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NOAA Technical Memorandum NOS CS 40

UPGRADE OF NOS LAKE ERIE OPERATIONAL FORECAST SYSTEM (LEOFS) TO FVCOM: MODEL DEVELOPMENT AND HINDCAST SKILL ASSESSMENT

Silver Spring, Maryland

February 2018

noaa National Oceanic and Atmospheric Administration

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

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

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LIST OF ACRONYMS

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

EXECUTIVE SUMMARY

NOS Lake Erie Operational Forecast System (LEOFS) is a three-dimensional lake forecast system which uses near real-time atmospheric observations and meteorological forecasts to generate hourly nowcast and forecast guidance out to 60 hours of three-dimensional water temperature and currents and two-dimensional water levels for Lake Erie. The original version of LEOFS uses the Great Lakes version of the Princeton Ocean Model (POMGL) as its core three-dimensional numerical oceanographic forecast model and has a horizontal resolution of 5 km and 11 vertical sigma (terrain-following) levels. A new version of LEOFS has been developed to use the Finite Volume Community Ocean Model (FVCOM) with a horizontal resolution ranging from 100 m near the shore to 2.5 km offshore and with 21 vertical sigma levels. The new version is a collaborative project between NOAA's Great Lakes Environmental Research Laboratory (GLERL), the National Ocean Service's Coast Survey Development Laboratory (CSDL) and the Center for Operational Oceanographic Products and Services (CO-OPS), and the FVCOM Development Team at the University of Massachusetts-Dartmouth.

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

The hindcast simulations were conducted for 2005 and 2006. These simulations were forced by hourly observed water levels at NOS NWLON gauges at Gibraltar, Mich. and Buffalo, N.Y., estimated water temperatures at the mouth of the Detroit River and hourly surface meteorological analyses generated by interpolating overwater and adjusted overland observations. The hindcasts were compared to water level observations at gauges along the U.S. and Canadian shore, to water temperature observations at coastal stations and offshore fixed buoys, and to water temperature data from thermistor strings during April – October 2005.

The hindcasts demonstrated excellent skill for hourly water levels and surface water temperatures during both years and met the NOS acceptance criteria at the majority of stations. However, the hindcasts failed to meet the NOS acceptance criteria at all verification gauges in predicting the amplitude and timing of extreme high and low water level events. The hindcasts of sub-surface water temperatures demonstrated satisfactory or excellent skill during 2005 in the top layers, but performed poorly in the mid-layers and in the deep portion of the eastern basin.

1. INTRODUCTION

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

The present GLOFS uses the Great Lakes version of the Princeton Ocean Model (POMGL) (Blumberg and Mellor, 1987) with separate computational grids for each lake. The horizontal grid resolutions used for Lakes Erie, Michigan, Ontario, and Huron is 5 km and is 10km for Lake Superior. The number of vertical sigma layers is 11 for Lake Erie and 20 for the other four lakes. GLOFS has hourly nowcast cycles and four daily forecast cycles which generate forecasts out to 60 hours. The nowcast cycles are forced by surface meteorological analyses of near-real-time data from overwater and overland observing platforms which are used to provide heat and radiation fluxes and wind stress to POMGL. The forecast cycles are forced by gridded surface wind and air temperature forecasts from the NWS National Digital Forecast Database. There are no heat or radiation fluxes input during the forecast cycle.

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

For water temperatures, GLOFS predicts well the surface water temperatures in terms of amplitude, horizontal distribution and seasonal time evolution. However, GLOFS exhibits an overestimation of water temperature during the nowcast cycle, possibly due to an underestimation of cloud cover over the lakes or an error in the SOLAR subroutine. In addition, GLOFS does poorly in predicting water temperatures during the spring and early summer warm up and also often exhibits unrealistic, high frequency water temperature oscillations. Because of these oscillations, the time series plots of water temperature predictions at forecast points are not shown on the CO-OPS' GLOFS web site. Finally, comparisons of hindcasts to subsurface water temperature data collected during field projects have indicated that GLOFS reproduces the basic features of the evolution of the three-dimensional thermal structures of the lakes, but produces a thermocline that is too diffuse and fails to capture frequent temperature fluctuations (Kelley et al., 2008).

In 2013, NOS and NOAA's Great Lakes Environmental Research Laboratory (GLERL) began a project to develop a new version of GLOFS to provide improved predictions of water levels, surface and subsurface water temperatures and currents for the Great Lakes. The Finite Volume Community Ocean Model (FVCOM) was selected for the new version due to its unstructured grid design that would allow for higher horizontal resolution along the shore. LEOFS was identified as the first of the five GLOFS domains to be migrated to FVCOM since GLERL had already done work on the development and testing of potential FVCOM grids.

This report documents the development of the new version of LEOFS using the FVCOM as its core oceanographic forecast modeling system and the results of the hindcast skill assessment (the skill assessment of the semi-operational nowcast and forecasts was conducted by CO-OPS and its results will be published in a separate CO-OPS technical report). A brief overview of Lake Erie's physical limnology is given first.

2. LAKE ERIE

Lake Erie is the smallest of the Great Lakes and the 13th largest lake in the world with a breadth of 92 km (57 mi) and a length of 388 km (241 mi). It has three distinct basins: a shallow western basin (mostly less than 10 m deep), a deep eastern basin (maximum depth of 64 m), and a relatively flat central basin (mostly 20-24 m deep) (Fig. 1). Water from Lakes Huron and St. Clair enters the lake in the western basin via the Detroit River and exits the lake via the Niagara River in the eastern basin.

Lake Erie, except for its shallow western basin, has a pronounced annual thermal cycle ranging from vertically well-mixed water in late autumn to thermal stratification across the entire lake with a well-developed summer thermocline (Boyce et al., 1989; Schertzer et al., 1987). Given the lake's relative shallowness, the entire water column cools rapidly in the autumn to the temperature of maximal density near 4^{o}C (Assel, 1990). In the winter, the surface water cools to 0^{o}C making ice formation possible. Ice formation on the lake proceeds from the shallow western basin in December to the deeper central and eastern basins in January (Assel, 1990). Similarly, in the spring and early summer, the lake warms rapidly. The central basin can be stratified as early as May (Boyce et al., 1989). The shape of the thermocline varies according to the basin. Typically, starting in July, a bowl-shaped thermocline begins to form in the central basin while a dome-shaped thermocline develops in the eastern basin (Beletsky et al, 2013).

Lake Erie responds quickly to the passage of weather systems due to its shallowness and southwest to northeast orientation. The lake responds to the wind stress by a combination of free and forced mode oscillatory responses in water level and thermocline position which give rise to periodic velocity and current structures (Bedford, 1992). The free mode is when the lake is subject to an imposed wind stress on its surface resulting in frequent and sometimes dramatic storm surges. Frequently, strong southwest winds will cause an increase in water level at Buffalo, N.Y. and a drawdown at Toledo, Ohio, at the western end. The positive surge will occur approximately three hours before the corresponding maximum drawdown at Toledo. After the storm passage, the potential energy stored in the surge is released and expressed as free oscillation gravity waves called seiches (Bedford, 1992). The lake, due to its relatively small size its circulation, is driven by a combination of tributary flow, water temperature gradients and wind (Simons, 1976; Beletsky et al., 2013). Additional information about the physical limnology of Lake Erie can be found in Beletsky et al. (1999), Boyce et al. (1989), Dingham and Bedford (1984), Bartish (1987), Mortimer (1987), and Saylor and Miller (1987).

3. MODEL SYSTEM AND SETUP FOR HINDCASTS

This section provides descriptions of the numerical three-dimensional hydrodynamic model, the model grid configuration, and how the lateral boundary, surface boundary, and initial conditions were specified for the hindcast runs. The configuration for the version of LEOFS-FVCOM to be run operationally on NOAA WCOSS will be different in terms of surface meteorological conditions and lateral boundary conditions for water temperatures.

3.1. Description of Model

FVCOM is a prognostic, unstructured-grid, finite-volume, free-surface, three-dimensional primitive equation coastal ocean circulation prediction model developed by the researchers at the UMASS-Dartmouth and Woods Hole Oceanographic Institution (Chen and Beardsley, 2003; Chen et al., 2013). The model consists of momentum, continuity, temperature, salinity and density equations and is closed physically and mathematically using turbulence closure sub-models. The horizontal grid is comprised of unstructured triangular cells. A generalized terrain-following vertical coordinate system is used. Several different turbulent closure schemes (TCS) are available in FVCOM. For LEOFS, the Mellor Yamada 2.5 TCS was used for the vertical and the Smagorinsky TCS was utilized for the horizontal. FVCOM is solved numerically by a second-order-accurate discrete flux calculation in the integral form of the governing equations over an unstructured triangular grid. According to Chen et al. (2007), this approach combines the best features of finite-element methods (grid flexibility) and finite-difference methods (numerical efficiency and code simplicity). The model three-dimensional 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. For LEOFS, an external mode time step of 10 seconds was used.

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

The FVCOM version used for the hindcasts was Version 3.2.0. This version includes the Fortran subroutines UZL and SOLAR. The SOLAR subroutine, which is also used by the present POMGL-GLOFS, calculates insolation and surface heat flux (McCormick and Meadows, 1988; Kelley, 1995). SOLAR relies on the subroutine UZL to calculate bulk aerodynamic coefficients for momentum and heat over a lake surface as a function of 10m AGL wind speed and air-sea temperature difference (Kelley, 1995). The SOLAR subroutine has the following inputs: 1) surface air temperature, 2) surface dew point temperature, 3) surface wind speed, 4) cloud cover, 5) surface water temperature, 6) bulk aerodynamic coefficient for heat, 7) bulk aerodynamic coefficient for momentum, 8) latitude, 9) longitude (west of Greenwich), 10) day of year, and 11) hour of day (local standard time). The output from the routine includes total surface heat flux and short wave radiation.

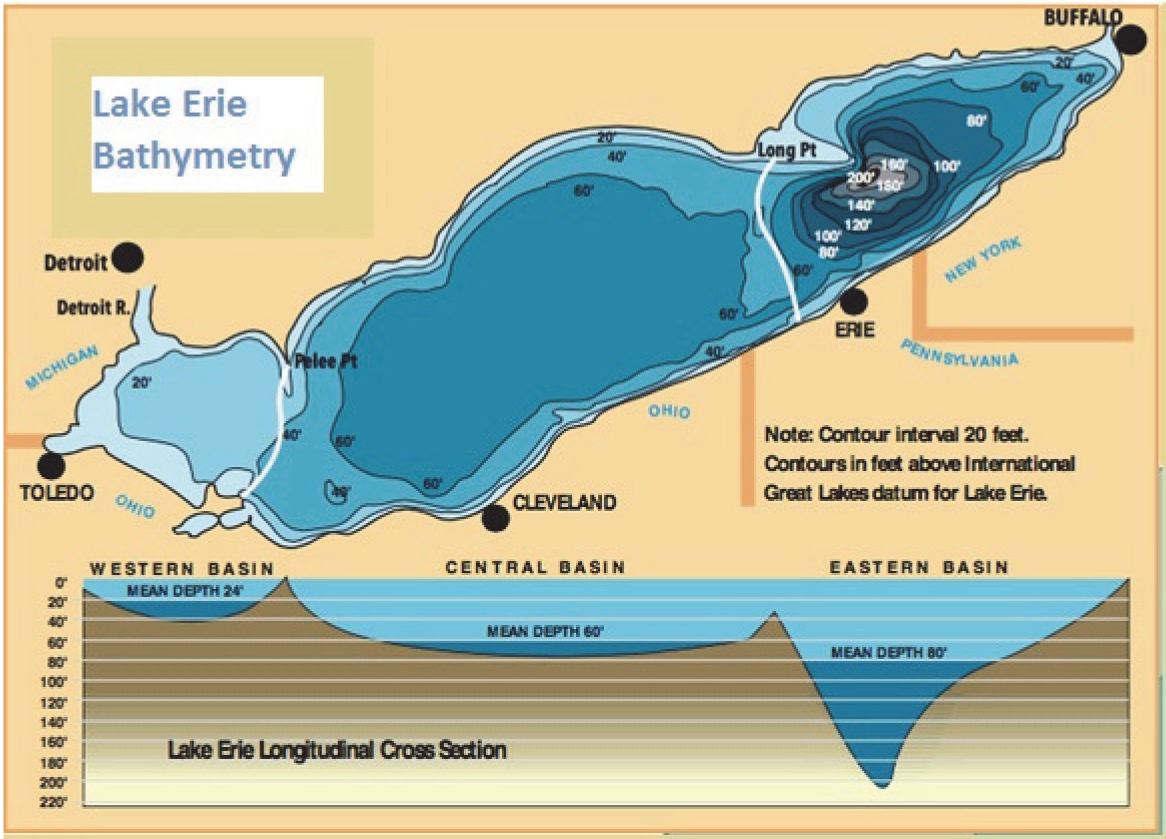


Figure 1. Map depicting Lake Erie bathymetry (feet) including longitudinal cross section. Modified from figure by Ted Walke of Pennsylvania Angler and Boater Fact Sheet.

3.2. Grid Configuration

LEOFS-FVCOM uses a model domain which covers all of Lake Erie and takes into account many land features including the islands in the western basin (e.g. Kelley Island, South Bass Island) as well as Long Point, Presque Isle, Rondeau Provincial Park, and Point Pele. The grid generation module of the Surface-Water-Modeling System (SMS) software was used by GLERL to generate the unstructured model grid. The grid size distribution is configured as dependent on the GLERL bathymetry (NOAA NGDC, 3 arc-second). The model bathymetry was obtained by interpolating the GLERL digital bathymetry onto each unstructured FVCOM model grid node. The model bathymetry is shown in Fig. 2.

High resolution NOAA coastline data was applied to delineate the land boundary. Since the Detroit River and Niagara River define the input and output for the lake, higher grid resolution was specified at the mouths of these rivers. The model grid in the horizontal is composed of 11,509 triangular elements and 6,106 nodes. The resolution varies from approximately 100 m near the shore to about 2.5 km offshore. The grid is depicted in Fig. 3. The model has 21 sigma levels with distribution referenced to the Great Lakes low water datum of 173.5 m. 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.

3.3. Lateral Boundary Conditions

For the hindcasts, the lateral boundary condition (LBC) for the temperature of the water entering the lake from the Detroit River and water levels at the western and eastern ends of the lake were specified in the following manner. The water temperatures at the Detroit River were specified using a relationship between observed river water temperatures and observed air temperatures recorded at the Automated Weather Observing System (AWOS) station at the Grosse Ile, Michigan, Municipal Airport (KONZ). The airport is located on Grosse Ile which is the largest island in the Detroit River. Using this method, the observed air temperature time series is smoothed and given a 7-day lag, resulting in time-series that closely approximates water temperatures entering the lake through the Detroit River. The method has been verified against observed water temperatures of the Detroit River.

The LBCs for water levels at the inlet and outlets of the lake were specified using FVCOM's open boundary conditions "Active (ASL)" method. The method used hourly observed water levels from the NOS/CO-OPS NWLON gauge at Gibraltar, Michigan, near the mouth of the Detroit River and the NWLON gauge at Buffalo, N.Y. near the mouth of the Niagara River (Fig. 4). This is different from the original, POMGL-based GLOFS which does not use water level boundary conditions and thus does not track absolute water level changes. The hourly water levels are contained in the file *erie_elj_obc.dat* and are referenced to the IGLD85 datum for Lake Erie of 173.5 m (this file was created by the Fortran program *eriebc.pro*). The text files of water levels and water temperatures are translated to netCDF by the Fortran program *xobc.pro*. The resulting netCDF file is *tsobc.nc* (Fig. 5)

3.4. Surface Boundary Forcing

For the hindcasts, the air-water surface boundary forcing consisted of hourly gridded surface meteorological analyses of u-wind and v-wind components, surface (2m AGL) air and dew point temperatures, and total cloud cover. The gridded analyses were created by interpolating surface observations of wind velocity, air temperature, dew point temperature, and total cloud cover using a natural neighbor technique (Sambridge et al., 1995). The interpolation is accomplished by the Fortran program *interpun.f* (Fig. 6). The observations are from both land-based stations such as ASOS and AWOS stations, coastal stations including NWS/NDBC C-MAN stations, ECCC automated stations on lighthouses and offshore platforms, NOS/CO-OPS NWLON meteorological stations, and Other Marine Reports (Fig. 7).

The LBCs consisted of verified hourly water level observations from the NOS Gibraltar and Buffalo NWLON stations obtained from the NOS/CO-OPS archives at https://tidesandcurrents.noaa.gov/stations.html?type=Historic+Water+Levels#GreatLakes-DetroitRiver.

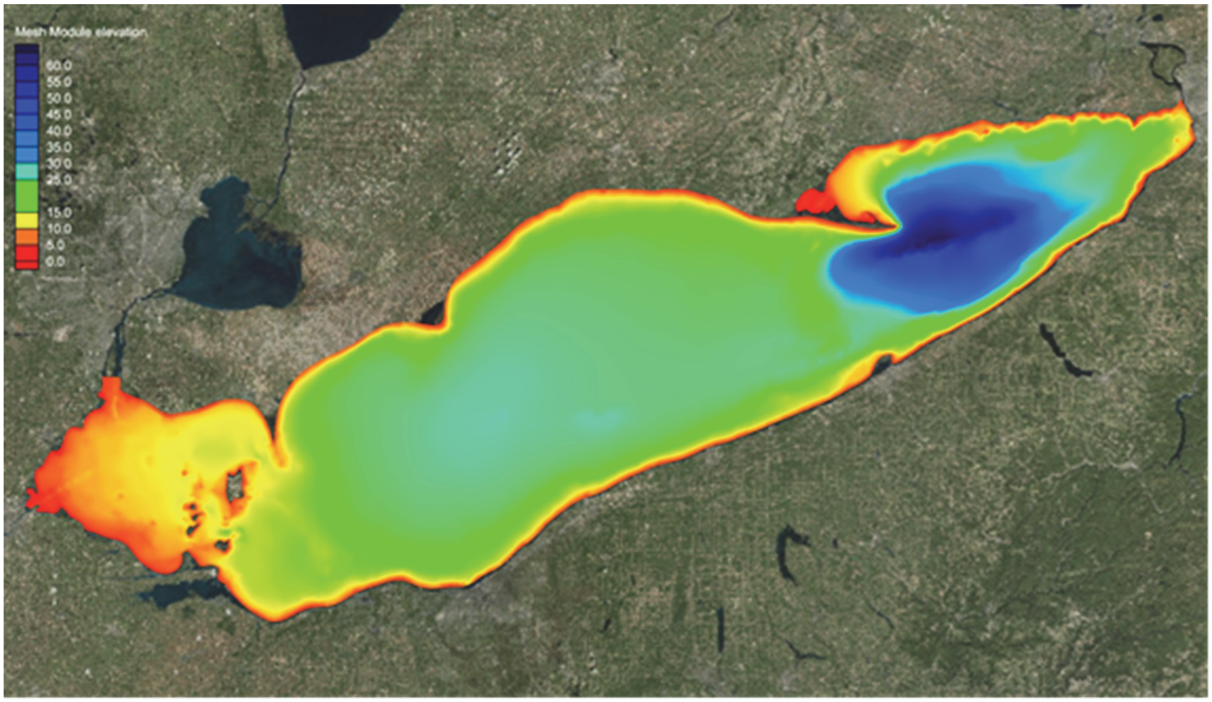


Figure 2. Map of the FVCOM model bathymetry (meters) for Lake Erie.

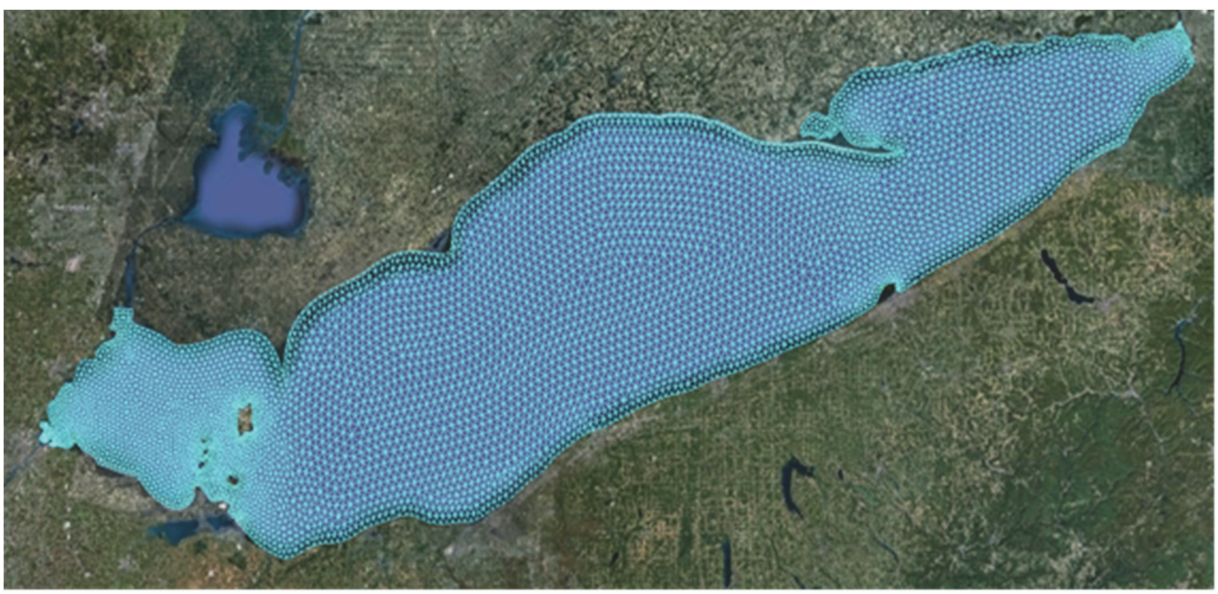


Figure 3. Map depicting the FVCOM grid domain for Lake Erie. The horizontal resolution ranges from 100 m near the shore to 2.5 km offshore with 21 vertical levels.

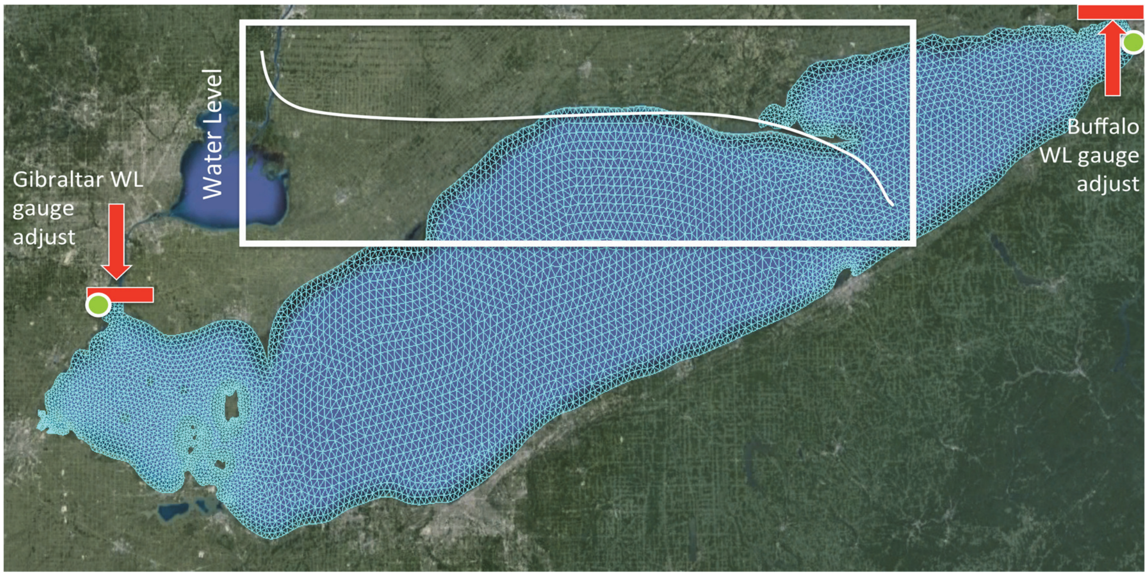


Figure 4. Map depicting the locations of the two NOS/CO-OPS NWLON gauges whose water level observations were used in specifying the lateral boundary conditions

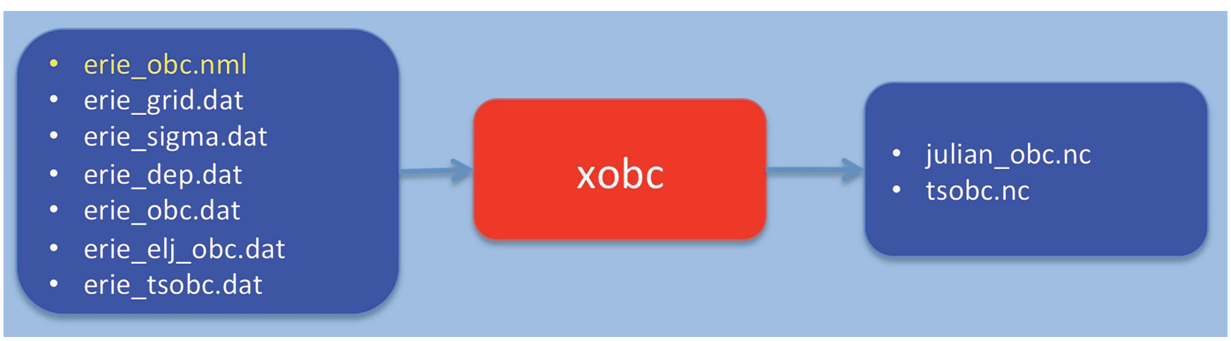


Figure 5. Flowchart depicting the inputs for generating the water temperature and water level lateral boundary conditions for LEOFS-FVCOM hindcast runs.

Before being interpolated, the surface wind observations are adjusted to a common anemometer height of 10m above the ground or water. Surface observations of wind direction, wind speed, air temperature, and dew point temperature from overland stations such as ASOS stations (e.g. airport stations) are adjusted to be more representative of overwater conditions. Both the height adjustment and adjustment of observations from overland stations use the previous day's lake average water temperature from GLERL's Great Lakes Surface Environmental Analysis (GLSEA). The adjustments to the observations are done by the Fortran program *metedit.f*. The Fortran program *xsurfaceforce.f* translates the text files of gridded surface meteorological analyses into a netCDF file called *erie_forcing.nc* for use by FVCOM.

The analyses are interpolated onto the FVCOM model domain at each node. The sensible heat, latent heat, and the net heat flux are then calculated at each node by the SOLAR subroutine of FVCOM.

3.5. Initial Conditions

LEOFS-FVCOM requires initial three-dimensional conditions including surface elevation field and three-dimensional velocity and water temperature fields at the beginning of the hindcasts. The model was initialized one year prior to the start of the hindcast period with uniform temperature of 2°C, 0.0 m elevation, and 0 m/s currents. The model was continuously forced with observed LBCs and surface meteorological analyses. The restart file after the one-year run was used as the initial conditions for the start of the hindcasts. The dates for the hindcast periods are given in the next section.

