NOAA Technical Memorandum NOS CS 58

NOAA HURON ERIE CONNECTING WATERWAYS FORECASTING SYSTEM (HECWFS): DEVELOPMENT AND HINDCAST SKILL ASSESSMENT OF WATER LEVELS, WATER TEMPERATURES AND ICE CONCENTRATION

Silver Spring, Maryland
August 2024

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

Office of Coast Survey National Ocean Service

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LIST OF ACRONYMS

ADCP	Acoustic Doppler Current Profiler
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	Coupled Ocean Atmosphere Response Experiment (COARE) Bulk Air Sea Flux algorithm
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)
HECOFS	Huron Erie Corridor Operational Forecast System
HECWFS	Huron Erie Connecting Waterways Forecasting System
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
NSIDC	National Snow and Ice Data Center
NWLON	National Water Level Observation Network
NWS	National Weather Service

OBC	Open boundary conditions
OCS	Office of Coast Survey
OSU	The Ohio State University
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

NOAA's Huron Erie Connecting Waterways Forecasting System (HECWFS) is a 3-D lake numerical forecast modeling system which generate hourly nowcasts and short-range forecast guidance of 3-D water temperatures and currents, 2-D water levels, and ice concentration and thickness for the St. Clair River, Lake St. Clair and the Detroit River.

HECWFS uses the Finite Volume Community Ocean Model (FVCOM) as its core 3-D hydrodynamic model. HECWFS has a mean horizontal resolution approximately 236 m (0.15 mi), and a median horizontal resolution approximately 175 m (0.11 mi). The system has 21 vertical sigma levels with an integrated, unstructured mesh version of the Los Alamos Community Ice CodE (UG-CICE). HECWFS was developed initially by Dr. Eric Anderson, Dr. David Schwab, and Mr. Greg Lang at NOAA's Great Lakes Environmental Research Laboratory (GLERL) for a beach water quality study in 2008 (Anderson et al., 2010). The FVCOM version used for this project started from v2.6 then upgraded to v3.2.5, and then to v4.3.1 by Mr. James Kessler in 2021. HECWFS was forced by model forecast guidance from National Weather Center (NWS) and river observations from USGS gauges and analyses from the NWS' National Water Model (NWM). HECWFS has been run in semi-operational mode on GLERL computer systems since 2008. Predictions from the latest runs of HECWFS can be seen at the GLERL website: https://www.glerl.noaa.gov/res/glcfs/hecwfs/.

The transition of HECWFS to National Ocean Service (NOS) for operational implementation has been on NOS' 5-year Operational Forecast System (OFS) plan for many years. If transitioned to NOS, HECWFS was to be renamed the Huron-Erie Corridor Operational Forecast System (HECOFS). As part of an OFS transition from research to operations, the NOS Coast Survey Development Laboratory (CSDL) and NOS' Center for Operational Oceanographic Products and Services (CO-OPS) conduct the standard NOAA skill assessment of an OFS. The accuracy of predictions of a freshwater OFS (e.g., Lake Erie OFS) usually 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 by CSDL personnel.

The HECWFS hindcasts were conducted by GLERL for 2019, 2020, and 2021 using FVCOM Version 4.3.1 with the UG-CICE model turned on and using 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 water level, HECWFS takes into account a number of physical drivers. These include atmospheric conditions (surface pressure, wind stress, etc.), water level conditions upstream and downstream of the model domain (Lake Huron and Lake Erie, respectively) and river inflows.

For the temperature of waters flowing into the lake, the water temperatures were specified at eight river locations: Black River, Pine River, Belle River, Clinton River (two inlet locations), Sydenham River, Thames River, and River Rouge.

Surface meteorological forcing for the HECWFS hindcasts was provided very short-range forecast guidance from the hourly forecast cycles of the NOAA's High-Resolution Rapid Refresh (HRRR) analysis and forecast modeling system. The 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.

The hindcasts of water levels and surface water temperatures for the three hindcast years, 2019, 2020, and 2021 were compared to in-situ observations in St. Clair River, Lake St. Clair, and Detroit River. 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 two observing platforms operated by NOS CO-OPS and Environment and Climate Change Canada (ECCC). Unfortunately, there were no sub-surface water temperature or currents observations for comparison to the hindcasts.

The hindcasts of water levels demonstrated good skill overall for simulating water levels during the three hindcast years. The hindcasts passed the majority of NOS Standard acceptance Criteria at all the U.S. and Canadian gauges. The average Mean Algebraic Error (bias) and the mean Root Mean Square Error (RMSE) for hindcasts over the three years among the fifteen gauges are approximately 3.75 cm and 8.55 cm, respectively. The maximum overpredictions mainly happened near the Lake Clair shore during the ice seasons. The ice jams and ice breaking activities could be the major contribution to the discrepancies.

The hindcasts of water temperatures closely matched the observations at the two verification sites, capturing both the seasonal trend, and sudden cooling and warming events. The average bias for the hindcasts was about -0.2 ℃ with an average RMSE of 0.6 ℃.

The hindcasts of ice concentrations for the three ice seasons (2018-2019, 2019-2020, 2020-2021) showed high agreement with the National Ice Center's Lake St. Clair ice analysis. HECWFS tends to predict longer ice periods compared to the analyses, i.e., earlier first-day-of-ice, and late last-day-of-ice. Compared to the climatology, the daily lake-wide ice concentration showed similar trends and peaks, however slightly overpredicted the ice coverages, especially during the beginning and the end of the ice seasons. Overall, the ice coverage forecast guidance is better than climatology. The assessment of HECWFS' ice hindcasts marked the first time NOS has evaluated ice predictions from NOS OFS.

NOS/CO-OPS management decided in mid-2023 not to move forward in transitioning HECWFS into the NOS OFS suite due to concerns about the bathymetry and mesh and also staff limitations. It is hoped that the results presented in this report will be useful to future model developers when a new lake forecast modeling system is developed, tested, and implemented for the Huron-Erie Corridor during the next three to five years.

1. INTRODUCTION

NOAA's Huron Erie Connecting Waterways Forecasting System (HECWFS), which is considered part of the Great Lakes Operational Forecasting System (GLOFS), was designed to provide nowcasts and short-range forecast guidance of two-dimensional water levels, three-dimensional currents and water temperatures, and ice conditions for this important waterway channel connecting Lake Huron with Lake Erie. HECWFS uses the Finite Volume Community Ocean Model (FVCOM) as the core numerical ocean circulation or hydrodynamic forecast model 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. One single mesh was used to cover the St. Clair River, Lake St. Clair, and the Detroit River to provide accurate hydraulic and hydrodynamic predictions given that these three water bodies are hydraulically linked.

HECWFS was developed and has been run semi-operationally at GLERL since 2008. The system was originally meant to become part of the NOS GLOFS (Chu et al., 2011) as the Huron Erie Corridor Operational Forecast System (HECOFS) to generate forecast guidance of water levels, currents, water temperatures, and potentially ice concentration and thickness out to 120 hours. However, NOS/CO-OPS management decided in 2023 not to transition HECWFS into operations, due to concerns about the bathymetry and mesh and also staff limitations.

This report documents the development and testing of the HECWFS as well as the results of a skill assessment of hindcasts for water levels, surface water temperatures during 2019, 2020 and 2021 and the ice concentrations during ice seasons of 2018-2019, 2019-2020, and 2020-2021. A brief overview of the Huron-Erie corridor is given first.

2. HURON-ERIE CORRIDOR

The 150 km (90 mi) Huron-to-Erie Corridor (HEC) stretches from the southern end of Lake Huron through the northern tip of Lake Erie and encompasses the Detroit and St. Clair rivers, as well as Lake St. Clair. The corridor is a critical part of the Great Lakes Navigation System, a continuous 27-foot-deep draft waterway that extends from the western end of Lake Superior at Duluth, MN to the Gulf of St. Lawrence in the Atlantic Ocean. In addition, millions of people on the U.S. and Canadian sides of the corridor rely on the St. Clair-Detroit River System for drinking water, and the coastal wetlands of the region are critical habitat for many species of animals (EGLE, 2024).

Figure 1. The Huron-Erie Corridor (Hondorp et al., 2014).

The St. Clair River (French: Rivière Sainte-Claire), which some consider a strait, is approximately 64 km (40 mi) long flowing in the southward direction. The fall in water level from Lake Huron to Lake St. Clair is about 1.5 m (5 ft). The river has three distinct reaches with mid-channel depths varying between 8.3 m to 21.3 m (27 ft to 70 ft) (USCE, 2023). Water flow rates in the river can range from 230,000 cubic feet per second (cfs) to 130,000 cfs. According to USCE (2023), the river is a significant Great Lakes connecting channel with 53.7 metric tons of commerce passing through in 2021. The St. Clair River feeds Lake St. Clair, but prior to entering the lake, the river divides into several channels and canals creating an extensive delta known as the St. Clair Delta or Flats. These include the St. Clair Channel, St. Clair Canal, North Channel, Middle Channel, and South Channel. The St. Clair Delta is the only major river delta in the Great Lakes and is considered the world's largest delta that enters a freshwater lake.

Lake St. Clair measures about 42 km (26 mi) from north to south and about 39 km (24 mi) from east to west. With a surface area of 1,114 square km (430 sq mi) and an average depth of 3.4 m (11 ft), Lake St. Clair is far smaller and shallower than the other Great Lakes. However, it is 8.2 m (27 ft) deep in the navigation channel which is dredged for lake freighters by the U.S. Army Corps of Engineers (Lake St. Clair Conference Summary Report, 2000). There are two distinct areas of the lake: the main body of the lake, lying south and west of the St. Clair Delta and the northern Anchor Bay area, north of a line between Huron Point and the Middle Channel. The average water residence time for the lake is about seven days, but can be as little as two days for water flowing through the maintained navigation channel which bisects the lake (Great Lakes Commission, 2000).

The Detroit River flows west and south for 44 km (28 mi) from Lake St. Clair to Lake Erie, and is 0.8 to 4.0 km (0.5 to 2.5 mi) wide. By definition, the river can be classified as both a river and a straight — a strait being a narrow passageway connecting two large bodies of water. This is how the Detroit River earned its name from early French settlers (i.e., from the French Rivière du Détroit, translated as "River of the Strait"). The river's main channels are dredged by the USCE to provide a 7.8 m (25.5 ft) for safe marine navigational draft.

The driving forces of the hydrodynamics in the connecting channel are driven by water levels at Lake Huron and Lake Erie, the inflow from tributaries, as well as by wind stress on Lake St. Clair (Anderson et al., 2010). Thus, for the lake, its circulation pattern is determined by the flow of water from St. Clair River and the winds over the lake. With regards to currents, during sustained strong northerly to northeasterly winds on Lake Huron, water current velocities in the upper St. Clair River are increased. During the majority of the time, the flow in the Detroit River is from the north to the south; however, during rare occasions and for a short period of time, the flow reverses in which the water flows from south to north. This flow reversal in the river when an easterly wind temporarily raises the water level in the western basin of Lake Erie, as high as seven feet above LWD.

During the winter months, ice cover can be a significant factor in both rivers and Lake St. Clair. The upper St. Clair River does not usually freeze over and is generally free of ice above the delta (Derecki and Quinnl, 1986). However, during certain weather conditions, Lake Huron can provide an almost unlimited supply of ice flows which produce heavy ice concentrations and severe ice jams in the lower part of the river (Derecki and Quinn, 1986). These ice jams can have significant impacts on marine navigation (e.g., stopping traffic, ships trapped in the ice) and cause flooding along the river, often between Algonac and St. Clair, MI. One of the most famous ice jams occurred in April 1984 which lasted for 24 days (Derecki and Quinn, 1986). Icebreaking ships from the U.S. and Canadian Coast Guards are used to break up the ice often with technical advice from the USCE.

Given its shallowness and surface area, ice conditions in Lake St. Clair can respond quickly to wind and air temperature fluctuations. The lake is usually covered by ice by the end of January and becomes free of ice in March. During the period of the greatest ice cover, the ice is typically shore-fast and thick in the bays and pancake ice in the middle of the lake (Melby et al., 2012). The area of the lake near the head of the Detroit River is usually ice free because of an ice bridge forms above the river head in Lake St. Clair; however, the area could fill up with drift ice following extratropical cyclone-forced breakup of the ice bridge (Melby et al., 2012). During breakup, the drift ice will move to the entrance of the Detroit River where strong river currents move it downstream towards Lake Erie. According to Derecki and Quinn (1986), ice issues on the Detroit River are usually much less severe and large ice jams are rare.

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 the lateral boundary, surface boundary, and initial conditions that were specified for the HECWFS hindcast runs. These configurations do not necessarily reflect possible future operational model product for the Huron-Erie Corridor system, which would run operationally on the NOAA Weather and Climate Operational Supercomputing System (WCOSS2) located in Manassas, VA and Phoenix, AZ, as these configurations will be subject to operational decisions made by NOS/CO-OPS.

3.1. Description of Model

The core numerical coastal ocean circulation model used by HECWFS is FVCOM, a prognostic, unstructured-mesh, finite-volume, free-surface, three-dimensional primitive equation ocean model. It was 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 HECWFS, the Mellor Yamada 2.5-level 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 and depth-averaged velocities are obtained by solving vertically averaged momentum and mass (volume) conservation 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), LOOFS (Kelley et al., 2023) 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). UG-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 UG-CICE model includes components for ice thermodynamics and ice dynamics, using elastic-viscous-plastic rheology for internal stress, and produces 2-D fields of ice concentration, thickness, and velocity. A multi-category ice thickness distribution (ITD) model is employed in UG-CICE to resolve mechanical deformation as well as growth and decay. UG-CICE allows the specification of several categories of ice thickness. The ice surface albedo depends on surface temperature and thickness of ice, and also snow cover, melt ponds on the 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 C_{Dai} is a function of wind speed U, given as $C_{Dai} = (1.43 + 0.052U) \times 10^{-3}$ 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 (Liu and Schwab, 1987). The SOLAR algorithm was developed at the NOAA/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). 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).

For HECWFS, FVCOM Version 4.3.1 and the COARE Version 2.6 bulk flux algorithm were used for the HECWFS 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 HECWFS 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 176.784 m (580 ft) above the International Great Lakes Datum (IGLD) of 1985. This value was chosen such that all depths would be negative in the model grid. Though the surface of Lake St. Clair is at 175 m IGLD85, the domain includes regions upstream which are at higher elevation. The model bathymetry is shown in Fig. 2.

High resolution NOAA coastline data were applied to delineate the land boundary. The model mesh in the horizontal is composed of 36,477 triangular elements and 20,689 nodes. The total area is around 1,340 km^2, and the mean resolution is 236 m, the median resolution is 175 m. The resolution ranges from 100 m in the rivers to 300 m in Lake St. Clair and 50 m in the tributaries. The mesh is depicted in Fig. 3. The model has 21 uniform sigma levels with distribution referenced to the Great Lakes low water datum for Lake St. Clair. 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.

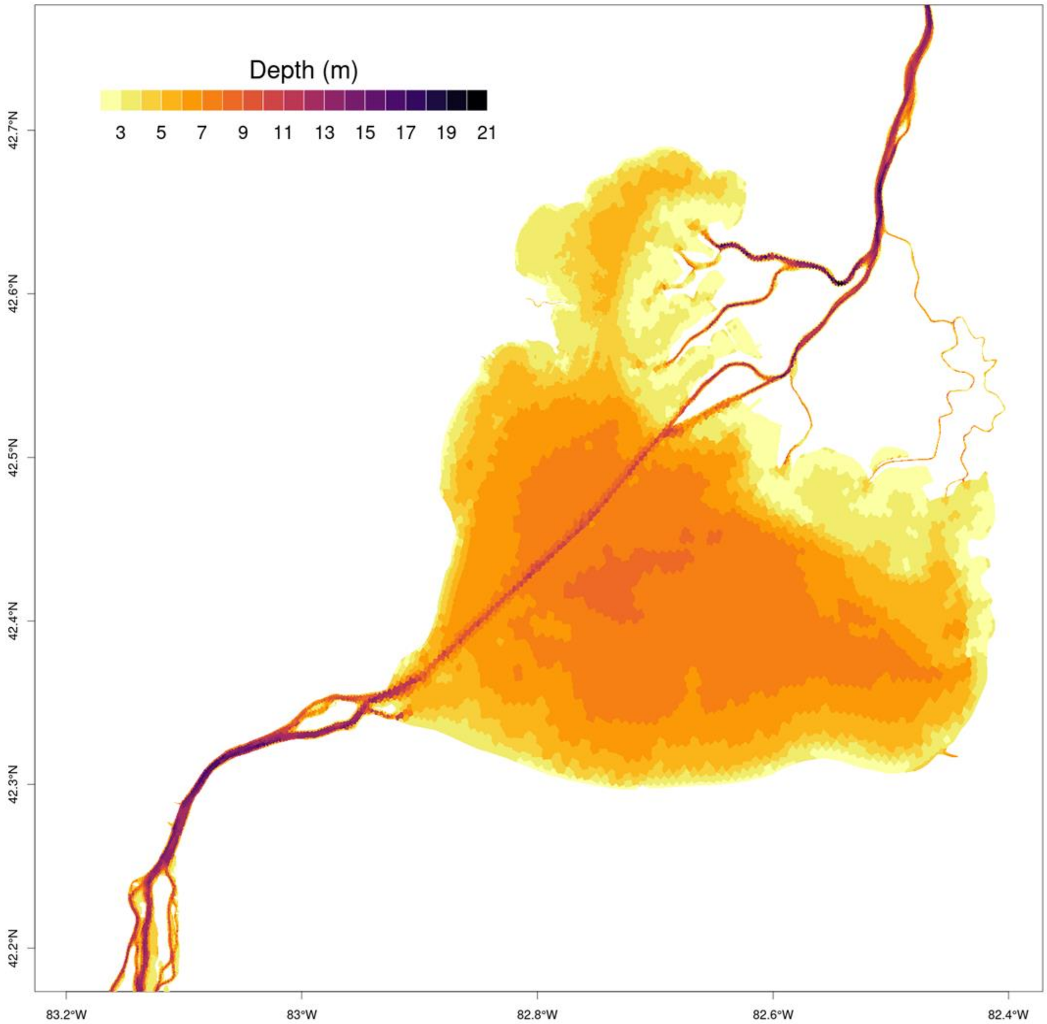
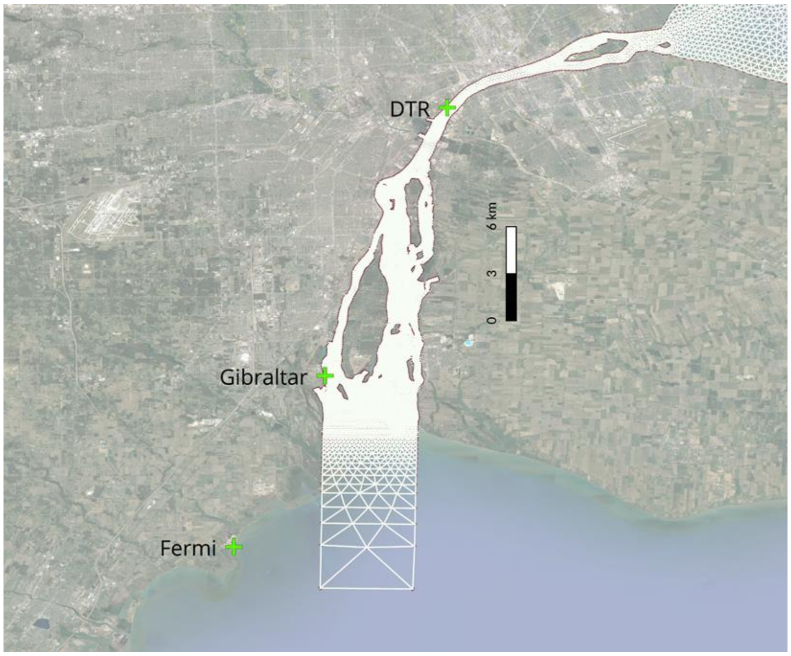


Figure 2. Map of the Huron Erie Corridor bathymetry (m) used by HECWFS, referenced to 179.784 m (580 ft) above IGLD of 1985. The mean depth is 5.7 m (18.8 ft).

Figure 3. Map depicting the FVCOM mesh domain for HECWFS. The mean horizontal resolution is 236 m with 21 vertical sigma levels.

The mesh is artificially extended at both the inlet at Lake Huron and the outlet at Lake Erie to a single element (Figure 4). According to Anderson et al. (2010), an iterative process was used to design the inlet and outlet boundary so that a single element could be used to represent a boundary condition that provides stability and the correct flow in the realistic geometry. The extensions were implemented to eliminate the flow anomalies (e.g., erroneous eddies) that can occur near the open-boundaries of unstructured meshes, but do not affect the results in the realistic part of the mesh (Anderson et al., 2010).

(a) Upstream



(b) Downstream

Figure 4. Mesh settings at open boundaries: (a) Upstream and (b) Downstream.

3.4. Lateral Boundary Conditions

The lateral boundary conditions for the HECWFS hindcasts included the observed water levels near Lake Huron and Lake Erie and tributary inflows along the corridor. The water level along the outlet at the mouth of the Detroit River (southern boundary) was prescribed using the two nearest gauges at Gibraltar (upstream of the outlet) and Fermi Power Plant (downstream outlet) using the following equation,

$$G - \alpha(G - F) + \beta$$

where G = Gibraltar (cm), F = Fermi (cm), α = 1.8 cm, β = 17.8 cm.

Parameters α and β were calibrated to optimize model predictions of water level, as compared to gauges in the Detroit River, and discharge measurements made in the river. The mesh and water level parameterization were done to allow for the possibility of flow reversals (i.e., water flows north instead of south), which occurs sometimes in the Detroit River.

At the upstream boundary condition near Lake Huron, the water level is prescribed from the Dunn Paper gauge through an adjustment (+0.018 m). The adjusted value was calibrated to optimize modeled water levels and flows as compared to gauge and Acoustic Doppler Current Profiler (ADCP) observations.

Discharge for eight tributaries along the corridor were prescribed by analyses from the NWS National Water Model (NWM). The locations of these eight tributaries are given in Fig. 5.

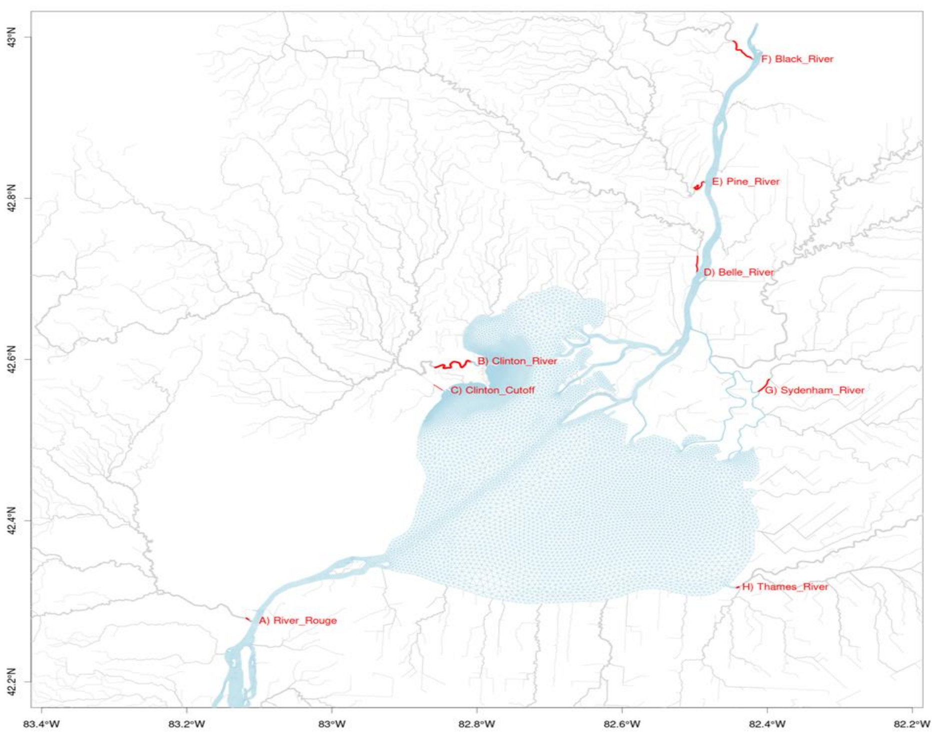


Figure 5. The National Water Model (NWM) stream network forecast points. Highlighted in red are the eight locations where NWM predictions are used by HECWFS.

The water temperatures were specified for eight rivers for the Lake Huron-Erie Corridor. Due to limited availability of stream gauges that have water temperature data in near-real time, the available temperature from one or two USGS gauges were applied to all eight streams. The water temperatures for all 8 rivers are defined by the USGS Clinton River gauge (04165500). Comparison over previous years when multiple temperature gauges were available for more rivers show that the seasonal variability is much greater than the spatial variability by an order of magnitude (i.e., it's reasonable to assume that one temperature is fairly representative of all the rivers at a given time of year). The water temperatures for these locations are specified in the FVCOM *casename_river.nc* file.

3.4. Surface Boundary Forcing

The surface meteorological forcing used by HECWFS 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, 4) u- and v-wind components (~10 m AGL), 5) downward short-wave radiation, and 6) downward long-wave radiation.

The +2-hour forecast projection output from HRRR Version 3 was used for forcing the hindcasts from July 12, 2018 to Dec. 1, 2020 and the +1-hour forecast projection output from HRRR Version 4 was used for Dec. 2, 2020 to Dec. 31, 2021. The HRRR output was obtained from the NOAA High Performance Storage System (HPSS) runtime history archives maintained by NCEP Central Operations. 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

For accurate operation, the model requires a realistic water surface profile along the corridor from Lake Huron to Lake Erie. In order to achieve this profile, the model was initialized with a single water level for the entire domain, corresponding to a typical value from the headwaters near Lake Huron, and constant bottom roughness, z_0, for all model elements. The downstream water level boundary condition was decreased incrementally in simulation until it reached a typical value for the outlet at Lake Erie, resulting in a water surface profile that roughly approximated the realistic or observed profile from NOAA gauges along the corridor. Further refinement was achieved by calibrating the bottom roughness, z_0, by river reach, where each reach was defined as the elements between pairs of water level gauges along the domain. The calibration consisted of seven steady-state scenarios adopted from Holtschlag and Koschik (2002 a, b) and detailed in Anderson et al. (2010). In summary, the steady-state scenarios consisted of mean flow measurements at several cross-sections throughout the corridor and the associated water levels from ten NOAA gauges. Beginning with the first scenario, the model was adjusted to match the inlet and outlet water levels for the given period. Working from the outlet (Lake Erie) to the inlet (Lake Huron), the z_0 for all elements in a given river reach were adjusted until the steady-state flow in that reach matched the observed flow. This procedure was repeated across all scenarios, and the bottom roughness for the given reach was determined to minimize the differences between flow and water level across all scenarios. The process was then carried out by working upstream, sequentially, for all reaches within the domain. The result of the calibration was a set of bottom roughness values for each model element as determined by river reach. Further detail is provided in Anderson et al. (2010).

4. HINDCAST PERIODS

Three hindcast model simulations using the FVCOM-based HECWFS were conducted by GLERL on their Linux cluster in Ann Arbor, MI. The hindcast verification period for water levels and surface water temperatures covered from Jan. 1 to Dec. 31, 2019; Jan. 1 to Dec. 31, 2020; and Jan. 1 to Dec. 31, 2021. The series of three simulations thus serves as a continuous 3-year simulation without reinitialization or data assimilation. For the evaluation of the ice coverage, the following ice seasons were used: Dec. 1, 2018 to May 30, 2019; Dec. 1, 2019 to May 30, 2020; and Dec. 1, 2020 to May 30, 2021.

4.1 Description of Hindcast Periods

Monthly water levels during 2019, 2020, and 2021 in Lake St. Clair were above the long-term average as depicted in Fig. 6.

