NOAA Technical Memorandum NOS CS 12

SKILL ASSESSMENT OF NOS LAKE ERIE OPERATIONAL FORECAST SYSTEM (LEOFS)

Silver Spring, Maryland
June 2007

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
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ASOS	Automated Surface Observing System
AVHRR	Advanced Very High Resolution Radiometer
AWOS	Automated Weather Observing System
BUFR	Binary Universal Form for the Representation of Meteorological Data
C-MAN	Coastal-Marine Automated Network
CCIW	Canada Centre for Inland Waters
CCS	NCEP Central Computer System
CO-OPS	Center for Operational Oceanographic Products and Services
CORMS	Continuously Operating Real-Time Monitoring System
CSDL	Coast Survey Development Laboratory
DOD	Department of Defense
EPA	Environmental Protection Agency
ETA	Eta Mesoscale Numerical Weather Prediction Model
GLCFS	Great Lakes Coastal Forecast System
GLERL	Great Lakes Environmental Research Laboratory
GLFS	Great Lakes Forecasting System
GLOFS	Great Lakes Operational Forecast System
GLSEA	Great Lakes Surface Environmental Analysis
GRIB	GRIdded Binary
LEOFS	Lake Erie Operational Forecast System
LMOFS	Lake Michigan Operational Forecast System
MMAP	Marine Modeling and Analysis Programs
NAM	North America Mesoscale Model
NCEP	National Centers for Environmental Prediction
NCOP	National Coastal Ocean Program
NDBC	National Data Buoy Center
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
NWLON	National Water Level Observation Network
NWS	National Weather Service
ODAAS	Operational Data Acquisition and Archive System
OSU	The Ohio State University
POMGL	Princeton Ocean Model – Great Lakes version
USCG	United States Coast Guard
VOS	Voluntary Observing Ship

EXECUTIVE SUMMARY

This document describes the Lake Erie Operational Forecast System (LEOFS) and an assessment of its skill. The lake forecast system, based on a hydrodynamic model, uses near real-time atmospheric observations and numerical weather prediction forecast guidance to produce three-dimensional forecast guidance of water temperature and currents and two-dimensional forecasts of water levels.

LEOFS is the result of technology transfer of the Great Lake Forecasting System (GLFS) and the Great Lakes Coastal Forecasting System (GLCFS) from The Ohio State University (OSU) and NOAA's Great Lakes Environmental Research Laboratory (GLERL) to NOAA's National Ocean Service.

The skill assessment of LEOFS followed the scenarios specified by Hess et al. (2003) for use with non-tidal water bodies. These scenarios included 1) the hindcast, 2) the semi-operational nowcast, and 3) the semi-operational forecast. The hindcast is a long simulation using the best available observed meteorological observations and verification data. The semi-operational nowcast and forecast are simulations made in a real-time environment where there are occasional periods of missing inputs (i.e. meteorological observations and/or forecast guidance from atmospheric forecast models).

For the hindcast scenario, the dissertation results of Kuan (1995b) were used to satisfy NOS requirements (Hess et al. 2003). Kuan performed a skill assessment of the Princeton Ocean Model for Lake Erie from May to October 1979. Kuan compared model simulations to surface observations from NOS water level gauges and surface and sub-surface data from specially deployed buoys, current meters and thermistor strings. The primary statistics used to assess the model performance for water levels and surface water temperatures were Root Mean Square Error (RMSE), Index of Agreement (IOA), and a Skill Score. The RMSE is a statistic parameter required by Hess et al. (2003) for evaluating predicted water levels in non-tidal regions. The other NOS required statistics include Mean Algebraic Error (MAE), Series Mean (SM), Standard Deviation (SD), Central Frequency (CF), Negative Outlier Frequency (NOF), Positive Outlier Frequency (POS), Maximum Duration of Positive Outlier (MDPO), and Maximum Duration of Negative Outlier (MDNO) were not available from Kuan's dissertation.

For the semi-operational nowcast and forecast scenarios, evaluation of GLERL's Great Lakes Coastal Forecast System (GLCFS) for Lake Erie was used to satisfy NOS requirements (Hess et al. 2003). The GLCFS was run in near real-time, 4 times/day for nowcast and 2 times/day for the forecast cycles. Although, Hess et al. (2003) recommends conducting evaluations for 365 days in order to capture all expected seasonal conditions, GLCFS nowcasts and forecasts were evaluated for the period from for mid-April to early-December 2004 during the ice-free season. Due to lack of regularly monitored currents and sub-surface water temperatures, only water levels and surface water temperatures nowcasts at a few sites could be evaluated for Lake Erie.

The primary statistics used to assess the model performance for water levels and surface water temperatures are those required by NOS for evaluating predicted water levels in non-tidal regions. These included Series Means (SM), Mean Algebraic Difference (MAE), Root Mean Square Error (RMSE), Standard Deviation (SD), negative outlier frequency (NOF), positive outlier frequency (POF), maximum duration of positive outlier (MDPO), and maximum duration of negative outlier (MDNO).

The skill statistics for the *hindcast scenario* are summarized below by variable:

1) Water Levels:

The simulated water surface elevation matched well in both phase and magnitude with the corresponding observed data by picking up almost every single significant spike appearing in the observed water level elevations. The average RMSE was quite small indicating that the model can be considered quite good in simulating water surface elevation of the lake. The average IOA and amplitude Skill Score also support this observation, obtaining high values of 0.95 and 9.72, respectively.

2) Water Currents:

For the current velocity simulation, except the nearshore zone and the very unsteady flow region, the velocity predictions over transect C-C' were quite satisfactory. Good simulations both in phase and magnitude were found at most of the current meter locations.

3) Water Temperatures:

Surface:

As for lake surface temperature, the model predictions compared exceptionally well with the observed data at all six Canada Centre for Inland Waters (CCIW) meteorological buoy locations. Computed values not only pick up almost every single spike found in the observed data, but the average RMSE was as low as 1^{o}C over the entire test period of 150 days.

10m Depth:

The model also demonstrated good skill as predicting water temperatures in the deeper portion of the lake. When the lake was well mixed, the model predictions were as good as those for the lake surface. However, when lake was thermally stratified, the simulations under predicted the water temperature above the thermocline region and over predicted the water temperature in the hypolimnion.

The skill statistics for the *semi-operational nowcast and forecast scenarios* are summarized below by variable and type of prediction (e.g.nowcast or forecast guidance):

(1) Water Levels:

Nowcasts:

The hourly nowcasts passed NOS criteria for NOF, CF, POF, MDPO, and MDNO at all eight NOS gauge locations. The mean algebraic errors ranged between -2.9 and +3.4 cm and the RMSE ranged between 4 and 8 cm. The greatest errors were at Toledo, OH, Buffalo, NY, and Fairport, OH. The nowcasts under predicted the water levels at Toledo and over predicted them at Buffalo.   Toledo and Buffalo, located at the extreme SW and NE ends of the lake, respectively, experience the greatest hourly water level variability and are the most difficult locations to predict.   It is not clear why the MAE and RMSE were large at Fairport while differences at gage locations to the north and south were only ~0.8 cm.

The ability of the nowcasts to predict extreme high and low water level events was also assessed using a proposed addition to the evaluation procedure of the NOS standards. The nowcasts' amplitude predictions of high water level events passed the NOS acceptance criteria for NOF, CF, POF, MDNO, and MDPO at only Cleveland and Marblehead. The nowcasts simulations of extreme low water level passed NOS acceptance criteria for amplitude at Erie and Fairport and were close to passing at Toledo and Marblehead. The nowcasts predictions of the timing of the high and low water level events did not pass the NOS acceptance criteria at any gauge.

Forecast Guidance:

The hourly forecasts passed the criteria at 7 of the 8 NOS gauges, failed only at Toledo. The mean algebraic errors or differences ranged between -3 and +4.4 cm and the RMSE ranged between 4.1 cm at Cleveland and 10.7 cm at Toledo.   Similar to the nowcasts, the greatest errors were at Buffalo and Toledo, located at the extreme ends of the lake. The forecasts under-predicted the water levels at Toledo and over-predicted the levels at Buffalo. There was some increase in the RMSE values as forecast projection increased.

The forecasts of extreme high water level passed the NOS acceptance criteria for amplitude only at Cleveland and Marblehead, OH. The forecasts of extreme low water level passed NOS acceptance criteria for amplitude at Erie, Fairport, and Cleveland. The forecast guidance ability to predict the timing of these events did not pass NOS acceptance criteria for at any gauge.

(2) Surface Water Temperature:

Nowcasts:

The hourly water temperature nowcasts at the NWS/NDBC fixed buoy located at the boundary between the western and central basins passed the NOS acceptance criteria. The MAE was ~1^{o}C and the RMSE was 1.3^{o}C. The time series plot of nowcasts vs. observations at the buoy indicated some seasonally differences in model skill. The nowcasts were in close agreement to observations (+0.5 to +1^{o}C) from mid- April until early May, but then began to deviate from the observations by +1 to +2^{o}C until late May. After that the nowcasts differed from observations by +0.5^{o}C till mid August. The nowcasts then deviated by +1 to +2^{o}C until early October. During the remaining days of autumn through the end of the period in mid December, the nowcasts generally differed from observations by +0.5^{o}C.

Forecast Guidance:

The hourly water temperature forecast guidance at 24 hours at the NWS/NDBC fixed buoy passed the NOS acceptance criteria. The MAE was +0.7^{o}C and RMSE was 1.3^{o}C. The MAE was 0.3^{o}C less for the forecast guidance than for the nowcasts. The RMSE at 24 hours was about the same as for the nowcasts. The MAE decreased with increasing forecast projection: 1.1^{o}C at 0 hour to 0.7^{o}C at 24 hours. This indicates that the lake model is cooling with time during the forecast cycle and implies that there is an excess of surface heat flux into the lake during the nowcast cycle.

1. INTRODUCTION

The Great Lakes Forecasting System (GLFS) was developed by The Ohio State University (OSU) and NOAA's Great Lakes Environmental Research Laboratory (GLERL) starting in the late 1980s to provide nowcasts and short-range forecasts of the physical conditions (temperature, currents, water level, and waves) of the five Great Lakes. The development of GLFS was directed by Drs. Keith Bedford (OSU) and David Schwab (GLERL) and involved over a dozen OSU graduate students, research assistants and post doctoral researchers at GLERL and OSU, and other OSU faculty members. The development of GLFS was funded by 36 contracts from 25 different sources. From the beginning, GLERL and OSU were interested in working cooperatively with NOAA (i.e. NWS) in “assessing the potential benefits [of GLFS] to NOAA’s scientific and operational programs in the coastal ocean”. In April 1991, Drs. Bedford and Schwab met with National Weather Service (NWS) and National Coastal Ocean Program (NCOP) representatives in Silver Spring, MD to discuss how they could work with NOAA line offices to have GLFS products carefully evaluated through a demonstration program prior to NWS adopting the products as ‘guidance tools’, and which products might be distributed directly to end users.

GLFS used the Princeton Ocean Model (Blumberg and Mellor 1987; Mellor 1996) and GLERL-Donelan wave model (Schwab et al. 1984). The first 3-D nowcast for the Great Lakes was made for Lake Erie in 1992 at the Ohio Supercomputer Center on the OSU Columbus campus (Yen et al. 1994; Schwab and Bedford 1994). Starting in July 1995, twice per day forecasts were made for Lake Erie (Schwab and Bedford 1996). GLFS was recognized with an award in 2001 by the American Meteorological Society as the first U.S. coastal forecasting system to make routine real-time predictions of currents, temperatures, and key trace constituents.

In 1996, GLFS was ported to a GLERL workstation in Ann Arbor, MI. The workstation version of GLFS called the Great Lakes Coastal Forecast System (GLCFS) has been running for Lake Erie in semi-operational mode at GLERL since February 1997 (Schwab et al. 1999). GLCFS for Lake Erie generates nowcasts 4 times/day and forecast guidance out to 60 hours twice per day. The predictions are displayed on the GLERL web page (http://www.glerl.noaa.gov/res/glcfs/) and digital output is made available in GRIB format to NWS Weather Forecast Offices in the region. GLCFS nowcasts and forecasts are archived at GLERL.

In 2004, the hydrodynamic model code of GLCFS for all five Great Lakes was ported to NOS Center for Operational Oceanographic Products and Services (CO-OPS) in Silver Spring, MD. GLCFS was reconfigured to run in the NOS Coastal Ocean Modeling Framework (COMF) and to use surface meteorological observations from NOS Operational Data Acquisition and Archive System (ODAAS). GLCFS for Lake Erie was renamed the Lake Erie Operational Forecast System (LEOFS). LEOFS began making routine operational nowcasts and forecasts at CO-OPS for Lake Erie on September 30, 2005.

LEOFS along with the operational nowcast/forecast system represents the first NOS forecast systems to be implemented for non-tidal water bodies. The predictions from LEOFS like those from NOS estuarine forecast systems must be evaluated to inform users about the skill of the nowcasts and forecast guidance. In evaluating LEOFS, NOS sought to take advantage of previous evaluations done by researchers at OSU and GLERL to fulfill the hindcast scenario requirements described in Hess et al. (2003). In addition, NOS also utilized the nowcasts and forecasts routinely produced by GLERL to fulfill the semi-operational nowcasts and forecast scenarios required by Hess et al. (2003).

This report describes the model performance based on NOS requirements for operational nowcast/forecast systems (Hess et al. 2003). An overview of Lake Erie and LEOFS are 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 an average depth of 19 m (62ft) with a maximum depth of 64 m (210 ft) in the eastern basin. Lake Erie, similar to the other Great Lakes, 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). Since the lake is relatively shallow it warms rapidly in the spring and summer and frequently freezes over during the winter.

Lake Erie responds quickly to the passage of weather systems due to its shallowness and southwest to northeast orientation (Fig. 1). 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 SW winds will cause an increase in water level at Buffalo, NY and a drawdown at Toledo, OH. The positive surge will occur approximately 3 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). Additional information about the physical limnology of Lake Erie can be found in Boyce et al. (1989), Dingham and Bedford (1984), Bartish (1987), Mortimer (1987), and Saylor and Miller (1987).

3. SYSTEM OVERVIEW

This section provides a brief description of the numerical hydrodynamic model used by LEOFS. Similar descriptions of the model as it has been applied to Lake Erie have been given by Kuan (1995b), Kelley (1995), Kelley et al. (1998), Hoch (1997), Chu (1998), and O’Connor et al. (1999).

3.1. Description of Model

The core numerical model in LEOFS is the Princeton Ocean Model (POM) developed by Blumberg and Mellor (Mellor 1996). The model is a fully three-dimensional, non-linear primitive equation coastal ocean circulation model, with a second order Mellor-Yamada turbulence closure

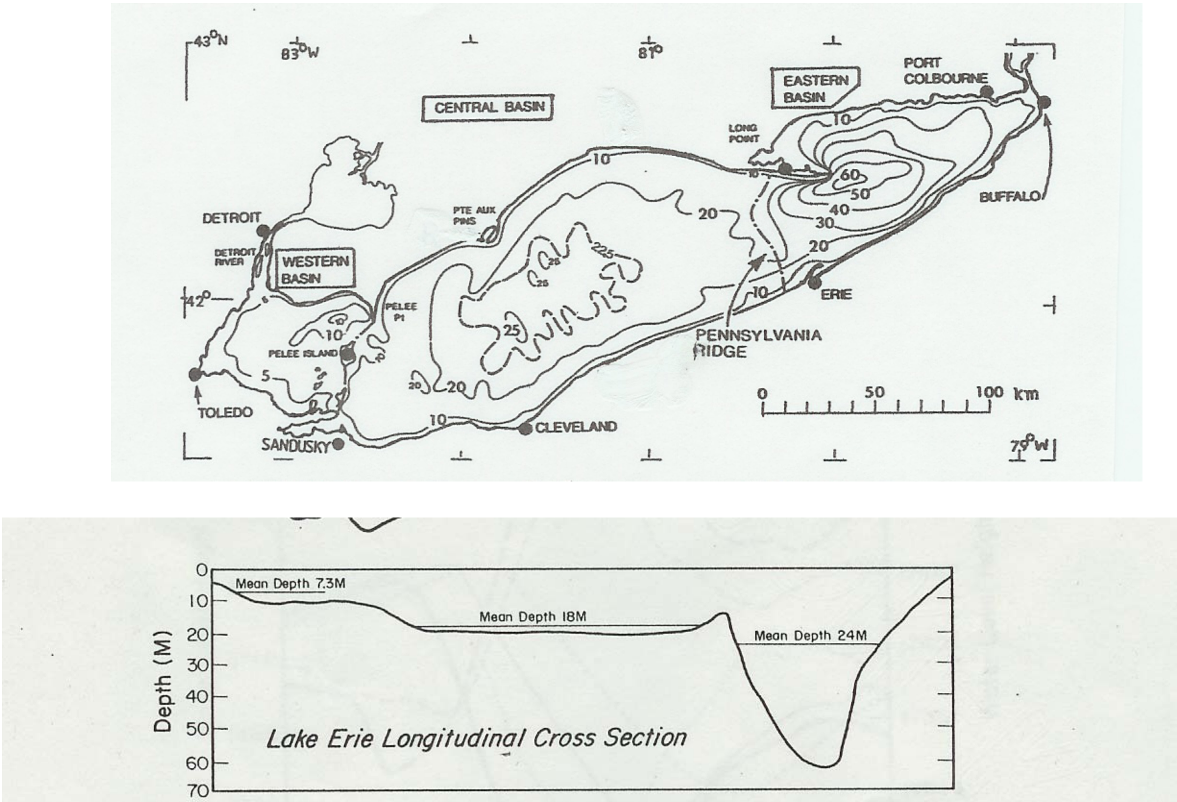


Figure 1. Map depicting Lake Erie bathmetry including longitudinal cross section Modified from Mortimer (1987) and Dingman and Bedford (1984).

scheme to provide parameterization of vertical mixing processes. The model solves continuity momentum and conservation equations for temperature simultaneously in an iterative fashion and the resulting predictive variables are free upper surface elevation, full three-dimensional velocity and temperature fields, Turbulence Kinetic Energy (TKE) and turbulence macroscale. Other main features of the model include: terrain following coordinate in the vertical (sigma coordinate), finite difference numerical scheme, Boussinesq and hydrostatic approximation, and mode splitting technique.