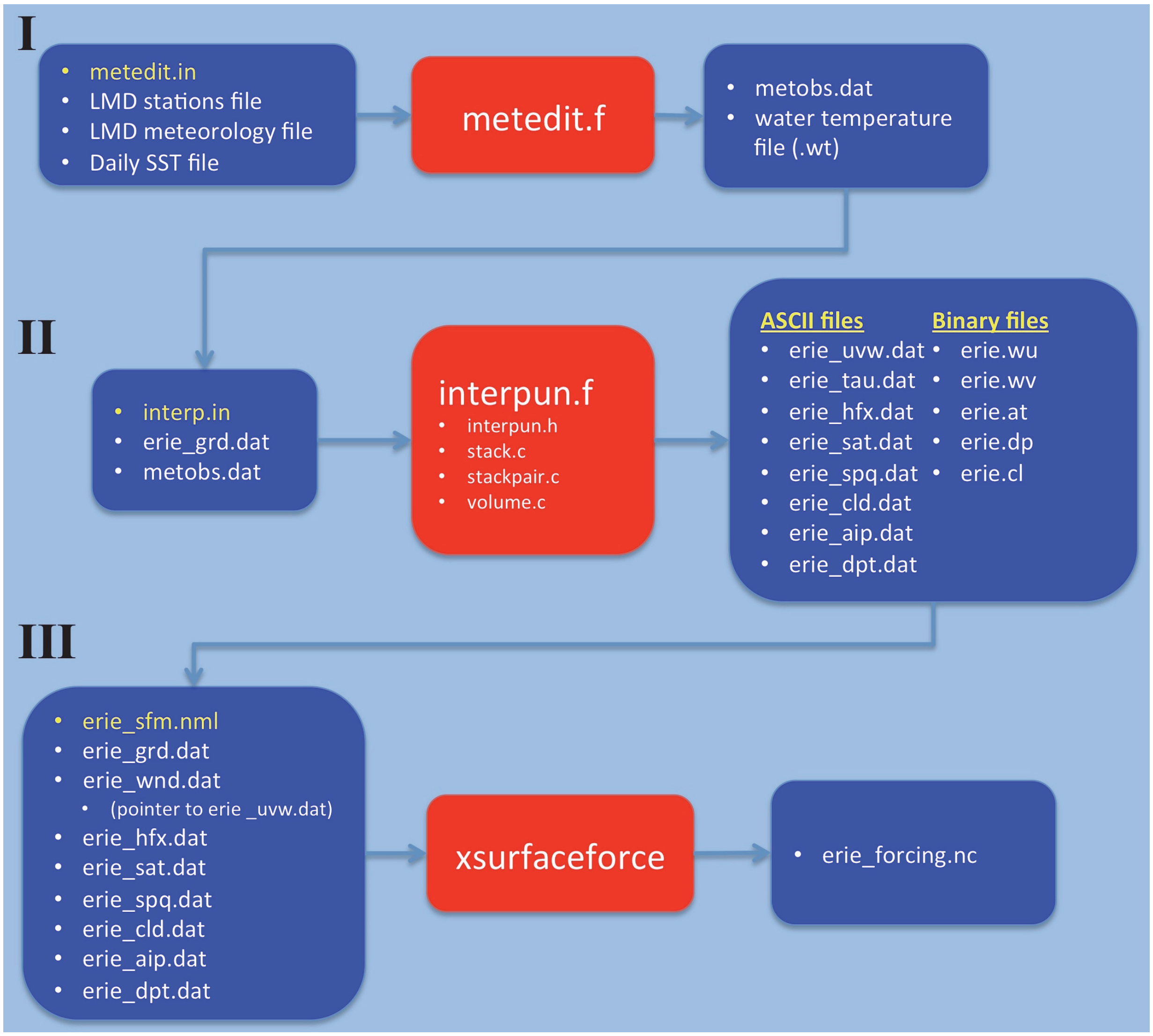


Figure 6. Flowchart depicting the method used to create a surface meteorological analysis and integrate into a single netCDF file for FVCOM hindcast runs for Lake Erie.

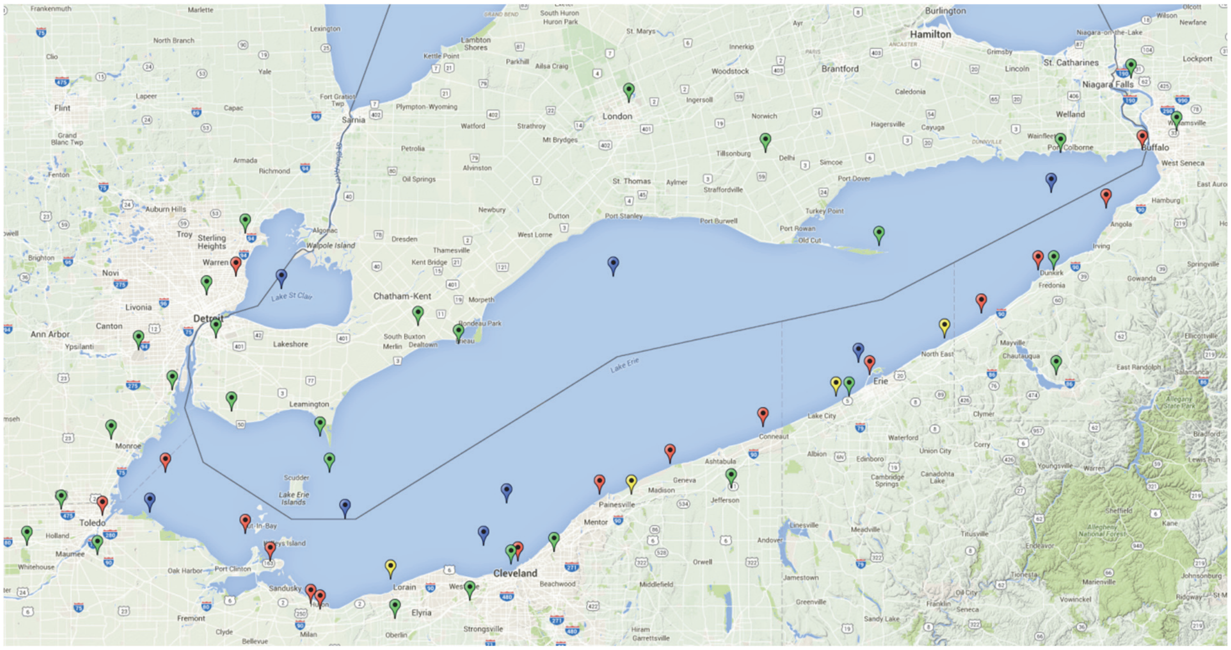


Figure 7. Map depicting the locations of different observing stations and platforms whose observations were used in the creation of surface meteorological analyses. (Dark blue=NDBC and EC buoys, Red=NWS C-MAN and NOS/CO-OPS stations, and GLOS stations, Yellow=Other Marine Reports, and Green=Surface Airway Stations [ASOS, AWOS]).

4. DESCRIPTION OF HINDCAST PERIODS

Two hindcast model simulations using LEOFS-FVCOM were conducted by GLERL on their Linux cluster. Hindcast #1 covered the period from Jan. 1, 2005, to Dec. 31, 2005. A plot of the verified daily mean water levels at the NOS Buffalo, N.Y. gauge during the year is given in Fig. 8. Hindcast #2 covered the period from Jan. 1, 2006, to Dec. 31, 2006. A plot of verified daily mean water levels at NOS Buffalo, N.Y. gauge during the year is given in Fig. 9.

The year 2005 was selected for Hindcast #1 because there was a significant amount of physical limnological data available for the lake due to the data collected during the 2005 International Field Year on Lake Erie (IFYLE). The IFYLE was conducted from May through October 2005. The IFYLE includes data from thermistor strings, transmissometers, ADCPs, and wave sensors. Additional information about the IFYLE datasets can be found at https://www.glerl.noaa.gov/res/projects/ifyle/data/data.mooring.html. During this hindcast period, there were several strong extratropical cyclones which caused significant water level events: Jan. 18-19, Jan. 23-24, Mar. 22-23, Apr. 2-3, Apr. 23-24, May 12-13, Sep. 28-29, Nov. 5-6, Nov. 15-16, Nov. 23-24, and Dec. 10, 2005. The highest water level and most dramatic change in water levels at the Buffalo gauge in 2005 occurred during the storm of Dec. 10 (Fig. 10). Surface water temperatures at the three offshore buoys and coastal stations are given in Fig. 12 and 13, respectively.

Hindcast #2 was for the year 2006. During this hindcast period, there were also several intense storms which resulted in significant water level events on Lake Erie: Jan 17-18, Feb. 4-5, Mar. 13-14, May 20-21, Sep. 2-3, Oct. 12-13, Oct. 28-29, Dec. 2-4, Dec. 8-9, and Dec. 23-24, 2006. The highest wave levels observed at the Buffalo gauge in 2006 were during the storm of Dec. 1-2 (Fig. 11). Surface water temperatures at the buoys and coastal stations during 2006 as well as 2005 are given in Fig. 12 and 13, respectively.

In comparing the observed surface water temperatures between the two hindcast periods at the three offshore buoys (Fig. 12), temperatures in 2006 were warmer than 2005 during the spring months until Day 155 (Jun. 4), about the same or slightly cooler during the summer, Day 155-240 (Jun. 4 – Sep. 2), and colder during the fall months. Similar differences between 2005 and 2006 water temperatures were observed at the coastal stations (Fig. 13) but the dates differed. For example, temperatures in 2006 were colder than 2005 at coastal stations starting around Day 220 (Aug. 8) compared to Day 245 (Sep. 2) at the buoys.

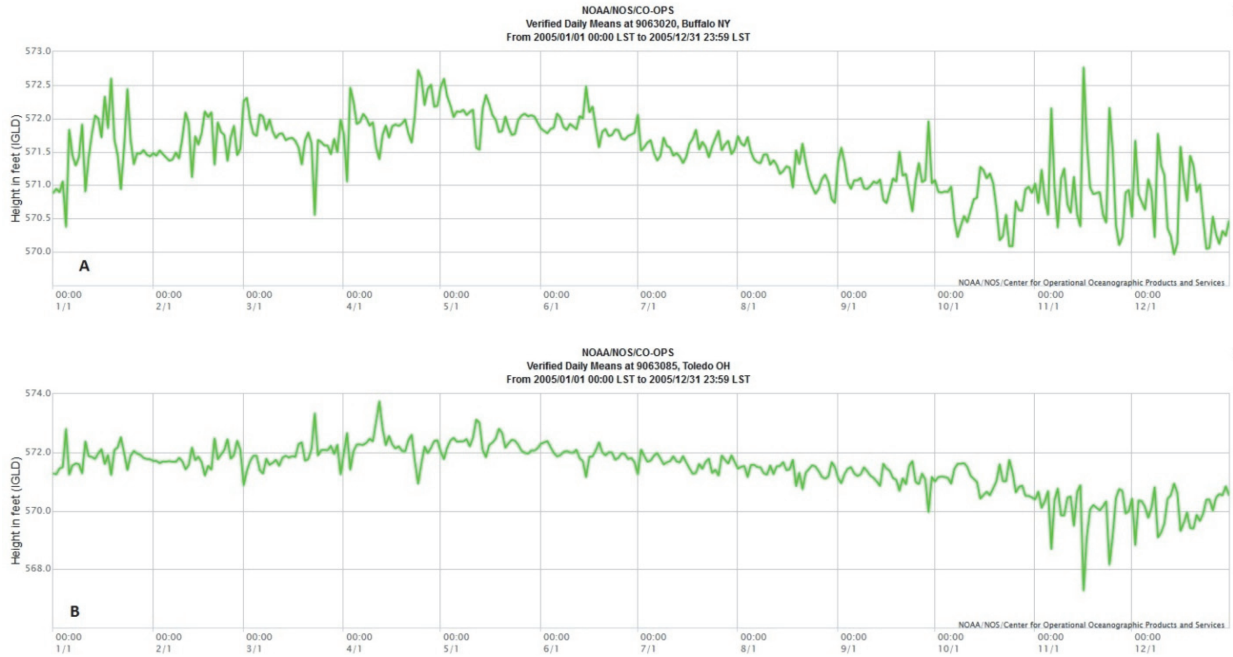


Figure 8. Daily mean water levels at the NOS Buffalo, N.Y. (a) and Toledo, Ohio (b) gauges during 2005. The time zone is EST.

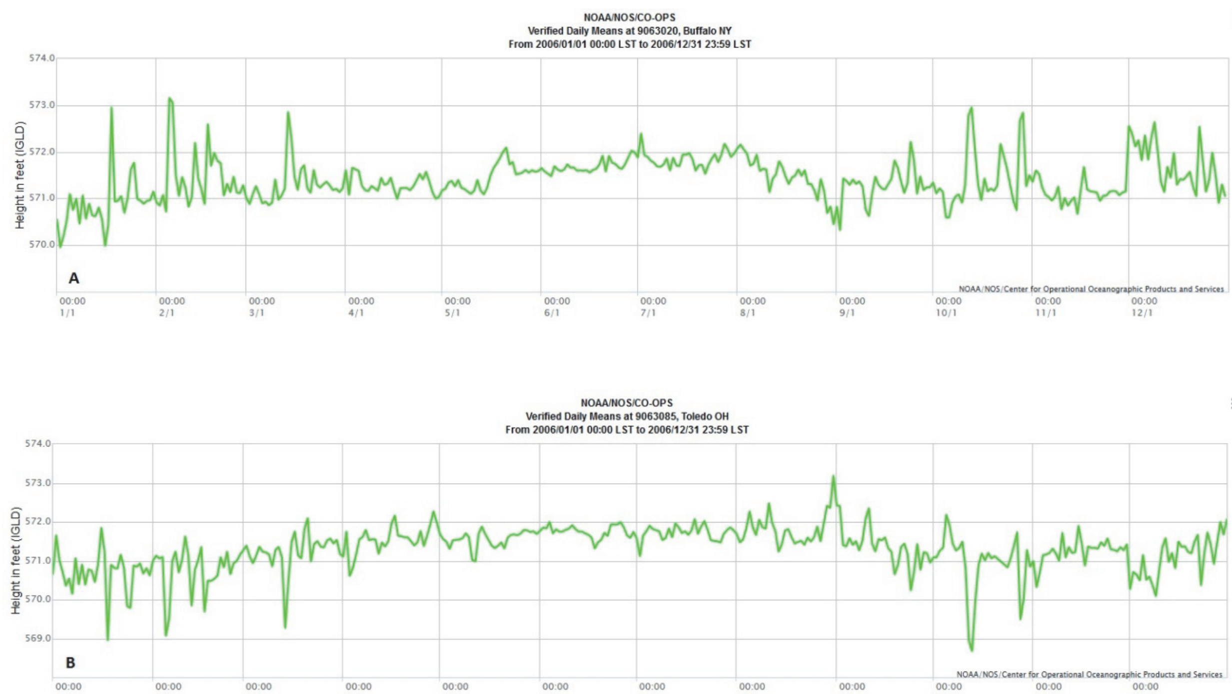


Figure 9. Daily mean water levels at NOS Buffalo, N.Y. (a) and Toledo, Ohio (b) gauges during 2006. The time zone is EST.

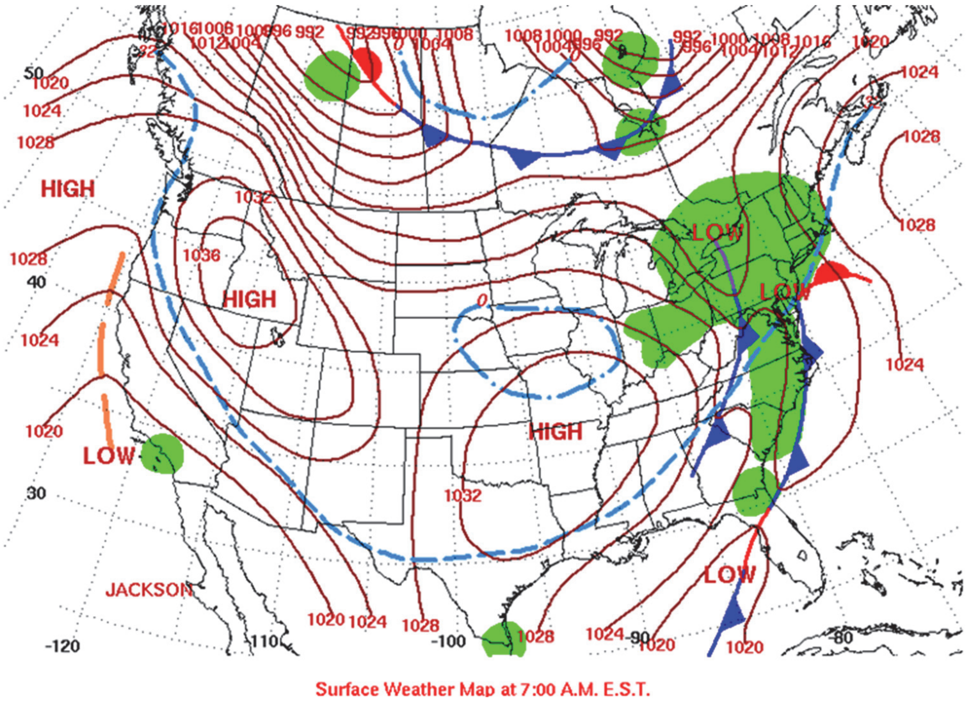


Figure 10. NWS Daily Weather Map valid at 12 UTC (07 UTC) on Dec. 9, 2005 (Day 343).

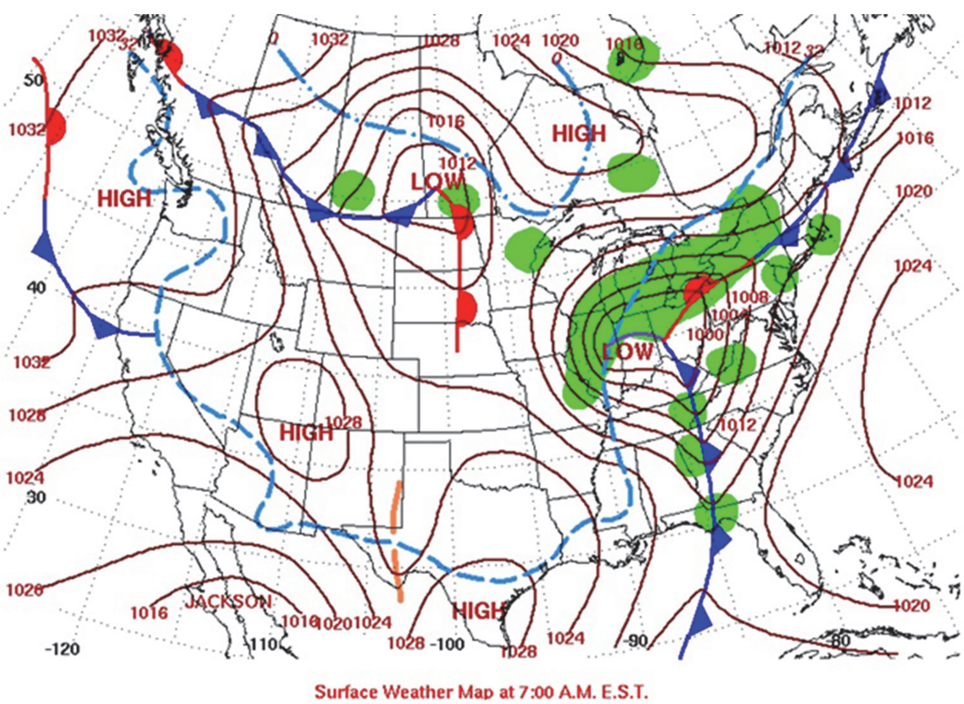


Figure 11. NWS Daily Weather Map valid at 12 UTC (07 EST) on Dec. 1, 2006 (Day 335).

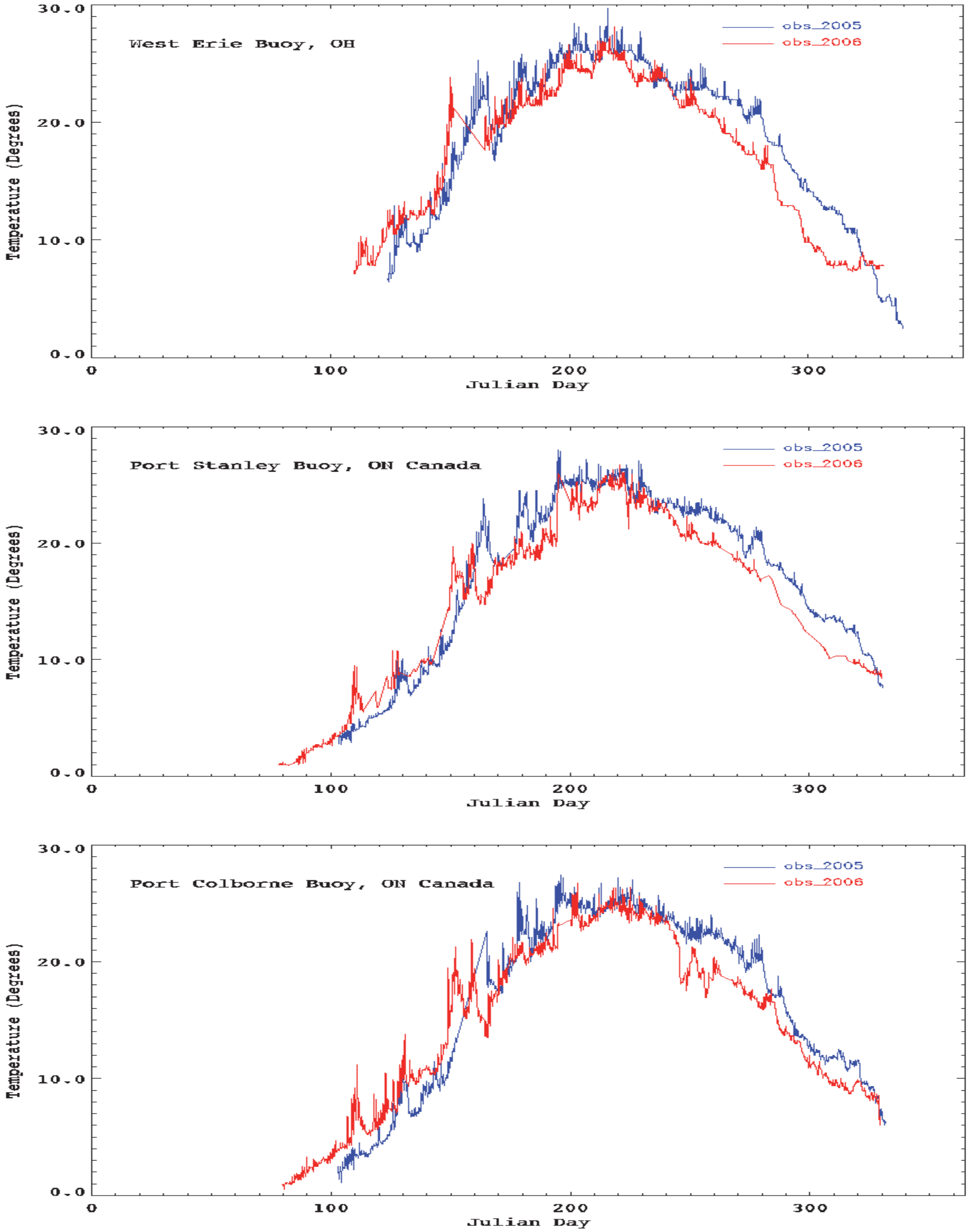


Figure 12. Time series plots of Surface water temperatures at the NWS/NDBC and ECCC offshore fixed buoys during 2005 and 2006.

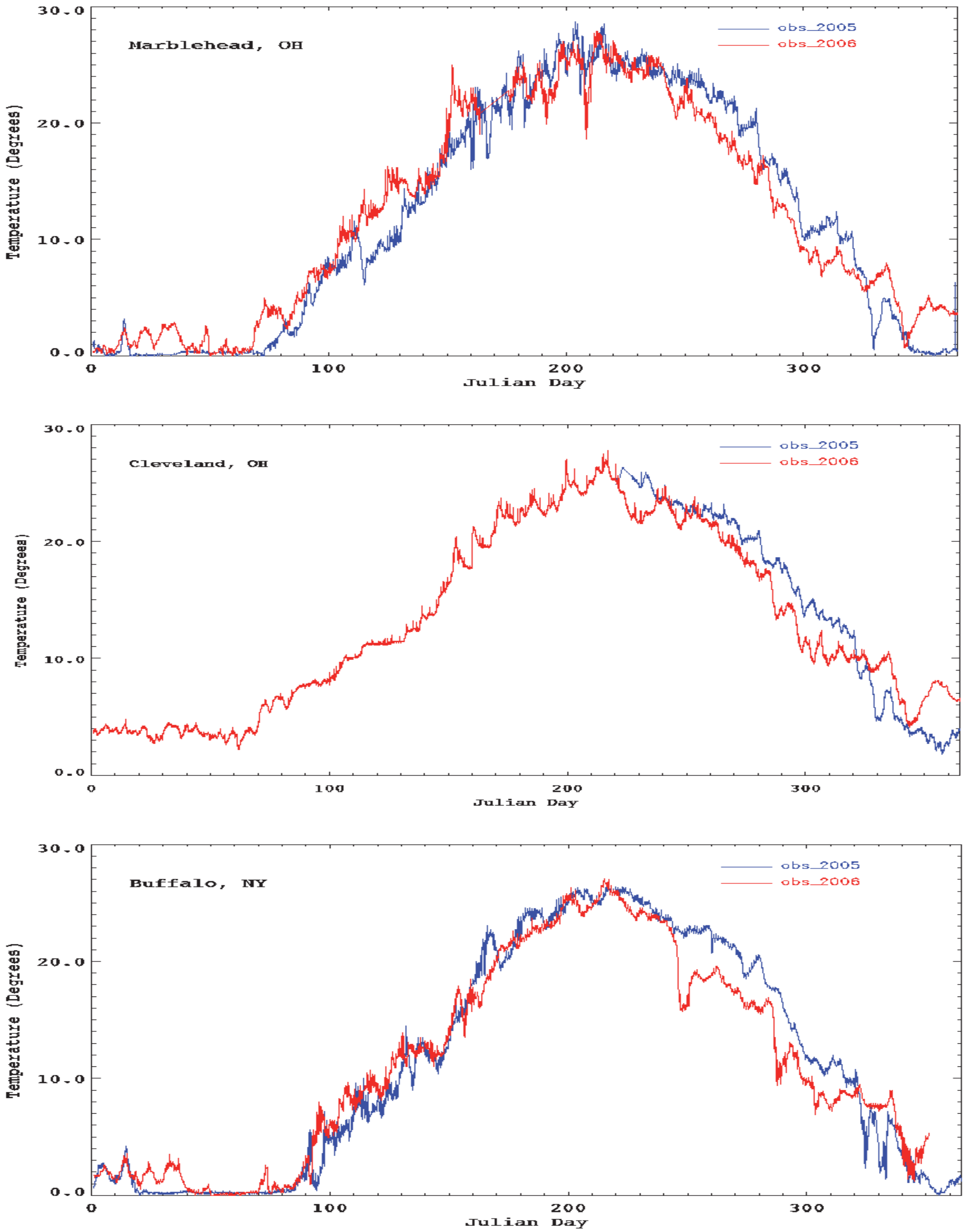


Figure 13. Time series plots of surface water temperatures at NOS NWLON gauges at Marblehead, Ohio, Cleveland, Ohio, and Buffalo, N.Y. during 2005 and 2006.

