). The station is near where the water level LBC is specified. The hindcasts of extreme high events during 2016 passed all the acceptance criteria at De Tour Village, Goderich, and Essexville. However, the CF criteria was not met at Lakeport and Fort Gratiot and the NOF criteria was not met at Fort Gratiot. The CF criteria for timing was not met at Lakeport, Fort Gratiot and Alpena.

In comparing LMHOFS and LHOFS predictions, LHOFS had smaller amplitude RMSEs at Lakeport and Fort Gratiot while at De Tour Village and Essexville had higher amplitude MAEs and RMSEs. There were no LHOFS nowcasts available for stations Alpena and Goderich in the LHOFS station netCDF output file.

Table 16. Summary of skill assessment statistics evaluating the ability of LMHOFS hindcasts to predict extreme high water level events at NOS NWLON and CHS gauges in Lake Huron during 2015. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9075099 De Tour Village **LMHOFS** N=2		9075065 Alpena **LMHOFS** N=3		9075014 Harbor Beach **LMHOFS** N=3	
	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	-0.006	0.000	-0.045	0.333	-0.020	0.333
RMSE (m) (hr)	0.027	0.000	0.052	0.577	0.037	0.577
SD (m) (hr)	0.037	0.000	0.032	0.577	0.038	0.577
NOF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0	0.0	0.0
CF [15 cm or 90 min] (%)	100.0	100.0	100.0	100.0	100.0	100.0
POF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0	0.0	0.0
MDNO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0
MDPO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0

C11860 Goderich **LMHOFS** N=3		9075035 Essexville **LMHOFS** N=5		9075002 Lakeport **LMHOFS** N=6		9014098 Fort Gratiot **LMHOFS** N=10	
Amp.	Time	Amp.	Time	Amp.	Time	Amp.	Time
-0.172	-0.667	-0.046	-0.800	-0.051	0.000	-0.157	-0.400
0.184	1.414	0.100	1.265	0.072	0.577	0.179	1.095
0.082	1.528	0.099	1.095	0.055	0.632	0.089	1.075
0.0	0.0	0.0	0.0	0.0	0.0	10.0	0.0
33.3	66.7	80.0	60.0	100.0	100.0	60.0	80.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 17. Summary of skill assessment statistics evaluating the ability of LMHOFS hindcasts and LHOFS nowcasts to predict extreme high water level events at NOS NWLON and CHS stations in Lake Huron during 2016. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9075099 De Tour Village				9075065 Alpena		
	LMHOFS N=2		**LHOFS** N=3		**LMHOFS** N=4		**LHOFS N/A**
	Amp.	Time	Amp.	Time	Amp.	Time	
Mean Alg. Error (m) (hr)	0.024	-0.500	-0.069	-0.667	-0.050	-0.250	
RMSE (m) (hr)	0.030	0.707	0.097	1.555	0.058	1.500	
SD (m) (hr)	0.024	0.707	0.083	1.555	0.035	1.708	
NOF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0	0.0	0.0	
CF [15 cm or 90 min] (%)	100.0	100.0	100.0	66.7	100.0	50.0	
POF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0	0.0	0.0	
MDNO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0	
MDPO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0	

C11860 Goderich			9075035 Essexville			
LMHOFS N=3		**LHOFS** N/A	**LMHOFS** N=9		**LHOFS** N=6	
Amp.	Time		Amp.	Time	Amp.	Time
-0.104	0.000		-0.029	0.222	-0.003	1.167
0.107	0.816		0.076	0.667	0.126	1.354
0.033	1.000		0.075	0.667	0.138	0.753
0.0	0.0		0.0	0.0	0.0	0.0
100.0	100.0		100.0	100.0	83.3	66.7
0.0	0.0		0.0	0.0	0.0	0.0
0.0	0.0		0.0	0.0	0.0	0.0
0.0	0.0		0.0	0.0	0.0	0.0

Table 17. Continued

9075002 Lakeport				9014098 Fort Gratiot			
LMHOFS N=5		**LHOFS** N=3		**LMHOFS** N=6		**LHOFS** N=6	
Amp.	Time	Amp.	Time	Amp.	Time	Amp.	Time
-0.133	0.200	-0.115	1.333	-0.158	0.833	-0.027	0.833
0.147	1.183	0.130	1.414	0.182	1.354	0.048	1.225
0.071	1.304	0.074	0.577	0.098	1.169	0.043	0.983
0.0	0.0	0.0	0.0	16.7	0.0	0.0	0.0
80.0	80.0	66.7	66.7	66.7	66.7	100.0	66.7
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

6.1.2.3. Northern Lake Michigan

For northern Lake Michigan, LMHOFS hindcasts underestimated the extreme high water level amplitudes during 2015, except at station Mackinaw City where it over-estimated (Table 18). The MAE of amplitude ranged from -21.7 cm at Green Bay to 1.2 cm at Mackinaw City. The RMSE of amplitude ranged from 6.6 cm at Port Inland to 23.1 cm at Green Bay. The hindcasts of extreme high events passed all the acceptance criteria for amplitude at Port Inland, Mackinaw City, and Sturgeon Bay Canal, but failed at Green Bay for NOF and CF. The average RMSE for timing over the five stations was 1.31 hours. No station passed all the NOS acceptance criteria for time.

For 2016, LMHOFS hindcasts again underestimated extreme high water level amplitudes, and at this year, underestimated at Mackinaw City (Table 19) as well. The MAEs of amplitude of LMHOFS ranged from -17 cm at Green Bay to -2.1 cm at Mackinaw City. RMSEs ranged from 6.9 to 18.2 cm at Mackinaw City and Green Bay, respectively. The hindcasts of extreme high events passed all the acceptance criteria for amplitude at Port Inland, Mackinaw City, and Kewaunee, but failed to pass CF at Green Bay. Similar to 2015, no station passed all the acceptance criteria for time.

A comparison of RMSEs for amplitude between LMHOFS and LHOFS showed that LMHOFS hindcasts had smaller RMSEs at Mackinaw City and Port Inland, but slightly larger RMSEs at Green Bay, 18.2 vs. 11.2 cm. With respect to the timing at Green Bay, where the most high water levels were identified (nine events), LMHOFS and LHOFS had similar RMSEs, 1.16 hours for LMHOFS and 1.29 hours for LHOFS.

Table 18. Summary of skill assessment statistics evaluating the ability of the LMHOFS hindcasts to predict extreme high water level events at NOS NWLON stations in northern Lake Michigan during 2015. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9087096 Port Inland		9075080 Mackinaw City		9087072 Sturgeon Bay Canal	
	LMHOFS N=9		**LMHOFS** N=5		**LMHOFS** N=2	
	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	-0.049	-0.556	0.012	0.600	-0.101	0.500
RMSE (m) (hr)	0.066	1.000	0.067	1.612	0.101	1.581
SD (m) (hr)	0.046	0.882	0.074	1.673	0.016	2.121
NOF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0	0.0	0.0
CF [15 cm or 90 min] (%)	100.0	88.9	100.0	40.0	100.0	50.0
POF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0	0.0	0.0
MDNO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0
MDPO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0

9087079 Green Bay		9087068 Kewaunee	
LMHOFS N=8		**LMHOFS** N=7	
Amp.	Time	Amp.	Time
-0.217	0.250	-0.157	0.429
0.231	1.118	0.166	1.254
0.084	1.165	0.059	1.272
12.5	0.0	0.0	0.0
12.5	75.0	28.6	71.4
0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0

Table 19. Summary of skill assessment statistics evaluating the ability of LMHOFS hindcasts and LMOFS and LHOFS nowcasts to predict extreme high water level events at NOS NWLON stations in northern Lake Michigan during 2016. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9087096 Port Inland			
	LMHOFS N=7		**LMOFS** N=4	
	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	-0.078	-0.429	-0.124	0.000
RMSE (m) (hr)	0.088	1.254	0.151	0.707
SD (m) (hr)	0.045	1.272	0.098	0.816
NOF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0
CF [15 cm or 90 min] (%)	100.0	71.4	50.0	100.0
POF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0
MDNO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0
MDPO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0

9075080 Mackinaw City						9087079 Green Bay			
LMHOFS N=5		**LMOFS** N=9		**LHOFS** N=2		**LMHOFS** N=9		**LMOFS** N=9	
Amp.	Time	Amp.	Time	Amp.	Time	Amp.	Time	Amp.	Time
-0.021	-0.500	0.022	0.333	-0.164	0.500	-0.170	0.000	-0.090	1.222
0.069	1.354	0.071	1.528	0.191	0.707	0.182	1.155	0.113	1.291
0.072	1.378	0.072	1.581	0.140	0.707	0.069	1.225	0.074	0.441
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
100.0	66.7	88.9	44.4	50.0	100.0	44.4	77.8	77.8	77.8
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 19. Continued

9087068 Kewaunee			
LMHOFS N=2		**LMOFS** N=3	
Amp.	Time	Amp.	Time
-0.119	0.000	-0.171	0.000
0.119	1.000	0.181	1.633
0.005	1.414	0.073	2.000
0.0	0.0	0.0	0.0
100.0	100.0	33.3	33.3
0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0

6.1.2.4. Southern Lake Michigan

For southern Lake Michigan, LMHOFS hindcasts underestimated the extreme high water level amplitudes during 2015 at all four stations by an average of 14 cm. The MAE of amplitude ranged from -10.6 cm at Holland to -18.8 cm at Calumet (Table 20). The RMSEs of amplitude ranged from 11.9 to 19.9 cm at those stations. The hindcasts of extreme high events did not pass all the acceptance criteria for amplitude at any of the stations, due to failing to meet the CF criteria. The averaged RMSE for timing over the four stations was 1.31 hours. Only LMHOFS hindcasts at Ludington and Holland passed all acceptance criteria for time.

For 2016, LMHOFS hindcasts again underestimated extreme high water level amplitudes at all four stations by an average of 15.8 cm. The MAEs of amplitude ranged from -10.5 cm at Holland to -21.6 cm at Milwaukee. RMSEs ranged from 10.7 at Holland to 23.3 cm at Milwaukee, respectively. The hindcasts of extreme high events passed all the acceptance criteria for amplitude at Holland only. The average RMSE for timing over the four stations was 1.31 hours, ranging from 0.71 to 2.0 hours at Milwaukee and Ludington, respectively. Only LMHOFS hindcasts at Ludington and Milwaukee passed all acceptance criteria for time.

A comparison of RMSEs for amplitude between LMHOFS and LMOFS was difficult since there were only two events identified by LMHOFS at three of the stations. However, at Calumet Harbor, LMHOFS had 4 events and LMOFS had 3 events. For this station, LMHOFS' RMSE for amplitude was 5 cm smaller and the RMSE for timing was 0.30 hours smaller compared with LMOFS. It is interesting to note that LMOFS also failed to pass all acceptance criteria at all the three stations where LMOFS could be compared to LMHOFS.

Table 20. Summary of skill assessment statistics evaluating the ability of the LMHOFS hindcasts to predict extreme high water level events at NOS NWLON gauges in southern Lake Michigan during 2015. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9087023 Ludington		9087031 Holland		9087057 Milwaukee		9087044 Calumet Harbor	
	LMHOFS N=2		**LMHOFS** N=2		**LMHOFS** N=5		**LMHOFS** N=6	
	Amp.	Time	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	-0.133	0.000	-0.106	-1.000	-0.129	-1.000	-0.188	-0.833
RMSE (m) (hr)	0.136	0.707	0.119	1.000	0.131	1.183	0.199	1.225
SD (m) (hr)	0.032	0.816	0.075	0.000	0.026	0.707	0.070	0.983
NOF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0	0.0	0.0	16.7	0.0
CF [15 cm or 90 min] (%)	75.0	100.0	50.0	100.0	60.0	80.0	33.3	83.3
POF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MDNO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MDPO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 21. Summary of skill assessment statistics evaluating the ability of the LMHOFS hindcasts and LMOFS nowcasts to predict extreme high water level events at NOS NWLON gauges in Lake Michigan during 2016. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9087023 Ludington				9087031 Holland		
	LMHOFS N=2		**LMOFS** N=5		**LMHOFS** N=2		**LMOFS** N/A
	Amp.	Time	Amp.	Time	Amp.	Time	
Mean Alg. Error (m) (hr)	-0.133	-2.000	-0.165	-0.400	-0.105	-0.667	
RMSE (m) (hr)	0.139	2.000	0.172	1.414	0.107	1.414	
SD (m) (hr)	0.054	0.000	0.054	1.517	0.022	1.528	
NOF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0	0.0	0.0	
CF [15 cm or 90 min] (%)	50.0	0.0	40.0	60.0	100.0	66.7	
POF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0	0.0	0.0	
MDNO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0	
MDPO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0	

9087057 Milwaukee				9087044 Calumet Harbor			
LMHOFS N=2		**LMOFS** N=4		**LMHOFS** N=4		**LMOFS** N=3	
Amp.	Time	Amp.	Time	Amp.	Time	Amp.	Time
-0.216	-0.500	-0.226	0.250	-0.179	0.750	-0.224	0.667
0.233	0.707	0.258	0.866	0.184	1.118	0.235	0.816
0.124	0.707	0.143	0.957	0.049	0.957	0.087	0.577
50.0	0.0	25.0	0.0	0.0	0.0	33.3	0.0
50.0	100.0	50.0	100.0	50.0	75.0	0.0	100.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

6.1.3. Extreme Low Water Level Events

6.1.3.1. Georgian Bay

Tables 22 and 23 showed the skill assessment statistics of the LMHOFS hindcasts for the extreme low water level events during 2015 and 2016 at CHS stations located in the Georgian Bay region. Water level observations were available at four CHS gauges in 2015; however, Midland gauge's observations were missing in 2016. Both 2015 and 2016 hindcasts overestimated the extreme low water levels during events. The MAEs of amplitude of the 2015 hindcast ranged from 11.0 cm at Midland to 14.3 cm at Little Current; the MAEs of amplitude of the 2016 hindcast ranged from 10.1 cm at Collingwood to 15.4 cm at Little Current. In comparison, the MAEs of amplitude of LHOFS nowcasts ranged from 14.2 cm at Thessalon to 29.0 cm at Collingwood for 2016. LHOFS nowcasts also overestimated the extreme low water levels at stations. LMHOFS hindcasts passed all criteria for amplitude at all stations except for CF.