POM was modified by researchers at OSU and GLERL for use in the Great Lakes (Bedford and Schwab 1991, O'Connor and Schwab 1993). For the rest of this report, the modified version of the POM for the Great Lakes will be referred to as POMGL. Lake Erie, like the other Great Lakes is treated as an enclosed basin. Therefore, there are no inflow/outflow boundary conditions: no fluid exchange between the lake and its tributaries, between the lake and ground water sources, or between the lake and anthropogenic influences. Thus model simulations do not include seasonal changes in lake wide mean water level due to precipitation and evaporation. To account for these seasonal changes, a mean lake water level is estimated based on observations from NOS gauges for the past 7 days and added to POMGL's predictions of water level displacement (Section 5.2) prior to dissemination. GLERL is presently evaluating the impact of using climatological estimates of river discharges on POMGL predictions.

3.2. Grid Domain

The model domain for Lake Erie consists of a rectangular grid with a 5-km horizontal resolution in both the x- and y-directions (Fig. 2). The domain has 1944 grid points with 81 points in the x-direction and 24 points in the y-direction. The grid domain has been rotated 27.33 degrees counterclockwise so that the x-coordinate is along the longitudinal axis of the lake and the y-axis is across the lake. The bottom topography for the domain is based on GLERL's 2-km digital bathymetry data compiled by Schwab and Sellers (1980) but slightly smoothed to minimize the development of 2 delta x noise. The model bathymetry ranges from 4 m in the extreme western basin to 62 m in the eastern basin. The model uses 11 sigma levels in the vertical: 0, -.05, -.10, -.15, -.25, -.35, -.45, -.55, -.70, -.85, and -1.00.

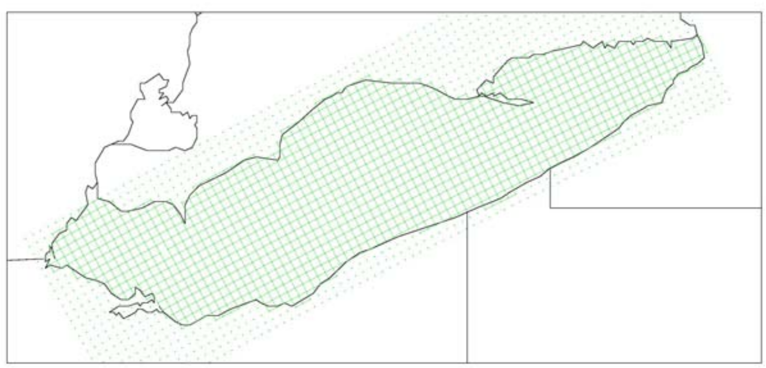


Figure 2. Map depicting the POMGL grid domain with a grid increment of 5 km.

3.3. Data Ingest

The nowcast cycle relies on surface meteorological observations obtained from NOS' Operational Data Acquisition and Archive System (ODAAS). ODAAS acquires meteorological observations from NWS/NCEP/NCO's observational 'data tanks' located on NCEP's Central Computer Systems (CCS) twice per hour at approximately 25 and 48 minutes past the top of the hour. The observations are original in unblocked BUFR format but are reblocked, decoded, and written out to a text file for use by LEOFS and other NOS operational forecast systems. The surface observation text file is available to LEOFS within a minute of receiving the observations from the CCS.

The surface observations are obtained from a variety of observing networks on and around Lake Erie. On land, the networks include Automated Surface Observing System (ASOS), Coastal-Marine Automated Network (C-MAN), and NOS National Water Level Observing Network (NWLON). Presently, the surface meteorological observations from USCG stations around the lake are not available in the NCEP data tanks.

Over water, the networks include the NWS/NDBC's and Environment Canada's fixed buoys as well as observations from ships participating in the Voluntary Observing Ship (VOS) program. However, observations from VOS ships are not presently used by LEOFS at NOS.

3.4. Nowcast Cycle

The nowcast cycle of LEOFS is run hourly at NOS to generate updated nowcasts of the 3-D state of Lake Erie, including 3-D water temperatures and currents. The cycle also generates hourly nowcasts of 2-D water levels.

The initial conditions for the nowcast cycle are provided by the end of the previous hour's nowcast cycle. The nowcast cycle is forced by gridded surface meteorological analyses valid at two times, one hour prior to the time of the nowcast and the current time of the nowcast. The gridded surface meteorological analyses are generated by interpolating surface observations of wind, air temperature, dew point temperature, and cloud cover using the natural neighbor technique (Sambridge et al. 1995). This is accomplished by the program interpnn.f.

Before being interpolated, the surface wind and air temperature observations are adjusted to a common anemometer height of 10 m above the ground or water. Surface observations of wind direction, wind speed, air temperature, and dew point temperature from overland stations are adjusted to be more representative of overwater conditions. Both the height adjustment and adjustment of observations from overland stations uses the previous day's lake average water temperature from GLERL's Great Lakes Surface Environmental Analysis (GLSEA). The GLSEA temperature analysis is generated using SST retrievals derived from the Advanced High Resolution Radiometer data obtained from NOAA's polar-orbiter satellites. The adjustments to the observations along with simple quality control checks are done by the program edit_sfcmarobs.f

The gridded surface wind fields are then used by POMGL to calculate wind stress at each model grid point. The surface meteorological fields along with POMGL lake surface water temperatures predictions from POMGL are used by a heat flux scheme (McCormick and Meadows (1988) to estimate the net rate of heat transfer for the lake at each grid point. The heat flux scheme can be found in POMGL's subroutine FLUX1. Additional information on the wind stress and heat flux schemes can be found in Kelley (1995).

3.5. Forecast Cycle

The forecast cycle of LEOFS is run four times per day to generate forecast guidance of the 3-D state of Lake Erie. The forecast cycle uses the most recent nowcast as its initial conditions. The surface meteorological forcing is provided by the latest forecast guidance of surface (10 m AGL) u- and v-wind components and surface air temperature (2 m AGL) from the 0, 06, 12, or 18 UTC forecast cycles of NWS/NCEP's North American Mesoscale (NAM) model. Presently, NAM has a spatial resolution of 12 km and uses the Eta model as its core. The surface wind velocity forecast guidance from the NAM model is valid at a height of 10 m above the ground or lake surface.

The NAM model forecast guidance is obtained from ODAAS which acquires the NAM output from NCEP's CCS in GRIB format four times per day at 3 hour increments out to 60 hours. ODAAS decodes the GRIB files and then encodes the output into NetCDF files following NOS COMF standards (Gross and Lin 2007).

3.6. Operational Environment and Scheduling

LEOFS is run operational on a Linux workstation at NOS' Center for Operational Oceanographic Products and Services in Silver Spring, MD. Each hourly nowcast cycle is launched at 50 minutes past the top of the hour, three minutes after the surface meteorological observations are received and processed by ODAAS at CO-OPS.

The forecast cycle of LEOFS is run four times per day at 0, 6, 12, and 18 UTC at 50 minutes past the top of the hour. The forecast horizon of each forecast cycle is 30 hours.

LEOFS and the forecast system for Lake Michigan (LMOFS) were officially implemented as an operational forecast system at CO-OPS on the afternoon of September 30, 2005, and the products are available to the general public at http://tidesandcurrents.noaa.gov.

4. HINDCAST SKILL ASSESSMENT

NOS standards (Hess et al. 2003) require the hydrodynamic model of any NOS nowcast/forecast system to run under hindcast scenario. A hindcast is defined as a long simulation using the best available gap-filled data for observed boundary water levels, wind, and river flows.

For LEOFS, the simulations and evaluation performed by Kuan (1995a, 1995b) will serve as the basis for the hindcast scenario assessment.   Kuan preformed model simulations during a six month period for the year 1979 when there was extensive field data available for verifying simulations at both the surface and subsurface. Kuan's dissertation and book chapter were reviewed and summarized in the following section.

4.1. Description of Hindcast Runs

The hindcast model simulations conducted by Kuan differ from the present pre-operational nowcasts done at the NOS CSDL and CO-OPS. First, the configuration of the POM model in Kuan's simulations used a 2 kilometer spatial resolution while the LEOFS is at 5 kilometer. Second, the number of vertical sigma layers was 14 while LEOFS has 11 layers. Finally, Kuan used the more traditional two-pass Barnes spatial interpolation technique for interpolating the surface meteorological observations while the LEOFS uses GLERL's natural neighbor interpolation scheme. However, both Kuan's simulations and LEOFS used GLERL's heat flux model to generate gridded heat flux fields for input to POM.

4.2. Method of Evaluation

Kuan (1995a, 1995b) applied several methods to evaluate the performance of POMGL, including the traditional Root Mean Square Error (RMSE), an Index of Agreement (IOA), a skill score, and Empirical Orthogonal Function (EOF) or Principal Component Analysis.

A map depicting the locations of observing sites in Lake Erie where Kuan compared model simulations to observations is given in Fig. 3.

In the following section, results from the RMSE, IOA and skill score assessment are summarized and tabulated. One of the most widely used statistical measurements between the observed data and the predictive variable is the RSME, basically the measurement of the difference or distance between the computed values and the corresponding observed variables. The IOA is a relative measures that reflects the degree to which the observed values is accurately estimated by the simulated variables. The skill score uses set of non-parametric based statistical tools developed by Dingman and Bedford (1986) to assess the credibility of the model in simulating major water level events. In estimating the skill score one point is deducted from a scale of 10 for every 0.05 meter difference between the observed value and the computed value with a minimum score of 0 when the difference is greater than 0.5 meter. This method can also be used to access the performance for water temperature and current velocity where 1 point is deducted for every 0.5 degree temperature variation and every 1cm/sec deviation respectively. Table 1 lists the skill score rule for water level simulation.

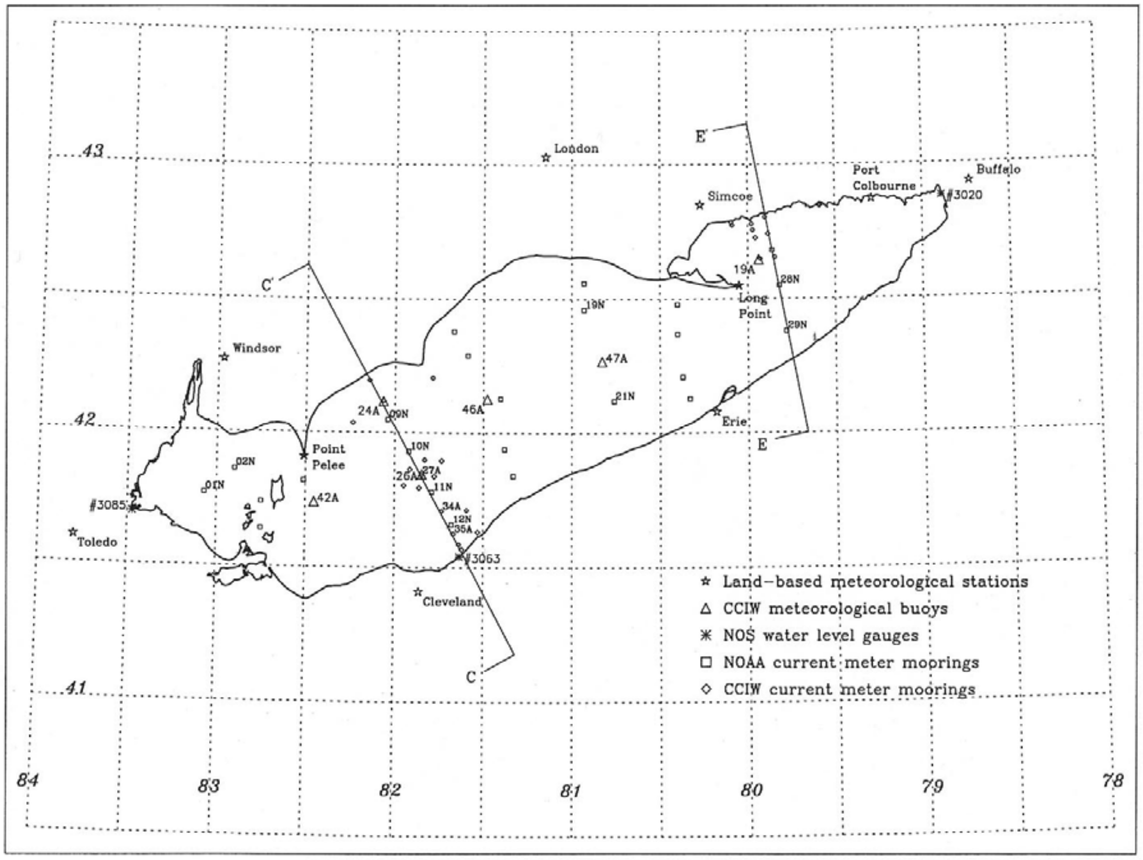


Figure 3. Map depicting locations of observing sites where POMGL simulations were evaluated at (Kuan, 1995b).

Table 1. Skill scores for assessing the difference between simulated and and observed water levels.

Assigned Point Value	Absolute Difference between the Predicted (P) and Observed (O) Water Level Values (cm)
10	| P – O| < 5
9	5 <= | P – O| < 10
8	10 <= | P – O| < 15
7	15 <= | P – O| < 20
6	20 <= | P – O| < 25
5	25 <= | P – O| < 30
4	30 <= | P – O| < 35
3	35 <= | P – O| < 40
2	40 <= | P – O| < 45
1	45 <= | P – O| < 50
0	50 <= | P – O|

4.3. Skill Assessment of Surface Hindcasts

Skill assessments of water level, current velocity, and surface water temperature simulations were performed by Kuan (1995b). Model performance is categorized for overall skills, seasonal performance and skill during strong wind events and between storm events. Evaluation statistics from Kuan (1995b) are summarized and tabulated in the following sections.

4.3.1. Water Levels

Model simulations of water levels at the model grid points closest to NOS water level gauges at Buffalo, NY, Cleveland, OH, and Toledo, OH were compared with the observed values at the corresponding gauges. The measures used in the evaluations are the statistical measures and the amplitude skill scores. The RMSE for water elevation hindcasts during the entire evaluation period (May 29 to October 26, 1979) at NOS water level gauges at Buffalo, Cleveland, and Toledo were 4.82cm, 3.0 cm and 6.18 cm, respectively. The amplitude skill scores for the entire test period were 9.73, 9.91 and 9.52 for Buffalo, Cleveland, and Toledo, respectively.

Table 2. Summary of water level hindcast evaluation statistics by NOS gauge station for 5 time periods in 1979.

Period		NOS Station Name	RMSE (cm)	Skill Score (0-10)
Days of Year	Calendar Days			
149-177	5/29-6/28/79	Buffalo	4.05	9.81
149-177	5/29-6/28/79	Cleveland	2.89	9.93
149-177	5/29-6/28/79	Toledo	5.51	9.61
179-207	6/28-7/28/79	Buffalo	3.84	9.85
179-207	6/28-7/28/79	Cleveland	2.65	9.93
179-207	6/28-7/28/79	Toledo	4.97	9.64
209-237	7/28-8/27/79	Buffalo	4.54	9.73
209-237	7/28-8/27/79	Cleveland	2.94	9.90
209-237	7/28-8/27/79	Toledo	6.27	9.51
239-267	8/27-9/26/79	Buffalo	4.25	9.77
239-267	8/27-9/26/79	Cleveland	2.37	9.96
239-267	8/27-9/26/79	Toledo	5.73	9.57
269-297	9/26-10/26/79	Buffalo	6.80	9.49
269-297	9/26-10/26/79	Cleveland	3.93	9.82
269-297	9/26-10/26/79	Toledo	7.99	9.27

A detailed evaluation on a seasonal basis was also performed to evaluate water level simulations during the heating, stratified and cooling seasons (Table 3). Heating season was defined from May 29 (Day 149) to July 23 (Day 204). The stratified season began on July 24 (Day 205) and ended on September 6 (Day 249) and the cooling season began at the end of stratified season.