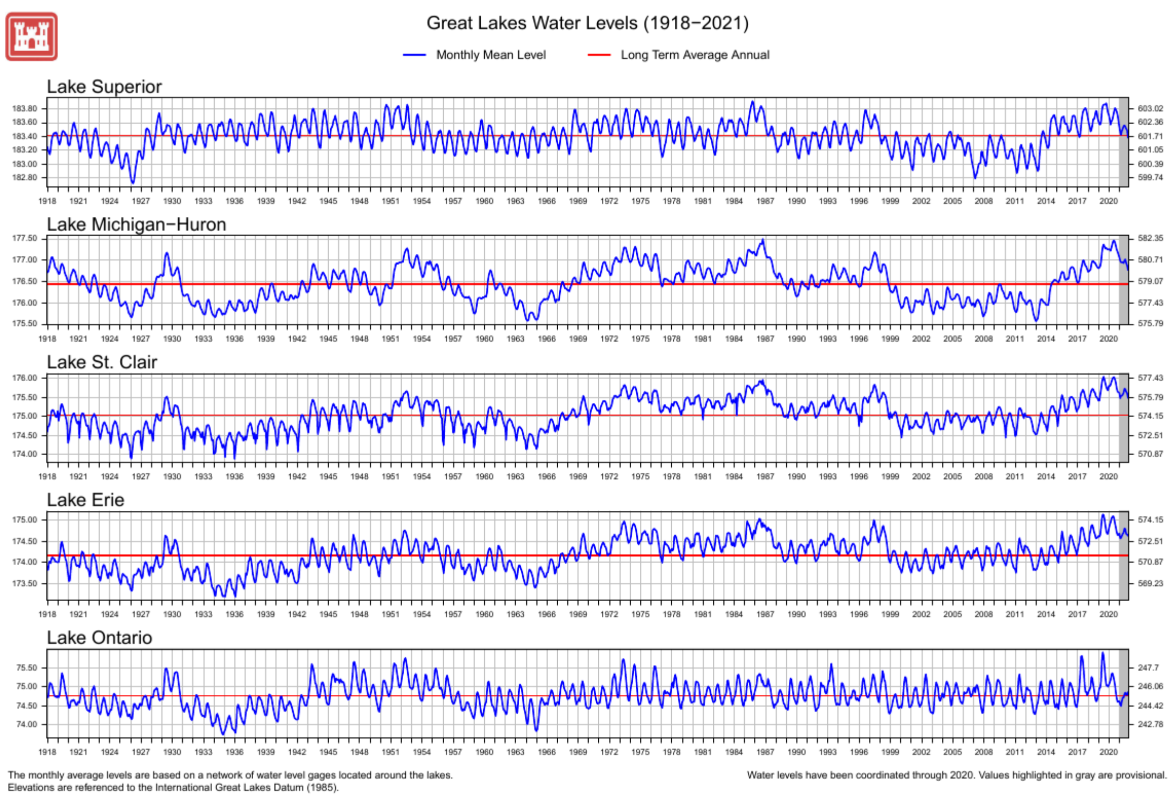


Figure 6. Time series of monthly mean lake-wide water levels for each of the Great Lakes from 1918 to 2021. Elevations are referenced to the International Great Lakes Datum (1985). (Source: https://www.lre.usace.army.mil/Missions/Great-Lakes-Information/Great-Lakes-Information-2/Water-Level-Data/).

The fig. 7 indicates that the annual maximum ice cover for Lake St. Clair for the three hindcast years was about 100% for 2019, 77% for 2020, and 100% for 2021, respectively. The dates of maximum ice coverage were Jan. 30-Feb. 12, March 1, Feb. 21-23 for the ice seasons of 2018-19, 2019-20, and 2020-21, respectively. (https://coastwatch.glerl.noaa.gov/statistic/statistic.html).

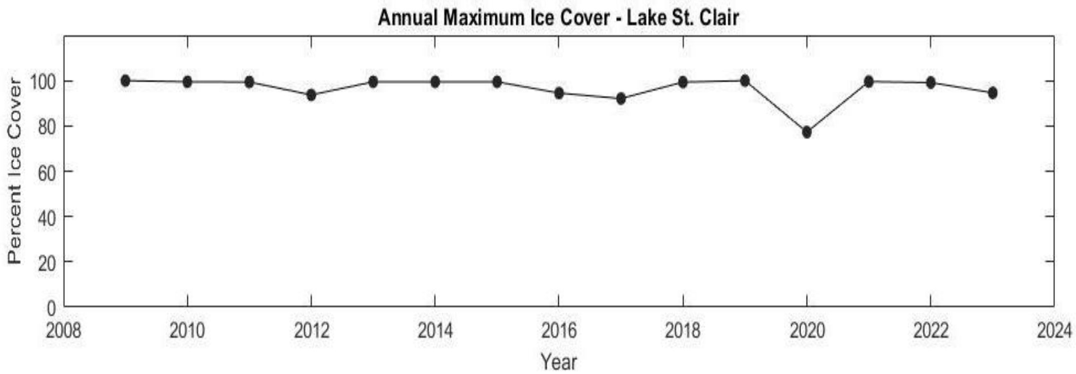


Figure 7. Lake St. Clair annual maximum ice cover (percent) from ice season 2008-09 to 2022-23. (Source: https://coastwatch.glerl.noaa.gov/statistic/ice/xlsx/gl_ice_1973-2022.xlsx).

The ice season of 2018-2019 was classified by NOAA as “average” (Maffia, 2019). According to Maffia (2019), “environmental conditions proved to be challenging due to a Polar Vortex in late January that rapidly formed ice. Additionally, persistent wide-swinging temperature fluctuations through February made track maintenance difficult. Ice jams coupled with high water levels in the major rivers put many coastal communities on flood alert. A heavy wind event in March pressurized massive amounts of ice in western Lake Erie which created pressure ridges that were several feet thick and required the attention of Canada's polar rated icebreakers.” The USCG end of season ice report for the 2018-2019 ice season stated that maximum ice conditions in Lake St. Clair/St. Clair River was 12-18 inches plate ice with 2-4 inches brash accumulations and for the Detroit River, 6-12 inches free floating plate ice (Maffia, 2019).

The 2019-2020 Great Lakes ice season was classified by NOAA as a “well below normal ice cover, below normal ice thickness, and below normal extent” (NAIS, 2020). According to NAIS (2020), the “coldest consistent temperatures of the year occurred from mid-February until early March. During the second week of February ice formed across much of Lake St. Clair and the western basin [of Lake Erie] in concentrations from 5 to 9 tenths of new and thin lake ice. Peak ice cover occurred in the first week of March behind the late February low pressure system. Ice was mainly new and thin lake ice in Lake St. Clair and the western basin [of Lake Erie].” The USCG end of season ice report was not found for the 2019-2020 ice season.

The 2020-2021 Great Lakes ice season was classified by NOAA as a “below average” normal ice year (Floyd, 2021). According to Floyd (2021), in “early February, sustained cold temperatures settled upon the [Great Lakes] region causing rapid ice growth in the St. Clair River and Western Lake Erie, prompting the initiation of Operation Coal Shovel. The cold temperatures caused high water levels resulting in flooding in the St. Clair River. Freezing temperatures persisted throughout the month of February and part way into March. Ice began melting throughout March and commercial vessels were able to transit unhindered by ice by late March." The end of season ice report for the 2020-2021 ice season stated that maximum ice conditions in Lake St. Clair/St. Clair River was 2-6 inches plate ice and apparently no ice for the Detroit River. The St. Clair River was available for navigation 91% of the time.

5. METHOD OF EVALUATION

The HECWFS 6-min (for NOS stations) or 3-hourly (for CHS stations) hindcasts of water levels and 3-hourly water temperatures for 2019, 2020 and 2021 were verified against observations with the same frequencies in the Huron-Erie corridor. The hindcasts of ice concentrations were compared with daily NOAA/GLERL Great Lakes Surface Environmental Analysis (GLSEA) and also NWS/National Ice Center (NIC) Ice Charts. The GLSEA is a "digital map of the Great Lakes surface water temperature and ice cover produced daily".

5.1 Acquisition of Hindcasts and Nowcasts at Verification Locations

Following the completion of the hindcasts, the 6-min or 3-hourly values of water levels at the nearest FVCOM mesh points to NOS and CHS gauges were extracted and written to netCDF files. Similarly, 3-hourly values of the surface (sigma layer 0) water temperatures at the mesh points closest to the NOS/CO-OPS gauge and the ECCC buoy were written to netCDF files.

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 HECWFS 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 6-min and 3-hourly water levels was based on comparisons of time series from the FVCOM-based hindcasts to observations during 2019, 2020, and 2021. The comparison of time series of the water level hindcast vs. observation was 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 water levels. 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 hindcasts were compared with the observed water levels recorded at NOS/CO-OPS National Water Level Observing Network (NWLON) and Canadian Hydrographic Service (CHS) gauges which are located within the HECWFS domain (Fig. 8). Information about these stations is given in Table 2. The 6-minute water level observations from the NOS/CO-OPS NWLON gauges were obtained from CO-OPS online archives at http://tidesandcurrents.noaa.gov. The 3-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.

(a) NOS gages (b) CHS gages

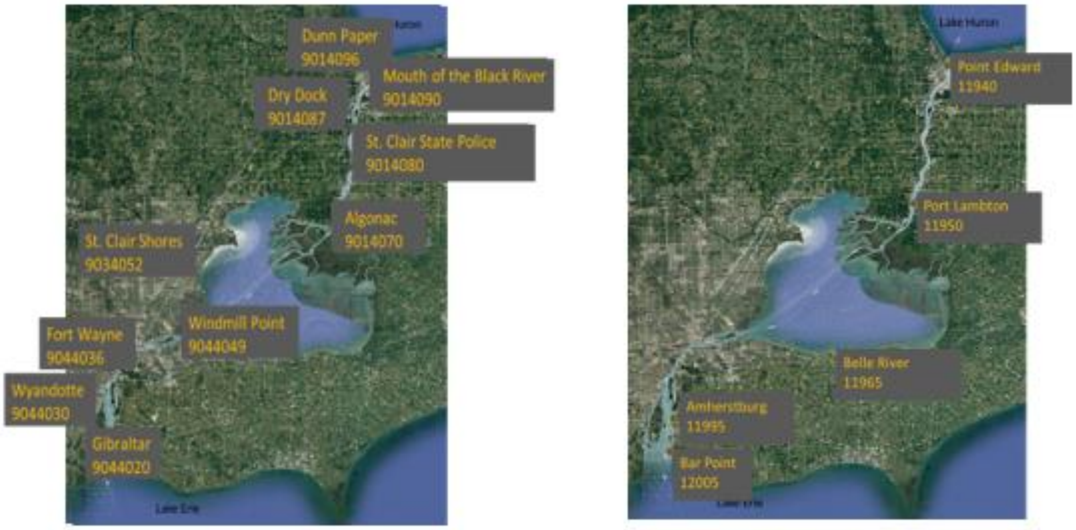


Figure 8. Locations of NOS and CHS water-level gauges used to evaluate HECWFS water level hindcasts.

Table 2. Information on NOAA/NOS/CO-OPS and CHS gauges whose water level observations were used to evaluate the HECWFS 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)
Dunn Paper	MI	9014096	N/A	43.003	82.422
Mouth of the Black River	MI	9014090	MBRM4	42.975	82.418
Dry Dock	MI	9014087	N/A	42.945	82.443
St. Clair State Police	MI	9014080	N/A	42.812	82.485
Algonac	MI	9014070	AGCM4	42.622	82.527
St. Clair Shores	MI	9034052	N/A	42.473	82.880
Windmill Point	MI	9044049	N/A	42.357	82.930
Fort Wayne	MI	9044036	N/A	42.298	83.093
Wyandotte	MI	9044030	N/A	42.202	83.147
Gibraltar	MI	9044020	N/A	42.092	83.187
Point Edward	ON	11940	N/A	42.991	82.421
Port Lambton	ON	11950	N/A	42.657	82.507
Belle River	ON	11965	N/A	42.296	82.711
Amherstburg	ON	11995	N/A	42.144	83.114
Bar Point	ON	12005	N/A	42.062	83.115

5.4. Evaluation of Surface Water Temperature Hindcasts

The evaluation of 3-hourly hindcasts of the surface water temperatures was based on comparisons of time series between the hindcasts and observations at two locations in Lake Huron-Erie Corridor. 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 °C to meet the acceptable error of draft of 7.5 cm (3 inches), as water density is a function of water temperature and salinity. Since the Great Lakes are considered freshwater and non-tidal, there is no preset standard for lake temperature predictions. However, 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, former physical oceanographer at NOAA/GLERL, suggested a 3ºC criteria for water temperature skill assessment in the Great Lakes region (personal communication). Therefore, 3°C (5.4°F) criteria for water temperature were used for the Great Lakes, the same criteria used in earlier evaluations of GLOFS (Chu et al., 2007; Kelley et al., 2018).

The HECWFS 3-hourly hindcasts were compared to 3-hourly observations at the CO-OPS Algonac gauge (9014070) in the St. Clair River and at ECCC Lake St. Clair buoy (45147) in the middle of Lake St. Clair (Fig. 8). The 3-hourly water temperature observations from two sites were obtained from the CO-OPS and ECCC websites. Geographic information for the two sites is given in Table 3. Unfortunately, historical water temperature observations associated with the USGS Detroit River at Fort Wayne, MI Doppler current meter (04165710) and from the Belle Island, MI water intake at the eastern end of Belle Isle, MI, where Lake St. Clair flows into the Detroit River, were not easily accessible and thus were not used to evaluate the hindcasts.

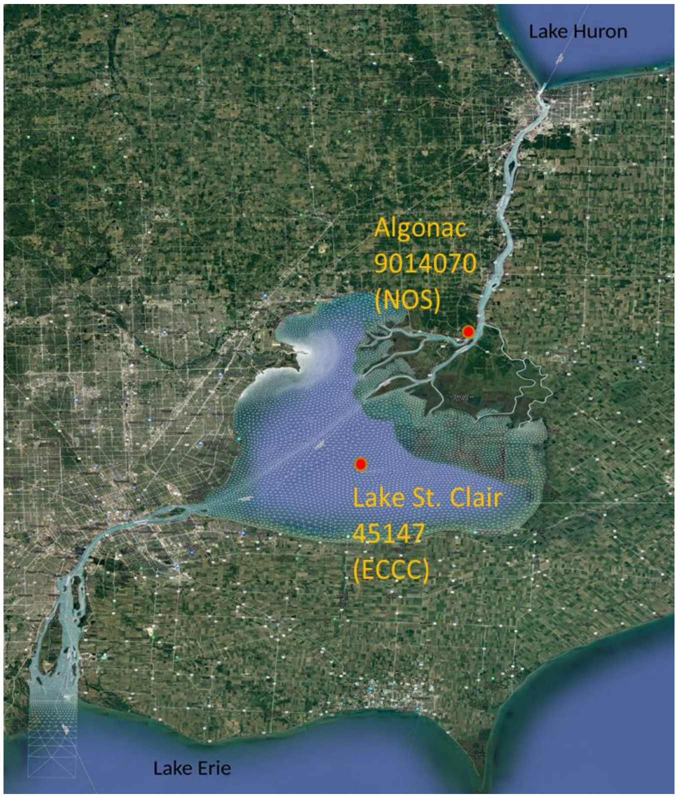


Figure 9. Locations of the NOS/CO-OPS Algonac gauge and the ECCC Lake St. Clair fixed buoy used to evaluate HECWFS surface water temperature hindcasts.

Table 3. Information about NOS/CO-OPS gauge and ECCC open lake fixed buoy whose surface water temperature observations were used to evaluate the HECWFS hindcasts.

Buoy Name	Agency	Prov. or State	NOS Buoy Platform ID	Water Depth (m)	Sensor Depth (m)	Coordinates	
						Latitude (deg N)	Longitude (deg W)
Algonac	NOS/CO-OPS	MI	9014070	N/A	1.92	42.622	82.527
Lake St. Clair	ECCC	ON	45147	6	N/A	42.430	76.870

The water temperature sensor on the CO-OPS gauge is located approximately 6.3 ft (1.92 m) below Low Water Datum (LWD). The specific depth of the water temperature sensor under the ECCC buoy is unknown, but likely similar to the depths of NWS/NDBC buoy’s temperature sensors in the Great Lakes (i.e., about 1 m).

6. HINDCAST SKILL ASSESSMENT RESULTS

The results of the skill assessment of the 2019, 2020, and 2021 hindcasts are presented in this section. The results of the water level assessment are given first followed by discussions of the surface water temperature and ice coverage results.

6.1. Assessment of Water Level Hindcasts

The standard suite of skill assessment statistics evaluated the accuracy of the hindcasts to predict 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 6-minute and 3-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, respectively.

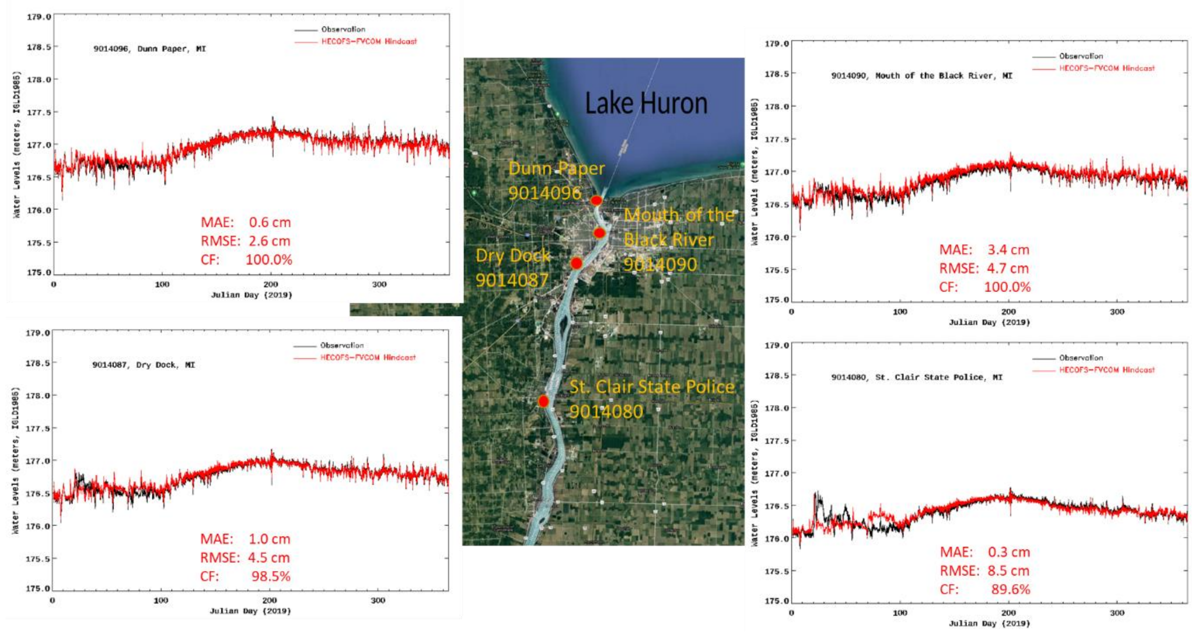
6.1.1. Water Levels

The time series plots of water levels at the CO-OPS gauges (6-minute) and CHS gauges (3-hourly) during 2019, 2020, and 2021 are shown in Figures 10-18. The MAE and RMSE of the hindcast are highlighted on all hindcast time series plots. Full skill assessment statistical tables are available from Tables 4 to 12. The skill assessment results are discussed by sections of the corridor: St. Clair River, Lake St. Clair, and Detroit River.

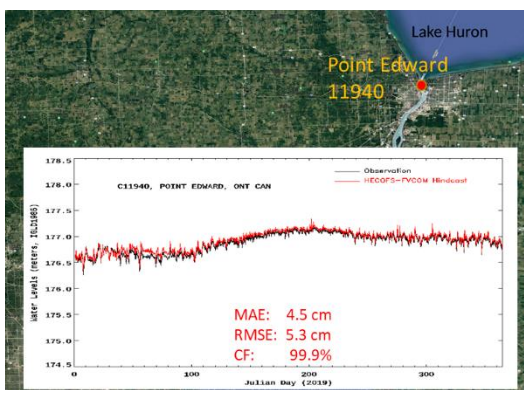
6.1.1.1. St. Clair River

Along the St. Clair River, there are four NOS/CO-OPS NWLON gauges (Dunna Paper, Mouth of the Black River, Dry Dock, and St. Clair State Police) and one CHS gauge (Point Edward) that measure the water levels. Their locations and the individual water level time series plots can be found in Figures 10 to12 for hindcast years 2019, 2020, and 2021, respectively.

The skill statistics assessing the ability of the hindcasts to predict the 6-minute (for NOS/CO-OPS gauges) and 3-hourly (for CHS gauge) water levels at CHS gauges are given in Tables 4, 5, and 6.



(a)



(b)

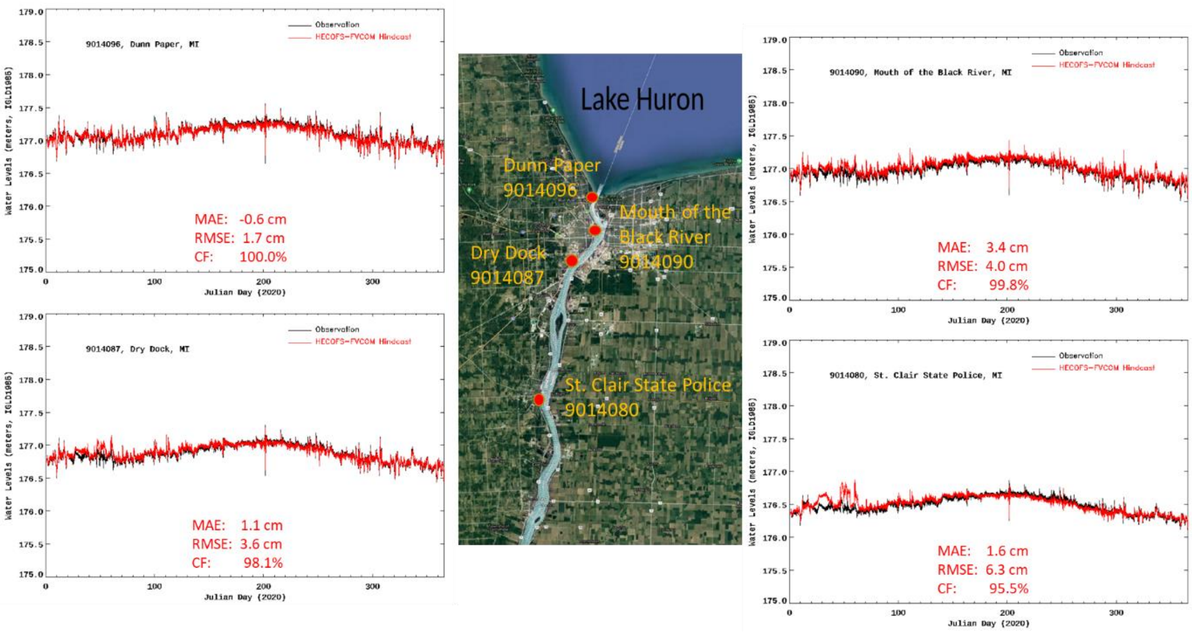
Figure 10. Time series plots of 6-minute (NOS/CO-OPS) or 3-hourly (CHS) HECWFS hindcast of water levels (red) vs. observations (black) in the St. Clair River at (a) NOS/CO-OPS gauges: Dunn Paper, MI, Mouth of the Black River, MI, Dry Dock, MI, and St. Clair State Police, MI, and at (b) CHS gauge: Point Edward, ONT during 2019. MAE and RMSE (cm), and CF at each gauge are shown individually on each panel.

For 2019, the MAEs for the water levels hindcasts at the NOS gauges along St. Clair River ranged from 0.3 to 3.4 cm and the RMSE ranged from 2.6 to 8.5 cm (Table 4). The hindcasts had positive MAEs at all four gauges indicating over prediction of water levels by the hindcasts. Compared to the other three gauges, the hindcasts at St. Clair State Police had much higher RMSE. The time series plot also showed higher inconsistency between hindcast and observation during the ice season at this gauge, especially from mid-January to early April. The hindcasts passed all NOS acceptance criteria at each of the four gauges except for CF and MDNO at St. Clair State Police, MI.

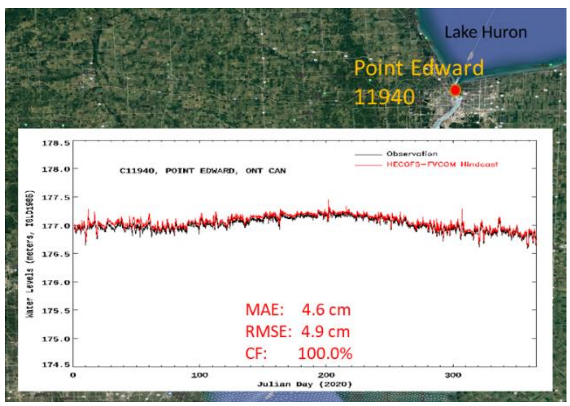
Table 4. Summary of skill assessment statistics evaluating the ability of the HECWFS hindcasts to predict 6-min or 3-hourly water levels at NOS/CO-OPS and CHS gauges along the St. Clair River during 2019. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9014096 Dunn paper	9014090 Mouth of the Black River	9014087 Dry Dock	9014080 St. Clair State Police	11940 Point Edward
	NOS 6-min	**NOS 6-min**	**NOS 6-min**	**NOS 6-min**	**CHS 3-hourly**
Number of Comparisons	87599	87599	87599	87599	2912
Mean Alg. Error (m)	0.006	0.034	0.010	0.003	0.045
RMSE (m)	0.026	0.047	0.045	0.085	0.053
SD (m)	0.026	0.031	0.043	0.085	0.027
NOF [2×15 cm] (%)	0.0	0.0	0.0	1.5	0.0
CF [15 cm] (%)	100.0	100.0	98.5	89.6	99.9
POF [2×15 cm] (%)	0.0	0.0	0.0	0.2	0.0
MDNO [2×15 cm] (hr)	0.0	0.0	0.0	81.8	0.0
MDPO [2×15 cm] (hr)	0.0	0.0	0.0	6.8	0.0

During 2020, the MAEs for the water level hindcasts at the NOS gauges ranged from -0.6 to 3.4 cm and the RMSE ranged from 1.7 to 6.3 cm (Table 5). On average, the RMSE for the hindcasts was 3.9 cm at NOS gauges in this area. Similar to 2019, the hindcasts did poorer at St. Clair State Police than the other three. The hindcasts passed all NOS acceptance criteria at the four gauges.