As for the timing of extreme low water level events, the MAEs of timing for the 2015 LMHOFS hindcasts are mostly positive and ranged from 0.125 to 0.5 hours, except one negative value (-0.25 hours) at the station Little Current. The MAEs of timing for the 2016 hindcasts at Little Current and Collingwood are 0.0 hour, which indicated a perfect match of timing in extreme low water levels for nine events. At Thessalon, the MAE of time was 0.333 hours. The LMHOFS of extreme low water level events passed all the acceptance criteria for time only at Little Current in 2015 and at Little Current and Thessalon in 2016.

Table 22. Summary of skill assessment statistics evaluating the ability of the LMHOFS hindcasts to predict extreme low water level events at CHS stations in Lake Huron's Georgian Bay during 2015. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	C11070 Thessalon		C11195 Little Current		C11445 Midland		C11500 Collingwood	
	LMHOFS N=4		**LMHOFS** N=4		**LMHOFS** N=4		**LMHOFS** N=3	
	Amp.	Time	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	0.113	0.500	0.143	-0.250	0.110	0.200	0.126	0.125
RMSE (m) (hr)	0.118	1.732	0.182	0.500	0.121	1.612	0.130	1.061
SD (m) (hr)	0.039	1.915	0.129	0.500	0.055	1.789	0.030	1.126
NOF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CF [15 cm or 90 min] (%)	75.0	25.0	25.0	100.0	60.0	40.0	75.0	87.5
POF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MDNO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MDPO [2x15 cm or 90min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 23. Summary of skill assessment statistics evaluating the ability of LMHOFS hindcasts and LHOFS nowcasts to predict extreme low water level events at CHS stations in Lake Huron's Georgian Bay during 2016. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	C11070 Thessalon			
	LMHOFS N=4		**LHOFS** N=6	
	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	0.109	0.333	0.142	0.333
RMSE (m) (hr)	0.121	0.816	0.168	0.816
SD (m) (hr)	0.059	0.816	0.098	0.816
NOF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0
CF [15 cm or 90 min] (%)	66.7	100.0	50.0	83.3
POF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0
MDNO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0
MDPO [2x15 cm or 90min] (hr)	0.0	0.0	0.0	0.0

C11195 Little Current				C11500 Collingwood			
LMHOFS N=9		**LHOFS** N=7		**LMHOFS** N=9		**LHOFS** N=7	
Amp.	Time	Amp.	Time	Amp.	Time	Amp.	Time
0.154	0.000	0.181	0.571	0.101	0.000	0.290	-0.571
0.161	0.667	0.246	1.195	0.104	1.247	0.302	1.069
0.048	0.707	0.181	1.134	0.028	1.323	0.090	0.976
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
55.6	100.0	42.9	71.4	88.9	77.8	0.0	85.7
0.0	0.0	28.6	0.0	0.0	0.0	42.9	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

6.1.3.2. Lake Huron – Main Stem

Tables 24 and 25 provide the skill assessment statistics for LMHOFS during 2015 and 2016 at eight stations in the main stem of Lake Huron. The statistics indicated that LMHOFS underestimated the extreme low water levels at the Essexville and Fort Gratiot gauges during the periods. At the remaining six stations LMHOFS tended to overestimate the extreme low water levels. The hindcasts of extreme low water level events passed all the acceptance criteria for amplitude at all stations in 2015 except Alpena and Essexville. The hindcasts of extreme low events at Harbor Beach, Goderich, Lakeport, and Fort Gratiot passed all the acceptance criteria for amplitude in 2016. The MAEs of amplitude ranged from -5.2 cm at Essexville, to 9.3 cm at Alpena for year 2015. The range of MAEs of time from -1.0 hour at Harbor Beach to 0.3 hour at Fort Gratiot for year 2015. The zero MAEs at Rock Cut and Alpena showed perfect match in terms of peak times during 12 extreme low water level events in 2015. The smallest and largest MAEs of amplitude occurred, respectively, at Essexville and Alpena for year 2016. The minimum value was -8.5 cm and the maximum was 8.4 cm. The MAE of time ranged from -0.4 hours at Alpena to 0.7 hours at Rock Cut for the 2016 LMHOFS hindcasts. The MAEs of amplitude ranged from -5.7 cm at Rock Cut to 19.2 cm at Fort Gratiot for the 2016 LMOFS nowcasts. The MAEs of timing ranged from -1.3 hours at Harbor Beach to 0.7 hours at Goderich for the 2016 LMOFS nowcasts.

Table 24. Summary of skill assessment statistics evaluating the ability of LMHOFS hindcasts to predict extreme low water level events at NOS NWLON and CHS gauges in Lake Huron during 2015. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9076024 Rock Cut **LMHOFS** N=12		9075065 Alpena **LMHOFS** N=12		9075099 De Tour Village **LMHOFS** N=4	
	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	0.074	0.000	0.093	0.000	0.067	-0.500
RMSE (m) (hr)	0.091	1.155	0.105	1.354	0.073	1.000
SD (m) (hr)	0.056	1.206	0.052	1.414	0.033	1.000
NOF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0	0.0	0.0
CF [15 cm or 90 min] (%)	91.7	83.3	83.3	58.3	100.0	75.0
POF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0	0.0	0.0
MDNO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0
MDPO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0

9075014 Harbor Beach **LMHOFS** N=2		C11860 Goderich **LMHOFS** N=2		9075035 Essexville **LMHOFS** N=12		9075002 Lakeport **LMHOFS** N=16		9014098 Fort Gratiot **LMHOFS** N=12	
Amp.	Time	Amp.	Time	Amp.	Time	Amp.	Time	Amp.	Time
0.052	-1.000	0.013	-0.500	-0.052	0.167	0.015	0.125	-0.032	0.333
0.054	1.414	0.028	0.707	0.173	0.913	0.064	1.323	0.082	1.581
0.020	1.414	0.035	0.707	0.172	0.937	0.065	1.360	0.079	1.614
0.0	0.0	0.0	0.0	8.3	0.0	0.0	0.0	0.0	0.0
100.0	50.0	100.0	100.0	66.7	91.7	100.0	62.5	100.0	41.7
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 25. Summary of skill assessment statistics evaluating the ability of LMHOFS hindcasts and LHOFS nowcasts to predict extreme low water level events at NOS NWLON and CHS gauges in Lake Huron during 2016. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9076024 Rock Cut				9075065 Alpena		
	LMHOFS N=14		**LHOFS** N=14		**LMHOFS** N=7		**LHOFS** N/A
	Amp.	Time	Amp.	Time	Amp.	Time	
Mean Alg. Error (m) (hr)	0.081	0.714	-0.057	-0.214	0.084	-0.429	
RMSE (m) (hr)	0.106	1.134	0.119	1.102	0.101	1.363	
SD (m) (hr)	0.071	0.914	0.108	1.122	0.060	1.397	
NOF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0	0.0	0.0	
CF [15 cm or 90 min] (%)	85.7	78.6	78.6	85.7	71.4	57.1	
POF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0	0.0	0.0	
MDNO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0	
MDPO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0	

9075099 De Tour Village				9075014 Harbor Beach			
LMHOFS N=8		**LHOFS** N=7		**LMHOFS** N=5		**LHOFS** N=3	
Amp.	Time	Amp.	Time	Amp.	Time	Amp.	Time
0.073	0.000	0.137	0.143	0.063	0.600	0.112	-1.333
0.087	1.323	0.157	1.134	0.097	1.342	0.112	1.414
0.050	1.414	0.084	1.215	0.082	1.342	0.007	0.577
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
87.5	62.5	57.1	71.4	100.0	60.0	100.0	66.7
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 25. Continued

C11860 Goderich				9075035 Essexville			
LMHOFS N=6		**LHOFS** N=6		**LMHOFS** N=12		**LHOFS** N=8	
Amp.	Time	Amp.	Time	Amp.	Time	Amp.	Time
0.046	0.167	0.099	0.667	-0.085	0.250	-0.036	0.375
0.064	1.354	0.110	1.291	0.136	1.118	0.100	0.935
0.049	1.472	0.054	1.211	0.112	1.138	0.100	0.916
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
100.0	66.7	83.3	66.7	66.7	83.3	87.5	87.5
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

9075002 Lakeport				9014098 Fort Gratiot			
LMHOFS N=11		**LHOFS** N=16		**LMHOFS** N=13		**LHOFS** N=15	
Amp.	Time	Amp.	Time	Amp.	Time	Amp.	Time
0.079	0.091	0.134	0.188	-0.009	0.692	0.192	0.133
0.104	0.905	0.148	0.829	0.065	1.271	0.198	0.816
0.070	0.944	0.065	0.834	0.067	1.109	0.050	0.834
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
100.0	90.9	68.8	100.0	100.0	69.2	13.3	93.3
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

6.1.3.3. Northern Lake Michigan

Tables 26 and 27 provide the skill assessment statistics of LMHOFS during 2015 and 2016 at six NOS NWLON stations in the northern part of Lake Michigan. The hindcasts of extreme low events passed all the acceptance criteria of amplitude at the Port Inland, Mackinaw City, and Sturgeon Bay Canal gauges for year 2015 and at the Port Inland, Sturgeon Bay Canal and Kewaunee gauges for year 2016. Both 2015 and 2016 LMHOFS hindcasts overestimated the amplitude of water level at extreme low events. The MAEs of amplitude of the 2015 hindcasts ranged from 5.8 cm at Sturgeon Bay Canal to 9.0 cm at Kewaunee. The MAEs of amplitude of the 2016 hindcasts ranged from 1.9 cm at Menominee to 8.0 cm at Green Bay.

The MAEs of timing for the hindcasts of 2015 and 2016 at stations were positive except at Kewaunee in 2015 and at Green Bay in 2016. The predictions of arrival time of extreme low water level events at most NWLON stations during both hindcast periods are in general earlier than they were observed. The MAEs of time of the 2015 hindcast ranged from -0.7 hours at Kewaunee to 0.5 hours at Mackinaw City. The MAEs of amplitude of the 2016 hindcasts ranged from -0.6 hours at Green Bay to 0.8 hours at both Mackinaw City and Kewaunee.

For 2016, LMHOFS predictions at the majority of stations had smaller MAEs and RMSEs of extreme low water levels than those of LMOFS. The Mackinaw City station, which was covered by all the three OFSs, had the MAEs of amplitude for 2016 extreme low water level events of 7.3 cm for LMHOFS, 10.8 cm for LMOFS, and 14.5 cm for LHOFS. The MAEs of time at this station for 2016 extreme low water level events were 0.8 hour for LMHOFS, 0 hours for LMOFS, and 0.4 hours for LHOFS.

Table 26. Summary of skill assessment statistics evaluating the ability of the LMHOFS hindcasts to predict extreme low water level events at NOS NWLON gauges in northern Lake Michigan during 2015. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9087096 Port Inland		9075080 Mackinaw City		9087088 Menominee	
	LMHOFS N=3		**LMHOFS** N=6		**LMHOFS** N=7	
	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	0.074	0.333	0.059	0.500	0.065	0.143
RMSE (m) (hr)	0.078	0.577	0.098	1.354	0.093	1.254
SD (m) (hr)	0.028	0.577	0.085	1.378	0.072	1.345
NOF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0	0.0	0.0
CF [15 cm or 90 min] (%)	100.0	100.0	100.0	66.7	85.7	71.4
POF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0	0.0	0.0
MDNO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0
MDPO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0

9087072 Sturgeon Bay Canal		9087079 Green Bay		9087068 Kewaunee	
LMHOFS N=4		**LMHOFS** N=12		**LMHOFS** N=7	
Amp.	Time	Amp.	Time	Amp.	Time
0.058	0.250	0.072	0.167	0.090	-0.714
0.069	0.866	0.143	1.080	0.102	1.648
0.042	0.957	0.129	1.115	0.052	1.604
0.0	0.0	0.0	0.0	0.0	0.0
100.0	100.0	75.0	83.3	85.7	42.9
0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0

Table 27. Summary of skill assessment statistics evaluating the ability of LMHOFS hindcasts and LMOFS and LHOFS nowcasts to predict extreme low water level events at NOS NWLON gauges in northern Lake Michigan during 2016. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9087096 Port Inland			
	LMHOFS N=6		**LMOFS** N=5	
	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	0.073	0.167	0.126	-0.200
RMSE (m) (hr)	0.091	1.080	0.142	1.342
SD (m) (hr)	0.061	1.169	0.072	1.483
NOF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0
CF [15 cm or 90 min] (%)	100.0	83.3	80.0	60.0
POF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0
MDNO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0
MDPO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0

9075080 Mackinaw City						9087088 Menominee			
LMHOFS N=5		**LMOFS** N=8		**LHOFS** N=5		**LMHOFS** N=7		**LMOFS** N=5	
Amp.	Time	Amp.	Time	Amp.	Time	Amp.	Time	Amp.	Time
0.073	0.800	0.108	0.000	0.145	0.400	0.019	0.429	0.154	0.200
0.085	1.265	0.122	0.500	0.152	1.414	0.041	1.254	0.167	1.612
0.048	1.095	0.060	0.535	0.050	1.517	0.039	1.272	0.073	1.789
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
100.0	80.0	87.5	100.0	60.0	60.0	100.0	71.4	60.0	40.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 27. Continued

9087072 Sturgeon Bay Canal				9087079 Green Bay			
LMHOFS N=2		**LMOFS** N=2		**LMHOFS** N=9		**LMOFS** N=4	
Amp.	Time	Amp.	Time	Amp.	Time	Amp.	Time
0.038	0.000	0.076	-0.500	0.080	-0.556	-0.016	0.750
0.038	1.000	0.078	0.707	0.098	0.882	0.157	1.118
0.011	1.414	0.025	0.707	0.059	0.726	0.180	0.957
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
100.0	100.0	100.0	100.0	88.9	100.0	50.0	75.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

9087068 Kewaunee			
LMHOFS N=7		**LMOFS** N=4	
Amp.	Time	Amp.	Time
0.032	0.800	0.114	-0.250
0.040	0.894	0.117	1.118
0.028	0.447	0.028	1.258
0.0	0.0	0.0	0.0
100.0	100.0	100.0	75.0
0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0

6.1.3.4. Southern Lake Michigan

Tables 28 and 29 provide the skill assessment statistics of the LMHOFS hindcasts of extreme low water level events at three NWLON stations in 2015, and four stations in 2016 in southern Lake Michigan. The hindcast at all the three stations passed all the NOS acceptance criteria for amplitude and time for year 2015, except the CF for time at the station Calumet Harbor. The MAEs of amplitude of the 2015 hindcast at southern Lake Michigan ranged from 3.3 cm at Calumet Harbor to 8.2 cm at Milwaukee. The hindcast overestimated the water level amplitude during 2015 extreme low water level events. The MAEs of time ranged from -0.3 hours at Milwaukee to 1 hour at Calumet Harbor in the same region. The 2016 hindcast of the amplitudes for extreme low water level events showed excellent match to the observations. The minimum MAE value was 1.0 cm at Ludington, the maximum value was 3.6 cm at Calumet Harbor. The 2016 hindcast of time for extreme low water level events is also very good; the MAEs of time ranged from -0.25 hours at Calumet Harbor to 0.2 hours at Ludington in southern Lake Michigan. The hindcasts passed all the acceptance criteria for amplitude and time for both 2015 and 2016 except for the CF of time at station Calumet Harbor in 2015 and at Milwaukee in 2016, as well as the CF of amplitude and time at Calumet Harbor in 2016.