Table 3. Seasonal evaluation statistics for water level simulations during heating, stratified, and cooling seasons in 1979.

Season	NOS Station	RMSE (cm)	IOA	Skill Score
Heating	Buffalo	3.95	0.89	9.83
"	Cleveland	2.79	0.72	9.93
"	Toledo	5.28	0.92	9.62
Stratified	Buffalo	4.27	0.96	9.77
"	Cleveland	2.74	0.88	9.92
"	Toledo	5.69	0.94	9.58
Cooling	Buffalo	6.01	0.95	9.58
"	Cleveland	3.41	0.94	9.87
"	Toledo	7.41	0.96	9.35

The RMSE and amplitude skill scores indicate that the water level simulations are equally good for all seasons. The average RMSE between the computed and observed values were 4.01cm, 4.23 cm, and 5.61 cm with the corresponding average Skill Scores of 9.97, 9.76 and 9.60 for the heating, stratified and cooling seasons, respectively.

In addition to the overall and seasonal evaluation, an evaluation based on episodic strong storm events was also performed by Kuan. The statistics are summarized in Table 4.

Table 4. Evaluation statistics for water level simulations at NOS water level gauge stations during the inter-storm and stormy periods during 1979.

Period	Location	RMSE (cm)	IOA	Skill Score
Inter-storm	Buffalo	2.76	0.84	9.94
"	Cleveland	2.33	0.62	9.98
"	Toledo	2.59	0.83	9.82
"	Average	2.86	0.76	9.91
Stormy	Buffalo	82.7	0.91	9.24
"	Cleveland	4.70	0.85	9.72
"	Toledo	9.68	0.91	8.97
"	Average	7.55	0.89	9.31

The results showed that POMGL performed better for the inter-storm period in terms of RSME and the amplitude skill scores. The IOA, on the other hand, gave an average value of 0.89 for the stormy periods and 0.76 for the inter-storm periods.

4.3.2. Surface Water Temperatures

To evaluate POMGL's performance in simulating lake surface temperatures, field data measured at 6 CCIW meteorological buoys were used by Kuan. RMSE, IOA and skill scores for all 6 buoys over the entire test period are summarized in Table 5.

Table 5. Evaluation statistics for surface water temperature simulations during 1979 at CCIW buoys.

CCIW Buoy ID	RMSE (^oC)	IOA	Skill Score
NWRI19A	1.16	0.97	8.66
NWRI24A	1.07	0.97	8.65
NWRI26A	0.92	0.98	8.98
NWRI42A	1.06	0.97	8.69
NWRI46A	0.90	0.98	9.04
NWRI47A	0.87	0.98	9.02

Throughout the entire test period the POMGL simulations matched very well with the observed data at all six buoys. Each fluctuation found in the observed data was reproduced in the simulation, although slight differences existed between the observed and computed values in terms of magnitude. Occasionally, the model simulations deviated more than 2 ^oC from the observed data and most of the significant discrepancies were over predictions (i.e. too warm). From Table 5, the average skill score was 8.84 and the average IOA was 0.97, both indices showed good agreement between the predicted and observed values. The average RMSE was only 1^oC which is also an indication that POMGL simulated lake surface temperature very well.

In general, the POMGL performed equally well in simulating surface water temperature during different seasons. The computed values followed the trend of the observed data closely. According to Kuan, if a critique must be made, the performance of the model for the cooling season was a bit weaker than the other two seasons and depending upon buoy locations. During the cooling season, surface water temperatures were consistently over predicted by about 1.5^o C. As seen in the in Tables 6 and 7, the model had better skill, in term of RMSE and skill scores for the heating and stratified seasons than the cooling season. In addition, the stratified season maintained a lower IOA than the other two.

Table 6. Seasonal evaluation statistics for surface water temperature simulations by heating, stratified, and cooling seasons in 1979.

Season	CCIW Buoy ID	RMSE (^oC)	IOA	Skill Score
Heating	NWRI19A	1.07	0.98	9.01
"	NWRI24A	1.00	0.97	8.77
"	NWRI26A	1.25	0.96	8.43
"	NWRI42A	0.96	0.97	8.97
"	NWRI46A	1.04	0.97	8.82
"	NWRI47A	0.99	0.98	8.83
Stratified	NWRI19A	0.99	0.83	8.90
"	NWRI24A	1.12	0.79	8.74
"	NWRI26A	0.56	0.94	9.51
"	NWRI42A	0.81	0.89	9.22
"	NWRI46A	0.60	0.93	9.47
"	NWRI47A	0.74	0.89	9.34
Cooling	NWRI19A	1.41	0.89	8.05
"	NWRI24A	1.13	0.95	8.44
"	NWRI26A	0.80	0.97	9.11
"	NWRI42A	1.38	0.95	7.89
"	NWRI46A	1.00	0.96	8.89
"	NWRI47A	0.86	0.97	8.93

Table 7. Average seasonal analysis results for surface water temperature simulations.

Heating Season			Stratified Season			Cooling Season		
RMSE (^oC)	IOA	Skill Score	RMSE (^oC)	IOA	Skill Score	RMSE (^oC)	IOA	Skill Score
1.05	0.97	8.81	0.80	0.88	9.20	1.10	0.95	8.55

Simulations of surface water temperatures were also evaluated for inter-storm and stormy periods. The results (Table 8) indicate better scores in each category for the storm event simulations.

Table 8. Evaluation statistics for surface water temperature simulation during stormy and inter-storm periods in 1979 at CCIW Buoys.

Season	CCIW Buoy ID	RMSE (^oC)	IOA	Skill Score
Inter-storm	NWRI19A	1.39	0.73	7.85
“	NWRI24A	1.48	0.74	7.65
“	NWRI26A	1.32	0.74	7.88
“	NWRI42A	1.56	0.74	7.51
“	NWRI46A	1.59	0.73	7.48
“	NWRI47A	1.39	0.73	7.82
“	Average	1.46	0.74	7.70
Stormy	NWRI19A	1.89	0.75	6.82
“	NWRI24A	1.35	0.86	7.88
“	NWRI26A	0.82	0.93	8.91
“	NWRI42A	1.45	0.89	7.71
“	NWRI46A	1.29	0.86	8.04
“	NWRI47A	0.65	0.96	9.01
“	Average	1.24	0.88	8.06

4.3.3. Surface Currents

Since observed surface current data were not available, the surface current velocities were not evaluated by Kuan. However, subsurface currents at 18 different locations across the lake were used by Kuan to assess the skill of POMGL to simulate sub-surface currents. A summary of Kuan’s evaluation of subsurface currents is given in section 4.4.1.

4.4. Skill Assessment of Sub-Surface Hindcasts

4.4.1. Sub-Surface Currents

In order to evaluate POMGL’s performance of current velocities and flow behaviors at a transect, direct point-by-point comparisons were made to measurements for the cross section areas C-C’ and E-E’ in Fig. 3. Data from 14 current meters over section C-C’ and 4 current meters over section E-E’ were used for comparison purpose. Data from those 18 current meters were converted into both the u- and v-current components, and the model simulated values were interpolated from the surrounding grid point at sigma levels based on the current meters’ deployment depth.

Current velocity simulations are examined through the used of statistical measure and the Skill Scores. The RMSE and the skill score for each current meter over the whole testing period are summarized in the Tables 9 and 10. The last two digits of each meter's thermistor ID represent the depth in meters where the instrument was deployed. For example, the 09N10 current meter was at 10 meters below the water surface.

Table 9. Evaluation statistics for the simulation of current velocity u-component in 1979 for two cross sections. See Fig. 3 for the location of the cross sections.

Cross Section	Station ID	RMSE (cm/sec)	Skill Score
C-C'	09N10	5.62	6.53
"	10N10	5.23	6.58
"	27A10	4.49	7.10
"	11N10	6.08	6.08
"	34A10	5.11	6.66
"	12N10	6.21	5.74
"	35A10	7.68	4.68
"	35A14	5.67	6.20
"	27A15	7.02	5.79
"	34A18	5.01	6.81
"	34A19	3.97	7.46
"	27A20	5.84	6.35
"	11N21	3.57	7.63
"	10N22	3.54	7.68
E-E'	28N10	7.91	5.15
"	29N10	7.30	5.17
"	29N25	8.02	5.06
"	28N33	5.84	6.16

Table 10. Evaluation statistics for the simulation of current velocity v-component in 1979 at two cross sections. See Fig. 3 for the location of the cross sections.

Cross Section	Station ID	RMSE (cm/sec)	Skill Score
C-C'	09N10	5.03	7.00
"	10N10	5.25	6.68
"	27A10	4.43	7.15
"	11N10	5.68	6.37
"	34A10	3.79	7.71
"	12N10	3.78	7.88
"	35A10	3.91	7.63
"	35A14	3.93	7.61
"	27A15	6.40	5.97
"	34A18	4.26	7.41
"	34A19	3.02	8.17
"	27A20	5.50	6.44
"	11N21	3.00	8.04
"	10N22	3.09	8.01
E-E'	28N10	6.93	5.32
"	29N10	6.54	5.86
"	29N25	6.79	5.71
"	28N33	5.35	6.53

Table 11. Summary of evaluation statistics for velocity simulations by season in 1979.

Location	Heating Season			Stratified Season			Cooling Season		
	RMSE (cm/s)	IOA	Skill Score	RMSE (cm/s)	IOA	Skill Score	RMSE (cm/s)	IOA	Skill Score
C-C'x	5.12	0.72	6.62	5.83	0.69	6.17	5.03	0.71	6.82
C-C'y	4.21	0.69	7.36	4.99	0.60	6.82	3.73	0.59	7.65
E-E'x	5.75	0.74	6.14	7.65	0.71	5.27	8.23	0.62	4.71
E-E'y	5.78	0.74	6.16	7.40	0.71	5.09	5.88	0.59	6.17

The average RMSE and skill scores showed similar model skill for heating and cooling seasons at C-C' for both u and v components but only for the v component along E-E' (see Table 11). Simulations during the stratified season show the lowest scores for both cross sections and both directions, except the u component at E-E'. The IOA also showed better skill in the heating season than other seasons and the cooling season had the lowest IOA.

The average RMSE of u, v component at C-C' are smaller during the inter-storm period than that of the stormy period (see Tables 12, 13, 14 and 15). The average RMSE for u and v components at inter-storm period are 3.41 and 2.72 cm/sec while the average RMSE for u and v components at stormy period are 5.55 and 4.05, respectively. However, the average skill score during stormy period shows better skill than the score during inter-storm period for both u and v components.

Table 12. Evaluation statistics for u-component current velocity at C-C' during the inter-storm period in 1979.

Current meter ID	RMSE (cm/s)	IOA	Amp. Skill Score
09N10	3.14	0.50	8.04
10N10	3.64	0.59	7.65
27A10	2.87	0.64	8.28
11N10	4.28	0.51	6.83
34A10	2.87	0.65	8.04
12N10	3.32	0.71	7.68
35A10	4.53	0.70	6.63
35A14	3.49	0.72	7.51
27A15	3.14	0.72	8.20
34A18	2.15	0.78	8.70
34A19	3.68	0.71	7.18
27A20	3.11	0.77	8.17
11N21	3.49	0.69	7.72
10N22	4.04	0.64	7.41
Average	3.41	0.67	7.72

Table 13. Evaluation statistics for u-component current velocity at C-C' during the stormy period in 1979.

Current meter ID	RMSE (cm/s)	IOA	Amp. Skill Score
09N10	3.95	0.77	7.37
10N10	4.20	0.75	7.09
27A10	3.85	0.74	7.43
11N10	5.93	0.37	5.63
34A10	3.92	0.78	7.38
12N10	5.49	0.72	5.81
35A10	6.58	0.62	5.24
35A14	6.20	0.63	5.72
27A15	9.17	0.41	4.56
34A18	5.64	0.70	6.27
34A19	5.63	0.71	6.05
27A20	8.08	0.47	4.53
11N21	5.33	0.66	6.03
10N22	3.77	0.71	7.36
Average	5.55	0.65	6.18

Table 14. Evaluation statistics for v-component current velocity at C-C' during inter-storm periods in 1979.

Current meter ID	RMSE (cm/s)	IOA	Amp. Skill Score
09N10	2.70	0.53	8.30
10N10	2.52	0.58	8.47
27A10	3.57	0.65	7.56
11N10	3.38	0.50	7.84
34A10	2.16	0.57	8.88
12N10	1.90	0.65	9.00
35A10	1.98	0.70	8.98
35A14	1.85	0.77	8.94
27A15	3.59	0.70	7.41
34A18	1.66	0.83	9.11
34A19	2.34	0.52	8.53
27A20	3.70	0.76	7.23
11N21	3.26	0.70	7.53
10N22	3.46	0.69	7.74
Average	2.72	0.65	8.25

Table 15. Evaluation statistics for v-component current velocity at C-C' during the stormy periods in 1979.

Current meter ID	RMSE (cm/s)	IOA	Amp. Skill Score
09N10	3.45	0.47	7.73
10N10	2.95	0.52	8.04
27A10	3.26	0.55	7.80
11N10	7.91	0.69	3.99
34A10	3.11	0.50	8.14
12N10	1.85	0.78	8.92
35A10	3.01	0.62	8.09
35A14	2.99	0.65	8.26
27A15	7.11	0.36	5.42
34A18	4.68	0.48	7.12
34A19	3.63	0.62	7.60
27A20	7.10	0.46	5.23
11N21	2.83	0.76	8.14
10N22	2.81	0.61	8.29
Average	4.05	0.58	7.34

4.4.2. Sub-Surface Water Temperatures

POMGL water temperature simulations at six meters or deeper were examined at two thermistor locations deployed in the western basin and also at thermistors over the same cross sectional areas for the current evaluations in the central (C-C') and eastern (E-E') basin. The observed data for comparison included water temperatures from twenty-three measurement locations: two in the western basin, 16 in the central basin and five in the eastern basin. The overall performance of POMGL in simulating sub-surface water temperatures in the western basin was more than acceptable. This conclusion was also supported by the results of the statistical analysis and amplitude skill test. Compared with the observation, the average skill score was 8.2, the average IOA was 0.95, and the average RMSE was only 1.35^{o}C for the entire period (Table 16).

Table 17 shows the statistics for water temperature at selected water column depth for all the thermistors listed on Table 16. The RMSE, IOA and skill scores are excellent when depths are less than 20 meters while RMSE increases and IOA decreases as the water depth exceeds 20 meters. The results clearly show the model's limitation in reproducing thermal structure in the deeper portion of the water body.

Table 16. Evaluation statistics for water temperature simulations by thermistor location during 1979.

Thermistor ID	RMSE (^oC)	IOA	Skill Score
01N06	1.29	0.96	8.31
02N07	1.44	0.94	8.10
09N10	1.69	0.94	7.88
10N10	1.33	0.96	8.46
27A10	1.28	0.97	8.57
34A10	1.33	0.97	8.24
12N10	1.47	0.95	8.02
35A10	1.91	0.93	7.27
35A14	1.49	0.95	7.95
27A15	0.85	0.99	9.07
10N17	1.68	0.95	8.04
12N17	3.01	0.82	6.57
34A18	2.07	0.93	7.95
34A19	3.74	0.80	5.52
27A20	4.04	0.81	5.82
09N21	5.13	0.73	4.05
11N21	5.14	0.74	4.16
10N22	4.61	0.77	4.53
28N10	1.37	0.96	8.42
29N10	1.65	0.95	7.74
29N25	3.53	0.85	5.64
28N33	8.25	0.71	1.52
29N38	9.30	0.71	1.05

Table 17. Average evaluation statistics for water temperature at selected water column depths for 1979.

Water Depth	RMSE (^oC)	IOA	Skill Score
$D < 15m$	1.42	0.96	8.17
$15m < D < 20m$	2.90	0.86	6.78
$20m < D < 25m$	4.83	0.77	4.60
$25m < D$	8.78	0.71	1.29

The average values of the RMSE, IOA and skill scores at various depths during different seasons are listed in Table 18 and 19. The model's skill decreased as the depth increases, and the model had the poorest skill during the stratified season in each of the categories.

Table 18. Average seasonal analysis results for water column simulations in 1979.

Location	Heating Season			Stratified Season			Cooling Season		
	RMSE (oC)	IOA	Score	RMSE	IOA	Score	RMSE	IOA	Score
Western	0.81	0.98	9.10	0.79	0.87	9.03	2.14	0.90	6.23
C-C'x	1.96	0.86	7.12	3.69	0.71	5.15	1.48	0.89	8.56
E-E'x	3.60	0.81	4.75	5.75	0.70	4.12	4.81	0.79	5.68

Table 19. Seasonal average evaluation statistics for water temperature simulations at selected water column depths for 1979.