5. METHOD OF EVALUATION

LEOFS-FVCOM's hourly hindcasts of water levels and water temperatures for 2005 and 2006 were compared to hourly observations from coastal and offshore observing platforms in Lake Erie. In addition, subsurface water temperatures were compared to data from thermistor strings in 2005. The evaluation used the standard NOS suite of skill assessment statistics. These statistics included Error, or more commonly referred to as Mean Algebraic Error (MAE), Root Mean Squared Error (RMSE), Central Frequency (CF), Positive Outlier Frequency (POF), Negative Outlier Frequency (NOF), Maximum Duration of Positive Outliers (MDPO), and Maximum Duration of Negative Outliers (MDNO). These statistics are described briefly in Table 1 while more detailed descriptions can be found in Hess et al. (2003). The comparisons were done using the NOS standard skill assessment software (Zhang et al., 2010 and Zhang et al., 2013).

The calculation of the target frequency of occurrence skill statistics, CF, POF, MDPO and MDNO, required the assignment of 1) acceptable magnitude errors for water level and water temperature amplitudes, 2) acceptable timing error for water levels, and 3) maximum allowable time durations for consecutive positive and negative water level outliers. The same acceptable errors and maximum allowable time duration used to evaluate GLOFS, when it was first implementation operationally at NOS, were employed in evaluating the 2005 and 2006 hindcasts (see last column in Table 1). These specific values for the water level and temperature skill assessments will be discussed in the Sections 5.1 and 5.2, respectively.

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

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

The resulting values for each statistic were then judged against the NOS Acceptance Criteria (Table 1) for that statistic. The critieria includes target frequencies of occurrence for CF, NOF, and POF and limits on the duration of errors (i.e. maxium length of time of consecutive occurrences) for MDPO and MDNO. Any new or upgraded NOS nowcast/forecast modeling system is expected to meet or exceed most of the NOS Acceptance Criteria (targets) in order to be implemented operationally.

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

Statistic	Units	Description	NOS Acceptance Criterion
Mean Algebraic Error	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.	<= 1%
NOF(X)	%	Negative Outlier Frequency. Fraction (percentage) of errors that are less than -X.	<= 1%
MDPO(2X)	Hours	Maximum Duration of Positive Outliers. A positive outlier event is two or more consecutive occurrences of an error greater than +2X. MDPO is the length of time in hours (based on the number of consecutive occurrences) of the longest positive outlier event.	<= L
MDNO(2X)	Hours	Maximum Duration of Negative Outliers. A negative outlier event is two or more consecutive occurrences of an error less than -2X. MDNO is the length of time in hours (based on the number of consecutive occurrences) of the negative outlier longest event.	<= L
NOS Standard Criteria		where X=acceptable error magnitude (cm or minutes) X = +- 15cm for water level amplitude errors X = +- 1.5 hours (90 minutes) for water level timing errors X = +- 3.0^{o}C for water temperature amplitude errors	where L=time limit or max. allowable duration L=24 hours

5.1. Evaluation of Water Level Hindcasts

The comparison of time series differences between the 2005 and 2006 water level hindcasts used the statistics SM, RMSE, SD, NOF, POF, MDPO, and MDNO described in the previous section. The assessment evaluated the ability of the hindcasts to predict hourly water levels and also extreme high and low water events. The identification of extreme high and low water events during the hindcast periods in the Great Lakes was accomplished using the method described in Chu et al. (2007).

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

The time series of hourly hindcasts were compared to observed hourly water levels recorded at NOS/CO-OPS NWLON and Canadian Hydrographic Service (CHS) stations along the Lake Erie shore (Fig. 14). The NWLON station at Fairport, OH was not used in the assessment because of noticeable subsidence in the area of the station, which affected the water level data. The NWLON station at Gibraltar was also not used since its observations were used in defining the lateral boundary conditions. CO-OPS has adjusted the archived data from the Fairport gauge back to Sept. 2006 in order to bring the values more in line with the rest of the lake (Grodsky, 2016). Information about these stations is given in Table 2. The hourly water level observations for the NOS NWLON gauges were obtained from CO-OPS online archives at http://tidesandcurrents.noaa.gov. Hourly water levels for CHS gauges were obtained from Canada's Dept. of Fisheries and Oceans online archives at http://www.meds-sdmm.dfo-mpo.gc.ca/isdm-gdsi/twl-mne/inventory-inventaire/list-liste-eng.asp?user=isdm-gdsi&region=CA&tst=1. All observations were plotted as time series and visually inspected for erroneous data. Any erroneous data was removed prior to conducting the skill assessment.

Figure 14. Map depicting the locations of the water level gauges used to evaluate the hindcasts of water levels.

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

Station Name	State or Prov.	NOS or CHS Station ID	NWS Station ID	Coordinates	
				Lat. (deg N)	Lon. (deg W)
Buffalo	NY	9063020	BUFN6	42.88	78.89
Sturgeon Point	NY	9063028	PSTN6	42.69	79.05
Erie	PA	9063038	EREP1	42.15	80.08
Cleveland	OH	9063063	CNDO1	41.54	81.64
Marblehead	OH	9063079	MRH01	41.55	82.73
Toledo	OH	9063085	THR01	41.69	83.47
Fermi Power Plant	MI	9063090	NS	41.96	83.26
Bar Point	ON	C12005	NA	42.05	83.12
Kingsville	ON	C12065	NA	42.03	82.92
Erieau	ON	C12250	NA	42.27	81.92
Port Stanley	ON	C12400	NA	42.67	81.22
Port Dover	ON	C12710	NA	42.78	80.20
Port Colborne	ON	C12865	NA	42.87	79.25

5.2. Evaluation of Surface Water Temperature Hindcasts

The evaluation of hourly hindcasts of surface water temperatures was based on comparisons of time series differences between the hindcasts and observations at both offshore and coastal locations in Lake Erie. The comparisons were done using SM, RMSE, SD, NOF, POF, MDPO, and MDNO. In evaluating predicted water temperature in tidal regions, NOS sets an acceptable error of 7.7°C to meet the acceptable error of draft of 7.5 cm (3 inches), as water density is a function of temperature and salinity. However for the Great Lakes, a 3°C criteria for water temperature was assigned, the same criteria used in earlier evaluations of GLOFS (Chu et al., 2007; Kelley et al., 2008).

During the generation of the hindcasts, it was discovered that FVCOM outputted unrealistic water temperatures as low as -4°C during the winter months. CO-OPS decided to impose a -2°C lower limit on FVCOM's water temperature predictions in the operational version of LEOFS. Thus, for the evaluation of the 2005 and 2006 hindcasts, this lower limit was imposed on the hindcasts.

Hindcasts at offshore locations were compared to observations at three 3-m fixed disk buoys in the lake. The buoys are operate d by the NOAA/NWS/National Data Buoy Center (NDBC) or ECCC (Fig. 15). The comparison of the hindcasts to observations from Canadian as well as NDBC buoys follows the recommendation of Kelley et al. (2008). The lake surface temperatures at NDBC Buoys are measured using a Yellow-Springs thermistor sealed in epoxy in a copper slug clamped to the inside of the buoy's hull (Gillhousen, 1987). The thermistor depth is 0.5 m and is sampled once per hour. The point evaluations were conducted by comparing surface (highest sigma layer) temperature hindcasts at the nearest grid points to the buoys. Geographic information for the three buoys is given in Table 3.

Hindcasts at coastal locations were compared to observations at the three NOS/CO-OPS NWLON stations at Marblehead, OH, Cleveland and Buffalo (Fig. 15). The water temperature sensors at the NWLON stations are located approximately 1.5 m below the low water datum (LWD) for the lake. According to Grodsky (personal communication, 2014), the sensors are located fairly close to the shore structure that the water level gauges are mounted to. The Buffalo and Cleveland gauges are attached to the seawall located next to the gauge house. The sensor at the Marblehead station is mounted in a conduit that is welded to the bulkhead. The sensors do not have any heating element directly associated with them (Grodsky, 2014). This station is the least sheltered by manmade wave breakers or landforms of the three locations while the Cleveland station is the most sheltered. Geographic information about the NWLON temperature stations is provided in Table 4 with more detailed information about sensor exposure at each station in Appendix A.

The hourly water temperature observations for the NWS fixed buoys were obtained from the NDBC online archives at http://www.ndbc.noaa.gov. Hourly temperatures at the two Canadian buoys were obtained from Government of Canada's Department of Fisheries and Oceans' Oceanography and Scientific Data Web sites: http://isdm.gc.ca/isdm-gdsi/waves-vagues/search-recherche/list-liste/data-donnees-eng.asp?medsid=C45132 and http://isdm.gc.ca/isdm-gdsi/waves-vagues/search-recherche/list-liste/data-donnees-eng.asp?medsid=C45132. Hourly temperatures from the NOS coastal stations were obtained from the CO-OPS online archives at http://tidesandcurrents.noaa.gov. All the observations were plotted as time series and visually inspected for erroneous data. The temperature data at the CO-OPS stations were found to have a considerable number of spikes. These spikes were removed from the datasets prior to conducting the comparisons.

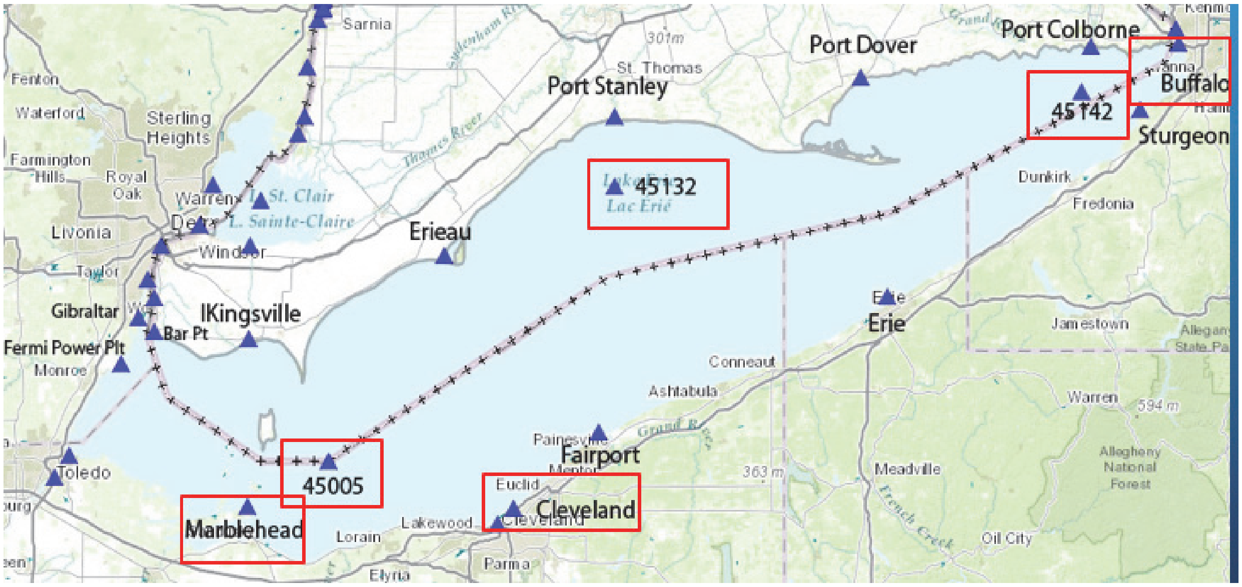


Figure 15. Map depicting the locations of offshore and coastal platforms used to evaluate the hindcasts of surface water temperatures, indicated by red boxes.

5.3. Evaluation of Sub-Surface Water Temperature Hindcasts

The evaluation of the sub-surface water temperature hindcasts were based on comparisons to observed temperatures at three thermistor strings locations in Lake Erie during 2005. The three thermistor stations were selected from an extensive array of thermistor stations operated by GLERL and Canadian National Water Research Institute (NWRI) during International Field Year of Lake Erie (IFYLE) 2005. The stations were chosen in order to evaluate subsurface water temperatures in each of the three basins of the lake. These stations were found to be representative of the data collected at nearby stations in their respective basins. The three stations were T05 in the western basin, T07 in the central basin, and T12 in the eastern basin (Table 5). A map depicting the locations of the thermistor strings is given in Fig. 16. Temperature data from the thermistor stations were available every 30 minutes from approximately mid-June to late-October 2005. Data were recorded at different depths depending on location. Data were available at 4 and 11m at T05, at 1, 3, 5, 7, 9, 13, 15, 16.5, 17.0, and 17.5 m at T07, and at 1, 3, 5, 7, 9, 11, 13, 15, 18.5, 19.0, 28.5, 43.5, and 52.5 m at T12.

The types of thermistors varied at some stations. At T05, Brancker T-1000 thermistors were used. At T07 and T12, three different types of thermistors were used: Onsett, Seabird SBE 39, and Brancker T-1000. Additional information on thermistor arrays can be found at https://www.glerl.noaa.gov/res/projects/ifyle/data/Mooring/therm/Station.php?sta=All&year=2005.

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

Buoy Name	Agency	Prov. or State	NWS Buoy Platform ID	Coordinates	
				Latitude (deg N)	Longitude (deg W)
West Erie	NWS/NDBC	OH	45005	41.68	82.40
Port Stanley	Envir. Canada	ON	45132	42.47	81.22
Port Colborne	Envir. Canada	ON	45134	42.74	79.29

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

Station Name	State	NOS Station ID	NWS Station ID	Coordinates	
				Latitude (deg N)	Longitude (deg W)
Marblehead	OH	9063079	MRHO1	41.55	82.73
Cleveland	OH	9063063	CND01	41.50	81.64
Buffalo	NY	9063020	BUFN6	42.88	78.89

Table 5. Information about GLERL thermistor stations whose observations were used to evaluate the hindcasts of sub-surface water temperatures.

Station Name	Station ID	Basin	Coordinates		Depth (m)
			Latitude (deg N)	Longitude (deg W)	
Station 5	T05	Western	41.67	82.62	12
Station 7	T07	Central	41.94	81.65	24.5
Station 12	T12	Eastern	42.57	79.91	53.5

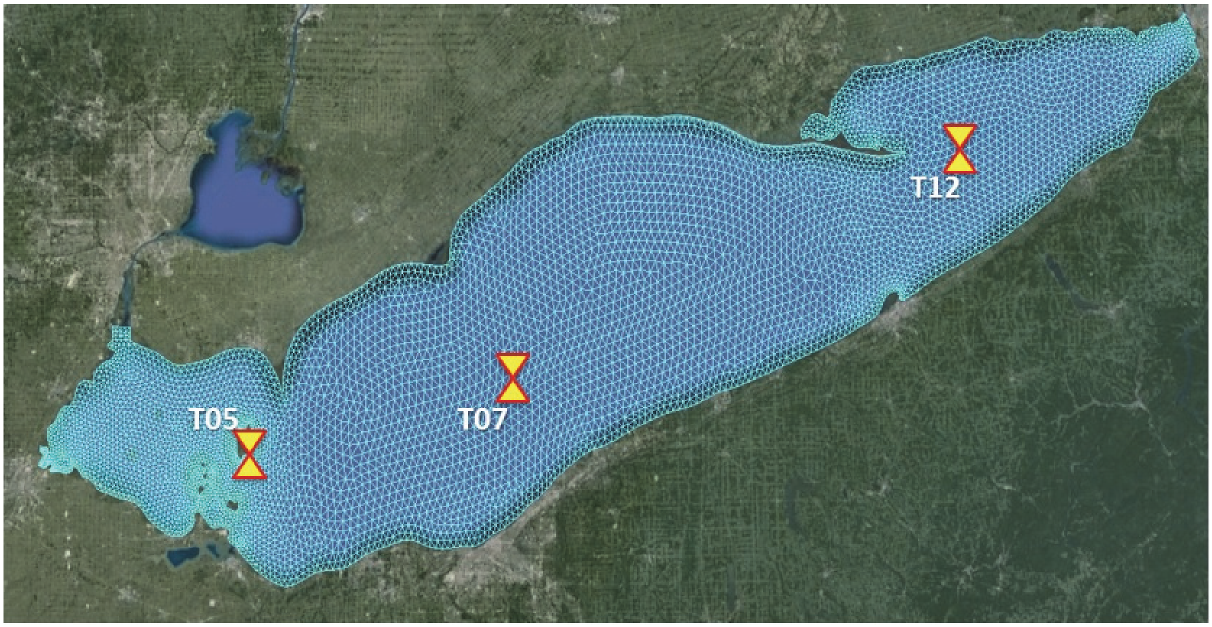


Figure 16. Map depicting the locations of NOAA/GLERL thermistors used to evaluate the hindcasts of sub-surface water temperatures during 2005.

6. HINDCAST SKILL ASSESSMENT RESULTS

6.1. Assessment of Water Level Hindcasts

Time series plots of the water level hindcasts vs. observations at the Buffalo and Toledo gauges are given for 2005 and 2006 in Fig. 17 and 18, respectively. Toledo and Buffalo, located at the extreme SW and NE ends of the lake, respectively, experience the greatest hourly water level variability. Plots for all the NOS and CHS gauges are given in Appendices B and C for 2005 and 2006, respectively.

The standard suite of skill assessment statistics evaluated the ability of the hindcasts to predict hourly and extreme high and low water levels at NOS and CHS gauges during 2005 and 2006. The results of the assessment of the hourly hindcasts are described in Section 6.1.1 and the assessment results of extreme high and low water events is given in Section 6.1.2.

6.1.1. Hourly Water Levels

The skill statistics assessing the ability of the hindcasts to predict hourly water levels at NOS and CHS gauges in 2005 are given in Tables 6 and 7. Similar tables for 2006 are given in Tables 8 and 9. The mean algebraic errors (MAE) during 2005 ranged between -6.3 and 0.0 cm and the RMSE ranged between 6.1 and 10.9 cm. For 2006, the MAEs ranged from -6.9 to -1.8 cm and the RMSE ranged from 6.0 to 11.0 cm. The greatest MAEs during 2005 and 2006 were at Toledo. The hindcasts for 2005 and 2006 passed all the NOS Acceptance Criteria at all NWLON and CHS stations, except for the NOF and CF at Toledo during 2005, CF at Toledo during 2006, and NOF at Port Colborne and Port Dover during 2006. However, it failed to meet the CF and NOF targets at these stations by very small amounts.

6.1.2. Extreme High Water Level Events

The skill statistics assessing the ability of hindcasts to predict the amplitude and timing of extreme high water level events at NOS and CHS gauges during 2005 and 2006 are given in Tables 10 and 11, respectively. Similar tables for NOS and CHS gauges for 2006 are given in Tables 12 and 13. Examples of extreme high water level events at Buffalo are depicted in Fig. 19, corresponding to the extra-tropical cyclones of Dec. 9, 20015 (Fig. 8) and the Dec. 1, 2006 (Fig. 9).

During 2005, the hindcasts under-predicted the extreme high events at all stations with MAEs ranging from -18 cm at Dover to -4 cm at Cleveland. The RMSEs ranged from 10.8 cm to Cleveland to 23 cm at Port Dover. The MAEs for timing ranged from -0.026 hour at Sturgeon Point to about +0.4 hour at Cleveland and Port Stanley. The RMSEs for timing generally ranged from 0.54 to 1.3 hours. The hindcasts of extreme high events passed all the NOS Acceptance Criteria for amplitude at only Cleveland and Erieau. (However, there were only six events at Erieau due to the short data period available.) The NOS targets for timing were met at Fermi Power Plant and Bar Point.

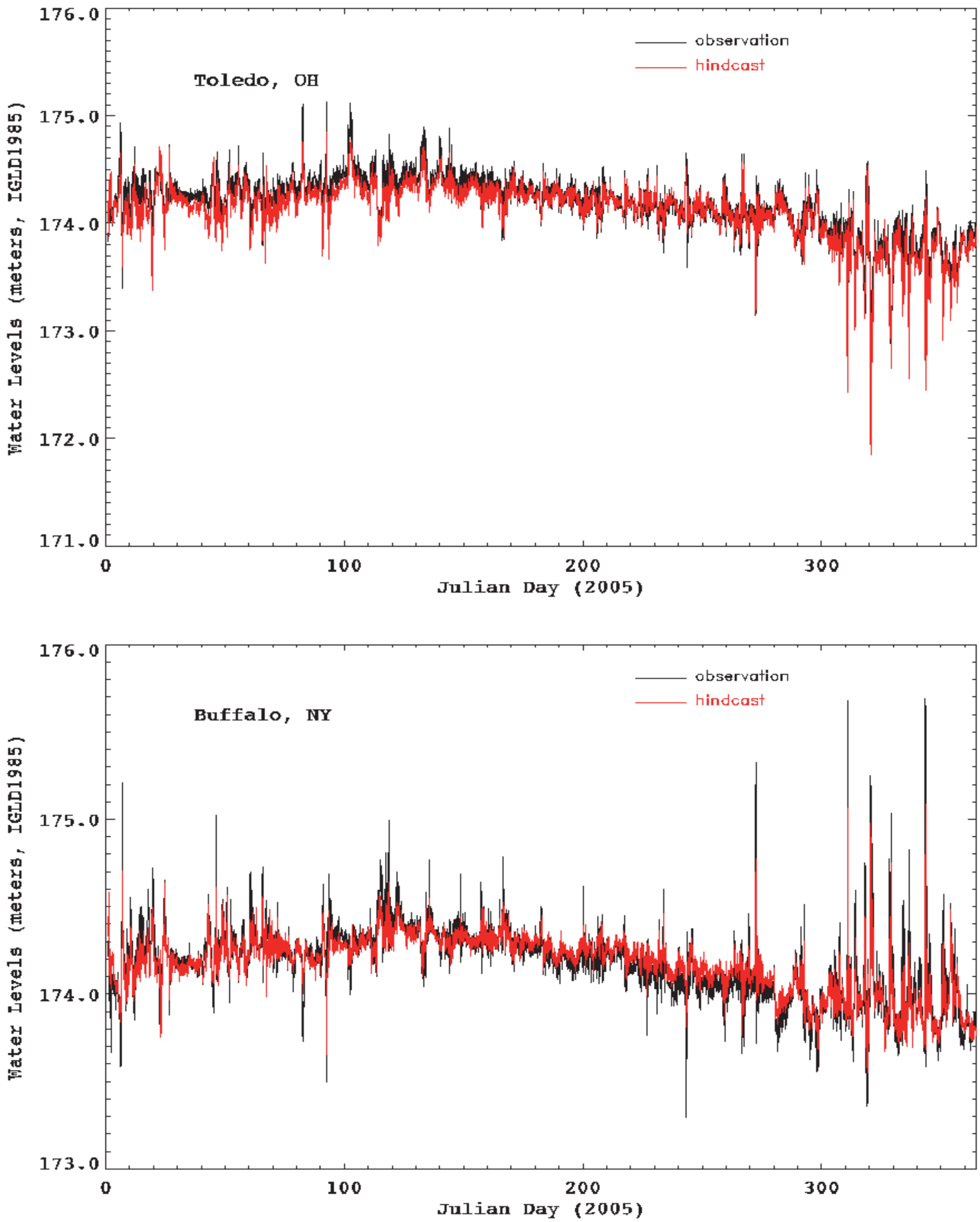
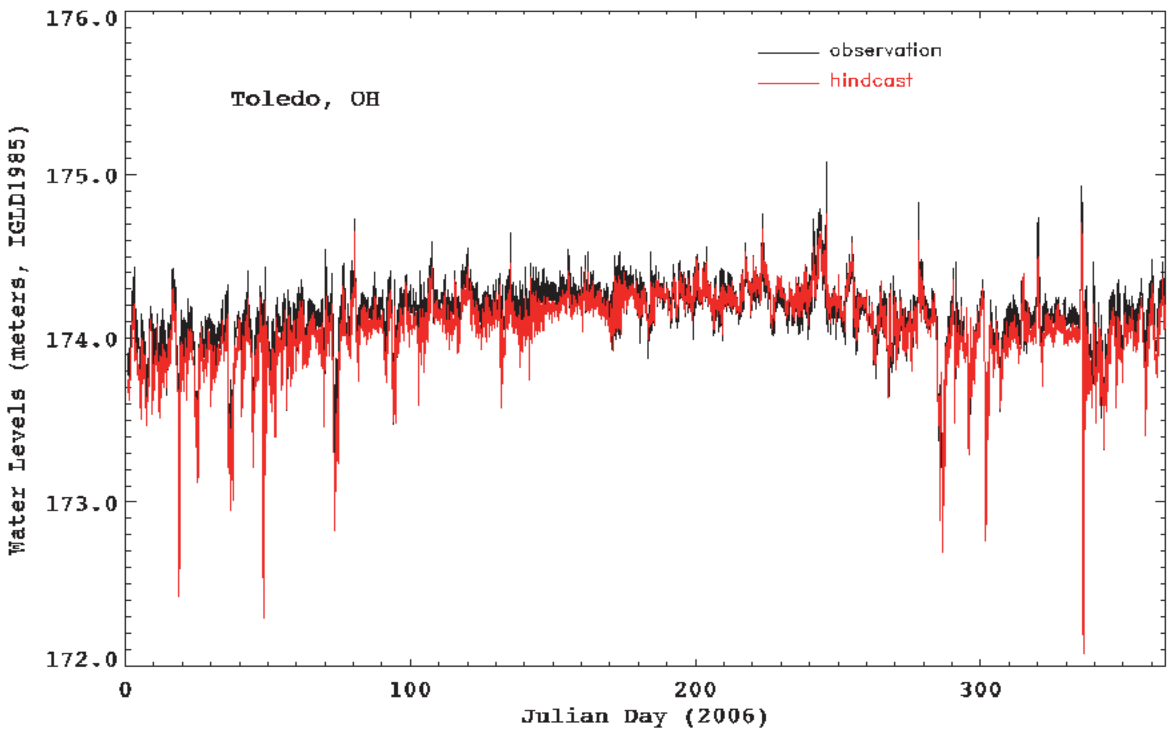


Figure 17. Time series plots of hourly hindcasts of water level vs. observations at NOS NWLON gauges at Toledo, Ohio and Buffalo, N.Y. during 2005.