The MAEs of LMOFS nowcasts of amplitude ranged from 7.3 cm at Milwaukee to 11.9 cm at Holland for 2016. LMOFS nowcasts overestimated the amplitudes of extreme low water level events in 2016. The MAEs of LMOFS nowcasts of time for extreme low water level events ranged from -0.7 hours at Holland to 0.5 hours at Calumet Harbor for the same region. The LMOFS nowcasts passed all the acceptance criteria for amplitude and time for year 2016 at Milwaukee, and for amplitude only at Ludington station. The comparisons between the skill of the hindcasts and nowcasts for the extreme low water level events in 2016 showed significant improvements in this region.

Table 28. Summary of skill assessment statistics evaluating the ability of LMHOFS hindcasts to predict extreme low water level events at NOS NWLON gauges in southern Lake Michigan during 2015. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9087057 Milwaukee **LMHOFS** N=3		9087031 Holland **LMHOFS** N=2		9087044 Calumet Harbor **LMHOFS** N=9	
	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	0.082	-0.333	0.053	0.500	0.033	1.000
RMSE (m) (hr)	0.087	0.577	0.067	0.707	0.058	1.291
SD (m) (hr)	0.035	0.577	0.059	0.707	0.050	0.866
NOF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0	0.0	0.0
CF [15 cm or 90 min] (%)	100.0	100.0	100.0	100.0	100.0	66.7
POF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0	0.0	0.0
MDNO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0
MDPO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0

Table 29. Summary of skill assessment statistics evaluating the ability of LMHOFS hindcasts and LMOFS nowcasts to predict extreme low water level events at NOS NWLON stations in southern Lake Michigan during 2016. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9087023 Ludington			
	LMHOFS N=5		**LMOFS** N=3	
	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	0.010	0.200	0.092	0.333
RMSE (m) (hr)	0.018	0.775	0.093	1.732
SD (m) (hr)	0.017	0.837	0.015	2.082
NOF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0
CF [15 cm or 90 min] (%)	100.0	100.0	100.0	33.3
POF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0
MDNO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0
MDPO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0

9087057 Milwaukee				9087031 Holland			
LMHOFS N=7		**LMOFS** N=4		**LMHOFS** N=4		**LMOFS** N=3	
Amp.	Time	Amp.	Time	Amp.	Time	Amp.	Time
0.016	-0.143	0.073	0.000	0.016	0.000	0.119	-0.667
0.036	0.845	0.077	0.707	0.026	0.707	0.125	1.155
0.035	0.900	0.027	0.816	0.024	0.816	0.046	1.155
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
100.0	85.7	100.0	100.0	100.0	100.0	66.7	66.7
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 29. Continued

9087044 Calumet Harbor			
LMHOFS N=12		**LMOFS** N=8	
Amp.	Time	Amp.	Time
0.036	-0.250	0.105	0.500
0.091	1.118	0.139	1.414
0.087	1.138	0.097	1.414
0.0	0.0	0.0	0.0
83.3	75.0	75.0	62.5
0.0	0.0	12.5	0.0
0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0

6.2. Assessment of Surface Water Temperature Hindcasts

The results of the skill assessment of LMHOFS hourly hindcasts of surface water temperatures for 2015 and 2016 are given in this section for the following basins: Northern Lake Michigan, Central Lake Michigan, Southern Lake Michigan, Georgian Bay of Lake Huron, Northern Lake Huron and Southern Lake Huron. The number of basins used to assess the water temperature hindcasts are greater than was done for water levels is due to the high number of stations and buoys available for temperature assessment and also the unique temperature fluctuations found in the observations and hindcasts in the different basins.

6.2.1. Northern Lake Michigan

The negative MAEs (except at the South Green Bay buoy) showed on Figure 19's time series plots indicate the underestimation of surface water temperature by the LMHOFS hindcasts during 2015 in the northern Lake Michigan region. The underestimation is most evident at the coastal stations: Mackinaw City and Menominee and the buoys in Little Transverse Bay and Northern Michigan. The MAEs of the 2015 hindcasts ranged from -3 ºC at Little Traverse Bay Buoy to 0.1 ºC at South Green Bay with an average of -1.4 ^{o}C. The corresponding RMSEs ranged from 1.1 ºC at Mackinac Straits West to 3.5 ºC at Little Traverse Bay Buoy. Table 30

shows that the hindcasts at the stations of Mackinac Straits West, South Green Bay, and N. Michigan passed all the acceptance criteria for water temperature for 2015.

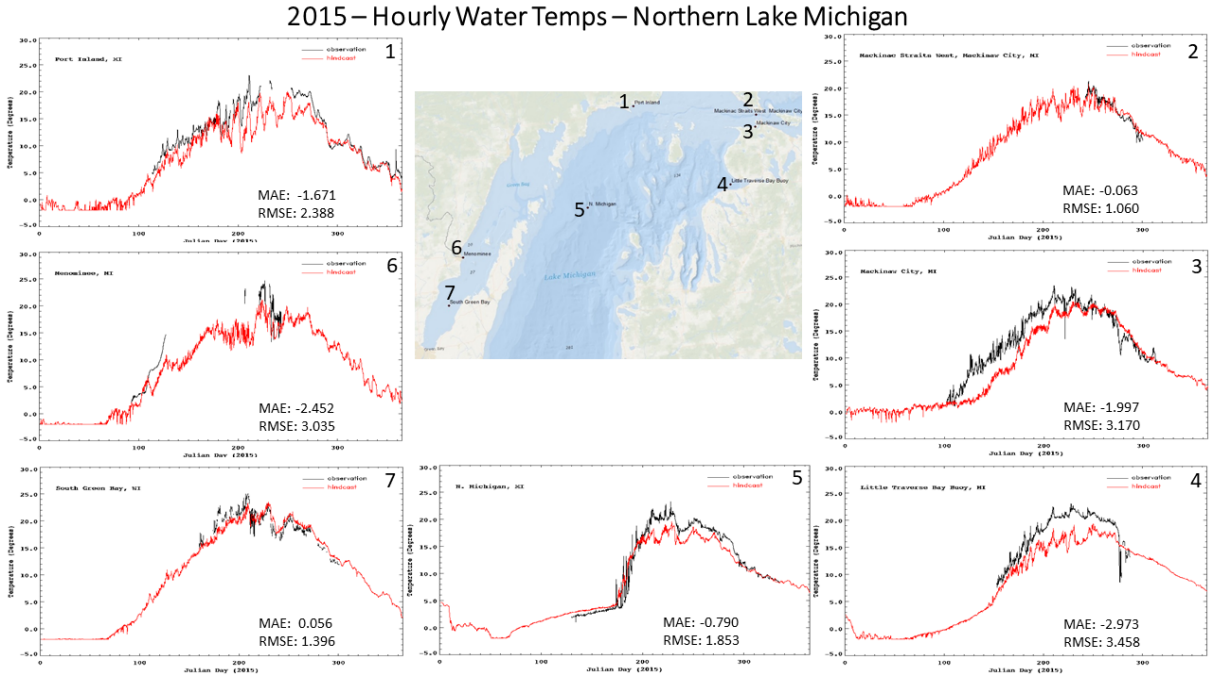

Figure 19. Time series plots of hourly hindcasts of surface water temperature (red) vs. observations (black) at CO-OPS NWLON coastal stations and NDBC buoys (1. Port Inland, MI, 2. Mackinac Straits West, MI, 3. Mackinaw City, MI, 4. Little Traverse Bay Buoy, MI, 5. N. Michigan, MI, 6. Menominee, MI, and 7. South Green Bay, WI) at northern Lake Michigan during 2015. MAE and RMSE (ºC) at each station are shown individually on each panel.

Table 30. Summary of skill assessment statistics of the hourly LMHOFS hindcasts of surface water temperature at NOS NWLON Stations and the fixed buoys in northern Lake Michigan during 2015. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Time Period, Statistic, Acceptable Error [ ], and Units ( )		9087096 Port Inland	9075080 Mackinaw City	45175 Mackinac Straits West	45022 Little Traverse Bay Buoy
Time Period	Begin	04/23/2015	04/12/2015	08/30/2015	06/02/2015
	End	01/03/2016	11/09/2015	10/27/2015	10/14/2015
Model		**LMHOFS**	**LMHOFS**	**LMHOFS**	**LMHOFS**
N		5313	5000	1392	3129
Mean Alg. Error (°C)		-1.671	-1.997	-0.063	-2.973
RMSE (°C)		2.388	3.170	1.060	3.458
SD (°C)		1.707	2.463	1.059	1.767
NOF [2x3°C] (%)		1.7	5.8	0.0	2.0
CF [3°C] (%)		78.9	61.2	99.8	51.3
POF [2x3°C] (%)		0.0	0.0	0.0	0.3
MDNO [2x3°C] (hr)		18.0	40.0	0.0	49.0
MDPO [2x3°C] (hr)		0.0	0.0	0.0	7.0

45002 N. Michigan	9087088 Menominee	45014 South Green Bay
05/10/2015	04/02/2015	06/08/2015
11/30/2015	08/31/2015	10/27/2015
LMHOFS	**LMHOFS**	**LMHOFS**
1259	1259	2005
-0.790	-2.452	0.056
1.853	3.035	1.396
1.676	1.788	1.396
0.0	0.5	0.0
90.6	55.4	97.4
0.0	0.0	0.0
0.0	0.0	0.0
0.0	0.0	0.0

For 2016, the hindcasts at four stations: Mackinac Straits West, Menominee, Mackinaw City, N. Michigan, and South Green Bay passed all the acceptance criteria for surface water temperature. The MAEs of hindcast ranged from -2.9 ºC at Little Traverse Bay Buoy to 0.8 ºC at Menominee. The RMSEs of 2016 hindcasts ranged from 1.2 ºC at South Green Bay Buoy to 3.4 ºC at Little Traverse Bay Buoy. A comparison of 2015 and 2016 LMHOFS hindcasts showed similar magnitudes of underestimation of hourly surface water temperatures at Port Inland, Little Transverse Bay buoy, and South Green Bay buoy. However, the performance of LMHOFS was better in 2016 at Mackinaw City and Menominee.

The time series of the hourly LMOFS surface water temperature nowcasts at the three stations (blue lines on Figure 20) showed obvious oscillations not shown on LMHOFS hindcasts and observation plots. The MAEs of LMOFS nowcasts for 2016 were much larger than for LMHOFS hindcasts. In contract to the hindcasts, LMOFS nowcasts tended to overestimate water temperatures, especially at Mackinaw City. The MAE and RMSE were 3.3 ºC and 3.7 ºC, respectively, at this station. The LHOFS also had nowcasts at Mackinaw City where the MAE and RMSE were 0.9 ºC and 2.3 ºC, respectively.

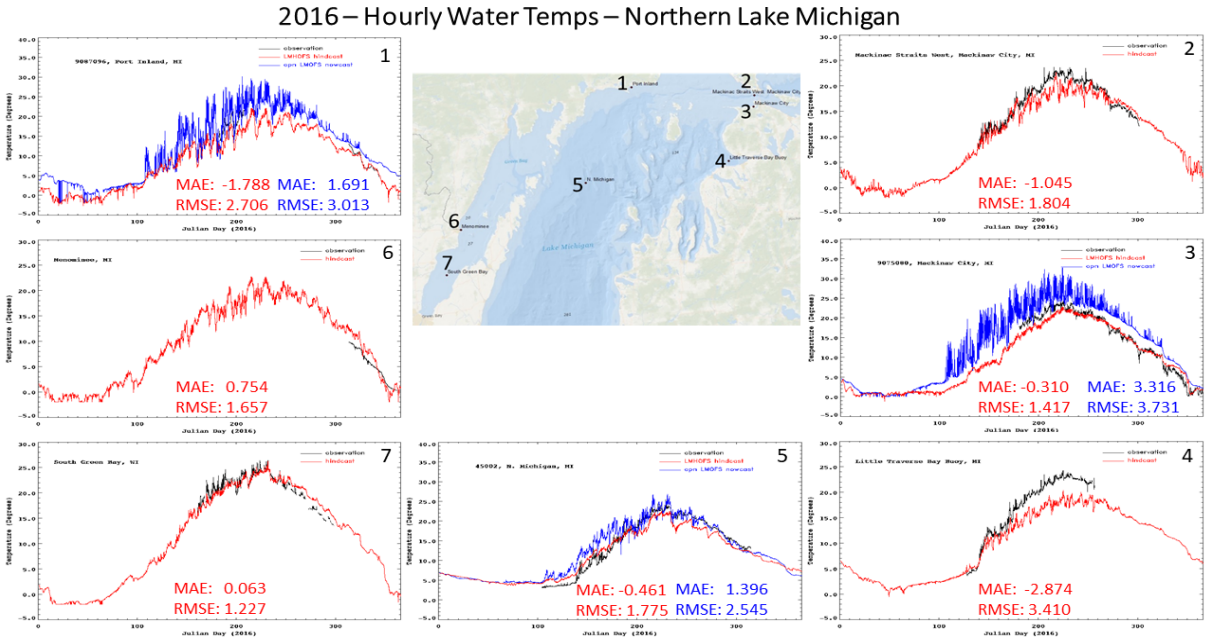

Figure 20. Same as Figure 19 except includes operational nowcasts from LMOFS for 2016 if available.

