NOAA Technical Memorandum NOS CS 56

UPGRADE OF NOS LAKE ONTARIO OPERATIONAL FORECAST SYSTEM TO FVCOM: MODEL DEVELOPMENT AND HINDCAST SKILL ASSESSMENT

Silver Spring, Maryland
April 2023

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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noaa **National Oceanic and Atmospheric Administration**

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LIST OF ACRONYMS

AGL	Above Ground Level
ASOS	Automated Surface Observing System
AWOS	Automated Weather Observing System
CHS	Canadian Hydrographic Service
CICE	Los Alamos Community Ice Code (Sea Ice) Model
CMMB	Coastal Marine Modeling Branch
C-MAN	Coastal-Marine Automated Network
COARE	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
LSOFS	Lake Superior Operational Forecast System
LOOFS	Lake Ontario Operational Forecast System
NAM	North American 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 Ontario Operational Forecast System (LOOFS) is a 3-D lake numerical forecast modeling system which uses near real-time atmospheric analyses, river observations, and numerical weather prediction model forecast guidance to generate hourly nowcasts and short-range forecast guidance of 3-D water temperatures and currents and two-dimensional water levels for Lake Ontario. The present operational LOOFS uses the Great Lakes version of the Princeton Ocean Model (POMGL) as its core numerical oceanographic forecast model with a horizontal resolution of 5 km (3.1 mi) and 21 vertical sigma levels out to 60 hours.

A new version of LOOFS has been developed using the Finite Volume Community Ocean Model (FVCOM) with a horizontal resolution ranging from approximately 200 m (0.2 mi) near the shore to about 2.5 km (1.6 mi) offshore and with 21 vertical sigma levels with an integrated, unstructured version of the Los Alamos Community Ice CodE (UG-CICE). The upgrade of LOOFS is a 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. The forecast systems for Lakes Erie, Huron, and Michigan have already been upgraded to FVCOM.

The accuracy of predictions of an upgraded LOOFS are evaluated by comparisons to observations in two NOS skill assessment scenarios: 1) hindcasts and 2) the semi-operational nowcast and forecast guidance. This report describes the results of the hindcast skill assessment. A similar skill report of the semi-operational nowcasts and forecast guidance is being prepared by NOS/CO-OPS.

The hindcasts were conducted by GLERL for 2017, 2018, and 2019 using FVCOM Version 4.3.1 with the UG-CICE model turned on and the COARE Version 2.6 bulk flux algorithm. In the UG-CICE, five categories of ice thickness were defined: 5, 25, 65, 125, and 205 cm along with a sea-ice floe diameter of 300 m.

In order to simulate the lake level, LOOFS takes into account over-lake precipitation, over-lake evaporation, inflow from tributaries, and inflow and outflow of connecting channels. First, the inflows and outflows were estimated through near-real-time discharge observations from five United States Geological Survey (USGS) and two Environment and Climate Change Canada (ECCC) river gauges. Second, the observed water level change over the previous five days at eight NOS CO-OPS and ECCC gauges 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.

For the temperature of waters flowing into the lake, the water temperatures were specified at eight river locations: Don River, Humber River, Niagara River, Genesee River, Oswego River, Salmon River, Black River, and St. Lawrence River (outflow) based on observed surface water temperatures at three USGS and NOS gauges.

Surface meteorological forcing for the LOOFS hindcasts were provided by 2-hr or 1-hr forecast guidance from the hourly forecast cycles of the NOAA's High-Resolution Rapid Refresh (HRRR) analysis and forecast modeling system. The +2 hour forecast projection of every HRRR Version 2 hourly forecast cycle was used for forcing the hindcasts from Jan. 1, 2017 to July 11, 2018 and +1 hour forecast projection of every HRRR Version 3 hourly forecast cycle was used for July 12, 2018 to Dec. 31, 2019 (HRRR version update: https://rapidrefresh.noaa.gov/hrrr/). The specific HRRR meteorological variables used to force the COARE algorithm were the following: surface air temperature (2 m Above Ground Level [AGL]), surface relative humidity (2 m AGL), surface wind velocity (10 m AGL), mean sea level pressure, downward short-wave radiation, and downward long-wave radiation. HRRR has a horizontal resolution of 3 km (1.86 miles).

The hindcasts of water levels and surface water temperatures for the three hindcast years were compared to in-situ observations in Lake Ontario. Specifically, the water level hindcasts were compared to observational data recorded at NOS and Canadian Hydrographic Service (CHS) gauges. Water temperature hindcasts were evaluated against observations at four fixed buoys operated by the National Weather Service (NWS)' National Data Buoy Center (NDBC) or ECCC. In addition, the hindcasts were compared with the performance of the nowcasts from the present POMGL-based LOOFS. Unfortunately, there were no sub-surface water temperature or currents observations for comparison to the hindcasts and nowcasts.

Overall, the hindcasts of water levels demonstrated good skill for simulating hourly water levels during the hindcast years. The hindcasts passed the majority of NOS Standard acceptance Criteria (Zhang et al., 2013) at all the U.S. and Canadian gauges. The average Mean Algebraic Error (bias) for hindcasts over the three years among the eight gauges averaged approximately -2.75 cm with the greatest RMSEs found at the western and eastern ends of the lake. Similar to the nowcasts, the hindcasts also underpredicted the hourly water levels, but did so by 1.2 cm more than the nowcasts. The RMSE for the hindcasts was 1 cm greater than for the nowcasts.

The hindcasts of water temperatures closely matched the observations at the open lake and nearshore buoys, capturing both the seasonal trend, sudden cooling and warming events, and simulated much better than the nowcasts especially during the spring warmup and autumn cool down periods. The average bias for the hindcasts was about 0.5 ℃ with an average RMSE of 1.5 ℃. The bias was about 0.4 ℃ lower than for the nowcasts and the RMSE was 1.4 ℃ lower.

The FVCOM based LOOFS is anticipated to become operational on NOAA's new Cray Shasta System, referred to as the Weather and Climate Operational Supercomputing II (WCOSS2) during late Summer 2022 or early Autumn 2022, along with the upgraded Lake Superior Operational Forecast System (LSOFS).

1. INTRODUCTION

NOS' Great Lakes Operational Forecast System (GLOFS) provides 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 (Chu et al., 2011). GLOFS predictions are used by commercial and recreational mariners, NWS weather and 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 Erie, Michigan, Ontario, and Huron was 5 km (3.1 mi) and was 10 km (6.2 mi) for Lake Superior. The number of vertical sigma levels was 21 for each of the five lakes. GLOFS has four daily nowcast and forecast cycles, which generate forecast guidance out to 60 hours. The nowcast cycles were 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.

Starting in 2013, NOS and NOAA's Great Lakes Environmental Research Laboratory (GLERL) began a collaborative project to develop a new version of GLOFS to provide improved lake predictions and to extend the forecast horizon out to 120 hours. The Finite Volume Community Ocean Model (FVCOM) was selected as the core numerical ocean circulation or hydrodynamic forecast model for the new version due to its unstructured mesh 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 on NOAA's Weather and Climate Operational Supercomputer System (WCOSS). The separate Lake Huron Operational Forecast System (LHOFS) and the Lake Michigan Operational Forecast System (LMOFS) were replaced by the FVCOM-based one-mesh Lake Michigan and Huron Operational Forecast System (LMHOFS) and became operational on WCOSS in July 2019. The remaining GLOFS lake domains to be migrated to FVCOM were the Lake Superior Operational Forecast System (LSOFS) and Lake Ontario Operational Forecast System (LOOFS).

The new version of LOOFS has become operational in early FY23 to generate forecast guidance of water levels, currents, and water temperatures and potentially ice concentration and thickness out to 120 hours. This report documents the development and testing of the upgraded LOOFS using FVCOM as well as the results of a skill assessment of hindcasts for water levels and surface water temperatures during 2017, 2018, and 2019. The skill assessment of the semi-operational nowcasts and forecast guidance will be conducted by CO-OPS and its results will be published in a separate technical report. The results of the planned skill assessment of ice hindcasts of LOOFS and of the other three OFS domains will be presented in a separate report. A brief overview of the physical limnology of Lake Ontario is given first.

2. LAKE ONTARIO

Lake Ontario's name comes from the Iroquois word "kanadario", meaning "sparkling" water (https://www.canada.ca/en/canadian-heritage/services/provincial-territorial-symbols-canada/ontario.html). Lake Ontario is the smallest in surface area and the third deepest of the Great Lakes of North America and the 14th largest lake in the world. Lake Ontario is about 311 km (193 mi) in length and 85 km (53 mi) in width, with a surface area of 18,960 sq. km (7,340 sq mi), a volume of 1,650 cubic km (393 cubic mi), and a shoreline including islands of 1,146 km (712 mi). The mean surface elevation of the lake is about 74 m (283 ft) above sea level. Located downstream of Niagara Falls, Lake Ontario is 99 m (325 ft) below the level of Lake Erie. The mean depth is 86 m (283 ft) with the deepest point at 244 m (802 ft). The water retention time is approximately eight years (Quinn 1992). The primary inlet to the lake is the Niagara River from Lake Erie. The other tributaries flowing in the lake include Genesee River, Oswego River, Salmon River, Black River, Humber River, and Don River. The lake drains into the St. Lawrence River near Kingston, Ontario. The lake is generally free of outlying shoals except for at the northeast end of the lake in the approach to the St. Lawrence River and those of the Niagara Bar off the mouth of the Niagara River (NOS BookletChart Lake Ontario NOAA Chart 14800).

The Moses-Saunders Power Dam on the St. Lawrence Seaway regulates the water level of the lake. The water level of the lake fluctuates within a year due to seasonal precipitation changes and also across years due to interannual variation in precipitation and evaporation. The lake experiences seiches as the other Great Lakes. However, the longitudinal seiches in Lake Ontario have a period of approximately 6 hours and rarely exceed 0.5 m in amplitude (Boyce et 1989) compared to up to 6 m in Lake Erie.

Thermal stratification in Lake Ontario usually occurs in late June and lasts through October when fall overturn occurs. During the rest of the year, the lake is typically nearly homogenous throughout the entire water column, with very little ice cover in the winter in offshore regions. The average surface water temperatures range from 23 ℃ in August to between 0 ℃ and 4 ℃ during January to March. During the summer, the prevailing southwesterly winds down the long axis of the lake frequently result in upwelling on the north shore and downwelling on the south shore with the transition occurring on the ends of the lake (Boyce et al., 1989). When the winds weaken, this unbalanced state relaxes through internal Kelvin waves which propagate alongshore in a counter-clockwise direction a few kilometers from the coast (Boyce et al, 1989).

The principal ports on Lake Ontario are at Oswego, NY, Rochester, NY, Hamilton, ON, and Toronto, ON. Other ports include Port Credit, ON; Picton, ON; Bath, ON. There are four navigational canals: Welland Canal, New York State Barge Canal, Trent Canal, and Rideau Canal. The Welland Canal bypasses the falls of the Niagara River and provides a navigable connection between the lake and the upper lakes.

There are four nuclear generating power stations on Lake Ontario: Nine Mile Point Nuclear Facility in Oswego County, NY; Robert E. Ginna Nuclear Power Plant in Wayne County, NY; Pickering Nuclear Generating Station in Pickering, Ontario; and Darlington Nuclear Generating Station in Clarington, Ontario.

Lake Ontario provides drinking water to over 9 million residents in the Province of Ontario, Canada and the State of New York. The U.S. Environmental Protection Agency (EPA) in their 2017 State of the Great Lakes report (https://binational.net/2017/06/19/sogl-edgl-2017/) indicates that the overall health of Lake Ontario is fair and unchanging.

3. MODEL SYSTEM AND SETUP FOR HINDCASTS

This section provides descriptions of the three-dimensional hydrodynamic (ocean circulation) numerical forecast model, the mesh configuration, and how the lateral boundary, surface boundary, and initial conditions were specified for the LOOFS hindcast runs. The configurations for LOOFS, when it is run operationally on WCOSS2, will be different in terms of surface meteorological forcing and lateral boundary conditions for water temperatures and water levels due to operational decisions made by NOS/CO-OPS personnel.

3.1. Description of Model

FVCOM is a prognostic, unstructured-mesh, finite-volume, free-surface, three-dimensional primitive equation coastal ocean circulation 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, water temperature, salinity, and density equations and is closed physically and mathematically using turbulence closure sub-models. The horizontal mesh is comprised of unstructured triangular cells with a generalized terrain-following vertical coordinate system. Several different turbulent closure schemes (TCS) are available in FVCOM. For LOOFS, 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 mesh. 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. The free surface, defined as the external mode, is integrated by solving vertically averaged equations with a smaller time step, while 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., 2013). FVCOM has been successfully applied in several coastal ocean regions to simulate oceanographic conditions. FVCOM is used by the NOS' Northern Gulf of Mexico Operational Forecast System (Wei et al., 2014; Wei et al., 2015; Zhang et al., 2022), LEOFS (Kelley et al, 2018), LMHOFS (Kelley et al, 2020, Peng et al., 2019), and the San Francisco Operational Forecast System (Schmalz, 2014).

An unstructured mesh version of the Los Alamos Community Ice CodE (UG-CICE; Hunke et al., 2010; Fujisaki- Manome, 2020) has been included and coupled within FVCOM (Gao et al, 2011; Anderson et al., 2018). CICE is governed by energy-conserving thermodynamics equations with four layers of ice and one layer of snow in each of the five ice categories, elastic-viscous-plastic ice momentum equations and energy-based ridging schemes, and ice strength parameterizations (Gao et al., 2011). Specifically, the CICE model includes components for ice thermodynamics and ice dynamics, using elastic-viscous-plastic rheology (deformation and flow matter) for internal stress, and produces two-dimensional fields of ice concentration, thickness, and velocity. A multi-category ice thickness distribution (ITD) model is employed in CICE to resolve mechanical deformation as well as growth and decay. CICE allows the specification of several categories of ice thickness. The ice surface albedo depends on surface temperature and thickness of ice, as well as the visible and infrared spectral bands of the incoming solar radiation.

At ice-covered cells, the net momentum transfer is calculated as a weighted average of the air-water and ice-water stresses by areal fraction of ice. The air-ice drag coefficient CD_ai is a function of wind speed U, given as CD_ai = $(1.43 + 0.052U) \times 10^{-3}$ and the ice-water drag coefficient is 5.5×10^{-3} (Anderson et al., 2018). Similarly, the net heat transfer is calculated as a weighted average of the air-water and ice-water heat fluxes (Anderson et al., 2018). The ice-water heat fluxes are calculated based on the bulk transfer formula (BTF). BTF are linear equations relating surface latent and sensible heat fluxes to corresponding humidity or temperature gradients multiplied by empirical wind speed. Size diameter of an average sea-ice floe, which is a cohesive sheet of ice floating in water, can be set depending on the water body.

The FVCOM-CICE has two options for heat flux calculations. The first option is the SOLAR flux algorithm. The SOLAR algorithm was developed at the NOAA Great Lakes Environmental Research Laboratory (GLERL) for application to the Great Lakes with a few modifications by researchers at The Ohio State University. It solves standard bulk flux expressions for latent and sensible heat based on Monin-Obukhov Similarity Theory (Foken, 2006; Kantha and Clayson, 2004). SOLAR served as the flux algorithm for the POMGL-based implementation of GLOFS. The second option is the Coupled Ocean Atmosphere Response Experiment (COARE) Bulk Air Sea Flux algorithm (Fairall et al., 2003). A freshwater parameterization of COARE is included in FVCOM starting with Version 4.0. It uses Monin-Obukhov Similarity Theory with minor differences in stability functions relative to the SOLAR algorithm (Gronewold et al., 2019). The FVCOM-based LEOFS uses the SOLAR algorithm, while the FVCOM-based LMHOFS and LSOFS use the COARE algorithm.

For LOOFS, FVCOM Version 4.3.1 and the COARE Version 2.6 bulk flux algorithm were used for the LOOFS hindcast runs. CICE was turned on and five categories of ice thickness were defined (5, 25, 65, 125, and 205 cm) along with a sea-ice floe diameter of 300 m.

3.2. Mesh Configuration

An unstructured model mesh was generated for LOOFS by GLERL personnel using the Surface-Water-Modeling System (SMS) software. The mesh size distribution is configured to be dependent on the GLERL bathymetry (NOAA/NCEI, 3 arc-second). The model bathymetry was obtained by interpolating the GLERL digital bathymetry onto each unstructured FVCOM model mesh node, referenced to the Low Water Datum (LWD) (chart datum) for Lake Ontario, which is 74.2 m (243.3 ft) 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 mesh in the horizontal is composed of 64,453 triangular elements and 34,395 nodes. The resolution varies from approximately 200 m (0.2 mi) near the shore to about 2.5 km (1.6 mi) offshore. The mesh is depicted in Fig. 2. The model has 21 uniform sigma levels with distribution referenced to the Great Lakes low water datum for Lake Ontario. 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.

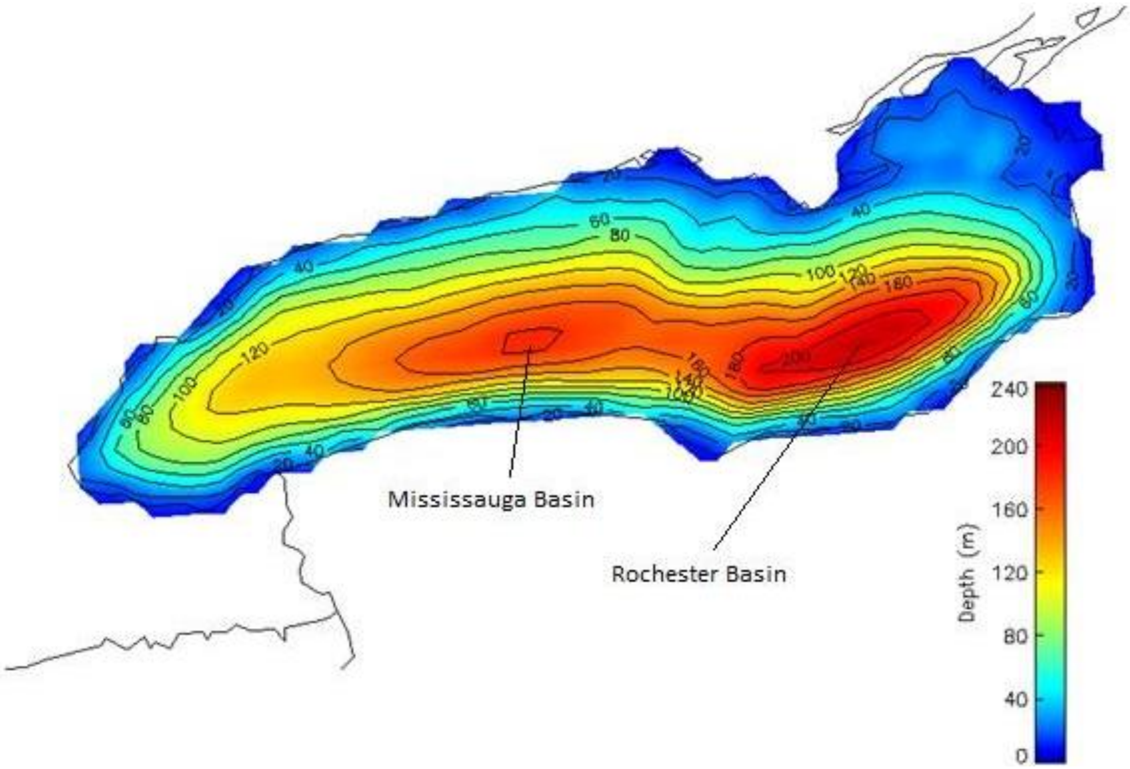

Figure 1. Map of the Lake Ontario bathymetry (m) used by LOOFS, referenced to Low Water Datum (LWD) of 74.2 m (243.3 ft) above IGLD of 1985. The average depth is 86 m (283 ft) and the maximum depth is 244 m (802 ft).