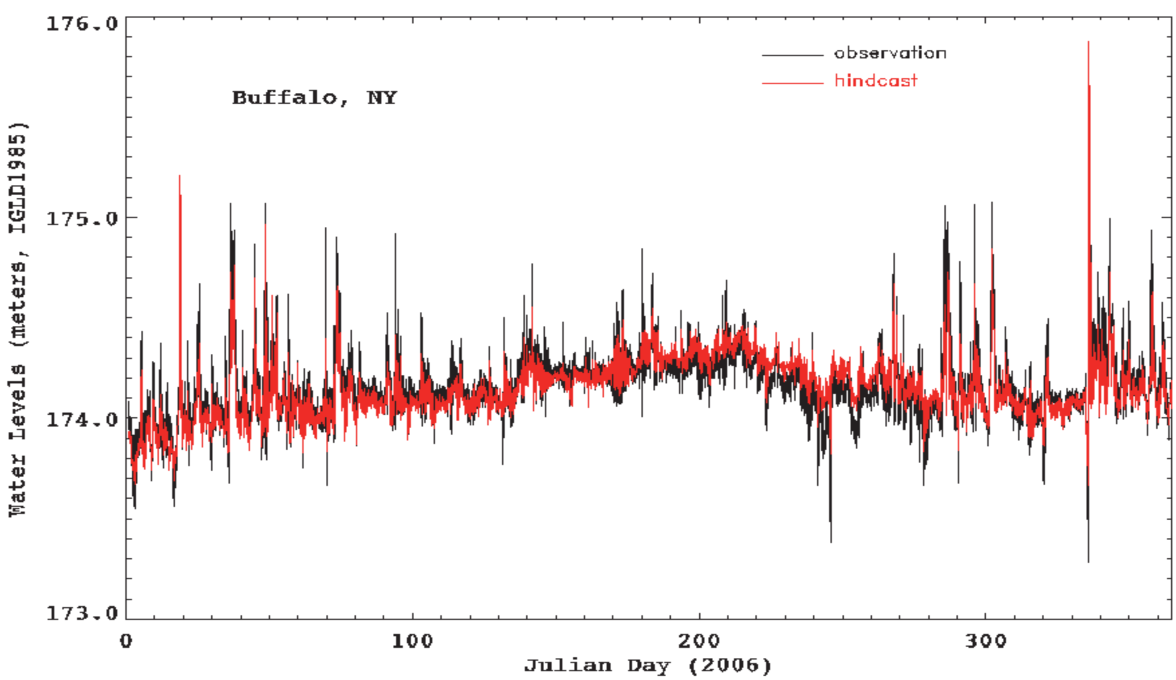


Figure 18. Time series plots of hourly hindcasts of water level vs. observations at the NOS NWLON gauges at Toledo, Ohio and Buffalo, N.Y. during 2006.

Table 6. Summary of skill assessment statistics evaluating the ability of the hindcasts to predict hourly water levels at NOS NWLON stations in Lake Erie for 2005. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	Buffalo	Sturgeon Pt.	Erie	Cleve-land	Toledo	Fermi Power Plant
N	8759	8740	8759	8759	8759	8752
Mean Alg. Error (m)	0.000	0.007	-0.021	-0.020	-0.063	-0.030
RMSE (m)	0.084	0.080	0.066	0.059	0.109	0.071
SD (m)	0.084	0.080	0.062	0.055	0.089	0.065
NOF [2x15 cm] (%)	0.7	0.6	0.2	0.0	1.2	0.2
CF [15 cm] (%)	94.0	94.9	96.8	98.4	86.5	96.5
POF [2x15 cm] (%)	0.2	0.1	0.0	0.1	0.1	0.1
MDNO [2x15 cm] (hr)	4.0	6.0	4.0	0.0	14.0	6.0
MDPO [2x15 cm] (hr)	5.0	5.0	1.0	1.0	2.0	1.0

Table 7. Summary of skill assessment statistics of hindcasts of hourly water levels at Canadian Hydrographic stations in Lake Erie for 2005. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	Port Colborne	Port Dover	Port Stanley	Erieau	Kings-ville	Bar Point
N	8315	8472	8134	8472	8472	8472
Mean Alg. Error (m)	-0.009	-0.018	-0.032	-0.029	-0.029	-0.040
RMSE (m)	0.081	0.073	0.061	0.069	0.069	0.067
SD (m)	0.080	0.071	0.052	0.062	0.062	0.053
NOF [2x15 cm] (%)	0.7	0.4	0.0	0.0	0.0	0.0
CF [15 cm] (%)	94.0	95.4	98.4	96.8	96.8	97.6
POF [2x15 cm] (%)	0.0	0.0	0.0	0.0	0.0	0.0
MDNO [2x15 cm] (hr)	7.0	5.0	0.0	0.0	0.0	0.0
MDPO [2x15 cm] (hr)	2.0	0.0	0.0	1.0	1.0	0.0

Table 8. Same as Table 6 except for 2006.

Statistic, Acceptable Error [ ], and Units ( )	Buffalo	Sturgeon Pt.	Erie	Cleve-land	Marble-head	Toledo	Fermi Power Plant
N	8759	8362	8759	8759	451	8648	8759
Mean Alg. Error (m)	-0.018	-0.009	-0.036	-0.028	-0.061	-0.069	-0.033
RMSE (m)	0.089	0.084	0.077	0.061	0.074	0.110	0.071
SD (m)	0.088	0.084	0.068	0.054	0.043	0.086	0.063
NOF [2x15cm] (%)	1.0	0.8	0.4	0.0	0.0	1.0	0.0
CF [15cm] (%)	92.2	93.7	95.5	99.1	99.1	85.7	97.6
POF [2x15cm] (%)	0.1	0.1	0.0	0.0	0.0	0.1	0.1
MDNO [2x15cm] (hr)	6.0	6.0	7.0	0.0	0.0	8.0	0.0
MDPO [2x15cm] (hr)	8.0	5.0	1.0	0.0	0.0	2.0	2.0

Table 9. Same as Table 7 except for 2006.

Statistic, Acceptable Error [ ], and Units ( )	Port Colborne	Port Dover	Port Stanley	Erieau	Kingsville	Bar Point
N	8059	8472	8472	8472	8472	8472
Mean Alg. Error (m)	-0.029	-0.037	-0.043	-0.037	-0.042	-0.045
RMSE (m)	0.092	0.086	0.064	0.060	0.072	0.073
SD (m)	0.088	0.078	0.048	0.048	0.059	0.058
NOF [2x15 cm] (%)	1.3	1.1	0.0	0.0	0.0	0.0
CF [15 cm] (%)	91.7	93.6	99.1	99.8	97.5	97.8
POF [2x15 cm] (%)	0.1	0.0	0.0	0.0	0.0	0.0
MDNO [2x15 cm] (hr)	12.0	8.0	0.0	0.0	0.0	0.0
MDPO [2x15 cm] (hr)	5.0	0.0	0.0	0.0	0.0	0.0

Table 10. Summary of skill assessment statistics evaluating the ability of the hindcasts to predict extreme high water level events at NOS NWLON stations in Lake Erie during 2005. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	Buffalo N=31		Sturgeon Point N=38		Erie N=32	
	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	-0.200	0.000	-0.149	-0.026	-0.128	0.094
RMSE (m) (hr)	0.258	1.136	0.219	1.064	0.167	1.159
SD (m) (hr)	0.167	1.155	0.162	1.078	0.109	1.174
NOF [2x15 cm or 90 min] (%)	22.6	0.0	13.2	0.0	9.4	0.0
CF [15 cm or 90 min] (%)	48.4	77.4	57.9	78.09	71.9	78.1
POF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0	0.0	0.0
MDNO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0
MDPO [2x15 cm or 90min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0

Cleveland N=27		Toledo N=31		Fermi Power Plant N=24	
Amp.	Time	Amp.	Time	Amp.	Time
-0.071	0.407	-0.116	-0.129	-0.113	-0.208
0.108	1.319	0.143	0.842	0.128	0.540
0.083	1.279	0.086	0.846	0.060	0.509
0.0	0.0	0.0	0.0	0.0	0.0
92.6	66.7	67.7	93.5	70.8	100.0
0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0

Table 11. Summary of skill assessment statistics evaluating the ability of the hindcasts to predict extreme high water level events at CHS stations in Lake Erie during 2005. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	Port Colborne N=26		Port Dover N=21		Port Stanley N=12		Erieau N=6		Kingsville N=26		Bar Point N=31	
	Amp.	Time	Amp.	Time	Amp.	Time	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	-0.122	0.038	-0.180	-0.238	-0.102	0.417	-0.044	-0.500	-0.108	0.308	-0.105	-0.129
RMSE (m) (hr)	0.190	1.056	0.230	1.215	0.120	1.041	0.062	1.354	0.131	1.000	0.117	0.622
SD (m) (hr)	0.149	1.076	0.146	1.221	0.065	0.996	0.049	1.378	0.075	0.970	0.054	0.619
NOF [2x15 cm or 90 min] (%)	19.2	0.0	23.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CF [15 cm or 90 min] (%)	61.5	80.8	47.6	76.2	75.0	83.3	100.0	66.7	73.1	84.6	83.9	96.8
POF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MDNO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MDPO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 12. Same as Table 10 except for 2006.

Statistic, Acceptable Error [ ], and Units ( )	Buffalo, NY N=34		Sturgeon Point, NY N=39		Erie, PA N=34	
	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	-0.186	0.176	-0.151	0.128	-0.134	0.000
RMSE (m) (hr)	0.249	1.000	0.203	1.098	0.162	1.029
SD (m) (hr)	0.167	0.999	0.138	1.105	0.092	1.044
NOF [2x15 cm or 90 min] (%)	23.5	0.0	15.4	0.0	5.9	0.0
CF [15 cm or 90 min] (%)	58.8	82.4	59.0	74.4	64.7	82.4
POF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0	0.0	0.0
MDNO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0
MDPO [2x15 cm or 90min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0

Cleveland N=31		Toledo N=16		Fermi Power Plant N=21	
Amp.	Time	Amp.	Time	Amp.	Time
-0.088	0.323	-0.147	0.062	-0.106	-0.048
0.104	1.016	0.172	0.829	0.127	0.845
0.055	0.979	0.091	0.854	0.071	0.865
0.0	0.0	12.5	0.0	4.8	0.0
87.1	83.9	75.0	87.5	76.2	95.2
0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0

Table 13. Same as Table 11 except for 2006.

Statistic, Acceptable Error [ ], and Units ( )	Port Colborne N=32		Port Dover N=32		Port Stanley N=10	
	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	-0.177	-0.125	-0.151	-0.094	-0.053	-0.400
RMSE (m) (hr)	0.231	0.968	0.195	1.046	0.066	1.265
SD (m) (hr)	0.151	0.976	0.124	1.058	0.040	1.265
NOF [2x15 cm or 90 min] (%)	15.6	0.0	12.5	0.0	0.0	0.0
CF [15 cm or 90 min] (%)	53.1	87.5	62.5	81.2	100.0	70.0
POF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0	0.0	0.0
MDNO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0
MDPO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0

Erieau N=9		Kingsville N=18		Bar Point N=25	
Amp.	Time	Amp.	Time	Amp.	Time
-0.097	0.111	-0.112	0.556	-0.111	-0.120
0.104	1.291	0.126	1.106	0.128	0.917
0.038	1.364	0.060	0.984	0.066	0.927
0.0	0.0	0.0	0.0	4.0	0.0
88.9	66.7	77.8	77.8	76.0	88.0
0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0

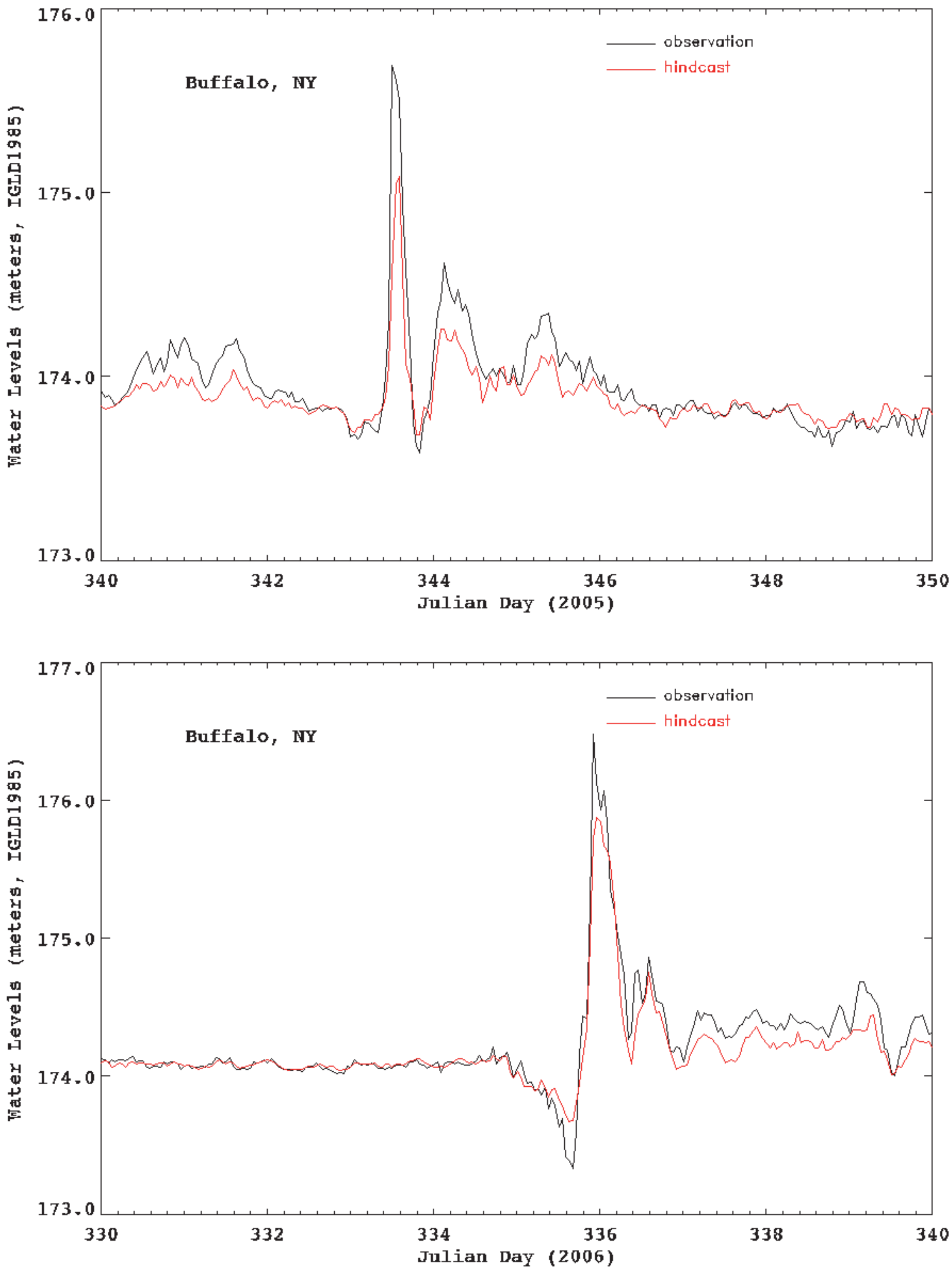


Figure 19. Time series plots of hourly hindcasts vs. observations at NOS NWLON Buffalo, N.Y. gauge during the period from Dec. 1 to Dec. 16, 2005 (top) and from Nov. 26 to Dec. 6, 2006 (bottom).

During 2006, the hindcasts under-predicted the extreme high events at all stations. MAEs ranged from -14.7 cm at Buffalo to -5.3 cm at Port Stanley. The RMSEs ranged from 10 to 25 cm. The MAEs for timing ranged from -0.40 hour at Port Stanley to +0.32 hour at Cleveland. The RMSEs ranged between 0.89 and 1.29 hours. The hindcasts of extreme high events passed all the NOS acceptance criteria for amplitude only at Port Stanley. The NOS targets for timing were only completely met at Fermi Power Point.

6.1.3. Extreme Low Water Level Events

The skill statistics assessing the ability of the hindcasts to predict extreme low water level events at the NOS and CHS gauges in Lake Erie during 2005 are given Tables 14 and 15, respectively. Similar tables for 2006 are presented in Tables 16 and 17. Examples of extreme low water level events at Toledo are depicted in Fig. 20, corresponding to the extra-tropical cyclones of Dec. 9, 2005 (Fig. 8) and Dec. 1, 2006 (Fig. 9).

During 2005, the hindcasts over-predicted the extreme low water events at 11 of the 12 stations with MAEs ranging from 3.3 cm at Fairport to 13.1 cm at Buffalo. The RMSEs ranged from 1.9 cm to 15.9 cm. MAEs for timing ranged from -0.35 hour at Fermi Power Plant to 0.41 hour at Port Stanley. The RMSEs ranged from -0.35 to 0.27 hours. The hindcasts of extreme low events only passed all the NOS Acceptance Criteria for amplitude at Erie, Erieau, Bar Point, and Port Stanley, but came very close to passing at Kingsville and Port Dover. The NOS targets for timing were completely met only at Fermi Power Plant, but came very close to passing at Bar Point and Kingsville.

During 2006, the hindcasts over-predicted the extreme low water events at nine stations but under predicted at three stations, including Port Stanley, Toledo, and Bar Point. At the under predicting stations, the MAEs ranged from -0.3 cm at Bar Point to -6.5 cm at Toledo. At the over predicting stations, the MAEs ranged from 0.5 cm at Erieau to 11 cm at Buffalo. The RMSEs ranged from -6.5 to 18 cm. Comparing the hindcasts at the two stations at the opposite ends of the lake, the MAE at Buffalo was 11cm and -6.5 cm at Toledo. The MAEs for timing ranged from -0.07 hour at Toledo to 0.62 hour at Erie. The RMSEs at the majority of stations were approximately 1 hour. The hindcasts of extreme low events only passed all the NOS Acceptance Criteria for amplitude at Cleveland, Erieau, King Point, Bar Point, and Port Stanley but came very close at Fermi Power Plant. The NOS targets for timing were not met completely at any station.

6.2. Assessment of Water Temperature Hindcasts

The results of the skill assessment of LEOFS-FVCOM hindcasts of surface water temperatures for 2005 and 2006 are given in this section. As noted earlier in Section 5.2, the assessment was conducted with the -2°C lower limit on the water temperature hindcasts. The assessment results for the three offshore locations are presented in Section 6.2.1 and for the three coastal locations are described in Section 6.2.2.

6.2.1. Offshore Locations

Time series plots of the hindcasts vs. observations at buoys West Erie (45005), Port Stanley (45132), and Port Colbrone (45142) for 2005 and 2006 are depicted in Fig. 21 and Fig. 22, respectively. The skill statistics assessing the ability of the hindcasts to predict surface water temperatures at the three offshore fixed buoys for 2005 and 2006 are given in Tables 18 and 19, respectively.

Table 14. Summary of skill assessment statistics evaluating the ability of hindcasts to simulate extreme low water level events at NOS NWLON Stations in Lake Erie during 2005. Gray shading, if present, indicates that the statistic did not pass the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	Buffalo N=45		Sturgeon Point N=40		Erie N=49	
	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	0.131	0.267	0.123	0.100	0.064	0.204
RMSE (m) (hr)	0.159	1.555	0.148	0.949	0.091	1.069
SD (m) (hr)	0.091	1.136	0.083	0.955	0.064	1.060
NOF [2x15 cm or 90min] (%)	0.0	0.0	0.0	0.0	0.0	0.0
CF [15 cm or 90 min] (%)	66.7	77.8	72.5	87.5	91.8	83.7
POF [2x15 cm or 90 min] (%)	4.4	0.0	2.5	0.0	2.0	0.0
MDNO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0
MDPO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0

Cleveland N=39		Toledo N=45		Fermi Power Plant N=53	
Amp.	Time	Amp.	Time	Amp.	Time
0.068	0.462	-0.014	-0.067	0.067	-0.340
0.111	1.177	0.142	0.978	0.120	0.824
0.089	1.097	0.143	0.986	0.100	0.758
0.0	0.0	2.2	0.0	0.0	0.0
82.1	79.5	77.8	88.9	77.4	92.5
2.6	0.0	2.2	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0

Table 15. Summary of standard statistics evaluating the ability of hindcasts to simulate extreme low water level events at Canadian Hydrographic stations in Lake Erie during 2005. Gray shading, if present, indicates that the statistic did not pass the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	Port Colborne N=41		Port Dover N=48		Port Stanley N=39	
	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (min)	0.113	0.024	0.078	0.250	0.019	0.410
RMSE (m) (min)	0.129	1.158	0.100	1.225	0.061	1.155
SD (m) (min)	0.062	1.172	0.063	1.212	0.059	1.093
NOF [2x15 cm or 90min] (%)	0.0	0.0	0.0	0.0	0.0	0.0
CF [15 cm or 90 min] (%)	70.7	75.6	89.6	72.9	97.4	76.9
POF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0	0.0	0.0
MDNO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0
MDPO [2x15 cm or 90min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0

Erieu N=30		Kingsville N=55		Bar Point N=63	
Amp.	Time	Amp.	Time	Amp.	Time
0.039	-0.200	0.049	0.145	0.025	-0.206
0.081	1.238	0.095	0.953	0.071	0.917
0.072	1.243	0.082	0.951	0.067	0.901
0.0	0.0	0.0	0.0	0.0	0.0
90.0	70.0	87.3	89.1	98.4	87.3
0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0

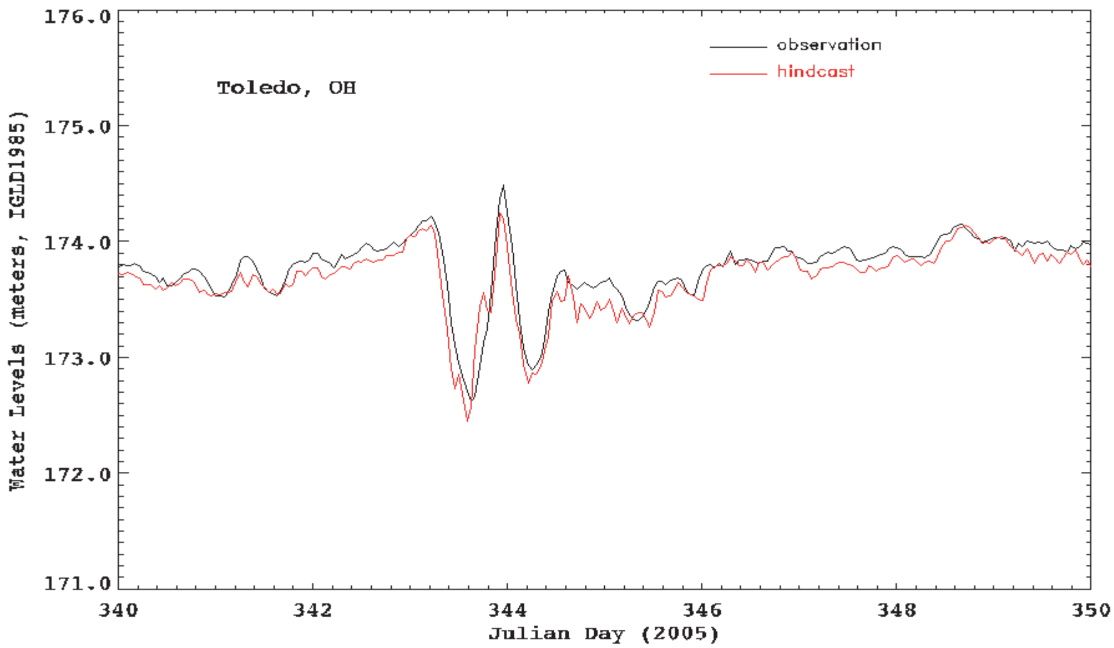
Table 16. Same as Table 14 except for 2006.

Statistic, Acceptable Error [ ], and Units ( )	Buffalo N=34		Sturgeon Point N=28		Erie N=34	
	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (min)	0.112	0.147	0.099	0.357	-0.134	0.618
RMSE (m) (min)	0.148	1.098	0.139	1.000	0.162	1.071
SD (m) (min)	0.098	1.105	0.100	0.951	0.092	0.888
NOF [2x15 cm or 90min] (%)	0.0	0.0	0.0	0.0	5.9	0.0
CF [15 cm or 90 min] (%)	76.5	82.4	78.6	89.3	64.7	82.4
POF [2x15 cm or 90 min] (%)	5.9	0.0	3.6	0.0	0.0	0.0
MDNO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0
MDPO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0

Cleveland N=44		Toledo N=54		Fermi Power Plant N=76	
Amp.	Time	Amp.	Time	Amp.	Time
0.055	0.205	-0.054	0.037	0.042	0.132
0.092	1.034	0.154	1.000	0.095	0.889
0.074	1.025	0.146	1.009	0.085	0.885
0.0	0.0	9.3	0.0	0.0	0.0
93.2	84.1	68.5	88.9	90.8	93.4
0.0	0.0	0.0	0.0	1.3	0.0
0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0

Table 17. Same as Table 15 except for 2006.

Statistic, Acceptable Error [ ], and Units ( )	Port Colborne N=32		Port Dover N=35		Port Stanley N=13		Erieau N=35		Kingsville N=63		Bar Point N=74	
	Amp.	Time	Amp.	Time	Amp.	Time	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (hr)	0.082	0.219	0.056	0.400	-0.012	-0.692	0.005	0.400	0.022	0.079	-0.003	-0.027
RMSE (m) (hr)	0.126	1.075	0.097	1.069	0.071	1.144	0.051	1.095	0.072	0.951	0.072	0.944
SD (m) (hr)	0.097	1.070	0.080	1.006	0.072	0.947	0.051	1.035	0.070	0.955	0.073	0.950
NOF [2x15 cm or 90min] (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CF [15 cm or 90 min] (%)	84.4	84.4	88.6	80.0	92.3	76.9	100.0	80.0	95.2	88.9	95.9	86.5
POF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MDNO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MDPO [2x15 cm or 90 min] (hr)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0



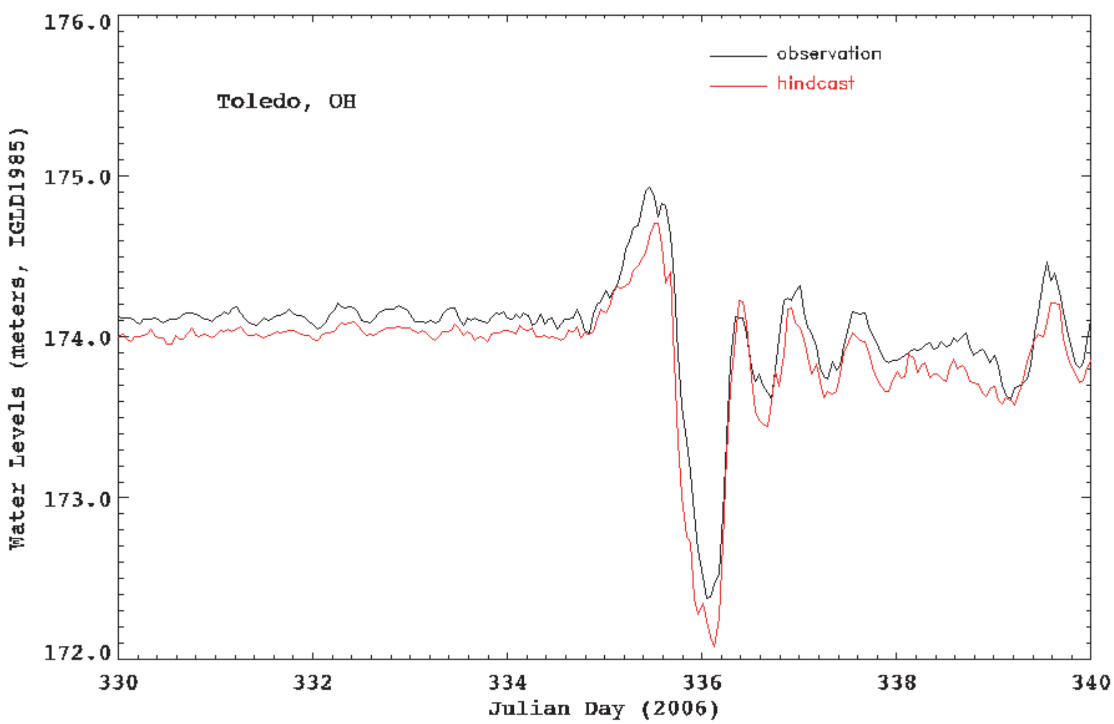


Figure 20. Time series plots of hourly hindcasts vs. observations at NOS NWLON Toledo, Ohio gauge during the period from Dec. 1 to Dec. 16, 2005 (top) and from Nov. 26 to Dec. 6, 2006 (bottom).