Table 31. Summary of skill assessment statistics of the hourly LMHOFS hindcasts and LMOFS/LHOFS nowcasts of surface water temperatures at NOS NWLON Stations and the fixed buoys in northern Lake Michigan during 2016. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Time Period, Statistic, Acceptable Error [ ], and Units ( )		9087096 Port Inland		9075080 Mackinaw City			45175 Mackinac Straits West
Time Period	Begin	06/28/2016		06/28/2016			05/18/2016
	End	12/08/2016		01/03/2017			10/27/2016
Model		**LMHOFS**	**LMOFS**	**LMHOFS**	**LMOFS**	**LHOFS**	**LMHOFS**
N		1399	1399	4474	4467	4467	3893
Mean Alg. Error (°C)		-1.788	1.691	-0.310	3.316	0.895	-1.045
RMSE (°C)		2.706	3.013	1.417	3.731	2.296	1.804
SD (°C)		2.032	2.495	1.383	1.711	2.114	1.471
NOF [2x3°C] (%)		2.0	0.0	0.0	0.0	0.3	0.0
CF [3°C] (%)		69.5	75.9	96.1	48.7	79.5	90.6
POF [2x3°C] (%)		0.0	5.7	0.0	8.1	1.2	0.0
MDNO [2x3°C] (hr)		17.0	0.0	0.0	0.0	10.0	0.0
MDPO [2x3°C] (hr)		0.0	11.0	0.0	15.0	30.0	0.0

Table 31. Continued

45022 Little Traverse Bay Buoy	45002 N. Michigan		9087088 Menominee	45014 South Green Bay
05/06/2016	04/13/2016		11/08/2016	06/08/2016
09/12/2016	11/09/2016		01/03/2017	10/24/2016
LMHOFS	**LMHOFS**	**LMOFS**	**LMHOFS**	**LMHOFS**
3129	4906	5035	1278	2292
-2.874	-0.461	1.396	0.754	0.063
3.410	1.775	2.545	1.657	1.227
1.835	1.714	2.128	1.476	1.225
0.5	0.1	0.0	0.0	0.0
41.8	96.3	74.6	98.0	99.7
0.0	0.0	1.9	0.0	0.0
4.0	1.0	0.0	0.0	0.0
0.0	0.0	22.0	0.0	0.0

6.2.2. Central Lake Michigan

Table 32 indicates that the 2015 hindcasts passed all the acceptance criteria for surface water temperature at the buoys at Muskegon, and Holland. The 2015 time series plots of all stations (Fig. 21) indicated season-long unrealistic temperature oscillations of observational data at the NOS NWLON station Holland. The minimum MAE (except Holland, MI) was -0.6 ºC at the Holland Buoy and the maximum MAE was 0.2 ºC at Ludington Buoy for 2015 hindcasts. The minimum and maximum RMSEs for 2015 hindcasts were 1.5 ºC at Holland Buoy, and 2.4 ºC at Atwater Park, respectively.

Figure 22 is the composite of surface water temperature time series plots for all stations during 2016. Both LMHOFS hindcasts and LMOFS nowcasts are shown for Holland. The minimum MAE of 2016 hindcasts was -0.25 ºC at Muskegon Buoy and the maximum MAE was 0.9 ºC at Holland. The minimum and maximum RMSEs were 1.4 ºC at Holland and 2.4 ºC at Atwater Park respectively for 2016 hindcasts (Table 33). NOS Acceptance Criteria were met at the Holland and Holland Buoys.

A comparison between LHOFS and LMHOFS was only possible at Holland since only nowcasts from this station was available in the LHOFS station netCDF output file. LMHOFS performed better than LHOFS with smaller MAE and RMSE and also passed all NOS acceptance criteria. LMHOFS captured the large drops in surface water temperature along the eastern shore from Ludington to Atwater Park during 2015 and 2016.

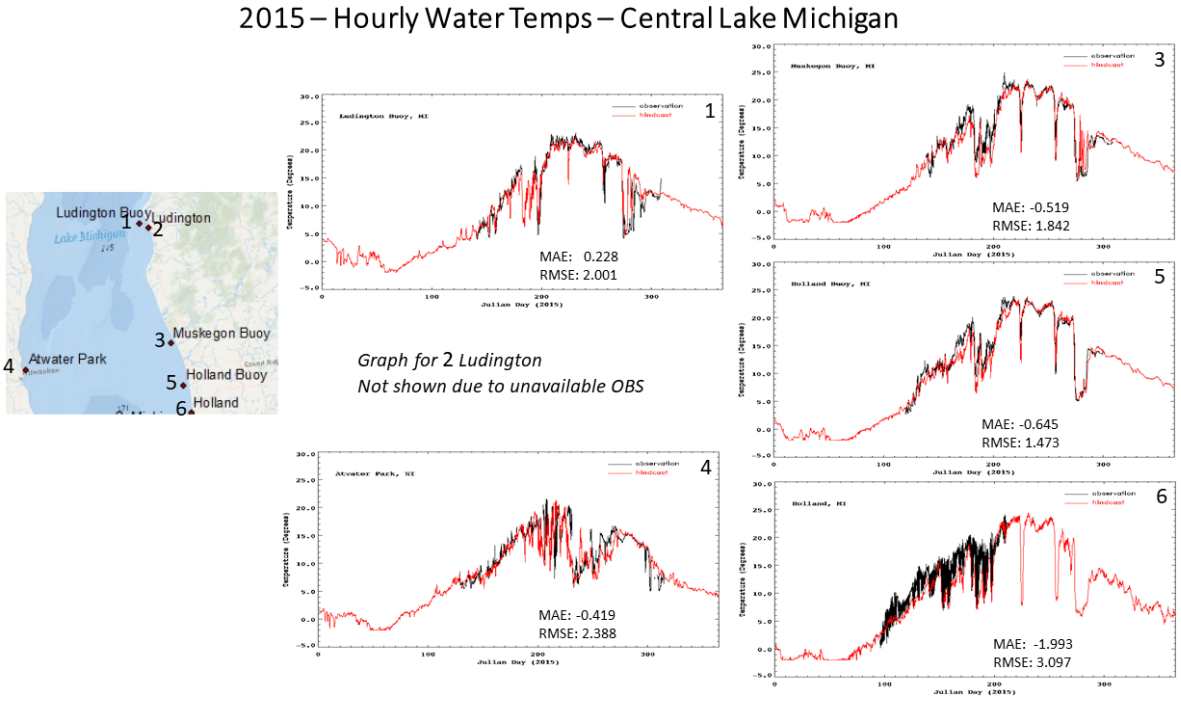

Figure 21. Time series plots of hourly hindcasts of surface water temperature (red) vs. observations (black) at NOS NWLON and NDBC stations (1. Ludington Buoy, MI, 2. Ludington, MI (N/A), 3. Muskegon Buoy, MI, 4. Atwater Park, WI, 5. Holland Buoy, MI, 6. Holland, MI) in Central Lake Michigan during 2015. MAE and RMSE (ºC) at each station are shown individually on each panel.

Table 32. Summary of skill assessment statistics of the hourly LMHOFS hindcasts of surface water temperatures at NOS NWLON stations and the fixed buoys in central Lake Michigan during 2015. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Time Period, Statistic, Acceptable Error [ ], and Units ( )		45024 Ludington Buoy	45161 Muskegon Buoy	45013 Atwater Park	45029 Holland Buoy	9087031 Holland
Time Period	Begin	05/20/2015	05/18/2015	05/08/2015	04/29/2015	04/06/2015
	End	11/04/2015	11/04/2015	11/10/2015	10/26/2015	07/13/2015
Model		**LMHOFS**	**LMHOFS**	**LMHOFS**	**LMHOFS**	**LMHOFS**
N		3821	3919	3842	4319	2763
Mean Alg. Error (°C)		0.228	-0.519	-0.419	-0.645	-1.993
RMSE (°C)		2.001	1.842	2.388	1.473	3.097
SD (°C)		1.988	1.768	2.351	1.325	2.371
NOF [2x3°C] (%)		0.1	0.0	3.2	0.0	6.1
CF [3°C] (%)		92.9	90.0	84.9	94.6	71.0
POF [2x3°C] (%)		2.8	0.7	1.1	0.0	0.0
MDNO [2x3°C] (hr)		1.0	0.0	49.0	0.0	5.0
MDPO [2x3°C] (hr)		63.0	10.0	14.0	0.0	0.0

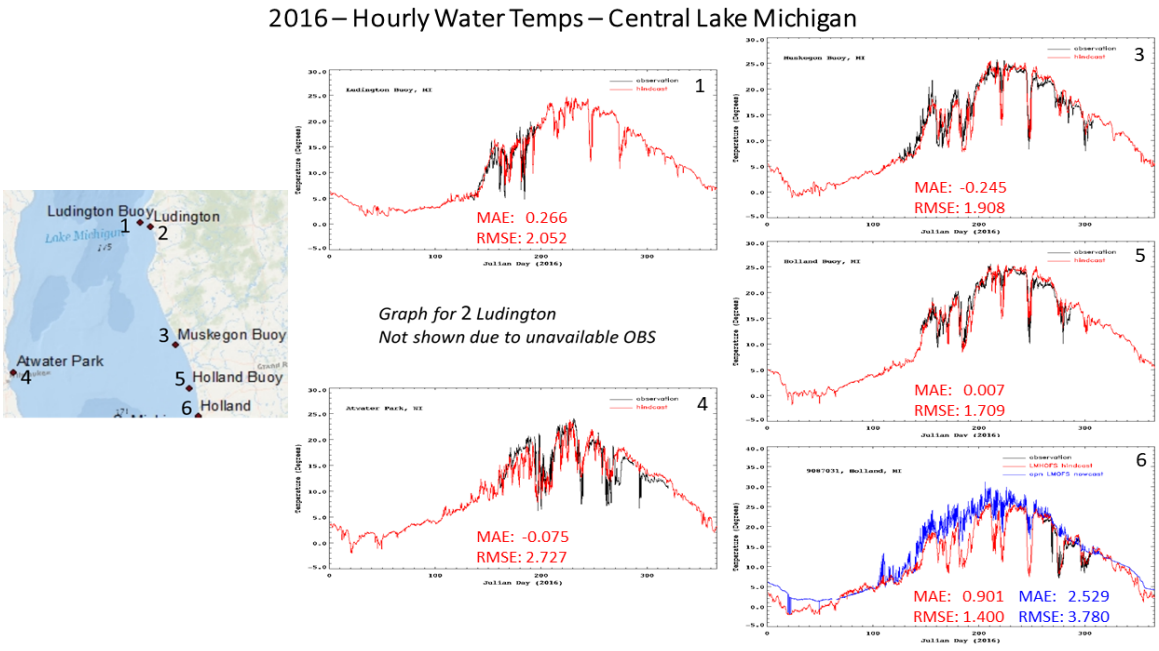

Figure 22. Same as Figure 21 except includes operational nowcasts from LMOFS for 2016 if available.

Table 33. Summary of skill assessment statistics of the hourly LMHOFS hindcasts and LMOFS nowcasts of surface water temperatures at NOS NWLON stations and the fixed buoys in central Lake Michigan during 2016. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Time Period, Statistic, Acceptable Error [ ], and Units ( )		45024 Ludington Buoy	45161 Muskegon Buoy	45013 Atwater Park	45029 Holland Buoy
Time Period	Begin	05/12/2016	05/03/2016	06/08/2016	05/23/2016
	End	07/17/2016	11/02/2016	11/14/2016	10/12/2016
Model		**LMHOFS**	**LMHOFS**	**LMHOFS**	**LMHOFS**
N		1567	4254	3146	3409
Mean Alg. Error (°C)		0.266	-0.245	-0.075	-0.007
RMSE (°C)		2.052	1.908	2.727	1.709
SD (°C)		2.035	1.893	2.726	1.709
NOF [2x3°C] (%)		0.6	1.0	1.4	0.6
CF [3°C] (%)		86.9	89.4	75.6	91.7
POF [2x3°C] (%)		1.1	0.0	2.4	0.0
MDNO [2x3°C] (hr)		9.0	9.0	7.0	9.0
MDPO [2x3°C] (hr)		6.0	0.0	34.0	0.0

9087031 Holland	
09/17/2016	
10/31/2016	
LMHOFS	**LMOFS**
1067	1067
0.901	2.529
1.400	3.780
1.072	2.811
0.1	0.0
97.0	72.9
0.6	13.6
0.0	0.0
2.0	56.0

6.2.3. Southern Lake Michigan

The hindcasts of surface water temperature at eight stations in southern Lake Michigan were evaluated for both 2015 and 2016. Time series of the hindcasts vs. observations are shown in Figures 23 and 24. Detailed skill statistics are provided in Tables 34 and 35. The hindcasts of 2015 passed all the NOS acceptance criteria for temperature at buoys S. Michigan, Cook Nuclear Plant, and Michigan City. The MAEs of the 2015 hindcasts at this region ranged from -2.2 ºC at Calumet Beach to 1 ºC at Wilmette Buoy. The corresponding RMSEs ranged from 1 ºC at S. Michigan to 2.8 ºC at Montrose Ave. Beach buoy, respectively.

The hindcasts of 2016 passed all the NOS acceptance criteria for temperature at S. Michigan, South Haven Buoy, and Michigan City. The MAEs of the 2016 hindcasts at this region ranged from -2 ºC at Calumet Beach to 1.3 ºC at S. Michigan. The corresponding RMSEs ranged from 1.4 ºC at Michigan City Buoy to 3.1 ºC at Calumet Beach.

LMHOFS predicted the sudden drops in surface water temperature observed on the eastern shore of both southern and central Lake Michigan during 2015 and 2016.

There is only one location, S. Michigan where the LMOFS nowcasts were available in the LMOFS station netCDF file for 2016. The MAE of the hindcast at S. Michigan buoy was 1.3 ºC vs. 0.7 ºC for the nowcast. The RMSE of the hindcast at S. Michigan was 1.5 ºC for the hindcasts vs. 2.4 ºC for the nowcast.