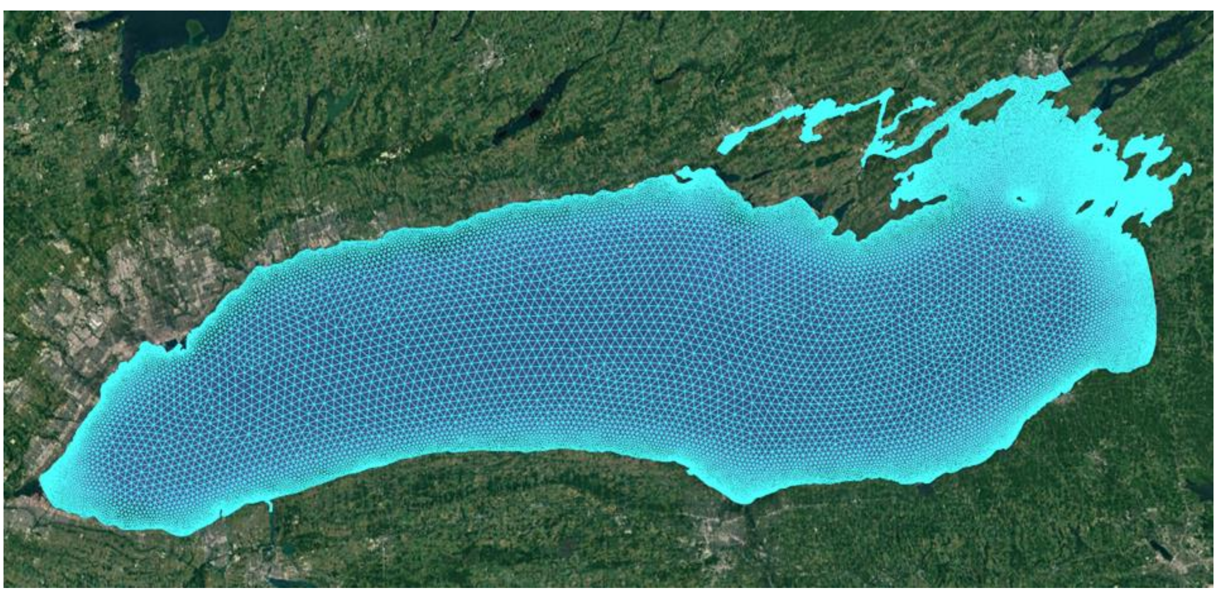

Figure 2. Map depicting the FVCOM mesh domain for LOOFS. The horizontal resolution ranges from around 200 m (0.12 mi) near the shore to approximately 2.5 km (1.6 mi) offshore with 21 vertical sigma levels.

3.3. Lateral Boundary Conditions

The lateral boundary conditions (LBCs) for the hindcasts were prescribed for water temperatures and inflows/outflows. Since over-lake precipitation, over-lake evaporation and inflow from tributaries and inflow and outflow of connecting channels are of the same order of magnitude for Lake Ontario, the sum of these components must be estimated for LOOFS to track low-frequency changes (e.g., seasonal hydrology) in lake levels.

The components were estimated in the following equation

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

where dV = change in lake volume, and Q = discharge.

$Q_{\text{St. Lawrence River}}$ outflow is estimated using near-real-time discharge observations from the USGS gauge, *St. Lawrence River Near Brockville Ontario Canada* (Station ID 04260901, this station is managed by the NY Water Science Center Potsdam).

The estimation of $Q_{\text{Tributaries}}$, the inflow from other tributaries is determined from near-real-time (and long-term daily climatological when near-real-time data is not available) discharge observations from both the U.S. Geological Survey (USGS) and Environment and Climate Change Canada (ECCC) gauges. The five USGS gauges are *Niagara River at Fort Niagara, NY (0421964005)*, *Genesee River at Ford Street Bridge, Rochester NY (04231600)*, *Oswego River at Lock 7, Oswego NY (04249000)*, *Salmon River at Pineville, NY (04250200)*, and *Black River at Watertown, NY (04260500)*. The two ECCC gauges are *Don River at Todmorden, ON (02HC024)* and *Humber River at Weston, ON (02HC003)*.

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, over-lake precipitation and evaporation, and error terms are represented in the term, Q_{Residual}. The Q_{Residual} is added to FVCOM using its formulation for mass addition/subtraction via the precipitation/evaporation forcing file, *casename_pre_evap.nc*.

The dV/dt is calculated by multiplying the lake surface area by the average observed water level change over the previous five days at the following eight 'Master' Water Level Gauges: 1) *St. Lawrence River*, 2) *Black River*, 3) *Salmon River*, 4) *Oswego River*, 5) *Genesee River*, 6) *Niagara River*, 7) *Humber River*, and 8) *Don River*. 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, five days end up being the best balance of these two objectives. The prescribed inflows and outflows are depicted in Figure 3.

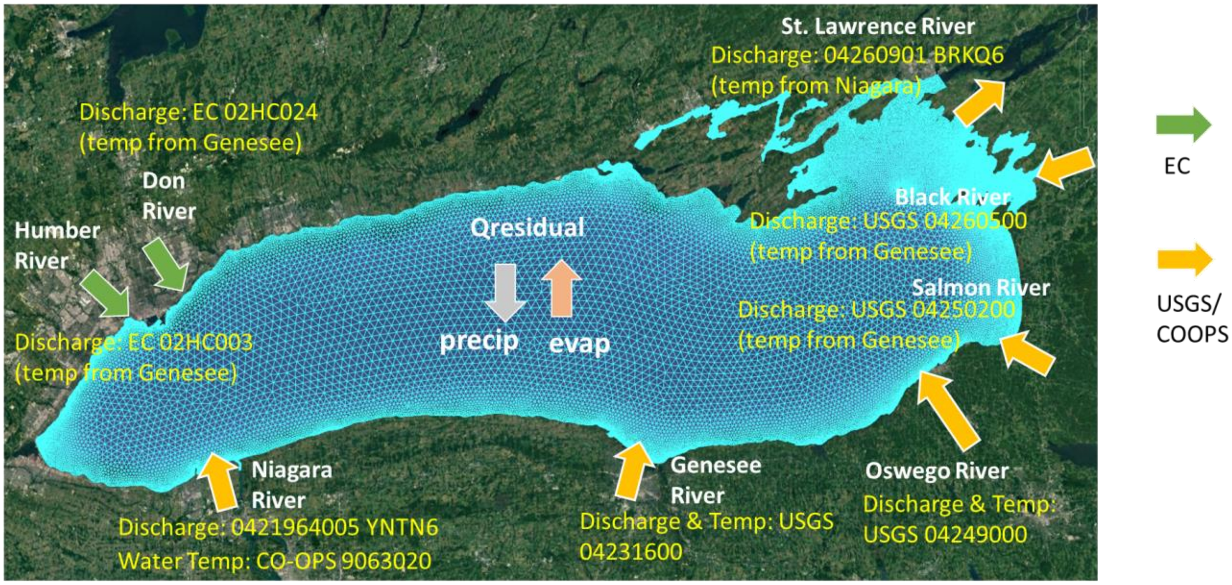

Figure 3. River and interconnecting channels boundary conditions and locations where surface water temperatures are specified for LOOFS.

The temperature of waters flowing into Lake Ontario were specified for eight rivers (Fig. 3). The water temperature for the Genesee River is based on the observation at the USGS gauge 04231600 in the river. The temperatures of water flowing into the lake from the Don, Humber, Black, and Salmon Rivers are specified using water temperature observations at the Genesee River USGS gauge. This approach was taken since there were no near-real-time water temperature observations available in these rivers when FVCOM was applied and tested by GLERL. The water temperature for the Niagara River is based on the observation at the NOS gauge 9063020 in the river. The water temperature for St. Lawrence River is specified using the temperature at the Niagara River NOS gauge because at the time of development there was no near-real-time observation available in the St. Lawrence River. The temperature from the Niagara River was used as a proxy since it is also a large river. The temperature prescribed at the outflow is not critical for FVCOM; it does not impact the elements or nodes at the prescribed outflow location. The water temperature for the Oswego River is based on the observation at the USGS Gauge 04249000 in the river. The water temperatures for these locations are specified in the *casename_river.nc* file.

3.4. Surface Boundary Forcing

The surface meteorological forcing used by LOOFS to generate the hindcasts was supplied by very-short range forecast guidance from the hourly forecast cycles of the NOAA's High-Resolution Rapid Refresh (HRRR) System. HRRR is a 3-D numerical weather prediction analysis and forecast modeling system (Benjamin et al., 2016). HRRR provides analyses and forecast guidance at a horizontal resolution of 3 km (1.86 mi) out to 48 hours every 6 hours. The

HRRR variables used as input to the COARE algorithm 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) u- and v-wind components (~10 m AGL), 5) downward short-wave radiation, and 6) downward long-wave radiation. All variables were obtained from the 2-hr forecast of the HRRR. The HRRR v2/v3 analyses (0-hr) and the 1-hr forecast were not used because of artificially sharp gradients, artifacts from the HRRR's assimilation system (Stan Benjamin, personal communication).

The +2 hour forecast projection output from HRRR Version 2 was used for forcing the hindcasts from Jan. 1, 2017 to July 11, 2018 and the +1 hour forecast projection output from HRRR Version 3 was used for July 12, 2018 to Dec. 31, 2018 and 2019. 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 and provided to GLERL researchers. The latent and sensible heat fluxes were calculated from several of the meteorological variables using the freshwater version of the COARE Version 2.6 algorithm of FVCOM (HEATING_CALCULATED_GL).

3.5. Initial Conditions

LOOFS required three-dimensional initial conditions including surface elevation field and three-dimensional velocity and water temperature fields at the beginning of the hindcasts. A one-year spin up was started on January 1, 2016 to provide initial conditions for the start of the hindcast period on January 1, 2017. The model was initialized on January 1, 2016 with surface water temperatures derived from NOAA Advanced Very High-Resolution Radiometer (AVHRR) imagery obtained through the Great Lakes CoastWatch program and prescribed from the NOAA Great Lakes Surface Environmental Analysis (GLSEA). The GLSEA is valid at an approximate depth of 10 µm or 1×10^{-6} m (Songzhi Liu, Personal Communication). Sub-surface water temperatures below 10 m (32.8 ft) were set to a uniform water temperature of 2 ℃ (36 ℉). The water level was specified at 0.0 m elevation (relative to LWD) and the water currents were set to 0 m/s. 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 (spin-up) was used as the initial conditions for the start of the hindcasts. Details on the hindcast period are given in the next section.

4. HINDCAST PERIODS

Three hindcast model simulations using the FVCOM-based LOOFS were conducted by GLERL on their Linux cluster in Ann Arbor, MI. Hindcast Period #1 covered from Jan. 1, 2017 to Dec. 31, 2017. Hindcast Period #2 was from Jan. 1, 2018 to Dec. 31, 2018, and hindcast period #3 was from Jan. 1, 2019 to Dec. 31, 2019. Hindcast Periods #2 and #3 were restarted (hot-started) from the end of the previous hindcast simulation. The series of three simulations thus serves as a continuous 3-year simulation without reinitialization or data assimilation.

4.1 Description of Hindcast Periods

Monthly water levels during 2017, 2018, and 2019 in Lake Ontario were above the long-term average as indicated in Figure 4. Due to the significant flooding and erosion along the lakeshore in 2017 and 2019, the State of New York spent $400 million on flood relief projects on the NY lakeshore to protect against rising waters, including the construction during 2021 of a $14 million break wall to protect the City of Olcott, NY (https://buffalonews.com/news/local/a-new-risk-on-lake-ontario-falling-water-levels/article_1fc09ffc-9c7c-11eb-b51e-b3f613da32d6.html).

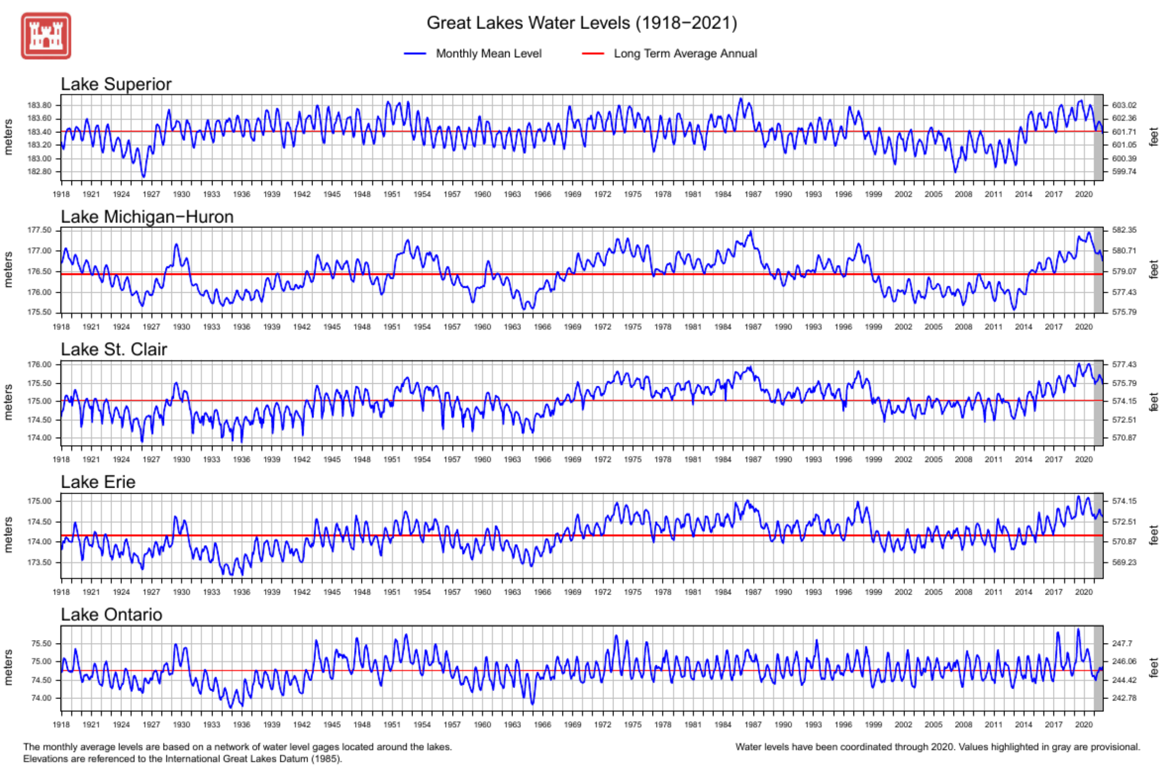

Figure 4. Time series of monthly mean lake-wide water levels for each of the Great Lakes from 1918 to 2021. Source: https://www.lre.usace.army.mil/Missions/Great-Lakes-Information/Great-Lakes-Information-2/Water-Level-Data/).

The annual maximum ice cover for Lake Ontario for the three hindcast years was about 5% for 2017, 25% for 2018, and 40% for 2019 (Fig. 5). The dates of maximum ice cover were March 16, January 17, and March 1 for the years 2017, 2018, and 2019, respectively (https://www.glerl.noaa.gov/data/ice/glicd/dates_AMIC.txt).

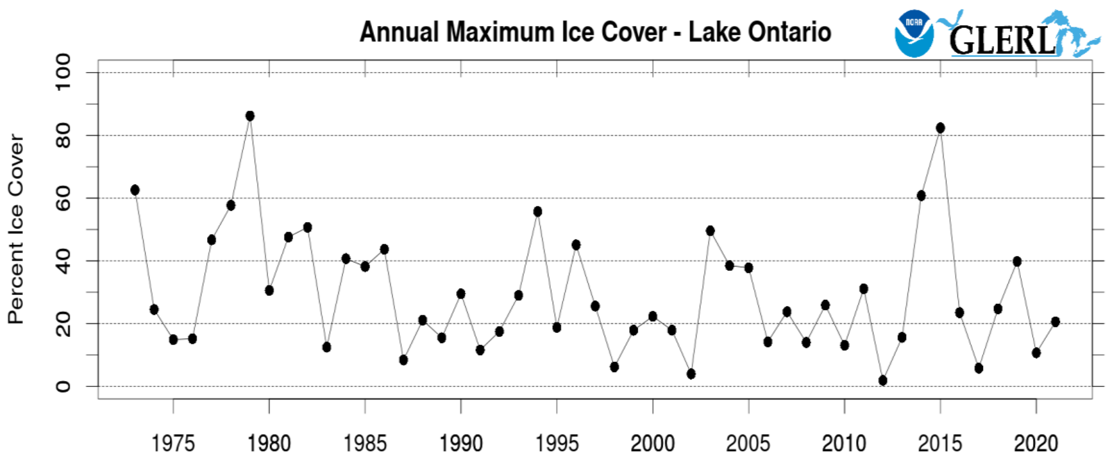

Figure 5. Annual Maximum Ice Cover for Lake Ontario from 1973 to 2021 (Source: https://www.glerl.noaa.gov/data/ice/glicd/AMIC/Ontario.png).

5. METHOD OF EVALUATION

FVCOM-based LOOFS hourly hindcasts of water levels and water temperatures for 2017, 2018 and 2019 were verified against hourly observations from observing platforms in Lake Ontario. In addition, the hourly hindcasts of water level and water temperature were compared with hourly nowcasts from the operational POMGL-based LOOFS at locations, when and where hindcasts were also available.

5.1 Acquisition of Hindcasts and Nowcasts at Verification Locations

Following the completion of the hindcasts, the hourly values of water levels at nearest mesh points to NOS and CHS gauges were extracted and written to netCDF files. Similarly, hourly values of the water surface (sigma layer 0) temperatures at NWS/NDBC and ECCC buoys were written to netCDF files.

Nowcasts during hindcast years were obtained from the NOS/CO-OPS archives of the netCDF ‘station files’ generated by the operational POMGL-based LOOFS. Nowcasts were not available at all the gauges and buoys during the hindcast years.

5.2 Skill Assessment Statistics

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) or bias, 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; Zhang et al., 2013).

The calculation of the target frequency of 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 implemented operationally at NOS, were employed in evaluating these hindcasts (see last row in Table 1). These specific values for the water level and temperature skill assessments will be discussed in later sections.

The standard skill assessment code has a coarse quality assurance (QA) function that is applied to all downloaded 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 subroutine calculates average and standard deviation (SD) 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 set prior to running the skill assessment program.

Extreme high or low water events were selected from the observed data and hindcasts using the equations h_{upper} = mean + factor × SD and h_{lower} = 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 criteria include target frequencies for CF, NOF, and POF and limits on the duration of errors (i.e., maximum duration between 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 Criteria (targets) used to evaluate LOOFS hindcasts.

Statistic	Units	Description	NOS Acceptance Criterion
Mean Algebraic Error (MAE) or Bias	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 ±X.	≥ 90%
POF(X)	%	Positive Outlier Frequency. Fraction (percentage) of errors that are greater than X.	POF(2X) ≤ 1%
NOF(X)	%	Negative Outlier Frequency. Fraction (percentage) of errors that are less than -X.	NOF(2X) ≤ 1%
MDPO(X)	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.	MDPO(2X) ≤ L
MDNO(X)	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.	MDNO(2X) ≤ L
NOS Standard Acceptance Criteria		where X = acceptable error magnitude (cm or minutes) X = ± 15 cm for water level amplitude errors X = ± 1.5 hours (90 minutes) for water level timing errors X = ± 3.0 °C for water temperature amplitude errors	Where L=time limit or max. allowable duration L= 24 hours

5.3. Evaluation of Water Level Hindcasts

The evaluation of hourly water levels was based on comparisons of time series from the FVCOM-based hindcasts to observations during 2017, 2018, and 2019 and also to comparisons of nowcasts from the operational POMGL-based LOOFS. The comparison of time series of the water level hindcast vs. observation were used to calculate the statistics MAE (bias), 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 were 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 of hourly hindcasts were compared with hourly observed water levels recorded at NOS/CO-OPS National Water Level Observing Network (NWLON) and Canadian Hydrographic Service (CHS) gauges along the shores of Lake Ontario (Fig. 6). Information about these stations is given in Table 2. The hourly water level observations from the NOS/CO-OPS 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 Department 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 were removed prior to conducting the skill assessment.