During 2005, hindcasts agreed closely with observations at the three sites throughout the year. MAEs ranged from 0.9 to 1.1 ºC. The RMSEs were between 1.2 to 1.3ºC. The hindcasts passed the NOS Acceptance Criteria at all three buoys. Although the hindcasts closely matched observations at the buoys throughout the year, there were differences depending on time of year and location. The best agreement during the year at all the buoys occurred in the spring until to approximately Day 170 (Jun. 19) when hindcasts were within +- 0.5ºC of observations. Hindcasts at 45005 continued to match very well beyond Day 170 (Jun. 19) during summer, autumn, and early winter. However, at the Port Stanley buoy (45132) and at the Port Colborne buoy (45142), the hindcasts ran warmer than observations by approximately 1 to 1.5ºC, especially at the Port Colborne buoy, until Day 310 (Nov. 6). After that the hindcasts were almost identical to observations up to the last day the buoys were still in the lake for the warm season.

During 2006, hindcasts matched observations at the buoys throughout the year. The MAEs ranged from 0.09 to 0.88ºC. The RMSEs ranged from 1.0 to 1.4ºC. The hindcasts passed the acceptance criteria at all the buoys. Although the hindcasts matched the observations throughout the year, there were a few notable departures between observations and hindcasts during a portion of the year. At West Erie buoy (45005), the hindcasts ran warmer than observations by approximately 1-1.5ºC from Day 160 (Jun. 9), following a rapid rise in observed water temperatures during the previous 15 days, to Day 250 (Sep. 7). At the Port Stanley buoy (45132), the hindcasts ran warmer by about 1-1.5ºC from Day 230 (Aug. 18) to Day 270 (Sep. 27). In addition, hindcasts did not simulate well three spikes in the observations at Port Stanley which occurred around Days 110 (Apr. 20), 130 (May 10), and 150 (May 30) and a similar spike on Day 110 at 45132.

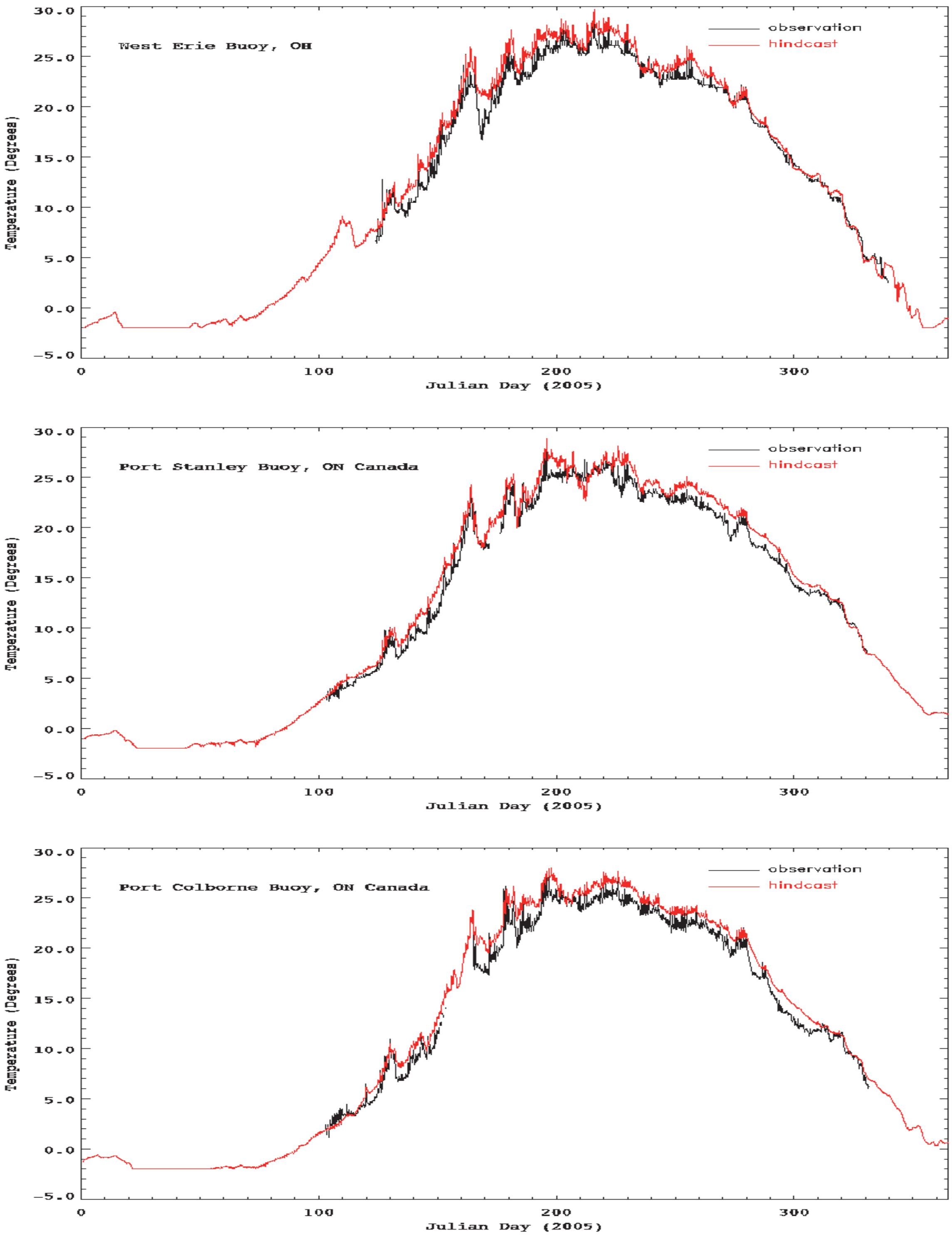


Figure 21. Time series plots of hourly hindcasts of surface water temperatures vs. observations at three offshore fixed buoys during 2005.

Table 18. Summary of skill assessment statistics of the hourly hindcasts of surface water temperatures at the fixed buoys in Lake Erie during 2005. Gray shading indicates that the statistic did not pass the NOS acceptance criteria.

Time Period, Statistic, Acceptable Error [ ], and Units ( )	45005 West Erie N=5179	45132 Port Stanley N=5318	45142 Port Colborne N=5122
Time Period	5/3-12/5/05	6/25-10/19/05	6/13-11/27/05
Mean Alg. Error (°C)	0.886	0.940	1.064
RMSE (°C)	1.210	1.177	1.289
SD (°C)	0.825	0.708	0.727
NOF [2x3°C] (%)	0.0	0.0	0.0
CF [3°C] (%)	99.1	99.8	99.3
POF [2x3°C] (%)	0.0	0.0	0.0
MDNO [2x3°C] (hr)	0.0	0.0	0.0
MDPO [2x3°C] (hr)	0.0	0.0	0.0

Table 19. Same as Table 18 except it is for 2006.

Time Period, Statistic, Acceptable Error [ ], and Units ( )	45005 West Erie N=5007	45132 Port Stanley N=3977	45142 Port Colborne N=5484
Time Period	6/13-11/27/06	3/25-4/16/06	9/24-11/24/06
Mean Alg. Error (°C)	0.875	0.600	0.089
RMSE (°C)	1.242	1.361	0.985
SD (°C)	0.882	1.221	0.981
NOF [2x3°C] (%)	0.0	0.0	0.0
CF [3°C] (%)	99.7	96.6	98.5
POF [2x3°C] (%)	0.0	0.0	0.0
MDNO [2x3°C] (hr)	0.0	0.0	1.0
MDPO [2x3°C] (hr)	0.0	0.0	0.0

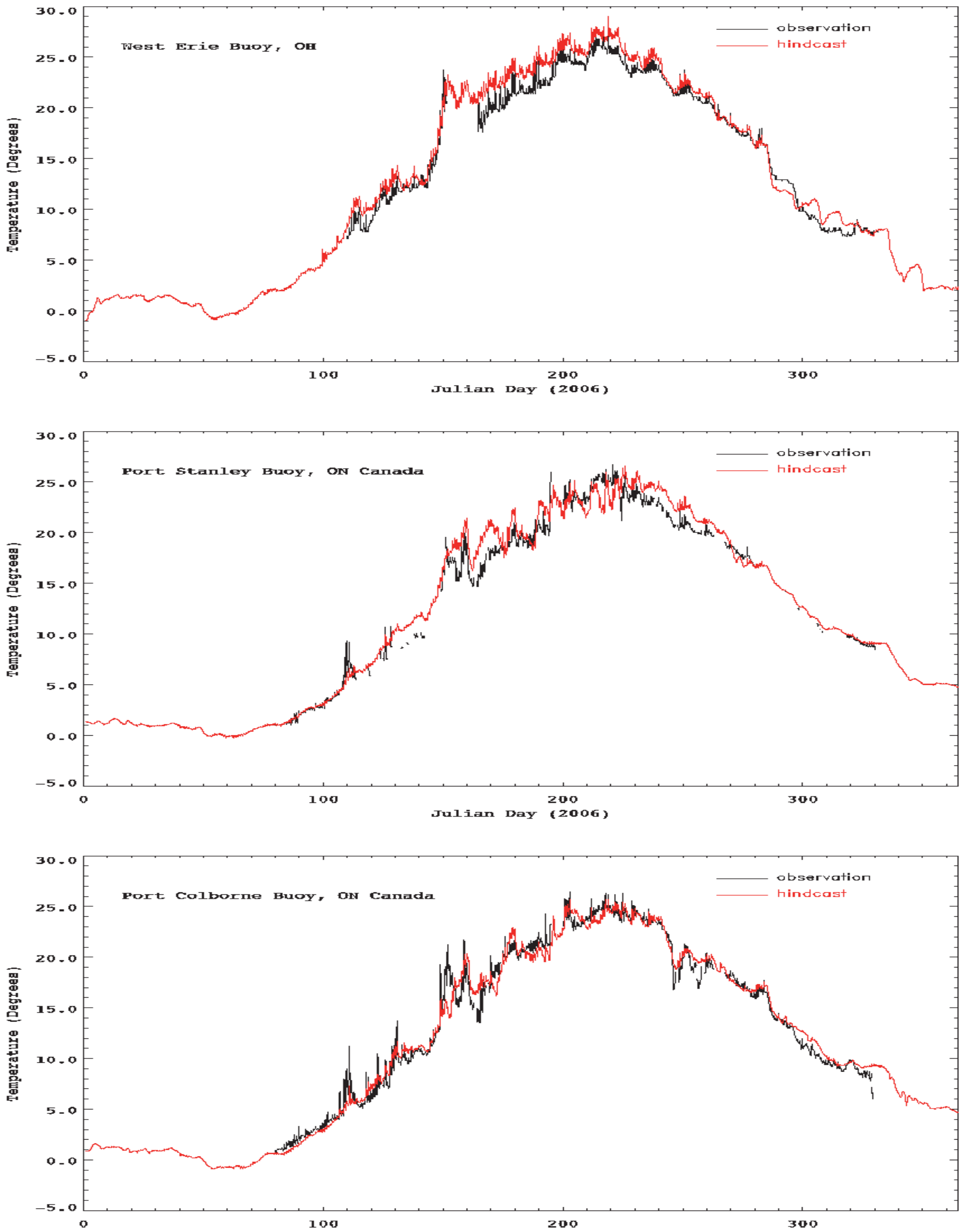


Figure 22. Time series plots of hourly hindcasts of surface water temperatures vs. observations at three offshore fixed buoys during 2006.

6.2.2. Coastal Station Locations

Time series plots of the hindcasts vs. observations at Marblehead, Cleveland, and Buffalo for 2005 and 2006 are depicted in Fig. 23 and Fig. 24, respectively. The skill statistics assessing the ability of the hindcasts to predict surface water temperatures at the three coastal stations for 2005 and 2006 are given in Tables 20 and 21, respectively.

For 2005, the hindcasts agreed very closely with observations at the three sites throughout the year. However, the hindcasts were consistently slightly warmer than observations at Marblehead and Buffalo during the warm season from approximately Day 170 (June 19) until 270 (Sept. 27). In addition, at Cleveland, the hindcasts were consistently cooler than observations starting around Day 300 (Oct. 27). At Marblehead and Buffalo, where there were a full year of observations for statistical comparison, the MAEs were -0.1 and -0.4ºC, respectively. The RMSEs at these two stations were between 1.8 and 2.0ºC. The hindcasts met all NOS Acceptance Criteria at Buffalo and Marblehead.

For 2006, the hindcasts agreed very closely with observations. However, once again the hindcasts were consistently warmer than observations at Marblehead and Buffalo during the warm season, this time from approximately Day 180 (Jun. 29) to Day 270 (Sept. 27) and at Cleveland from about Day 170 (Jun. 19) to Day 260 (Sept. 17). At Cleveland, the hindcasts were cooler than observations during the cold season from about Day 300 (Oct. 27, 2015) until Day 125 (May 5, 2016) and from Day 310 (Nov. 6) through the end of 2016 (Dec. 31, 2016). The MAEs ranged from -1.5ºC at Cleveland to 0.1ºC at Marblehead. The RMSEs ranged between 1.2ºC at Marblehead and 2.5ºC at Cleveland. The hindcasts met all NOS Acceptance Criteria at Buffalo and Marblehead but did not pass the CF criteria at Cleveland.

6.3. Assessment of Sub-Surface Water Temperature Hindcasts

The results of the skill assessment of LEOFS-FVCOM's hindcasts of sub-surface water temperatures at the three thermistor locations, one in each of the three basins of Lake Erie during 2005, are given in this section. The results are presented for each thermistor station.

Station T05 – Western Basin

Time series plots of the hindcasts vs. observations at Station T05 in the western basin at 4 and 11 m depths is depicted in Fig. 25. Plots of temperature vs. depth and time for both hindcasts and observations are given in Fig. 26. The skill statistics assessing the ability of the hindcasts to accurately predict sub-surface water temperatures at the two depths are given in Tables 22. Overall, the hindcasts closely matched observations at 4 and 11 m depths. However, the hindcasts were consistently slightly warmer than observations at the 4 m depth from Day 170 (Jun. 19) to Day 280 (Oct. 7). The hindcasts successfully predicted five high amplitude (up to 7ºC) temperature events at the 11 m depth and four events at the 5 m depth which occurred between approximately June 1 and August 28. The MAE at 4m depth was about 1ºC and 0.2ºC at the 11.9 m depth. The RMSEs were 1.3 and 1.4ºC at the 4 and 11 m depths, respectively. The hourly hindcasts passed the NOS Acceptance Criteria at both depths.

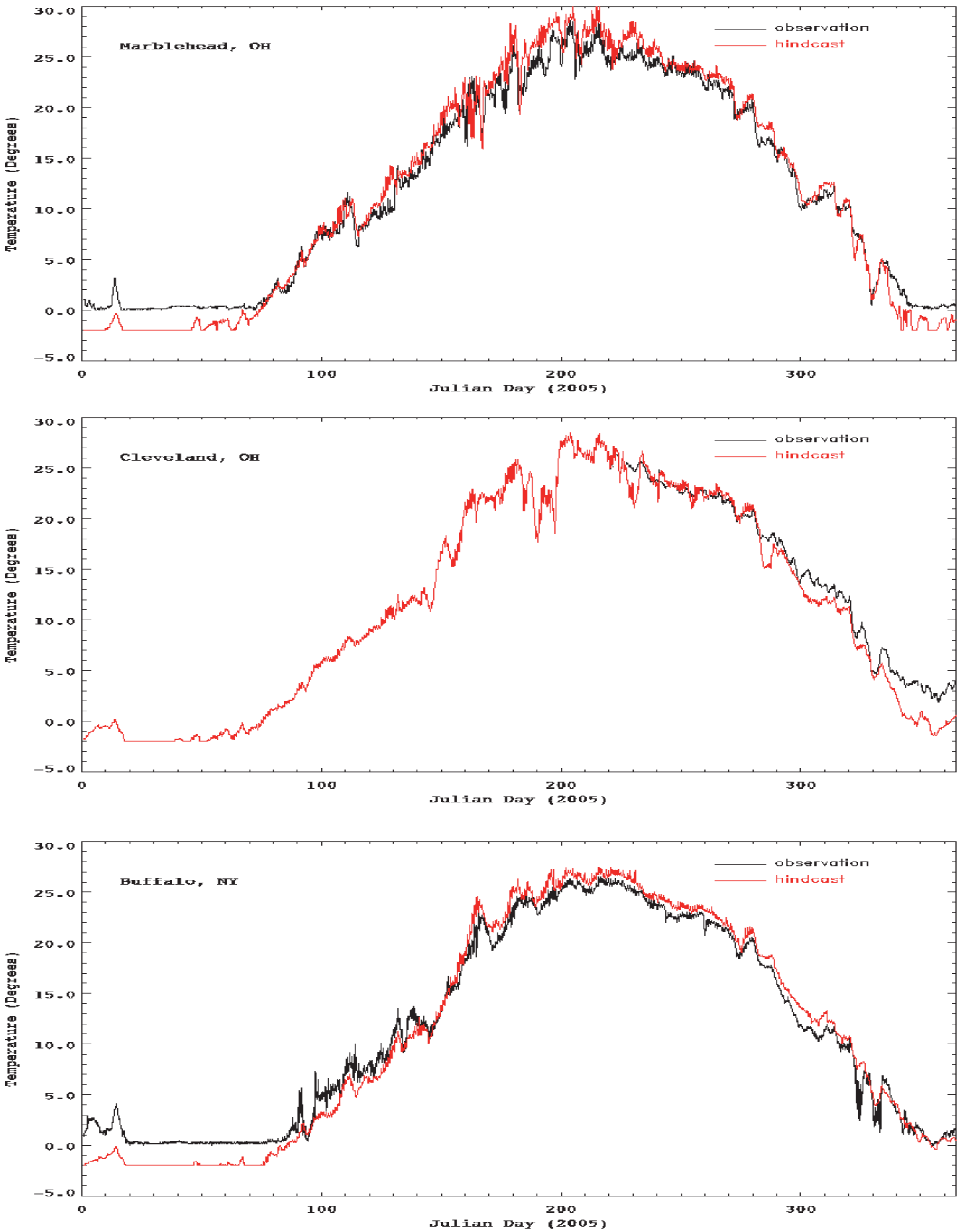


Figure 23. Time series plots of hourly hindcasts of surface water temperatures vs. observations at NOS NWLON gauges at Marblehead, Ohio, Cleveland, Ohio, and Buffalo, N.Y. during 2005

Table 20. Summary of skill assessment statistics of the hourly hindcasts of surface water temperatures at coastal stations in Lake Erie during 2005. Gray shading indicates that the statistic did not pass the NOS acceptance criteria. Observational data were not available from Fairport, Ohio station.

Time Period, Statistic, Acceptable Error [ ], and Units ( )	Marblehead N=8759	Cleveland N=3364	Buffalo N=8759
Time Period	1/1/05-1/2/06	8/15/05-1/2/06	1/1/05-1/2/06
Mean Alg. Error (ºC)	0.078	-1.163	-0.242
RMSE (ºC)	1.634	1.867	1.594
SD (ºC)	1.632	1.460	1.575
NOF [2x3ºC] (%)	0.0	0.0	0.0
CF [3ºC] (%)	95.3	83.9	96.1
POF [2x3ºC] (%)	0.0	0.0	0.0
MDNO [2x3ºC] (hr)	1.0	0.0	0.0
MDPO [2x3ºC] (hr)	0.0	0.0	0.0

Table 21. Same as Table 21 except it is for 2006.

Time Period, Statistic, Acceptable Error [ ], and Units ( )	Marblehead N=8464	Cleveland N=8759	Buffalo N=8368
Time Period	6/24/06-1/2/07	1/1/06-1/2/07	3/14/06-8/29/06
Mean Alg. Error (ºC)	0.118	-1.472	0.081
RMSE (ºC)	1.205	2.456	1.264
SD (ºC)	1.199	1.966	1.261
NOF [2x3ºC] (%)	0.1	0.4	0.0
CF [3ºC] (%)	98.8	73.8	97.2
POF [2x3ºC] (%)	0.0	0.0	0.0
MDNO [2x3ºC] (hr)	5.0	18.0	0.0
MDPO [2x3ºC] (hr)	0.0	0.0	2.0

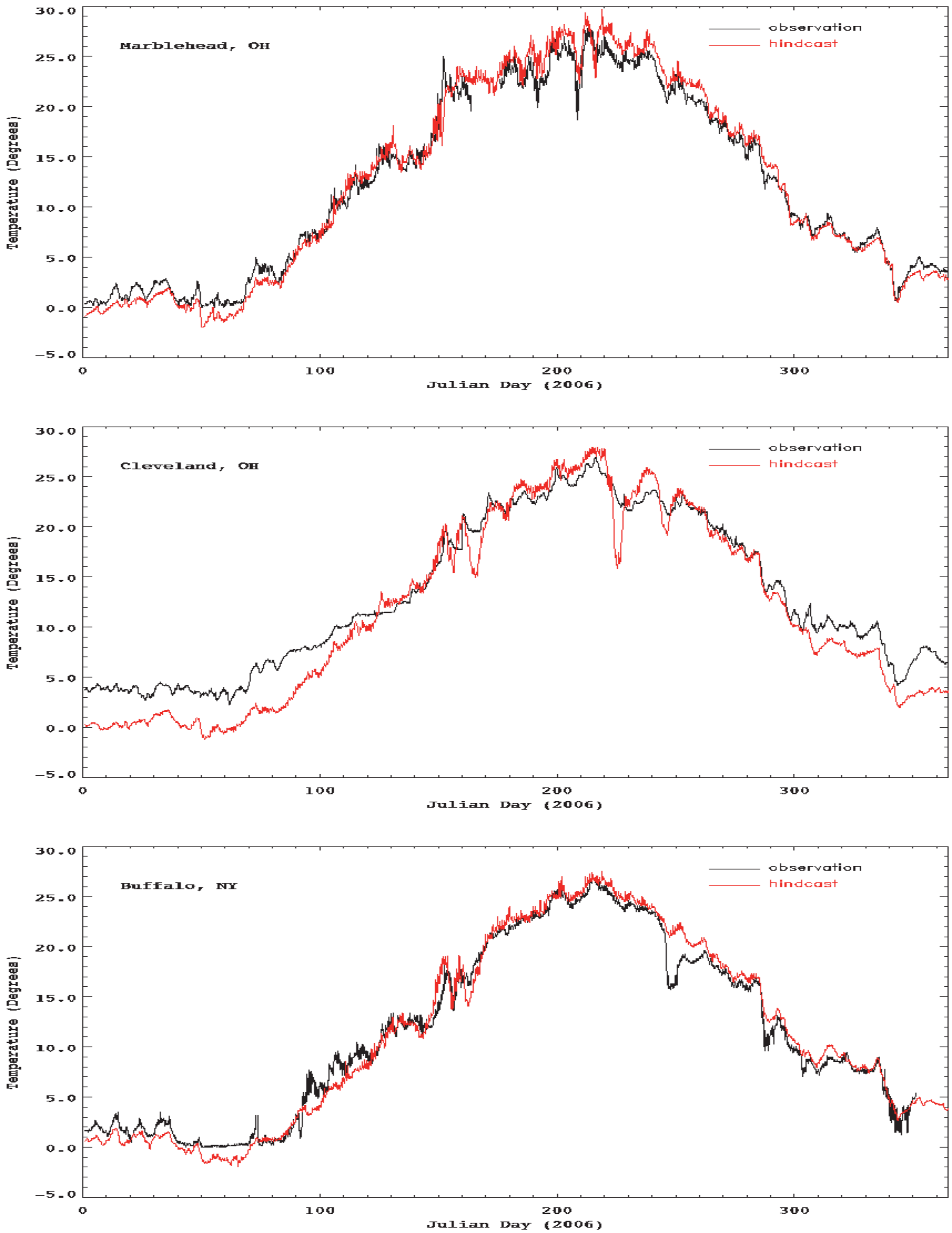


Figure 24. Time series plots of hourly hindcasts of surface water temperatures vs. observations at NOS NWLON gauges at Marblehead, Ohio, Cleveland, Ohio, and Buffalo, N.Y. during 2006.

Table 22. Summary of skill assessment statistics of the hourly hindcasts of subsurface water temperatures at the Thermistor String T05 in the western basin of Lake Erie during 2005. Gray shading indicates that the statistic did not pass the NOS acceptance criteria.