(a)



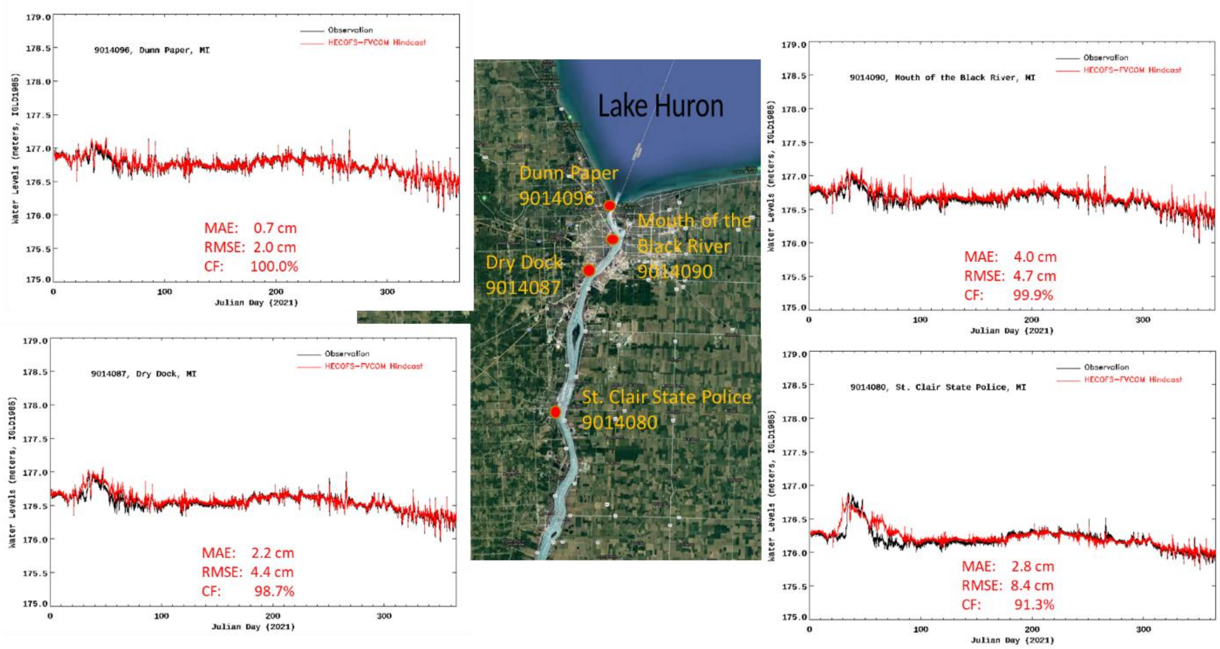
(b)

Figure 11. Time series plots of 6-minute (NOS/CO-OPS) or 3-hourly (CHS) HECWFS hindcast of water levels (red) vs. observations (black) in the St. Clair River at (a) NOS/CO-OPS gauges: Dunn Paper, MI, Mouth of the Black River, MI, Dry Dock, MI, and St. Clair State Police, MI, and (b) CHS gauge: Point Edward, ONT during 2020. MAE and RMSE (cm), and CF at each gauge are shown individually on each panel.

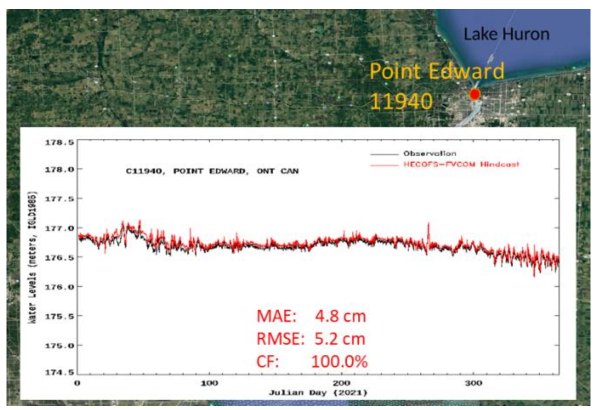
Table 5. Summary of skill assessment statistics evaluating the ability of the HECWFS hindcasts to predict 6-min or 3-hourly water levels at NOS/CO-OPS and CHS gauges along the St. Clair River during 2020. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9014096 Dunn paper	9014090 Mouth of the Black River	9014087 Dry Dock	9014080 St. Clair State Police	11940 Point Edward
	NOS 6-min	**NOS 6-min**	**NOS 6-min**	**NOS 6-min**	**CHS 3-hourly**
Number of Comparisons	87391	87839	87839	87839	2918
Mean Alg. Error (m)	-0.006	0.034	0.011	0.016	0.046
RMSE (m)	0.017	0.040	0.036	0.063	0.049
SD (m)	0.016	0.021	0.034	0.061	0.019
NOF [2×15 cm] (%)	0.0	0.0	0.0	0.0	0.0
CF [15 cm] (%)	100.0	99.8	98.1	95.5	100.0
POF [2×15 cm] (%)	0.0	0.0	0.0	0.6	0.0
MDNO [2×15 cm] (hr)	0.0	0.0	0.0	0.0	0.0
MDPO [2×15 cm] (hr)	0.0	0.0	0.0	20.2	0.0

During 2021, the MAEs for the water level hindcasts at NOS sites ranged from 0.7 to 4.0 cm and the RMSE ranged from 2.0 to 8.4 cm (Table 6). The hindcasts overpredicted at all four gauges. Similar to the previous two years, the RMSE for the hindcasts increased along the river's downstream direction. During both 2019 and 2020, the hindcasts did the worst at St. Clair State Police, the RMSE at this site is the largest in the region. However, the hindcasts again passed all NOS acceptance criteria at the four gauges except the MDPO at St. Clair State Police.



(a)



(b)

Figure 12. Time series plots of 6-minute (NOS/CO-OPS) or 3-hourly (CHS) HECWFS hindcast of water levels (red) vs. observations (black) in the St. Clair River at (a) NOS/CO-OPS gauges: Dunn Paper, MI, Mouth of the Black River, MI, Dry Dock, MI, and St. Clair State Police, MI, and at (b) CHS gauge: Point Edward, ONT during 2021. MAE and RMSE (cm), and CF at each gauge are shown individually on each panel.

Table 6. Summary of skill assessment statistics evaluating the ability of the HECWFS hindcasts to predict 6-min or 3-hourly water levels at NOS/CO-OPS and CHS gauges along the St. Clair River during 2021. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

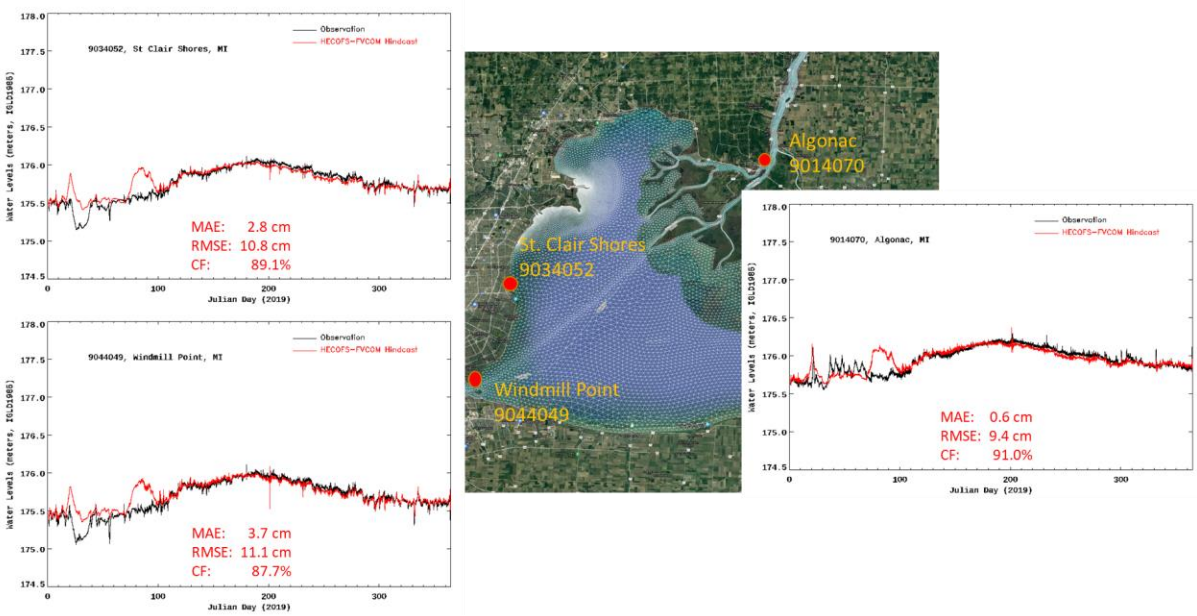
Statistic, Acceptable Error [ ], and Units ( )	9014096 Dunn paper	9014090 Mouth of the Black River	9014087 Dry Dock	9014080 St. Clair State Police	11940 Point Edward
	NOS 6-min	**NOS 6-min**	**NOS 6-min**	**NOS 6-min**	**CHS 3-hourly**
Number of Comparisons	87599	87599	87599	87599	2911
Mean Alg. Error (m)	0.007	0.040	0.022	0.028	0.048
RMSE (m)	0.020	0.047	0.044	0.084	0.052
SD (m)	0.019	0.024	0.039	0.080	0.021
NOF [2×15 cm] (%)	0.0	0.0	0.0	0.0	0.0
CF [15 cm] (%)	100.0	99.9	98.7	91.3	100.0
POF [2×15 cm] (%)	0.0	0.0	0.0	1.3	0.0
MDNO [2×15 cm] (hr)	0.0	0.0	0.0	0.0	0.0
MDPO [2×15 cm] (hr)	0.0	0.0	0.0	107.3	0.0

6.1.1.2. Lake St. Clair Basin

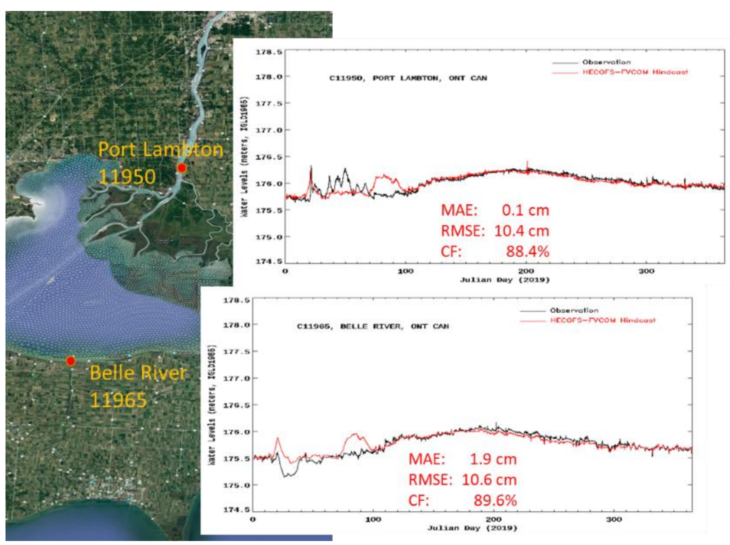
There are three NOS/CO-OPS and two CHS gauges in the Lake St. Clair Basin: Algonac, MI, St. Clair Shores, MI, Windmill Point, MI, Port Lambton, ON, and Belle River, ON. The gauges at Algonac and Port Lambton are technically located in the St. Clair River near the beginning section of the St. Clair River Delta. However, an examination of the water levels during the three hindcast years indicated that water levels at these two gauges more closely match the responses at the gauges along the shores of the lake. Thus, Algonac and Port Lambton were considered lake gauges for this purpose of this assessment.

The locations of the five gauges and their individual water level time series plots can be found in Figures 13 to 15 for the hindcast years 2019, 2020, and 2021, respectively. The skill statistics assessing the ability of the hindcasts to predict the 6-minute (for NOS/CO-OPS stations) and 3-hourly (for CHS stations) water levels at CHS gauges are given in Tables 7 to 9.

For 2019, the MAEs for the water levels hindcasts at the two CHS gauges were 0.1 cm to 1.9 cm and the RMSEs were 10.4 cm and 10.6 cm (Table 7). In comparison, the MAEs for the NOS/CO-OPS gauges ranged from 0.6 cm to 3.7 cm and the RMSEs ranged from 9.4 cm to 11.1 cm. On average, RMSEs for the hindcasts in this region, no matter NOS or CHS stations are much larger than the St. Clair River region. Similarly, despite the output interval (6-min for NOS and 3-hourly for CHS) the time series plots showed differences between the hindcasts and observations for all five gauges during the ice season. None of the five gauges passed all NOS acceptance criteria. However, the CF values were very close to passing.



(a)



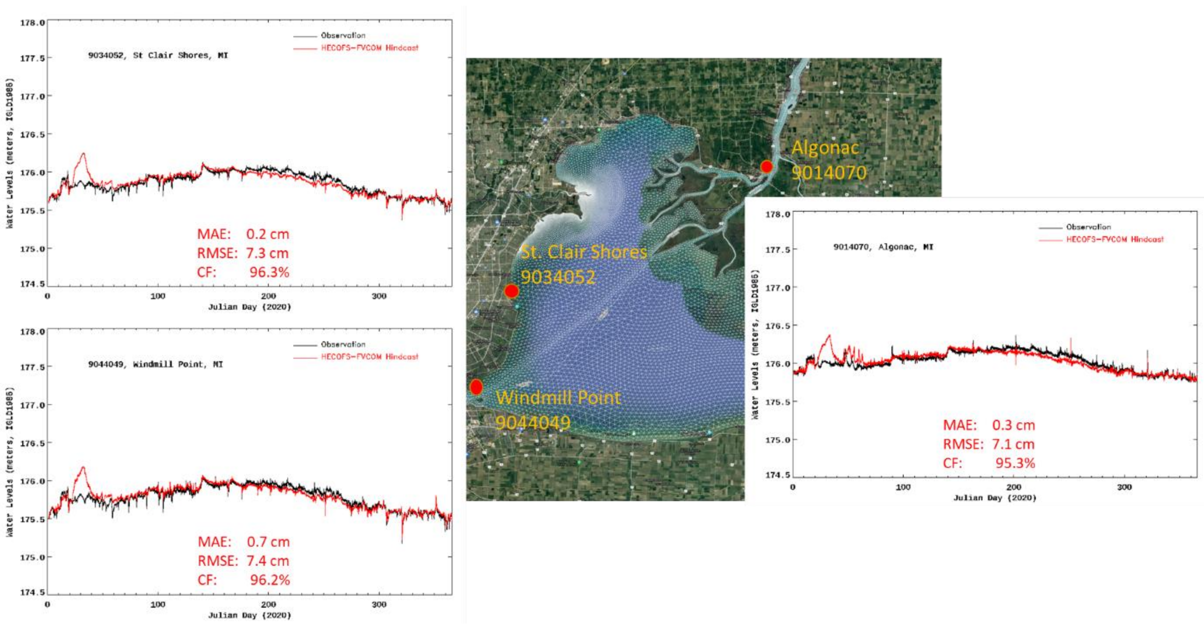
(b)

Figure 13. Time series plots of 6-minute (NOS/CO-OPS) or 3-hourly (CHS) HECWFS hindcast of water levels (red) vs. observations (black) in Lake St. Clair at (a) NOS/CO-OPS gauges: Algonac, MI, St. Clair Shores, MI, and Windmill Point, MI, and at (b) CHS gauge: Point Lambton, ONT and Belle River, ONT during 2019. MAE and RMSE (cm), and CF at each gauge are shown individually on each panel.

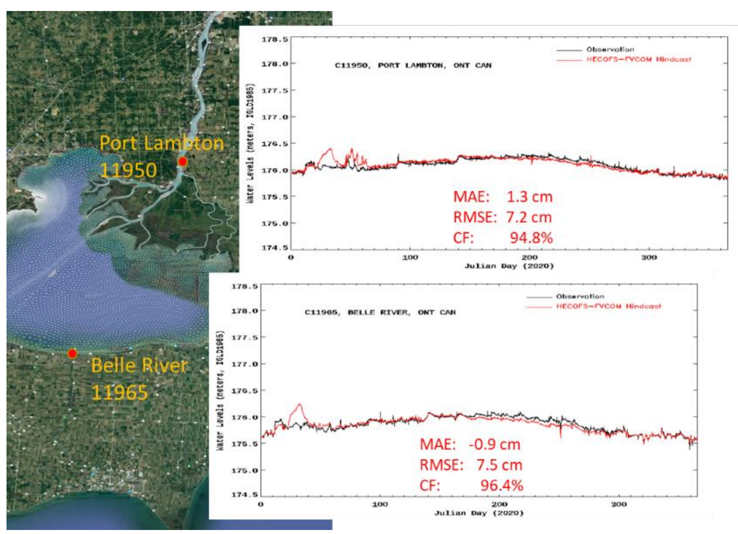
Table 7. Summary of skill assessment statistics evaluating the ability of the HECWFS hindcasts to predict 6-min or 3-hourly water levels at NOS/CO-OPS and CHS gauges at Lake St. Clair basin during 2019. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9014070 Algonac	9034052 St. Clair Shores	9044049 Windmill	11950 Port Lambton	11965 Belle River
	NOS 6-min	**NOS 6-min**	**NOS 6-min**	**CHS 3-hourly**	**CHS 3-hourly**
Number of Comparisons	87539	87599	87599	2912	2911
Mean Alg. Error (m)	0.006	0.028	0.037	0.001	0.019
RMSE (m)	0.094	0.108	0.111	0.104	0.106
SD (m)	0.094	0.104	0.105	0.104	0.105
NOF [2×15 cm] (%)	0.0	0.0	0.0	1.1	0.0
CF [15 cm] (%)	91.0	89.1	87.7	88.4	89.6
POF [2×15 cm] (%)	3.8	5.2	5.5	3.7	4.9
MDNO [2×15 cm] (hr)	0.0	0.0	0.8	87.0	0.0
MDPO [2×15 cm] (hr)	290.1	166.6	203.2	255.0	174.0

For 2020, the MAEs for the water levels hindcasts at NOS/CO-OPS gauges ranged from 0.2 cm to 0.7 cm and the RMSEs were very close to 7 cm (Table 8). The MAEs for the hindcasts at CHS gauges were -0.9 cm and 1.3 cm, and the RMSEs were 7.2 cm and 7.5 cm. The time series plots also showed some similarity of overpredicting the WLs from the mid-January to early February at both the U.S. and the Canadian gauges. Of the five locations, the hindcasts underpredicted the water level at Canadian's Belle River site, and overpredicted at the other four. The hindcasts failed the MDPO, but passed all other NOS acceptance criteria at each of the five gauges.



(a)



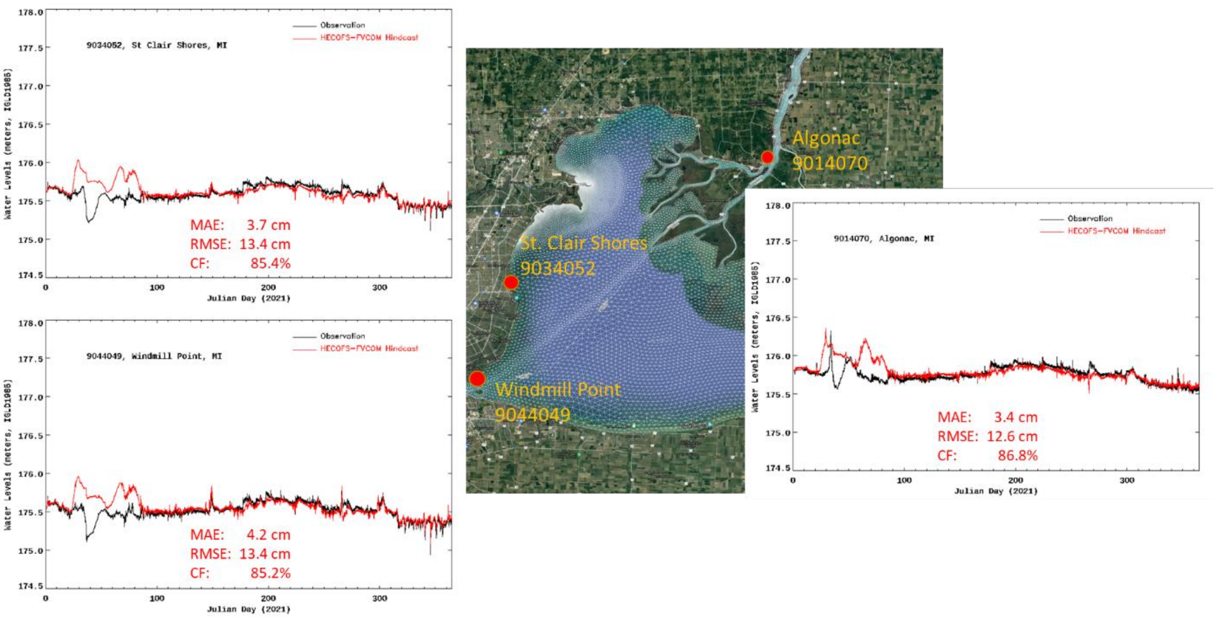
(b)

Figure 14. Time series plots of 6-minute (NOS/CO-OPS) or 3-hourly (CHS) HECWFS hindcast of water levels (red) vs. observations (black) in the lower part of the St. Clair River and in Lake St. Clair at (a) NOS/CO-OPS gauges: Algonac, MI, St. Clair Shores, MI, and Windmill Point, MI, and at (b) CHS gauge: Point Lambton, ONT and Belle River, ONT during 2020. MAE and RMSE (cm), and CF at each gauge are shown individually on each panel.

Table 8. Summary of skill assessment statistics evaluating the ability of the HECWF hindcasts to predict 6-min or 3-hourly water levels at NOS/CO-OPS and CHS gauges at Lake St. Clair basin during 2020. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9014070 Algonac	9034052 St. Clair Shores	9044049 Windmill	11950 Port Lambton	11965 Belle River
	NOS 6-min	**NOS 6-min**	**NOS 6-min**	**CHS 3-hourly**	**CHS 3-hourly**
Number of Comparisons	87839	87839	87668	2919	2920
Mean Alg. Error (m)	0.003	0.002	0.007	0.013	-0.009
RMSE (m)	0.071	0.073	0.074	0.072	0.075
SD (m)	0.071	0.073	0.073	0.071	0.074
NOF [2×15 cm] (%)	0.0	0.0	0.0	0.0	0.0
CF [15 cm] (%)	95.3	96.2	96.2	94.8	96.4
POF [2×15 cm] (%)	0.9	1.3	1.3	1.1	1.3
MDNO [2×15 cm] (hr)	0.0	0.0	0.0	0.0	0.0
MDPO [2×15 cm] (hr)	79.0	112.2	111.4	66.0	108.0

For 2021, the MAEs for the water levels hindcasts ranged from 3.4 cm to 4.2 cm and the RMSE ranged from 12.6 cm to 13.4 cm at the NOS sites (Table 9). The MAEs and the RMSEs for the CHS sites were very similar were 2.7 cm and 3.3 cm and 11.4 cm and 13.2 cm, respectively. The MAEs showed over predictions at all five gauges regardless of the output frequency. On average, the hindcast missed all significant peaks and drops during the ice season, but did fairly well in matching observations for the rest of the year. However, the hindcasts passed only NOF and MDNO, but failed the NOS acceptance criteria of CF, POF, and MDPO at each of the five gauges.



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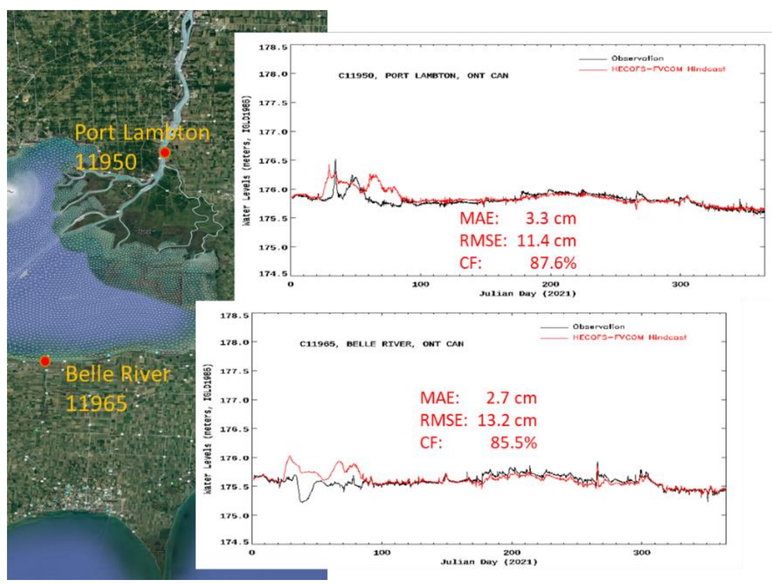


(b)

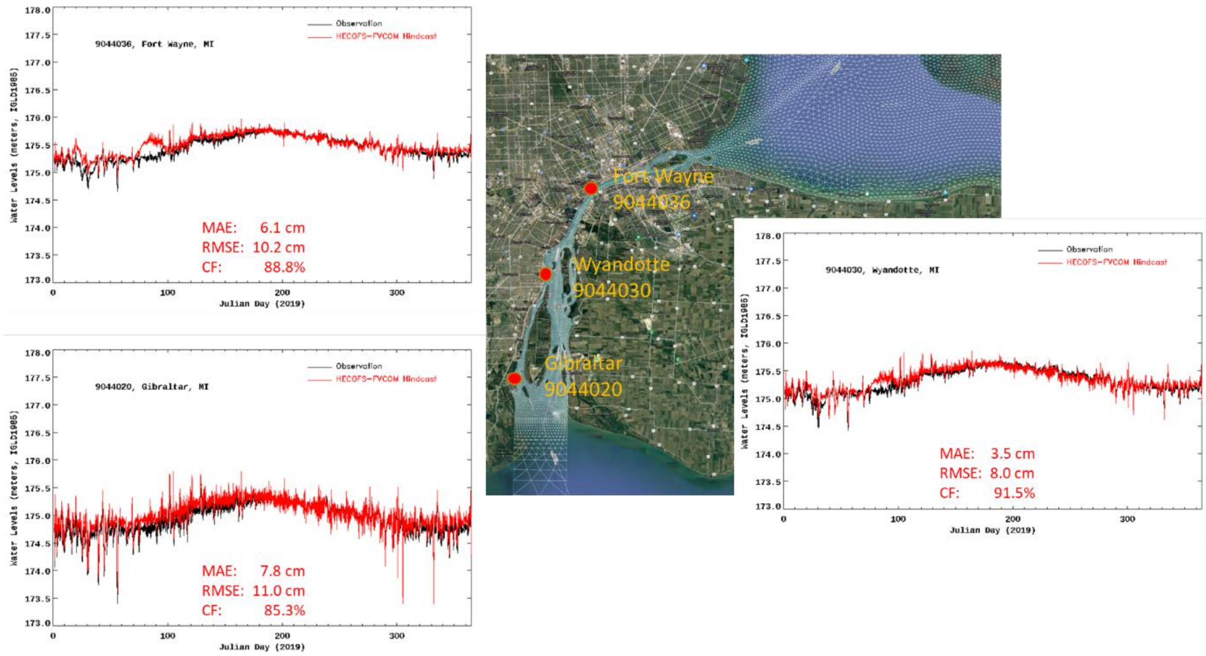
Figure 15. Time series plots of 6-minute (NOS/CO-OPS) or 3-hourly (CHS) HECWFS hindcast of water levels (red) vs. observations (black) in the lower part of St. Clair River and in Lake St. Clair at (a) NOS/CO-OPS gauges: Algonac, MI, St. Clair Shores, MI, and Windmill Point, MI, and at (b) CHS gauge: Point Lambton, ONT and Belle River, ONT during 2021. MAE and RMSE (cm), and CF at each gauge are shown individually on each panel.