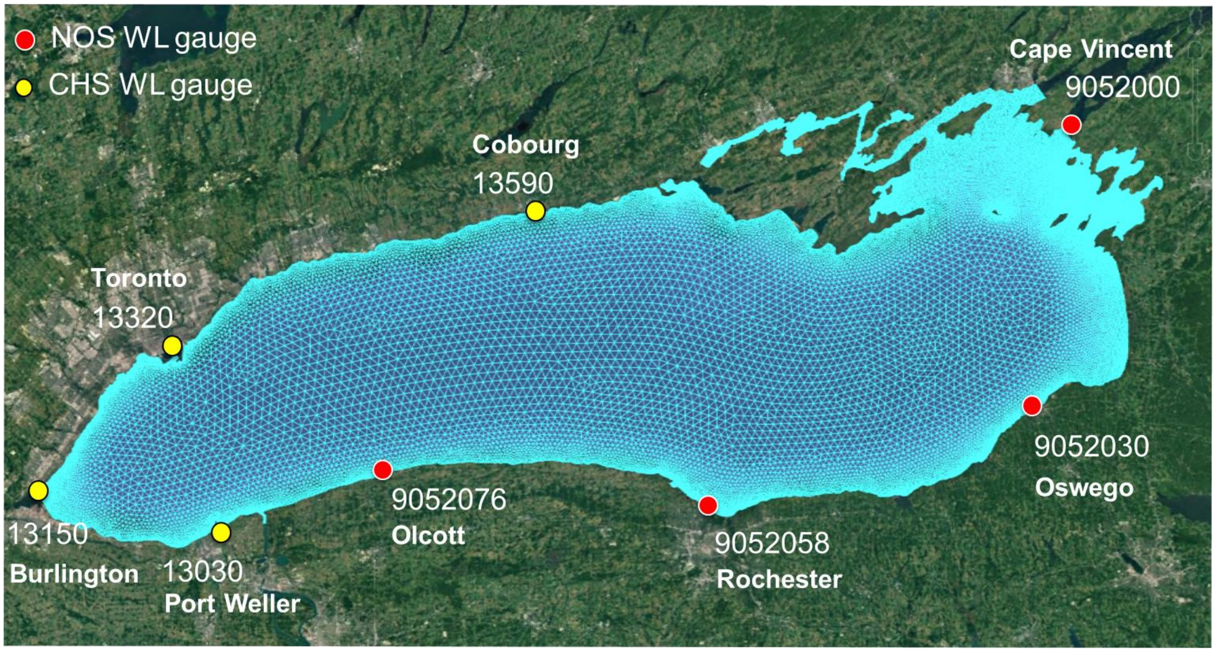

Figure 6. Locations of NOS and CHS water-level gauges used to evaluate LOOFS water level hindcasts.

Table 2. Information on NOAA/NOS/CO-OPS and CHS gauges whose water level observations were used to evaluate the LOOFS hindcasts. N/A indicates that an official NWS station ID has not been assigned to the station yet or not applicable since it is a CHS gauge.

Station Name	State or Prov.	NOS or CHS Station ID	NWS Station ID	Coordinates	
				Lat. (deg N)	Lon. (deg W)
Cape Vincent	NY	9052000	N/A	44.130	76.332
Oswego	NY	9052030	OSGN6	43.464	76.512
Rochester	NY	9052058	RCRN6	43.269	77.626
Olcott	NY	9052076	OLCN6	43.338	78.727
Port Weller	ON	C13030	N/A	43.237	79.220
Burlington	ON	C13150	N/A	43.299	79.793
Toronto	ON	C13320	N/A	43.640	79.380
Cobourg	ON	C13590	N/A	43.956	78.164

5.4. Evaluation of Surface Water Temperature Hindcasts

The evaluation of hourly hindcasts of the surface water temperatures was based on comparisons of time series between the hindcasts and the hourly observations at both offshore and nearshore locations in Lake Ontario. The hindcasts were also compared with operational hourly nowcasts from the LOOFS-POMGL. The comparisons were done using MAE (bias), SM, RMSE, SD, NOF, POF, MDPO, and MDNO.

In evaluating predicted water temperatures in tidal regions, NOS sets an acceptable error of 7.7 ℃ to meet the acceptable error of draft of 7.5 cm (3 inches), as water density is a function of water temperature and salinity. However, since the Great Lakes are considered freshwater and non-tidal, there is no preset standard for lake temperature predictions. Based on ten years of experience in running GLERL's Great Lakes Coastal Forecasting System (GLCFS) 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 ℃ (5.4 °F) criteria for water temperature was used for the Great Lakes, the same criteria used in earlier evaluations of GLOFS (Chu et al., 2007; Kelley et al., 2018).

The hourly hindcasts at nearshore and open lake locations were compared with hourly observations at four fixed buoys in the lake (Fig. 7). The buoys are operated by the NOAA/NWS/National Data Buoy Center (NDBC) and ECCC. The hourly water temperature observations were obtained from the GLERL marine weather observations archives. Geographic information for the buoys is given in Table 3.

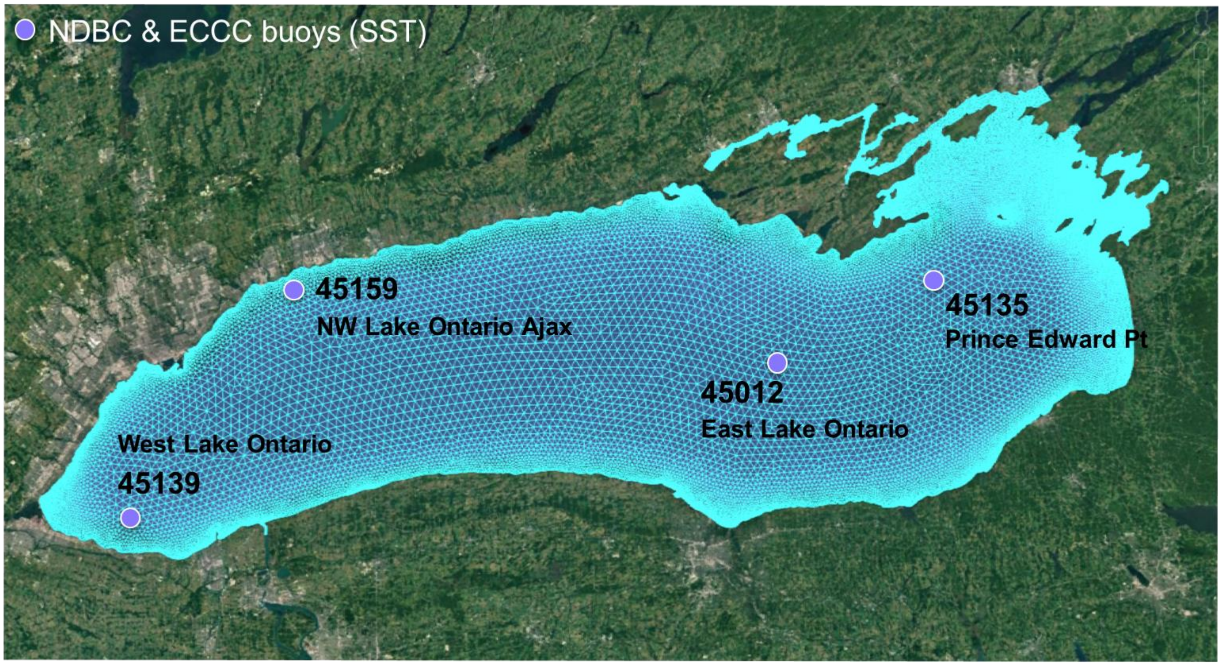

Figure 7. Locations of the NWS/NDBC and ECCC buoys used to evaluate LOOFS surface water temperature hindcasts.

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

Buoy Name	Agency	Prov. or State	NWS Buoy Platform ID	Water Depth (m)	Coordinates	
					Latitude (deg N)	Longitude (deg W)
E Lake Ontario	NWS/NDBC	NY	45012	143	43.621	77.401
Prince Edward Pt.	ECCC	ON	45135	68	43.780	76.870
W Lake Ontario	ECCC	ON	45139	35	43.250	79.530
NW Lake Ontario Ajax	ECCC	ON	45159	54	43.770	78.980

The water temperature sensor on the NDBC buoys is located approximately 1.3 m below the waterline of Lake Ontario. The specific depth of the sensor on ECCC buoys is unknown, but likely similar to the depth of NDBC buoys' water temperature sensors.

6. HINDCAST SKILL ASSESSMENT RESULTS

The results of the skill assessment of the 2017, 2018, and 2019 hourly hindcasts are presented in this section. In addition, the skill assessment of the operational hourly nowcasts from the present POMGL-based LOOFS during the three hindcast years are also discussed in relation to the hindcasts. The results of the water level assessment are given first followed by a discussion of the surface water temperature evaluation results.

6.1. Assessment of Water Level Hindcasts

The standard suite of skill assessment statistics evaluated the accuracy of the hindcasts to predict hourly water level and the ability to capture the extreme high and low water level events at NOS/CO-OPS NWLON and CHS gauges during the three hindcast years. The results of the assessment of the hourly hindcasts are described in Section 6.1.1. The assessment results of extreme high and low water events are given in Sections 6.1.2 and 6.1.3 followed by an evaluation of the hindcasts during several selected high/low water events associated with significant extra-tropical cyclones passing through the Great Lakes Region.

6.1.1. Hourly Water Levels

The hourly water level time series plots at different water level gauges of 2017, 2018, and 2019 are shown in Figures 8-13. The MAE and RMSE of the hindcast are highlighted on all hindcast time series plots. The time series plots contain both hindcasts and operational nowcasts (if station output is available) of hourly water levels and MAE and RMSE for both LOOFS-FVCOM and LOOFS-POMGL versus observations. Full skill assessment statistical tables are available from Tables 4 to 9. The skill assessment results are discussed at gauges along the U.S. lake shore and then along the Canadian shore of Lake Ontario.

6.1.1.1. United States Lakeshore

Along the U.S. shore, there are five NOS/CO-OPS NWLON gauges that measure the water levels. Geographic locations of these five stations are labeled from 1 to 5 on the regional map and also on the individual water level time series plots in Figures 8-10.

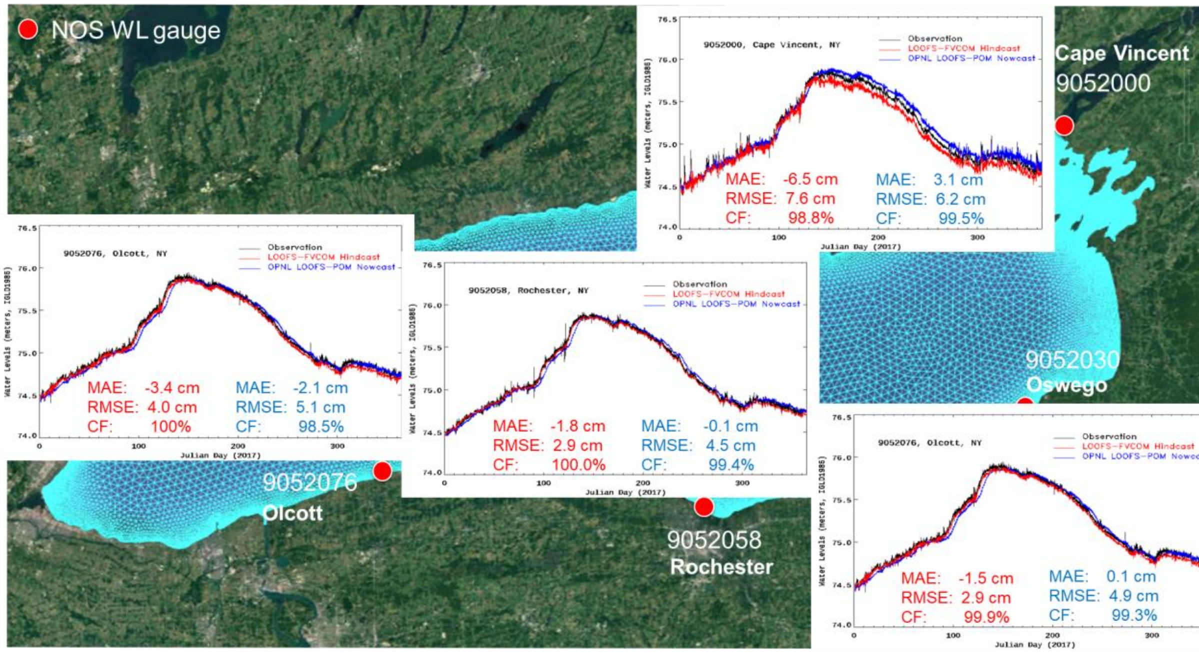

Figure 8. Time series plots of hourly LOOFS-POMGL nowcasts (blue) and LOOFS-FVCOM hindcast of water level (red) vs. observations (black) at Lake Ontario NOS gauges: Olcott, NY; Rochester, NY; Oswego, NY; and Cape Vincent during 2017. MAE and RMSE (cm), and CF at each gauge are shown individually on each panel for nowcasts (blue) and hindcasts (red).

For 2017, the MAEs for the water levels hindcasts at the NOS gauges ranged from -6.5 to -1.5 cm and the RMSE ranged from 2.9 to 7.6 cm (Table 4). In comparison, the MAEs for the nowcasts ranged from -2.1 to 3.1 cm and the RMSEs ranged from 4.5 to 6.2 cm. Thus, the hindcasts had smaller RMSE at three of the four gauges compared to the nowcasts, but the MAE was larger and negative, indicating under prediction of water levels by the hindcasts while the nowcasts over predicted. The hindcasts did worse at Cape Vincent where the hindcast under predicted the water levels, while the nowcasts over predicted, especially after mid-May and the RMSE for the hindcasts was 1.4 cm larger than for the nowcasts. However, the hindcasts as well as the nowcasts passed all NOS acceptance criteria at each of the four gauges.

Table 4. Summary of skill assessment statistics evaluating the ability of the LOOFS-FVCOM hindcasts and LOOFS-POMGL nowcasts to predict hourly water levels at NOS gauges in Lake Ontario during 2017. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9052000 Cape Vincent		9052076 Olcott		9052030 Oswego	
	FVCOM	**POMGL**	**FVCOM**	**POMGL**	**FVCOM**	**POMGL**
Number of Comparisons	8760	8759	8760	8759	8760	8759
Mean Alg. Error (m)	-0.065	0.031	-0.034	-0.021	-0.015	0.001
RMSE (m)	0.076	0.062	0.040	0.051	0.029	0.049
SD (m)	0.039	0.054	0.022	0.047	0.025	0.049
NOF [2×15 cm] (%)	0.0	0.0	0.0	0.0	0.0	0.0
CF [15 cm] (%)	99.8	99.5	100.0	98.5	99.9	99.3
POF [2×15 cm] (%)	0.0	0.0	0.0	0.0	0.0	0.0
MDNO [2×15 cm] (hr)	0.0	0.0	0.0	0.0	0.0	0.0
MDPO [2×15 cm] (hr)	0.0	0.0	0.0	0.0	0.0	0.0

Statistic, Acceptable Error [ ], and Units ( )	9052058 Rochester	
	FVCOM	**POMGL**
Number of Comparisons	8760	8759
Mean Alg. Error (m)	-0.018	-0.001
RMSE (m)	0.029	0.045
SD (m)	0.022	0.045
NOF [2×15 cm] (%)	0.0	0.0
CF [15 cm] (%)	100.0	99.4
POF [2×15 cm] (%)	0.0	0.0
MDNO [2×15 cm] (hr)	0.0	0.0
MDPO [2×15 cm] (hr)	0.0	0.0

During 2018, the MAEs for the water level hindcasts at the NOS gauges ranged from -3.1 to 1.8 cm and the RMSE ranged from 1.8 to 4.2 cm (Table 5). In comparison, the MAEs for the nowcasts ranged from -2.1 to 3.2 cm and the RMSEs ranged from 3.3 to 5.3 cm. On average, the RMSE for the hindcasts was 1.3 cm smaller than for the nowcasts. Similar to 2017, the hindcasts did the worst at Cape Vincent where the hindcast underpredicted the water levels by 3.1 cm while the nowcasts overpredicted by 3.2 cm. The hindcasts, as well as the nowcasts, passed all NOS acceptance criteria at the four gauges.

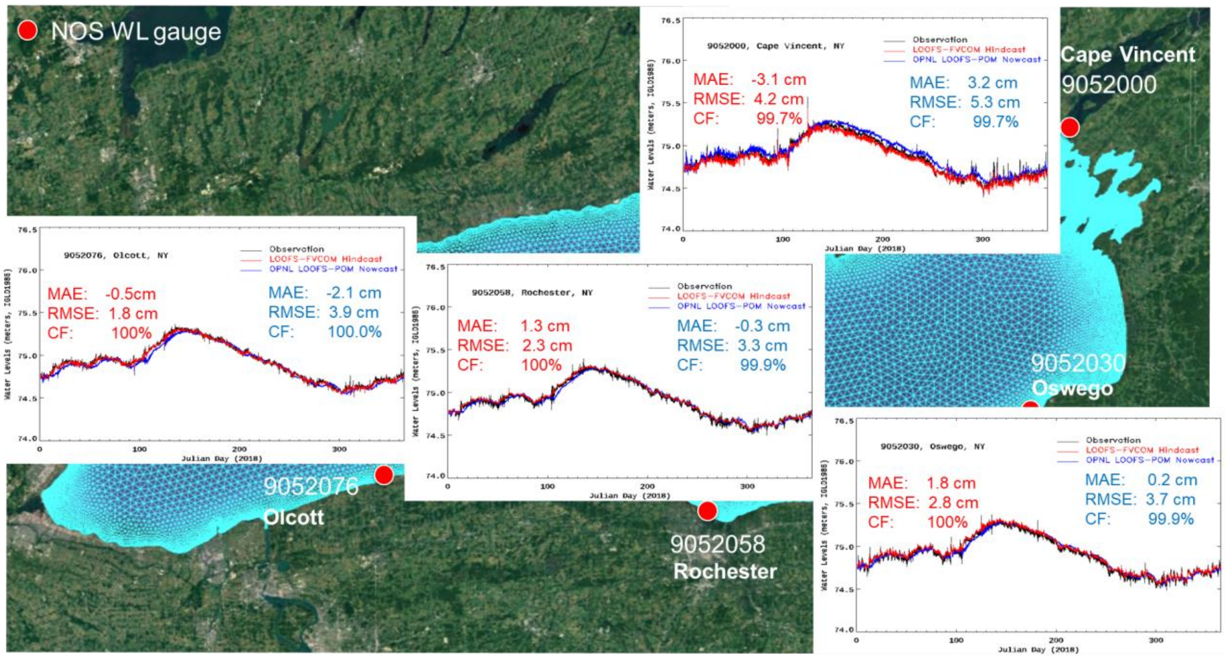

Figure 9. Time series plots of hourly LOOFS-POMGL nowcasts (blue) and LOOFS-FVCOM hindcast of water level (red) vs. observations (black) at Lake Ontario NOS gauges: Olcott, NY; Rochester, NY; Oswego, NY; and Cape Vincent during 2018. MAE and RMSE (cm) at each gauge are shown individually on each panel for nowcasts (blue) and hindcasts (red).