Time Period, Statistic, Acceptable Error [ ], and Units ( )	Depths (meters)		NOS Acceptance Criteria
	-4.0	-11.0	
Time Period	6/1-10/31/05	6/1-10/31/05	na
Number of Hours	3663	3663	365
Mean Alg. Error (ºC)	0.990	0.220	na
RMSE (ºC)	1.302	1.417	na
SD (ºC)	0.845	1.400	na
NOF [2x3ºC] (%)	0.0	0.3	≤ 1%
CF [3ºC] (%)	98.8	95.5	≥ 90%
POF [2x3ºC] (%)	0.0	0.0	≤ 1%
MDNO [2x3ºC] (hr)	0.0	11.0	≤ 24 hrs
MDPO [2x3ºC] (hr)	0.0	0.0	≤ 24 hrs

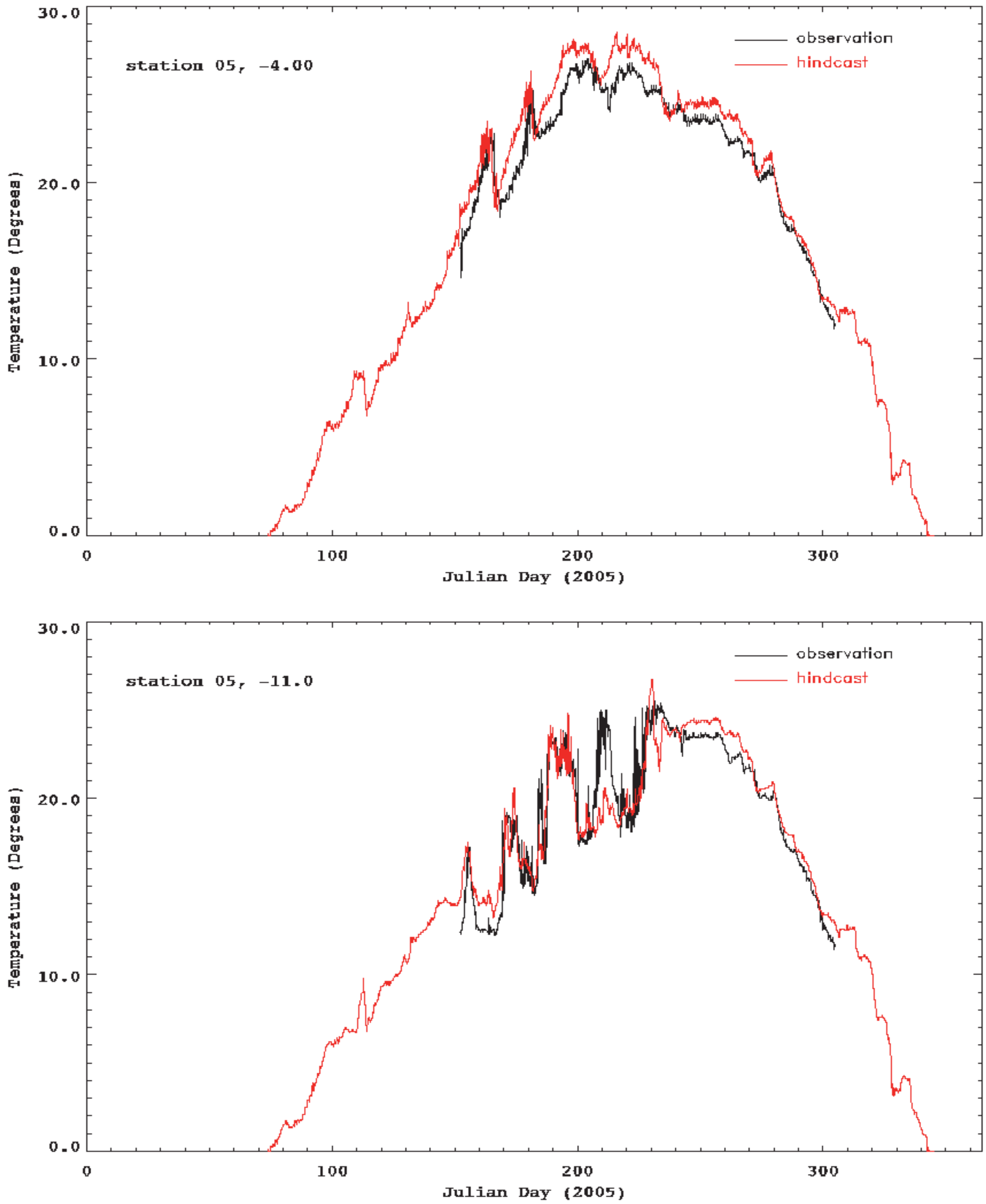


Figure 25. Time series plots of hourly hindcasts vs. observations at 4 and 11.9 m depths during 2005 at the Thermistor Station T05 Located in the Western Basin of Lake Erie.

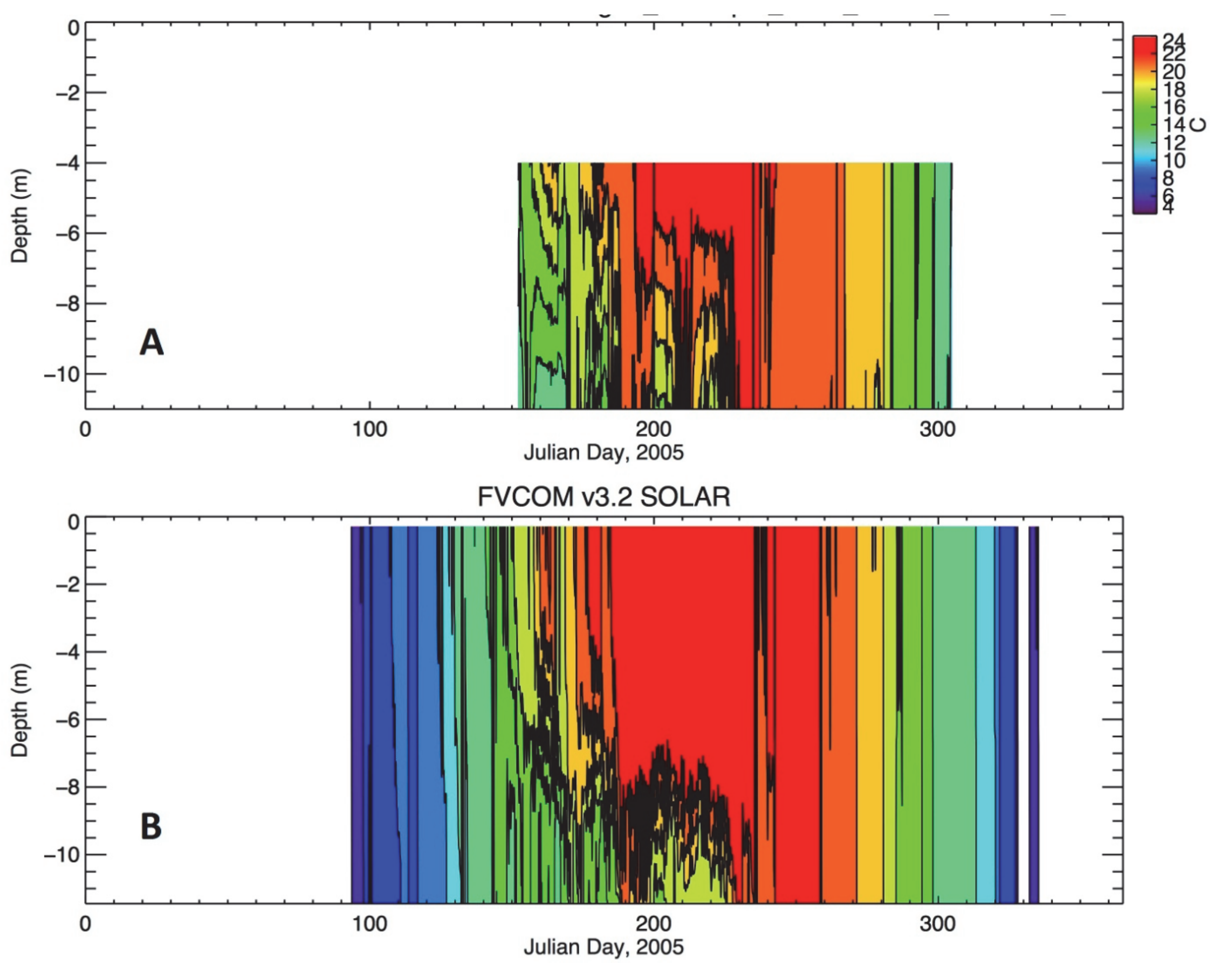


Figure 26. Hindcasts of water temperature (b) vs. observations (a) from 4 to 11 m depth at Thermistor Station T05 in the Eastern Basin from early May to late October 2005.

Station T07 – Central Basin

Time series plots of the hindcasts vs. observations at 1, 5, 11, 15, 20.5, and 23.5 m depths at Station T07 are given in Fig. 27. Plots of the hindcasts and observations vs. depth and time are given in Fig. 28. The skill statistics at all 15 available depths are given in Table 23. The hindcasts closely matched observations throughout the year at all depths except at the depths from 13 to 18.5 m, with the worst agreement at 13 and 15 m. The hindcasts met the NOS Acceptance Criteria at 1, 21.5, 22.5, and 23.5 m depths and came very close at 3, 5, 7, and 9 m.

A detailed assessment of the hindcasts at 1, 5, 11, 15, and 20.5 m depths at T07 station is given next. At 1 and 5 m depths at T07, the hindcasts were warmer than observations by 1-2ºC from Day 130 (May 10) until about Day 250 (Sept. 7). After that date the hindcasts and observations were within 1 degree C. For the entire period, the MAEs were about 1.3ºC and RMSEs were around 1.8ºC.

At 11 m depth, the hindcasts were warmer from Day 130 (May 10) until Day 165 (Jun 14) and then they were colder than observations until Day 215 (Aug. 3). After Day 215, the hindcasts closely matched the observations through Day 304 (Oct. 31) when the thermistors were removed from the lake. However, during this period, the hindcasts failed to simulate a sudden 5 degree C drop in temperature at Day 215 (Aug. 3) and simulated a significant but brief 9ºC drop in temperature around Day 260 (Sep. 17), which was not seen in the observations.

At the 15 m depth, the hindcasts were significantly colder than observations from Day 170 (Jun. 19) until Day 215 (Aug. 3). The hindcasts failed to simulate large fluctuations ranging from 5 to 20ºC, which lasted from 1 to 5 days. After Day 215, hindcasts switched back and forth from between being warmer or colder than observations until Day 240 (Aug. 28). From that date until Day 275 (Oct. 2), the hindcasts were over 10ºC colder. After Day 275, the hindcasts closely matched the observations.

At the 20.5 m depth, the hindcasts were 1-1.5ºC colder than observations from Day 135 (May 15) to Day 215 (Aug. 3) and then slightly warmer until Day 270 (Sept. 27). The hindcasts successfully simulated the sudden 8ºC rise in temperature at Day 270, although it was about 2.5ºC colder than the observed maximum. However, the hindcasts simulated a sudden drop around Day 285 (Oct. 11) that was not observed. At 23.5 m, comparisons between the hindcasts and observations were similar to those at 20.5 m.

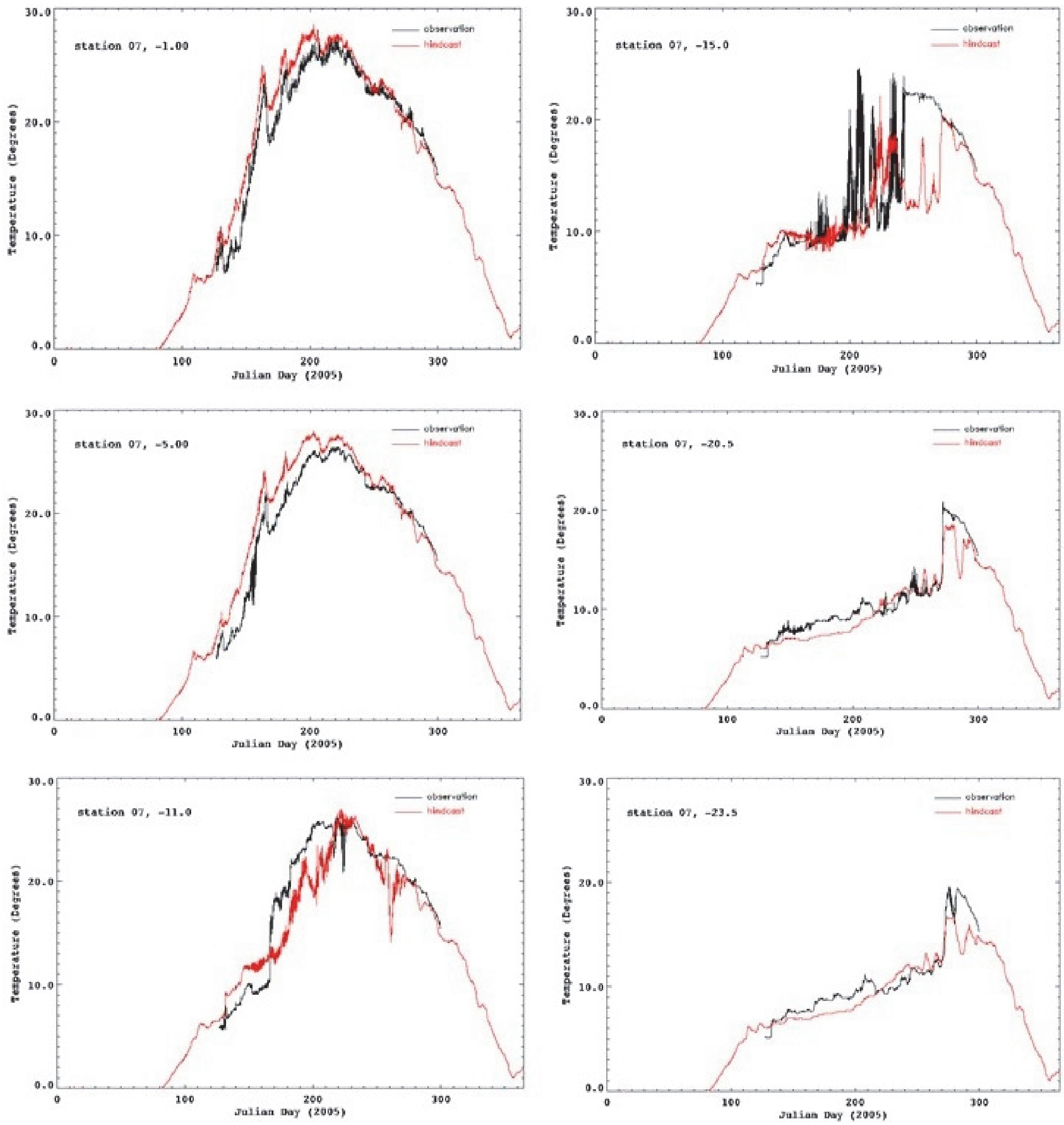


Figure 27. Time series plots of hourly hindcasts of water temperature vs. observations at six depths of the Thermistor String T07 located in the central basin of Lake Erie during 2005.

Table 23. Summary of skill assessment statistics of the hourly hindcasts of subsurface water temperatures at the Thermistor String T07 in the central basin of Lake Erie during 2005. Gray shading indicates that the statistic did not pass the NOS acceptance criteria.

Time Period, Statistic, Acceptable Error [], and Units ()	Depths (m)							
	-1.0	-3.0	-5.0	-7.0	-9.0	-11.0	-13.0	-15.0
Time Period	5/6-10/26	5/6-10/26	5/6-10/26	5/6-10/26	5/6-10/26	5/6-10/26	5/6-10/26	5/6-10/26
Number of Hours	4151	4151	4151	4151	4151	4151	4151	4151
Mean Alg. Error (ºC)	1.155	1.282	1.438	1.385	0.194	-0.953	-2.998	-1.567
RMSE (ºC)	1.754	1.880	2.063	2.102	1.786	2.737	5.148	4.536
SD (ºC)	1.320	1.376	1.478	1.581	1.776	2.565	4.185	4.257
NOF [2x3ºC] (%)	0.0	0.0	0.0	0.0	0.0	2.9	27.4	19.4
CF [3ºC] (%)	93.0	88.8	84.9	85.9	87.9	75.8	51.2	68.4
POF [2x3ºC] (%)	0.0	0.0	0.1	1.8	0.0	0.0	1.4	1.7
MDNO [2x3ºC] (hr)	0.0	0.0	0.0	0.0	0.0	40.0	474.0	320.0
MDPO [2x3ºC] (hr)	0.0	0.0	2.0	9.0	0.0	0.0	10.0	11.0

Depths (m)							
-16.5	-17.0	-17.5	-18.5	-20.5	-21.5	-22.5	-23.5
5/6-10/26	5/6-10/26	5/6-10/26	5/6-10/26	5/6-10/26	7/21-10/26	5/6-10/26	8/3-10/26
4151	4151	4151	4151	4151	4058	4151	4014
-1.579	-1.518	-1.654	-1.250	-0.739	-0.744	-0.864	-0.702
3.933	3.908	3.697	2.768	1.488	1.615	1.715	1.605
3.602	3.602	3.307	2.470	1.292	1.434	1.482	1.443
15.3	15.1	15.2	8.2	0.0	0.0	0.0	0.0
80.0	79.3	83.4	87.7	96.0	93.9	91.7	94.5
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
320.0	311.0	312.0	186.0	0.0	0.0	0.0	0.0
1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

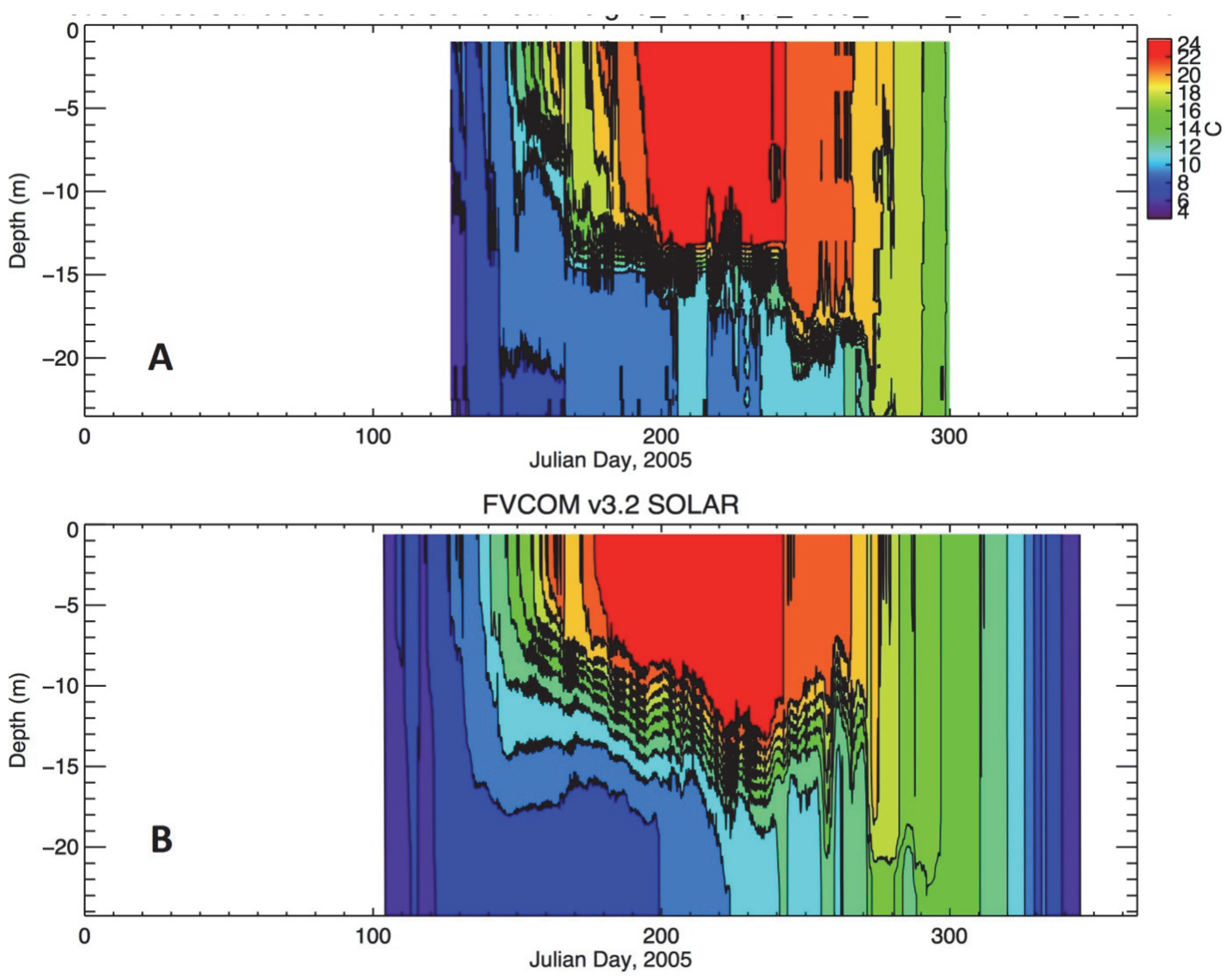


Figure 28. Hindcasts of water temperature (b) vs. observations (a) from 1 to 25 m depth at Thermistor Station T07 in the Central Basin from early May to late October 2005.

Station T12 Eastern Basin

Time series plots of the hindcasts vs. observations at 1, 5, 11, 15, 20.5, and 23.5 m depths at Station T12 are given in Fig. 29. Plots of the hindcasts and observations vs. depth and time are given in Figure 30. The skill statistics at all 15 depths are given in Table 24.

MAEs ranged from 0.8 to 4.2ºC and RMSEs ranged from 1.9 to 5.8ºC. However, the hindcasts did not meet the NOS Acceptance Criteria at these depths but came close to passing the criteria at 1, 3, 5, and 9 m depths. The hindcasts were significantly far from meeting the criteria at the mid depths of 11, 13, 15, 18.5, 19, 28.5, 48.5, and 52.5 m.

A detailed assessment of the hindcasts at difference depths at T12 station is given next. At the shallower depths of 1 – 9 m, the hindcasts closely matched the observations throughout the year but was 1 to 2ºC warmer until Day 280 (Oct. 7). After that date, hindcasts were less than 0.5ºC from observations. For the entire period, MAEs ranged from 0.8 to 1.9ºC and RMSEs 1.9 to 2.5ºC.

At the mid depths of 11, 13, 15, 18.5, and 19 m, the hindcasts simulated the seasonal warmup and cool down. However, the hindcasts failed the majority of the time to simulate the large amplitude and frequency of water temperature fluctuations as well as extended periods of colder or warmer water. The hindcasts matched very closely the observations starting on Day 280 (Oct. 7). MAEs and RMSEs ranged from 1.7 to 4.2ºC and 3.6 to 5.8ºC, respectively.

At the bottom depths of 28.5, 43.5 and 52.5 m, the hindcasts were within 1ºC of the observations until Day 190 (Jul 20). After Day 190, the hindcasts continued to rise steadily while observations remained at approximately 9ºC at 23.5 m, 6ºC at 43.5 m, and 5ºC at 52.5 m until approximately Day 290 (Oct. 17), the day the thermistor strings were removed from the lake. By that date, the observed temperatures had risen at all three depths but the differences between hindcasts and observed varied at the three depths. At 28.5 m, the observed temperature had suddenly risen to 17ºC and matched the hindcasts almost exactly. However, at the 43.5 and 52.5 m depths, the difference between hindcasts and observations was about 6ºC. At the three bottom depths, MAEs ranged from 2.6 to 3.7ºC and RMSEs ranged from 3.7 to 5.0ºC for the entire period.

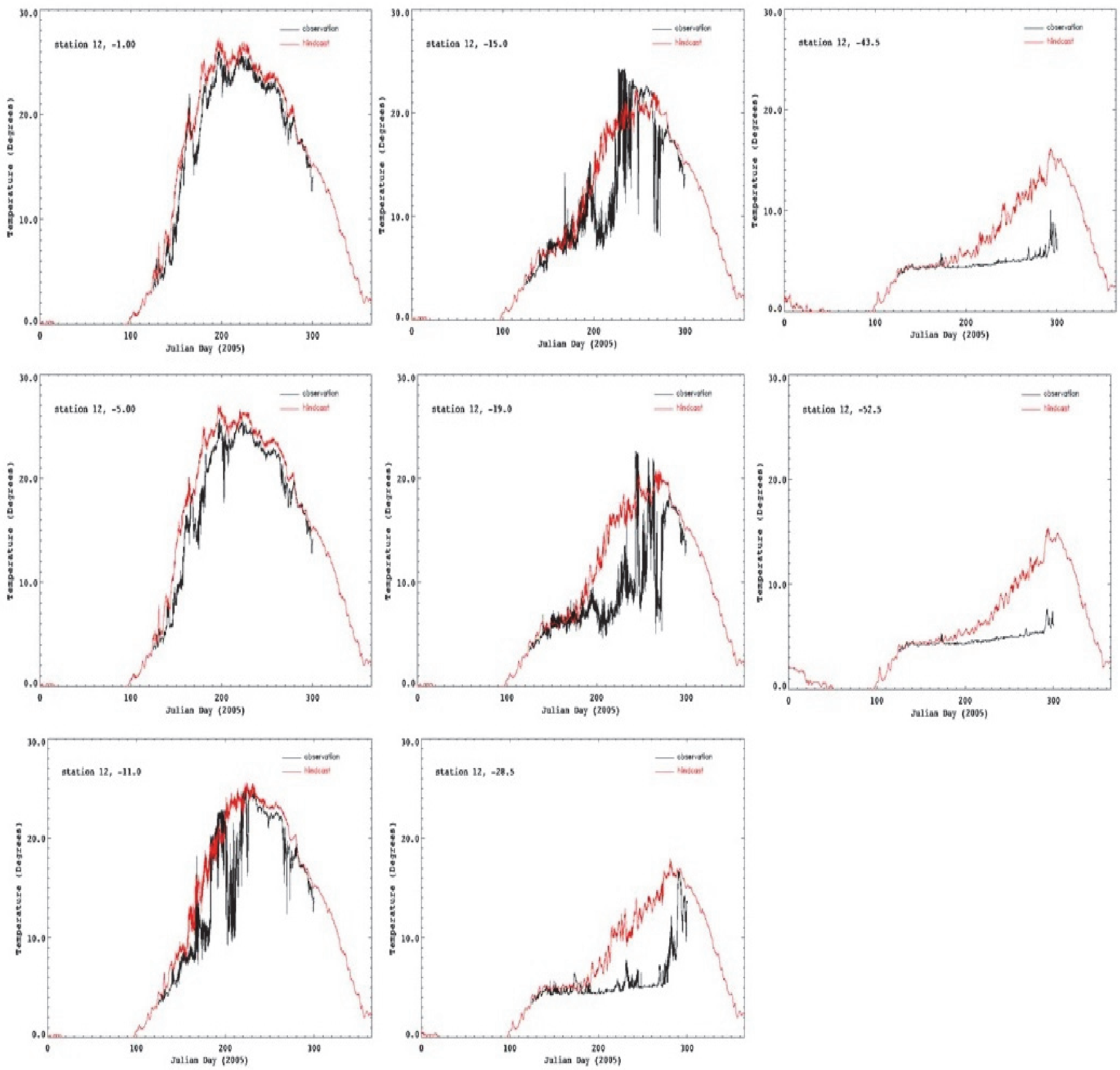


Figure 29. Time series plots of hourly hindcasts of water temperature vs. observations during 2005 at eight depths of the Thermistor Station T12 located in the eastern basin of Lake Erie.

Table 24. Summary of skill assessment statistics of the hourly hindcasts of subsurface water temperatures at the Thermistor String T12 in the eastern basin of Lake Erie during 2005. Gray shading indicates that the statistic did not pass the NOS acceptance criteria.