Depth	Heating Season			Stratified Season			Cooling Season		
	RMSE (^oC)	IOA	Skill Score	RMSE (^oC)	IOA	Skill Score	RMSE (^oC)	IOA	Skill Score
D < 15m	1.36	0.94	8.18	1.61	0.73	7.73	1.08	0.95	8.52
15m<D< 20m	2.09	0.84	7.01	4.37	0.68	4.62	1.56	0.87	8.47
20m<D< 25m	3.28	0.74	4.85	6.78	0.71	1.28	3.01	0.71	7.30
25m < D	5.58	0.73	1.62	10.61	0.75	0.00	9.62	0.69	2.08

Similar to the lake surface temperature field, the water temperatures along the C-C' section were over predicted by the model at all thermistor locations during both the inter-storm and stormy periods (Table 20 and 21). The RMSE, IOA and amplitude skill scores show the model performed slightly better for the stormy period than for the inter-storm period.

Table 20. Evaluation statistics for water temperature simulations at C-C' during inter-storm periods in 1979.

Current meter ID	RMSE (^oC)	IOA	Skill Score
09N10	1.12	0.74	8.22
10N10	0.95	0.75	8.61
27A10	0.81	0.75	9.00
34A10	0.94	0.75	8.70
12N10	1.02	0.75	8.33
35A10	0.89	0.75	8.72
35A14	1.18	0.74	8.08
27A15	0.98	0.75	8.50
10N17	0.94	0.75	8.62
12N17	1.28	0.74	7.91
34A18	1.23	0.74	7.89
34A19	1.19	0.74	8.35
27A20	0.98	0.75	8.57
09N21	1.24	0.75	7.91
11N21	1.14	0.75	8.00
10N22	1.01	0.75	8.60
Average	1.06	0.75	8.37

Table 21. Evaluation statistics for water temperature simulation at C-C' during the stormy periods in 1979.

Current meter ID	RMSE (^oC)	IOA	Skill Score
09N10	1.26	0.88	7.96
10N10	1.00	0.90	8.57
27A10	0.68	0.95	9.20
34A10	0.73	0.95	8.92
12N10	0.82	0.94	8.75
35A10	0.90	0.93	8.73
35A14	0.89	0.93	8.68
27A15	0.75	0.94	8.99
10N17	1.03	0.90	8.47
12N17	0.79	0.94	8.96
34A18	0.76	0.94	8.96
34A19	0.70	0.95	9.11
27A20	0.76	0.94	8.99
09N21	1.31	0.87	7.90
11N21	0.74	0.94	9.07
10N22	1.05	0.89	8.51
Average	0.89	0.93	8.74

4.5. Summary

The extensive evaluation by Kuan (1995a, 1995b) has demonstrated the ability of POMGL to reproduce the barotropic motions of the lake in terms of water surface elevations in the Lake Erie.

Several specific conclusions were drawn from Kuan's study. The simulated water surface elevation matched well in both phase and magnitude with the corresponding observed data by picking up almost every single significant spike appearing in the observed water level elevations. The average RMSE was quite small indicating that the model can be considered quite well in simulating water surface elevation of the lake. The average IOA and amplitude skill score also supported this, with high values of 0.95 and 9.72, respectively. It should be emphasized that the water level fluctuations were caused by random wind stress fields and that the persistent strong low frequency, repetitious tidal physics found in marine or continental shelf applications did not exist in the lake simulations. The result was very encouraging as all the water level fluctuations result from probabilistic wind fields, not from deterministic tidal motions. The average RMSE of only 4.67 cm over the whole 150 day simulation period indicated that the major features of the wind driven barotropic response have been simulated well.

For the current velocity simulation, except for the nearshore zone and the very unsteady flow region, the predictions over C-C' were quite satisfactory. Good simulation both in phase and magnitude can be found at most of the current meter locations. The velocity predictions over E-E' were not as good as those for C-C' likely due to the fact that there was only one over water meteorological buoy in the eastern basin while there were five buoys in the central basin. The interpolated meteorological fields in the eastern basin were therefore not as good as the central basin. The estimated momentum and heat fluxes were all derived from the interpolated meteorological fields, thus the eastern basin results were not as accurate as the central basin simulation. However, very good agreement both in phase and magnitude between the observed and computed values can be found occasionally during the strong wind stress events.

As for lake surface temperature, the model predictions compared exceptionally well with the observed data at all six CCIW meteorological buoy locations. The simulated values not only depicted almost every single spike found in the observed data, but the average RMSE was as low as 1^oC over the entire test period of 150 days. The model also demonstrated good skill at predicting water temperatures in the deeper portion of the lake. When the lake was well mixed, the model predictions were as good as those for the lake surface. However, when lake was thermally stratified, the simulations under predicted the water temperature above the thermocline region and over predicted the water temperature in the hypolimnion. This result was due to the model's inability to reproduce the thermocline structure with the given vertical grid resolution. In addition, evaluations also showed that improper calculation of the lake thermal structure did not seem to affect the model ability to simulate lake water levels as the model attained similar Skill Scores for each of the seasons. However, the results did indicate the model performed better during the heating and cooling seasons than the stratified season for the current velocity simulation, though the difference was marginal.

For water temperature simulations, the model performed equally well during the heating, cooling and stratified seasons with a consistent slight over prediction at all six CCIW buoys during the cooling season. There was no evidence that the thermal structure of the lake significantly affected the model's capability in predicting the lake water surface temperature. The results also indicated that the model performed better in simulating water levels and current velocity during the inter storm period, while it had better skill scores for water temperature at both the surface and deeper portion of the lake during the stormy period.

A comprehensive summary of model skill for all variables based on seasonal variation is given in Table 22. Summary of IOA for all the variables categorized by seasons is given in Table 23.

Table 22. Comprehensive seasonal model skill in terms of the amplitude skill score.

Variable	Heating Season	Stratified Season	Cooling Season
Water level	9.793	9.757	9.600
Current velocity	6.80	6.201	6.837
Surface water temp.	8.805	9.197	8.552
Deep water temp.	7.424	6.180	8.490
Overall Skill Score	8.206	7.834	8.370

Table 23. Comprehensive seasonal model skill analysis in terms of the IOA.

Variable	Heating Season	Stratified Season	Cooling Season
Water level	0.84	0.93	0.95
Current velocity	0.71	0.66	0.64
Surface water temp.	0.97	0.88	0.95
Deep water temp.	0.88	0.72	0.89
Overall IOA	0.85	0.80	0.86

In summary, Kuan concluded that the difference between the POMGL water level and surface temperature simulations and observations were quite small. Kuan's results also indicated that the model simulation results compared well in both phase and magnitude with the observed data. Temperature and current velocity in the deeper portion of the lake also compared well with the observation data. However, model simulations of temperature and velocity in the nearshore did not compare well to observations indicating that the simulation in the coastal and thermocline regions were not correct.

5. SEMI-OPERATIONAL NOWCAST SKILL ASSESSMENT

This section describes the model system performance based on NOS requirements of an operational nowcast/forecast system (Hess et al. 2003). According to Hess et al. (2003), the definition of the model run scenario for a semi-operational nowcast is the following:

"In this scenario, the model is forced with actual observational input data streams including open ocean boundary water levels, wind stresses, river flows, and water density variations. Significant portions of the data may be missing, so the model must be able to handle this." (In the case of non-tidal water bodies as the Great Lakes, the data streams could include wind stresses, surface heat flux, and river flows.)

LEOFS, as described in Chapter 2, is based on NOAA/GLERL's Great Lakes Coastal Forecast System (GLCFS) for Lake Erie. Both LEOFS and GLCFS for Lake Erie have a spatial grid increment of 5 km and 11 sigma layers and use similar surface meteorological forcing. Neither of the systems employed any river inflow or assimilated any limnologic data.

Due to the similar characteristics of LEOFS and GLCFS, the assessment of the LEOFS semi-operational nowcasts was done using GLERL's archived nowcasts from GLCFS four times/day nowcast cycles.

This section includes a description of the GLCFS nowcast cycles, method of evaluation including time period and assessment statistics, and the evaluation results.

5.1. Description of Nowcast Cycles

GLCFS performs four times/day nowcasts for Lake Erie, and the other four Great Lakes year round. The surface forcing for the nowcast cycles are provided by objective analyses of surface meteorological observations from land-based and overwater observing stations. The four nowcast cycles produce nowcasts valid at 0000, 0600, 1200, and 1800 UTC each day. The nowcast cycles are launched at approximately 80 minutes past the valid time of the nowcasts. For example, the nowcast cycle to generate a nowcast valid at 0000 UTC is launched at 0120 UTC to allow for observations from late reporting Canadian fixed buoys and NDBC C-MAN stations to be received at GLERL via NOAAPORT. Hourly model results are archived at GLERL.

5.2. Method of Evaluation

The hourly model results from the GLCFS nowcasts were compared to observations from coastal and offshore observing platforms in the lake for the period from mid-April to mid-December 2004. This was a period when there was no significant ice cover on the lake.

The evaluation used the standard NOS suite of assessment statistics, as defined in Hess et al. (2003). The standard suite of statistics is given in Table 24. The target frequencies of the associated statistics are the following:

CF(X) ≥90%, POF(2X) ≤1%, NOF(2X) ≤1%, WOF(2X) ≤0.5%,
MDPO(2X) ≤ L, MDNO(2X) ≤ L

Table 24. NOS Skill Assessment Statistics (Hess et al. 2003).

Variable	Explanation
Error	The error is defined as the predicted value, p, minus the reference (observed or astronomical tide value, r : $e_i = p_i - r_i$.
SM	Series Mean. The mean value of a series y. Calculated as $\bar{y} = \frac{1}{N}\sum_{i=1}^{N} y_i$.
RMSE	Root Mean Square Error. Calculated as $RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N} e_i^2}$.
SD	Standard Deviation. Calculated as $SD = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N} (e_i - \bar{e})^2}$
CF(X)	Central Frequency. Fraction (percentage) of errors that lie within the limits ±X.
POF(X)	Positive Outlier Frequency. Fraction (percentage) of errors that are greater than X.
NOF(X)	Negative Outlier Frequency. Fraction (percentage) of errors that are less than -X.
MDPO(X)	Maximum Duration of Positive Outliers. A positive outlier event is two or more consecutive occurrences of an error greater than X. MDPO is the length of time (based on the number of consecutive occurrences) of the longest event.
MDNO(X)	Maximum Duration of Negative Outliers. A negative outlier event is two or more consecutive occurrences of an error less than -X. MDNO is the length of time (based on the number of consecutive occurrences) of the longest event.
WOF(X)	Worst Case Outlier Frequency. Fraction (percentage) of errors that, given an error of magnitude exceeding X, either (1) the simulated value of water level is greater than the astronomical tide and the observed value is less than the astronomical tide, or (2) the simulated value of water level is less than the astronomical tide and the observed value is greater than the astronomical tide.

Notes:
X is defined for different variables in Table 26.

There are three types of data sets (Table 25): Group 1, a time series of values at uniform time intervals; Group 2, a set of values representing the consecutive occurrences of an event (such as high or low water); and Group 3, a set of values representing a forecast valid at a given projection time. The acceptable error limits (X) and maximum duration limits (L) for the associated variable applied to the nowcasts and forecasts are presented in Table 26.

Table 25. Data series groups and the variables in each. Note that upper case letters indicate a prediction series (e.g., H), and lower case letters (e.g., h) indicate a reference series (observation) (Modified from Hess et al. 2003).

Group	Variable	Symbol
Group 1 (Time Series)	Water level Water temperature	H, h T, t
Group 2 (Values at at Extreme Event)	Amplitude of high water Amplitude of low water Time of high water Time of low water	AHW, ahw ALW, ahw THW, thw TLW, tlw
Group 3 (Values from a Forecast)	Water level at forecast projection time of nn hrs Water temperature at forecast projection time of nn hrs	Hnn, hnn Tnn, tnn

Table 26. Acceptance error limits (X) and the maximum duration limits (L) modified from Hess et al. (2003) for use in the Great Lakes.

Variables	X	L (hours)
H, Hnn, AHW, ALW	15 cm	24
THW, TLW	1.5 hours^{+}	25
T, Tnn,	$3^{o}C$*	24

Notes: $^{+}$1.0 hours for tidal regions, *$7.7^{o}C$ for tidal regions.

The evaluation utilized the NOS skill assessment software (Zhang et al. 2006), but was modified for use in the Great Lakes. The software computes the skill assessment scores automatically using files containing observations and nowcast or forecast guidance. Since the GLCFS output was not in NetCDF files, the output was reformatted to meet the input text format requirements of the skill assessment code.

<u>Nowcasts of Water Levels</u>

The evaluation of GLCFS nowcasts of water levels were based on time series of observed and model-based water levels at eight NOS NWLON stations along the Lake Erie shore line from Buffalo, NY to Fermi Power Plant, MI (Fig. 4). Time series of observed hourly water levels at NOS stations in Buffalo, NY and Toledo, OH during the period from 1 April to 31 December is given in Fig. 5.

Since water level nowcasts and forecasts generated by GLCFS were vertical displacements relative to the flat lake, further adjustment is necessary to bring the water levels relative to the mean lake level. An offset value based on dynamic 7-day average mean water level was computed and added to the model nowcast of water level displacement. This is the same method used by CO-OPS prior to displaying the LEOFS nowcasts on the web. The final nowcast water levels were then compared with the observational data.

The evaluation of GLCFS water level nowcasts for Lake Erie was done by comparing time series differences using SM, RMSE, SD, NOF, POF, MDPO, and MDNO statistics described in Hess et al. (2003). Since tides are not significant in the Great Lakes there was no comparison of the times and amplitudes of tidally-forced high and low waters. However, significant high amplitude water events do occur in Lake Erie. Following the recommendations of Hess et al. (2003), a method was developed and implemented in the NOS skill assessment software to analyze the forecast system's ability to simulate large amplitude events in the Lake Erie and the other Great Lakes. This is the first attempt at evaluating the ability of a NOS forecast system to simulate high and low water events in non-tidal regions. Other methods such as described by Dingman and Bedford (1986) and used by Kelley (1995) and Hoch (1997) may be considered for addition to the NOS evaluation statistics suite.