Table 5. Summary of skill assessment statistics evaluating the ability of the LOOFS-FVCOM hindcasts and LOOFS-POMGL nowcasts to predict hourly water levels at NOS gauges in Lake Ontario during 2018. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9052000 Cape Vincent		9052076 Olcott		9052030 Oswego	
	FVCOM	**POMGL**	**FVCOM**	**POMGL**	**FVCOM**	**POMGL**
Number of Comparisons	8760	7727	8760	7727	8760	7727
Mean Alg. Error (m)	-0.031	0.032	-0.005	-0.021	0.018	0.002
RMSE (m)	0.042	0.053	0.018	0.039	0.028	0.037
SD (m)	0.028	0.042	0.017	0.033	0.021	0.037
NOF [2×15 cm] (%)	0.0	0.0	0.0	0.0	0.0	0.0
CF [15 cm] (%)	99.7	99.7	100.0	99.9	100.0	99.9
POF [2×15 cm] (%)	0.0	0.0	0.0	0.0	0.0	0.0
MDNO [2×15 cm] (hr)	0.0	0.0	0.0	0.0	0.0	0.0
MDPO [2×15 cm] (hr)	0.0	0.0	0.0	0.0	0.0	0.0

Statistic, Acceptable Error [ ], and Units ( )	9052058 Rochester	
	FVCOM	**POMGL**
Number of Comparisons	8760	7727
Mean Alg. Error (m)	0.013	-0.003
RMSE (m)	0.023	0.033
SD (m)	0.019	0.033
NOF [2×15 cm] (%)	0.0	0.0
CF [15 cm] (%)	100.0	99.9
POF [2×15 cm] (%)	0.0	0.0
MDNO [2×15 cm] (hr)	0.0	0.0
MDPO [2×15 cm] (hr)	0.0	0.0

During 2019, the MAEs for the water level hindcasts at NOS sites ranged from -5.7 to -0.3 cm and the RMSE ranged from 2.3 to 6.4 cm (Table 6). The hindcasts underpredicted at all four gauges. In comparison, the MAEs for the nowcasts ranged from -2.3 to 3.2 cm and the RMSEs ranged from 4.2 to 6.1 cm. On average, the RMSE for the hindcasts was 1.3 cm smaller than for the nowcasts. Similar to both 2017 and 2018, the hindcasts did the worst at Cape Vincent where the hindcasts underpredicted the water levels by 5.7 cm, while the nowcasts over predicted by 3.2 cm. However, the hindcasts, as well as the nowcasts, again passed all NOS acceptance criteria at the four gauges.

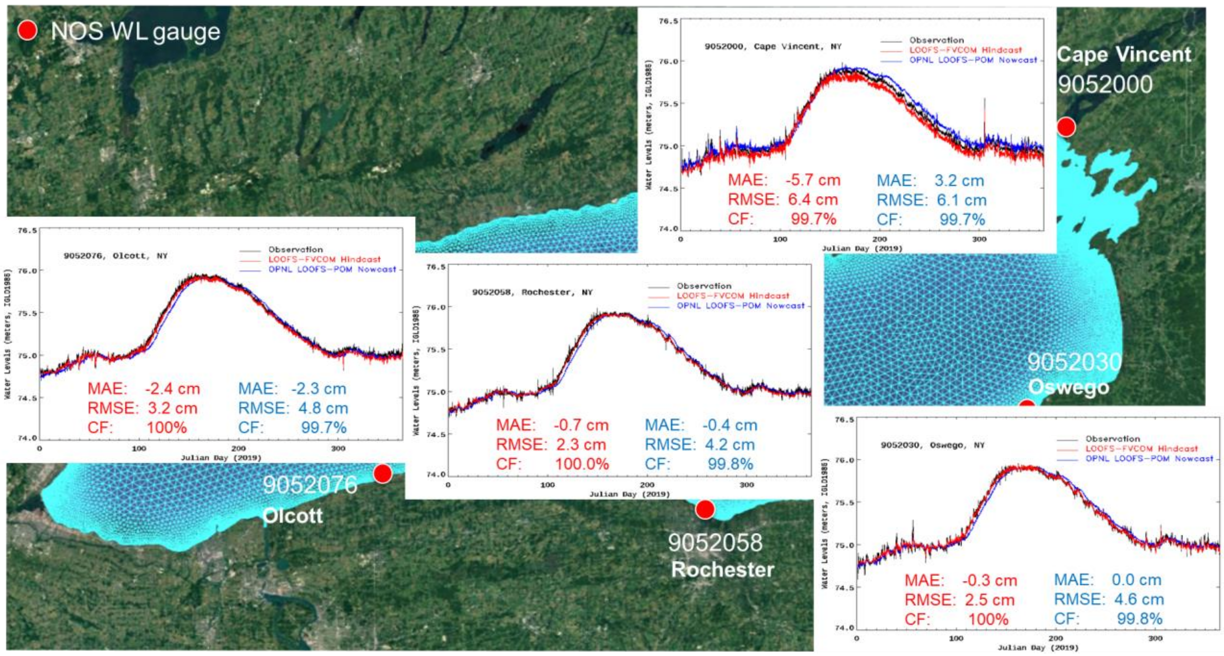

Figure 10. Time series plots of hourly LOOFS-POMGL nowcasts (blue) and LOOFS-FVCOM hindcast of water level (red) vs. observations (black) at Lake Ontario NOS gauges: Olcott, NY; Rochester, NY; Oswego, NY; and Cape Vincent during 2019. MAE and RMSE (cm) at each gauge are shown individually on each panel for nowcasts (blue) and hindcasts (red).

Table 6. Summary of skill assessment statistics evaluating the ability of the LOOFS-FVCOM hindcasts and LOOFS-POMGL nowcasts to predict hourly water levels at NOS NWLON gauges in Lake Ontario during 2019. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9052000 Cape Vincent		9052076 Olcott		9052030 Oswego	
	FVCOM	**POMGL**	**FVCOM**	**POMGL**	**FVCOM**	**POMGL**
Number of Comparisons	8760	6564	8740	6550	8744	6548
Mean Alg. Error (m)	-0.057	0.032	-0.024	-0.023	-0.003	0.000
RMSE (m)	0.064	0.061	0.032	0.048	0.025	0.046
SD (m)	0.030	0.052	0.021	0.042	0.024	0.046
NOF [2×15 cm] (%)	0.0	0.0	0.0	0.0	0.0	0.0
CF [15 cm] (%)	99.7	99.7	100.0	99.7	100.0	99.8
POF [2×15 cm] (%)	0.0	0.0	0.0	0.0	0.0	0.0
MDNO [2×15 cm] (hr)	0.0	0.0	0.0	0.0	0.0	0.0
MDPO [2×15 cm] (hr)	0.0	0.0	0.0	0.0	0.0	0.0

Statistic, Acceptable Error [ ], and Units ( )	9052058 Rochester	
	FVCOM	**POMGL**
Number of Comparisons	8760	6564
Mean Alg. Error (m)	-0.007	-0.004
RMSE (m)	0.023	0.042
SD (m)	0.022	0.042
NOF [2×15 cm] (%)	0.0	0.0
CF [15 cm] (%)	100.0	99.8
POF [2×15 cm] (%)	0.0	0.0
MDNO [2×15 cm] (hr)	0.0	0.0
MDPO [2×15 cm] (hr)	0.0	0.0

6.1.1.2. Canadian Lakeshore

Along the Canadian shore of Lake Ontario, there are four CHS gauges: Toronto, Cobourg, Burlington, Port Weller. Their locations are labeled in Figure 6 and also on the individual water level time series plots in Figures 11-13 for hindcast years 2017, 2018, and 2019, respectively. The skill statistics assessing the ability of the hindcasts to predict the hourly water levels at CHS gauges are given in Tables 7-9 along with skill statistics for operational POMGL-based LOOFS nowcasts.

For 2017, the MAEs for the water levels hindcasts ranged from -6.9 cm to -1.7 cm and the RMSE ranged from 3.1 cm to 7.6 cm at the CHS gauges (Table 7). In comparison, the MAEs for the nowcasts ranged from -4.7 cm to -0.1 cm and the RMSEs ranged from 4.8 cm to 6.8 cm. On average, RMSE for the hindcasts was only 0.2 cm smaller than for the nowcasts. Of the four locations, the hindcasts did the worst at Burlington where the hindcast underpredicted the water levels by 6.9 cm and had an RMSE of 7.6 cm. The nowcasts also did the worst at this location with an MAE and RMSE of -4.7 cm and 6.8 cm, respectively. However, the hindcasts, as well as the nowcasts, passed all NOS acceptance criteria at each of the four gauges.

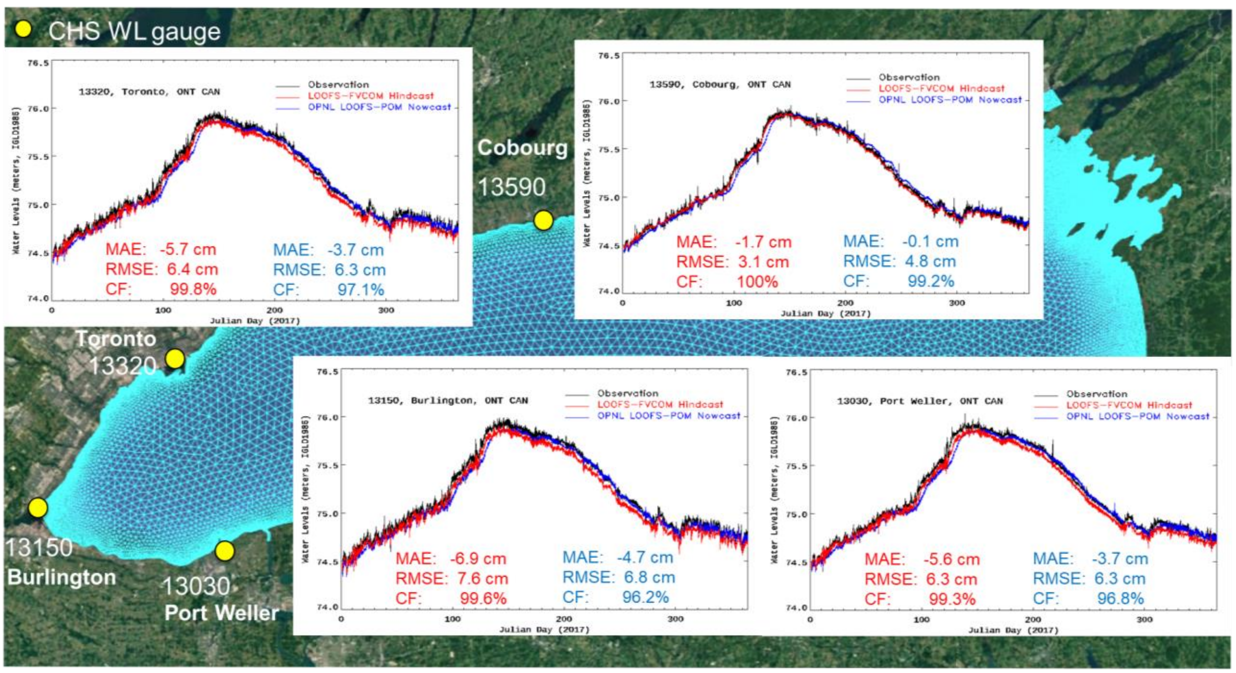

Figure 11. Time series plots of hourly LOOFS-POMGL nowcasts (blue) and LOOFS-FVCOM hindcasts of water level (red) vs. observations (black) at Lake Ontario CHS gauges: Burlington, ONT; Toronto, ONT; Port Weller, ONT; and 3. Cobourg, ONT during 2017. MAE and RMSE (cm) at each gauge are shown individually on each panel for nowcasts (blue) and hindcasts (red).

Table 7. Summary of skill assessment statistics of LOOFS-FVCOM hindcasts and LOOFS-POMGL nowcasts of hourly water levels at CHS gauges in Lake Ontario during 2017. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	C13030 Port Weller		C13150 Burlington		C13320 Toronto	
	FVCOM	**POMGL**	**FVCOM**	**POMGL**	**FVCOM**	**POMGL**
Number of Comparisons	8737	8737	8737	8737	8737	8737
Mean Alg. Error (m)	-0.056	-0.037	-0.069	-0.047	-0.057	-0.037
RMSE (m)	0.063	0.063	0.076	0.068	0.064	0.063
SD (m)	0.029	0.052	0.032	0.049	0.030	0.050
NOF [2×15 cm] (%)	0.0	0.1	0.0	0.0	0.2	0.0
CF [15 cm] (%)	99.3	96.8	99.6	96.2	99.8	97.1
POF [2×15 cm] (%)	0.0	0.0	0.0	0.0	0.0	0.0
MDNO [2×15 cm] (hr)	0.0	1.0	0.0	0.0	0.0	0.0
MDPO [2×15 cm] (hr)	0.0	0.0	0.0	0.0	0.0	0.0

Statistic, Acceptable Error [ ], and Units ( )	C13590 Cobourg	
	FVCOM	**POMGL**
Number of Comparisons	8737	8737
Mean Alg. Error (m)	-0.017	-0.001
RMSE (m)	0.031	0.048
SD (m)	0.025	0.048
NOF [2×15 cm] (%)	0.0	0.0
CF [15 cm] (%)	100.0	99.2
POF [2×15 cm] (%)	0.0	0.0
MDNO [2×15 cm] (hr)	0.0	0.0
MDPO [2×15 cm] (hr)	0.0	0.0

For 2018, the MAEs for the water levels hindcasts ranged from -4.2 cm to 1.3 cm and the RMSE ranged from 2.5 cm to 5.0 cm at the CHS gauges (Table 8). In comparison, the MAEs for the nowcasts ranged from -5.2 to -0.2 cm and the RMSEs ranged from 3.5 cm to 6.6 cm. Both the hindcasts and the nowcasts generally underpredicted the water levels at all the gauges except for the hindcasts at Cobourg, Ontario. On average, RMSE for the hindcasts was 1.6 cm smaller than for the nowcasts. Of the four locations, the hindcasts did the worst at Burlington, as was the case with the 2017 hindcasts. The hindcast underpredicted the water levels by 4.2 cm and had an RMSE of 5.0 cm. The nowcasts also did the worst at this location with a MAE and RMSE of -5.2 cm and 6.6 cm, respectively. However, the hindcasts, as well as the nowcasts, passed all NOS acceptance criteria at each of the four gauges.

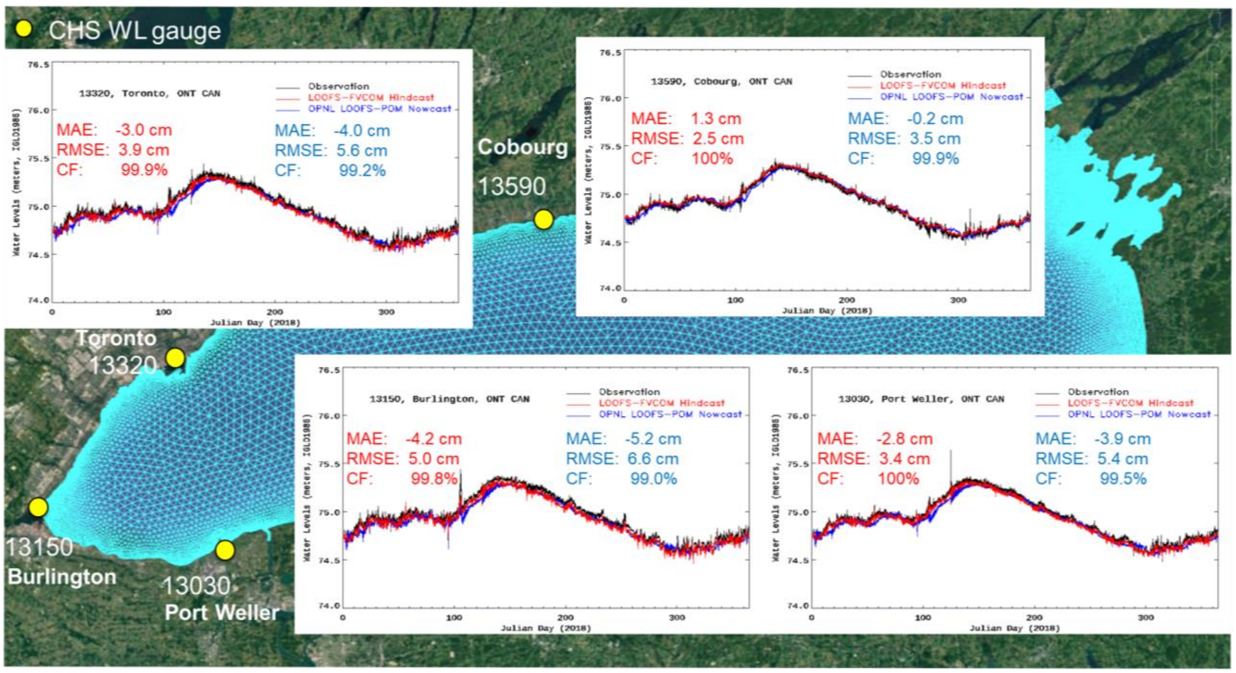

Figure 12. Time series plots of hourly LOOFS-POM nowcasts (blue) and LOOFS-FVCOM hindcasts of water level (red) vs. observations (black) at Lake Ontario CHS gauges: Burlington, ONT; Toronto, ONT; Port Weller, ONT; and 3. Cobourg, ONT during 2018. MAE and RMSE (cm) at each gauge are shown individually on each panel for nowcasts (blue) and hindcasts (red).

Table 8. Summary of skill assessment statistics of LOOFS-FVCOM hindcasts and LOOFS-POMGL nowcasts of hourly water levels at CHS gauges in Lake Ontario during 2018. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	C13030 Port Weller		C13150 Burlington		C13320 Toronto	
	FVCOM	**POMGL**	**FVCOM**	**POMGL**	**FVCOM**	**POMGL**
Number of Comparisons	8737	7710	8711	7684	8737	7710
Mean Alg. Error (m)	-0.028	-0.039	-0.042	-0.052	-0.030	-0.040
RMSE (m)	0.034	0.054	0.050	0.066	0.039	0.056
SD (m)	0.020	0.038	0.026	0.040	0.025	0.039
NOF [2×15 cm] (%)	0.0	0.0	0.0	0.1	0.0	0.0
CF [15 cm] (%)	100.0	99.5	99.8	99.0	99.9	99.2
POF [2×15 cm] (%)	0.0	0.0	0.0	0.0	0.0	0.0
MDNO [2×15 cm] (hr)	1.0	2.0	0.0	3.0	0.0	0.0
MDPO [2×15 cm] (hr)	0.0	0.0	0.0	0.0	0.0	0.0

Statistic, Acceptable Error [ ], and Units ( )	C13590 Cobourg	
	FVCOM	**POMGL**
Number of Comparisons	8737	7710
Mean Alg. Error (m)	0.013	-0.002
RMSE (m)	0.025	0.035
SD (m)	0.021	0.035
NOF [2×15 cm] (%)	0.0	0.0
CF [15 cm] (%)	100.0	99.9
POF [2×15 cm] (%)	0.0	0.0
MDNO [2×15 cm] (hr)	0.0	0.0
MDPO [2×15 cm] (hr)	0.0	0.0

For 2019, the MAEs for the water levels hindcasts ranged from -5.8 cm to -0.5 cm and the RMSE ranged from 2.5 cm to 6.9 cm at the CHS sites (Table 9). In comparison, the MAEs for the nowcasts ranged from -5.3 cm to -0.2 cm and the RMSEs ranged from 4.3 cm to 7.2 cm. Both the hindcast and the nowcasts generally under predicted the water levels at all gauges. On average, RMSE for the hindcast was 0.8 cm smaller than for the nowcasts. Of the four locations, the hindcasts did the worst at Burlington, as was the case with the 2017 and 2018 hindcasts. The hindcasts underpredicted the water levels by 5.6 cm and had an RMSE of 6.9 cm. The nowcasts also did the worst at this location with an MAE and RMSE of -5.3 cm and 7.2 cm, respectively. The hindcasts, as well as the nowcasts, again passed all NOS acceptance criteria at each of the four gauges.