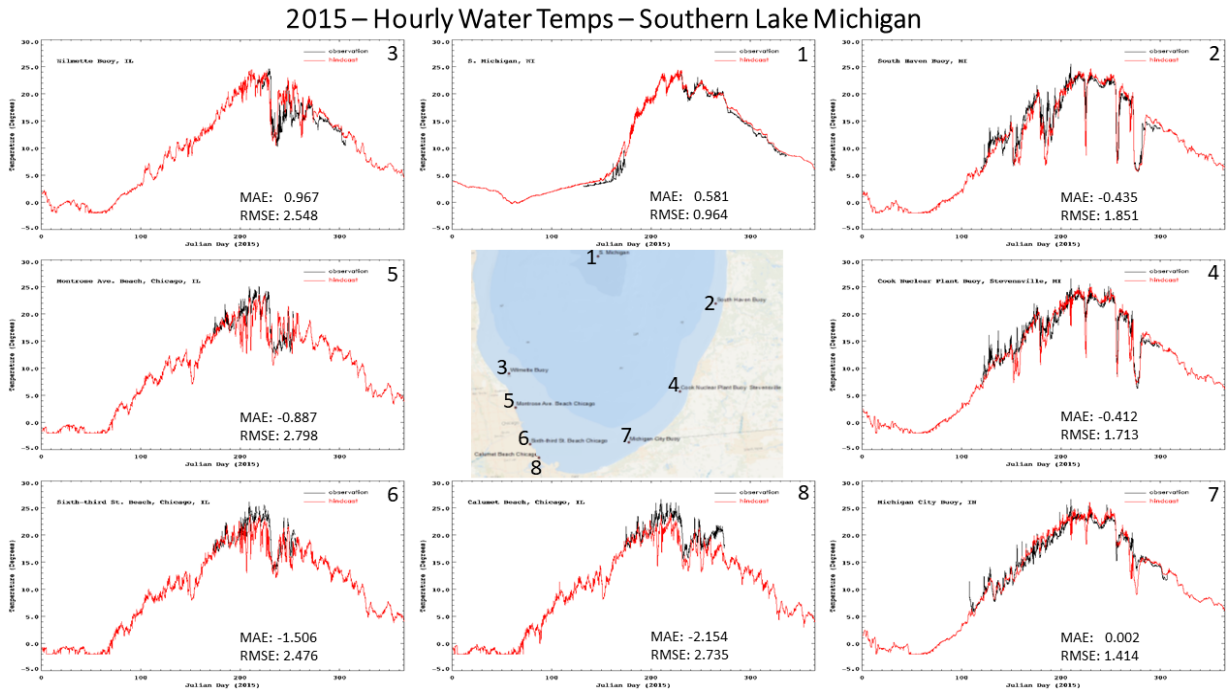

Figure 23. Time series plots of hourly hindcasts of surface water temperature (red) vs. observations (black) at NOS NWLON and NDBC stations (1. S. Michigan, WI, 2. South Haven Buoy, MI, 3. Wilmette Buoy, IL, 4. Cook Nuclear Plant Buoy, Stevensville, MI, 5. Montrose Ave. Beach, Chicago, IL, 6. Sixth-third St. Beach, Chicago, IL, 7. Michigan City Buoy, IN, 8. Calumet Beach, Chicago, IL) in southern Lake Michigan during 2015. MAE and RMSE (ºC) at each station are shown on each panel.

Table 34. Summary of skill assessment statistics of the hourly LMHOFS hindcasts of surface water temperatures at NOS NWLON stations and the fixed buoys in southern Lake Michigan during 2015. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Time Period, Statistic, Acceptable Error [ ], and Units ( )		45007 S. Michigan	45168 South Haven Buoy	45174 Wilmette Buoy	45026 Cook Nuclear Plant Buoy
Time Period	Begin	05/12/2015	04/29/2015	08/05/2015	04/29/2015
	End	12/02/2015	10/26/2015	11/01/2015	10/05/2015
Model		**LMHOFS**	**LMHOFS**	**LMHOFS**	**LMHOFS**
N		3479	4323	2118	4292
Mean Alg. Error (ºC)		0.581	-0.435	0.967	-0.412
RMSE (ºC)		0.964	1.851	2.548	1.713
SD (ºC)		0.769	1.800	2.358	1.663
NOF [2x3ºC] (%)		0.0	1.8	0.8	0.8
CF [3ºC] (%)		97.4	91.3	80.0	90.6
POF [2x3ºC] (%)		0.0	0.0	3.0	0.0
MDNO [2x3ºC] (hr)		0.0	21.0	13.0	7.0
MDPO [2x3ºC] (hr)		0.0	0.0	17.0	0.0

45018 Montrose Ave. Beach	45016 Sixth-third St. Beach	45170 Michigan City Buoy	45015 Calumet Beach
06/22/2015	06/22/2015	04/17/2015	06/22/2015
09/10/2015	09/14/2015	11/02/2015	09/30/2015
LMHOFS	**LMHOFS**	**LMHOFS**	**LMHOFS**
1738	1682	4777	2227
-0.887	-1.506	0.002	-2.154
2.798	2.476	1.414	2.735
2.655	1.965	1.414	1.686
6.0	2.2	0.3	1.9
75.0	76.7	94.4	70.9
0.2	0.0	0.0	0.0
31.0	9.0	4.0	26.0
1.0	0.0	0.0	0.0

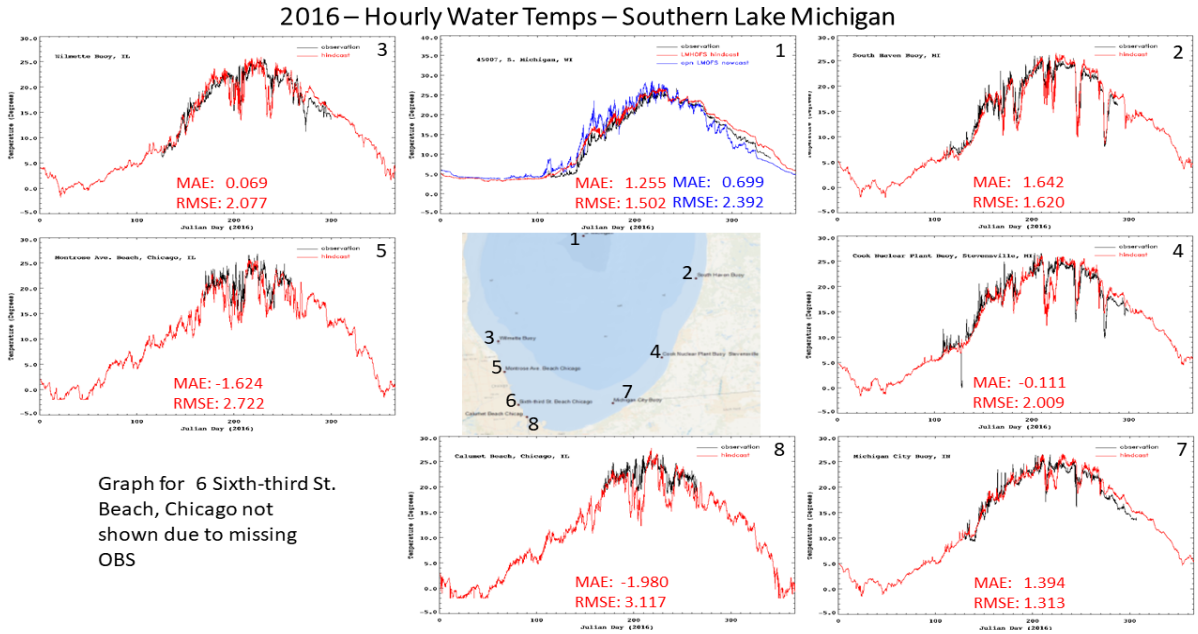

Figure 24. Same as Figure 23 except includes operational nowcasts from LMOFS for 2016 if available.

Table 35. Summary of skill assessment statistics of the hourly LMHOFS hindcasts and LMOFS nowcasts of surface water temperatures at NOS NWLON stations and the fixed buoys in southern Lake Michigan during 2016. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Time Period, Statistic, Acceptable Error [ ], and Units ( )		45007 S. Michigan		45168 South Haven Buoy	45174 Wilmette Buoy
Time Period	Begin	04/20/2016		04/20/2016	05/04/2016
	End	12/04/2016		10/14/2016	10/25/2016
Model		**LMHOFS**	**LMOFS**	**LMHOFS**	**LMHOFS**
N		5333	5482	4261	4181
Mean Alg. Error (°C)		1.255	0.699	-0.268	0.069
RMSE (°C)		1.502	2.392	1.642	2.077
SD (°C)		0.825	2.288	1.620	2.076
NOF [2x3°C] (%)		0.0	0.0	0.4	2.0
CF [3°C] (%)		98.7	80.0	93.4	89.4
POF [2x3°C] (%)		0.0	0.8	0.0	0.1
MDNO [2x3°C] (hr)		0.0	0.0	6.0	31.0
MDPO [2x3°C] (hr)		0.0	13.0	0.0	3.0

Table 35. Continued

45026 Cook Nuclear Plant Buoy	45018 Montrose Ave. Beach	45170 Michigan City Buoy	45015 Calumet Beach
04/16/2016	06/16/2016	05/09/2016	06/16/2016
10/25/2016	09/14/2016	11/01/2016	09/20/2016
LMHOFS	**LMHOFS**	**LMHOFS**	**LMHOFS**
4276	2117	4198	2176
-0.111	-1.624	0.467	-1.980
2.009	2.772	1.394	3.117
2.006	2.247	1.313	2.408
1.4	3.6	0.0	8.3
89.6	70.0	97.6	71.0
0.7	0.0	0.1	0.0
18.0	22.0	0.0	38.0
24.0	0.0	5.0	0.0

6.2.4. Georgian Bay-Lake Huron

The hindcasts of surface water temperatures at three ECCC buoys (North Channel East, ONT CAN, Georgian Bay, ONT CAN, and South Georgian Bay, ONT CAN) in Georgian Bay of Lake Huron were evaluated for both 2015 and 2016. Time series of the hindcasts vs. observations are given in Figures 25 and 26. Detailed skill statistics are provided in Tables 36 and 37.

The hindcasts during 2015 and 2016 passed all the acceptance criteria for water temperature at all the three ECCC buoys, except the CF at South Georgian Bay in 2015. For 2015 and 2016, the averaged MAE was -0.32 ^{o}C and the averaged RMSE was 1.5 ^{o}C, indicating an underestimation of surface water temperatures in the Bay by LMHOFS. The North Channel East buoy had the largest MAEs for the 2015 and 2016 hindcasts with -0.51 ºC for 2015 and -0.45 ºC for 2016. The Georgian Bay buoy had the smallest MAEs for both years: -0.3 ºC for 2015 and 0 ºC for 2016. The buoys, Georgian Bay and South Georgian Bay had the smallest and largest RMSEs, respectively for both the hindcasts. The RMSEs were 1.2 ºC for 2015 and 1.5 ºC for 2016 for Georgian Bay. The RMSEs were 1.8 ºC for 2015 and 1.7 ºC for 2016 at the South Georgian Bay buoy. There were no LHOFS nowcasts station output available at these buoys in 2016 to do a comparison.

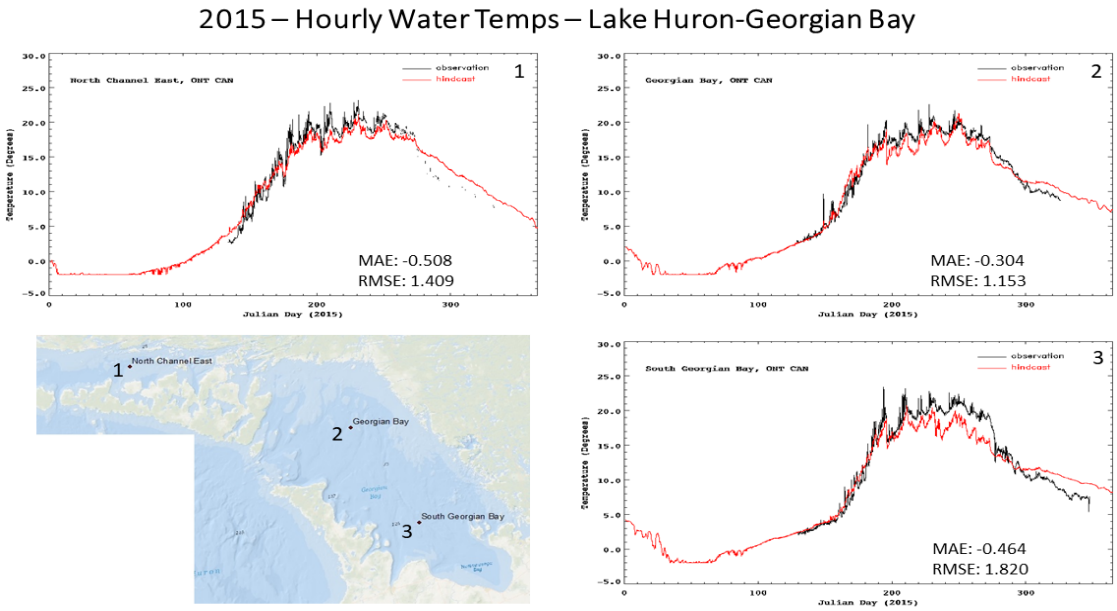

Figure 25. Time series plots of hourly hindcasts of surface water temperature (red) vs. observations (black) at ECCC fixed buoys (1. North Channel East, ONT CAN, 2. Georgian Bay, ONT CAN, 3. South Georgian Bay, ONT CAN) at Lake Huron's Georgian Bay during 2015. MAE and RMSE (ºC) at each station are shown individually on each panel.

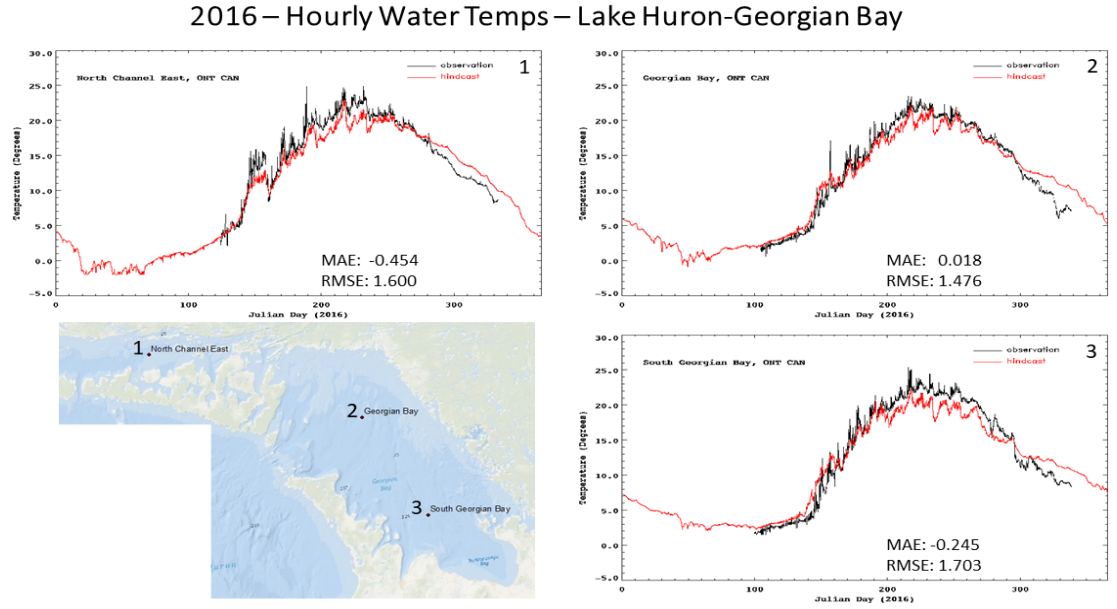

Figure 26. Same as Figure 25 but for 2016.