Table 9. Summary of skill assessment statistics evaluating the ability of the HECWFS hindcasts to predict 6-min or 3-hourly water levels at NOS/CO-OPS and CHS gauges at Lake St. Clair basin during 2021. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

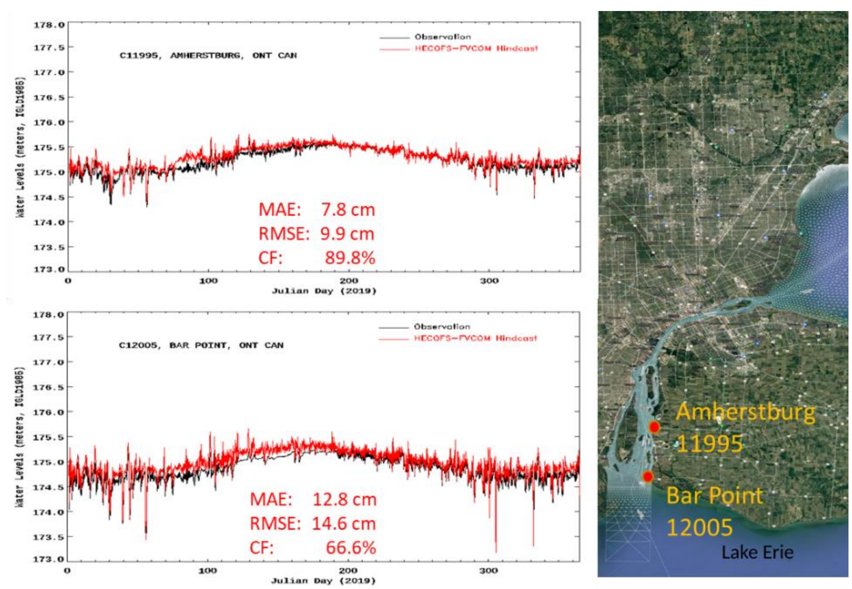
Statistic, Acceptable Error [ ], and Units ( )	9014070 Algonac	9034052 St. Clair Shores	9044049 Windmill	11950 Port Lambton	11965 Belle River
	NOS 6-min	**NOS 6-min**	**NOS 6-min**	**CHS 3-hourly**	**CHS 3-hourly**
Number of Comparisons	85938	87599	87064	2912	2912
Mean Alg. Error (m)	0.034	0.037	0.042	0.033	0.027
RMSE (m)	0.126	0.134	0.134	0.114	0.132
SD (m)	0.122	0.129	0.127	0.109	0.130
NOF [2×15 cm] (%)	0.0	0.0	0.0	0.0	0.0
CF [15 cm] (%)	86.8	85.4	85.2	87.6	85.5
POF [2×15 cm] (%)	6.7	7.8	7.5	4.4	7.0
MDNO [2×15 cm] (hr)	1.8	0.0	0.0	0.0	0.0
MDPO [2×15 cm] (hr)	229.5	273.0	269.0	237.0	267.0

6.1.1.3. Detroit River

There are three NOS/CO-OPS and two CHS water level gauges along the Detroit River: Fort Wayne, MI; Wyandotte, MI; Gibraltar, MI; Amherstburg, ON; and Bar Point, ON. Their locations and the individual water level time series plots are shown in Figures 16 to 18 for hindcast years 2019, 2020, and 2021, respectively. The skill statistics assessing the ability of the hindcasts to predict the 6-minute (for NOS/CO-OPS stations) and 3-hourly (for CHS stations) water levels at CHS gauges are given in Tables 10 to 12.



(a)



(b)

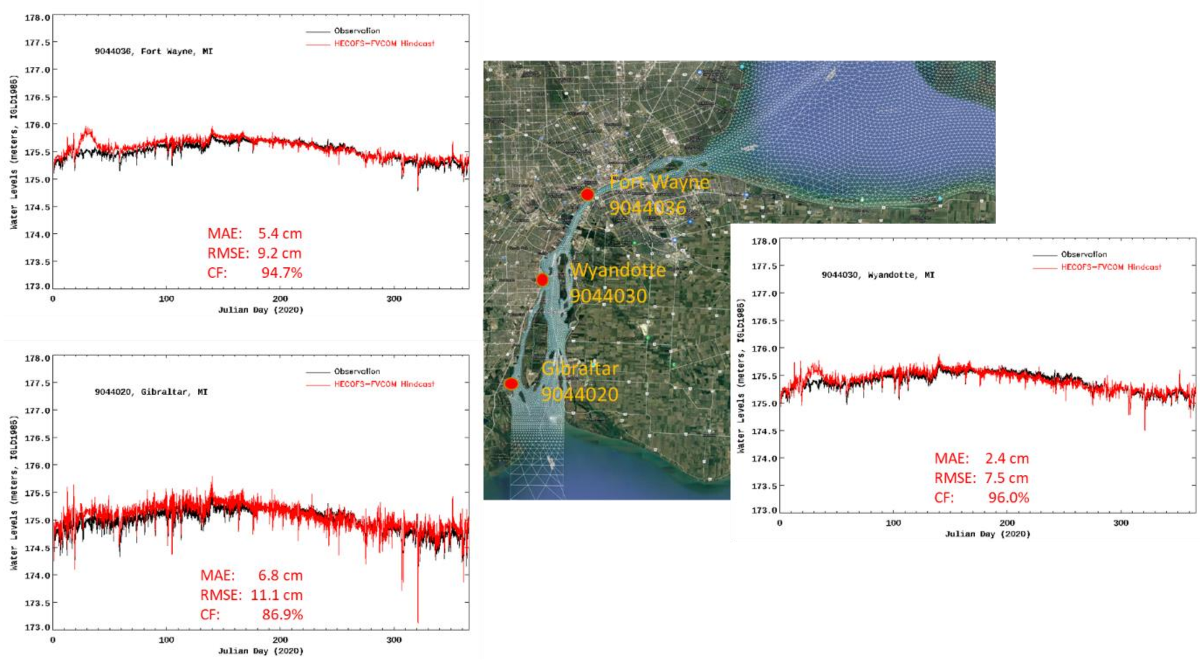
Figure 16. Time series plots of 6-minute (NOS/CO-OPS) or 3-hourly (CHS) HECWFS hindcast of water levels (red) vs. observations (black) along the Detroit River at (a) NOS/CO-OPS gauges: Fort Wayne, MI, Wyandotte, MI, Gibraltar, MI, and at (b) CHS gauge: Amherstburg, ON, and Bar Point, ON during 2019. MAE and RMSE (cm), and CF at each gauge are shown individually on each panel.

For 2019, the MAE for the water level hindcasts at the three CO-OPS and two CHS gauges ranged from 3.5 to 12.8 cm and the RMSE ranged from 8 to 14.6 m (Table 10). The worst performance was at Bar Point, Ontario, near the mesh boundary of Lake Erie. Excluding the Bar Point gauge, the average MAE and RMSE for the other four gauges are 6.3 cm and 9.8 cm, respectively. The hindcasts failed to pass the CF target at all five gauges and failed to pass the POF target at two gauges.

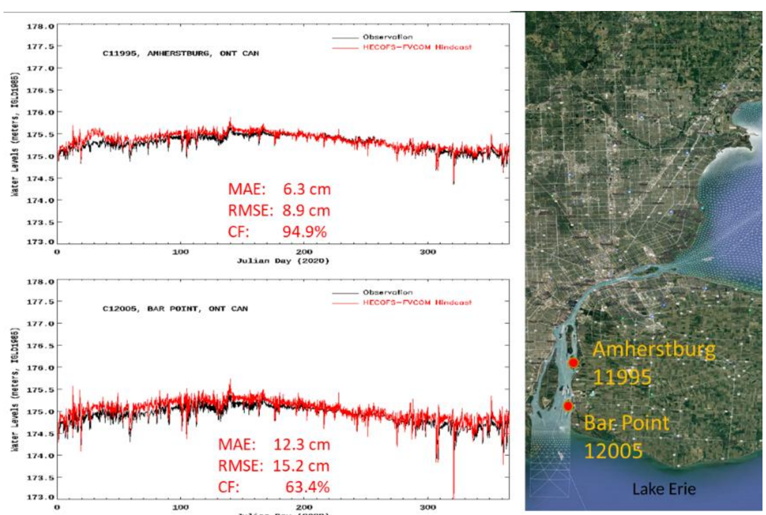
Table 10. Summary of skill assessment statistics evaluating the ability of the HECWFS hindcasts to predict 6-min or 3-hourly water levels at NOS/CO-OPS and CHS gauges along the Detroit River during 2019. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9044036 Fort Wayne	9044030 Wyandotte	9044020 Gibraltar	11995 Ambersburg	12005 Bar Point
	NOS 6-min	**NOS 6-min**	**NOS 6-min**	**CHS 3-hourly**	**CHS 3-hourly**
Number of Comparisons	86846	87599	87417	2906	2904
Mean Alg. Error (m)	0.061	0.035	0.078	0.078	0.128
RMSE (m)	0.102	0.080	0.110	0.099	0.146
SD (m)	0.082	0.072	0.078	0.061	0.071
NOF [2×15 cm] (%)	0.0	0.0	0.0	0.0	0.0
CF [15 cm] (%)	88.8	91.5	85.3	89.8	66.6
POF [2×15 cm] (%)	2.2	0.4	0.1	0.3	2.4
MDNO [2×15 cm] (hr)	0.0	0.0	0.5	0.0	0.0
MDPO [2×15 cm] (hr)	16.6	7.6	2.7	3.0	15.0

For 2020, the MAE for the water level hindcasts at the five gauges ranged from 2.4 to 12.3 cm and the RMSE ranged from 7.5 to 15.2 m (Table 11). The worst performance again was at Bar Point, Ontario. When the results at Bar Point were removed the average MAE and RMSE for the other four gauges were 5.2 cm and 9.2 cm, respectively. The hindcasts failed to pass the CF target at two gauges, failed to pass the POF target at two gauges, and failed to pass MDPO at one gauge.



(a)



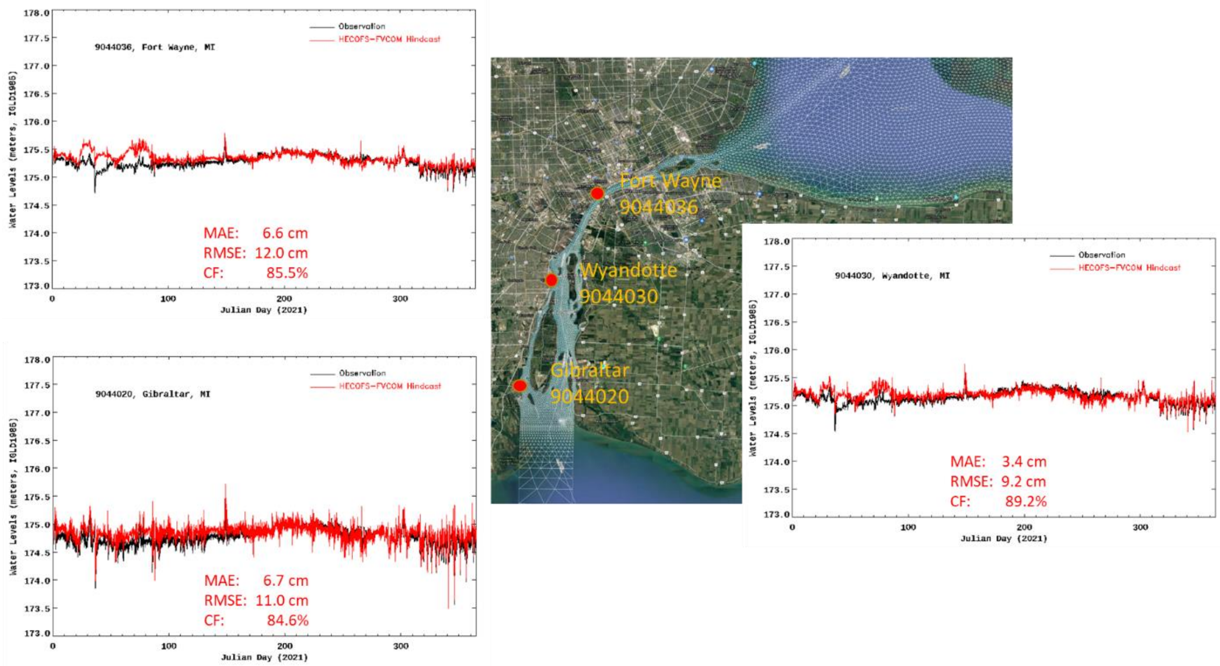
(b)

Figure 17. Time series plots of 6-minute (NOS/CO-OPS) or 3-hourly (CHS) HECWFS hindcast of water levels (red) vs. observations (black) along the Detroit River (a) NOS/CO-OPS gauges: Fort Wayne, MI, Wyandotte, MI, Gibraltar, MI, and (b) CHS gauge: Amherstburg, ON, and Bar Point, ON during 2020. MAE and RMSE (cm), and CF at each gauge are shown individually on each panel.

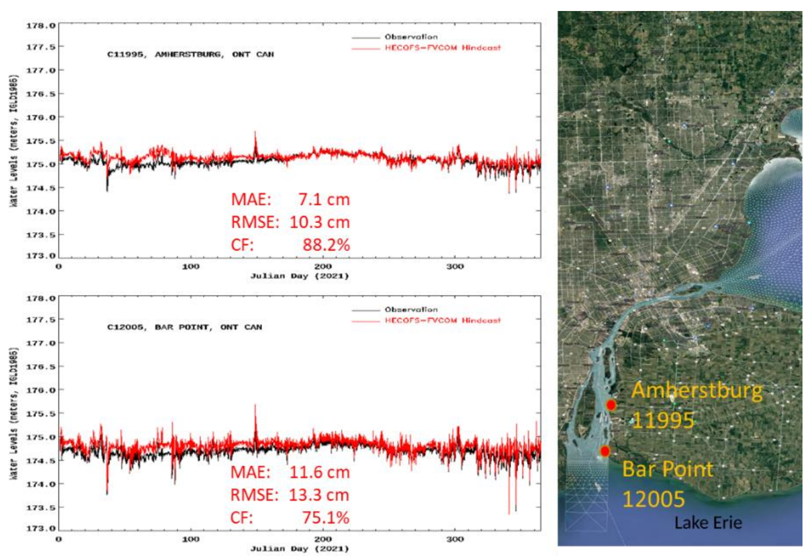
Table 11. Summary of skill assessment statistics evaluating the ability of the HECWFS hindcasts to predict 6-min or 3-hourly water levels at NOS/CO-OPS and CHS gauges along the Detroit River during 2020. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9044036 Fort Wayne	9044030 Wyandotte	9044020 Gibraltar	11995 Ambersburg	12005 Bar Point
	NOS 6-min	**NOS 6-min**	**NOS 6-min**	**CHS 3-hourly**	**CHS 3-hourly**
Number of Comparisons	87770	87839	87839	2901	2920
Mean Alg. Error (m)	0.054	0.024	0.068	0.063	0.123
RMSE (m)	0.092	0.075	0.111	0.089	0.152
SD (m)	0.074	0.071	0.088	0.063	0.089
NOF [2×15 cm] (%)	0.0	0.0	0.1	0.0	0.2
CF [15 cm] (%)	94.7	96.0	86.8	94.9	63.4
POF [2×15 cm] (%)	2.1	0.8	0.0	0.8	2.2
MDNO [2×15 cm] (hr)	0.0	0.0	2.4	0.0	3.0
MDPO [2×15 cm] (hr)	96.8	20.0	0.6	21.0	6.0

For 2021, the MAE for the water level hindcasts at the five gauges ranged from 3.4 to 11.6 cm and the RMSE ranged from 9.2 to 10.6 m (Table 12). The worst performance again was at Bar Point, Ontario. When the results at Bar Point were removed the average MAE and RMSE for the other four gauges are 6.0 cm and 10.6 cm, respectively. The hindcasts failed to pass the CF target at all five gauges, failed to pass the POF target at two gauges, and failed to pass MDPO at one gauge.



(a)



(b)

Figure 18. Time series plots of 6-minute (NOS/CO-OPS) or 3-hourly (CHS) HECWFS hindcast of water levels (red) vs. observations (black) along the Detroit River (a) NOS/CO-OPS gauges: Fort Wayne, MI, Wyandotte, MI, Gibraltar, MI, and (b) CHS gauge: Amherstburg, ON, and Bar Point, ON during 2021. MAE and RMSE (cm), and CF at each gauge are shown individually on each panel.

Table 12. Summary of skill assessment statistics evaluating the ability of the HECWFS hindcasts to predict 6-min or 3-hourly water levels at NOS/CO-OPS and CHS gauges along the Detroit River during 2021. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9044036 Fort Wayne	9044030 Wyandotte	9044020 Gibraltar	11995 Ambersburg	12005 Bar Point
	NOS 6-min	**NOS 6-min**	**NOS 6-min**	**CHS 3-hourly**	**CHS 3-hourly**
Number of Comparisons	87212	87599	87599	2912	2905
Mean Alg. Error (m)	0.066	0.034	0.067	0.071	0.116
RMSE (m)	0.120	0.092	0.110	0.103	0.133
SD (m)	0.100	0.085	0.087	0.075	0.065
NOF [2×15 cm] (%)	0.0	0.0	0.1	0.0	0.0
CF [15 cm] (%)	85.5	89.2	84.6	88.2	75.1
POF [2×15 cm] (%)	5.1	0.9	0.1	1.1	0.9
MDNO [2×15 cm] (hr)	0.0	0.0	0.4	0.0	0.0
MDPO [2×15 cm] (hr)	46.3	10.9	3.3	12.0	9.0

6.1.2. Extreme High Water Level Events

The skill statistics assessing the ability of HECWFS hindcasts to predict the amplitude and timing of extreme high water level events at gauges in the HEC region during 2019, 2020 and 2021 are presented in this section. The summary statistics for 2019, 2020, and 2021 are given in Tables 13, 14, and 15, respectively and arranged from north to south. The "N"s in the tables represent the numbers of high water events. Since the output frequency of the Canadian sites is 3-hourly, little significance can be extracted from the events, and therefore the results are not presented in this report.

Across the three years, the NOS gauges that consistently had nine or more extreme high events were at the gauges along the St. Clair River: Dunn Paper, Mouth of Black River, Dry Dock and St. Clair State Police. Along the Detroit River at the three gauges, Fort Wayne, Wyandotte, and Gibraltar, the number of events ranged only between two to three during 2020, but five to ten during 2019 and 2021. Gauges in Lake St. Clair at Algonac and Windmill Point experienced only two or three events each year during the hindcast years. Given the small number of events at these gauges, only the statistics at gauges along the St. Clair and Detroit Rivers will be discussed.

For the four gauges along the St. Clair River, the MAEs for amplitude were negative, except at Black River and ranged from -1.3 to -3.6 cm during the three years. The average RMSEs for amplitude ranged from 3.9 to 5 cm during these years. For the time of occurrence, the MAEs at the four gauges ranged from -0.50 to 0.29 hours and the average RMSEs ranged from 0.50 to 0.91 hours over the three years.

For the three gauges along the Detroit River, the MAEs for amplitude were all positive and ranged from 5.3 to 18.4 cm over the three years. The largest MAEs over the three years were consistently at Gibraltar, near the southern mesh open boundary, with an average MAE of 16.2 cm. The average RMSEs for the three ranges ranged from 10 to 15 cm during these years. For the time of occurrence, MAEs at these gauges ranged from -0.8 to 0.64 hours and the average RMSEs ranged from 0.21 hours to 1.0 hour during the three years.

Table 13. Summary of skill assessment statistics evaluating the ability of the HECWFS hindcasts 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 ( )	9014096 Dunn Paper		9014090 Mouth of the Black River		9014087 Dry Dock	
	N=9		N=10		N=15	
	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	-0.030	-0.211	0.014	-0.190	-0.020	0.060
RMSE (m) (hr)	0.040	0.878	0.031	0.769	0.026	0.093
SD (m) (hr)	0.028	0.903	0.030	0.785	0.016	0.074
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	88.9	100.0	90.0	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 2×90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0

Statistic, Acceptable Error [ ], and Units ( )	9014080 St. Clair State Police		9014070 Algonac		9044049 Windmill Point	
	N=11		N=2		N=2	
	Amp.	Time	Amp	Time	Amp	Time
Mean Alg. Error (m) (hr)	-0.014	0.291	-0.128	0.500	-0.036	-0.400
RMSE (m) (hr)	0.071	0.524	0.130	0.539	0.048	2.433
SD (m) (hr)	0.073	0.457	0.034	0.283	0.046	3.394
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] (%)	90.9	90.9	50.0	100.0	100.0	0.0
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 2×90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0

Statistic, Acceptable Error [ ], and Units ( )	9044036 Fort Wayne		9044030 Wyandotte		9044020 Gibraltar	
	N=5		N=8		N=10	
	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	0.101	-0.800	0.112	-0.088	0.184	-0.310
RMSE (m) (hr)	0.112	1.864	0.135	0.281	0.192	0.840
SD (m) (hr)	0.055	1.883	0.081	0.285	0.056	0.823
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	20.0	75.0	100.0	20.0	80.0
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 2×90 min] (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 HECWFS hindcasts to predict extreme high water level events at NOS gauges during 2020. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9014096 Dunn Paper		9014090 Mouth of the Black River		9014087 Dry Dock	
	N=16		N=14		N=10	
	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	-0.036	-0.112	0.009	0.050	-0.014	-0.140
RMSE (m) (hr)	0.041	0.684	0.015	0.317	0.033	0.800
SD (m) (hr)	0.020	0.697	0.013	0.325	0.032	0.830
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	93.8	100.0	100.0	100.0	90.0
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 2×90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0

Statistic, Acceptable Error [ ], and Units ( )	9014080 St. Clair State Police		9014070 Algonac		9044049 Windmill Point	
	N=13		N=2		N=2	
	Amp.	Time	Amp	Time	Amp	Time
Mean Alg. Error (m) (hr)	-0.014	0.031	-0.132	-0.950	-0.018	0.650
RMSE (m) (hr)	0.066	0.204	0.134	1.651	0.024	0.696
SD (m) (hr)	0.067	0.210	0.029	1.909	0.023	0.354
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] (%)	92.3	100.0	50.0	50.0	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 2×90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0

Statistic, Acceptable Error [ ], and Units ( )	9044036 Fort Wayne		9044030 Wyandotte		9044020 Gibraltar	
	N=3		N=2		N=3	
	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	0.081	0.067	0.053	0.100	0.130	0.333
RMSE (m) (hr)	0.093	0.182	0.072	0.100	0.138	0.337
SD (m) (hr)	0.058	0.208	0.069	0.000	0.056	0.058
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	33.3	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 2×90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0

Table 15. Summary of skill assessment statistics evaluating the ability of the HECWFS hindcasts to predict extreme high water level events at NOS gauges during 2021. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9014096 Dunn Paper		9014090 Mouth of the Black River		9014087 Dry Dock	
	N=14		N=16		N=18	
	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	-0.014	-0.500	0.028	-0.381	-0.013	-0.050
RMSE (m) (hr)	0.036	1.229	0.045	1.073	0.041	0.708
SD (m) (hr)	0.034	1.165	0.037	1.036	0.040	0.727
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	78.6	100.0	87.5	100.0	94.4
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 2×90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0

Statistic, Acceptable Error [ ], and Units ( )	9014080 St. Clair State Police		9014070 Algonac		9044036 Fort Wayne	
	N=11		N=3		N=7	
	Amp.	Time	Amp.	Amp.	Amp	Time
Mean Alg. Error (m) (hr)	-0.018	0.246	-0.014	0.067	0.109	-0.743
RMSE (m) (hr)	0.077	0.610	0.082	1.623	0.120	1.202
SD (m) (hr)	0.079	0.585	0.099	1.985	0.055	1.021
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] (%)	90.9	90.9	100.0	33.3	71.4	71.4
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 2×90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0

Statistic, Acceptable Error [ ], and Units ( )	9044030 Wyandotte		9044020 Gibraltar	
	N=5		N=5	
	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	0.107	0.640	0.140	0.160
RMSE (m) (hr)	0.124	1.534	0.155	0.276
SD (m) (hr)	0.070	1.558	0.075	0.251
NOF [2×15 cm or 2×90 min] (%)	0.0	0.0	0.0	0.0
CF [15 cm or 90 min] (%)	80.0	60.0	40.0	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

6.1.3. Extreme Low Water Level Events

The skill statistics assessing the ability of HECWFS hindcasts to predict the amplitude and timing of extreme low water level events at gauges in the HEC region during the years 2019, 2020 and 2021 are given in Tables 16, 17, and 18, respectively. The "N"s in the tables represent the numbers of high water events. Again, since the output frequency of the Canadian sites is 3-hourly, little significance can be extracted from the events, and therefore the results are not presented in this report.

Of the gauges along St. Clair River, Dunn Paper, Mouth of Black River, Dry Dock and St. Clair State Police, the average number of extreme events across the four gauges for the years 2019, 2020 and 2021 were 34, 18 and 23, respectively. At the four gauges along the Detroit River, Windmill Point, Fort Wayne, Wyandotte, and Gibraltar, the average number of events for these three gauges for 2019, 2020, and 2021 were 14, 20, and 13, respectively. Gibraltar consistently had the highest number of events compared to the other three gauges with an average of 22 events. The one gauge in Lake St. Clair, St. Clair Shores, had an average of about eight events during the three years.

For the four gauges along the St. Clair River, the MAEs were all positive and ranged from 2.7 to 5.8 cm over the three years. The average RMSE for the four gauges was about 5 cm during these years. For the time of occurrence, MAEs at these gauges ranged from -0.12 to 0.34 hours and the average RMSEs ranged from 0.53 to 1.02 hours during the three years.

For the three gauges along the Detroit River, the MAEs for amplitude ranged from -3.0 to 9.4 cm during the three years. The average RMSEs for amplitude were about 11 cm during these years. For the time of occurrence, the MAEs at the three gauges ranged from -0.21 to 0.42 hours and the average RMSE ranged from 0.83 to 1.1 hours over the three years.

Table 16. Summary of skill assessment statistics evaluating the ability of the HECWFS hindcasts to predict extreme low 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 ( )	9014096 Dunn Paper		9014090 Mouth of the Black River		9014087 Dry Dock	
	N=45		N=37		N=32	
	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	0.033	-0.004	0.055	0.181	0.045	0.341
RMSE (m) (hr)	0.043	1.081	0.060	0.939	0.057	0.865
SD (m) (hr)	0.027	1.093	0.025	0.934	0.036	0.808
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	82.2	100.0	83.8	100.0	81.2
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 2×90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0

Statistic, Acceptable Error [ ], and Units ( )	9014080 St. Clair State Police		9034052 St Clair Shores		9044049 Windmill Point	
	N=21		N=3		N=12	
	Amp.	Time	Amp	Time	Amp	Time
Mean Alg. Error (m) (hr)	0.039	0.133	0.161	0.400	0.081	0.417
RMSE (m) (hr)	0.054	1.226	0.186	0.779	0.124	1.393
SD (m) (hr)	0.038	1.248	0.116	0.819	0.098	1.388
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	76.2	66.7	100.0	83.3	58.3
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 2×90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0

Statistic, Acceptable Error [ ], and Units ( )	9044036 Fort Wayne		9044030 Wyandotte		9044020 Gibraltar	
	N=11		N=12		N=19	
	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	0.094	0.636	-0.006	0.525	0.000	0.126
RMSE (m) (hr)	0.118	0.859	0.058	0.787	0.152	0.709
SD (m) (hr)	0.075	0.605	0.060	0.612	0.157	0.717
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] (%)	81.8	90.9	100.0	91.7	63.2	94.7
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 2×90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0

Table 17. Summary of skill assessment statistics evaluating the ability of the HECWFS hindcasts to predict extreme low water level events at NOS gauges during 2020. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9014096 Dunn Paper		9014090 Mouth of the Black River		9014087 Dry Dock	
	N=28		N=18		N=17	
	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	0.027	0.129	0.058	0.106	0.037	0.218
RMSE (m) (hr)	0.039	0.698	0.065	0.480	0.059	0.384
SD (m) (hr)	0.028	0.699	0.031	0.482	0.047	0.326
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	85.7	100.0	94.4	94.1	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 2×90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0

Statistic, Acceptable Error [ ], and Units ( )	9014080 St. Clair State Police		9034052 St Clair Shores		9044049 Windmill Point	
	N=12		N=13		N=11	
	Amp.	Time	Amp	Time	Amp	Time
Mean Alg. Error (m) (hr)	0.029	0.175	0.074	0.838	0.082	0.364
RMSE (m) (hr)	0.034	0.556	0.084	1.395	0.113	1.165
SD (m) (hr)	0.019	0.551	0.041	1.160	0.082	1.161
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	61.5	90.9	72.7
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 2×90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0

Statistic, Acceptable Error [ ], and Units ( )	9044036 Fort Wayne		9044030 Wyandotte		9044020 Gibraltar	
	N=14		N=16		N=29	
	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	0.067	0.421	-0.001	0.169	-0.030	-0.069
RMSE (m) (hr)	0.100	0.870	0.079	0.782	0.148	0.834
SD (m) (hr)	0.077	0.790	0.082	0.789	0.147	0.846
NOF [2×15 cm or 2×90 min] (%)	0.0	0.0	0.0	0.0	6.9	0.0
CF [15 cm or 90 min] (%)	92.9	78.6	100.0	93.8	72.4	86.2
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 2×90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0

Table 18. Summary of skill assessment statistics evaluating the ability of the HECWFS hindcasts to predict extreme low water level events at NOS gauges during 2021. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	9014096 Dunn Paper		9014090 Mouth of the Black River		9014087 Dry Dock	
	N=29		N=24		N=23	
	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	0.039	0.266	0.050	-0.121	0.031	-0.019
RMSE (m) (hr)	0.045	0.742	0.052	0.948	0.035	0.571
SD (m) (hr)	0.022	0.705	0.016	0.960	0.016	0.576
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	93.1	100.0	83.3	100.0	95.7
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 2×90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0

Statistic, Acceptable Error [ ], and Units ( )	9014080 St. Clair State Police		9034052 St Clair Shores		9044049 Windmill Point	
	N=15		N=7		N=5	
	Amp.	Time	Amp	Time	Amp	Time
Mean Alg. Error (m) (hr)	0.038	0.040	0.056	0.114	0.126	0.980
RMSE (m) (hr)	0.074	0.946	0.077	1.399	0.187	1.240
SD (m) (hr)	0.065	0.978	0.056	1.506	0.155	0.850
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] (%)	93.3	80.0	100.0	71.4	80.0	60.0
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 2×90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0

Statistic, Acceptable Error [ ], and Units ( )	9044036 Fort Wayne		9044030 Wyandotte		9044020 Gibraltar	
	N=10		N=11		N=17	
	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	0.069	0.060	0.007	-0.209	-0.014	0.071
RMSE (m) (hr)	0.125	1.397	0.095	0.943	0.099	0.800
SD (m) (hr)	0.110	1.471	0.100	0.964	0.101	0.821
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] (%)	90.0	80.0	90.9	90.9	94.1	88.2
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 2×90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0

6.2. Assessment of Surface Water Temperature Hindcasts

The results of the skill assessment of the FVCOM-based HECWFS hourly hindcasts of surface water temperatures for 2019, 2020 and 2021 are given in this section. The water temperature hindcasts were evaluated at observing platforms in St. Clair River (NOS Gauge 9014070) and Lake St. Clair (ECCC Buoy 45147). Unfortunately, water temperature observations in the Detroit River were not accessible; thus, the hindcasts for that river could not be evaluated.