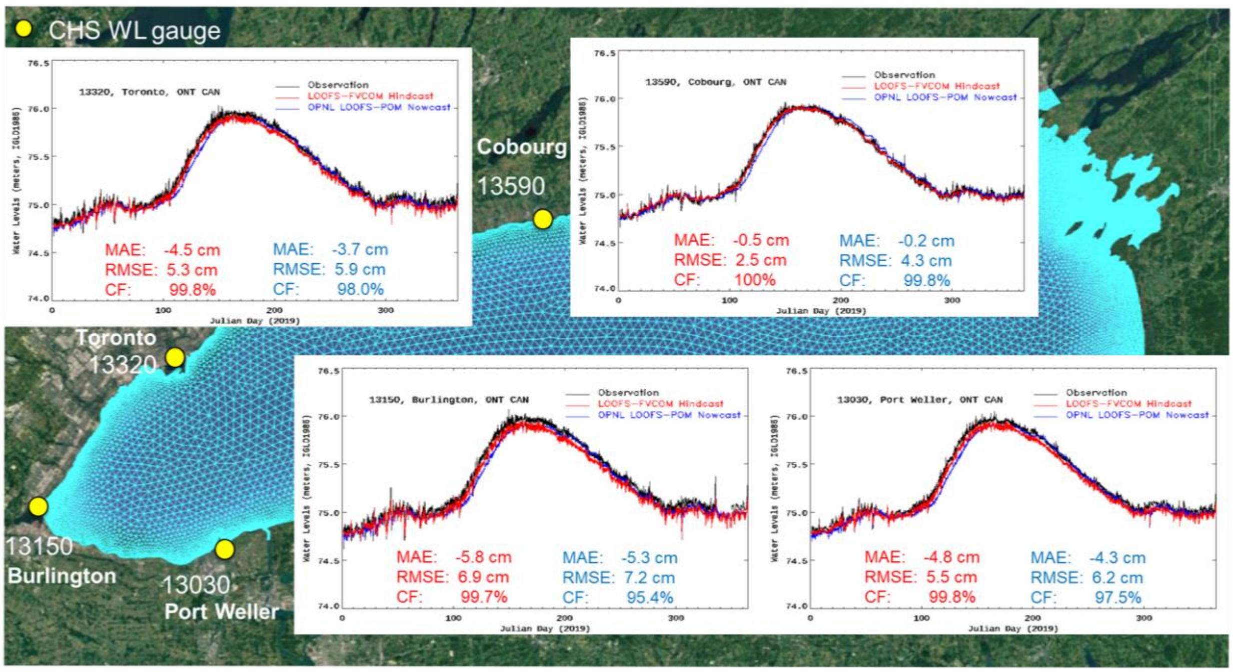

Figure 13. Time series plots of hourly LOOFS-POMGL nowcasts (blue) and LOOFS-FVCOM hindcasts of water level (red) vs. observations (black) at Lake Ontario CHS Water Level gauges: Burlington, ONT; Toronto, ONT; Port Weller, ONT; and 3. Cobourg, ONT during 2019. MAE and RMSE (cm) at each gauge are shown individually on each panel for nowcasts (blue) and hindcasts (red).

Table 9. Summary of skill assessment statistics of LOOFS-FVCOM hindcasts and LOOFS-POMGL nowcasts of hourly water levels at CHS gauges in Lake Ontario during 2019. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	C13030 Port Weller		C13150 Burlington		C13320 Toronto	
	FVCOM	**POMGL**	**FVCOM**	**POMGL**	**FVCOM**	**POMGL**
Number of Comparisons	8737	6547	8408	6302	8737	6547
Mean Alg. Error (m)	-0.048	-0.043	-0.058	-0.053	-0.045	-0.037
RMSE (m)	0.055	0.062	0.069	0.072	0.053	0.059
SD (m)	0.025	0.045	0.036	0.049	0.030	0.046
NOF [2×15 cm] (%)	0.0	0.0	0.0	0.1	0.0	0.0
CF [15 cm] (%)	99.8	97.5	99.7	95.4	99.8	98.0
POF [2×15 cm] (%)	0.0	0.0	0.0	0.0	0.0	0.0
MDNO [2×15 cm] (hr)	1.0	2.0	0.0	3.0	0.0	0.0
MDPO [2×15 cm] (hr)	0.0	0.0	0.0	0.0	0.0	0.0

Statistic, Acceptable Error [ ], and Units ( )	C13590 Cobourg	
	FVCOM	**POMGL**
Number of Comparisons	8737	6547
Mean Alg. Error (m)	-0.005	-0.002
RMSE (m)	0.025	0.043
SD (m)	0.024	0.043
NOF [2×15 cm] (%)	0.0	0.0
CF [15 cm] (%)	100.0	99.8
POF [2×15 cm] (%)	0.0	0.0
MDNO [2×15 cm] (hr)	0.0	0.0
MDPO [2×15 cm] (hr)	0.0	0.0

6.1.2. Extreme High Water Level Events

The skill statistics assessing the ability of LOOFS-FVCOM hindcasts to predict the amplitude and timing of extreme high water level events at gauges along the U.S. lakeshore during 2017, 2018, and 2019 are given in Tables 10, 11, and 12, respectively. The "N"s in the tables represent the numbers of high water events. Since there were very few high water events on the Canadian side and only at one gauge, little significance can be extracted from the events, and therefore the results are not presented in this report.

The LOOFS-FVCOM hindcasts as well as the LOOFS-POMGL nowcasts were evaluated at Cape Vincent and Oswego, NY during 2017, 2018 and 2019. These were the only U.S. gauges where extreme high water events were identified by the skill assessment software.

For these three hindcast years, the MAEs and RMSEs for amplitude at Cape Vincent ranged from -11.7 cm to -14.6 cm and 12.5 cm to 15.7 cm, respectively. The MAEs and RMSEs for timing ranged from -1.25 hours to 0.29 hours and 0.54 hours to 1.50 hours, respectively. At Cape Vincent, the skill assessment results passed all NOS targets, but generally failed the target for CF for amplitude and timing.

At Oswego, the MAEs and RMSEs for amplitude ranged from -11.3 cm to -5.6 cm and 5.6 cm to 12.4 cm, respectively. The MAEs and RMSEs for timing ranged from -1.25 hours to -0.50 hours and 1.29 hours to 1.58 hours, respectively. The skill assessment results passed all NOS targets, but generally failed the target for CF for amplitude and timing.

Skill statistics for the nowcasts were available at Cape Vincent and Oswego but only for 2017 (and Oswego in 2018). The nowcasts had comparable skill to the hindcasts during 2017.

Table 10. Summary of skill assessment statistics evaluating the ability of the LOOFS-FVCOM hindcasts and LOOFS-POMGL nowcasts to predict extreme high water level events at NOS gauges during 2017. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9052000 Cape Vincent			
	FVCOM N=7		**POMGL** N=7	
	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	-0.146	0.286	-0.080	0.000
RMSE (m) (hr)	0.157	0.535	0.106	1.069
SD (m) (hr)	0.062	0.488	0.075	1.155
NOF [2×15 cm or 2×90 min] (%)	0.0	0.0	0.0	0.0
CF [15 cm or 90 min] (%)	57.1	100.0	71.4	71.4
POF [2×15 cm or 2×90 min] (%)	0.0	0.0	0.0	0.0
MDNO [2×15 cm or 2×90 min] (hr)	0.0	0.0	0.0	0.0
MDPO [2×15 cm or 2×90 min] (hr)	0.0	0.0	0.0	0.0

Statistic, Acceptable Error [ ], and Units ( )	9052030 Oswego			
	FVCOM N=3		**POMGL** N=3	
	Amp.	Time	Amp	Time
Mean Alg. Error (m) (hr)	-0.105	-1.000	-0.121	-0.333
RMSE (m) (hr)	0.109	1.291	0.130	1.291
SD (m) (hr)	0.033	1.000	0.058	1.528
NOF [2×15 cm or 2×90 min] (%)	0.0	0.0	0.0	0.0
CF [15 cm or 90 min] (%)	100.0	66.7	66.7	66.7
POF [2×15 cm or 2×90 min] (%)	0.0	0.0	0.0	0.0
MDNO [2×15 cm or 2×90 min] (hr)	0.0	0.0	0.0	0.0
MDPO [2×15 cm or 2×90 min] (hr)	0.0	0.0	0.0	0.0

Table 11. Summary of skill assessment statistics evaluating the ability of the LOOFS-FVCOM hindcasts and LOOFS-POMGL nowcasts to predict extreme high water level events at NOS gauges during 2018. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9052000 Cape Vincent		
	FVCOM N=6		**POMGL** N/A
	Amp.	Time	
Mean Alg. Error (m) (hr)	-0.124	-0.167	
RMSE (m) (hr)	0.127	1.080	
SD (m) (hr)	0.033	1.169	
NOF [2×15 cm or 2×90 min] (%)	0.0	0.0	
CF [15 cm or 90 min] (%)	83.3	83.3	
POF [2×15 cm or 2×90 min] (%)	0.0	0.0	
MDNO [2×15 cm or 2×90 min] (hr)	0.0	0.0	
MDPO [2×15 cm or 2×90min] (hr)	0.0	0.0	

Statistic, Acceptable Error [ ], and Units ( )	9052030 Oswego			
	FVCOM N=4		**POMGL** N=3	
	Amp.	Time	Amp	Time
Mean Alg. Error (m) (hr)	-0.056	-1.250	-0.154	-0.667
RMSE (m) (hr)	0.056	1.323	0.159	1.155
SD (m) (hr)	0.011	0.500	0.049	1.155
NOF [2×15 cm or 2×90 min] (%)	0.0	0.0	0.0	0.0
CF [15 cm or 90 min] (%)	100.0	75.0	66.7	66.7
POF [2×15 cm or 2×90 min] (%)	0.0	0.0	0.0	0.0
MDNO [2×15 cm or 2×90 min] (hr)	0.0	0.0	0.0	0.0
MDPO [2×15 cm or 2×90min] (hr)	0.0	0.0	0.0	0.0

Table 12. Summary of skill assessment statistics evaluating the ability of the LOOFS-FVCOM hindcasts and LOOFS-POM nowcasts to predict extreme high water level events at NOS gauges during 2019. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9052000 Cape Vincent		
	FVCOM N=4		**POMGL** N/A
	Amp.	Time	
Mean Alg. Error (m) (hr)	-0.117	-1.250	
RMSE (m) (hr)	0.125	1.500	
SD (m) (hr)	0.050	0.957	
NOF [2×15 cm or 2×90 min] (%)	0.0	0.0	
CF [15 cm or 90 min] (%)	75.0	50.0	
POF [2×15 cm or 2×90 min] (%)	0.0	0.0	
MDNO [2×15 cm or 2×90 min] (hr)	0.0	0.0	
MDPO [2×15 cm or 2×90min] (hr)	0.0	0.0	

Statistic, Acceptable Error [ ], and Units ( )	9052030 Oswego		
	FVCOM N=2		**POMGL** N/A
	Amp.	Time	
Mean Alg. Error (m) (hr)	-0.113	-0.500	
RMSE (m) (hr)	0.124	1.581	
SD (m) (hr)	0.070	2.121	
NOF [2×15 cm or 2×90 min] (%)	0.0	0.0	
CF [15 cm or 90 min] (%)	50.0	50.0	
POF [2×15 cm or 2×90 min] (%)	0.0	0.0	
MDNO [2×15 cm or 2×90 min] (hr)	0.0	0.0	
MDPO [2×15 cm or 2×90min] (hr)	0.0	0.0	

6.1.3. Extreme Low Water Level Events

The skill statistics assessing the ability of hindcasts to predict the amplitude and timing of extreme low water level events at gauges along the U.S. and Canadian lakeshore during 2017, 2018 and 2019 are given in Tables 13 to 18. Depending on gauge location and hindcast year, the number of low water level events (the “N”s in the tables) at a gauge ranged from two to six. There were no low water events in the nowcasts during 2019 as determined by the skill assessment software.

LOOFS-FVCOM hindcasts as well as LOOFS-POMGL nowcasts were evaluated at U.S. gauges when available: at Olcott for all three years, at Oswego during 2017 and 2019, and at Cape Vincent just during 2019. On the Canadian side, the hindcasts and nowcasts were assessed at Port Weller, Burlington, and Toronto for all three years, but only during 2017 at Cobourg.

For the three hindcast years, the MAEs and RMSEs for amplitude at Olcott ranged from 2.5 to 5.2 cm and 3.3 to 5.2 cm, respectively. The MAEs and RMSEs for timing ranged from 0 to 0.50 hours and 0 to 1.63 hours, respectively. The skill assessment results passed all NOS targets including CF, except for timing in 2017. For 2017 and 2018, the nowcasts also passed all NOS targets including CF, but failed to meet the timing target for the events in 2017.

At Oswego, the MAEs and RMSEs for amplitude for 2017 and 2019 ranged from 3.8 cm to 5.4 cm and 4.9 cm to 6.4 cm, respectively. The MAEs and RMSEs for timing ranged from 0.2 hours to 0.5 hours and 0.71 hours to 1.18 hours, respectively. The skill assessment results passed all NOS targets, but failed the target for CF for timing during 2019. The nowcasts were only for 2017. For that year, the MAE for amplitude was 7.4 cm and the RMSE was 7.7 cm, higher than the values for the hindcasts. Both the hindcasts and the nowcasts met the CF target.

At Cape Vincent, the MAEs and RMSEs for amplitude for 2019 were -0.9 cm and 4.2 cm, respectively. The MAEs and RMSEs for timing were -1.33 hours and 1.41 hours, respectively. The skill assessment results passed all NOS targets, but failed the target for CF for timing. Nowcasts were not available for 2019 at this gauge.

On the Canadian shoreline at Port Weller, Ontario, the MAEs and RMSEs for amplitude during the three years ranged from -0.07 cm to 3.4 cm and 3.6 cm to 4.8 cm, respectively. The MAEs and RMSEs for timing ranged from -0.50 hours to 0.40 hours and 0.89 hours to 1.23 hours, respectively. The skill assessment results passed all NOS targets, but failed the target for CF for timing during 2017 as did the nowcasts.

At Burlington, the MAEs and RMSEs for amplitude during the three years ranged from -2.6 cm to 4.2 cm and 4.6 cm to 6.5 cm, respectively. The MAEs and RMSEs for timing ranged from -1.0 hours to 0.18 hours and 0.85 hours to 1.41 hours, respectively. The skill assessment results passed all NOS targets, but failed the target for CF for timing during 2017 and 2018 as did the nowcasts.

At Toronto, the MAEs and RMSEs for amplitude during the three years ranged from 1.8 cm to 3.6 cm and 3.0 cm to 5.8 cm, respectively. The MAEs and RMSEs for timing ranged from 0.13 hours to 1.17 hours and 1.06 hours to 1.47 hours, respectively. The skill assessment results passed all NOS targets, but failed the target for CF for timing during all three years. However, the nowcasts did pass the CF target during 2017 and 2018.

Table 13. Summary of skill assessment statistics evaluating the ability of the LOOFS-FVCOM hindcasts and LOOFS-POMGL nowcasts to predict extreme low water level events at NOS gauges in Lake Ontario during 2017. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9052076 Olcott			
	FVCOM N=3		**POMGL** N=4	
	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	0.025	0.000	0.036	-0.500
RMSE (m) (hr)	0.045	1.633	0.042	1.225
SD (m) (hr)	0.045	2.000	0.024	1.291
NOF [2×15 cm or 2×90 min] (%)	0.0	0.0	0.0	0.0
CF [15 cm or 90 min] (%)	100.0	33.3	100.0	75.0
POF [2×15 cm or 2×90 min] (%)	0.0	0.0	0.0	0.0
MDNO [2×15 cm or 2×90 min] (hr)	0.0	0.0	0.0	0.0
MDPO [2×15 cm or 2×90min] (hr)	0.0	0.0	0.0	0.0

Statistic, Acceptable Error [ ], and Units ( )	9052030 Oswego				9052058 Rochester		
	FVCOM N=2		**POMGL** N=2		**FVCOM** N/A	**POMGL** N=2	
	Amp.	Time	Amp.	Time		Amp.	Time
Mean Alg. Error (m) (hr)	0.038	0.500	0.074	-0.500		0.095	0.000
RMSE (m) (hr)	0.049	0.707	0.077	0.707		0.095	0.000
SD (m) (hr)	0.045	0.707	0.029	0.707		0.004	0.0
NOF [2×15 cm or 2×90 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 [2×15 cm or 2×90 min] (%)	0.0	0.0	0.0	0.0		0.0	0.0
MDNO [2×15 cm or 2×90 min] (hr)	0.0	0.0	0.0	0.0		0.0	0.0
MDPO [2×15 cm or 2×90min] (hr)	0.0	0.0	0.0	0.0		0.0	0.0

Table 14. Summary of skill assessment statistics evaluating the ability of the LOOFS-FVCOM hindcasts and LOOFS-POM nowcasts to predict extreme low water level events at NOS gauges in Lake Ontario during 2018. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9052076 Olcott			
	FVCOM N=2		**POMGL** N=2	
	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	0.052	0.500	0.035	-0.500
RMSE (m) (hr)	0.052	0.707	0.035	0.707
SD (m) (hr)	0.011	0.707	0.004	0.707
NOF [2×15 cm or 2×90 min] (%)	0.0	0.0	0.0	0.0
CF [15 cm or 90 min] (%)	100.0	100.0	100.0	100.0
POF [2×15 cm or 2×90 min] (%)	0.0	0.0	0.0	0.0
MDNO [2×15 cm or 2×90 min] (hr)	0.0	0.0	0.0	0.0
MDPO [2×15 cm or 2×90min] (hr)	0.0	0.0	0.0	0.0

Table 15. Summary of skill assessment statistics evaluating the ability of the LOOFS-FVCOM hindcasts and LOOFS-POMGL nowcasts to predict extreme low water level events at NOS gauges in Lake Ontario during 2019. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9052000 Cape Vincent			9052076 Olcott		
	FVCOM N=3		**POMGL** N/A	**FVCOM** N=3		**POMGL** N/A
	Amp.	Time		Amp.	Time	
Mean Alg. Error (m) (hr)	-0.009	-1.333		0.029	0.000	
RMSE (m) (hr)	0.042	1.414		0.033	0.000	
SD (m) (hr)	0.050	0.577		0.020	0.000	
NOF [2×15 cm or 2×90 min] (%)	0.0	0.0		0.0	0.0	
CF [15 cm or 90 min] (%)	100.0	66.7		100.0	100.0	
POF [2×15 cm or 2×90 min] (%)	0.0	0.0		0.0	0.0	
MDNO [2×15 cm or 2×90 min] (hr)	0.0	0.0		0.0	0.0	
MDPO [2×15 cm or 2×90min] (hr)	0.0	0.0		0.0	0.0	

Statistic, Acceptable Error [ ], and Units ( )	9052030 Oswego		
	FVCOM N=5		**POMGL** N/A
	Amp.	Time	
Mean Alg. Error (m) (hr)	0.054	0.200	
RMSE (m) (hr)	0.064	1.183	
SD (m) (hr)	0.039	1.304	
NOF [2×15 cm or 2×90 min] (%)	0.0	0.0	
CF [15 cm or 90 min] (%)	100.0	80.0	
POF [2×15 cm or 2×90 min] (%)	0.0	0.0	
MDNO [2×15 cm or 2×90 min] (hr)	0.0	0.0	
MDPO [2×15 cm or 2×90min] (hr)	0.0	0.0	