Table 36. Summary of skill assessment statistics of the hourly LMHOFS hindcasts of surface water temperatures at ECCC buoys in Lake Huron's Georgian Bay during 2015. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Time Period, Statistic, Acceptable Error [ ], and Units ( )		45154 North Channel East	45137 Georgian Bay	45143 South Georgian Bay
Time Period	Begin	05/13/2015	05/08/2015	05/09/2015
	End	11/28/2015	11/22/2015	12/13/2015
Model		**LMHOFS**	**LMHOFS**	**LMHOFS**
N		3037	4635	5156
Mean Alg. Error (ºC)		-0.508	-0.304	-0.464
RMSE (ºC)		1.409	1.153	1.820
SD (ºC)		1.315	1.113	1.760
NOF [2x3ºC] (%)		0.0	0.0	0.0
CF [3ºC] (%)		98.0	99.5	88.8
POF [2x3ºC] (%)		0.0	0.0	0.0
MDNO [2x3ºC] (hr)		0.0	0.0	0.0
MDPO [2x3ºC] (hr)		0.0	0.0	0.0

Table 37. Summary of skill assessment statistics of the hourly LMHOFS hindcasts of surface water temperatures at ECCC buoy in Lake Huron's Georgian Bay during 2016. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Time Period, Statistic, Acceptable Error [ ], and Units ( )		45154 North Channel East	45137 Georgian Bay	45143 South Georgian Bay
Time Period	Begin	05/02/2016	04/13/2016	04/08/2016
	End	11/27/2016	12/03/2016	12/03/2016
Model		**LMHOFS**	**LMHOFS**	**LMHOFS**
N		4912	5398	5679
Mean Alg. Error (ºC)		-0.454	0.018	-0.245
RMSE (ºC)		1.600	1.476	1.703
SD (ºC)		1.534	1.476	1.685
NOF [2x3ºC] (%)		0.0	0.0	0.0
CF [3ºC] (%)		96.6	94.7	96.0
POF [2x3ºC] (%)		0.0	0.0	0.0
MDNO [2x3ºC] (hr)		0.0	0.0	0.0
MDPO [2x3ºC] (hr)		0.0	0.0	0.0

6.2.5. Northern Lake Huron

The hindcasts of surface water temperatures at four locations in northern Lake Michigan were evaluated for both 2015 and 2016. Time series of the hindcasts vs. observations are given in Figures 27 and 28. Detailed skill statistics are provided in Tables 38 and 39. The hindcasts for both 2015 and 2016 passed all the acceptance criteria for temperature at De Tour Village. The MAEs for the 2015 hindcast ranged from -1.7 ºC at Thunder Bay Buoy to 0.9 ºC at Alpena. For 2016, the MAEs ranged from -1.7 ºC also at Thunder Bay Buoy to 1.2 ºC at Alpena. The smallest and largest RMSEs were at the same stations for the 2015 and 2016 hindcasts as well. The minimum RMSEs were at De Tour Village with 1.5 ºC for 2015 and 1.4 ºC for 2016. The maximum RMSEs were at Alpena with 3.7 ºC for 2015 and 4.6 ºC for 2016. All acceptance criteria were met at De Tour Village for both years and nearly met at the North Huron buoy for both years.

Compared to the LHOFS nowcasts during 2016, the LMHOFS hindcasts improved dramatically at station De Tour Village and North Huron buoy. The MAEs improved from 1.8 ºC and 1.4 ºC at De Tour Village and North Huron to 0.2 ºC and 0.5 ºC (LMHOFS), respectively. The RMSEs decreased from 2.9 ºC at De Tour Village and 3.0 ºC at North Huron

to 1.4 ºC and 1.8 ºC respectively (LMHOFS). The LMHOFS hindcasts also did not exhibit unrealistic high frequency temperature fluctuations as seen in the LHOFS nowcasts during 2016.

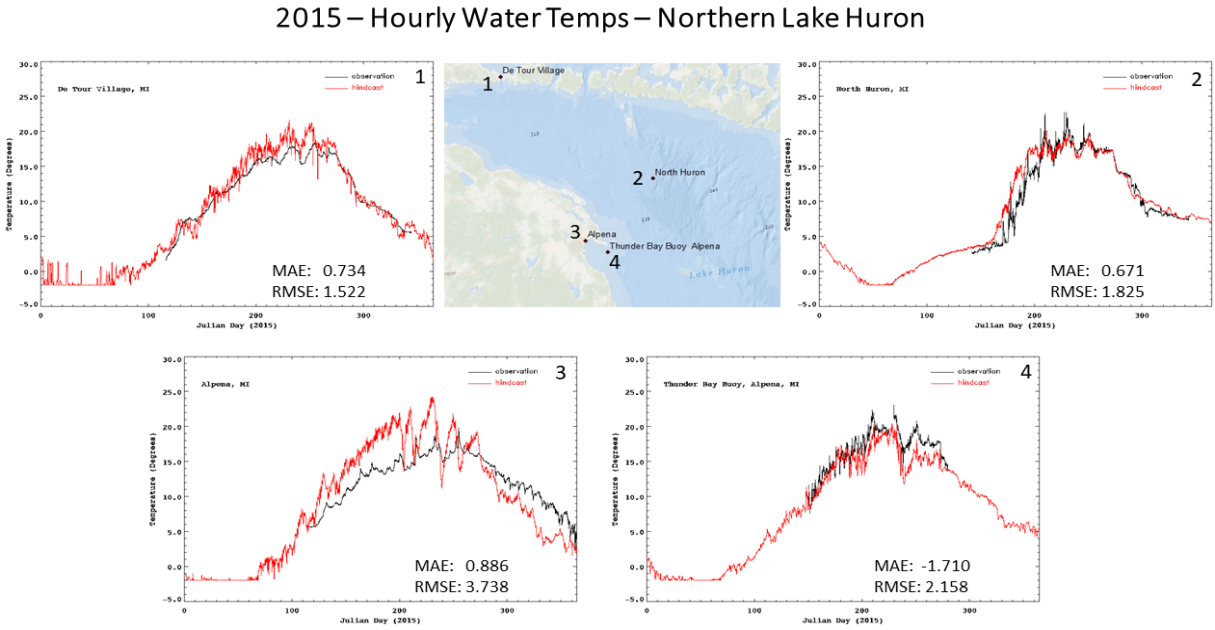

Figure 27. Time series plots of hourly hindcasts of surface water temperature (red) vs. observations (black) at CO-OPS NWLON and NDBC stations (1. De Tour Village, MI, 2. North Huron, MI, 3. Alpena, MI, 4. Thunder Bay Buoy, Alpena, MI) in northern Lake Huron during 2015. The MAE and RMSE (ºC) at each station are shown individually on each panel.

Table 38. Summary of skill assessment statistics of the hourly LMHOFS hindcasts of surface water temperatures at NOS NWLON stations and the fixed buoys in northern Lake Huron during 2015. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Time Period, Statistic, Acceptable Error [ ], and Units ( )		9075099 De Tour Village	45003 North Huron	9075065 Alpena	45162 Thunder Bay Buoy
Time Period	Begin	04/26/2015	05/21/2015	04/23/2015	05/29/2015
	End	12/09/2015	12/09/2015	01/03/2016	10/06/2015
Model		**LMHOFS**	**LMHOFS**	**LMHOFS**	**LMHOFS**
N		5457	4818	6033	2996
Mean Alg. Error (ºC)		0.734	0.671	0.886	-1.710
RMSE (ºC)		1.522	1.825	3.738	2.158
SD (ºC)		1.333	1.697	3.632	1.316
NOF [2x3ºC] (%)		0.0	0.0	1.0	0.0
CF [3ºC] (%)		94.6	87.0	45.2	81.5
POF [2x3ºC] (%)		0.0	0.7	6.7	0.0
MDNO [2x3ºC] (hr)		0.0	0.0	51.0	0.0
MDPO [2x3ºC] (hr)		0.0	32.0	86.0	0.0

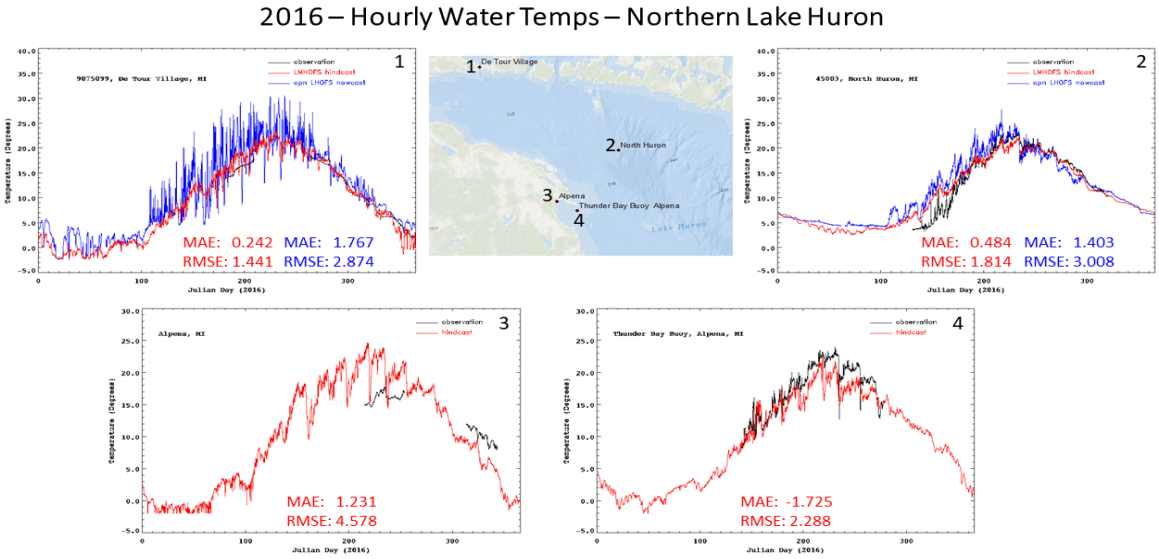

Figure 28. Same as Figure 27 except includes operational nowcasts from LHOFS for 2016 if available.

Table 39. Summary of skill assessment statistics of the hourly LMHOFS hindcasts and LHOFS nowcasts of surface water temperatures at NOS NWLON Stations and the fixed buoys in northern Lake Huron during 2016. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Time Period, Statistic, Acceptable Error [ ], and Units ( )		9075099 De Tour Village		45003 North Huron		9075065 Alpena	45162 Thunder Bay Buoy
Time Period	Begin	06/28/2016		05/10/2016		08/02/2016	05/19/2016
	End	01/03/2017		11/14/2016		12/08/2016	10/03/2016
Model		**LMHOFS**	**LHOFS**	**LMHOFS**	**LHOFS**	**LMHOFS**	**LMHOFS**
N		3241	3240	4447	4530	1654	3282
Mean Alg. Error (ºC)		0.242	1.767	0.484	1.403	1.231	-1.725
RMSE (ºC)		1.441	2.874	1.814	3.008	4.578	2.288
SD (ºC)		1.420	2.267	1.749	2.661	4.410	1.504
NOF [2x3ºC] (%)		0.0	0.4	0.0	0.0	0.0	0.6
CF [3ºC] (%)		96.2	83.1	86.6	70.8	30.6	80.7
POF [2x3ºC] (%)		0.0	5.9	0.0	6.2	17.9	0.0
MDNO [2x3ºC] (hr)		0.0	12.0	0.0	0.0	0.0	14.0
MDPO [2x3ºC] (hr)		0.0	33.0	1.0	44.0	114.0	0.0

6.2.6. Southern Lake Huron

The hindcasts of surface water temperatures at three buoys and one NWLON coastal station in southern Lake Huron were evaluated for both 2015 and 2016. Time series of the LMHOFS hindcasts, the LHOFS nowcasts, and observations along with MAEs and RMSEs are shown in Figures 29 and 30. Detailed skill statistics are provided in Tables 40 and 41. The hindcasts of both 2015 and 2016 passed all the acceptance criteria at the three buoys, South Huron, Saginaw Bay, and Southern Lake Huron, but not the coastal station, Harbor Beach. The hindcasts for both years, the NWLON Harbor Beach station had the greatest MAEs, -1.5 ºC for 2015 and -1.0 ºC for 2016. The RMSEs were also the largest at Harbor Beach with 2.3 ºC for 2015 and 2.1 ºC for 2016. The smallest MAEs were at Southern Lake Huron buoy of -0.01 ºC for 2015 and -0.04 ºC for 2016.

The statistical comparisons between the results for the LMHOFS hindcasts and the LHOFS nowcasts for 2016 showed noticeable improvements of surface water temperature predictions at the South Huron and Southern Lake Huron buoys. For example, for the South Huron buoy, the MAE and RMSE dropped from 2.2 ºC and 3.2 ºC to 0.7 ºC and 1.4 ºC, respectively.

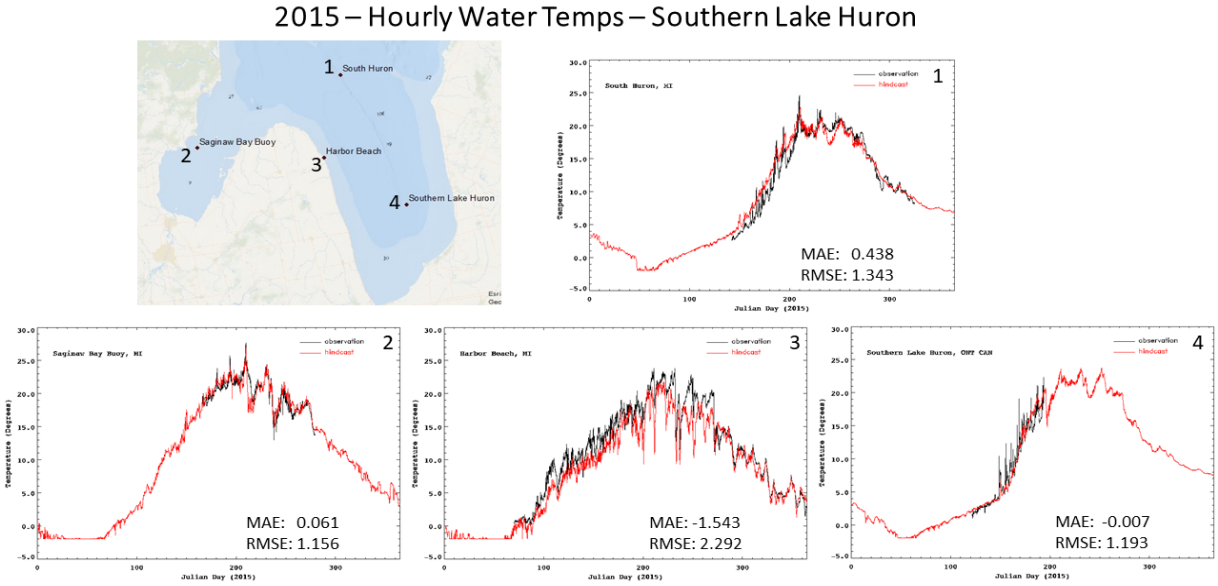

Figure 29. Time series plots of hourly hindcasts of surface water temperature (red) vs. observations (black) at CO-OPS NWLON, NDBC, and ECCC buoy stations (1. South Huron, MI, 2. Saginaw Bay Buoy, MI, 3. Harbor Beach, MI, 4. Southern Lake Huron, ONT) at southern Lake Huron during 2015. MAE and RMSE (ºC) at each station are shown individually on each panel.