The time series plots for 2019, 2020, and 2021 (Figs. 19, 20, and 21) indicate that the hindcasts closely matched the observations, capturing both the seasonal trend (e.g., Fall cool down and Spring warm up) in both St. Clair River and Lake St. Clair. HECWFS did well in simulating the frequent temperature fluctuations in the lake while predicting the less frequent fluctuations in the river.

At the Algonac gauge (9014070) in the St. Clair River, the MAEs during the three years ranged from -0.36 ℃ to -0.22 ℃ and the RMSE averaged 0.38 ℃. At Lake St. Clair buoy (45147), the MAEs ranged from -0.10 to 0.33 ℃ and the RMSE averaged 0.81 ℃. The hindcasts passed all NOS acceptance criteria at both the NOS gauge and ECCC buoy for all three years.

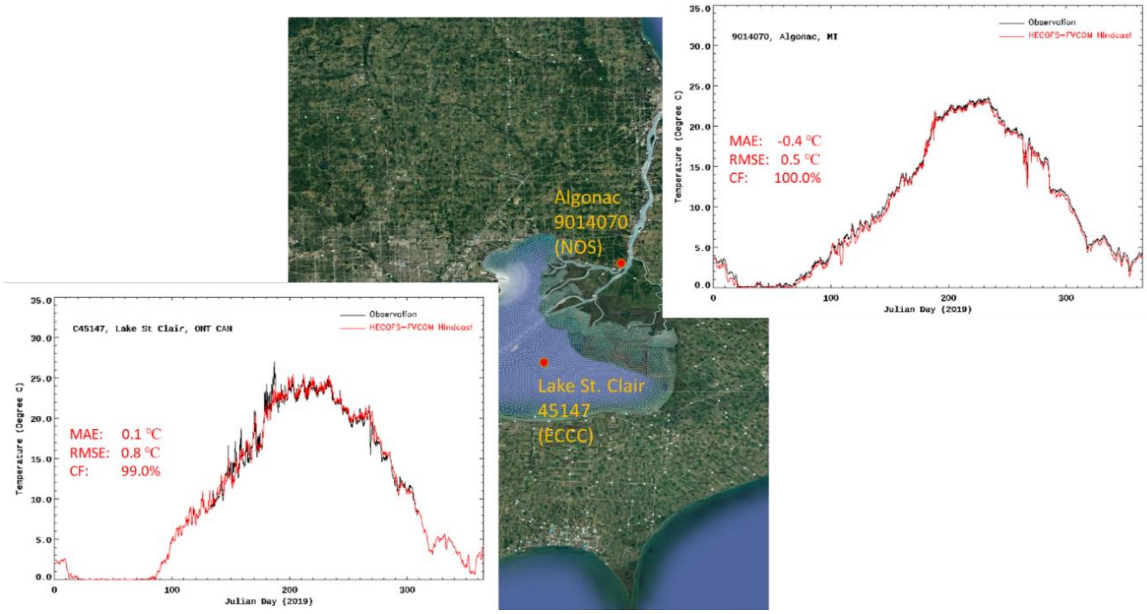


Figure 19. Time series plots of hourly HECWFS hindcasts of surface water temperature (red) vs. observations (black) at NOS/CO-OPS Algonac, MI gauge (9014070) and ECCC fixed buoy Lake St. Clair, ONT (C45147) during 2019. MAE, RMSE and CF at each station are shown individually on each panel.

Table 19. Summary of skill assessment statistics of the 3-hourly HECWFS hindcasts of surface water temperature at NOS/CO-OPS gauge and ECCC fixed buoy in Lake Huron-Erie Corridor during 2019. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Time Period, Statistic, Acceptable Error [ ], and Units ( )		9014070 Algonac	C45147 Lake St. Clair
Longest Continuous Observation Period	Begin	01/11/2019	08/16/2019
	End	02/25/2019	09/04/2019
Number of Comparisons		2829	1368
Mean Alg. Error (°C)		-0.364	0.124
RMSE (°C)		0.485	0.838
SD (°C)		0.321	0.829
NOF [2×3°C] (%)		0.0	0.0
CF [3°C] (%)		100.0	99.9
POF [2×3°C] (%)		0.0	0.0
MDNO [2×3°C] (hr)		0.0	0.0
MDPO [2×3°C] (hr)		0.0	0.0

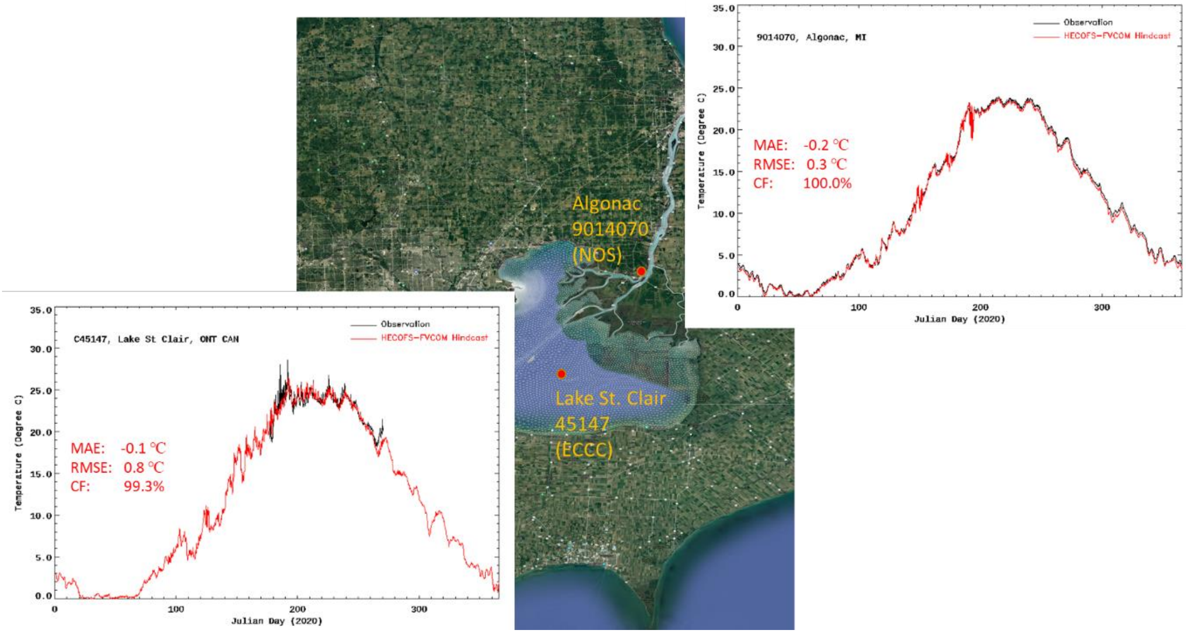


Figure 20. Time series plots of hourly HECWFS hindcasts of surface water temperature (red) vs. observations (black) at NOS/CO-OPS Algonac, MI gauge (9014070) and ECCC buoy Lake St. Clair, ONT (C45147) during 2020. MAE, RMSE, and CF at each station are shown individually on each panel.

Table 20. Summary of skill assessment statistics of the 3-hourly HECWFS hindcasts of surface water temperature at NOS/CO-OPS gauge and ECCC fixed buoy in Lake Huron-Erie Corridor during 2020. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Time Period, Statistic, Acceptable Error [ ], and Units ( )		9014070 Algonac	C45147 Lake St. Clair
Longest Continuous Observation Period	Begin	01/01/2020	06/25/2020
	End	02/06/2020	08/17/2020
Number of Comparisons		2839	724
Mean Alg. Error (°C)		-0.222	-0.102
RMSE (°C)		0.334	0.806
SD (°C)		0.250	0.800
NOF [2×3°C] (%)		0.0	0.0
CF [3°C] (%)		100.0	99.3
POF [2×3°C] (%)		0.0	0.0
MDNO [2×3°C] (hr)		0.0	0.0
MDPO [2×3°C] (hr)		0.0	0.0

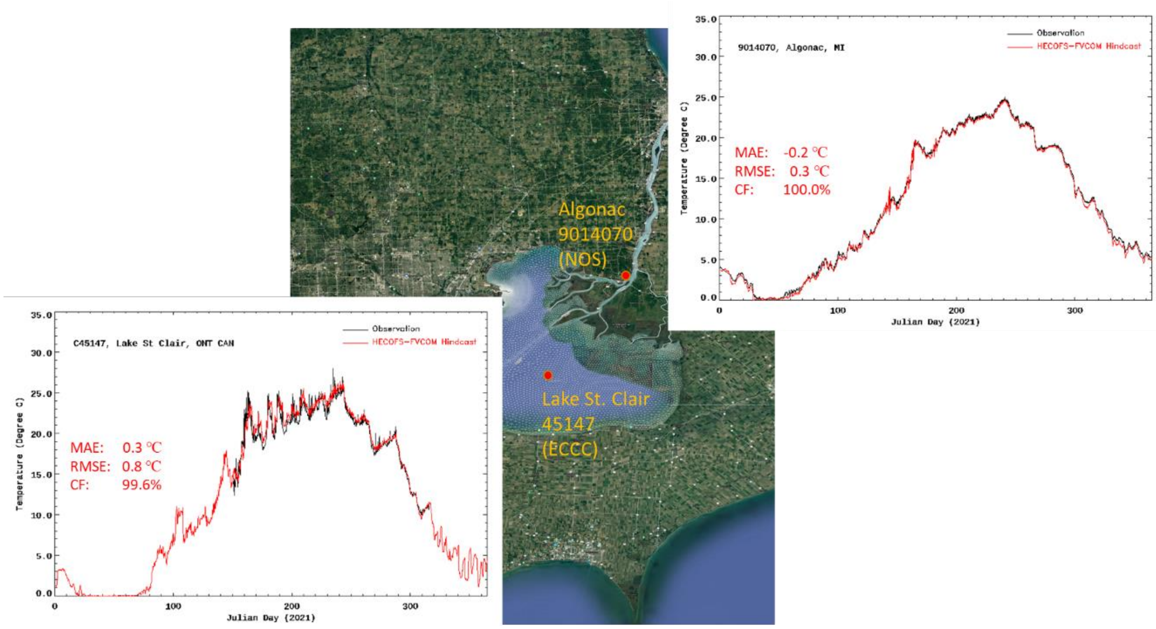


Figure 21. Time series plots of hourly HECWFS hindcasts of surface water temperature (red) vs. observations (black) at NOS/CO-OPS Algonac gauge (9014070) and ECCC buoy Lake St. Clair, ONT (C45147) during 2021. MAE, RMSE, and CF at each station are shown individually on each panel.

Table 21. Summary of skill assessment statistics of the 3-hourly HECWFS hindcasts of surface water temperature at NOS/CO-OPS and ECCC fixed buoys in Lake Huron-Erie Corridor during 2021. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Time Period, Statistic, Acceptable Error [ ], and Units ( )		9014070 Algonac	C45147 Lake St. Clair
Longest Continuous Observation Period	Begin	03/18/2021	07/29/2021
	End	05/17/2021	11/11/2021
Number of Comparisons		2711	1313
Mean Alg. Error (°C)		-0.225	0.332
RMSE (°C)		0.330	0.801
SD (°C)		0.242	0.729
NOF [2×3°C] (%)		0.0	0.0
CF [3°C] (%)		100.0	99.6
POF [2×3°C] (%)		0.0	0.0
MDNO [2×3°C] (hr)		0.0	0.0
MDPO [2×3°C] (hr)		0.0	0.0

6.3. Assessment of Ice Concentration Hindcasts

HECWFS provided hourly hindcasts of ice concentration, ice thickness, and ice velocity for the entire HEC including the St. Clair River, Lake St. Clair, and the Detroit River via the internal coupling of the FVCOM with UG-CICE model. The skill assessment of the ice hindcasts was conducted for the three ice seasons, 2018-2019, 2019-2020, and 2020-2021. A summary of the three ice seasons was given in Section 4.1

Due to the limited availability of “ground truth”, the skill assessment of the ice hindcasts was only possible for Lake St. Clair. The ground truth used for the assessment was the daily Great Lakes ice charts generated by the NWS/NCEP National Ice Center (NIC) and the ECCC Canadian Ice Service (CIS). The charts are produced from available data sources including Radarsat-2, Envisat, AVHRR, Geostationary Operational Environmental Satellites (GOES), and Moderate Resolution Imaging Spectroradiometer (Anderson et al., 2018). The spatial resolution of the ice charts is 1.8 km (1.1 mi). The charts provide ice concentration values from 0 to 100% at 10% increments. An example of a daily NIC/CIS ice concentration and ice thickness chart for the Great Lakes Region, including Lake St. Clair is given in Fig. 22.

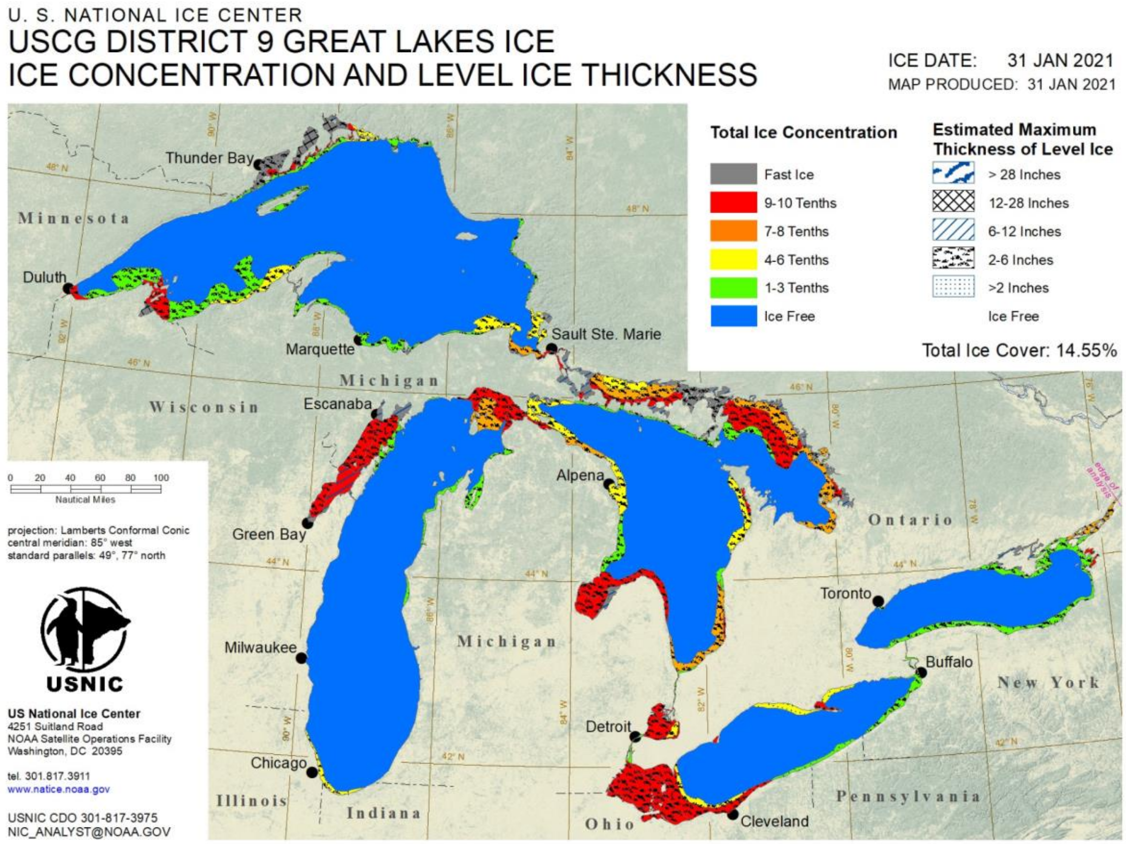


Figure 22. NWS/NCEP NIC Great Lakes Ice Chart of Ice Concentration and Thickness valid for January 31, 2021.

GLERL personnel acquired shapefiles of the NIC/CIS analyses of ice concentration (%) and ice thickness (mm) from the NIC web site. They then interpolated the NIC/CIS analyses onto GLERL/CoastWatch's Great Lakes Surface Environmental Analysis (GLSEA) regular grid and inserted GLSEA satellite-derived lake surface temperature data for non-ice pixels. The combined GLSEA/NIC-CIS product was then outputted into netCDF files.

The skill assessment of the ice hindcasts was accomplished using the draft skill statistics and software, which builds upon work done by personnel at NOAA/GLERL (Anderson et al., 2018). These statistics and software have been used previously to do preliminary skill assessment of ice concentration predictions from NOS GLOFS. The skill statistics used to compare the HECWFS hindcasts for Lake St. Clair to the NIC/CIS ice concentration analyses for the three ice years were the following: 1) ice-onset and ice-off dates of ice coverage, 2) spatial pattern of ice coverage, and 3) spatial distribution of ice concentration RMSE. The statistics and software should be considered preliminarily and will be redefined in the coming years as NOS gains more experience in the ice prediction evaluation and feedback from the maritime community, NIC ice analysts, and NWS weather forecasters. HECWFS ice thickness hindcasts were not evaluated since NOS still needs to develop the skill assessment software to compare the hindcasts against the NIC/CIC analyses of estimated maximum thickness of level ice.

In order to compare the HECWFS ice concentration hindcasts to the NIC/CIS ice concentration analyses, the hindcasts were first interpolated onto the GLSEA regular grid used for the analyses prior to the evaluation.

Unlike ice area which is the integral sum of the product of ice concentration and area of all grid cells with at least a certain ice concentration (threshold), ice extent is the integral sum of the areas of all grid cells that above the threshold ice concentration which defines a region as either "ice-covered" or "not ice-covered". Ice extent is typically reported in square kilometers.

Since ice data products are often based on ice concentration which is generally expressed as a percentage of how much ice exists in the area covered by each grid cell. Although area and extent may sound synonymous, they are different measurements, rendering different numbers, even from the same satellite observations. Both area and extent calculations require a concentration threshold, and grid cells with concentrations below that threshold are dropped from the total. Scientists use that threshold because it provides consistent agreement between satellite and surface observations.

Sea ice concepts were borrowed to evaluate lake ice in this report. For the Great Lakes area, a threshold of 10% ice cover is used, meaning that if the data cell has equal or greater than 10% ice concentration, the cell is labeled as "ice-covered". To calculate lake ice extent and area, for example, ice extent is the total region with at least 10% ice cover, while ice area is the integral sum of multiplying the area covered by each grid cell by the percentage of ice it contains for all grid cells with at least 10% ice concentration. An example of ice area and ice extent can be found below at Figure 23.

Area can be a useful measurement of precisely how much sea ice fills a particular portion of the ocean. However, there is greater agreement among sea ice experts across institutions about sea ice extent than there is about sea ice area. National Snow and Ice Data Center (NSIDC) usually reports extent, which gives higher values than area. There are multiple reasons that scientists prefer ice extent instead of ice area. One answer relates to confidence in the estimates during the melt season: since sensors do not always distinguish well between ocean water and surface meltwater, potentially underestimating concentration. Getting the extent figure right does not require precisely measuring the sea ice concentration of every grid cell. Instead, it just means identifying the grid cells that meet the threshold. In addition, simply counting the grid cells that meet the threshold, which includes most grid cells within the sea ice perimeter, reduces day-to-day variability in sea ice numbers. (https://nsidc.org/learn/ask-scientist/what-difference-between-sea-ice-area-and-extent#:~:text=Although%20area%20and%20extent%20may,15%20percent%20sea%20ice%20cover.)

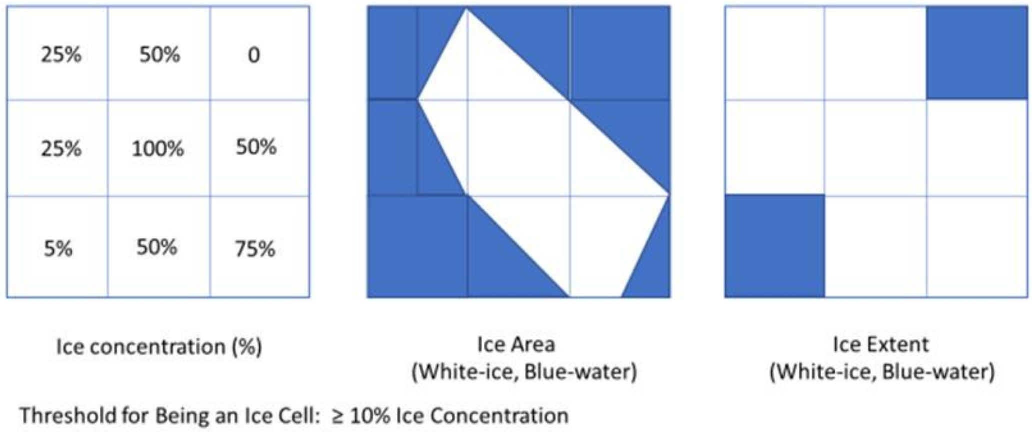


Figure 23. An example of ice area and ice extent.

The GLSEA and CICE/FVCOM lake pixels were included to calculate the daily lake-wide RMSE when the ***total lake-wide*** ice concentration from ***both*** GLSEA and from CICE/FVCOM were equal or greater than 10%.

The daily lake-wide RMSE of ice concentration is defined as follows:

RMSE= $\sqrt{\frac{\sum_{i=1}^{N}(x_i - x_{GLSEA})^2}{N}}$, where x is the pixel ice concentration, N= number of lake water pixels. Otherwise, the daily lake-wide RMSE=0.

Then the daily lake-wide RMSE was normalized by the mean ice extent from the GLSEA. $RMSE_{normalized} = \frac{RMSE}{Mean(Extent_{GLSEA})}$. For the GLSEA analysis data, a lake cell is considered as an "ice cell" or pixel and is marked as "1", if its ice concentration is 10% or greater; "0" otherwise.

6.3.1 Assessment of Ice–Onset and Ice–Off Dates of Ice Coverage

Ice coverage refers to the ratio of total iced cell number to total lake cell number. A cell is considered as an iced one when its ice concentration is equal or greater than the threshold of 10%. The Ice-Onset Date is defined as the first day when the lake-wide averaged ice coverage exceeded 10% for five consecutive days. The Ice-Off Date is the first day when the lake-wide averaged ice coverage is less than 10% for five consecutive days.

HECWFS' predictions of Ice-Onset and Ice-Off Dates of Ice Coverage for Lake St. Clair were estimated from the ice concentration hindcasts for each of the three ice years. The hindcasts were available every three hours, but averaged over the day in order to be compared to similar dates, estimated from the daily NIC/CIS ice concentration charts. The Ice-Onset and -Off Dates for both the hindcasts and NIC/CIC charts along with the difference between them are given in Table 22.

Table 22. Hindcasts vs. NIC/CIS Analysis Dates of Ice-Onset and Ice-Off for Lake St. Clair.

		2018 – 2019 Season	**2019 – 2020 Season**	**2020 – 2021 Season**
Ice Onset	Hindcasts	2019-01-16	2020-02-03	2021-01-13
	NIC/CIS Analysis	2019-01-18	2020-02-27	2021-02-01
	Difference	2 Days Too Early	24 Days Too Early	18 Days Too Early
Ice Off	Hindcast	2019-04-08	2020-03-15	2021-03-26
	NIC/CIS Analysis	2019-03-27	2020-03-10	2021-03-15
	Difference	11 Days Too Late	5 Days Too Late	11 Days Too Late

Over the three ice years, the hindcasts predicted the ice onset too early and an ice off too late, thus estimating a longer ice season than observed. The number of days too early ranged from 2 days during the 2018-2019 ice year to 24 days during the well below normal ice year of 2019-2020. The hindcasts did better in predicting the date of ice off with the number of lagging days ranging from five to 11 days.

6.3.2 Lake-Wide Average Ice Concentration

The time series of hindcasts of the lake-wide average ice concentration, as expressed in ice concentration, vs. ice coverage from the NIC/CIS analysis vs. GLERL ice concentration climatology for the three ice years are given in Fig. 24.

Overall, the hindcasts successfully simulated the lake-wide concentration for each ice year. The hindcasts did better than climatology in depicting the freeze up of the lake across all three ice years; the climatology was too early. The hindcasts predicted the three peaks during the 2019-2020 year. However, the hindcasts did not show a decrease in ice concentration during the second peak of that ice year in early February as indicated by the NIC ice chart.

With regards to predicting when the lake-average ice concentration would reach approximately 10% in the Spring, the hindcasts did the best during 2019-2020 and was better than climatology. For the other two years, the hindcasts were too slow in melting the ice. The hindcasts did about the same as climatology during 2018-2019, but better than climatology during 2020-2021.