Table 16. Summary of skill assessment statistics evaluating the ability of LOOFS-FVCOM hindcasts and LOOFS-POMGL nowcasts to predict extreme low water level events at CHS gauges in Lake Ontario during 2017. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	C13030 Port Weller				C13150 Burlington			
	FVCOM N=4		**POMGL** N=4		**FVCOM** N=10		**POMGL** N=12	
	Amp.	Time	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	0.010	-0.500	0.029	-0.250	-0.026	-1.000	0.019	-0.167
RMSE (m) (hr)	0.048	1.225	0.034	1.118	0.046	1.414	0.032	1.000
SD (m) (hr)	0.054	1.291	0.019	1.258	0.040	1.054	0.027	1.030
NOF [2×15 cm or 2×90 min] (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CF [15 cm or 90 min] (%)	100.0	75.0	100.0	75.0	100.0	60.0	100.0	83.3
POF [2×15 cm or 2×90 min] (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MDNO [2×15 cm or 2×90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MDPO [2×15 cm or 2×90min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Statistic, Acceptable Error [ ], and Units ( )	C13320 Toronto				C13590 Cobourg			
	FVCOM N=6		**POMGL** N=4		**FVCOM** N=4		**POMGL** N=4	
	Amp.	Time	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	0.018	1.167	0.019	0.250	0.088	0.500	0.094	-1.250
RMSE (m) (hr)	0.030	1.472	0.031	0.866	0.095	1.581	0.102	1.500
SD (m) (hr)	0.025	0.983	0.029	0.957	0.042	1.732	0.045	0.957
NOF [2×15 cm or 2×90 min] (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CF [15 cm or 90 min] (%)	100.0	50.0	100.0	100.0	100.0	50.0	100.0	50.0
POF [2×15 cm or 2×90 min] (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MDNO [2×15 cm or 2×90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MDPO [2×15 cm or 2×90min] (hr)	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 LOOFS-FVCOM hindcasts and LOOFS-POMGL nowcasts to predict extreme low water level events at CHS gauges in Lake Ontario during 2018. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	C13030 Port Weller			C13150 Burlington			
	FVCOM N=5		**POMGL** N/A	**FVCOM** N=3		**POMGL** N=3	
	Amp.	Time		Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	0.034	0.000		0.042	-0.500	-0.006	1.000
RMSE (m) (hr)	0.037	0.894		0.052	0.913	0.038	1.291
SD (m) (hr)	0.016	1.000		0.034	0.837	0.046	1.000
NOF [2×15 cm or 2×90 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	83.3	100.0	66.7
POF [2×15 cm or 90 min] (%)	0.0	0.0		0.0	0.0	0.0	0.0
MDNO [2×15 cm or 2×90 min] (hr)	0.0	0.0		0.0	0.0	0.0	0.0
MDPO [2×15 cm or 2×90 min] (hr)	0.0	0.0		0.0	0.0	0.0	0.0

Statistic, Acceptable Error [ ], and Units ( )	C13320 Toronto			
	FVCOM N=5		**POMGL** N=3	
	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	0.036	0.600	0.021	0.667
RMSE (m) (hr)	0.040	1.183	0.030	0.816
SD (m) (hr)	0.021	1.140	0.026	0.577
NOF [2×15 cm or 2×90 min] (%)	0.0	0.0	0.0	0.0
CF [15 cm or 90 min] (%)	100.0	80.0	100.0	100.0
POF [2×15 cm or 2×90 min] (%)	0.0	0.0	0.0	0.0
MDNO [2×15 cm or 2×90 min] (hr)	0.0	0.0	0.0	0.0
MDPO [2×15 cm or 2×90 min] (hr)	0.0	0.0	0.0	0.0

Table 18. Summary of skill assessment statistics evaluating the ability of LOOFS-FVCOM hindcasts and LOOFS-POMGL nowcasts to predict extreme low water level events at CHS gauges in Lake Ontario during 2019. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	C13030 Port Weller			C13150 Burlington		
	FVCOM N=5		**POMGL** N/A	**FVCOM** N=11		**POMGL** N/A
	Amp.	Time		Amp.	Time	
Mean Alg. Error (m) (hr)	-0.007	0.400		0.025	0.182	
RMSE (m) (hr)	0.036	0.894		0.065	0.853	
SD (m) (hr)	0.040	0.894		0.063	0.874	
NOF [2×15 cm or 2×90 min] (%)	0.0	0.0		0.0	0.0	
CF [15 cm or 90 min] (%)	100.0	100.0		100.0	100.0	
POF [2×15 cm or 2×90 min] (%)	0.0	0.0		0.0	0.0	
MDNO [2×15 cm or 2×90 min] (hr)	0.0	0.0		0.0	0.0	
MDPO [2×15 cm or 2×90 min] (hr)	0.0	0.0		0.0	0.0	

Statistic, Acceptable Error [ ], and Units ( )	C13320 Toronto		
	FVCOM N=8		**POMGL** N/A
	Amp.	Time	
Mean Alg. Error (m) (hr)	0.034	0.125	
RMSE (m) (hr)	0.058	1.061	
SD (m) (hr)	0.050	1.126	
NOF [2×15 cm or 2×90 min] (%)	0.0	0.0	
CF [15 cm or 90 min] (%)	100.0	75.0	
POF [2×15 cm or 2×90 min] (%)	0.0	0.0	
MDNO [2×15 cm or 2×90 min] (hr)	0.0	0.0	
MDPO [2×15 cm or 2×90 min] (hr)	0.0	0.0	

6.1.4. Selected High and Low Water Level Events

The hindcasts were qualitatively assessed for three high/low water level events which occurred as extra-tropical cyclones passed through the Great Lakes region during the hindcast years of 2017, 2018, and 2019. During the Spring of 2017 and the Spring of 2019, record high lake levels occurred on Lake Ontario which caused wide-spread flooding, erosion, and other high water impacts. The dates of the three selected periods were the following: 1) April 29 – May 3, 2017, 2) April 3-7, 2018, and 3) May 20-June 2, 2019.

During the extratropical cyclone of April 29 – May 3, 2017, wind-driven flooding occurred along the south shore of Lake Ontario according to press reports, as the low (central MSLP 990 mb) moved SW to NE across Lake Michigan. Water level observations during the period at the NOS gauges are depicted in Fig. 14 along with the surface weather map valid for 7 AM EST, May 1, 2017. A comparison of the hindcasts to observations and nowcasts (Fig. 15) at NOS and CHS gauges indicates that the hindcasts:

1) matched the overall water level trend at Cobourg, Olcott, Oswego, and Rochester gauges,
2) exhibited larger fluctuations in water levels than was observed at Cape Vincent,
3) were on average at least 0.25 m lower than the observed levels at Burlington and Toronto,
4) failed to capture sudden low and high water events at Cobourg, Oswego, Rochester (e.g., Day of Year [DOY] 122 high water 0.3 m spike at Rochester), Burlington and Toronto, and
5) exhibited more fluctuations than the nowcasts at all gauges.

Water level observations at NOS gauges during the April 3-7, 2018 extratropical cyclone are depicted in Fig. 16 along with the surface weather map valid for 7 AM EST, April 4, 2018. The most noticeable events were the sudden water level drop at Olcott on the 4^{th} and the sudden rise at Oswego and Cape Vincent on the 4^{th} as the intense low-pressure area (central MSLP 988 mb) moved northeastward across Lake Ontario from the 3^{rd} to the 4^{th}. A comparison of the hindcasts to observations and nowcasts (Fig. 17) at NOS and CHS gauges indicates that the hindcasts:

1) predicted well the amplitude and phase of the low water level event on Day 94 (Apr. 4^{th}) at Toronto, Burlington, Port Weller, and Olcott,
2) predicted the water level trend at Cobourg and Rochester, but not the fluctuations from DOYs 93 to 95,
3) predicted the timing of the high water level event at Cape Vincent and Oswego but underpredicted the amplitude, and
4) nowcasts captured the low and high water level events but overall under predicted water levels.

Water level observations at NOS gauges from May 20 to June 2, 2019 are depicted in Fig. 18 along with the surface weather map valid for 7 AM EST, May 28, 2019. During this time several extratropical cyclones passed the Great Lakes region, the strongest ones occurring on May 23, 25, 28 and Jun. 2. According to press reports, flooding due to a combination of high water levels and waves caused damage to thousands of residential and commercial properties on both the Quebec and New York shores, especially during the period from the 28^{th} to the 31^{st}. The average water level for Lake Ontario broke the record high that was previously set in late May 2017. The observed water level exhibited a steady increase during the period as well as the effect of the four low pressure systems. A comparison of the hindcasts to observations and nowcasts (Fig. 19) at NOS and CHS gauges indicates that the hindcasts:

1) matched the overall water level trend at Cobourg, Olcott, Oswego, and Rochester gauges,
2) exhibited larger fluctuations in water levels than was observed at Cape Vincent,
3) were on average about 0.1 m lower than the observed levels at Port Weller, Burlington, Toronto, and Cape Vincent,
4) failed to capture sudden low and high water events at all gauges (e.g. DOYs 144, 146, and 150 at Oswego and Rochester), and
5) exhibited more fluctuations than the nowcasts at all gauges.

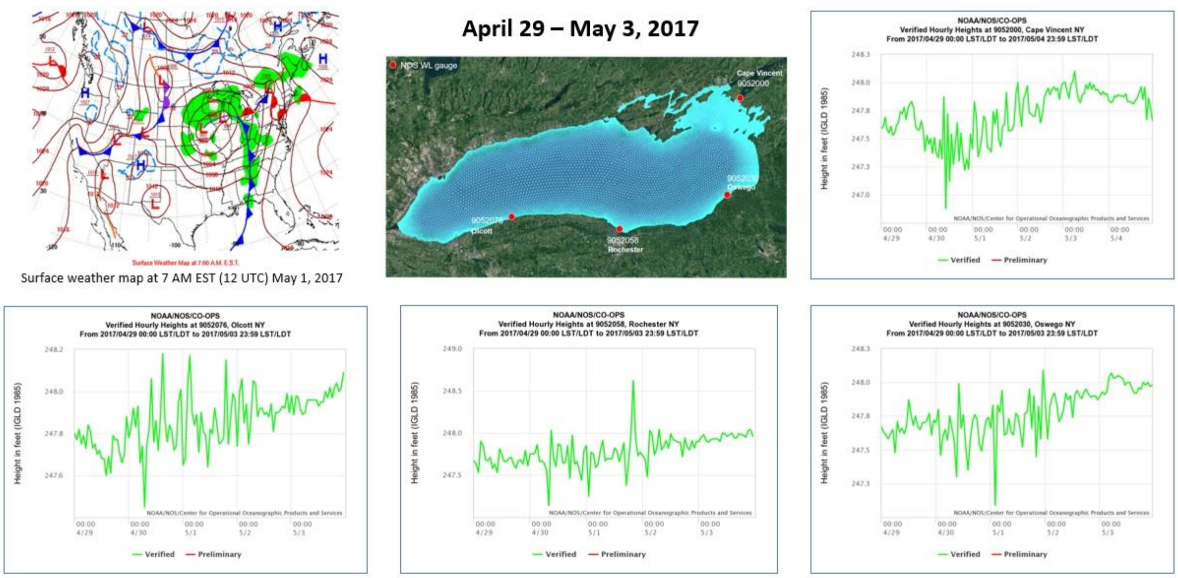

Figure 14. Time series of hourly observed water levels (feet) at NOS gauges from April 29 to May 3, 2017 and the NWS Daily Weather Map valid at 12 UTC, May 1, 2017.

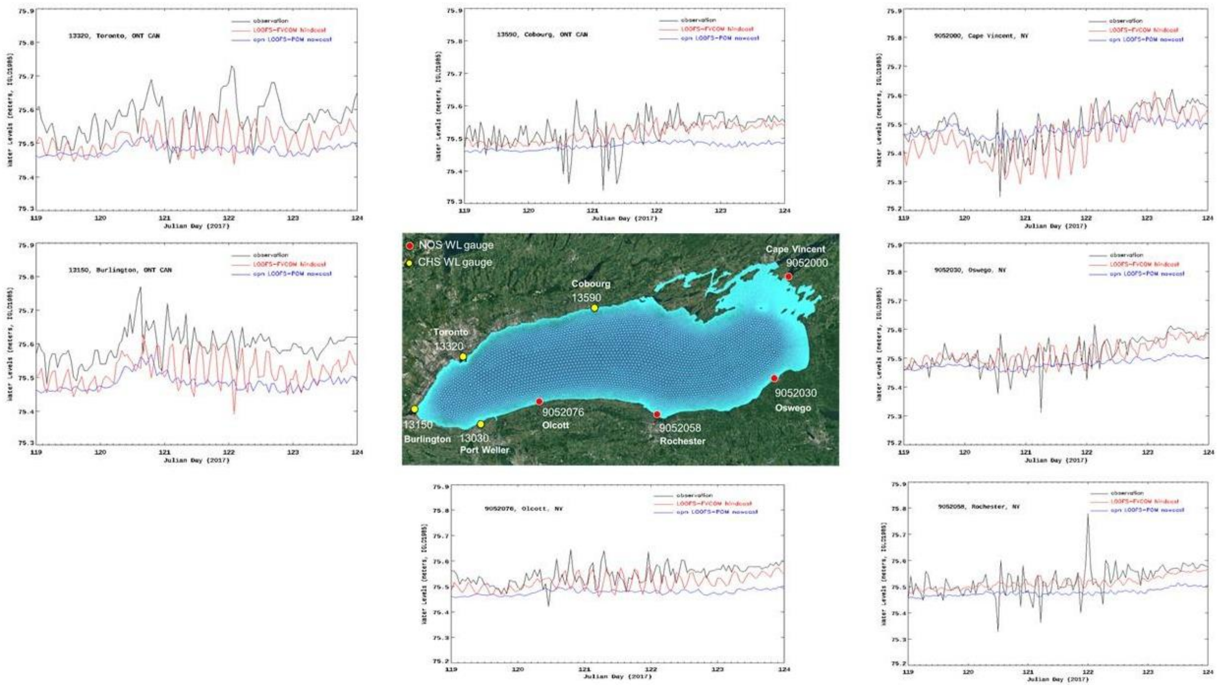

Figure 15. Time series of hindcasts, nowcasts, and observed water levels at NOS and CHS gauges during the period of April 29 to May 3, 2017.

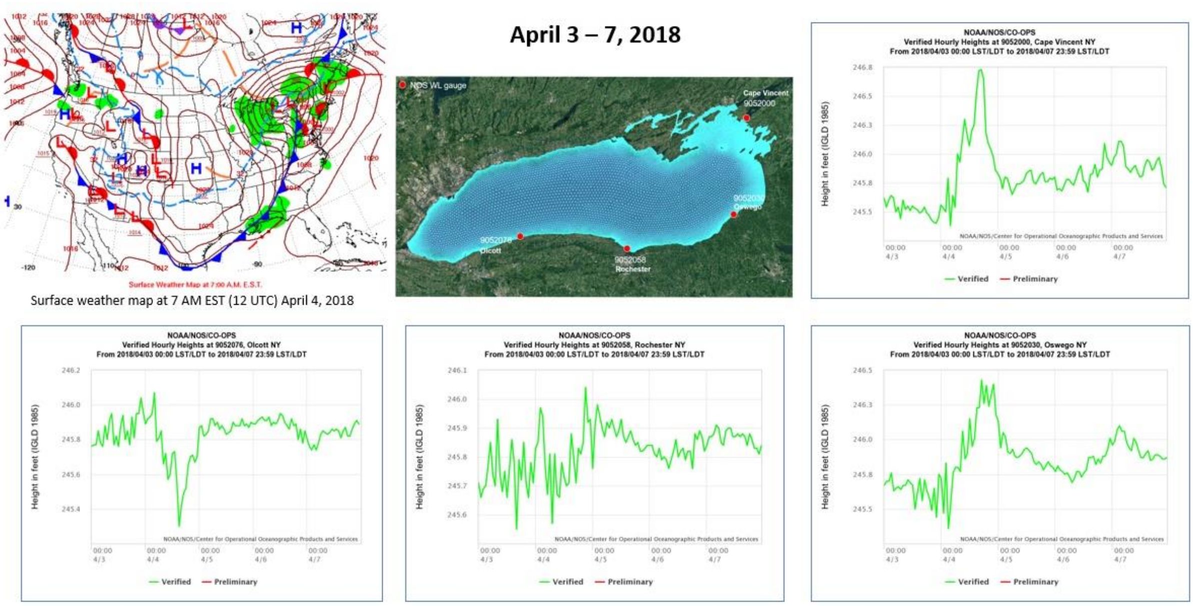

Figure 16. Time series of observed water levels at NOS gauges from April 3 to 7, 2018 and the NWS Daily Weather Map valid at 12 UTC, April 4, 2018.

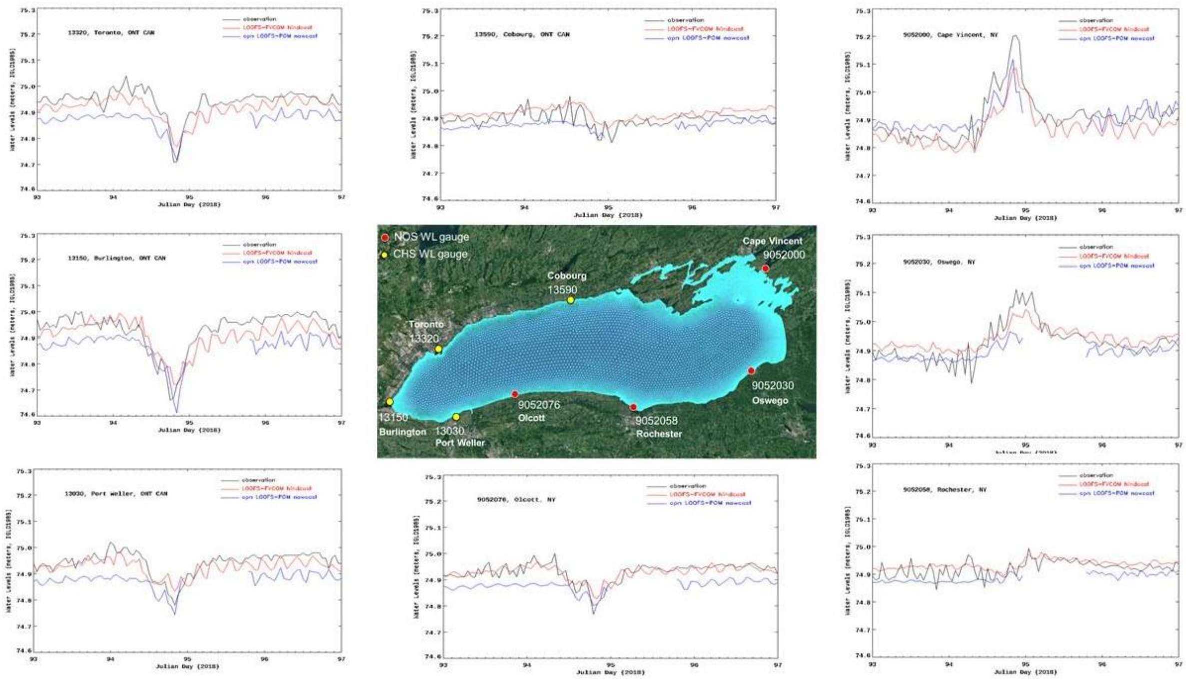

Figure 17. Time series of hindcasts, nowcasts, and observed water levels at NOS and CHS gauges during the period of April 3 to 7, 2018.