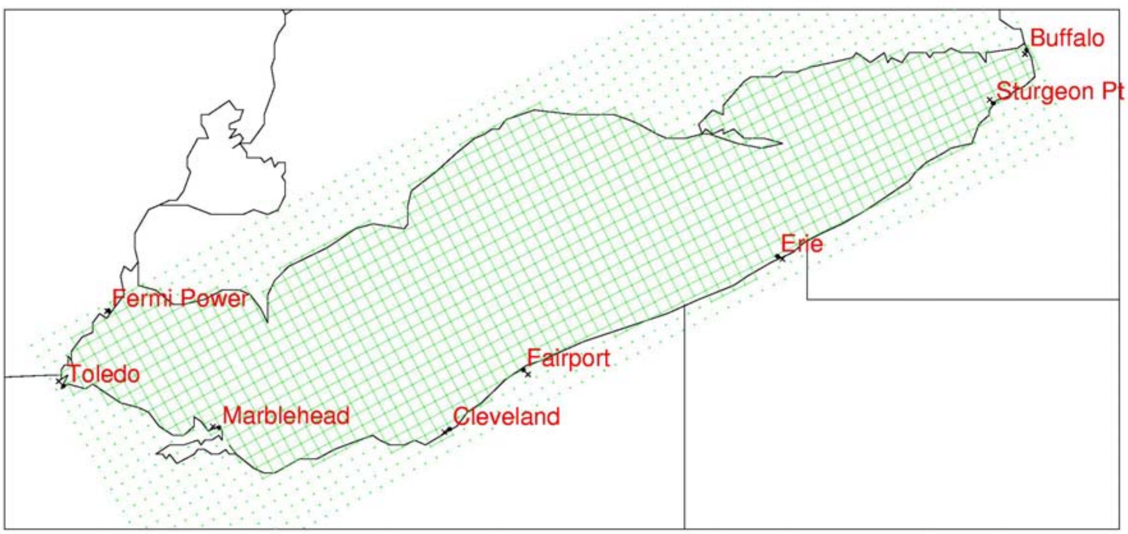
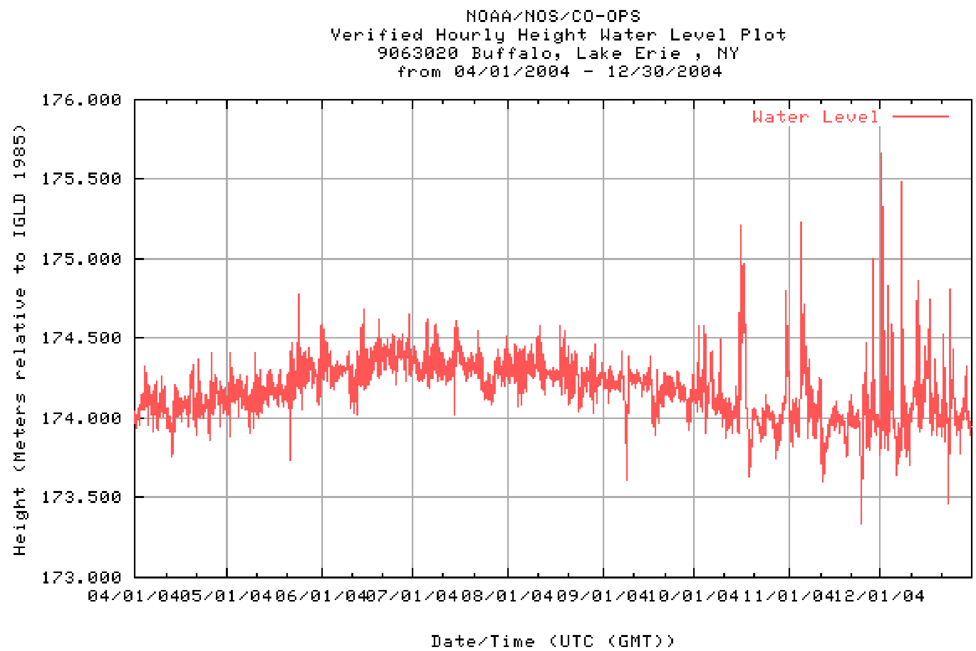
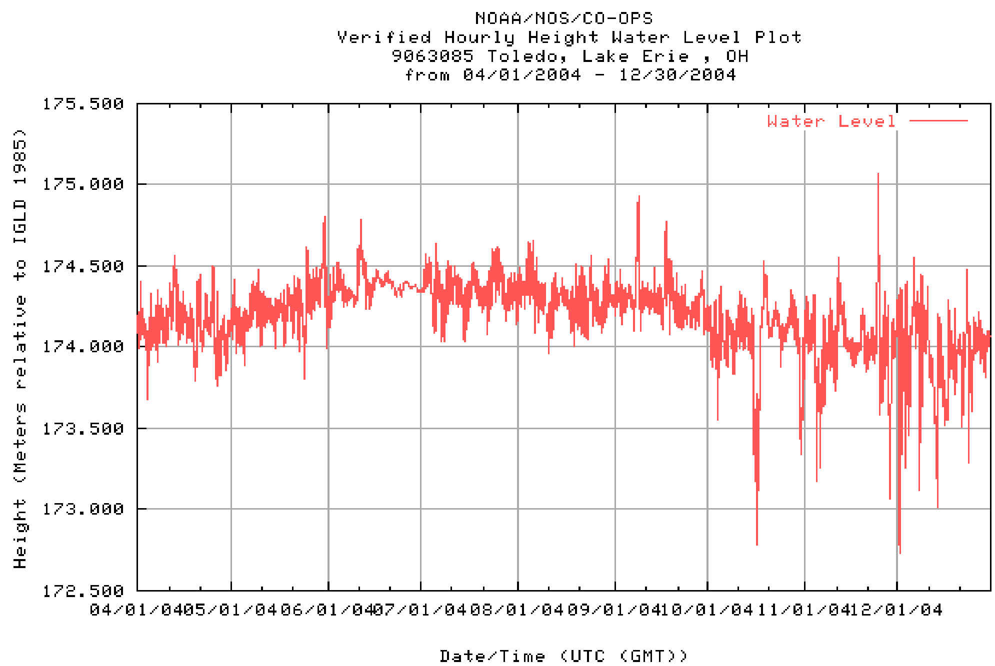


Figure 4. Map depicting the location of NOS NWLON stations in Lake Erie.



(a)



(b)

Figure 5. Observed water levels at NOS NWLON stations in Buffalo, NY (a) and Toledo, OH (b) during the period 1 April to 31 December 2004.

The NOS skill assessment software identifies high and low water events in the Great Lakes using the following method.

Step 1. For the observed time series of water level, pick all high and low values. A data point is selected if it is either higher or lower than its two neighboring points (both sides).

Step 2. For each selected peak from Step 1, a seven day window is centered on the particular peak and the mean value and standard deviation (called sigma hereafter) of the observed time series are computed within the seven day period. Upper/lower limits are then computed as the mean value +/- 2 sigma.

Step 3. The peak is identified as a high/low water level event if it exceeds the upper and lower limits. (Step 2 was performed to remove the impact of periodical variations, such as semi-diurnal and diurnal frequency signals on event selection.)

Step 4. For each high and low water level event in the observed time series, the maximum/minimum water level value and occurrence time are selected from the model simulated time series within a 12 hour window (the occurrence time of the observed event is centered), and paired with the observed events for comparison and statistic evaluation.

Step 5. The paired observed and simulated extreme events are compared to each other to assess the ability of the forecast system to simulate large amplitude events.

Nowcasts of Surface Water Temperatures

The evaluation of GLCFS nowcasts of surface water temperatures were based on comparisons of time series of observed vs. model-predicted temperatures at one 3-m fixed disk buoy locations in Lake Erie. The buoys are operated by NOAA/National Data Buoy Center (NDBC). Information on the buoy is given in Table 27. The lake surface temperatures at NDBC Buoy 45005 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 nowcasts at the nearest grid points to surface observations from the buoys. A map depicting the location of NDBC fixed buoy 45005 is given in Fig. 6.

The evaluation of GLCFS surface water temperature nowcasts for Lake Erie was done by comparing time series differences using SM, RMSE, SD, NOF, POF, MDPO, and MDNO statistics described in Hess et al. (2003). No attempt was made to assess the forecast system's ability to simulate diurnal or larger temperature fluctuations. Other methods for evaluating water temperature predictions such as those used by Kelley (1995) and Hoch (1997) may be implemented in the future.

In evaluating predicted water temperature in tidal regions, NOS sets an acceptable error of 7.7^{o}C to meet the acceptable error of draft of 7.5 cm (3 inches), as water density is a function of temperature and salinity. Since the Great Lakes are considered fresh water and non-tidal, there is no preset standard for lake temperature prediction. Based on the ten years experience on running Great Lakes Forecasting System and input from Great Lakes user community, Dr. David Schwab of NOAA/GLERL suggested a 3^{o}C criteria for water temperature skill assessment in the Great Lakes region (personal communication). Thus all the statistical evaluation and skill scores are based on the 3^{o}C criteria.

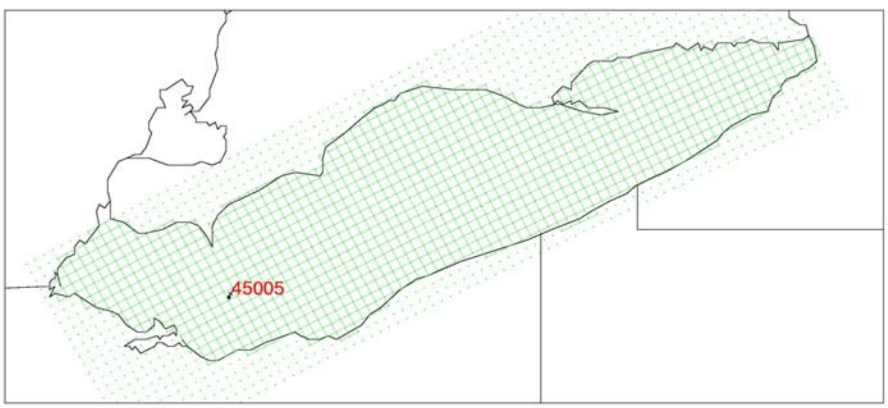


Figure 6. Map depicting the location of the NWS/NDBC fixed buoy 45005 in Lake Erie along with the grid points of the GLOFS-Erie model grid.

Table 27. Information on NOAA/NOS NWLON stations whose observations were used to evaluate LEOFS semi-operational nowcasts and forecast guidance of water levels.

Station Name	State	NOS Station ID Number	NWS Station ID	Station		Corresponding LEOFS Grid Point Coordinates	
				Latitude (deg N)	Longitude (deg W)	I	J
Buffalo	NY	9063020	BUFN6	42.88	78.89	80	8
Sturgeon Point	NY	9063028	NS	42.69	79.05	76	6
Erie	PA	9063038	NS	42.15	80.08	56	3
Fairport	OH	9063053	NS	41.75	81.28	34	4
Cleveland	OH	9063063	NS	41.54	81.64	26	2
Marblehead	OH	9063079	MRH01	41.55	82.73	10	11
Toledo	OH	9063085	THR01	41.69	83.47	2	20
Fermi Power Plant	MI	9063090	NS	41.96	83.26	8	23

Notes: NS = An official NWS station ID has not been assigned the station yet.

Table 28. Information of a NWS/NDBC fixed buoy whose observations were used to evaluate LEOFS semi-operational nowcasts and forecast guidance of surface water temperatures.

Buoy Name	Agency	Prov. or State	NWS Buoy ID	Buoy		Corresponding LEOFS Grid Point Coordinates	
				Latitude (deg N)	Longitude (deg W)	I	J
West Erie	NWS/ NDBC	OH	45005	41.68	82.40	17	10

5.3. Assessment of Water Level Nowcasts

The standard suite of skill assessment statistics evaluating the ability of semi-operational nowcasts and forecast guidance to predict hourly and extreme water levels at eight NOS gauges from 15 April to 17 December 2004 are given in Appendix A. Time series plots of the nowcasts vs. observations at the gauges are given in Appendix B.

The skill statistics assessing the ability of the nowcasts to predict hourly water levels at the eight NOS gauges are presented together in Table 29 along with the NOS acceptance criteria. The hourly nowcasts passed NOS criteria for NOF, CF, POF, MDPO, and MDNO at all eight NOS gauge locations. The mean algebraic differences ranged between -2.9 and +3.4 cm and the RMSE ranged between 4 and 8 cm. The greatest differences were at Toledo, OH, Buffalo, NY, and Fairport, OH (Fig. 4). The nowcasts under predicted at Toledo and over predicted at Buffalo. Toledo and Buffalo, located at the extreme SW and NE ends of the lakes, respectively experience the greatest hourly water level variability and are the most difficult locations to predict for. It was not clear why the MAE and RMSE were large at Fairport when the differences at gage locations to the north (Erie, PA) and south (Cleveland, OH) were only 0.8 cm.

Table 29. Summary of Skill assessment Statistics of *Semi-Operational Nowcasts* of Hourly Water Levels at eight NOS NWLON Stations in Lake Erie for the Period 15 April to 17 December 2004. A total of 5832 nowcasts were used in the assessment. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	Buffalo, NY	Sturgeon Pt., NY	Erie, PA	Fairport, OH	Cleveland, OH	Marblehead, OH
Mean Alg. Error (m)	0.026	0.034	0.008	-0.031	0.008	0.000
RMSE (m)	0.080	0.076	0.045	0.044	0.040	0.050
SD (m)	0.076	0.068	0.044	0.031	0.040	0.050
NOF (2x15cm) (%)	0.8	0.5	0.0	0.0	0.0	0.0
CF [15 cm] (%	95.6	96.4	98.9	99.7	99.1	98.4
POF [2x15 cm] (%)	0.0	0.0	0.0	0.0	0.1	0.0
MDNO [2x15 cm] (hour)	4.0	4.0	1.0	0.0	0.0	0.0
MDPO [2x15 cm] (hour)	0.0	0.0	0.0	0.0	2.0	1.0

Statistic, Acceptable Error [ ], and Units ( )	Toledo, OH	Fermi Power Plant, MI	NOS Accept. Criteria
Mean Alg. Error (m)	-0.029	-0.005	na
RMSE (m)	0.080	0.065	na
SD (m)	0.075	0.065	na
NOF (2x15cm) (%)	0.3	0.1	$\leq$ 1%
CF [15 cm] (%	94.0	96.6	$\geq$ 90%
POF [2x15 cm] (%)	0.1	0.1	< 1%
MDNO [2x15 cm] (hour)	3.0	2.0	$\leq$ 24 hours
MDPO [2x15 cm] (hour)	0.0	2.0	$\leq$ 24 hours

Notes: na = not applicable

The skill statistics assessing the ability of nowcasts to predict the amplitude and timing of extreme high water level events at NOS gauges during 2004 are given together in Table 30 along with the NOS acceptance criteria. The nowcasts' amplitude predictions of high water level events passed the NOS acceptance criteria for NOF, CF, POF, MDNO, and MDPO at only Cleveland and Marblehead. (It came close to passing at Toledo). The nowcasts' ability to predict the timing of these events did not pass NOS acceptance criteria for NOF, CF, and POF at any gauge location.

Table 30. Summary of Standard Statistics Evaluating the Ability of the *Semi-Operational Nowcasts* to Predict Extreme High Water Level Events at Eight NOS NWLON stations in Lake Erie during the Period 15 April to 17 December 2004. Gray shading, if present, indicates that it did not meet the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	Buffalo, NY N=33		Sturgeon Point, NY N=35		Erie, PA N=32	
	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (min)	-0.168	0.727	-0.118	-1.286	-0.088	-0.906
RMSE (m) (min)	0.282	5.111	0.189	5.079	0.119	5.452
SD (m) (min)	0.231	5.137	0.150	4.986	0.082	5.462
NOF [2x15cm or 90 min] (%)	21.2	12.1	20.0	17.1	0.0	18.8
CF [15 cm or 90 min] (%)	75.8	60.6	71.4	65.7	71.9	53.1
POF [2x15 cm or 90 min] (%)	0.0	18.2	0.0	2.9	0.0	9.4
MDNO [2x15 cm or 90 min] (#)	0.0	0.0	0.0	0.0	0.0	0.0
MDPO [2x15 cm or 90min] (#)	0.0	0.0	0.0	0.0	0.0	0.0

Statistic, Acceptable Error [ ], and Units ( )	Fairport, OH N=18		Cleveland, OH N=18		Marblehead, OH N=22	
	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (min)	-0.082	-0.389	-0.041	0.222	-0.046	0.909
RMSE (m) (min)	0.112	5.652	0.068	4.955	0.061	5.745
SD (m) (min)	0.078	5.802	0.056	5.094	0.041	5.806
NOF [2x15cm or 90 min] (%)	0.0	16.7	0.0	22.2	0.0	4.5
CF [15 cm or 90 min] (%)	77.8	38.9	100.0	50.00	100.0	59.1
POF [2x15 cm or 90 min] (%)	0.0	11.1	0.0	16.7	0.0	18.2
MDNO [2x15 cm or 90 min] (#)	0.0	0.0	0.0	0.0	0.0	0.0
MDPO [2x15 cm or 90min] (#)	0.0	0.0	0.0	0.0	0.0	0.0

Statistic, Acceptable Error [ ], and Units ( )	Toledo, OH N=19		Fermi Power Plant, MI N=21		NOS Accept. Criteria
	Amplitude	Time	Amplitude	Time	
Mean Alg. Error (m) (min)	-0.119	0.790	-0.075	1.286	na
RMSE (m) (min)	0.142	3.269	0.100	5.490	na
SD (m) (min)	0.079	3.259	0.069	5.469	na
NOF [2x15cm or 90 min (%)	5.3	10.5	0.0	9.5	$\leq$ 1%

CF [15 cm or 90 min] (%)	84.2	36.8	81.0	61.9	≥ 90
POF [2x15 cm or 90 min] (%)	0.0	21.1	0.0	19.0	≤ 1%
MDNO [2x15 cm or 90 min] (#)	0.0	0.0	0.0	0.0	≤ 24 hours
MDPO [2x15 cm or 90 min] (#)	0.0	0.0	0.0	0.0	≤ 24hours

Notes: na = not applicable

The skill statistics to predict extreme low water level events at the NOS gauges in Lake Erie during 2004 are given together in Table 31. The nowcasts of extreme low water level passed NOS acceptance criteria for amplitude at Erie and Fairport and were close to passing at Toledo and Marblehead. The nowcasts ability to simulate the timing of these events did not pass NOS acceptance criteria at any gauge location.