Time Period, Statistic, Acceptable Error [ ], and Units ( )	Depths (meters)												
	-1.0	-3.0	-5.0	-7.0	-9.0	-11.0	-13.0	-15.0	-18.5	-19.0	-28.5	-43.5	-52.5
Time Period	5/4-10/27	5/4-10/27	5/4-10/27	5/4-10/27	5/4-10/27	5/4-10/27	5/4-10/27	5/4-10/27	5/4-10/27	5/4-10/27	5/4-10/27	5/4-10/27	5/4-10/27
Number of Hours	4212	4212	4212	4212	4212	4212	4212	4212	4212	4212	4212	4212	4212
Mean Alg, Diff. (°C)	1.469	1.608	1.907	1.702	0.829	2.182	1.716	1.584	4.151	3.368	3.689	2.932	2.561
RMSE (°C)	1.901	2.063	2.507	2.342	1.919	3.611	3.585	3.678	5.787	5.077	4.983	4.126	3.667
SD (°C)	1.207	1.293	1.628	1.610	1.731	2.877	3.149	3.319	4.032	3.800	3.351	2.903	2.626
NOF [2x3°C] (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0
CF [3°C] (%)	88.6	85.9	80.8	84.5	88.1	74.7	79.3	75.2	52.6	59.6	51.9	60.1	64.1
POF [2x3°C] (%)	0.0	0.0	3.0	3.0	0.7	11.4	11.3	14.7	35.6	29.0	30.5	22.4	16.4
MDNO [2x3°C] (hr)	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	1.0	3.0	0.0	0.0	0.0
MDPO [2x3°C] (hr)	0.0	0.0	15.0	25.0	8.0	68.0	171.0	276.0	390.0	345.0	807.0	352.0	560.0

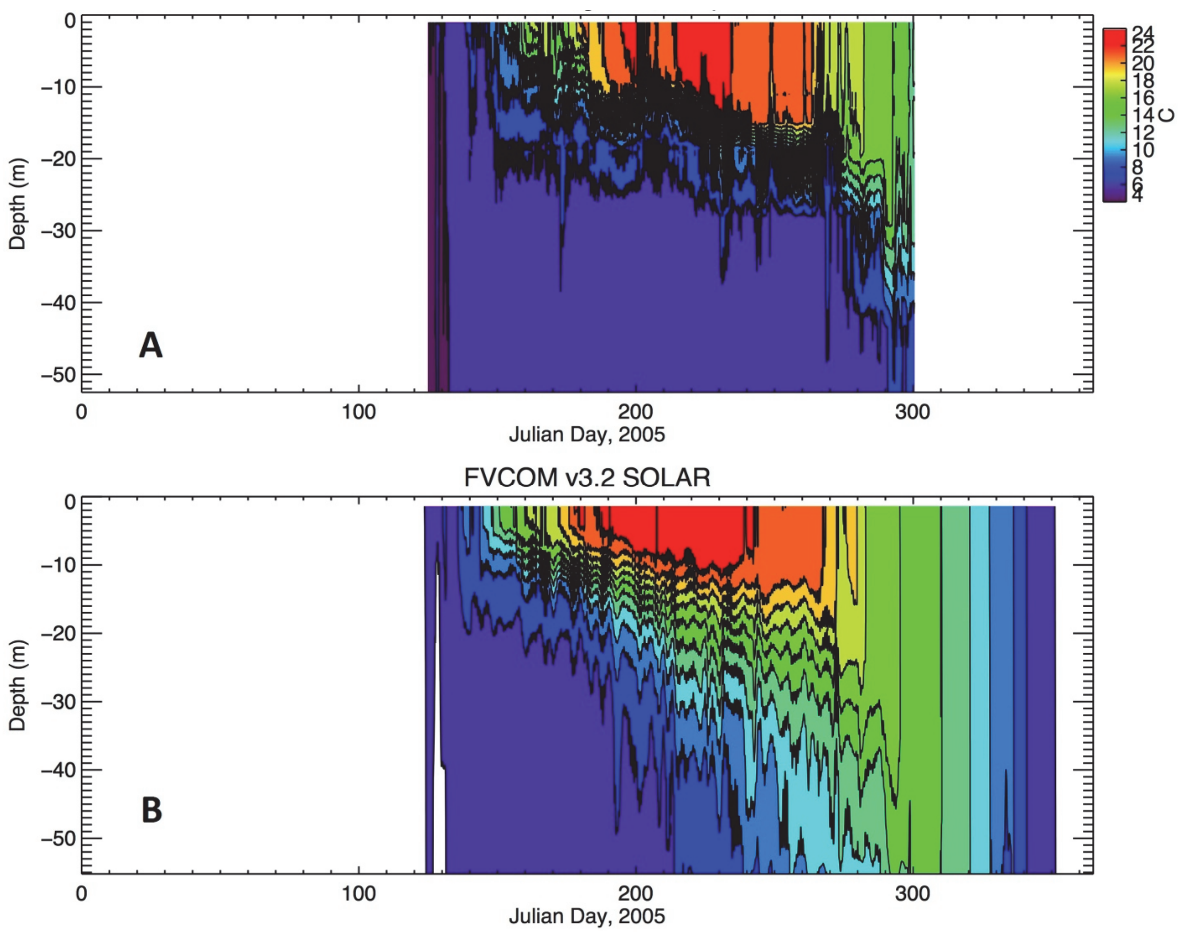


Figure 30. Hindcasts of water temperature (b) vs. observations (a) from 1 to 53 m depth at Thermistor Station T12 in the Eastern Basin from early May to late October 2005.

7. SUMMARY AND DISCUSSION

NOAA/GLERL's water level and water temperature hindcasts from LEOFS-FVCOM for 2005 and 2006 were compared to water level observations at NOS NWLON and Canadian Hydrographic Service gauges. Hindcasts of surface water temperatures were compared to observations from NWS/NDBC and ECCC fixed offshore buoys and coastal NWLON gauges. In addition, the hindcasts of subsurface temperatures were compared to data from three thermistor chains in each basin collected during April to October 2005.

Water Levels

The hindcasts for 2005 and 2006 did well overall in predicting hourly water levels including the reproduction of seiches following strong wind events. The MAEs ranged from -6.9 to 0 cm and RMSE ranged from 6 to 10 cm. The greatest MAE and RMSE in both years were found at Toledo while the smallest values were at the eastern end of the lake at Buffalo, Sturgeon and Port Colborne. The skill assessment of LEOFS-POMGL's nowcasts for 2004 also exhibited the greatest MAEs at Toledo (Kelley, 2007). The hourly hindcasts passed the NOS acceptance criteria at nine of the 12 NOS and CHS gauges and came very close to passing at the other three gauges.

However, the hindcasts did not do well in predicting the amplitude and timing of extreme high or low water level events. The hindcasts *under* predicted the amplitude of extreme high water level events during both years. The MAEs ranged from -18 to -4 cm and RMSEs were between 10 and 28 cm. For extreme low water level events, the hindcasts *over* predicted the amplitude at 11 of the 12 gauges during 2005. MAE ranged from 3 to 13 cm and RMSE ranged from 2 to 16 cm. During 2006, the hindcasts *over* predicted at nine gauges but *under* predicted at three stations. MAEs ranged from -6.5 cm at Toledo to 11 cm at Buffalo. With regards to timing of high water levels, the MAEs ranged from -0.4 to 0.3 hours and the RMSEs were from 0.5 to 1.3 hours and for low water level events, the MAEs ranged from -0.1 to 0.6 hours and the RMSEs were mainly around 1 hour. The hindcasts of high water level events in terms of amplitude and timing only passed the acceptance criteria at one or two gauges depending on the year. For low water level events, the hindcast passed the amplitude acceptance criteria at five gauges in 2005 and four gauges in 2006 but passed the timing acceptance criteria at only one gauge during 2005 and at no gauges in 2005.

The lack of skill of the hindcasts to predict the amplitude and timing of extreme water level events was also seen in the evaluation of LEOFS-POMGL 2004 nowcasts (Chu et al., 2007). The difficulty of hydrodynamic models to predict the amplitude and timing of high and low water level events in Lake Erie has been discussed by Kelley et al. (1998), O'Connor et al. (2010), Beletsky et al. (2013) and others. These studies stressed the importance of accurately representing the surface wind fields in both space and time over the lake for hydrodynamic models. Underestimation of wind speeds over the lake will lead to reduced surface momentum flux and heat fluxes which will in turn affect the simulation of the water level amplitudes, water temperatures, and currents (Beletsky et al., 2013).

Surface Water Temperatures

The surface water temperature hindcasts agreed closely with observations at the three fixed offshore buoys during both 2005 and 2006. The MAEs ranged from 0.1 to 0.9ºC and RMSE ranged from 1.1 to 1.4ºC. These MAE and RMSE values are similar to results of the skill assessment of LEOFS-POMGL (5 km horizontal resolution, 11 vertical layers) 2004 nowcasts. However, a significant improvement was that the hindcasts did not exhibit the unrealistic high frequency and high amplitude water temperature fluctuations exhibited by the 2004 nowcasts (Chu et al., 2007) and the present operational nowcasts and forecast guidance. The hindcasts passed the NOS Acceptance Criteria at all three buoys in both years.

Although the hindcasts performed well and passed acceptance criteria, there are some notable seasonal differences in the skill. The hindcasts differed the most from observations at the three buoys from approximately early summer to early autumn 2005. During this period, the hindcasts were 1 to 1.5ºC warmer than observations. The 2006 hindcasts at the central basin buoy (45132) also showed a warm bias during these same months which was not seen at the buoys in the eastern and western basins that year. This may be related to the ability of the interpolated meteorological analyses over the central basin to accurately represent the spatial structure of the meteorological fields (e.g. cloud cover, winds) due to their dependence on land-based stations and buoys close to the shoreline. A similar conclusion was made by Beletsky et al. (2013) that observations-based wind fields may not always be suitable for central basin hydrodynamic modeling in summer when attempting to simulate the structure of the thermocline and circulation pattern. An examination of hindcasts vs. observations for additional years would be necessary to confirm it.

The water temperature hindcasts at the three coastal stations Marblehead, Cleveland, and Buffalo agreed closely with observations during 2005 and 2006. The MAEs ranged from 0.1 to -1.5ºC and the RMSE ranged between 1.2 to 2.5ºC. The hindcasts met all NOS Acceptance Criteria at Buffalo and Marblehead for both years and did not meet all the criteria in Cleveland in either year. The poor performance at Cleveland may be related to the CO-OPS station in Cleveland being located in a marina sheltered by a large peninsula, a manmade wave breaker which itself is behind an extensive wave breaker, in shallow water (~5 ft), and near three concrete public boat ramps. During the cold months (e.g. mid-Oct to late April), the observed temperatures at Cleveland were warmer than the hindcast by as much as 3ºC.

An examination of the observations at the three coastal stations indicate a significant temperature disturbance with a sudden drop of approximately 6 to 11ºC within 2 to 5 days during the stratified summer months, first appearing at Marblehead on Day 208 (July 28), at Cleveland on Day 225 (August 13), and then at Buffalo on Day 245 (Sept. 2). The apparent counter-clockwise time progression of the temperature disturbance would suggest the movement of an internal Kelvin wave (a stratified response). Internal Kelvin waves propagate counter-clockwise along the shore of the Great Lakes (Boyce et al., 1989). The hindcasts during this period also show a similar temperature disturbance at these stations but about one half the amplitude present in the observations.

Sub-Surface Water Temperatures

The sub-surface water temperature hindcasts for 2005 agreed closely with observations in the top part of the water column (above 11 m depth) in the three basins. The MAEs in this part of the water column ranged from -1 to 2.2ºC and RMSEs ranged between 1.3 to 3.6ºC. The hindcasts did very well in simulating several large water temperature fluctuations in the upper water column that occurred in all three basins.

However, the hindcast did not do as well in the mid-layers of the central and eastern basins (~ 12 to 20 m). The MAEs ranged from -3.0 to 4.2ºC and RMSEs from 2.8 to 5.7ºC. Although the hindcasts simulated the time evolution of thermocline very well when compared to observations, it was more diffuse and extended too deep, especially in the eastern basin. In addition, the hindcasts frequently could not simulate several large temperature fluctuations seen in the observations (e.g. 14ºC change in five days) in both the central and eastern basins.

The hindcasts also did poorly in the deep parts of the eastern basin (~ 22 to 53 m). The hindcasts deviated significantly from observations starting in mid-June 2005 and by early-October was over 7ºC warmer than the observed temperature. This reflected the fact that the hindcasts simulated a thermocline too diffuse and deep. Following the convective overturning in fall, the hindcasts more closely matched observations. The MAEs ranged from -0.7 to 3.7ºC and RMSEs from 1.6 to 5ºC.

The difficulty of the hindcasts to simulate the thermocline in Lake Erie is not surprising given the results of previous modeling-based studies. Beletsky et al. (2013) states that Lake Erie is a difficult lake to model because its thermocline is one of the sharpest of all the Great Lakes and thermal structure is very sensitive to wind vorticity. He found that the maximum model errors occurred in the thermocline at and below 15 m, similar to what was found in this skill assessment. He attributes his model's poor performance in simulating temperatures in the mid layers to the following: 1) a diffuse model thermocline possibly due to numerical diffusion, penetrative short-wave radiation specification, and unresolved internal waves, and 2) large vertical displacement errors of the thermocline due to improperly simulated Ekman pumping caused by inaccuracies in the analyzed wind field (Beletsky et al., 2013).

LEOFS-FVCOM code package was delivered to NOS/CO-OPS for setting up real-time semi-operational nowcast/forecast runs on NOAA's WCOSS in FY2014 Q4. Changes were made in the specification of the lateral boundary conditions and in the choice of surface meteorological forcing. The system was run in semi-operational nowcast/forecast mode starting in April 2015. The system was delivered to NCO for parallel testing on WCOSS in December 2015. NCO's 30-day evaluation period was conducted from March 10 to April 9, 2016. LEOFS-FVCOM became operational on WCOSS on April 26, 2016.

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APPENDIX A. Information about NOS/CO-OPS water temperature observing stations in Lake Erie.

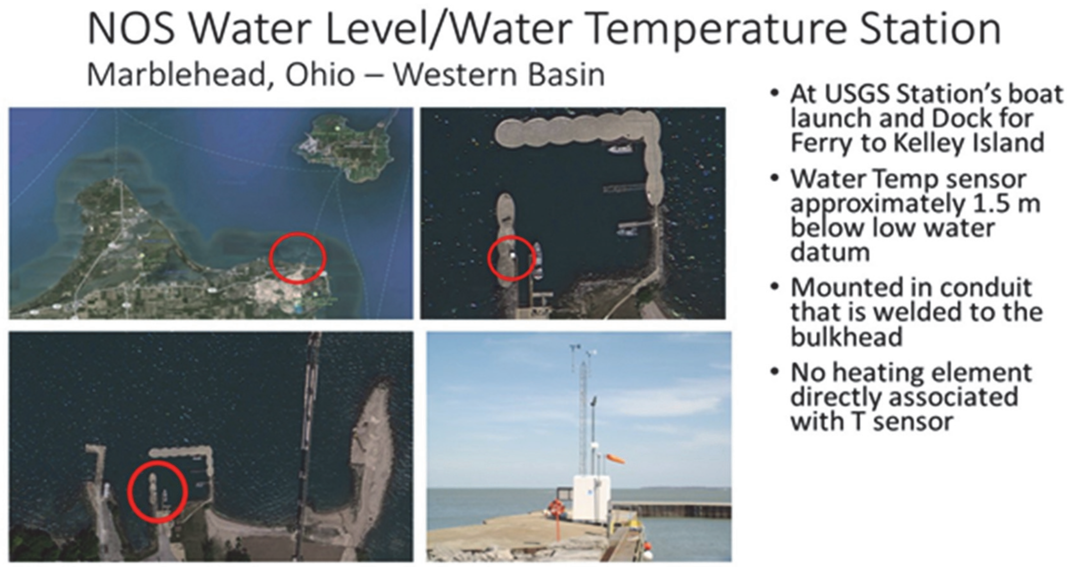


Figure A-1. Satellite imagery depicting location of NOS/NWLON station in Marblehead, Ohio. The red circle indicates the location of the station. Also shown is a photo of the station.

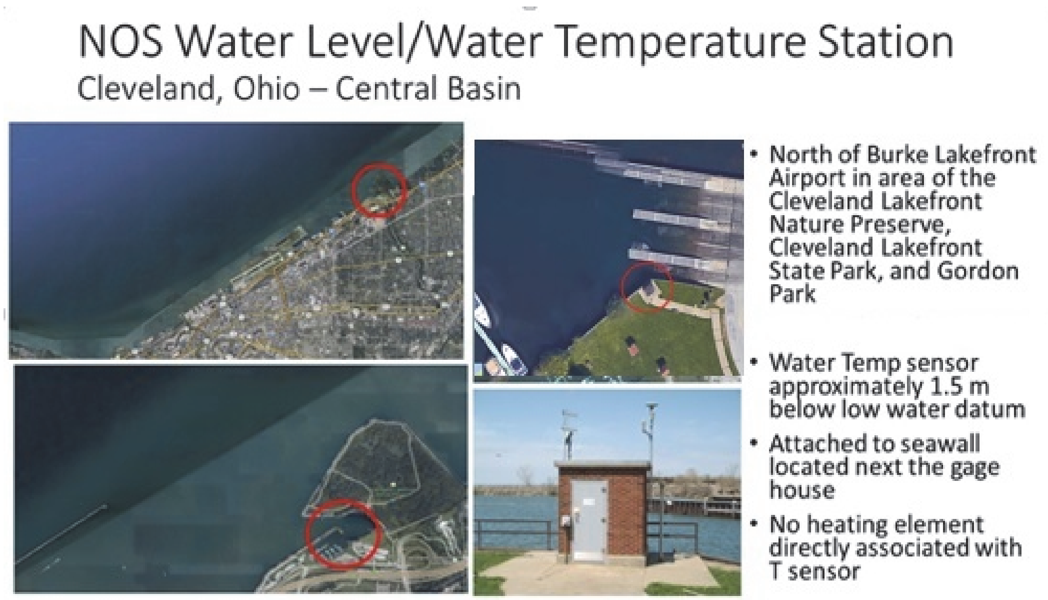


Figure A-2. Satellite imagery depicting location of NOS/NWLON station in Cleveland, Ohio. The red circle indicates the location of the station. Also shown is a photo of the station.

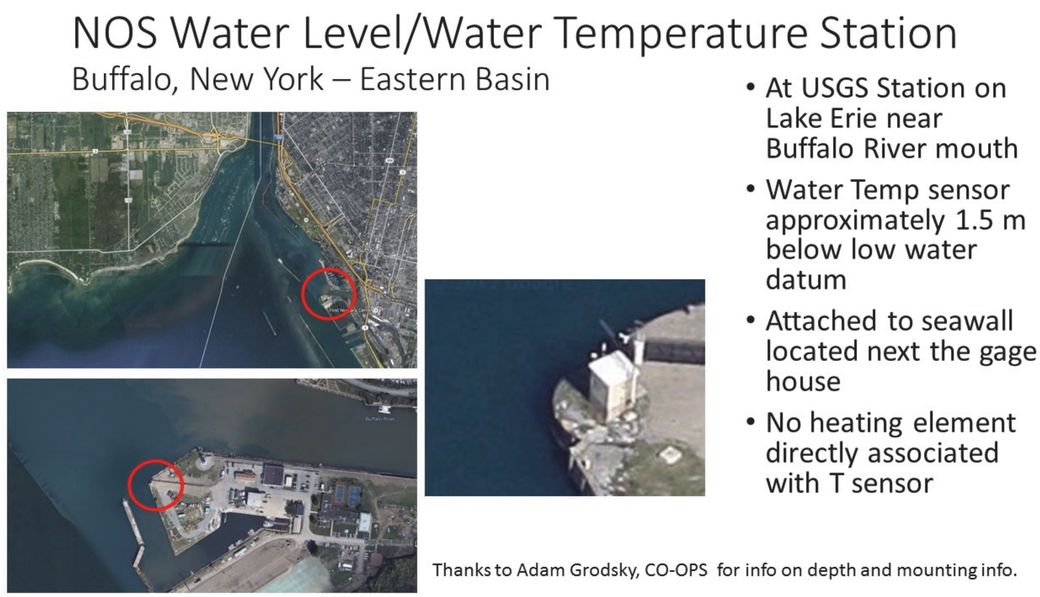
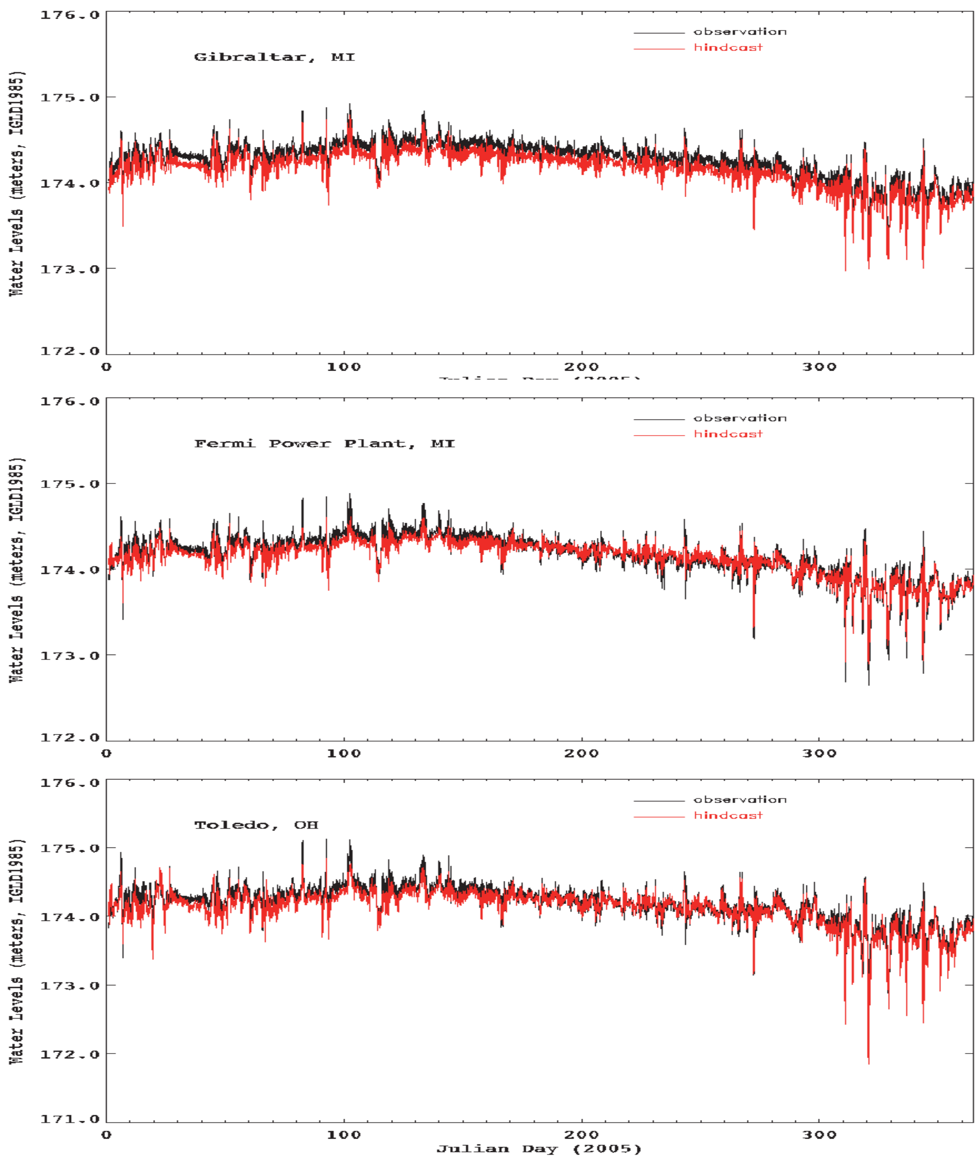
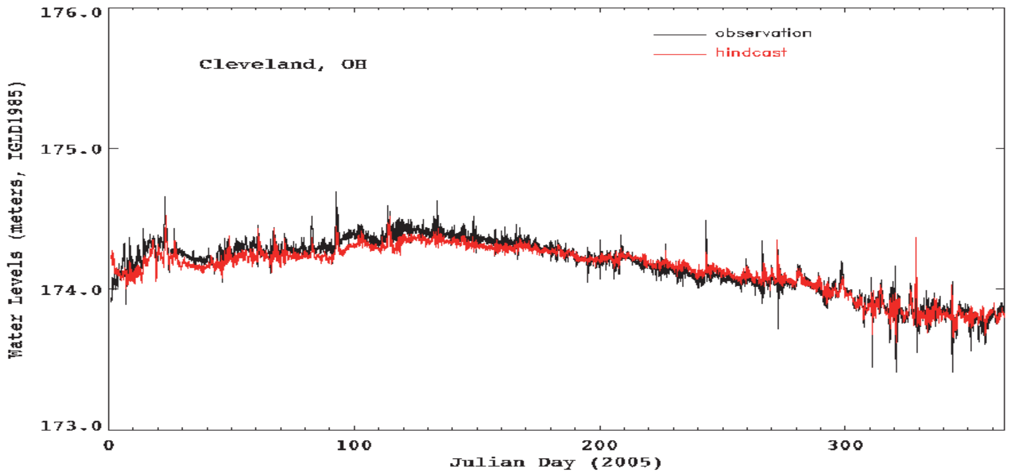


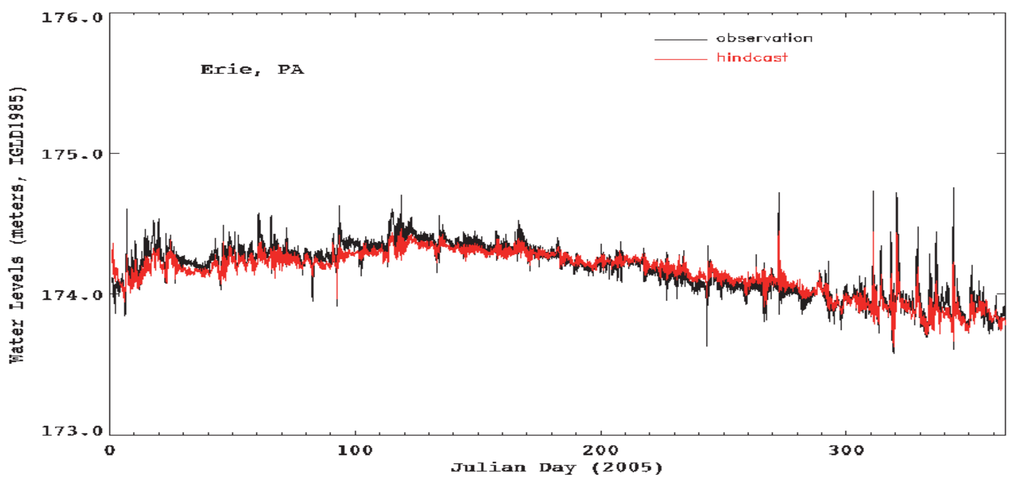
Figure A-3. Satellite imagery depicting location of NOS/NWLON station in Buffalo, New York. The red circle indicates the location of the station. Also shown is a photo of the station.