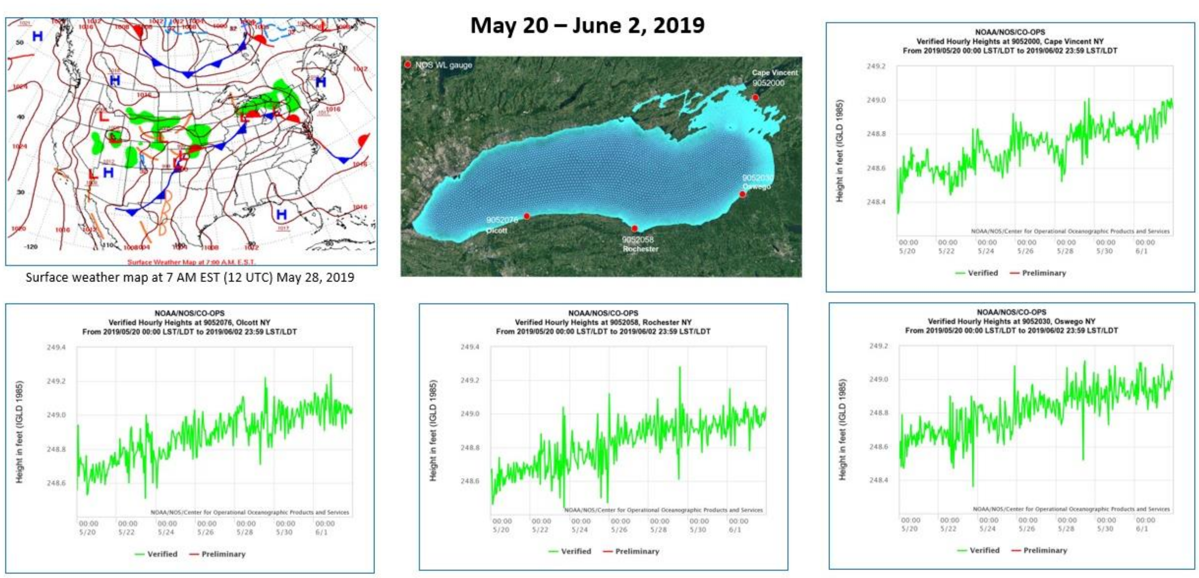

Figure 18. Time series of observed water levels at NOS gauges from May 20 to June 2, 2019 and the NWS Daily Weather Map valid at 12 UTC, May 28, 2019.

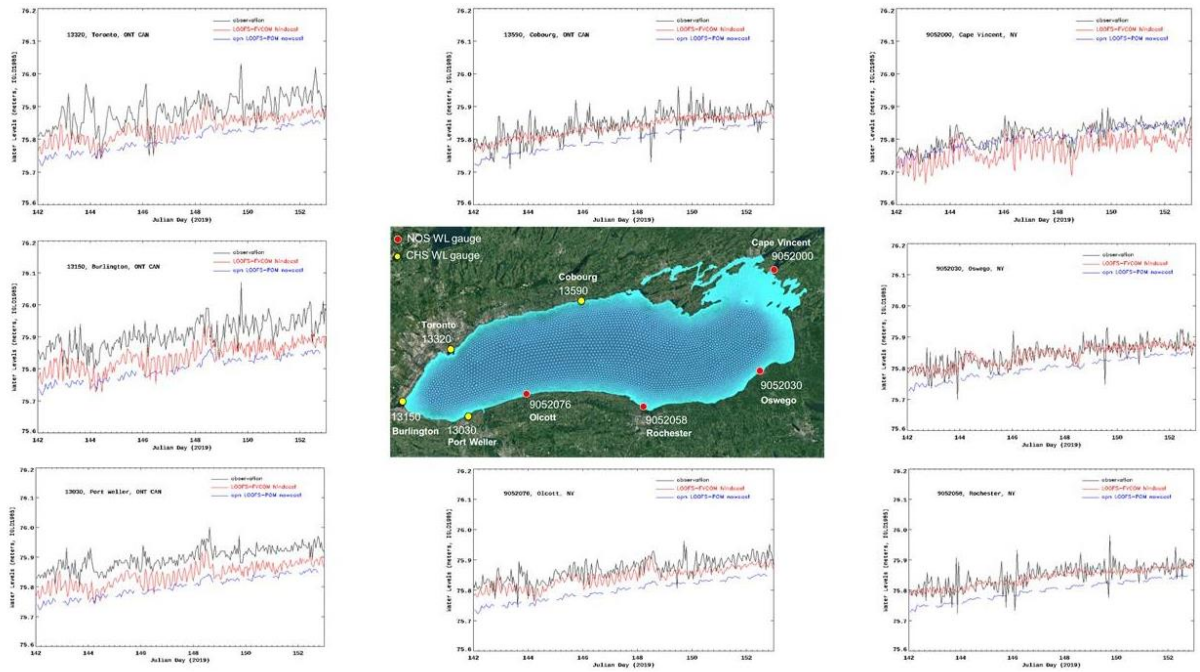

Figure 19. Time series of hindcasts, nowcasts, and observed water levels at NOS and CHS gauges during the period of May 20 to June 2, 2019.

6.2. Assessment of Surface Water Temperature Hindcasts

The results of the skill assessment of the FVCOM-based LOOFS hourly hindcasts of surface water temperatures for 2017, 2018 and 2019 are given in this section. In addition, skill results for the POMGL-based LOOFS nowcasts for all three years are given. Both the NDBC and ECCC observations were used to skill assess the hindcasts and nowcasts. The two nearshore buoys have water depths of 35 m and 54 m at 45139 and 45159, respectively, whereas the depths at the buoys in the open lake were 68 m and 143 m at 45135 and 45012, respectively. It should be noted that the number of hindcasts and nowcasts evaluated were approximately the same in 2017 and 2018, but the number of hindcasts evaluated in 2019 exceeded the number of nowcasts by approximately 1000.

The time series plots for 2017, 2018, and 2019 (Figs. 20, 21, and 22) indicate that the hindcasts closely matched the observations, capturing both the seasonal trend and sudden cooling and warming events. The most notable events were at 45159 in late October/early November during both 2018 and 2019. In comparison to the nowcasts, the hindcasts performed better at all four buoys during the three years. The plots also show that the hindcasts had less high-frequency water temperature fluctuations than the nowcasts and more closely matched the observations than the nowcasts. In addition, the hindcasts did not exhibit the too fast spring warmup as exhibited by the nowcasts, especially at the two offshore buoys. In terms of the fall cool down, the hindcasts did the same or better, except at 45012 when the nowcasts did better in October of both 2018 and 2019.

For 2017, the MAEs for the hindcasts ranged from -0.15 ℃ to 0.2 ℃ and the RMSE ranged from 0.69 ℃ to 1.47 ℃ (Table 19). In comparison to the nowcasts, the RMSEs for the hindcasts were on average 1.33 ℃ lower. The hindcasts passed all NOS acceptance criteria, while the nowcasts did not meet the CF criteria at any of the buoys and failed to pass the criteria for NOF and POF at 45159.

During 2018, the MAEs for the hindcasts ranged from -0.19 ℃ to 0.3 ℃ and the RMSEs ranged from 1.19 ℃ to 1.56 ℃ (Table 20). The RMSEs for the hindcasts, in comparison to the nowcasts, averaged 1.67 ℃ lower. The hindcasts passed all the acceptance criteria, while the nowcasts failed to meet the CF criteria at any of the four buoys. The nowcasts at the buoys also failed to meet the threshold for POF, NOF, or both.

For 2019, the MAEs for the hindcasts ranged from 0.24 ℃ to 0.76 ℃ and RMSEs ranged from 0.96 ℃ to 1.9 ℃ (Table 21). In comparison to the nowcasts, the RMSEs for the hindcasts were on average 1.19 ℃ lower. The hindcasts passed all the criteria at three of the buoys, but not at 45012 where it failed to meet the CF and POF targets. The nowcasts also failed to meet these targets at 45012. Unlike the hindcasts, the nowcasts failed to meet the CF target at 45135 and the CF and NOF targets at 45159.

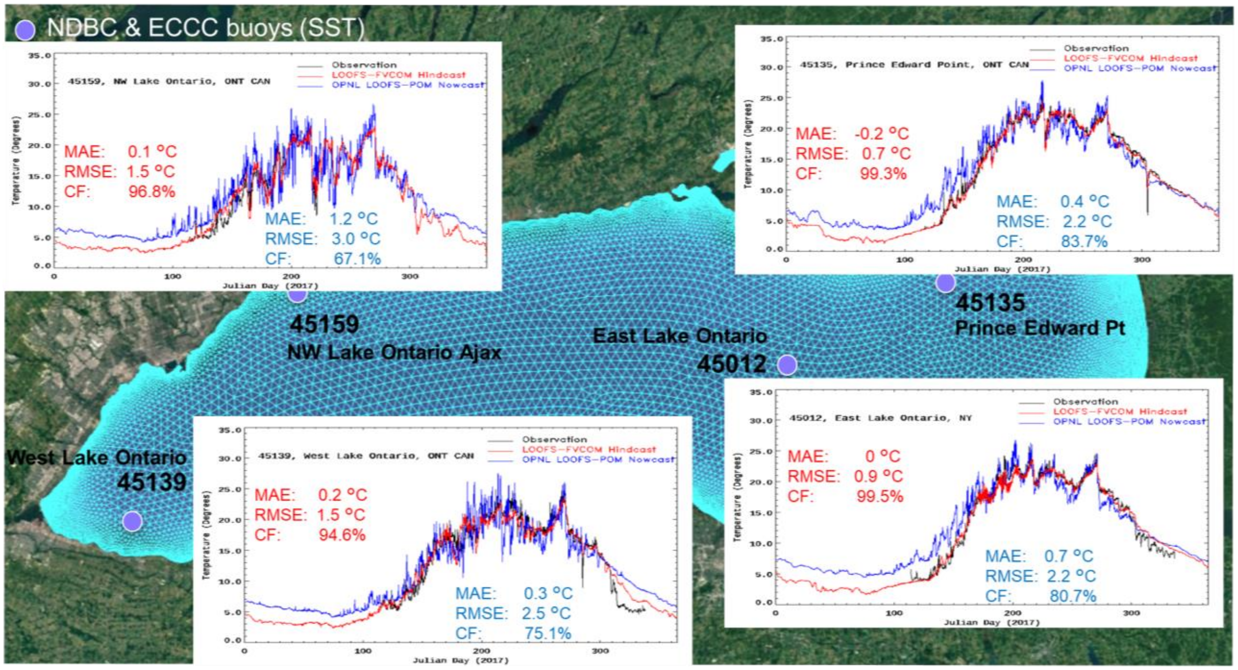

Figure 20. Time series plots of hourly LOOFS-POMGL nowcasts (blue) and LOOFS-FVCOM hindcasts of surface water temperature (red) vs. observations (black) at NDBC and ECCC buoys during 2017: 45139, West Lake Ontario, ONT; 45159, NW Lake Ontario Ajax, ONT; 45012, East Lake Ontario, ONT; and 45135 Prince Edward Point, NY. MAE, RMSE and CF at each station are shown individually on each panel for nowcasts (blue) and hindcasts (red).

Table 19. Summary of skill assessment statistics of the hourly LOOFS-FVCOM hindcasts and LOOFS-POMGL nowcasts of surface water temperature at NDBC and ECCC fixed buoys in Lake Ontario during 2017. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Time Period, Statistic, Acceptable Error [ ], and Units ( )		45012 East Lake Ontario		45135 Prince Edward Point		45139 West Lake Ontario	
Time Period	Begin	06/06/2017		04/24/2017		06/04/2017	
	End	12/02/2017		08/28/2017		11/22/2017	
Model		**FVCOM**	**POMGL**	**FVCOM**	**POMGL**	**FVCOM**	**POMGL**
Number of Comparisons		5290	5290	5308	5308	5342	5342
Mean Alg. Error (℃)		-0.012	0.741	-0.154	0.408	0.192	0.342
RMSE (℃)		0.932	2.200	0.686	2.173	1.457	2.469
SD (℃)		0.932	2.072	0.668	2.134	1.444	2.445
NOF [2×3ºC] (%)		0.0	0.0	0.0	0.0	0.0	0.7
CF [3ºC] (%)		99.5	80.7	99.3	83.7	94.6	75.1
POF [2×3ºC] (%)		0.0	0.4	0.0	0.7	0.0	0.3
MDNO [2×3ºC] (hr)		0.0	0.0	0.0	0.0	0.0	19.0
MDPO [2×3ºC] (hr)		0.0	6.0	0.0	33.0	0.0	9.0

Time Period, Statistic, Acceptable Error [ ], and Units ( )		45159 NW Lake Ontario	
Time Period	Begin	04/25/2017	
	End	06/07/2017	
Model		**FVCOM**	**POMGL**
Number of Comparisons		2266	2266
Mean Alg. Error (℃)		0.069	1.186
RMSE (℃)		1.473	2.977
SD (℃)		1.472	2.731
NOF [2×3℃] (%)		0.0	1.4
CF [3℃] (%)		96.8	67.1
POF [2×3℃] (%)		0.0	2.3
MDNO [2×3℃] (hr)		0.0	9.0
MDPO [2×3℃] (hr)		0.0	6.0

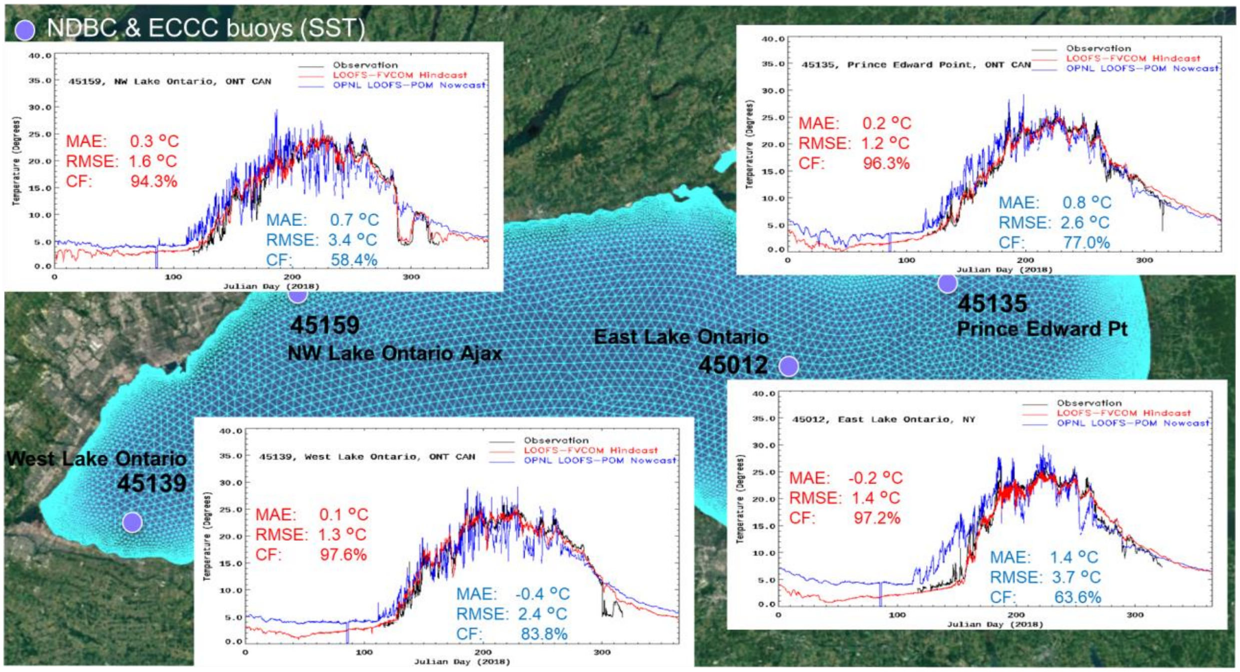

Figure 21. Time series plots of hourly LOOFS-POMGL nowcasts (blue) and LOOFS-FVCOM hindcasts of surface water temperature (red) vs. observations (black) at NDBC and ECCC buoys during 2018: 45139, West Lake Ontario, ONT; 45159, NW Lake Ontario Ajax, ONT; 45012, East Lake Ontario, ONT; and 45135 Prince Edward Pt, NY. MAE, RMSE, and CF at each station are shown individually on each panel for nowcasts (blue) and hindcasts (red).

Table 20. Summary of skill assessment statistics of the hourly LOOFS-FVCOM hindcasts and LOOFS-POMGL nowcasts of surface water temperature at NDBC and ECCC fixed buoys in Lake Ontario during 2018. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Time Period, Statistic, Acceptable Error [ ], and Units ( )		45012 East Lake Ontario		45135 Prince Edward Point		45139 West Lake Ontario	
Time Period	Begin	07/28/2018		08/22/2018		05/07/2018	
	End	11/10/2018		11/10/2018		07/26/2018	
Model		**FVCOM**	**POMGL**	**FVCOM**	**POMGL**	**FVCOM**	**POMGL**
Number of Comparisons		4823	4087	4818	4085	4068	3528
Mean Alg. Error (℃)		-0.188	1.380	0.243	0.849	0.117	-0.357
RMSE (℃)		1.376	3.679	1.194	2.600	1.295	2.368
SD (℃)		1.363	3.411	1.169	2.457	1.290	2.342
NOF [2×3ºC] (%)		0.0	1.2	0.0	0.0	0.0	2.0
CF [3ºC] (%)		97.2	63.6	96.3	77.0	97.6	83.8
POF [2×3ºC] (%)		0.0	11.2	0.0	3.4	0.0	0.1
MDNO [2×3ºC] (hr)		0.0	0.0	0.0	0.0	0.0	12.0
MDPO [2×3ºC] (hr)		0.0	97.0	0.0	39.0	0.0	3.0

Time Period, Statistic, Acceptable Error [ ], and Units ( )		45159 NW Lake Ontario	
Time Period	Begin	08/22/2018	
	End	11/10/2018	
Model		**FVCOM**	**POMGL**
Number of Comparisons		4861	4122
Mean Alg. Error (℃)		0.299	0.746
RMSE (℃)		1.561	3.442
SD (℃)		1.532	3.360
NOF [2×3ºC] (%)		0.1	2.8
CF [3ºC] (%)		94.3	58.4
POF [2×3ºC] (%)		0.2	5.6
MDNO [2×3ºC] (hr)		2.0	0.0
MDPO [2×3ºC] (hr)		6.0	11.0

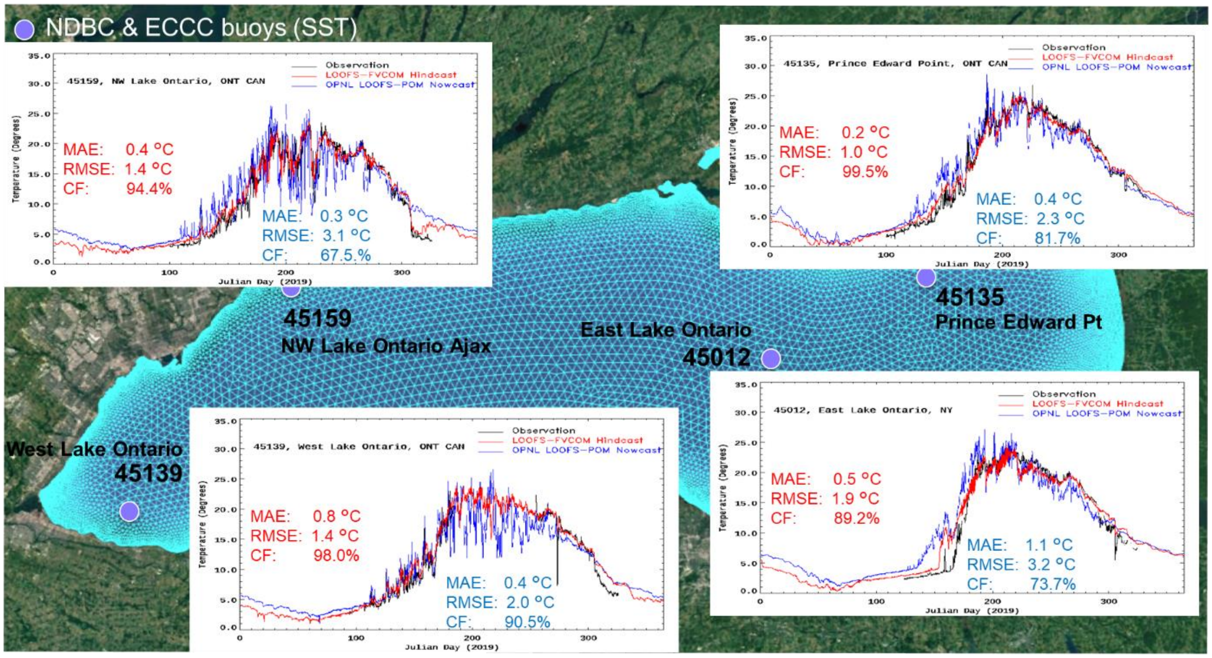

Figure 22. Time series plots of hourly LOOFS-POMGL nowcasts (blue) and LOOFS-FVCOM hindcasts of surface water temperature (red) vs. observations (black) at NDBC and ECCC buoys during 2019: 45139, West Lake Ontario, ONT; 45159, NW Lake Ontario Ajax, ONT; 45012, East Lake Ontario, ONT; and 45135 Prince Edward Pt, NY. MAE, RMSE and CF at each station are shown individually on each panel for nowcasts (blue) and hindcasts (red).