Table 31. Summary of Standard Statistics Evaluating the Ability of *Semi-Operational Nowcasts* to Simulate Extreme Low Water Level Events at Eight NOS NWLON Stations in Lake Erie for the Period 15 April to 17 December 2004. Gray shading, if present, indicates that the statistic did not pass the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	Buffalo, NY N=36		Sturgeon Point, NY N=33		Erie, PA N=41	
	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (min)	0.108	0.727	0.113	-0.030	0.064	-0.537
RMSE (m) (min)	0.117	5.111	0.121	2.623	0.072	2.263
SD (m) (min)	0.045	5.137	0.043	2.663	0.032	2.226
NOF [2x15cm] (90min) %	0.0	12.1	0.0	9.1	0.0	7.3
CF [15 cm or 90 min] (%)	83.3	60.6	81.8	60.6	100.0	68.3
POF [2x15 cm or 90 min] (%)	0.0	18.2	0.0	15.2	0.0	7.3
MDNO [2x15 cm or 90 min] (#)	0.0	0.0	0.0	0.0	0.0	0.0
MDPO [2x15 cm or 90min] (#)	0.0	0.0	0.0	0.0	0.0	0.0

Statistic, Acceptable Error [ ], and Units ( )	Fairport, OH N=15		Cleveland, OH N=27		Marblehead, OH N=42	
	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (min)	0.032	-0.667	0.090	0.037	0.073	-0.238
RMSE (m) (min)	0.056	2.503	0.113	2.009	0.107	2.390
SD (m) (min)	0.047	2.498	0.070	2.047	0.079	2.407
NOF [2x15cm or 90min (%)	0.0	13.3	0.0	3.7	0.0	7.1
CF [15 cm or 90 min] (%)	100.0	73.3	81.5	66.7	85.7	59.5
POF [2x15 cm or 90 min] (%)	0.0	0.0	0.0	7.4	2.4	9.5
MDNO [2x15 cm or 90 min] (#)	0.0	0.0	0.0	0.0	0.0	0.0
MDPO [2x15 cm or 90min] (#)	0.0	0.0	0.0	0.0	0.0	0.0

Statistic, Acceptable Error [ ], and Units ( )	Toledo, OH N=42		Fermi Power Plant, MI N=48		NOS Accept. Criteria
	Amplitude	Time	Amplitude	Time	
Mean Alg. Error (m) (min)	0.063	-0.381	0.088	0.083	na
RMSE (m) (min)	0.106	2.545	0.125	2.062	na
SD (m) (min)	0.086	2.547	0.089	2.082	na
NOF [2x15cm or 90min] (%)	0.0	11.9	0.0	2.1	≤ 1%
CF [15 cm or 90 min] (%)	85.7	57.1	83.3	66.7	≥ 90
POF [2x15 cm or 90 min] (%)	0.0	7.1	4.2	8.3	≤ 1%
MDNO [2x15 cm or 90 min] (#)	0.0	0.0	0.0	0.0	≤ 24 hours
MDPO [2x15 cm or 90min] (#)	0.0	0.0	0.0	0.0	≤ 24 hours

Notes: na=not applicable

5.4. Assessment of Water Temperature Nowcasts

The standard suite of skill assessment statistics evaluating the ability of semi-operational nowcasts to predict hourly lake surface water temperatures at the NWS/NDBC fixed buoy between the western and central basins of Lake Erie from mid-April to early December 2004 is given in Appendix D. A time series plot of the nowcasts (1st sigma level) vs. observations at the buoys is given in Appendix E. The time series plot indicates that the nowcasts were in close agreement to observations (+0.5 to +1 ^oC) from mid- April until early May, but then began deviate from the observations by +1 to +2^{o}C until late May. After that the nowcasts differ from observations by +0.5^{o}C until mid August. The nowcasts then deviated by +1 to +2^{o}C until early October. During the remaining days of Autumn through the end of the period in mid December, the nowcasts generally differed from observations by +0.5^{o}C.

The skill statistics to predict hourly surface water temperatures at the NDBC buoys are given in Table 32 along with the NOS acceptance criteria. The hourly water temperature nowcasts at the buoy did pass the NOS acceptance criteria for all the assessment statistics

Table 32. Summary of Skill Assessment Statistics of the *Semi-Operational Hourly Nowcasts* of Surface Water Temperatures at the NWS/NDBC fixed buoy in Lake Erie for the Period from Mid-April to Early December 2004. Gray shading indicates that the statistic did not pass the NOS acceptance criteria.

Time Period, Statistic, Acceptable Error [ ], and Units ( )	45005 West Erie N=5566	NOS Acceptance Criteria
Time Period (days)	202	365
Mean Difference (^{o}C)	0.951	na
RMSE (^{o}C)	1.292	na
SD (^{o}C)	0.875	na
NOF [2x3^{o}C] (%)	0.0	$\leq$ 1%
CF [3^{o}C] (%)	98.7	$\geq$ 90%
POF [2x3^{o}C] (%)	0.0	$\leq$ 1%
MDNO [2x3^{o}C] (hours)	0.0	$\leq$ 24 hrs
MDPO [2x3^{o}C] (hours)	0.0	$\leq$ 24 hrs

Notes: na=not applicable

6. SEMI-OPERATIONAL FORECAST SKILL ASSESSMENT

This section describes the model system performance for a semi-operational forecast scenario based on NOS requirements (Hess et al. 2003). According to Hess et al. (2003), the definition of the model run scenario for a semi-operational forecast is the following:

"In this scenario, the model is forced with actual forecast input data streams, including open ocean boundary water levels, wind, river flows, and water density variations. Initial conditions are generated by observed data. Significant portions of the data may be missing, so the model must be able to handle this." (Similar to the nowcast scenario, the data streams for the Great Lakes could include wind stresses, surface heat flux, and river flows.)

For the assessment of the semi-operational forecast scenario for LEOFS, archived forecast guidance from GLCFS twice per day forecast cycles (0000 and 1200 UTC) during 2004 were compared to available observations in the lake.

This chapter includes a description of the GLCFS forecast cycles, the method of evaluation including time period and assessment statistics, and the evaluation results.

6.1. Description of Forecast Cycles

GLCFS performs twice/day 60-hr forecast cycles for Lake Erie. The two forecast cycles are initialized at 0000 and 1200 UTC each day. The forecast cycles are launched at approximately 2 hours and 45 minutes past the valid time of the nowcasts to allow for complete ingestion of atmospheric forecast fields. For example, for the forecast cycle with initial conditions valid at 1200 UTC is launched at 1445 UTC. The initial conditions for each forecast cycle are provided by the nowcast cycle. The surface forcing for the forecast cycles consists of surface (10 m AGL) wind velocity and surface (2 m AGL) air temperatures from NWS/NCEP North America Mesoscale (NAM) Model. The wind velocity and air temperature are used to calculate surface wind stress for input into the lake model. The surface heat fluxes into the lake model during the forecast cycle are zero.

6.2. Method of Evaluation

The semi-operational forecast guidance at 1 hour increments from +1 to +24 hours from GLCFS were compared to water level observations from NOS NWLON stations in the lake from 15 April to 17 December 2004 and to a NWS/NDBC fixed buoy from mid-April to early November for the surface water temperature forecasts. This was a period when there was no significant ice cover on the lake.

The evaluation used the standard suite of assessment statistics as defined in Hess et al. (2003) but modified for non-tidal regions.   The evaluation of GLCFS forecasts of water levels were based on time series of observed and model-based water levels at the same eight NOS NWLON stations along the lake shore (Fig. 4) used in the evaluation of the nowcasts.

The evaluation of semi-operational forecast guidance of surface water temperatures were based on comparisons of time series of observed vs. model-predicted temperatures at the same NWS/NDBC fixed buoy used in the nowcast evaluation.

6.3. Skill Assessment of Water Level Forecast Guidance

The standard suite of skill assessment statistics evaluating the ability of semi-operational forecast guidance as well as nowcasts to predict hourly and extreme water levels at 8 NOS gauges from Early-April to Mid-December 2004 are given in Appendix A.   Time series plots of the forecast guidance from the 0000 UTC model forecast cycle vs. observations at the gauges are given in Appendix C.

For the convenience of the reader, the skill statistics assessing the ability of the forecast guidance to predict hourly water levels 24 hours in advance at 8 NOS gauges are presented together in Table 33 along with the NOS acceptance criteria. The hourly forecasts passed the criteria at 7 of the 8 gauges, failing only at Toledo. The mean algebraic errors or differences ranged between -3 and +4.4 cm and the RMSE ranged between 4.1 cm at Cleveland and 10.7 cm at Toledo. Similar to the nowcasts, the greatest errors were at Buffalo and Toledo, located at the extreme ends of the lake. The forecasts under predicted the water levels at Toledo and over predicted the levels at Buffalo. There was some increase in the RMSE values as forecast projection increased (Appendix A).

Table 33. Summary of Skill Assessment Statistics of *Semi-Operational 24-hr Forecast Guidance* of <u>Hourly Water Levels</u> at NOS NWLON Stations in Lake Erie for the Period 15 April to 17 December 2004. Gray shading, if present, indicates that the statistic did not pass the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	Buffalo, NY N=490	Sturgeon Point, NY N=490	Erie, PA N=490	Fairport, OH N=490	Cleveland, OH N=490	Marble-head, OH N=473
Mean Alg. Error (m)	0.036	0.044	0.017	-0.030	0.006	-0.008
RMSE (m)	0.088	0.084	0.052	0.044	0.041	0.065
SD (m)	0.080	0.072	0.050	0.032	0.041	0.065
NOF (2x15cm) (%)	0.4	0.4	0.2	0.0	0.0	0.4
CF [15 cm] (%	95.9	96.1	98.6	99.4	99.4	97.3
POF [2x15 cm] (%)	0.4	0.6	0.0	0.0	0.0	0.2
MDNO [2x15 cm] (hour)	0.0	0.0	0.0	0.0	0.0	0.0
MDPO [2x15 cm] (hour)	0.0	0.0	0.0	0.0	0.0	0.0

Table 33 (cont.)

Statistic, Acceptable Error [ ], and Units ( )	Toledo, OH N=489	Fermi Power Plant, MI N=477	NOS Accept. Criteria
Mean Alg. Error (m)	-0.034	-0.016	na
RMSE (m)	0.107	0.086	na
SD (m)	0.102	0.084	na
NOF (2x15cm) (%)	1.4	0.8	≤ 1%
CF [15 cm] (%	87.7	93.9	≥ 90%
POF [2x15 cm] (%)	0.2	0.2	< 1%
MDNO [2x15 cm] (hour)	12.0	0.0	≤ 24 hours
MDPO [2x15 cm] (hour)	0.0	2.0	≤ 24 hours

Notes: na=not applicable

The skill statistics to assess the ability of the forecast guidance to predict extreme high water level events at the eight NOS gauges during 2004 are given together in Table 34. The forecasts of extreme high water level passed the NOS acceptance criteria for amplitude only at Cleveland and Marblehead, OH. The forecasts ability to predict the timing of these events also did not pass NOS acceptance criteria at any gauge.

Table 34. Summary of Skill assessment Statistics Evaluating the Ability of *Semi-Operational Forecast Guidance* to Predict Extreme High Water Level Events at NOS NWLON Stations in Lake Erie during the Period 15 April to 17 December 2004. Gray shading, if present, indicates that the statistic did not pass the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	Buffalo, NY N=29		Sturgeon Point N=32		Erie, PA N=29	
	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (min)	-0.134	2.310	-0.147	0.938	-0.094	0.103
RMSE (m) (min)	0.204	5.392	0.248	5.500	0.138	4.924
SD (m) (min)	0.157	4.958	0.202	5.506	0.103	5.010
NOF [2x15cm] (90min) %	13.8	6.9	15.6	15.6	3.4	20.7
CF [15 cm or 90 min] (%)	65.5	48.3	68.8	37.5	82.8	37.9
POF [2x15 cm or 90 min] (%)	0.0	27.6	0.0	15.6	0.0	17.2

Table 34. (cont.).

Statistic, Acceptable Error [ ], and Units ( )	Fairport, OH N=16		Cleveland, OH N=15		Marblehead, OH N=20	
	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (min)	-0.104	1.063	-0.051	-0.533	-0.057	-0.850
RMSE (m) (min)	0.118	5.815	0.073	4.258	0.071	5.408
SD (m) (min)	0.057	5.904	0.054	4.373	0.043	5.480
NOF [2x15cm] (90min) %	0.0	12.5	0.0	20.0	0.0	20.0
CF [15 cm or 90 min] (%)	75.0	56.3	100.0	46.7	95.0	50.0
POF [2x15 cm or 90 min] (%)	0.0	25.0	0.0	13.3	0.0	5.0

Statistic, Acceptable Error [ ], and Units ( )	Toledo, OH N=21		Fermi Power Plant, MI N=19		NOS Accept. Criteria
	Amplitude	Time	Amplitude	Time	
Mean Alg. Error (m) (min)	-0.157	0.714	-0.082	0.684	na
RMSE (m) (min)	0.172	5.851	0.100	6.509	na
SD (m) (min)	0.073	5.951	0.060	6.650	na
NOF [2x15cm] (90min) %	0.0	9.5	0.0	21.1	≤ 1 %
CF [15 cm or 90 min] (%)	57.1	47.6	84.2	47.4	≥ 90
POF [2x15 cm or 90 min] (%)	0.0	23.8	0.0	15.8	≤ 1 %

Notes: na=not applicable

The skill statistics to assess the ability of the forecast guidance to predict extreme low water level events at the eight NOS gauges during 2004 are given together in Table 35. The forecasts of extreme low water level passed NOS acceptance criteria for amplitude at Erie, Fairport, and Cleveland. The forecasts ability to simulate the timing of these events did not pass NOS acceptance criteria at any location.

Table 35. Summary of Skill assessment Statistics Evaluating the Ability of *Semi-Operational Forecast Guidance* to Predict Extreme Low Water Level Events at NOS NWLON Stations in Lake Erie during the Period 15 April to 17 December 2004. Gray shading, if present, indicates that the statistic did not pass the NOS acceptance criteria.

Statistic, Acceptable Error [ ], and Units ( )	Buffalo, NY N=36		Sturgeon Pt, NY N=34		Erie, PA N=40	
	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (min)	0.131	-0.250	0.127	0.176	0.073	-0.350
RMSE (m) (min)	0.139	2.291	0.135	2.701	0.079	2.313
SD (m) (min)	0.047	2.310	0.047	2.736	0.032	2.316
NOF [2x15cm] (90min) %	0.0	8.3	0.0	8.8	0.0	15.0
CF [15 cm or 90 min] (%)	66.7	44.4	73.5	35.3	97.5	57.5
POF [2x15 cm or 90 min] (%)	0.0	2.8	0.0	11.8	0.0	2.5

Table 35 (cont.).

Statistic, Acceptable Error [ ], and Units ( )	Fairport, OH N=16		Cleveland, OH N=27		Marblehead, OH N=43	
	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Error (m) (min)	-0.034	0.429	0.081	0.407	0.076	-0.140
RMSE (m) (min)	0.053	2.171	0.095	2.822	0.117	2.728
SD (m) (min)	0.042	2.209	0.051	2.845	0.089	2.757
NOF [2x15cm] (90min) %	0.0	7.1	0.0	7.4	0.0	11.6
CF [15 cm or 90 min] (%)	100.0	64.3	96.3	48.1	88.4	53.5
POF [2x15 cm or 90 min] (%)	0.0	7.1	0.0	18.5	2.3	11.6

Statistic, Acceptable Error [ ], and Units ( )	Toledo, OH N=42		Fermi Power Plant, MI N=48		NOS Accept. Criteria
	Amplitude	Time	Amplitude	Time	
Mean Alg. Error (m) (min)	0.110	-0.357	0.116	-0.083	na
RMSE (m) (min)	0.173	2.493	0.160	2.769	na
SD (m) (min)	0.135	2.497	0.111	2.797	na
NOF [2x15cm] (90min) %	0.0	11.9	0.0	10.4	$\leq$ 1
CF [15 cm or 90 min] (%)	73.8	54.8	79.2	47.9	$\geq$ 90
POF [2x15 cm or 90 min] (%)	9.5	7.1	6.3	14.6	$\leq$ 1

Notes: na=not applicable

6.4. Skill Assessment of Surface Water Temperature Forecast Guidance

The standard suite of skill assessment statistics evaluating the ability of semi-operational forecast guidance to predict hourly lake surface water temperatures at one NWS/NDBC fixed buoy from mid-April to early December 2004 is given in Appendix D. The table provides skill statistics at the forecast projections of 0, 6, 12, 18, and 24 hours from the 0000 and 1200 UTC forecast cycles. A time series plot of the forecasts (1st sigma level) from the 0000 UTC forecast cycle vs. buoy observations is given in Appendix E. The time series plot indicates that the forecast guidance from the 0000 UTC forecast cycle resembles the nowcasts very closely. This reflects the fact that the lake model configuration (i.e. POMGL) used for the semi-operational forecast cycles do not input any surface heat flux either directly or indirectly from the NAM-12 model forecast guidance. Specifically, the lake model uses subroutine FLUX5 in which the heat fluxes are zero.

Similar to the nowcasts, the semi-operational forecast guidance were in close agreement to observations (+0.5 to +1^{o}C) from mid- April until early May, but then began to deviate from the observations by +1 to +2^{o}C until late May. After that the forecast guidance differed from observations by +0.5^{o}C until mid August. The guidance then deviated by +1 to +2^{o}C until early October. During the remaining days of autumn through mid December, the guidance generally differed from observations by +0.5^{o}C.

The skill statistics assessing the ability of semi-operational forecast guidance to predict surface water temperatures 24 hours in advance at the NDBC buoy is given in Table 36 along with the NOS acceptance criteria. The hourly forecast guidance at the buoy passed all criteria. The mean algebraic error or difference was -0.7^{o}C and the RMSE was 1.3^{o}C. The mean algebraic error and RMSE for the forecast guidance were slightly lower than for the nowcasts.

It is interesting to note that mean algebraic error and RMSE values decreased as forecast projection increased in time. The mean algebraic error was 1.07^{o}C at the 0-hr projection and 0.71^{o}C by the 24-hr projection (see Table D.1). This suggests that the surface heat flux is being overestimated during the nowcast cycle and that POMGL is cooling off during the forecast cycle when there is no surface heat flux input.

Table 36. Summary of Skill Assessment Statistics for Semi-Operational Forecast Guidance to Predict Surface Water Temperatures 24 hours in Advance at a NWS/NDBC fixed buoy in Lake Erie during the period from mid-April to early-November 2004. Gray shading, if present, indicates that the statistic did not pass the NOS acceptance criteria.