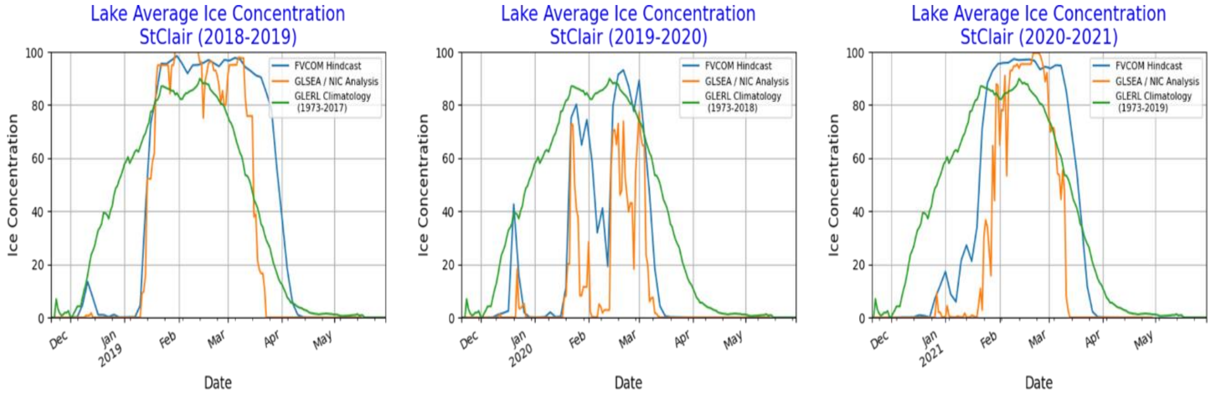


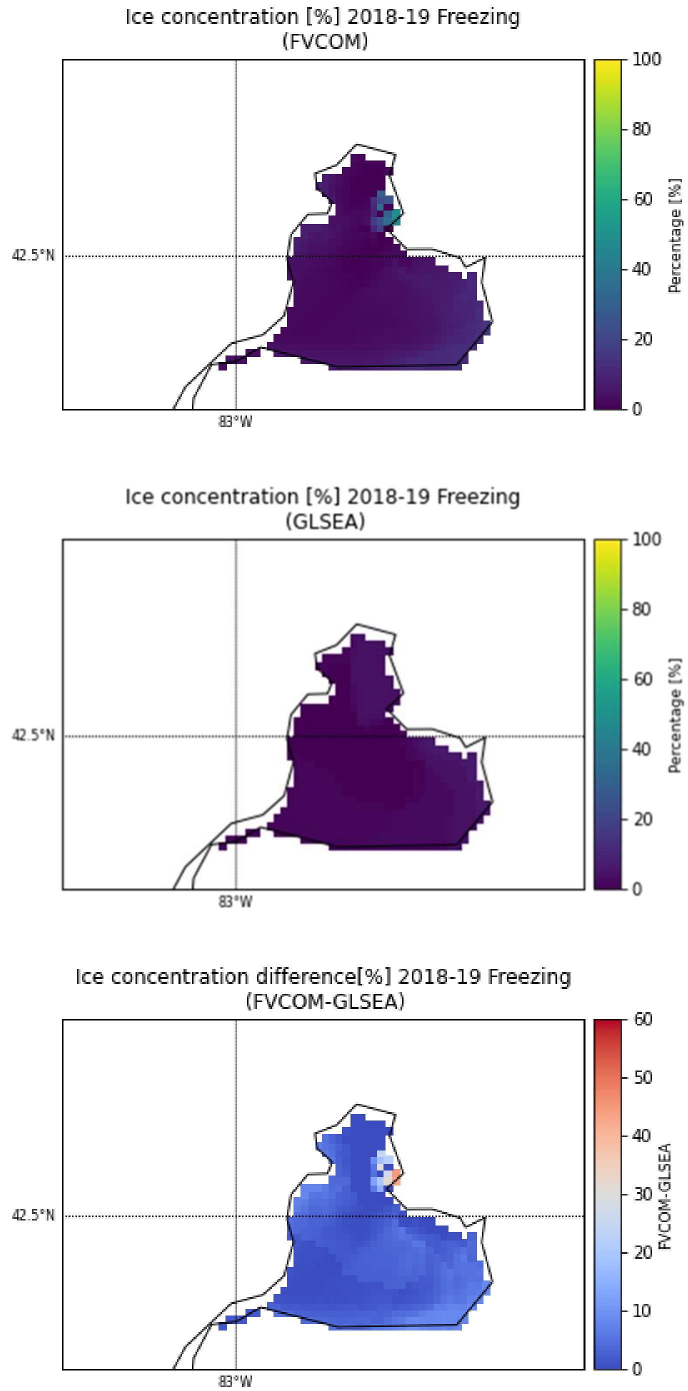
Figure 24. Lake-Wide Ice Concentration Hindcasts vs. NIC/CIS Analysis vs. Ice Climatology for Lake St. Clair for the three hindcast ice years.

6.3.3 Spatial Pattern of Ice Concentration

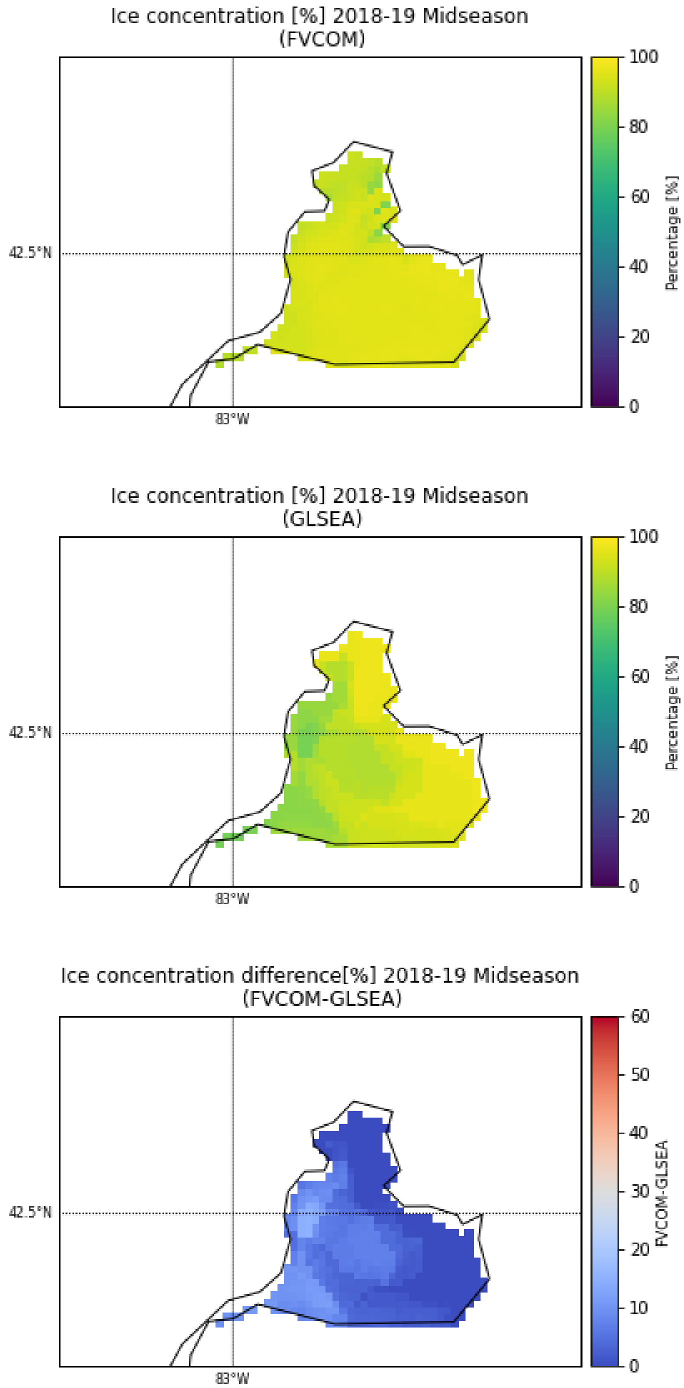
This section provides comparisons of the spatial patterns of the ice concentration hindcasts from HECWFS for Lake St. Clair vs. the NIC/CIS charts or analyses during the three ice years, 2018-2019, 2019-2020, and 2020-2021. The ice concentration hindcasts for the lake for the three phases of an ice season: freezing (12/01 to 1/15), mid-season (1/16 to 3/15), melting (3/16 to 5/01), and entire season, along with corresponding NIC/CIS analyses are depicted in Figures 25 to 27.

The spatial pattern is reasonably predicted in comparison with the NIC/CIS analyses for the three ice years. This includes the development of nearshore ice during the freezing period, peak ice cover, and in the offshore open water region in the mid-season and ice decay during the melting phase.

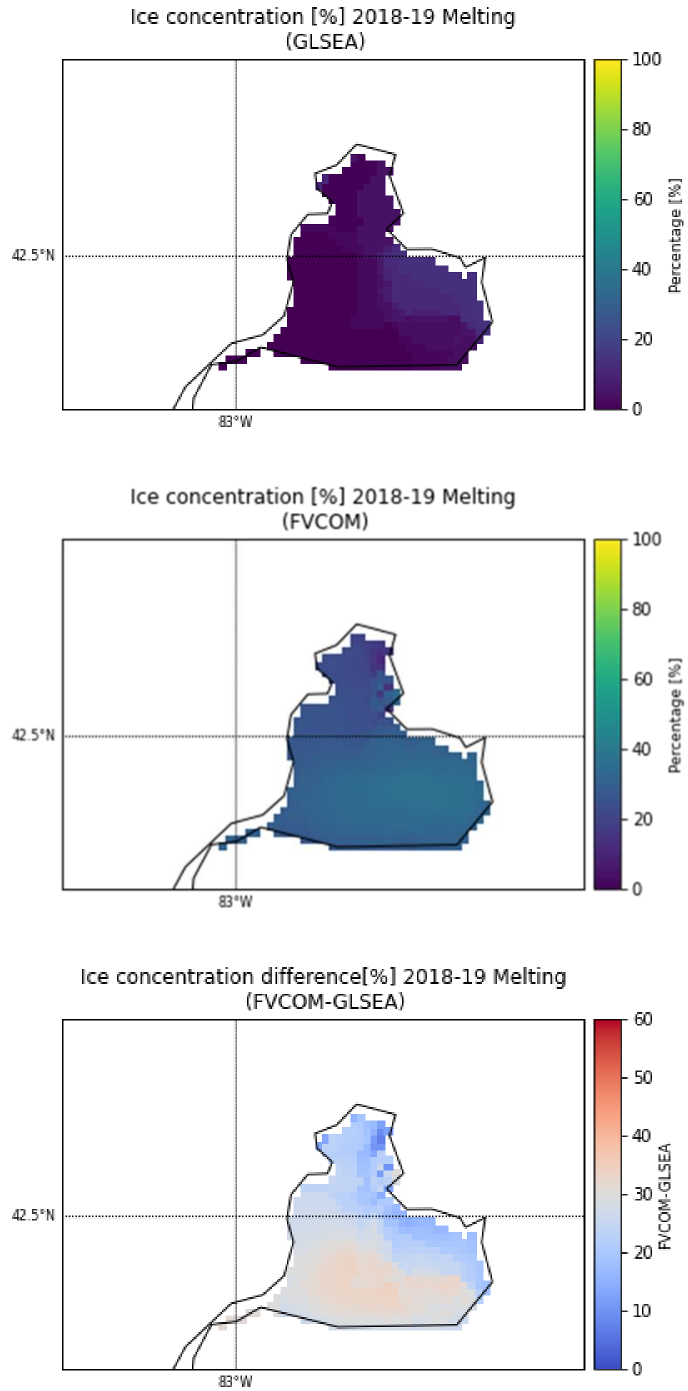
Comparisons between the HECWFS ice concentration hindcasts and the NIC/CIS Analyses for the entire season for each of the three ice years are given in Fig. 28. The figure depicts the seasonal ice concentration predicted by HECWFS, the concentration estimated by the NIC/CIS analysis, and the difference between the two (i.e., hindcast minus NIC/CIS analysis). The figure indicates slight differences in parts of Lake Clair. A distinct difference is evident in the area of the St. Clair River Delta, primarily during the freezing seasons of the three ice years. However, this difference in the Delta area may be due to the spatial resolution of the NIC/CIS regular grid vs. the HECWFS mesh in the area of the delta, as illustrated in Fig. 29.


Ice concentration [%] 2018-19 Freezing
(FVCOM)
42.5°N
83°W
Percentage [%]
0
20
40
60
80
100
Ice concentration [%] 2018-19 Freezing
(GLSEA)
42.5°N
83°W
Percentage [%]
0
20
40
60
80
100
Ice concentration difference[%] 2018-19 Freezing
(FVCOM-GLSEA)
42.5°N
83°W
FVCOM-GLSEA
0
10
20
30
40
50
60

(a) Freezing

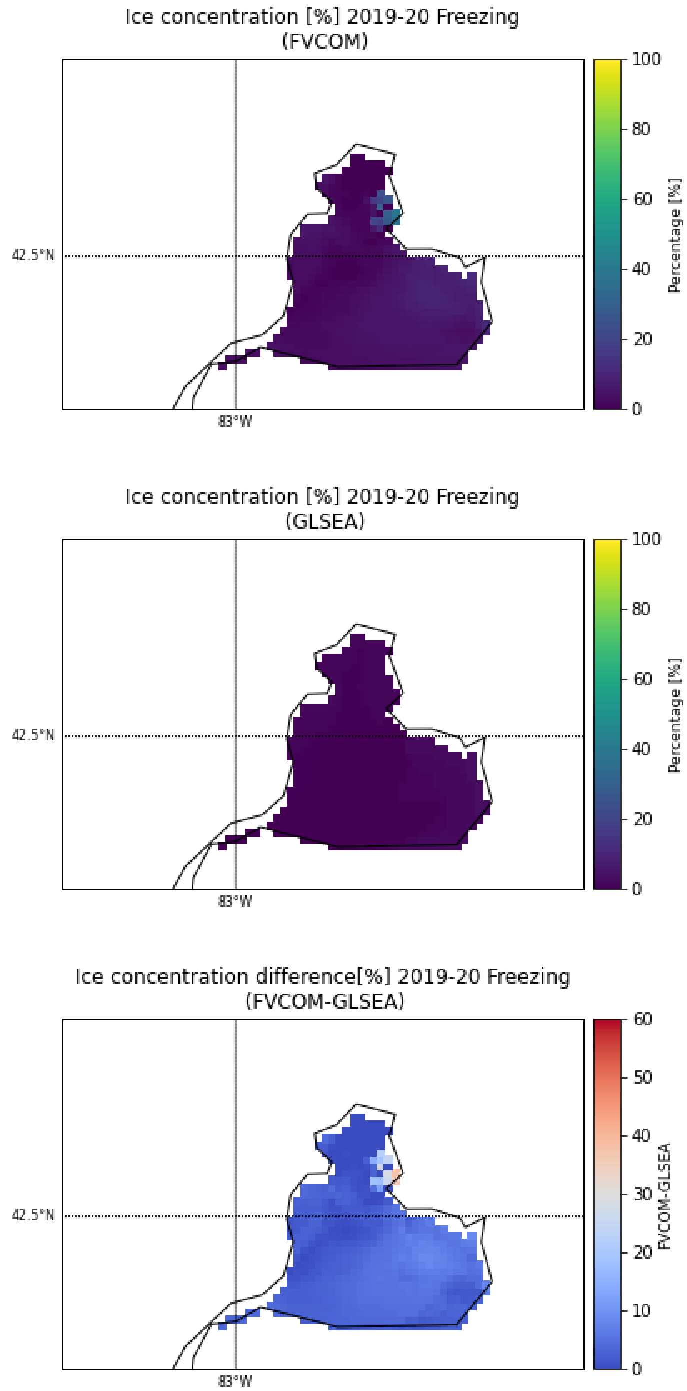

Ice concentration [%] 2018-19 Midseason
(FVCOM)
42.5°N
83°W
100
80
60
40
20
0
Percentage [%]
Ice concentration [%] 2018-19 Midseason
(GLSEA)
42.5°N
83°W
100
80
60
40
20
0
Percentage [%]
Ice concentration difference[%] 2018-19 Midseason
(FVCOM-GLSEA)
42.5°N
83°W
60
50
40
30
20
10
0
FVCOM-GLSEA

(b) Midseason

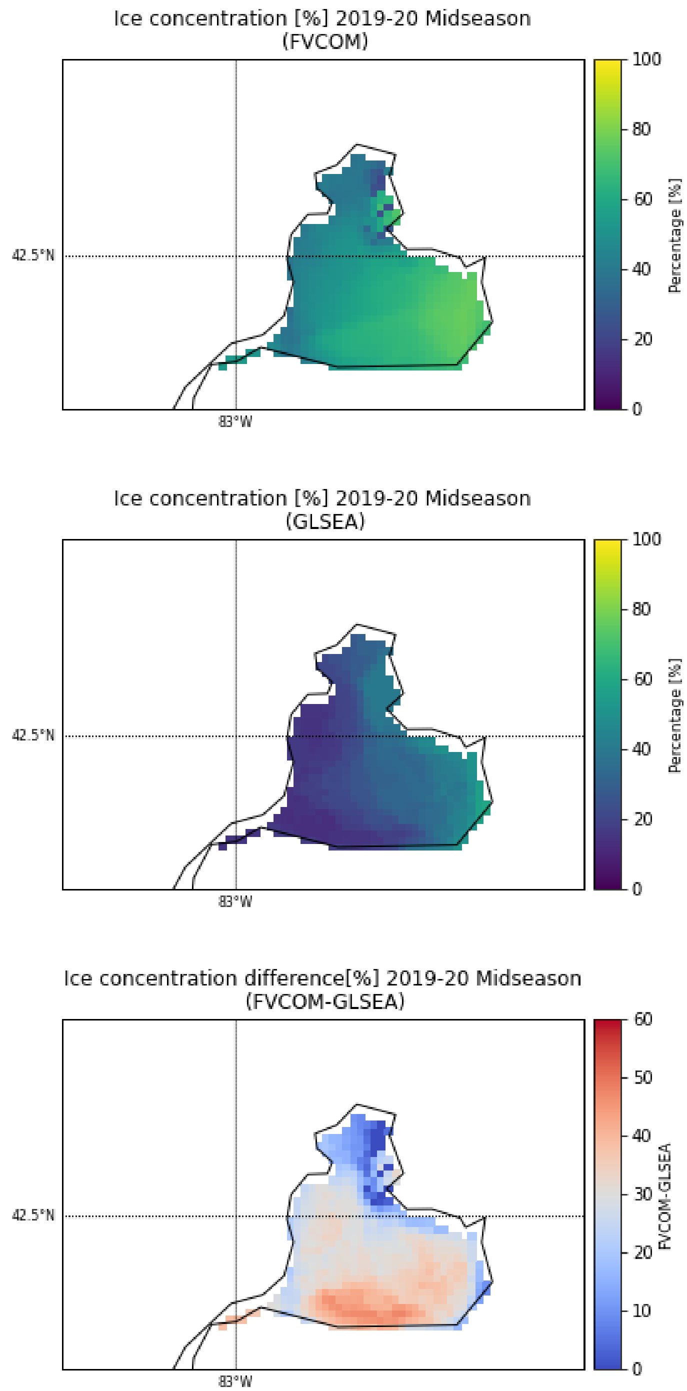


(c)Melting

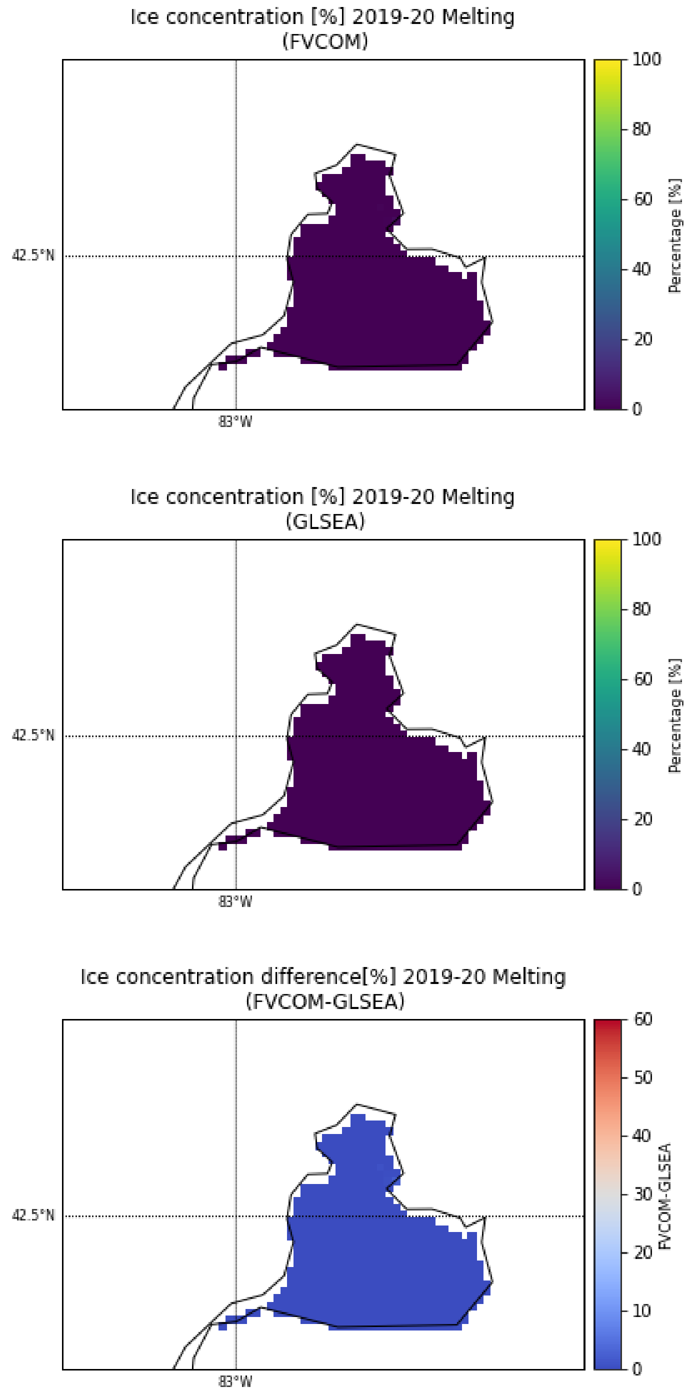
Figure 25. Ice concentration comparisons for three different ice stages: (a) freezing, (b) midseason, and (c) melting. For each stage: Top - Hindcast, Middle - NIC/CIS Analysis, Bottom - difference (HECWFS minus GLSEA), for the ice year 2018-2019.


Ice concentration [%] 2019-20 Freezing
(FVCOM)
42.5°N
83°W
Percentage [%]
0
20
40
60
80
100
Ice concentration [%] 2019-20 Freezing
(GLSEA)
42.5°N
83°W
Percentage [%]
0
20
40
60
80
100
Ice concentration difference[%] 2019-20 Freezing
(FVCOM-GLSEA)
42.5°N
83°W
FVCOM-GLSEA
0
10
20
30
40
50
60

(a) Freezing

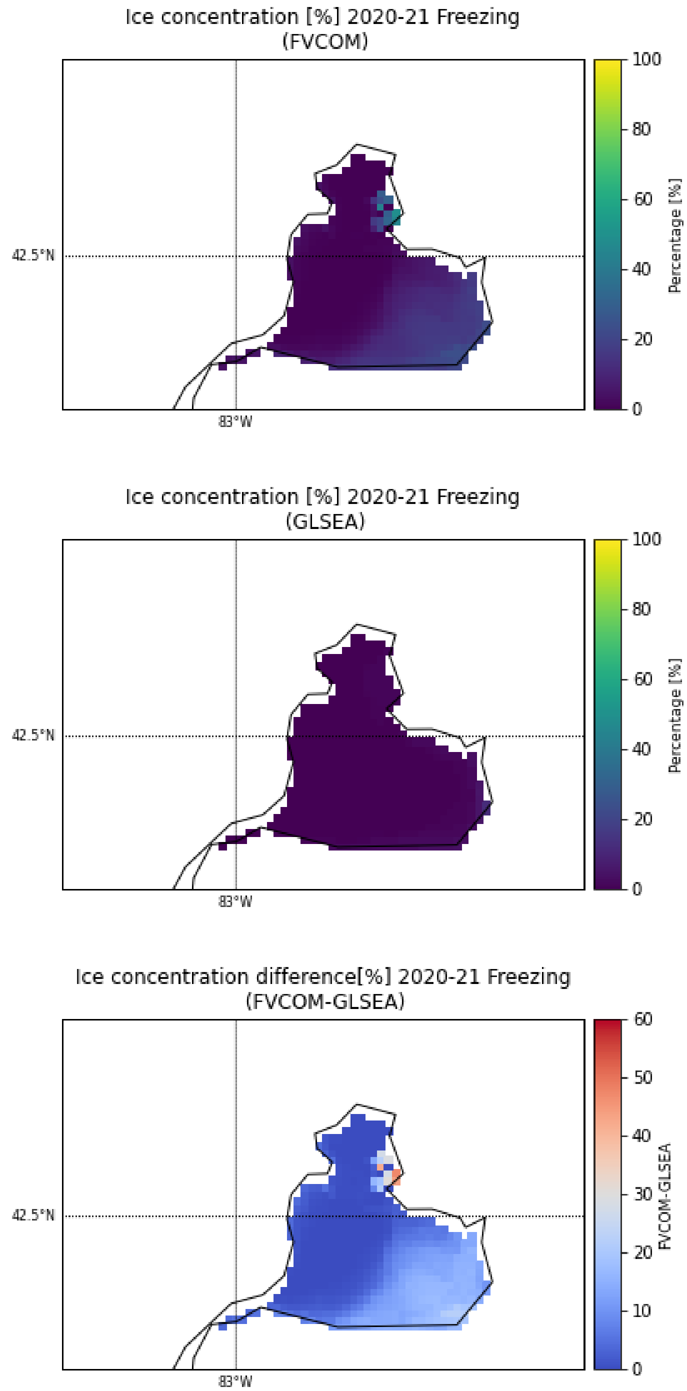

Ice concentration [%] 2019-20 Midseason
(FVCOM)
42.5°N
83°W
Percentage [%]
0
20
40
60
80
100
Ice concentration [%] 2019-20 Midseason
(GLSEA)
42.5°N
83°W
Percentage [%]
0
20
40
60
80
100
Ice concentration difference[%] 2019-20 Midseason
(FVCOM-GLSEA)
42.5°N
83°W
FVCOM-GLSEA
0
10
20
30
40
50
60

(b) Midseason

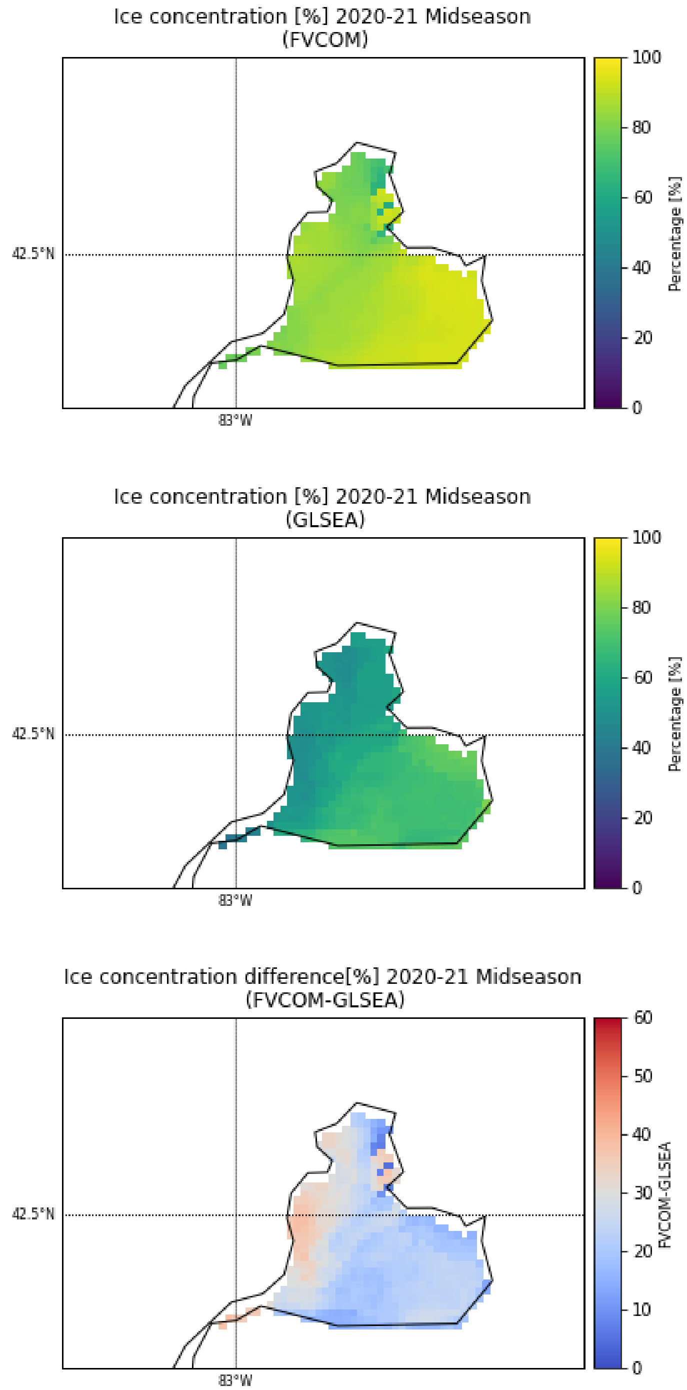


(b) Melting

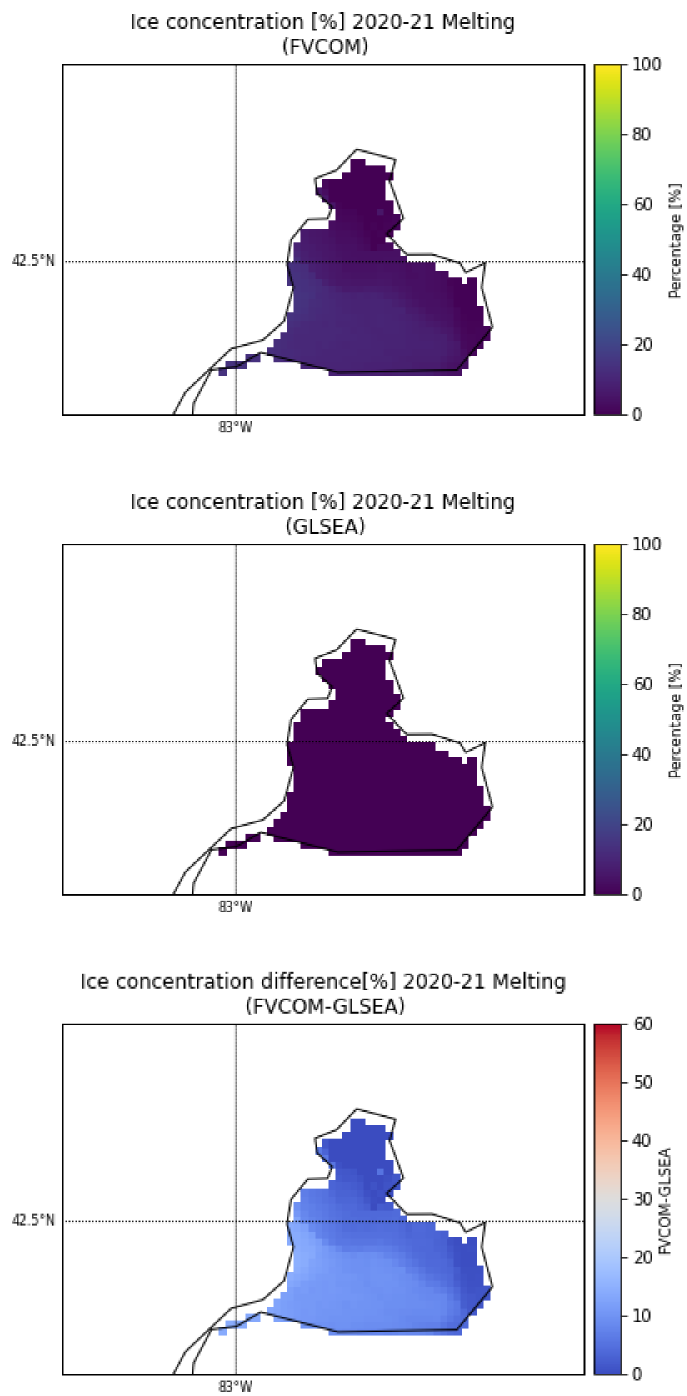
Figure 26. Same as above but for the ice year 2019-2020.