Table 21. Summary of skill assessment statistics of the hourly LOOFS-FVCOM hindcasts and LOOFS-POMGL nowcasts of surface water temperature at NDBC and ECCC fixed buoys in Lake Ontario during 2019. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Time Period, Statistic, Acceptable Error [ ], and Units ( )		45012 East Lake Ontario		45135 Prince Edward Point		45139 West Lake Ontario	
Time Period	Begin	06/24/2019		05/15/2019		05/15/2019	
	End	08/05/2019		10/12/2019		07/02/2019	
Model		**FVCOM**	**POMGL**	**FVCOM**	**POMGL**	**FVCOM**	**POMGL**
Number of Comparisons		4355	3270	5298	3968	3588	2695
Mean Alg. Error (℃)		0.522	1.054	0.239	0.413	0.763	0.427
RMSE (℃)		1.899	3.152	0.961	2.269	1.400	1.964
SD (℃)		1.826	2.971	0.931	2.232	1.174	1.918
NOF [2×3ºC] (%)		0.0	0.0	0.0	0.1	0.0	0.4
CF [3ºC] (%)		89.2	73.7	99.5	81.7	98.0	90.5
POF [2×3ºC] (%)		1.3	8.3	0.0	0.8	0.3	0.5
MDNO [2×3ºC] (hr)		0.0	0.0	0.0	0.0	0.0	0.0
MDPO [2×3ºC] (hr)		38.0	0.0	0.0	0.0	11.0	0.0

Time Period, Statistic, Acceptable Error [ ], and Units ( )		45159 NW Lake Ontario	
Time Period	Begin	05/15/2019	
	End	10/12/2019	
Model		**FVCOM**	**POMGL**
Number of Comparisons		5346	4004
Mean Alg. Error (℃)		0.427	0.329
RMSE (℃)		1.441	3.108
SD (℃)		1.376	3.091
NOF [2×3℃] (%)		0.1	4.5
CF [3℃] (%)		94.4	67.5
POF [2×3℃] (%)		0.1	0.9
MDNO [2×3℃] (hr)		3.0	9.0
MDPO [2×3℃] (hr)		2.0	6.0

7. SUMMARY AND DISCUSSION

NOS and NOAA's Great Lakes Environmental Research Laboratory (GLERL) conducted a collaborative project to develop a new version of GLOFS to provide improved lake predictions and to extend the forecast horizon out to 120 hours. NOAA/OAR/GLERL used FVCOM V4.3.1 with COARE V2.6 with the unstructured Los Alamos CICE turned on to conduct hindcasts for 2017, 2018, and 2019. The hindcast period was preceded by a one-year spin up. The years of 2017 and 2019 saw record high water levels in Lake Ontario. Meteorological forcing for the hindcasts was based on +1-hour forecast guidance from NOAA's High-Resolution Rapid Refresh (HRRR) V2 (Jan. 1, 2017 to July 14, 2018) and V3 (July 15, 2018 to Dec. 31, 2019). CSDL/CMMB personnel had the responsibility to skill assess the hindcasts in collaboration with the GLERL developers as part of the R2O transition of the FVCOM-based LOOFS from GLERL to NOS.

The FVCOM-based LOOFS hindcasts of water levels for the three hindcast years were compared to in-situ observations at eight NOS NWLON and CHS gauges. Water temperature hindcasts were evaluated against observations at four NWS/NDBC and ECCC fixed buoys. In addition, the hindcasts were compared to the performance of the nowcasts from the POMGL-based LOOFS. Unfortunately, there were no sub-surface water temperature or currents observations available to evaluate the hindcasts or the nowcasts during the hindcast years.

Water Levels

Overall, the hindcasts demonstrated good skill for simulating hourly water levels. The hindcasts passed the majority of NOS acceptance measures at all the U.S. and Canadian gauges. The average MAE (bias) for hindcasts over the three years among the eight gauges averaged approximately -2.75 cm (Table 22). The greatest RMSEs were found at the western and eastern ends of the lake where the MAE averaged -4.88 cm. Thus, the hindcasts underestimated the hourly water levels across the entire lake, especially at the western and eastern ends. RMSEs averaged 4.22 cm among the eight gauges with the greatest errors at the eastern and western ends with an average RMSE of 5.71 cm. In comparison to the nowcasts, hindcasts also underpredicted the hourly water levels but did so by 1.2 cm more than the nowcasts. The RMSE for the hindcasts was 1 cm smaller than for the nowcasts.

The assessment of the hindcasts to predict high water events was limited during the three years to two gauges: Oswego and Cape Vincent. The hindcast underpredicted the events by about 6 cm to 15 cm with RMSEs ranging from 5.6 cm to 15.7 cm with the greatest RMSEs at Cape Vincent. In the majority of instances, the hindcasts failed to pass the CF criteria for amplitude and timing. For the assessment of low water events, events occurred at more gauges, but not during all years. The MAEs ranged from -2.6 cm to 4.2 cm while the RMSEs ranged from 3.0 cm to 5.8 cm. The majority of hindcasts passed the NOS targets for amplitude, but failed to meet the CF target for timing.

Table 22. Summary of average MAE (bias) and RMSE for the three hindcast years (2017-2019) between LOOFS-FVCOM hindcasts vs. LOOFS-POMGL nowcasts of hourly water levels at U.S. and Canadian water level gauges.

Section of Lake	**NOS or CHS Water Level Gauge Name and Station ID**	**Statistic**	**LOOFS-FVCOM Hindcasts**	**LOOFS-POMGL Nowcasts**	**Difference (H – N)**
East	Cape Vincent	MAE	-5.10	3.17	-8.27
		RMSE	6.07	5.87	0.20
Middle	Olcott	MAE	-2.10	-2.17	0.07
		RMSE	3.00	4.60	-1.60
	Rochester	MAE	-0.03	-0.27	0.24
		RMSE	2.50	4.00	-1.50
	Oswego	MAE	0	0.20	-0.20
		RMSE	2.73	4.40	-1.67
	Cobourg	MAE	-0.30	-0.17	-0.13
		RMSE	2.70	4.20	-1.50
West	Toronto	MAE	-4.40	-3.80	-0.60
		RMSE	5.20	5.93	-0.73
	Burlington	MAE	-5.63	-5.07	-0.56
		RMSE	6.50	6.87	-0.37
	Port Weller	MAE	-4.40	-3.97	-0.43
		RMSE	5.07	5.97	-0.90
Entire Lake	**Average**	**MAE**	**-2.75**	**-1.51**	**-1.24**
		RMSE	**4.22**	**5.23**	**-1.01**

The hindcasts along with the nowcasts were also evaluated during three selected high/low water events associated with extra-tropical cyclones moving across the Great Lakes, one event for each hindcast year. Overall, the hindcasts underpredicted in the western and eastern ends and had higher frequency fluctuations than the nowcasts. The hindcasts did the best during the April 2018 event when surface winds resulted in low water in the western end while high water occurred in the eastern end. The nowcasts also did well for this event.

Surface Water Temperatures

Hindcasts closely matched the surface water temperature observations at the open lake and nearshore buoys, capturing both the seasonal trend and also sudden cooling and warming events during the three hindcast years. A summary of average MAE (bias) and RMSE over the three years at the four buoys is given in Table 23. The MAEs and RMSEs for hindcasts averaged around 0.5 ℃ and 1.5 ℃, respectively. The hindcasts passed the majority of NOS acceptance criteria at the buoys during the hindcast years. In comparison to the nowcasts, the hindcasts performed better at all four buoys during the hindcast years:

1) hindcasts more closely matched observations which resulted in lower MAEs by about 0.4 ℃ and lower RMSEs by 1.4 ℃ than the nowcasts,
2) hindcasts showed less unobserved high-frequency water temperature fluctuations than the nowcasts,
3) hindcasts did not exhibit the too fast spring warmup compared to the nowcasts, especially at the two offshore buoys, and
4) hindcasts did better overall in the fall cool down than nowcasts, except at 45012 during the month of October in both 2018 and 2019.

Table 23. Comparison of the average MAE (bias) and RMSE for the three hindcast years (2017-2019) between LOOFS-FVCOM hindcasts vs. LOOFS-POMGL nowcasts of surface water temperatures.

Buoy ID and Name	**Statistic (cm)**	**LOOFS-FVCOM Hindcasts**	**LOOFS-POMGL Nowcasts**	**Difference (H – N)**
45159 NW Lake Ontario Ajax	MAE	0.27	0.73	-0.46
	RMSE	1.50	3.17	-1.67
45012 East Lake Ontario	MAE	1.40	2.37	-0.97
	RMSE	2.00	3.67	-1.67
45135 Prince Edward Point	MAE	0.10	0.10	0.00
	RMSE	0.97	2.30	-1.33
45139 West Lake Ontario	MAE	0.37	0.53	-0.16
	RMSE	1.40	2.37	-0.97
Average	**MAE**	**0.54**	**0.93**	**-0.39**
	RMSE	**1.47**	**2.88**	**-1.41**

In summary, the hindcasts from the FVCOM-based LOOFS demonstrated good skill for simulating hourly water levels during the hindcast years. The hindcasts passed the majority of NOS acceptance criteria at all the U.S. and Canadian gauges. The water level hindcasts did worse in the western and eastern ends. In comparison to the nowcasts, the average RMSE was smaller by just 1 cm over the three years across the eight gauges. However, the bias for the hindcasts was higher than the nowcasts. Research is needed to determine the cause of the poor performance for water levels in these areas of the lake and implement changes in future upgrades of LOOFS. However, the hindcasts of surface water temperatures closely matched the observations at the open lake and nearshore buoys, capturing both the seasonal trend and sudden cooling and warming events, and simulating the spring warmup and autumn cool down much better than the nowcasts. Overall, the hindcasts performed better than the nowcasts.

The LOOFS-FVCOM code package was delivered to NOS/CO-OPS for setting up semi-operational nowcast/forecast runs on NOAA's WCOSS2 in FY2020 Q4. CO-OPS made changes in the specification of the lateral boundary conditions and in the choice of surface meteorological forcing in comparison to the semi-operational runs conducted by GLERL on their computer infrastructure. CO-OPS began semi-operational nowcast/forecast runs during the autumn of 2020. CO-OPS will continue their runs into 2022. The LOOFS became operational on WCOSS2 on October 26, 2022 along with the upgraded LSOFS.

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REFERENCES

Anderson, E.J., A. Fujisaki-Manome, J. Kessler, G.A. Lang, P. Y. Chu, J.G.W. Kelley, Y. Chen, and J. Wang, 2018: Ice forecasting in the next-generation Great Lakes Operational Forecast System (GLOFS*). J. Marine Science and Engineering*, 6, 123, doi:10.3390/jmse6040123.

Bechle, A., C. Wu, D.A.R. Kristovich, E. J. Anderson, D. J. Schwab, and A. B. Rabinovich, 2016: Meteotsunamis in the Laurentian Great Lakes. *Scientific Reports*, 6**,** 37832, doi.org/10.1038/srep37832.

Benjamin, S.G., S.S. Weygandt, J.M. Brown, M. Hu, C.R. Alexander, T.G. Smirnova, J.B. Olson, E.P. James, D.C. Dowell, G.A. Grell, H. Lin, S.E. Peckham, T.L. Smith, W.R. Moninger, J.S. Kenyon, and G.S. Manikin, 2016: A North American Hourly Assimilation and Model Forecast Cycle: The Rapid Refresh. *Mon. Wea. Rev.*, 144, 1669–1694. (Available at https://www.glerl.noaa.gov/pubs/fulltext/2017/20170011.pdf).

Boyce, F.M., M.A. Donelan, P.F. Hamblin, C.R. Murthy and T.J. Simons, 1989: Thermal structure and circulation in the Great Lakes, *Atmosphere-Ocean*, 27:4, 607-642, DOI: 10.1080/07055900.1989.9649358.

Chen, C., N. Liu, and R. Beardsley, 2003: An unstructured grid, finite-volume, three-dimensional primitive equations ocean model: Application to coastal ocean and estuaries. *J. Atmos. Oceanic Technol.*, 20, 159-186.

Chen, C., R. Beardsley, G. Cowles, J. Qi, Z. Lai, G. Gao, D. Stuebe, Q. Xu, P. Xue, J. Ge, S. Hu, R. Tian, H. Huang, L. Wu, and H. Lin, 2013: An Unstructured Grid, Finite-Volume Community Ocean Model FVCOM User Manual, fourth ed., SMAST/UMASSD, Technical Report-13-0701, UMASS-Dartmouth, Dartmouth, MA, 404 pp.

Chu, P., J. G. W. Kelley, A. J. Zhang, and K. W. Bedford, 2007: Skill Assessment of NOS Lake Erie Operational Forecast System (LEOFS). NOAA Technical Memorandum NOS CS 12, Silver Spring, MD, 73 pp (Available at https://repository.library.noaa.gov/view/noaa/2464).

Chu, P.Y., J.G.W. Kelley, G.V. Mott, A. Zhang, and G.A. Lang, 2011: Development, implementation, and skill assessment of the NOAA/NOS Great Lakes Operational Forecast System, *Ocean Dynamics*, 61, 1305-121, DOI: 10.10007/s10236-011-0424-5.

Fairall, C.W., E.F. Bradley, J.E. Hare, and A.A. Grachev, and J.B. Edson, 2003: Bulk parameterization of air-sea fluxes: updates and verification for the COARE algorithm, *J. Climate*, 16, 571-591.

Foken, T., 2006: 50 Years of the Monin–Obukhov Similarity Theory, *Boundary-Layer Meteorology,* 119**,** 431–447, doi.org/10.1007/s10546-006-9048-6.

Fujisaki-Manome, A., G.E. Mann, E.J. Anderson, P.Y. Chu, LE. Fitzpatrick, S.G. Benjamin, E.P. James, T.G. Smirnova, C.R. Alexander, and D.M. Wright, 2020: Improvements to lake-effect snow forecasts using a one-way air-lake model, *Journal of Hydrometeorology*, 21, 2813-2828, (Available at https://journals.ametsoc.org/view/journals/hydr/21/12/jhm-d-20-0079.1.xml).

Gat, G., C. Chen, J. Qi, and R.C. Beardsley, 2011. An unstructured-grid, finite-volume sea ice model: Development, validation, and application. *Journal of Geophysical Research*, 116, C00D04, doi: 10.1029/2010JC0066888.

Gronewold, A.D., E.J. Anderson and J. Smith, 2019. Evaluating operational hydrodynamic models for real-time simulation of evaporation from large lakes. *Geophysical Research Letters*, 46 (6), 3263-3269 (Available at https://doi.org/10.1029/2019GL082289).

Hess, K.W., T. F. Gross, R. A. Schmalz, J.G.W. Kelley, F. Aikman III, E. Wei, and M.S. Vincent, 2003: NOS Standards for Evaluating Operational Nowcast and Forecast Hydrodynamic Model System. NOAA Technical Report NOS CS 17, 48 pp (Available from https://repository.library.noaa.gov/view/noaa/2460).

Hunke, E.C., W.H. Lipscomb, A.K. Turner, N. Jeffery, and S. Elliott, 2010: CICE: The Los Alamos Sea Ice Model documentation and software user's manual. Tech. Rep. LA-CC-06-012, 116 pp.

Kantha, L.H. and C.A. Clayson, 2004: On the effect of surface gravity waves on mixing in the oceanic mixed layer. *Ocean Modelling,* 6**,** 101-124.

Kelley, J.G.W, Y. Chen, E.J. Anderson, G.A. Lang, and J. Xu, 2018: Upgrade of NOS Lake Erie operational forecast system (LEOFS) to FVCOM: Model development and hindcast skill assessment. NOAA Technical Memorandum NOS CS 40, 78 pp (Available at https://repository.library.noaa.gov/view/noaa/17253).

Kelley, J.G.W., Y. Chen, E.J. Anderson, G.A. Lang, and M. Peng, 2020: Upgrade of the NOS Lake Michigan and Lake Huron Operational Forecast System to FVCOM: Model Development and Hindcast Skill Assessment. NOAA Technical Memorandum NOS CS 42, 98 pp (Available at https://repository.library.noaa.gov/view/noaa/23891).

Peng, M., A. Zhang, E.J. Anderson, G.A. Lang, J.G.W. Kelley, and Y. Chen, 2019: Implementation of the Lakes Michigan and Huron Operational Forecast System (LMHOFS) and the Nowcast/Forecast Skill Assessment, NOAA Technical Report NOS CO-OPS 091, 28 pp. (Available at https://repository.library.noaa.gov/view/noaa/24001).

Quinn, F.H., 1992: Hydraulic residence times for the Laurentian Great Lakes, *Journal of Great Lakes Research*, 18(1), 22-28. (Available at https://www.glerl.noaa.gov/pubs/fulltext/1992/19920006.pdf).

Schmalz, R.A, Jr, 2014: Hydrodynamic model development for the San Francisco Bay Operational Forecast System (SFBOFS), NOAA Technical Report NOS CS 34, Silver Spring, MD, 294 pp (Available at https://repository.library.noaa.gov/view/noaa/2693).

Wei, E., Z. Yang, Y. Chen, J.G.W. Kelley, and A. Zhang, 2014: The Northern Gulf of Mexico Operational Forecast System (NGOFS): Model Development and Skill Assessment. NOAA Technical Report NOS CS 33, Silver Spring, MD, 190 pp.

Wei, E., Z. Yang, Y. Chen, J.G.W. Kelley, and A. Zhang, 2015: The Nested Northwest and Northeast Gulf of Mexico Operational Forecast Systems (NWGOFS and NEGOFS): Model Development and Hindcast Skill Assessment. NOAA Technical Report NOS CS 35, Silver Spring, MD, 33 pp.

Zhang, A., K.W. Hess, E. Wei, and E. Myers, 2013: Implementation of Model Skill Assessment Software for Operational Hydrodynamic Forecast System (Updated Version). NOAA Technical Report NOS CS 24, Silver Spring, MD, 64 pp.

Zhang, A., K.W. Hess, E. Wei, and E. Myers, 2006: Implementation of Model Skill Assessment Software for Water Levels and Currents in Tidal Regions. NOAA Technical Report NOS CS 24, Silver Spring, MD, 61 pp. (Available at https://repository.library.noaa.gov/view/noaa/2204).

Zhang, A., K.W. Hess, and F. Aikman, 2010: User-based skill assessment techniques for operational hydrodynamic forecast systems, *J. Oper. Oceanogr.*, 3(2), 11-24.

Zhang, A., P. Richardson, E. P. Myers, and L. Zheng, 2022: NOAA's Upgraded Northern Gulf of Mexico Operational Forecast System: Model Development and Hindcast Skill Assessment. NOAA Technical Report NOS CS 41, 94 pp. (Available at https://repository.library.noaa.gov/view/noaa/39504).