Time Period, Statistic, Acceptable Error [ ], and Units ( )	45005 N=460	NOS Acceptance Criteria
Time Period	202	365 days
Mean Alg. Error (^{o}C)	0.713	na
RMSE (^{o}C)	1.306	na
SD (^{o}C)	1.095	na
NOF [2x3^{o}C] (%)	0.0	$\leq$ 1%
CF [3^{o}C] (%)	98.7	$\geq$ 90%
POF [2x3^{o}C] (%)	0.0	$\leq$ 1%
MDPO [2x3^{o}C] (hours)	0.0	$\leq$ 24 hrs
MDNO [2x3^{o}C] (hours)	0.0	< 24 hrs

Notes: na=not applicable

7. SUMMARY

NOS' Lake Erie Operational Forecast System (LEOFS) generates hourly nowcasts and forecast guidance out to 30 hours four times per day. It is based on the Great Lakes Coastal Forecasting System (GLCFS) developed by the Ohio State University and NOAA/GLERL.

LEOFS became operational at CO-OPS in September 30, 2005. The hourly nowcast cycles are forced by surface wind stress and surface heat flux estimated from objectively analyzed surface meteorological fields and the initial conditions are provided by the previous hour's nowcast. The four times/day forecast cycle uses the most recent nowcasts for its initial conditions and surface air temperature and wind forcing from NWS/NCEP's NAM-12 weather prediction model. During the forecast cycle, the heat flux is set to zero.

An assessment of the LEOFS was conducted according to the NOS evaluation standards (Hess et al. 2003). To satisfy the *hindcast scenario* requirement, the results of the Ph.D. dissertation research of Kuan (1995b) at The Ohio State University were used and summarized in this report.

Water Levels

The simulated water surface elevation matched well in both phase and magnitude with the corresponding observed data by picking up almost every single significant spike appearing in the observed water level elevations. The average RMSE was quite small indicating that the model can be considered quite good in simulating water surface elevation of the lake. The average IOA and amplitude skill score also support this observation, obtaining high values of 0.95 and 9.72, respectively.

Water Temperatures

As for lake surface temperature, the model predictions compared exceptionally well with the observed data at all six CCIW meteorological buoy locations. The simulations not only pick up almost every single spike found in the observed data, but the average RMSE was as low as 1^{o}C over the entire test period of 150 days. The model also demonstrated good skill at predicting water temperatures in the deeper portion of the lake. When the lake was well mixed, the model predictions were as good as those for the lake surface. However, when the lake was thermally stratified, the simulations under predicted the water temperature above the thermocline region and over predicted the water temperature in the hypolimnion.

Water Currents

For the current velocity simulation, except for the nearshore zone and the very unsteady flow periods, the velocity predictions over C-C' (Fig. 3) were quite satisfactory. Good simulation both in phase and magnitude can be found at most of the current meter locations.

To comply with NOS' required *semi-operational nowcast and forecast scenarios* (Hess et al. 2003), the skill evaluation used archived output from NOAA/GLERL's GLCFS semi-operational nowcasts and forecasts for Lake Erie from 15 April to 17 December 2004. The semi-operational nowcasts and forecast guidance were compared to water level observations at 8 NOS NWLON stations and surface temperature temperatures at one NWS/NDBC fixed buoy in the lake. Due to the lack of sub-surface water temperatures and current observations, no assessment of these variables could be conducted for LEOFS.

Water Levels

The hourly semi-operational nowcasts passed NOS acceptance criteria at seven of the eight stations. The nowcasts and forecast guidance predictions of extreme high and low water level events failed to pass NOS acceptance criteria in terms of estimating the timing of these events. In terms of amplitude, for the nowcasts, the predictions met the criteria at two of the eight gauges for high and low water level events. For the forecast guidance, the predictions met the criteria at two of the eight gauges for high water events and three of the eight gauges for low water events.

Surface Water Temperatures

The semi-operational nowcasts and forecast guidance predicted the surface water temperatures at the western/central basin boundary in Lake Erie to within $+1^{o}C$ for the entire evaluation period and passed NOS criteria. However, from mid-August to late-October the predictions were 1 to $2^{o}C$ warmer than observations.

8. RECOMMENDATIONS FOR FUTURE WORK

Recommendation #1:

The NOS skill assessment statistics and code should be modified in the future to provide skill assessment information of interest to NWS Weather Forecast Offices in the Great Lakes region which have responsibility for issuing low water statements and Lakeshore Flood Warnings. A description of the NWS criteria used by the Weather Forecast Offices responsible for issuing warnings and low water statements for the Lake Erie shoreline is given in Appendix F.

Recommendation #2

GLERL is presently running a new semi-operational version of GLCFS for Lake Erie. The new version uses an ice module in POMGL, monthly mean river discharge for 28 rivers, a horizontal grid resolution of 2 km, and 21 vertical sigma levels. The new version was implemented at GLERL in 2006. The nowcasts and forecast guidance from this new version should be evaluated to determine if it has improved predictive skill.

Recommendation #3

The skill score developed by Dingman and Bedford (1986) should be considered for addition to the NOS standard suite of evaluation statistics.

Recommendation #4

An examination should be conducted to determine whether the dynamic 7 day average mean lake water level adds a significant error to the POMGL predictions and if yes, is there an alternative method to estimate the mean lake wide water level. A possible alternative is to use the U.S. Army Corp of Engineers' mean lake levels which are based on area-weighted averages of individual gauges (http://www.lre.usace.army.mil/_plugins/Programs/DailyWaterLevels/dialogs.cfm?units=metric&months=0&displaymode=detail) or use a similar methodology at NOS.

Recommendation #5

The LEOFS surface water temperature predictions should also be evaluated at the Canadian buoys 45132 and 45134 in the future.

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The development of the Great Lakes Forecasting System was a joint effort of The Ohio State University and NOAA's Great Lakes Environmental Research Laboratory lead by Dr. Keith Bedford (OSU) and Dr. David Schwab (GLERL). During the eleven year life of the GLFS the following OSU personnel been associated with the development of the system: fifteen graduate students; seven faculty; six postdocs; and seven research scientists. Funding came from many different sources ranging from small grants from private foundations and companies to several large federal grants. The operation and further development of GLCFS at GLERL has involved 2 research scientists and 3 support scientists.

The porting of the GLCFS from GLERL to NOS was conducted by the GLOFS System Development and Implementation Team consisting of personnel from GLERL, OSU, CO-OPS, CSDL, and Aqualinks.com. In particular, we acknowledge the hard work of Greg Mott, Mark Vincent, Zack Bronder, and others at CO-OPS.

The hindcast scenario requirement was based on the Ph.D. research of C. Kuan conducted at The Ohio State University. The archived GLCFS nowcast and forecast guidance used in the skill assessment to fulfill the semi-operational nowcast and forecast scenarios were provided by Greg Lang and David Schwab at NOAA/GLERL. The skill assessment software was modified for use in the Great Lakes based on suggestions from Kurt Hess and Eugene Wei at CSDL.

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REFERENCES

Bartish T., 1987: A review of exchange processes among the three basins of Lake Erie. *J. Great Lakes Res.*, **13**, 607-618.

Bedford, K. W., 1992: The physical effects of the Great Lakes on tributaries and wetlands. *J. Great Lakes Res*., **18**, 571-589.

Bedford, K.W. and D. J. Schwab, 1991: The Great Lakes Forecasting System-Lake Erie nowcasts/forecasts, *Proceedings, Marine Technology Society National Meeting*, New Orleans, LA, Marine Technology Society, 260-264.

Blumberg, A. F. and G. L. Mellor, 1987**:** "A Description of a Three-Dimensional Coastal Ocean Circulation Model," *Three-Dimensional Coastal Ocean Models*, Vol. 4, Ed. N. Heaps, American Geophysical Union, Washington, DC, 1-16.

Boyce, F. M., F. Chiocchio, B. Eid, F. Penicka, and F. Rosa, 1989: Hypolimnion flow between the central and eastern basins of Lake Erie during 1977. *J. Great Lakes Res*., **6**, 290-306.

Chu, Yi-Fei, 1998: The Incorporation of Hourly GOES Data in a Surface Heat Flux Model and Its Impacts on Operational Temperature Predictions in Bodies of Water, Ph.D. dissertation, The Ohio State University, 273 pp. [Available from Dept. of Civil and Environmental Engineering and Geodetic Science, 470 Hitchcock Hall, 2070 Neil Avenue, Ohio State University, Columbus, OH 43210-1275.]

Dingham, J. S. and K. W. Bedford, 1984: The Lake Erie response to the January 26, 1978, cyclone. *J. Geophysical Res*., **89C4**, 6427-6445.

Dingman, J. S. and K. W. Bedford, 1986: Skill tests and parametric statistics for model evaluation. *J. Hydraulic Eng*.**, 112**, 124-141.

Gillhousen, D.B., 1987: A field evaluation of NDBC moored buoy winds. *J. Atmos. Oceanic Technol*., **4**, 94-104.

Gross, T. and H. Lin, 2007: NOS Coastal Ocean Modeling Framework. NOAA Technical Report (in preparation).

Hess, K.W., T. F. Gross, R. A. Schmalz, J. G.W. Kelley, F. Aikman III, E. Wei, and M. S. Vincent, 2003: NOS Standards for Evaluating Operational Nowcast and Forecast Hydrodynamic Model System. NOAA Technical Report NOS CS 17, 48 pp.

Hoch, B., 1997: An evaluation of a one-way coupled atmosphere-lake model for Lake Erie. M.S. Thesis, Atmospheric Sciences Program, Ohio State University, 226 pp. [Available for Atmospheric Sciences Program, 1049 Derby Hall, 154 N. Oval Mall, Ohio State University, Columbus, OH 43210-1361.]

Kelley, J. G. W., 1995: One-way coupled atmospheric-lake model forecasts for Lake Erie. Ph.D. dissertation, Ohio State University, 450 pp. [Available from Atmospheric Sciences Program, 1049 Derby Hall, 154 N. Oval Mall, Ohio State University, Columbus, OH 43210-1361.]

Kelley, J. G. W., J. S. Hobgood, K. W. Bedford, and D. J. Schwab, 1998: Generation of three-dimensional lake model forecasts for Lake Erie, *Wea. Forecasting,* **13**, 659-687.

Kuan, C.-F., K. W. Bedford, and D. J. Schwab, 1995a**:** *A Preliminary Credibility Analysis of the Lake Erie Portion of the Great Lakes Forecasting System for Springtime Heating Conditions*. In Skill Assessment for Coastal Ocean Models, ed. D. Lynch and A. Davies, Amer.Geophysical Union, Wash. D.C., 397-424.

Kuan, C.-F., 1995b: Performance evaluation of the Princeton Circulation Model for Lake Erie. Ph.D. Dissertation, Ohio State University, 376 pp. [Available from Dept. of Civil and Environmental Engineering and Geodetic Science, 470 Hitchcock Hall, 2070 Neil Avenue, Ohio State University, Columbus, OH 43210-1275.]

McCormick, M. J., and G. A. Meadows, 1988: An intercomparison of four mixed layer models in a shallow inland sea. *J. Geophys. Res***., 93,** *6774-6788*.

Mellor, G. L., 1996: Users guide for a three-dimensional, primitive equation, numerical ocean model. 38 pp., Program in Atmospheric and Oceanic Sciences, Princeton University, Princeton, NJ, 39 pp. [Available from Program in Atmospheric and Oceanic Sciences, P.O. Box CN710, Sayre Hall, Princeton University, Princeton, NJ 08544-0710].

Mortimer, C. H., 1987: Fifty years of physical investigations and related limnological studies on Lake Erie, 1928-1977. *J. Great Lakes Res.*, **13**, 407-435.

O'Connor, W. P. and D. J. Schwab, 1993: Sensitivity of Great Lakes Forecasting System nowcasts to meteorological fields and model parameters. *Proceedings, ASCE Third Int. Conf. on Estuarine and Coastal Modeling*, Oak Brook, IL, Amer. Soc. Civil Eng., 149-157.

O'Connor, W. P., D. J. Schwab, and G. A. Lang, 1999: Forecast verification for Eta model winds using Lake Erie storm surge water levels. *Wea. Forecasting*, **14**, 119-133.

Sambridge, M., J. Braun, and H. McQueen, 1995: Geophysical parameterization and interpolation of irregular data using natural neighbors. *Geophys. J. Int.*, **122**, 837-857.

Saylor, J. H. and G. S. Miller, 1987: Studies of large-scale currents in Lake Erie, 1979-80. *J. Great Lakes Res.*, **13**, 487-514.

Schertzer, W. M., J. H. Saylor, F. M. Boyce, D. G. Robertson, and F. Rosa, 1987: Seasonal thermal cycle of Lake Erie. *J. Great Lakes Res*., **13**, 468-486.

Schwab, D. J. and D. L. Sellers, 1980: Computerized bathymetry and shorelines. NOAA Data Rep. ERL GLERL-16, Great Lakes Environmental Research Laboratory, Ann Arbor, MI, 13 pp. [Available from NOAA/Great Lakes Environmental Research Laboratory, Publications Office, 2205 Commonwealth Blvd., Ann Arbor, MI 48105-2945.]

Schwab, D. J., J. R. Bennett, P. C. Liu, M. A. Donelan, 1984**:** Application of a simple numerical wave prediction model to Lake Erie, *J. Geophys. Res.*, **89C3**, 3586-3592.

Schwab, D. J., and K.W. Bedford, 1994: Initial implementation of the Great Lakes Forecasting System: a real-time system for predicting lake circulation and thermal structure. *Water Poll. Res. J. of Canada*, **29(2/3)**, 203-220.

Schwab, D. J. and K.W. Bedford, 1996: GLCFS – A coastal forecasting system for the Great Lakes, *Preprints, Conference on Coastal Oceanic and Atmospheric Predictions*, Atlanta, GA, Amer. Meteor. Soc., 9-14.

Schwab, D. J., G. Lang, K.W. Bedford, and P. Chu: 1999: Recent development in the Great Lakes Forecasting System (GLFS), *Preprints, Third Conference on Coastal Atmospheric and Oceanic Predictions and Processes*, New Orleans, LA, Amer. Meteor. Soc., 201-206.

Yen, C.-C., J. Kelley and K. Bedford, 1994**:** Daily procedure for GLFS nowcasts. *Proceedings, National Conference on Hydraulic Engineering*, Buffalo, NY, Amer. Soc. Civil Eng., 202-206.

Zhang, A.-J., K. W. Hess, E. Wei, and E. Myers, 2006: Implementation of model skill assessment software for water level and current in tidal regions. NOAA Technical Report NOS CS 24, 61 pp. [Available from NOAA/NOS Coast Survey Development Lab, 1315 E-W Highway, Silver Spring, MD 20910].

APPENDIX A. Skill Assessment Scores of Semi-Operational Water Level Nowcasts and Forecast Guidance of Water Levels at six NOS Gauges in Lake Erie from 15 April to 17 December 2004.

Table A.1. Skill Assessment of Semi-Operational Predictions at NOS Gauge at Buffalo, NY (9063020) for 2004.

Station: Buffalo, Lake Erie, NY
Longest continuous data time period from: 4/15/2004 to 12/20/2004
Data gap is filled using SVD method
Data are filtered using 3.0 Hour Fourier Filter

VARIABLE	X	N	IMAX	SM	RMSE	SD	NOF	CF	POF	MDNO	MDPO
CRITERION	-	-	-	-	-	-	<1%	>90%	<1%	<N	<N
SCENARIO: SEMI-OPERATIONAL NOWCAST											
H			5832	174.224							
h			5832	174.198							
H-h	15 cm	24h	5832	0.026	0.080	0.076	0.8	95.6	0.0	4.0	0.0
AHW-ahw	15 cm	24h	33	-0.168	0.282	0.231	21.2	75.8	0.0	0.0	0.0
ALW-alw	15 cm	24h	36	0.108	0.117	0.045	0.0	83.3	0.0	0.0	0.0
THW-thw	1.50 hr	25h	33	0.727	5.111	5.137	12.1	60.6	18.2	0.0	0.0
TLW-tlw	1.50 hr	25h	36	-0.167	2.273	2.299	5.6	61.1	8.3	0.0	0.0
SCENARIO: SEMI-OPERATIONAL FORECAST											
H00-h00	15 cm	24h	494	0.036	0.073	0.064	0.4	96.8	0.0	0.0	0.0
H06-h06	15 cm	24h	490	0.019	0.082	0.080	0.8	93.9	0.0	24.0	0.0
H12-h12	15 cm	24h	490	0.036	0.076	0.066	0.2	95.7	0.4	0.0	0.0
H18-h18	15 cm	24h	490	0.019	0.087	0.085	1.4	94.1	0.2	24.0	0.0
H24-h24	15 cm	24h	490	0.036	0.088	0.080	0.4	95.9	0.4	0.0	0.0
AHW-ahw	15 cm	24h	29	-0.134	0.204	0.157	13.8	65.5	0.0		
ALW-alw	15 cm	24h	36	0.131	0.139	0.047	0.0	66.7	0.0		
THW-thw	1.50 hr	25h	29	2.310	5.392	4.958	6.9	48.3	27.6		
TLW-tlw	1.50 hr	25h	36	-0.250	2.291	2.310	8.3	44.4	2.8		

Table A.2. Skill Assessment of Semi-Operational Predictions at NOS Gauge at Sturgeon Point, NY (9063028) for 2004.