Table 40. Summary of skill assessment statistics of the hourly LMHOFS hindcasts of surface water temperatures at NOS NWLON Stations, the fixed buoys and the ECCC buoys in southern Lake Huron during 2015. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Time Period, Statistic, Acceptable Error [ ], and Units ( )		45008 South Huron N=4374	45163 Saginaw Bay Buoy N=2598	9075014 Harbor Beach N=7096	45149 Southern Lake Huron N=1698
Time Period	Begin	05/22/2015	06/15/2015	03/11/2015	05/01/2015
	End	11/20/2015	10/06/2015	01/03/2016	07/12/2015
Model		**LMHOFS**	**LMHOFS**	**LMHOFS**	**LMHOFS**
Mean Alg. Error (°C)		0.438	0.061	-1.543	-0.007
RMSE (°C)		1.343	1.156	2.292	1.193
SD (°C)		1.269	1.154	1.695	1.193
NOF [2x3°C] (%)		0.0	0.0	1.9	0.2
CF [3°C] (%)		98.8	96.6	82.8	98.2
POF [2x3°C] (%)		0.0	0.0	0.0	0.0
MDNO [2x3°C] (hr)		0.0	0.0	34.0	0.0
MDPO [2x3°C] (hr)		0.0	0.0	0.0	0.0

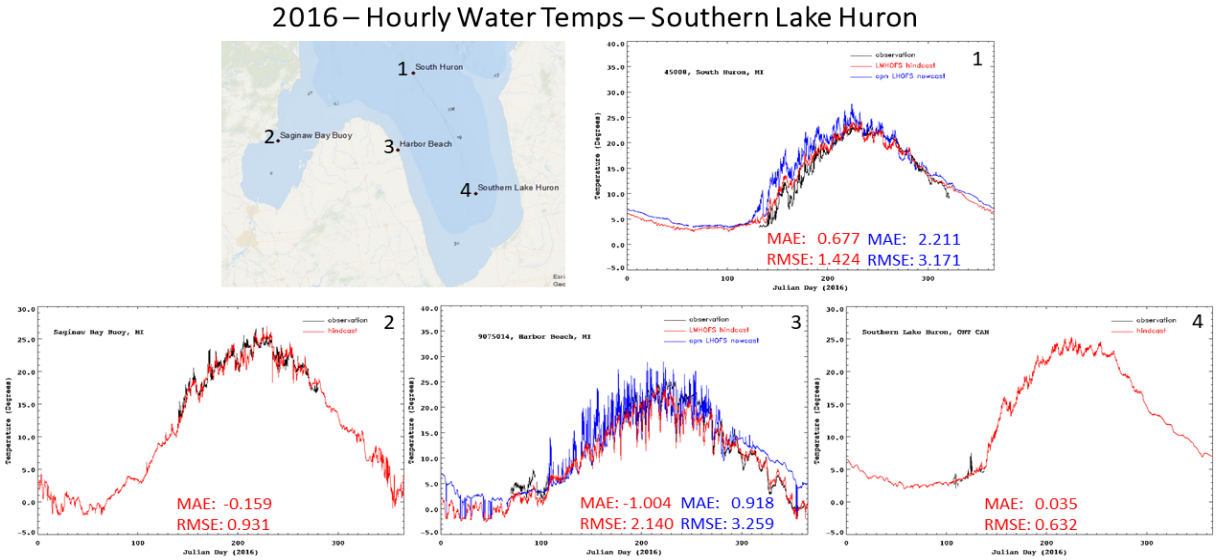

Figure 30. Same as Figure 29 except includes operational nowcasts from LMOFS for 2016 if available.

Table 41. Summary of skill assessment statistics of the hourly LMHOFS hindcasts and LHOFS nowcasts of surface water temperatures at NOS NWLON stations, the NWS buoys and ECCC buoys in southern Lake Huron during 2016. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Time Period, Statistic, Acceptable Error [ ], and Units ( )		45008 South Huron		45163 Saginaw Bay Buoy	9075014 Harbor Beach		45149 Southern Lake Huron	
Time Period	Begin	05/10/2016		05/18/2016	03/09/2016		04/15/2016	
	End	11/15/2016		10/06/2016	01/03/2017		05/18/2016	
Model		LMHOFS	LHOFS	LMHOFS	LMHOFS	LHOFS	LMHOFS	LHOFS
N		4412	4535	3367	5312	5305	285	410
Mean Alg. Error (ºC)		0.677	2.211	-0.159	-1.004	0.918	0.035	1.215
RMSE (ºC)		1.424	3.171	0.931	2.140	3.259	0.632	2.110
SD (ºC)		1.254	2.273	0.918	1.890	3.127	0.632	1.727
NOF [2x3ºC] (%)		0.0	0.0	0.0	1.6	2.7	0.0	0.0
CF [3ºC] (%)		95.1	66.5	98.9	85.4	62.1	100.0	92.4
POF [2x3ºC] (%)		0.0	7.1	0.0	0.0	3.7	0.0	5.6
MDNO [2x3ºC] (hr)		0.0	0.0	0.0	24.0	19.0	0.0	0.0
MDPO [2x3ºC] (hr)		0.0	86.0	0.0	0.0	73.0	0.0	0.0

6.3. Assessment of Sub-Surface Water Temperature Hindcasts

Observations of sub-surface water temperature measured by thermistor chains in three regions of Lake Michigan-Huron were used to evaluate the LMHOFS hindcasts of vertical thermal structure. The duration of available observations varied at the three locations. Figures 31-33 show color-coded vertical sub-surface temperature structure of both the observations and the model outputs for three locations. Statistic information can be found in Table 42. The hindcasts of sub-surface water temperature at all the three locations passed the NOS acceptance criteria. In southern Lake Michigan, the maximum RMSE was 2.03 ºC at 20 m depth. All the other RMSEs at this location were below 2 ºC, and below 52 m depth all RMSEs were less than 1 ºC. In the Straits of Mackinac, in much shallower water, the modeled temperatures had a maximum RMSE near the surface at 4 m depth (1.47 ºC), though all the values were similar, ranging from 1.47 at 4 m depth to 1.26 ºC at a depth of 35 m. Finally, at the deepest thermistor location, in mid-Lake Huron, the maximum RMSE of 2.35 ºC was found at 16 m depth, though all RMSEs below 37 m were under 2 ºC. In all cases, the modeled thermal structure captures the seasonal variation and summer stratification. The highest RMSEs in each location occur near a depth of 20 m, in the thermocline depth region, where gradients of temperature are observed to be the largest. Similar to previous hydrodynamic models (LHOFS and LMOFS included), the model

has a diffuse thermocline relative to observations. However, even with an overly diffuse thermocline all RMSEs of sub-surface water temperatures were at or below 2.35 °C.

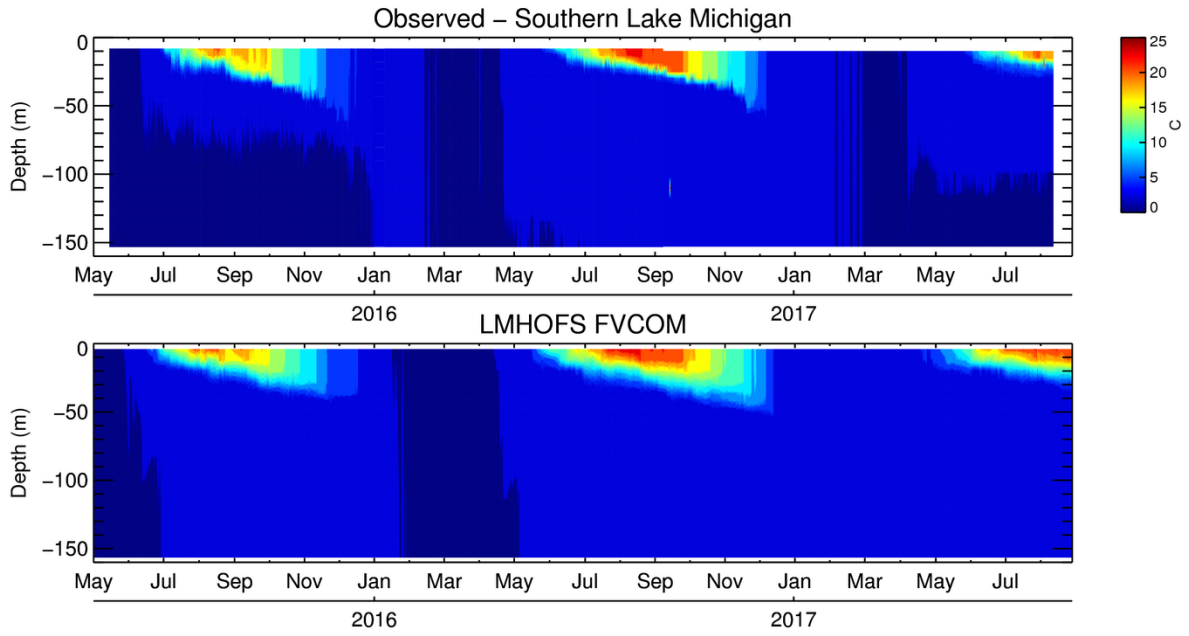

Figure 31. Observed and modeled sub-surface water temperatures in Southern Lake Michigan for the hindcast period 2015-2017.

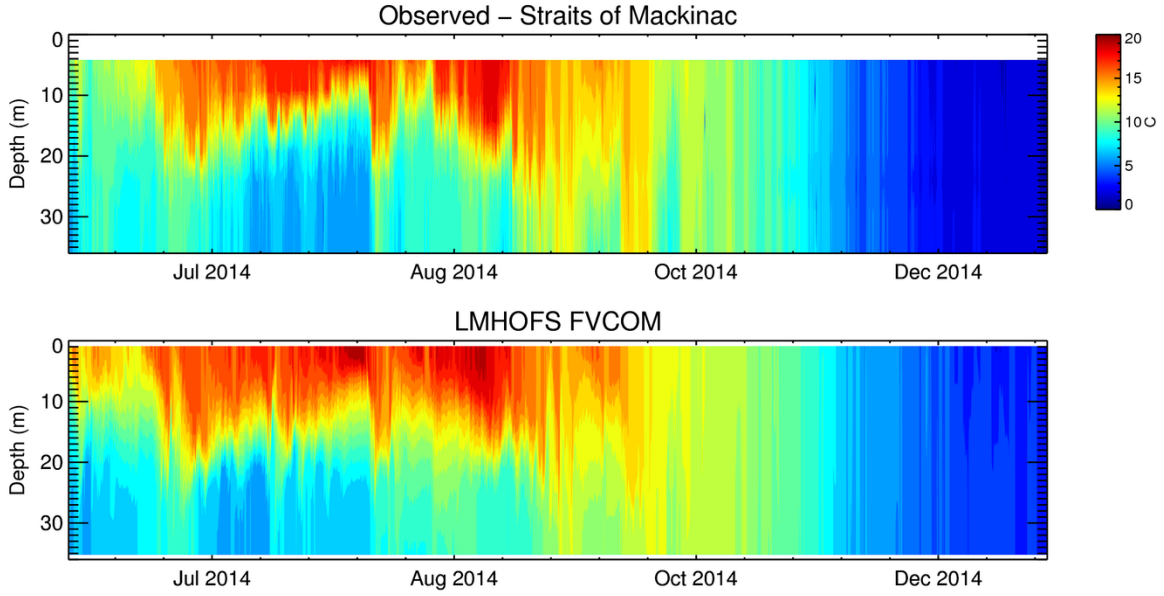

Figure 32. Observed and modeled sub-surface water temperatures in the Straits of Mackinac for the hindcast period in 2014.

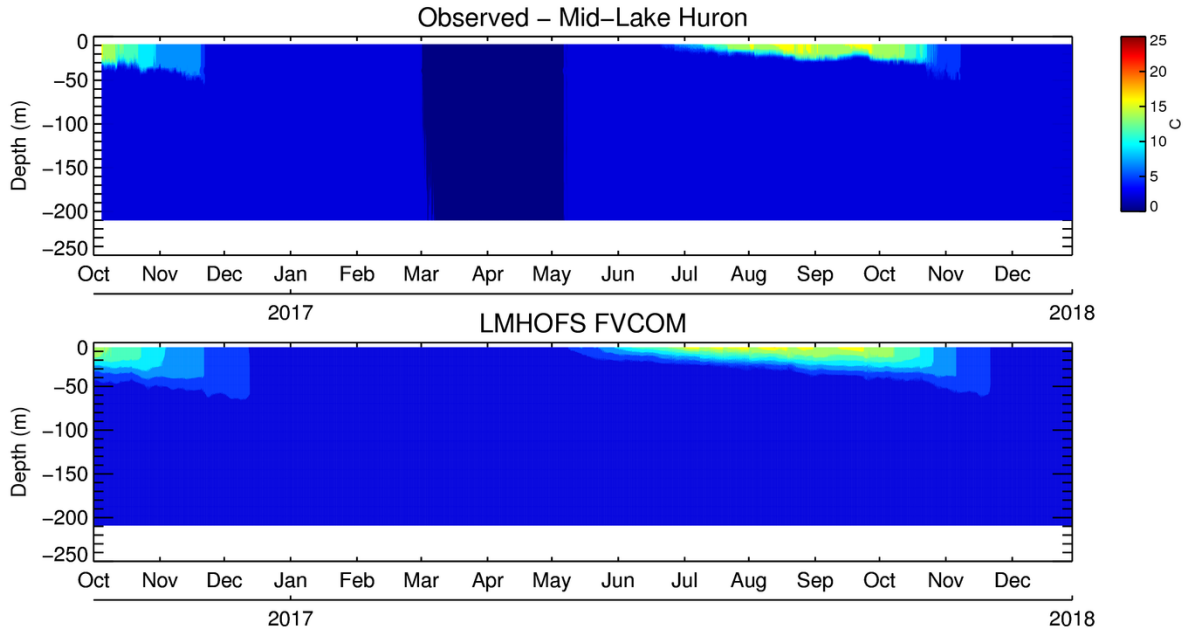

Figure 33. Observed and modeled sub-surface water temperatures in mid Lake Huron for the hindcast period 2016-2017.