Ice concentration [%] 2020-21 Freezing
(FVCOM)
42.5°N
83°W
100
80
60
40
20
0
Percentage [%]
Ice concentration [%] 2020-21 Freezing
(GLSEA)
42.5°N
83°W
100
80
60
40
20
0
Percentage [%]
Ice concentration difference[%] 2020-21 Freezing
(FVCOM-GLSEA)
42.5°N
83°W
60
50
40
30
20
10
0
FVCOM-GLSEA

(a) Freezing

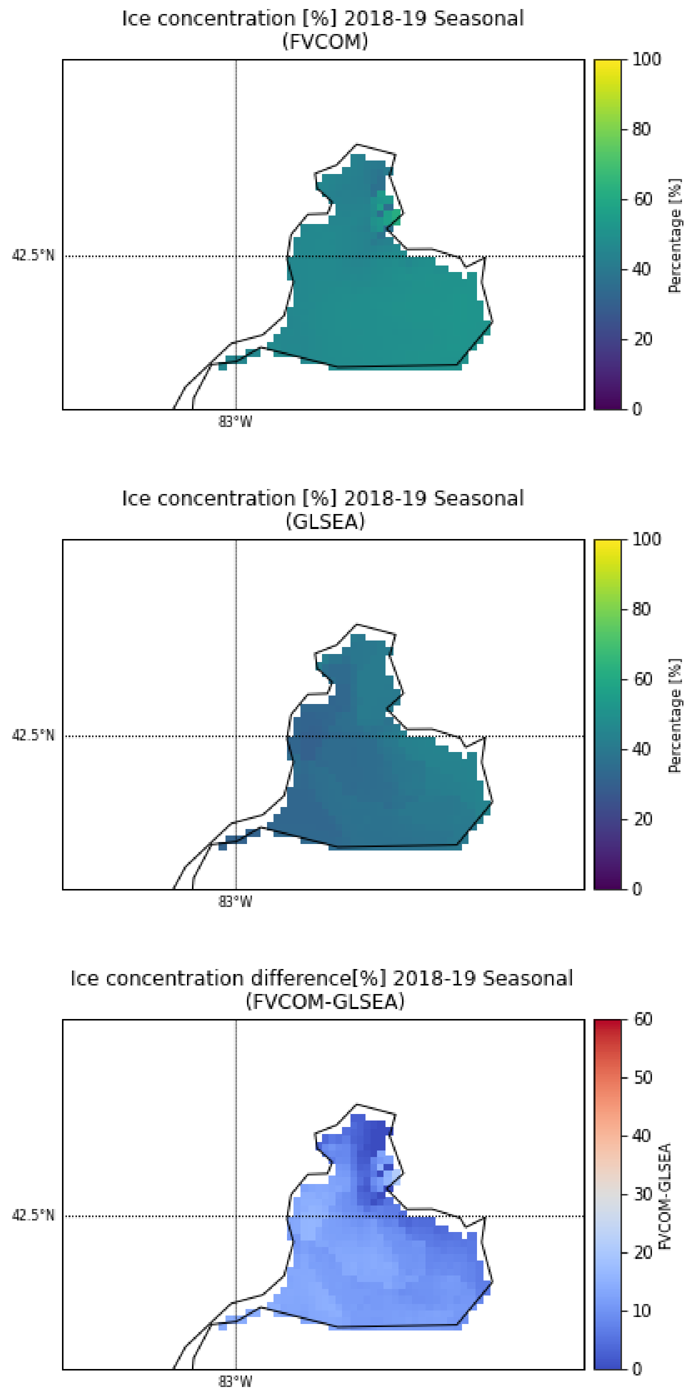

Ice concentration [%] 2020-21 Midseason
(FVCOM)
42.5°N
83°W
Percentage [%]
0
20
40
60
80
100
Ice concentration [%] 2020-21 Midseason
(GLSEA)
42.5°N
83°W
Percentage [%]
0
20
40
60
80
100
Ice concentration difference[%] 2020-21 Midseason
(FVCOM-GLSEA)
42.5°N
83°W
FVCOM-GLSEA
0
10
20
30
40
50
60

(b) Midseason

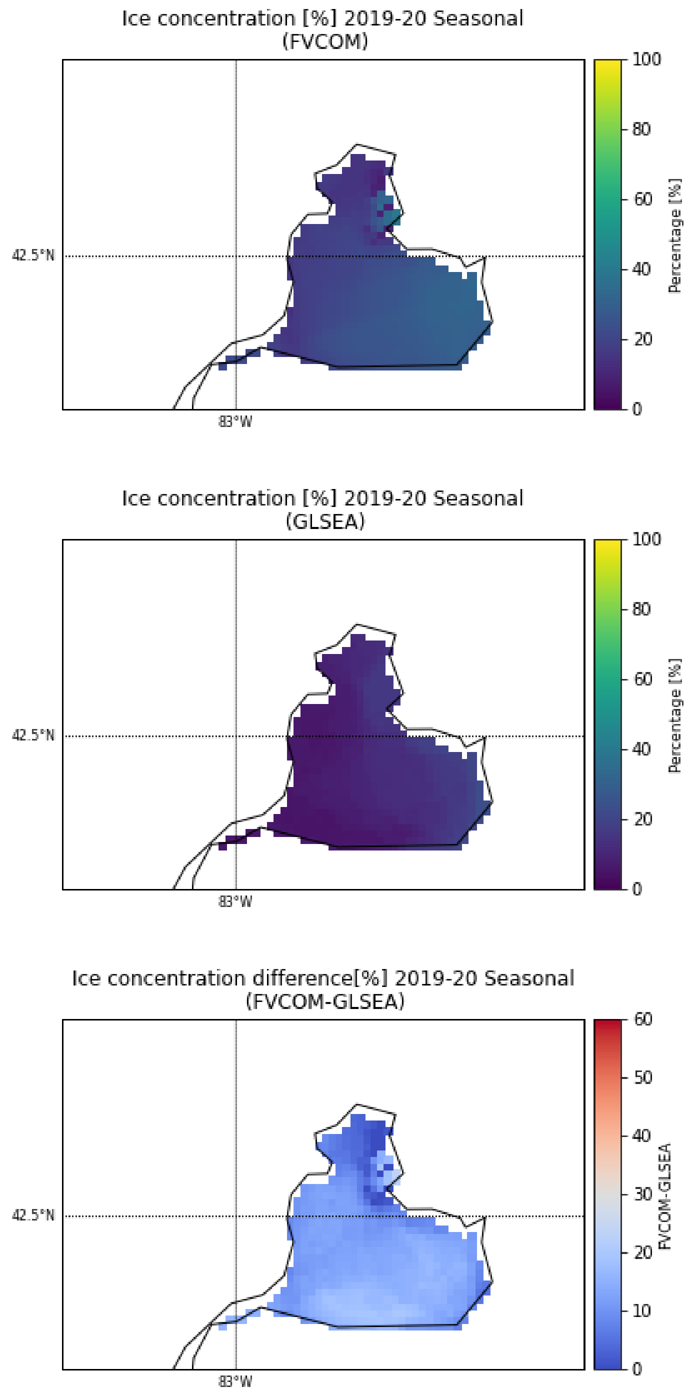


(c) Melting

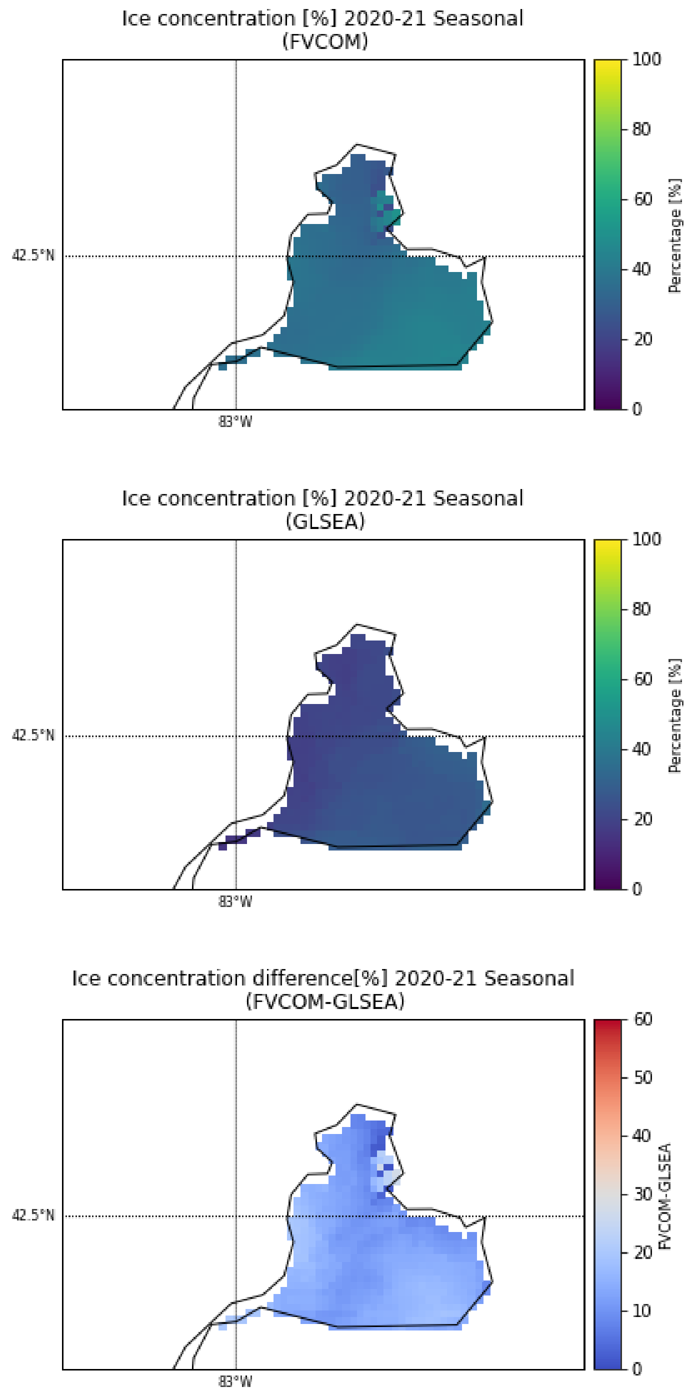
Figure 27. Same as above but for the ice year 2020-2021.


Ice concentration [%] 2018-19 Seasonal
(FVCOM)
42.5°N
83°W
0
20
40
60
80
100
Percentage [%]
Ice concentration [%] 2018-19 Seasonal
(GLSEA)
42.5°N
83°W
0
20
40
60
80
100
Percentage [%]
Ice concentration difference[%] 2018-19 Seasonal
(FVCOM-GLSEA)
42.5°N
83°W
0
10
20
30
40
50
60
FVCOM-GLSEA

(a)

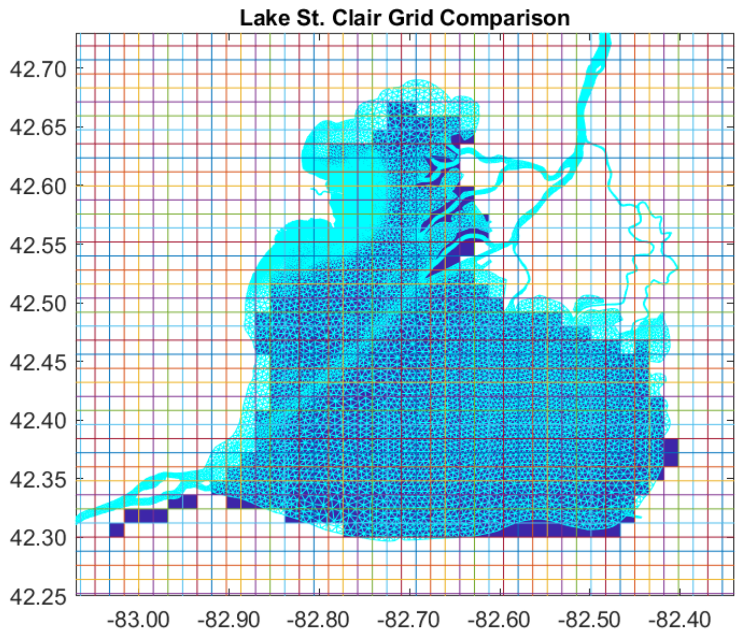

Ice concentration [%] 2019-20 Seasonal
(FVCOM)
100
80
60
40
20
0
Percentage [%]
42.5°N
83°W
Ice concentration [%] 2019-20 Seasonal
(GLSEA)
100
80
60
40
20
0
Percentage [%]
42.5°N
83°W
Ice concentration difference[%] 2019-20 Seasonal
(FVCOM-GLSEA)
60
50
40
30
20
10
0
FVCOM-GLSEA
42.5°N
83°W

(b)

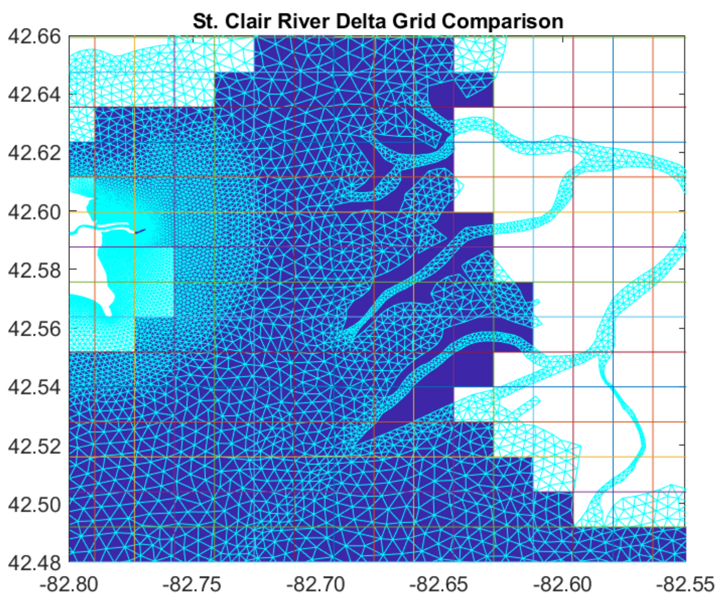


(c)

Figure 28. Seasonal ice concentration comparisons for the three different hindcast ice years: (a) 2018-2019, (b) 2019-2020, and (c) 2020-2021. Top - Hindcast, Middle - NIC/CIS Analysis, Bottom - difference (Hindcast minus GLSEA).



(a)



(b)

Figure 29. Overlay of the HECWFS FVCOM mesh (light blue) on top of the GLSEA regular grid (dark blue) for Lake St. Clair (a) and zoomed into the St. Clair River Delta (b).

6.3.4 Spatial Distribution of Ice Concentration RMSE

The ice concentration RMSE (%) between the hindcasts and the NIC/CIS analyses were calculated in each grid cell of Lake St. Clair and averaged over the entire duration of each ice year. This was done to identify any geographic areas with consistently high/low errors and any differences across the three years. The spatial RMSE of ice concentration maps for each of the hindcast years are given in Fig. 30.

The spatial RMSE of ice concentration (Fig. 30) is nearly homogeneous across the lake during the average and below average ice years, 2018-19 and 2020-21, respectively. During the well below normal ice year, 2019-2020, there appears to be a north to south difference, with smaller RMSE in shallow Anchor Bay and the bays near the Delta area and with larger RMSEs to the south in the deeper part of the lake.

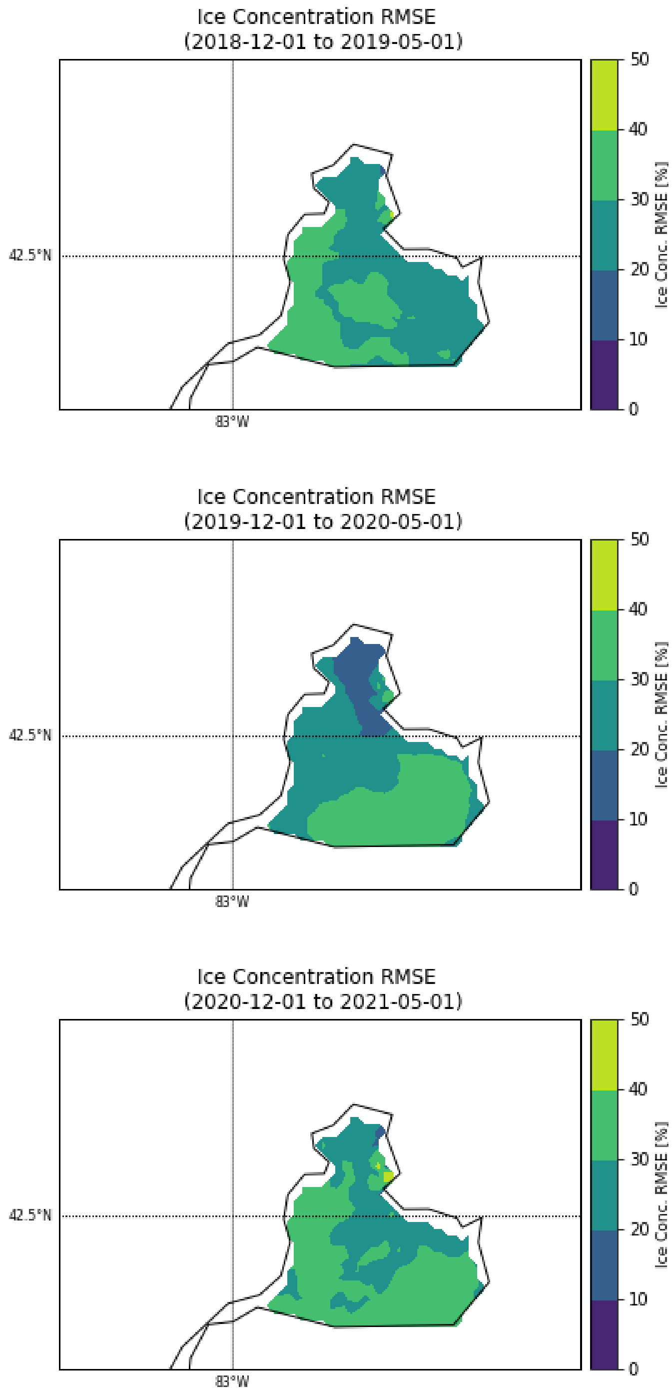


Figure 30. Spatial distribution of ice concentration RMSE averaged for the entire ice years for each of the three ice years: from left to right: 2018-2019, 2019-2020, and 2020-2021.

7. ASSESSMENT OF WATER LEVEL HINDCASTS WITH RESPECT TO ICE JAMS

As mentioned in Section 2, ice flow and ice jams in the St. Clair River can cause significant water level fluctuations in portions of the St. Clair River and Lake St. Clair. Water levels can rise suddenly and result in flooding along the river. Ice jams form in the St. Clair River when ice from Lake Huron enters the river and flows downstream to the St. Clair Flats (i.e., Lake St. Clair Delta) near Algonac, Michigan and Port Lambton, Ontario. The ice can accumulate in this area forming a restriction or ice jam. The jam can cause water levels downstream in the Delta and Lake Clair to decrease and levels upstream in the St. Clair River to increase. In addition, ice jams can close the rivers and the lake to marine navigation, which requires the U.S. and Canadian Coast Guards to deploy icebreaking ships to break up the ice jams. A list of the icebreaking missions during the three hindcast ice years is given in Table 23.

Table 23. Number of missions by U.S. and Canadian Icebreakers in the Huron-Erie Corridor by water type, mission purpose, and ice year. Courtesy of Isabelle Pelchat of the Canadian Coast Guard, Fisheries and Oceans Canada [DFO-MPO].

Water Body	**Mission Purpose**	**Ice Year**		
		2018-2019	**2019-2020**	**2020-2021**
St. Clair River and Lake St. Clair	Flood Control Ops	4	0	22
	Assist a Beset Ship	1	0	0
	Track Maintenance	2	3	19
	Escorts	46	1	47
Detroit River	Flood Control Ops	0	0	1
	Assist a Beset Ship	0	0	0
	Track Maintenance	1	0	1
	Escorts	48	0	48

Two notable ice jams on St. Clair River occurred during the three hindcasts. One occurred around January 20 to 22, 2019 and February 3, 2021. According to press reports, a strong north wind on January 20 pushed Lake Huron ice down the St. Clair River and caused an ice jam near Algonac. The jam caused water levels to rise in the river north of Algonac, as much as two feet near East China, MI resulting in flooding along the river and canals, especially in southern St. Clair County, MI (i.e., East China Township, Marine City). Some residents had to evacuate. The USCG (2019) reported that the Captain of the Port Detroit “imposed a one-way traffic pattern on the St. Clair River during the end of January [2019], all of February, and parts of March due to significant ice buildup causing ice jam and high water levels. These restrictions required alternating one-way traffic and frequently required icebreaker escorts between Marine City, Michigan and Lake St. Clair.”

The impact of the January 2019 ice jam on the observed water levels along the St. Clair River and Lake St. Clair can be seen in the time series plots in Figures 31 and 32, respectively. The hindcasts for the same time periods are also displayed in the plots. A very sudden rise in water levels is evident in observations around Day 20 (January 20) followed by more gradual decline. This rise and decline were captured by the hindcasts at the three gauges, especially at Port Lambton and Algonac (Fig. 31).

However, the hindcasts do not simulate the observed water levels rises and falls which started around Day 40 (February 9) and continued to Day 70 (March 11). As mentioned earlier, there were persistent wide-swinging temperature fluctuations through February and frequent icebreaker escorts occurred from late January into parts of March and could account for the frequent water level fluctuations. The hindcasts did simulate these fluctuations which one would expect since HECWFS did not have data assimilation and thus did not reveal any information of ice coverage changes due to icebreaking operations.

The hindcasts depicted an increase in water levels beginning around Day 70 and sustained until Day 100 (April 20). This was not seen in the observations. The overprediction of water level by the hindcasts may be due to an overprediction of the ice coverage in the St. Clair River.

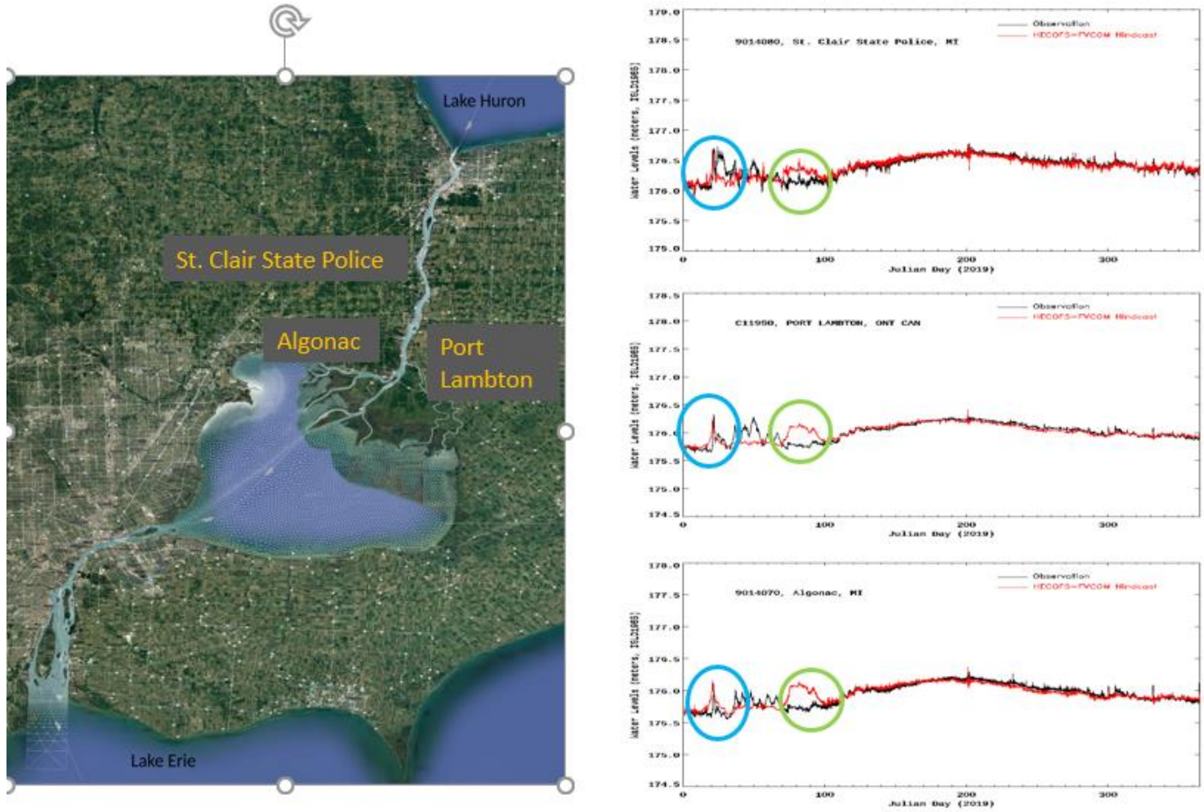


Figure 31. Time series plots of HECWFS hindcasts of water levels (red) vs. observations (black) at gauges along the St. Clair River: St. Clair State Police Station Gauge, Port Lambton Gauge, and Algonac during 2019. The hindcasts had a temporal frequency of 6 minutes while the observations from the NOS gauges were hourly and 3-hourly at the CHS gauge (Port Lambton). The blue circles indicate the period of the observed ice jam and green circles indicate hindcasts predicting high water levels.