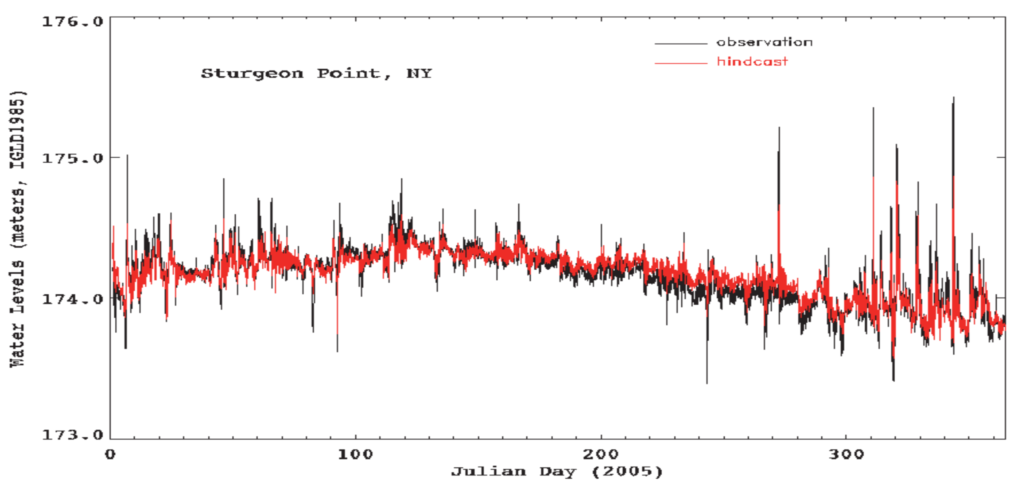
APPENDIX B. Time series plots of hourly hindcasts of water levels vs. observations at water levels gauges for 2005.

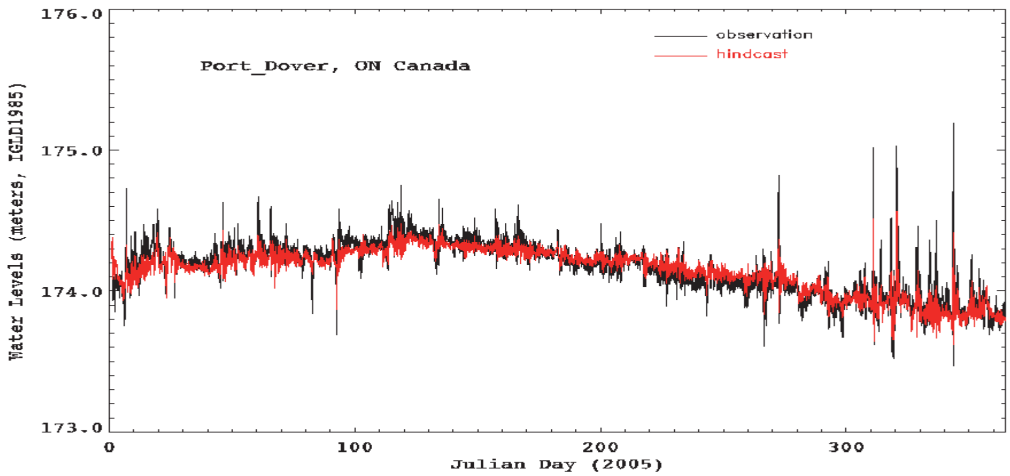


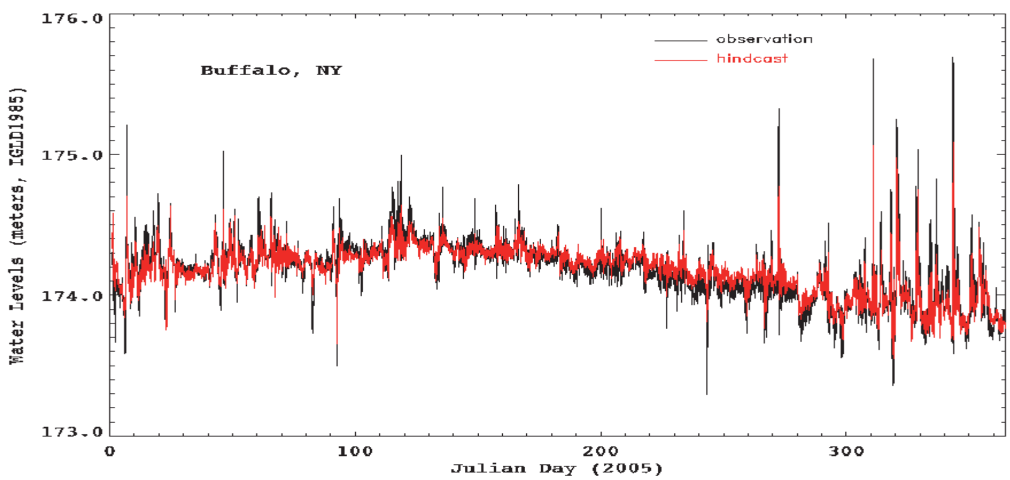
Observational data were not available at Marblehead during 2005.

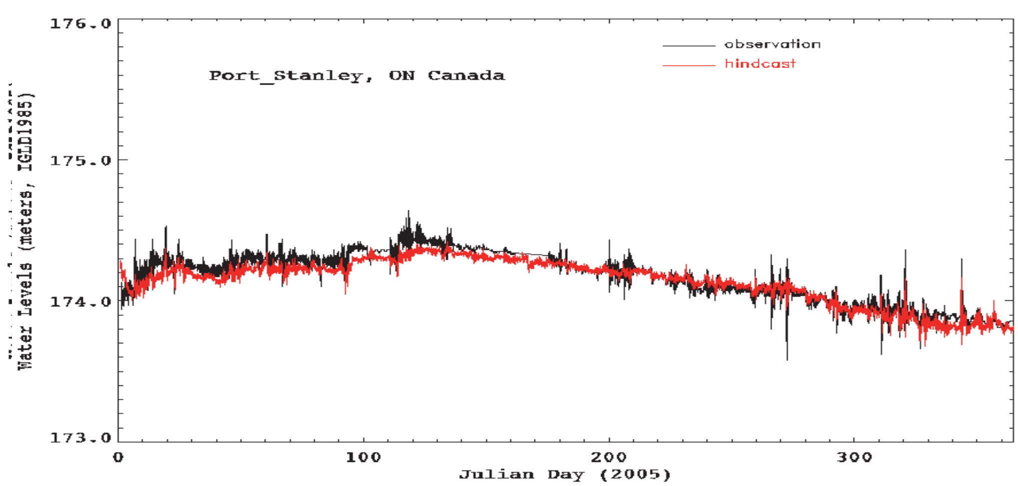

observation
hindcast
Cleveland, OH
Water Levels (meters, IGLD1985)
176.0
175.0
174.0
173.0
0
100
200
300
Julian Day (2005)


observation
hindcast
Erie, PA
Water Levels (meters, IGLD1985)
176.0
175.0
174.0
173.0
0
100
200
300
Julian Day (2005)


observation
hindcast
Sturgeon Point, NY
Water Levels (meters, IGLD1985)
176.0
175.0
174.0
173.0
0
100
200
300
Julian Day (2005)


176.0
175.0
174.0
173.0
Water Levels (meters, IGLD1985)
Port_Dover, ON Canada
observation
hindcast
0
100
200
300
Julian Day (2005)


176.0
175.0
174.0
173.0
Water Levels (meters, IGLD1985)
Buffalo, NY
observation
hindcast
0
100
200
300
Julian Day (2005)


176.0
175.0
174.0
173.0
Water Levels (meters, IGLD1985)
Port_Stanley, ON Canada
observation
hindcast
0
100
200
300
Julian Day (2005)

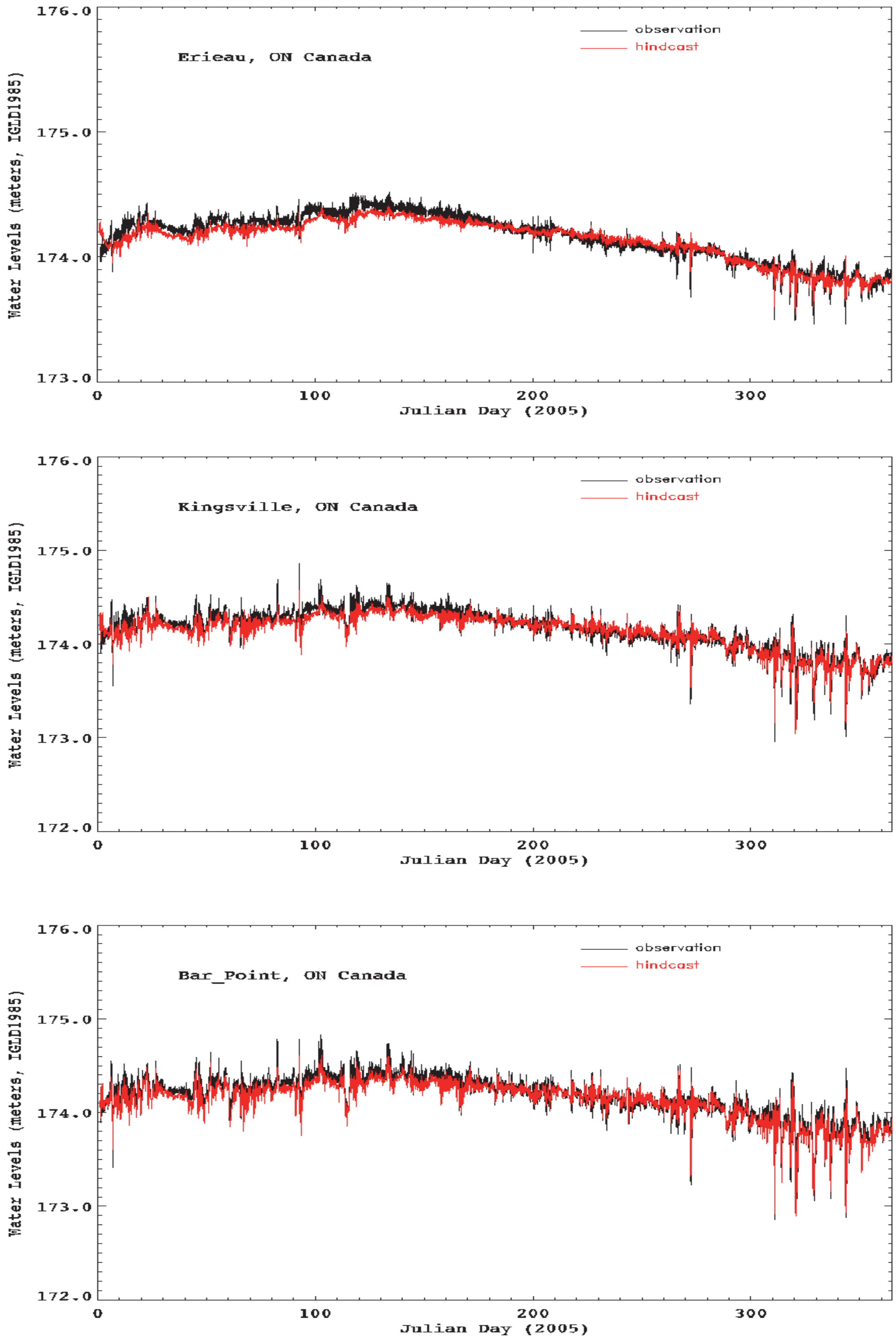
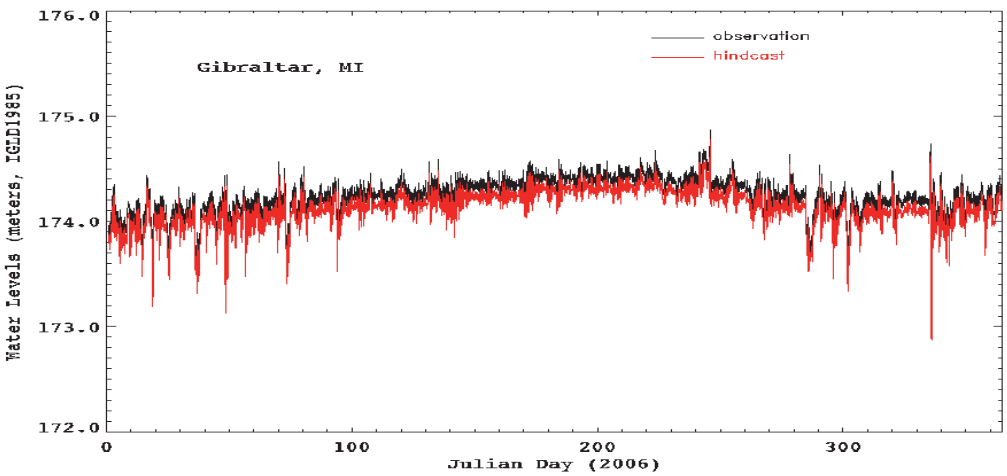
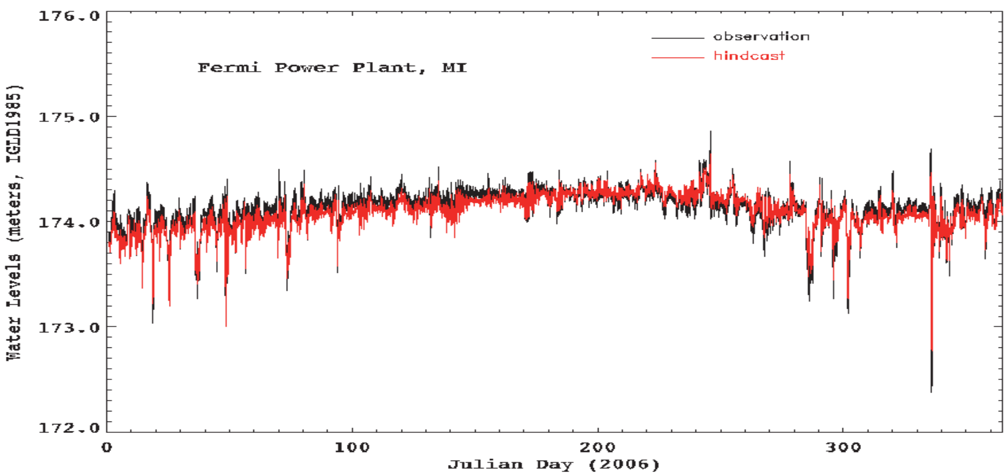
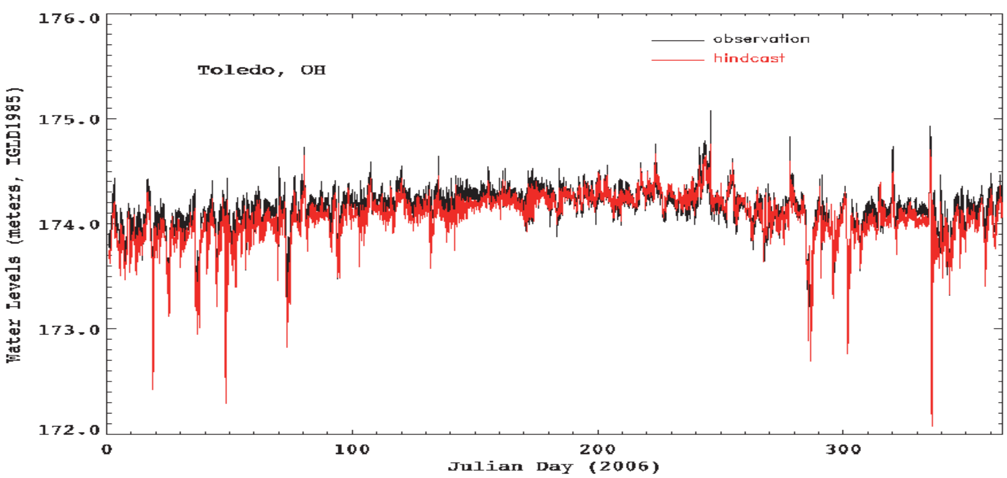


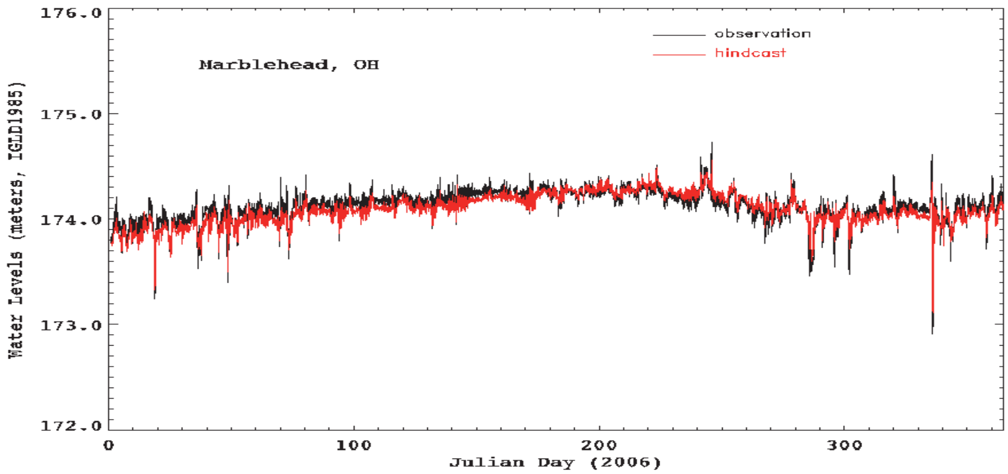
Figure B-1. Time series plots of hourly hindcasts of water levels vs. observations at NOS and CHC water levels gauges in Lake Erie for 2005.

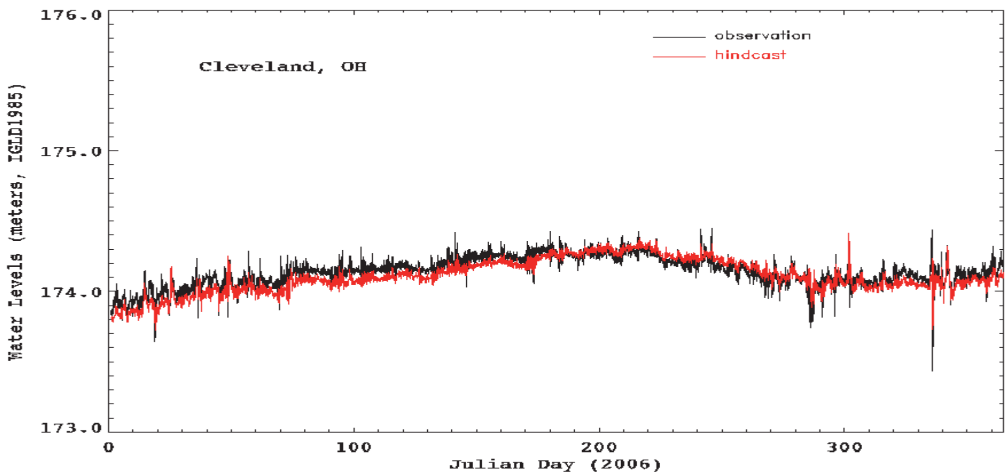
APPENDIX C. Time plots of hourly hindcasts of water levels vs. observations at water level gauges for 2006.

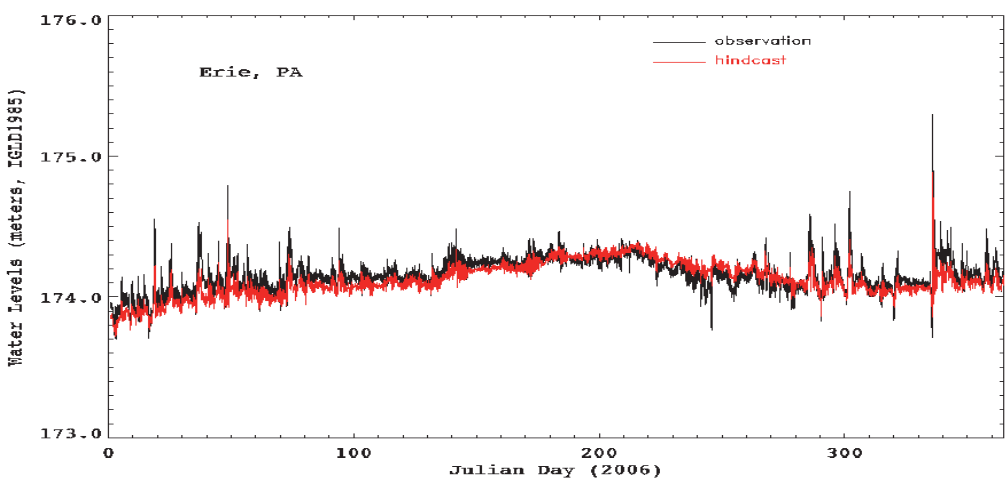


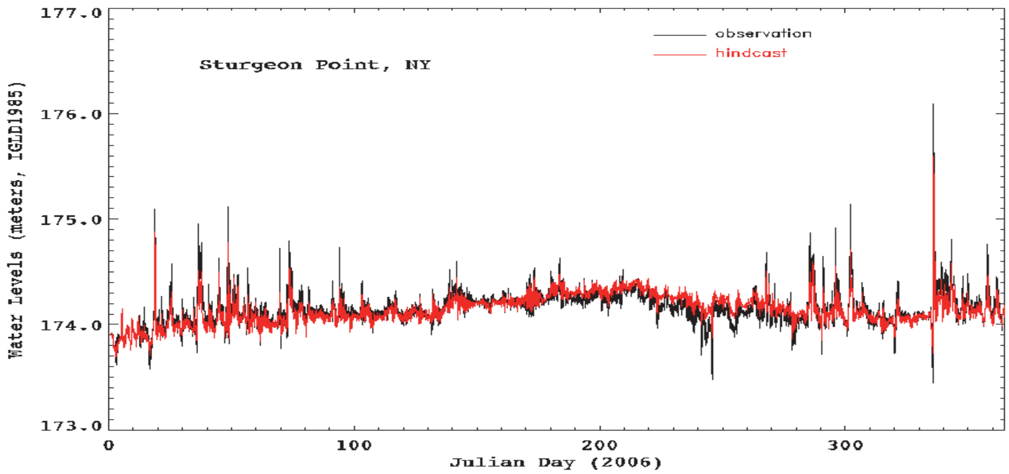


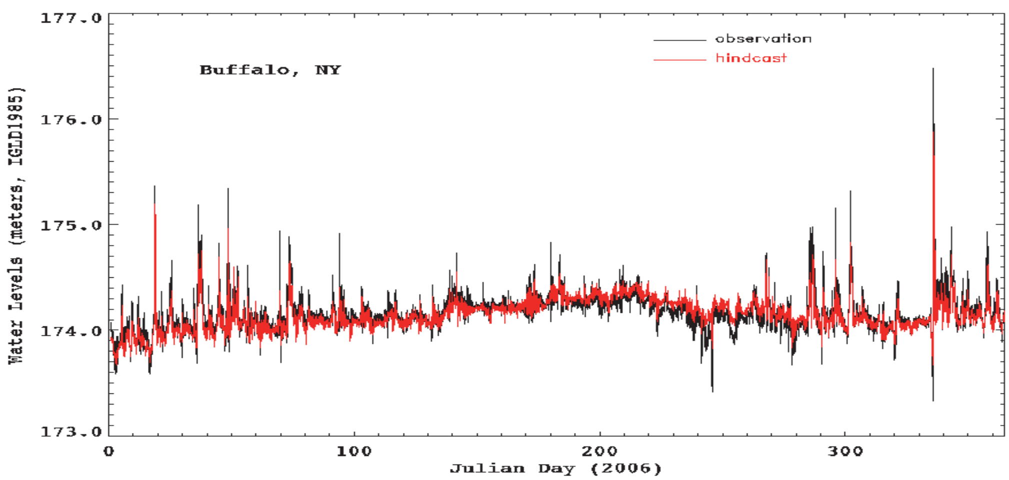



176.0
175.0
174.0
173.0
172.0
Water Levels (meters, IGLD1985)
Marblehead, OH
observation
hindcast
0
100
200
300
Julian Day (2006)

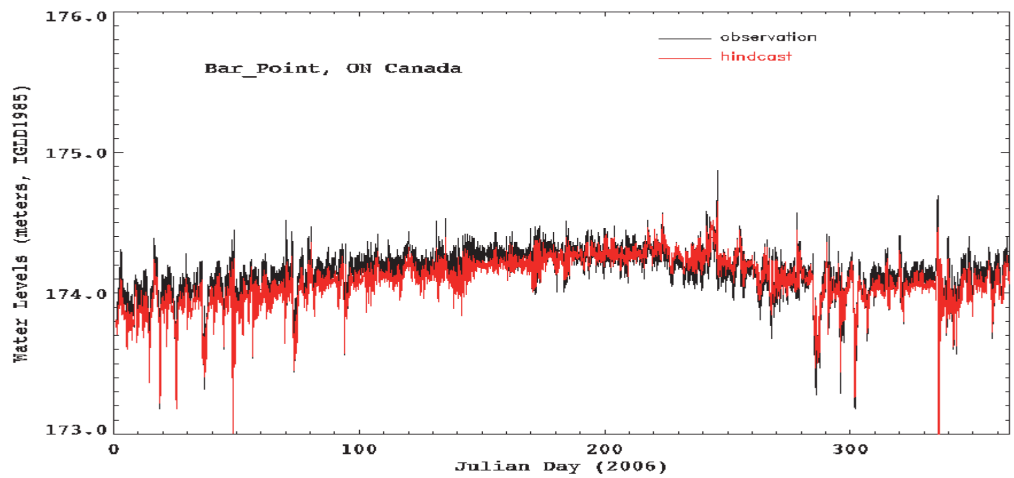

176.0
175.0
174.0
173.0
Water Levels (meters, IGLD1985)
Cleveland, OH
observation
hindcast
0
100
200
300
Julian Day (2006)


176.0
175.0
174.0
173.0
Water Levels (meters, IGLD1985)
Erie, PA
observation
hindcast
0
100
200
300
Julian Day (2006)





Observational data were not available from Port Colborne gauge during 2006.



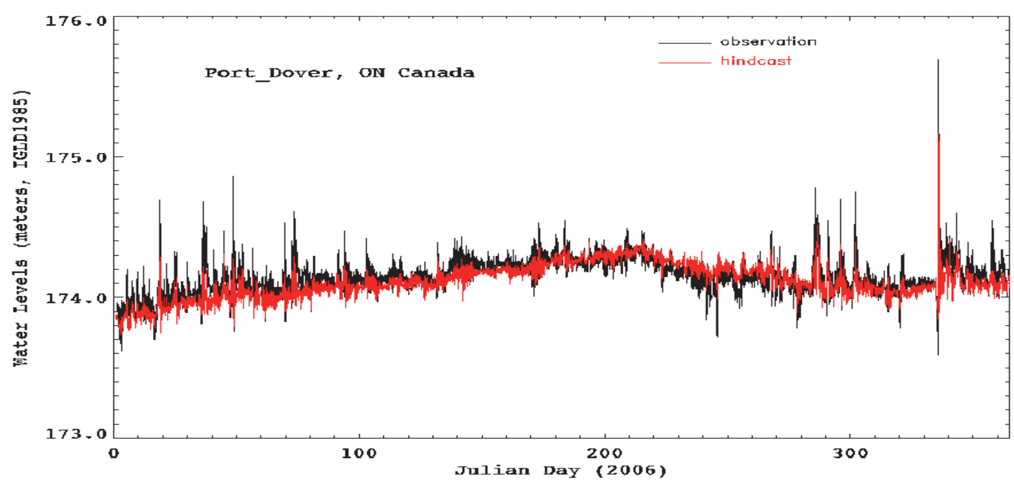


Figure C-1. Time series plots of hourly hindcasts of water levels vs. observations at NOS and CHC water levels gauges in Lake Erie for 2006.