Table 42. Summary of skill assessment statistics of the hourly LMHOFS hindcasts of sub-surface water temperatures at GLERL thermistor stations. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

		Southern Lake Michigan N=19974		Straits of Mackinac N=8247		Mid Lake Huron N=10876	
Time Period	Begin	05/14/2015		06/11/2014		10/4/2016	
	End	08/15/2017		05/21/2015		01/01/2018	
		Depth (m)	RMSE (ºC)	Depth (m)	RMSE (ºC)	Depth (m)	RMSE (ºC)
		12	1.81	4	1.47	16	2.35
		20	2.03	9	1.34	26	2.10
		28	1.68	14	1.43	37	1.92
		36	1.35	19	1.44	48	1.81
		44	1.13	24	1.42	58	1.75
		52	0.98	29	1.27	69	1.56
		60	0.85	35	1.26	80	1.44
		68	0.69			91	1.36
		76	0.54			101	1.31
		84	0.43			112	1.26
		92	0.37			123	1.22
		100	0.35			133	1.19
		108	0.55			155	1.15
		116	0.38			187	1.13
		132	0.31				
		153	0.30				

7. SUMMARY AND DISCUSSION

NOAA/GLERL's water level hindcasts from the FVCOM-based LMHOFS for 2015 and 2016 were compared with observations at NOS NWLON and Canadian Hydrographic Service gauges. Hindcasts of surface water temperatures were compared to observations from NWS/NDBC and ECCC fixed offshore buoys and coastal NWLON gauges. In addition, the 2016 hindcasts (both water level and surface water temperature) were compared to nowcast output from current operational POMGL-based LHOFS and LMOFS. Lastly, in order to evaluate LMHOFS' vertical thermal structure, the sub-surface temperatures hindcasts from 2014 to 2017 were compared to the thermistor chains based temperature observations in three regions of Lake Michigan-Huron.

Water Levels

The hindcasts for 2015 and 2016 performed well overall in predicting hourly water levels including the reproduction of seiches following strong wind events. The MAEs ranged from -6.8 to 6.8 cm and RMSE ranged from 3.4 to 10.2 cm for 2015. The MAEs ranged from -7.1 to 5.9 cm and RMSE ranged from 3.5 to 10.1 cm for year 2016. The greatest MAEs in both years were found at Little Current, while the smallest values were at the southern end of both lakes - Fort Gratiot and Calumet Harbor. The greatest RMSEs in both years was at Green Bay, the southern tip of Green Bay, and Lake Michigan. The skill assessment of LMOFS-POMGL's nowcasts for 2016 also exhibited the smallest MAEs at Calumet Harbor, but the greatest value was at Mackinaw City. The greatest RMSE of LMOFS-POMGL's nowcasts for 2016 was also at Green Bay, and had a value of 12.2 cm. The greatest MAEs of LHOFS-POMGL's nowcasts for 2016 were at Fort Gratiot as well, but the smallest value was at Goderich, ON, Canada. The greatest RMSE of LHOFS-POMGL's nowcasts for 2016 was also at Little Current with a value of 13.0 cm. A comparison of Root Mean Square Errors for LMOFS and LHOFS nowcasts vs. LMHOFS hindcasts by lake basins is given in Table 43. Overall, the RMSE values are smaller for LMHOFS hindcasts than for LMOFS or LHOFS nowcasts in all basins, except in Southern Lake Michigan.

Table 43. Comparisons of Root Mean Square Errors for LMOFS and LHOFS nowcasts vs. LMHOFS hindcasts by lake basins.

Water Area	Statistic	LMHOFS	LMOFS or LHOFS
Lake Huron-Georgian Bay	RMSE (m)	0.054 ~ 0.089	0.084 ~ 0.130
Lake Huron - Main	RMSE (m)	0.035 ~ 0.088	0.041 ~ 0.094
Northern Lake Michigan	RMSE (m)	0.054 ~ 0.101	0.052 ~ 0.122
Southern Lake Michigan	RMSE (m)	0.067 ~ 0.088	0.056 ~ 0.074

The hourly hindcasts passed the NOS acceptance criteria at 22 of the 23 NOS and CHS gauges and came very close to passing the CF at the Green Bay station of Lake Michigan. The hindcasts

of both 2015 and 2016 tended to over predict the water level at Lake Huron Georgian Bay region. The hindcasts made over predictions in most northern parts and under predictions in the rest of Lake Huron proper. The hindcasts of both years under predicted most of Lake Michigan, except for Port Inland and Mackinaw.

In examining the amplitude of extreme high or low water level events, the hindcasts under-predicted the amplitude of extreme high water level events in both years except at Lake Huron Georgian Bay region in 2015. The minimum MAE value was -22 cm for both years; it occurred in northern Lake Michigan in 2015, and in southern Michigan in 2016. The maximum MAE was 1.2 cm in year 2015, and was 2.4 cm in year 2016. The RMSEs ranged from 2 to 23 cm for year 2015 and from 3 to 23 cm in year 2016. For extreme low water level events, the hindcasts over predicted the amplitude at 26 of the 28 gauges for both years. The two under predicted stations were CO-OPS NWLON stations Essexville and Fort Gratiot. They both are located in southern Lake Huron region. Except for these two stations, the MAEs ranged from 1 to 14 cm, and RMSEs ranged from 3 to 18 cm for year 2015; and the MAEs ranged from 1 cm to 15 cm, and RMSEs ranged from 2 to 16 cm for year 2016. The minimum MAE was -5.2 cm for year 2015 and was -8.5 for year 2016.

With regards to timing of high water levels of 2015, the MAEs ranged from -1.0 to 0.6 hours and the RMSEs were from 0. to 1.6 hours. For low water level events in 2015, the MAEs ranged from -1.0 to 1.0 hours and the RMSEs were from 0.5 to 1.7 hours. The MAEs of timing of high water levels of 2016 ranged from -2.0 to 0.8 hours, and the RMSEs were from 0.7 to 2.0 hours. For low water level events in 2016, the MAEs ranged from -0.6 to 0.8 hours and the RMSEs were from 0.7 to 1.4 hours. There were quite a few stations at which the MAEs of timing for high or low water level events were zeros. The best case for predicting the timing of extreme water level events happened at De Tour Village in 2015. Both MAE and RMSE of timing at this station for high water level events were zeros.

The 2015 hindcast of high water level events in terms of amplitude passed the acceptance criteria at three out of four stations in the Georgian Bay region, four out of seven stations in Lake Huron region, and three out of five stations in northern Michigan region. The 2016 hindcasts of high water level events in terms of amplitude was similar to those in 2015 except one additional station in southern Michigan region. With regards to timing of high water levels for 2015, all four stations in the Georgian Bay region, four out of seven stations in Lake Huron region, two out of four stations in southern Michigan passed the acceptance criteria. The ratio of stations that pass the timing acceptance criteria for the 2016 hindcasts of high water level events was about the same as year 2015, except one fewer station in the Georgian region and one more station in northern Lake Michigan region.

For low water level events, the 2015 hindcast passed the amplitude acceptance criteria at all three stations in southern Lake Michigan region, three out of six stations in northern Lake Michigan region, and six out of eight stations at Lake Huron proper. However, all failed in Georgian Bay region. The same year hindcast passed the time acceptance criteria at two out of three stations in southern Lake Michigan region, two out of six stations in northern Lake Michigan region, two out of eight stations at Lake Huron, and one out of four stations at Georgian Bay. For the 2016

hindcasts, twelve out of twenty-one stations passed the amplitude acceptance criteria; eight out of twenty-one stations passed the timing acceptance criteria for low water level events. The results were quite similar to those of 2015.

Compared with the 2016 hindcast, the LMOFS and LHOFS nowcasts demonstrated less favorable skill of predicting the amplitude and timing of extreme water level events. For high water level events, the nowcasts (LHOFS and LMOFS together) passed the amplitude and timing acceptance criteria only at three out of fourteen stations, and five out of twenty-one stations for low water level events. The results showed adequate improvements that the new LMHOFS made both for hourly and for extreme events forecasts.

Surface Water Temperatures

The surface water temperature hindcasts agreed closely with observations at the NOS NWLON stations, NDBC, and ECCC's fixed offshore buoys in both 2015 and 2016.

The MAEs varied by region. In Lake Huron's Georgian Bay region, LMHOFS was generally 0.25 to 0.5 ºC cooler than the observations, especially in North Channel. The MAEs in Georgian Bay ranged from -0.5 to -0.3 ºC and the RMSEs ranged from 1.2 to 1.8 ºC at Georgian Bay region for year 2015. The MAEs were from -0.5 to 0.02 ºC and the RMSEs were between 1.5 to 1.7 ºC for year 2016. The MAEs ranged from -1.7 to 0.9 ºC at northern Huron proper, with the RMSEs ranging from 1.5 to 3.8 ºC for year 2015. In 2016 the MAEs were between -1.7 to 1.2 ºC and the RMSEs ranged from 1.4 to 4.6 ºC. At this region, the model was generally 0.5 to 1 ºC warmer than observations, except at Thunder Bay where it was 1.7 ºC cooler than the observations. The MAEs varied from -1.5 to 0.4 ºC and the RMSEs were between 1.3 and 2.3 ºC at southern Huron region for year 2015. The MAEs were between -1.0 and 0.7 ºC, with the RMSEs ranging from 0.6 to 1.4 ºC in 2016. The model was within ± 0.5 ºC of observations in the main stem and Saginaw Bay; however, it was 1.0 to 1.5 ºC cooler along the coast at Harbor Beach in southern Lake Huron.

LMHOFS hindcasts were cooler than observations primarily in the northern section of Lake Michigan and right along the SW coast (near Chicago). The hindcast at Little Traverse Bay Buoy was much cooler than those at the other stations; the MAE was as low as -2.9 ºC. The most accurate predictions were made at the South Green Bay buoy; the hindcasts were very close to the observations for both years (within 0.1 ºC). Overall, the model captured the rapidly changing, high amplitude temperature fluctuations along the west and east coasts of lake. The MAEs at northern Lake Michigan region ranged from -3 to 0.1 ºC for both years. The RMSEs ranged from 1.1 to 3 ºC in 2015 and 1.2 and 3.4 ºC in 2016. In the central Lake Michigan region, the MAEs ranged from -0.7 to 0.2 ºC, and RMSEs were from 2 to 2.3 ºC in 2015; the MAEs ranged from -0.3 to 0.9 ºC, and RMSEs were between 1.4 and 2.1 ºC in 2016. In southern Lake Michigan region, the MAEs ranged from -2.2 to 0.0 ºC, and the RMSEs were from 1 to 2.8 ºC in 2015; In 2016, the MAEs and RMSEs ranged from -2.0 to 1.7 ºC, and 1.3 to 3.1 ºC, respectively.

Compared with current operational LMOFS and LHOFS, the surface water temperature hindcasts from LMHOFS were more accurate, and had fewer unrealistic high frequency fluctuations (Table 44). A good example is the temperature hindcast and nowcast comparisons at Mackinaw City station. All three models had surface water temperature output at this CO-OPS NWLON station. The MAE of LMHOFS hindcast was -0.31 ºC, the RMSE was 1.4 ºC, while the MAE and RMSE of LMOFS were 3.3 and 3.7 ºC, and the MAE and RMSE of LHOFS at this station were 0.9 and 2.3 ºC, respectively. The improvements of water temperature hindcasts was the result of incorporating surface heat and radiation fluxes.

Table 44. Comparisons of Root Mean Square Errors for LMOFS and LHOFS nowcasts vs. LMHOFS hindcasts by lake basins.

Water Area	Statistic	LMHOFS	LMOFS or LHOFS
Lake Huron-Georgian Bay	RMSE (ºC)	1.48 ~ 1.70	N/A
Northern Lake Huron	RMSE (ºC)	1.44 ~ 4.58	2.87 ~ 3.01
Southern Lake Huron	RMSE (ºC)	0.63 ~ 1.42	2.11 ~ 3.26
Northern Lake Michigan	RMSE (ºC)	1.23 ~ 3.41	2.30 ~ 3.73
Central Lake Michigan	RMSE (ºC)	1.40 ~ 2.05	3.78
Southern Lake Michigan	RMSE (ºC)	1.31 ~ 3.12	2.39

The hindcasts passed all the NOS acceptance criteria only at around half of NWLON and buoy stations in both years. The nowcasts from LMOFS and LHOFS both failed the NOS acceptance criteria of temperature at all available stations. A lake-ice model might make more accurate surface temperature forecasts during wintertime.

Subsurface Water Temperatures

The hindcasts of sub-surface water temperature at all the three locations passed the NOS acceptance criteria. In general, the RMSEs decreased with increasing depth, except in southern Lake Michigan where the maximum RMSE was found to be 2.03 ºC at 20 m depth, and in Straits of Mackinac where the RMSE at 9 m was 1.34 ºC, which is slightly smaller than 1.47 ºC at 4 m and 1.43 ºC at 14 m. The highest RMSEs at three locations occur near a depth of 20 m approximately. In southern Lake Michigan, the RMSEs were less than 1.0 ºC when depth was deeper than 52m, and were almost all below 2 ºC between 4 m and 44 m (except at 20 m). In the mid part of Lake Huron, all RMSEs below 37 m were under 2 ºC, and the two maxima RMSEs were 2.35 ºC at 16 m depth and 2.10 ºC at 26 m. In the much shallower Straits of Mackinac, the RMSEs ranged from 1.26 ºC (35 m) to 1.47 ºC (near the surface at 4 m). In all cases, the modeled thermal structure captured the seasonal variation and summer stratification although its thermocline was somewhat diffuse, which is common for previous hydrodynamic models in this region.

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