The impact of the ice jam in the St. Clair River was also seen in the observed water levels at gauges in Lake St. Clair at St. Clair Shores, Windmill Point, and Belle River, which are highlighted with blue circles in Fig. 32. The observations show a sudden decrease in the water levels around Day 20 as one would expect due to the ice jam restricting water flowing into Lake St. Clair. The dip continued until Day 40. However, the hindcasts instead depicted a sudden increase followed by a slight decrease. Similarly, to what was depicted at the St. Clair River gauges, the hindcasts showed an increase in water levels from Day 70 to 100 (green circles), but was not seen in the observations. The possible reason is due to an overprediction of ice by HECWFS in Lake St. Clair that resulted in an overprediction of water levels along the lakeshore.

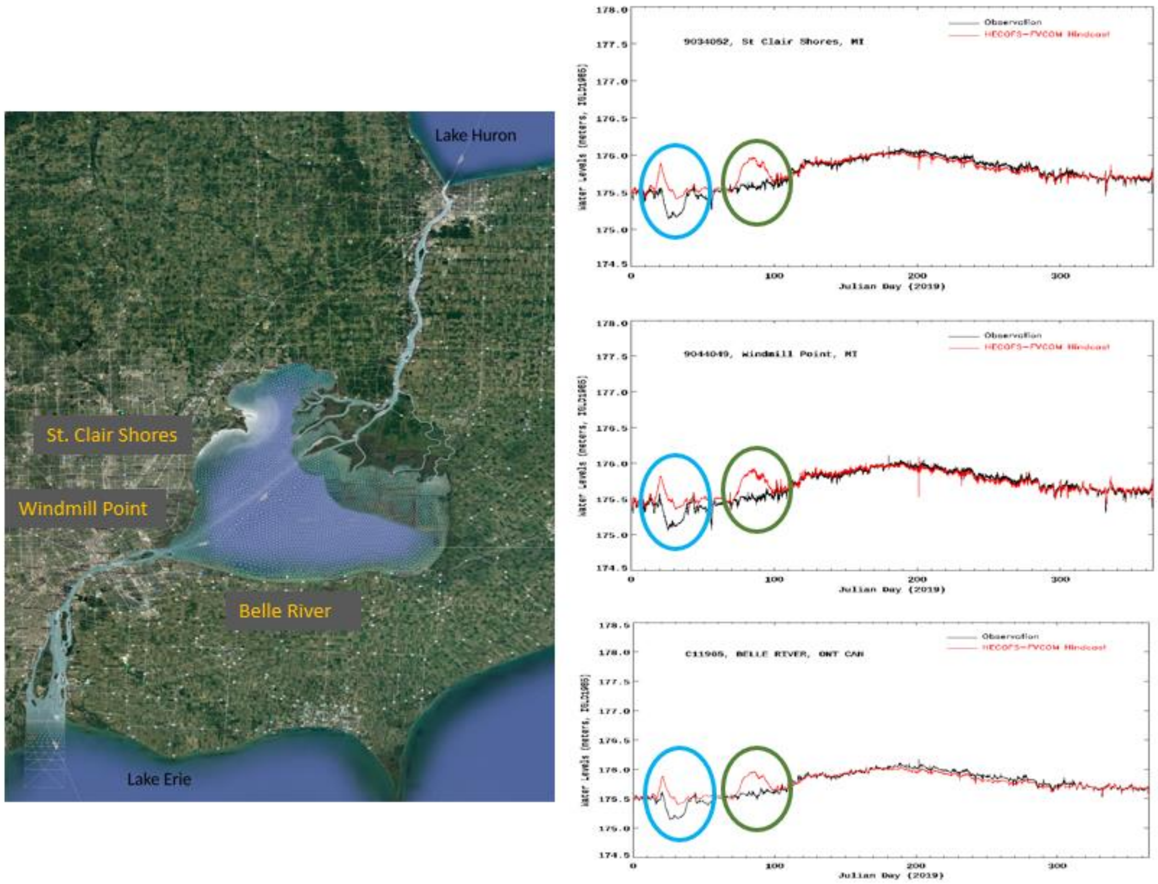


Figure 32. Time series plots of HECWFS hindcasts of water levels (red) vs. observations (black) at gauges in Lake St. Clair: St. Clair Shores, Windmill Point, and Belle River during 2019. The hindcasts had a temporal frequency of 6 minutes while the observations from the NOS gauges were hourly and 3-hourly at the CHS gauge (Belle River). The blue circles indicate the period of the observed ice jam and green circles indicate hindcasts predicting high water levels.

The other ice jam on St. Clair River began on February 2, 2021. The USCG end of season ice report (Floyd, 2021) stated that "in early February, sustained cold temperatures settled upon the region causing rapid ice growth in the St. Clair River and Western Lake Erie, prompting the initiation of Operation Coal Shovel [February 2]. The cold temperatures caused high water levels resulting in flooding in the St. Clair River. Freezing temperatures persisted throughout the month of February and part way into March." By February 5, a State of Emergency was declared by the Board of Commissioners in St. Clair County due to widespread or severe damage to hundreds of homes along the St. Clair River caused by flooding due to ice accumulation in the river. The damage was significant in East China Township and Marine City. On February 15, the St. Clair Region Conservation Authority (SCRCA, 2021) stated the following "Brash ice which accumulated and jammed in the lower reaches of the St. Clair River two weeks ago remains in place, extending from the St. Clair Flats to Sombra (Marine City, MI). Recent below-normal temperatures have developed extensive ice cover throughout the Great Lakes region, resulting in the reformation of an ice bridge across Southern Lake Huron which is currently preventing further ice flow from entering the St. Clair River." The SCRCA (2021) reported on February 15 that forecasted North/Northeast winds may promote the flow of water into St. Clair River resulting in elevated water levels and if the ice bridge separates, the ice flow into the river could exacerbate water levels and further build the ice jam. Ice began melting throughout March and commercial vessels were able to transit the river unhindered by ice by late March (Floyd, 2021). The USCG Operation Coal Shovel ended on March 14.

The impact of the February 2021 ice jam on the observed water levels along the St. Clair River can be seen in the observations depicted in the time series plots of Figure 33. The hindcasts for the same time periods are also displayed in the plots. At St. Clair State Police gauge in the St. Clair River, a very sudden rise in water levels is evident in observations around Day 35 (February 4) followed by a gradual decline to Day 60 (March 1). The hindcasts predicted the rise a bit earlier but closely matched observations afterwards. However, at Port Lambton and Algonac gauges, the water level hindcasts predicted an earlier rise than seen in the observations and also did not capture the sudden decrease, dip, and the following increase.

The hindcasts at all three gauges depicted an increase in water levels around Day 60 (March 1) which slowly decreased till Day 90 (March 31) as highlighted in the green circles. This behavior is not seen in the observations. During March, ice began melting and commercial vessels were able to transit unhindered by ice by late March (Floyd, 2021). The overprediction of water levels by hindcasts during this period may be due to an overprediction of ice in the St. Clair River.

The impact of the ice jam in the St. Clair River was also seen in the observed water levels (Fig. 34) at the downstream gauges in Lake St. Clair at St. Clair Shores, Windmill Point, and Belle River (blue circles). The observations show a sudden decrease in the water levels around Day 25 (January 25) as one would expect due to the ice jam restricting water flowing into Lake St. Clair. The dip continued until Day 35 (February 4). However, the hindcasts instead depicted a sudden increase followed by a slight decrease. Similar to what was depicted at the St. Clair River gauges, the hindcasts showed an increase in water levels from Day 60 (March 1) to Day 90 (March 31) (green circles), but was not seen in the observations. The possible reason is due to an overprediction of ice by the hindcasts in Lake St. Clair resulting in an overprediction of water levels along the lakeshore.

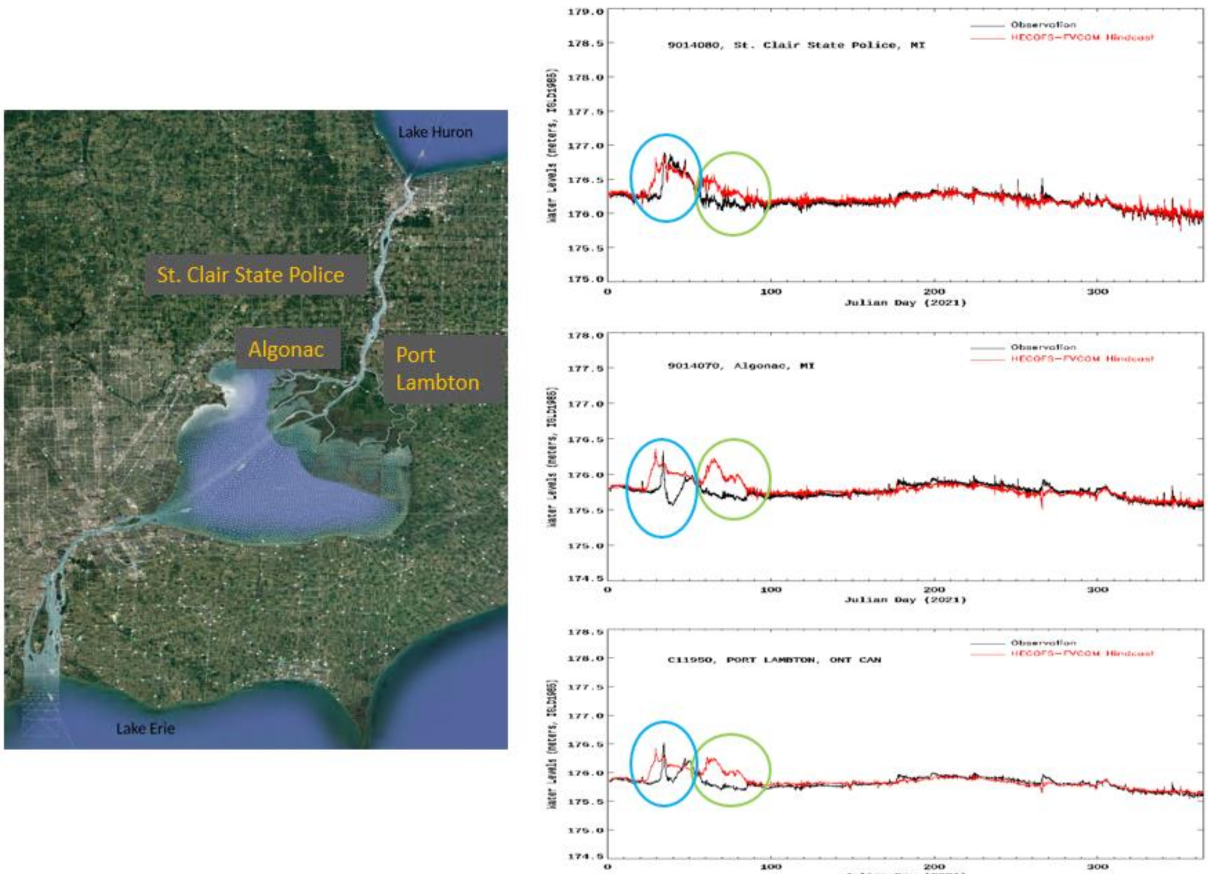


Figure 33. Time series plots of HECWFS hindcasts of water levels (red) vs. observations (black) at the St. Clair State Police Station Gauge, Port Lambton Gauge, and Algonac Gauge during 2021. The hindcasts had a temporal frequency of 6 minutes, whereas the observations from the NOS gauges were hourly and 3-hourly at the CHS gauge (Port Lambton). The blue circles indicate the period of the observed ice jam and green circles indicate hindcasts predicting high water levels.

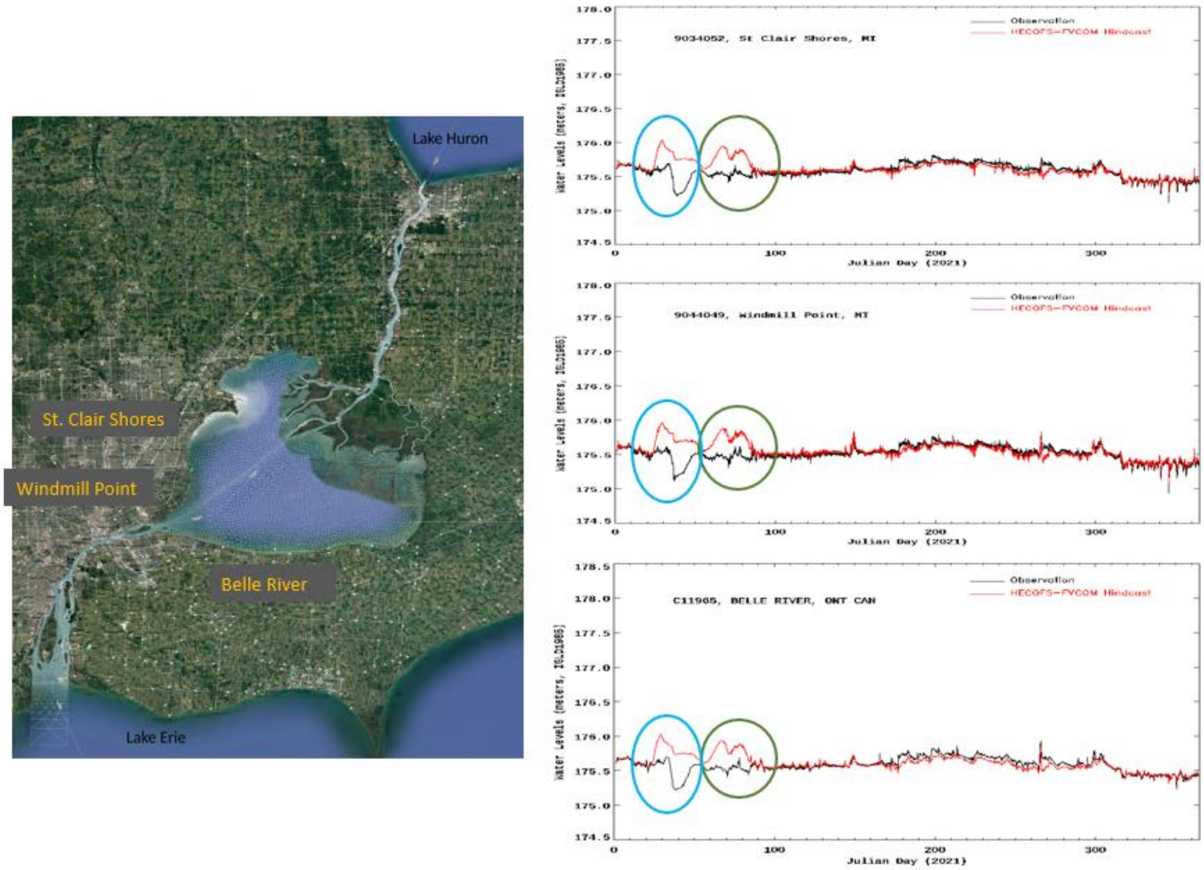


Figure 34. Time series plots of HECWFS hindcasts of water levels (red) vs. observations (black) at St. Clair Shores Gauge, Windmill Point Gauge, and Belle River Gauge during 2021. The hindcasts had a temporal frequency of 6 minutes, whereas the observations from the NOS gauges were hourly and 3-hourly at the CHS gauge (Belle River). The blue circles indicate the period of the observed ice jam and green circles indicate hindcasts predicting high water levels.

8. SUMMARY AND DISCUSSION

NOAA/GLERL Huron Erie Connecting Waterways Forecasting System (HECWFS) is a 3-D lake numerical forecast modeling system which generates short-range forecast guidance of water temperatures, water currents, water levels, ice concentration and ice thickness out to 120 hours for the Huron-Erie Corridor which includes the St. Clair River, Lake St. Clair, and the Detroit River. HECWFS was forced by model forecast guidance from National Weather Center (NWS) and river observations from USGS gauges and analyses from the NWS' National Water Model (NWM).

HECWFS uses the FVCOM as its core 3-D hydrodynamic model. HECWFS has a mean horizontal spatial resolution approximately 236 m (0.15 mi), and a median resolution approximately 175 m (0.11 mi). The system has 21 vertical sigma levels with an integrated, unstructured version of UG-CICE. HECWFS has been running in semi-operational mode on the GLERL computer systems since 2008.

The transition of HECWFS to NOS for operational implementation has been on NOS' 5-year Operational Forecast System (OFS) plan for many years. If being transitioned to NOS, HECWFS is to be renamed as the Huron-Erie Corridor Operational Forecast System (HECWFS). As part of an OFS transition from research to operations, NOS' CSDL personnel skill assessed the hindcasts that were conducted by GLERL for 2019, 2020, and 2021 using FVCOM Version 4.3.1 with the UG-CICE model turned on. The hindcast runs using COARE Version 2.6 bulk flux algorithm. For 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. Surface meteorological forcing for the hindcasts were provided very short-range forecast guidance from the hourly forecast cycles of the NOAA's HRRR analysis and forecast modeling system.

The hindcasts of water levels and surface water temperatures for the three hindcast years, 2019, 2020, and 2021 were compared to in-situ observations in St. Clair River, Lake St. Clair, and Detroit River. Specifically, the water level hindcasts were compared to observational data recorded at NOS/CO-OPS and CHS gauges. Water temperature hindcasts were evaluated against observations at two observing platforms operated by the NOS/CO-OPS and ECCC. Unfortunately, there were no sub-surface water temperature or currents observations for comparison to the hindcasts. Ice concentration hindcasts for Lake St. Clair were compared to the NIC/CIS ice charts for the three ice years: 2018-2019, 2019-2020, and 2020-2021.

Water Levels

A summary of the MAE (bias) and RMSE values for each hindcast year at each gauge as well as the average over the three hindcast years grouped by regions: St. Clair River, Lake St. Clair, and Detroit River is given in Table 24.

St. Clair River

Overall, the hindcasts at CO-OPS and CHS gauges overpredicted water levels. The three-year average MAE ranged from 0.2 to 4.6 cm and the RMSE across the seven gauges ranged from 2.1 to 7.7 cm. The average MAEs are within the 'acceptable magnitude error' of $\pm$ 15 cm for water level amplitude errors. The greatest MAEs were at Point Edward and Mouth of the Black River while the greatest RMSEs were at the southernmost gauges: St. Clair State Police Station. The hindcasts passed all NOS acceptance criteria at each of the four gauges during the three years, except the at St. Clair State Police, MI for MDNO, MDPO, or CF during 2019 and/or 2020.

Lake St. Clair

The hindcasts at the five lake gauges overpredicted water levels. The three-year average MAEs ranged from 1.2 to 2.9 cm. The averages for the RMSE ranged from 9.7 to 10.6 cm and thus are greater than at the St. Clair River gauges. The average MAEs were still below the $\pm$ 15 cm acceptable error. The hindcast missed significant peaks and drops during the ice season and also predicted erroneous peaks during the melting season during 2019 and 2021. The hindcasts simulated the water levels well during the ice-free period of all three years. The hindcasts failed to meet the NOS acceptance criteria for CF, POF, and MDPO at almost all five gauges during 2019 and 2021. The hindcasts failed to meet just the NOS target for MDPO at all five gauges in 2020.

Detroit River

The hindcasts at the five gauges in the Detroit River overpredicted water levels. The three-year average MAE ranged from 3.1 to 12.2 cm and the RMSE across the five gauges ranged from 8.2 to 14.4 cm. The greatest RMSE values were at the southernmost two gauges: Gibraltar and Bar Point, near the mesh boundary with Lake Erie boundary, with 11.0 and 14.4 cm, which is still below the ±15 cm acceptable error. The hindcasts failed to pass the NOS acceptance criteria for CF at each of the four gauges during 2019 and 2021. During 2020, the hindcasts failed to pass the criteria at two gauges.

Ice Jams

Ice flow and ice jams in the St. Clair River can cause significant water level fluctuations in portions of the St. Clair River and Lake St. Clair. Water levels can rise suddenly and result in flooding along the river, suspension of marine navigation, and use of icebreaking ships to break up the ice jams. Ice jams form in the St. Clair River when ice from Lake Huron enters the river and flows downstream to the St. Clair Flats near Algonac, Michigan and Port Lambton, Ontario. The ice can accumulate in this area forming a restriction or ice jam. The jam can cause water levels downstream in the Delta and Lake Clair to decrease and water levels upstream to increase.

Two notable ice jams on St. Clair River occurred during the three hindcasts. One occurred around January 20 to 22, 2019 and February 3, 2021 (maybe also Feb. 20). For the January 2019 ice jam, the hindcasts captured the sudden rise and decline as observed at the lower gauges in the St. Clair River and at the gauges in the Lake. However, the hindcasts did not predict the frequent water level fluctuations in the St. Clair River starting in early February and ending in mid-March. During this time there were persistent wide-swing in air temperatures and frequent icebreaker escorts. Also, the hindcasts predicted a sustained increase in water levels starting around mid-March and persisting into mid-April. This was not seen in the observations. This overprediction may be due to an overprediction of ice in the St. Clair River.

The hindcasts, during the February 3, 2021 ice jam on St. Clair River, predicted a sudden rise in water levels in the St. Clair River and Lake St. Clair, similar to the hindcasts for the January event. However, the hindcasts did not simulate, as well, the sudden drop in water levels in the River and Lake following the initial peak as the hindcasts did during the January event. Similar to the January event, the hindcasts also depicted a rise in water levels in the Spring, starting in early March and ending at the end of March. As with the January event, this overprediction of water levels may be due to an overprediction of ice in the St. Clair River.

NOS/CO-OPS management decided in mid-2023 not to move forward in transitioning HECWFS into the NOS OFS suite due to concerns about the bathymetry and mesh and also staff limitations. It is hoped that the results presented in this report will be useful to future model developers when a new lake forecast modeling system is developed, tested, and implemented for the Huron-Erie Corridor during the next three to five years.

Table 24. Summary of average MAE (bias) and RMSE for the three hindcast years (2019-2021) of 6-minute or 3-hourly water levels at U.S. and Canadian water level gauges.

Section of Huron-Erie Corridor	NOS or CHS Water Level Gauge Name and Station ID	Statistic (cm)	2019 Hindcasts	2020 Hindcasts	2021 Hindcast	3-Year Average
St. Clair River	Dunn paper	MAE	0.6	-0.6	0.7	**0.2**
		RMSE	2.6	1.7	2.0	**2.1**
	Point Edward	MAE	4.5	4.6	4.8	**4.6**
		RMSE	5.3	4.9	5.2	**5.1**
	Mouth of the Black River	MAE	3.4	3.4	4.0	**3.6**
		RMSE	4.7	4.0	4.7	**4.5**
	Dry Dock	MAE	1.0	1.1	2.2	**1.4**
		RMSE	4.5	3.6	4.4	**4.2**
	St. Clair State Police	MAE	0.3	1.6	2.8	**1.6**
		RMSE	8.5	6.3	8.4	**7.7**
Lake St. Clair	Port Lambton	MAE	0.1	1.3	3.3	**1.6**
		RMSE	10.4	7.2	11.4	**9.7**
	Algonac	MAE	0.6	0.3	3.4	**1.4**
		RMSE	9.4	7.1	12.6	**9.7**
	St. Clair Shores	MAE	2.8	0.2	3.7	**2.2**
		RMSE	10.8	7.3	13.4	**10.5**
	Windmill Point	MAE	3.7	0.7	4.2	**2.9**
		RMSE	11.1	7.4	13.4	**10.6**
	Belle River	MAE	1.9	-0.9	2.7	**1.2**
		RMSE	10.6	7.5	13.2	**10.4**
Detroit River	Fort Wyne	MAE	6.1	5.4	6.6	**6.0**
		RMSE	10.2	9.2	12.0	**10.5**
	Wyandotte	MAE	3.5	2.4	3.4	**3.1**
		RMSE	8.0	7.5	9.2	**8.2**
	Amherstburg	MAE	7.8	6.3	7.1	**7.1**
		RMSE	9.9	8.9	10.3	**9.7**
	Gibraltar	MAE	7.8	6.8	6.7	**7.1**
		RMSE	11.0	11.1	11.0	**11.0**
	Bar Point	MAE	12.8	12.3	11.6	**12.2**
		RMSE	14.6	15.2	13.3	**14.4**

Surface Water Temperatures

The hindcasts closely matched surface water temperature observations, capturing both the seasonal trend (e.g., Fall cool down and Spring warm up), at the gauge in the St. Clair River and at the fixed buoy in Lake St. Clair for all three hindcast years. In addition, the hindcasts did well in simulating the frequent water temperature fluctuations in the lake, while predicting the less frequent fluctuations in the river.

A summary of the MAE (bias) and RMSE values for each hindcast year at the two platforms as well as the average over the three hindcast years is given in Table 25. The three-average MAE at the Algonac gauge in St. Clair River was -0.3 ℃ and -0.10 ℃ at the buoy in Lake St. Clair. The average RMSE was 0.38 ℃ at Algonac gauge and 0.83 ℃ at the buoy. The MAEs are well below the ± 3 ℃ acceptable error magnitude for water temperature amplitude errors in the Great Lakes. The hindcasts passed all NOS acceptance criteria at both observing platforms for all three years.

Table 25. Comparison of the average MAE (bias) and RMSE for the three hindcast years (2019-2021) of surface water temperatures.

Buoy ID and Name	Statistic (℃)	2019 Hindcasts	2020 Hindcasts	2021 Hindcasts	3-Year Average
9014070 Algonac (Entire Year)	MAE	-0.36	-0.22	-0.23	**-0.27**
	RMSE	0.49	0.33	0.33	**0.38**
C45147 Lake St. Clair (~May 1 to `Nov 1)	MAE	0.12	-0.10	0.33	**-0.10**
	RMSE	0.84	0.86	0.80	**0.83**
Average	**MAE**	**-0.12**	**-0.16**	**0.05**	**-0.19**
	RMSE	**0.67**	**0.60**	**0.57**	**0.61**

Ice in Lake St. Clair

Over the three ice years, the hindcasts predicted the ice onset too early and an ice off too late, thus estimating a longer ice season than observed. The number of days too early ranged from two days during the 2018-2019 ice year to 24 days during the well below normal ice year of 2019-2020. The hindcasts did better in predicting the date of ice off. The predicted dates of ice off result was 5 to 11 days after the observed ice off dates.

Overall, the hindcasts successfully simulated the lake-wide concentration for each ice year. The hindcasts did better than climatology in depicting the freeze up of the lake across all three ice years; the climatology was too fast. The hindcasts predicted the three peaks during the 2019-2020 year. However, the hindcasts did not show a decrease in ice concentration during the second peak of that ice year in early February as indicated by the NIC chart.

With regards to predicting the date/time when the lake-average ice concentration would reach approximately 10% in the Spring, the hindcasts did the best during the 2019-2020 year and was better than climatology. For the other two years, the hindcasts were too slow in melting the ice. The hindcasts did about the same as climatology during the 2018-2019 year, but better than climatology during the 2020-2021 year.

With respect to predicting the spatial pattern of ice concentration for the three ice years. This includes the development of nearshore ice during the freezing period, peak ice cover, and in the offshore open water region in the mid-season and ice decay during the melting phase.

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