Station: Sturgeon Point, Lake Erie, NY
Longest continuous data time period from: 4/15/2004 to 12/20/2004
Data gap is filled using SVD method
Data are filtered using 3.0 Hour Fourier Filter

VARIABLE	X	N	IMAX	SM	RMSE	SD	NOF	CF	POF	MDNO	MDPO
CRITERION	-	-	-	-	-	-	<1%	>90%	<1%	<N	<N
SCENARIO: SEMI-OPERATIONAL NOWCAST											
H			5832	174.218							
h			5832	174.184							
H-h	15 cm	24h	5832	0.034	0.076	0.068	0.5	96.4	0.0	4.0	0.0
AHW-ahw	15 cm	24h	35	-0.118	0.189	0.150	20.0	71.4	0.0	0.0	0.0
ALW-alw	15 cm	24h	33	0.113	0.121	0.043	0.0	81.8	0.0	0.0	0.0
THW-thw	1.50 hr	25h	35	-1.286	5.079	4.986	17.1	65.7	2.9	0.0	0.0
TLW-tlw	1.50 hr	25h	33	-0.030	2.623	2.663	9.1	60.6	15.2	0.0	0.0
SCENARIO: SEMI-OPERATIONAL FORECAST											
H00-h00	15 cm	24h	494	0.043	0.071	0.056	0.2	97.4	0.0	0.0	0.0
H06-h06	15 cm	24h	490	0.030	0.076	0.069	0.2	94.1	0.0	0.0	0.0
H12-h12	15 cm	24h	490	0.044	0.075	0.061	0.0	96.3	0.6	0.0	0.0
H18-h18	15 cm	24h	490	0.029	0.079	0.074	0.8	94.9	0.0	12.0	0.0
H24-h24	15 cm	24h	490	0.044	0.084	0.072	0.4	96.1	0.6	0.0	0.0
AHW-ahw	15 cm	24h	32	-0.147	0.248	0.202	15.6	68.8	0.0		
ALW-alw	15 cm	24h	34	0.127	0.135	0.047	0.0	73.5	0.0		
THW-thw	1.50 hr	25h	32	0.938	5.500	5.506	15.6	37.5	15.6		
TLW-tlw	1.50 hr	25h	34	0.176	2.701	2.736	8.8	35.3	11.8		

Table A.3. Skill Assessment of Semi-Operational Predictions at NOS Gauge at Erie, PA (9063038) for 2004.

Station: Erie, Lake Erie, PA
Longest continuous data time period from: 4/15/2004 to 12/20/2004
Data gap is filled using SVD method
Data are filtered using 3.0 Hour Fourier Filter

VARIABLE	X	N	IMAX	SM	RMSE	SD	NOF	CF	POF	MDNO	MDPO
CRITERION	-	-	-	-	-	-	<1%	>90%	<1%	<N	<N
SCENARIO: SEMI-OPERATIONAL NOWCAST											
H			5832	174.208							
h			5832	174.200							
H-h	15 cm	24h	5832	0.008	0.045	0.044	0.0	98.9	0.0	1.0	0.0
AHW-ahw	15 cm	24h	32	-0.088	0.119	0.082	0.0	71.9	0.0	0.0	0.0
ALW-alw	15 cm	24h	41	0.064	0.072	0.032	0.0	100.0	0.0	0.0	0.0
THW-thw	1.50 hr	25h	32	-0.906	5.452	5.462	18.8	53.1	9.4	0.0	0.0
TLW-tlw	1.50 hr	25h	41	-0.537	2.263	2.226	7.3	68.3	7.3	0.0	0.0
SCENARIO: SEMI-OPERATIONAL FORECAST											
H00-h00	15 cm	24h	494	0.015	0.044	0.041	0.0	99.4	0.0	0.0	0.0
H06-h06	15 cm	24h	490	0.005	0.047	0.046	0.0	99.0	0.0	0.0	0.0
H12-h12	15 cm	24h	490	0.016	0.049	0.046	0.0	98.8	0.0	0.0	0.0
H18-h18	15 cm	24h	490	0.004	0.050	0.050	0.2	98.6	0.0	0.0	0.0
H24-h24	15 cm	24h	490	0.017	0.052	0.050	0.2	98.6	0.0	0.0	0.0
AHW-ahw	15 cm	24h	29	-0.094	0.138	0.103	3.4	82.8	0.0		
ALW-alw	15 cm	24h	40	0.073	0.079	0.032	0.0	97.5	0.0		
THW-thw	1.50 hr	25h	29	0.103	4.924	5.010	20.7	37.9	17.2		
TLW-tlw	1.50 hr	25h	40	-0.350	2.313	2.316	15.0	57.5	2.5		

Table A.4. Skill Assessment of Semi-Operational Predictions at NOS Gauge at Fairport, OH (9063053) for 2004.

Station: Fairport, Lake Erie, OH
Longest continuous data time period from: 4/15/2004 to 12/20/2004
Data gap is filled using SVD method
Data are filtered using 3.0 Hour Fourier Filter

VARIABLE	X	N	IMAX	SM	RMSE	SD	NOF	CF	POF	MDNO	MDPO
CRITERION	-	-	-	-	-	-	<1%	>90%	<1%	<N	<N
SCENARIO: SEMI-OPERATIONAL NOWCAST											
H		5832	174.200								
h		5832	174.231								
H-h	15 cm	24h	5832	-0.031	0.044	0.031	0.0	99.7	0.0	0.0	0.0
AHW-ahw	15 cm	24h	18	-0.082	0.112	0.078	0.0	77.8	0.0	0.0	0.0
ALW-alw	15 cm	24h	15	0.032	0.056	0.047	0.0	100.0	0.0	0.0	0.0
THW-thw	1.50 hr	25h	18	-0.389	5.652	5.802	16.7	38.9	11.1	0.0	0.0
TLW-tlw	1.50 hr	25h	15	-0.667	2.503	2.498	13.3	73.3	0.0	0.0	0.0
SCENARIO: SEMI-OPERATIONAL FORECAST											
H00-h00	15 cm	24h	494	-0.032	0.044	0.030	0.0	99.8	0.0	0.0	0.0
H06-h06	15 cm	24h	490	-0.032	0.044	0.030	0.0	100.0	0.0	0.0	0.0
H12-h12	15 cm	24h	490	-0.030	0.042	0.030	0.0	100.0	0.0	0.0	0.0
H18-h18	15 cm	24h	490	-0.032	0.045	0.031	0.0	99.8	0.0	0.0	0.0
H24-h24	15 cm	24h	490	-0.030	0.044	0.032	0.0	99.4	0.0	0.0	0.0
AHW-ahw	15 cm	24h	16	-0.104	0.118	0.057	0.0	75.0	0.0		
ALW-alw	15 cm	24h	14	0.034	0.053	0.042	0.0	100.0	0.0		
THW-thw	1.50 hr	25h	16	1.063	5.815	5.904	12.5	56.3	25.0		
TLW-tlw	1.50 hr	25h	14	0.429	2.171	2.209	7.1	64.3	7.1		

Table A.5. Skill Assessment of Semi-Operational Predictions at NOS Gauge at Cleveland, OH (9063063) for 2004.

Station: Cleveland, Lake Erie, OH
Longest continuous data time period from: 4/15/2004 to 12/20/2004
Data gap is filled using SVD method
Data are filtered using 3.0 Hour Fourier Filter

VARIABLE	X	N	IMAX	SM	RMSE	SD	NOF	CF	POF	MDNO	MDPO
CRITERION	-	-	-	-	-	-	<1%	>90%	<1%	<N	<N
SCENARIO: SEMI-OPERATIONAL NOWCAST											
H	5832	174.200									
h	5832	174.192									
H-h	15 cm	24h	5832	0.008	0.040	0.040	0.0	99.1	0.1	0.0	2.0
AHW-ahw	15 cm	24h	18	-0.041	0.068	0.056	0.0	100.0	0.0	0.0	0.0
ALW-alw	15 cm	24h	27	0.090	0.113	0.070	0.0	81.5	0.0	0.0	0.0
THW-thw	1.50 hr	25h	18	0.222	4.955	5.094	22.2	50.0	16.7	0.0	0.0
TLW-tlw	1.50 hr	25h	27	0.037	2.009	2.047	3.7	66.7	7.4	0.0	0.0
SCENARIO: SEMI-OPERATIONAL FORECAST											
H00-h00	15 cm	24h	494	0.006	0.039	0.038	0.0	99.4	0.0	0.0	0.0
H06-h06	15 cm	24h	490	0.006	0.038	0.038	0.0	99.2	0.0	0.0	0.0
H12-h12	15 cm	24h	490	0.006	0.038	0.038	0.0	99.6	0.0	0.0	0.0
H18-h18	15 cm	24h	490	0.006	0.039	0.039	0.0	99.6	0.0	0.0	0.0
H24-h24	15 cm	24h	490	0.006	0.041	0.041	0.0	99.4	0.0	0.0	0.0
AHW-ahw	15 cm	24h	15	-0.051	0.073	0.054	0.0	100.0	0.0		
ALW-alw	15 cm	24h	27	0.081	0.095	0.051	0.0	96.3	0.0		
THW-thw	1.50 hr	25h	15	-0.533	4.258	4.373	20.0	46.7	13.3		
TLW-tlw	1.50 hr	25h	27	0.407	2.822	2.845	7.4	48.1	18.5		

Table A.6. Skill Assessment of Semi-Operational Predictions at NOS Gauge at Marblehead, OH (9063079) for 2004.

Station: Marblehead, Lake Erie, OH
Longest continuous data time period from: 4/15/2004 to 10/23/2004
Data gap is filled using SVD method
Data are filtered using 3.0 Hour Fourier Filter

VARIABLE	X	N	IMAX	SM	RMSE	SD	NOF	CF	POF	MDNO	MDPO
CRITERION	-	-	-	-	-	-	<1%	>90%	<1%	<N	<N
SCENARIO: SEMI-OPERATIONAL NOWCAST											
H	5630	174.194									
h	5630	174.195									
H-h	15 cm	24h	5630	0.000	0.050	0.050	0.0	98.4	0.0	0.0	1.0
AHW-ahw	15 cm	24h	22	-0.046	0.061	0.041	0.0	100.0	0.0	0.0	0.0
ALW-alw	15 cm	24h	42	0.073	0.107	0.079	0.0	85.7	2.4	0.0	0.0
THW-thw	1.50 hr	25h	22	0.909	5.745	5.806	4.5	59.1	18.2	0.0	0.0
TLW-tlw	1.50 hr	25h	42	-0.238	2.390	2.407	7.1	59.5	9.5	0.0	0.0
SCENARIO: SEMI-OPERATIONAL FORECAST											
H00-h00	15 cm	24h	477	-0.007	0.048	0.048	0.0	99.4	0.0	0.0	0.0
H06-h06	15 cm	24h	474	0.002	0.055	0.056	0.0	97.7	0.2	0.0	0.0
H12-h12	15 cm	24h	473	-0.007	0.058	0.058	0.2	97.9	0.2	0.0	0.0
H18-h18	15 cm	24h	474	0.004	0.055	0.055	0.0	98.5	0.2	0.0	0.0
H24-h24	15 cm	24h	473	-0.008	0.065	0.065	0.4	97.3	0.2	0.0	0.0
AHW-ahw	15 cm	24h	20	-0.057	0.071	0.043	0.0	95.0	0.0		
ALW-alw	15 cm	24h	43	0.076	0.117	0.089	0.0	88.4	2.3		
THW-thw	1.50 hr	25h	20	-0.850	5.408	5.480	20.0	50.0	5.0		
TLW-tlw	1.50 hr	25h	43	-0.140	2.728	2.757	11.6	53.5	11.6		

Table A.7. Skill Assessment of Semi-Operational Predictions at NOS Gauge at Toledo, OH (9063085) for 2004.

Station: Toledo, Lake Erie, OH
Longest continuous data time period from: 8/10/2004 to 12/20/2004
Data gap is filled using SVD method
Data are filtered using 3.0 Hour Fourier Filter

VARIABLE	X	N	IMAX	SM	RMSE	SD	NOF	CF	POF	MDNO	MDPO
CRITERION	-	-	-	-	-	-	<1%	>90%	<1%	<N	<N
SCENARIO: SEMI-OPERATIONAL NOWCAST											
H			5823	174.173							
h			5823	174.202							
H-h	15 cm	24h	5823	-0.029	0.080	0.075	0.3	94.0	0.1	3.0	0.0
AHW-ahw	15 cm	24h	19	-0.119	0.142	0.079	5.3	84.2	0.0	0.0	0.0
ALW-alw	15 cm	24h	42	0.063	0.106	0.086	0.0	85.7	0.0	0.0	0.0
THW-thw	1.50 hr	25h	19	0.790	3.269	3.259	10.5	36.8	21.1	0.0	0.0
TLW-tlw	1.50 hr	25h	42	-0.381	2.545	2.547	11.9	57.1	7.1	0.0	0.0
SCENARIO: SEMI-OPERATIONAL FORECAST											
H00-h00	15 cm	24h	493	-0.037	0.087	0.079	0.6	93.3	0.2	0.0	0.0
H06-h06	15 cm	24h	489	-0.016	0.096	0.095	0.4	88.8	0.8	0.0	0.0
H12-h12	15 cm	24h	489	-0.034	0.102	0.096	1.2	89.8	0.0	0.0	0.0
H18-h18	15 cm	24h	489	-0.015	0.088	0.086	0.0	91.4	0.4	0.0	0.0
H24-h24	15 cm	24h	489	-0.034	0.107	0.102	1.4	87.7	0.2	12.0	0.0
AHW-ahw	15 cm	24h	21	-0.157	0.172	0.073	0.0	57.1	0.0		
ALW-alw	15 cm	24h	42	0.110	0.173	0.135	0.0	73.8	9.5		
THW-thw	1.50 hr	25h	21	0.714	5.851	5.951	9.5	47.6	23.8		
TLW-tlw	1.50 hr	25h	42	-0.357	2.493	2.497	11.9	54.8	7.1		

Table A.8. Skill Assessment of Semi-Operational Predictions at NOS Gauge at Fermi Power Plant, MI (9063090) for 2004.

Station: Fermi Power Plant, Lake Erie, OH
Longest continuous data time period from: 6/14/2004 to 12/20/2004
Data gap is filled using SVD method
Data are filtered using 3.0 Hour Fourier Filter

VARIABLE	X	N	IMAX	SM	RMSE	SD	NOF	CF	POF	MDNO	MDPO
CRITERION	-	-	-	-	-	-	<1%	>90%	<1%	<N	<N
SCENARIO: SEMI-OPERATIONAL NOWCAST											
H			5686	174.181							
h			5686	174.186							
H-h	15 cm	24h	5686	-0.005	0.065	0.065	0.1	96.6	0.1	2.0	2.0
AHW-ahw	15 cm	24h	21	-0.075	0.100	0.069	0.0	81.0	0.0	0.0	0.0
ALW-alw	15 cm	24h	48	0.088	0.125	0.089	0.0	83.3	4.2	0.0	0.0
THW-thw	1.50 hr	25h	21	1.286	5.490	5.469	9.5	61.9	19.0	0.0	0.0
TLW-tlw	1.50 hr	25h	48	0.083	2.062	2.082	2.1	66.7	8.3	0.0	0.0
SCENARIO: SEMI-OPERATIONAL FORECAST											
H00-h00	15 cm	24h	481	-0.016	0.071	0.069	0.6	95.8	0.2	0.0	0.0
H06-h06	15 cm	24h	478	0.002	0.073	0.073	0.0	95.8	0.8	0.0	0.0
H12-h12	15 cm	24h	477	-0.017	0.079	0.077	0.8	94.3	0.0	0.0	0.0
H18-h18	15 cm	24h	478	0.004	0.070	0.070	0.0	95.2	0.4	0.0	0.0
H24-h24	15 cm	24h	477	-0.016	0.086	0.084	0.8	93.9	0.2	0.0	0.0
AHW-ahw	15 cm	24h	19	-0.082	0.100	0.060	0.0	84.2	0.0		
ALW-alw	15 cm	24h	48	0.116	0.160	0.111	0.0	79.2	6.3		
THW-thw	1.50 hr	25h	19	0.684	6.509	6.650	21.1	47.4	15.8		
TLW-tlw	1.50 hr	25h	48	-0.083	2.769	2.797	10.4	47.9	14.6		

APPENDIX B. Time Series Plots of Semi-Operational Water Level Nowcasts vs. Observations from 15 April to 17 December 2004 at 8 NOS Gauges in Lake Erie.

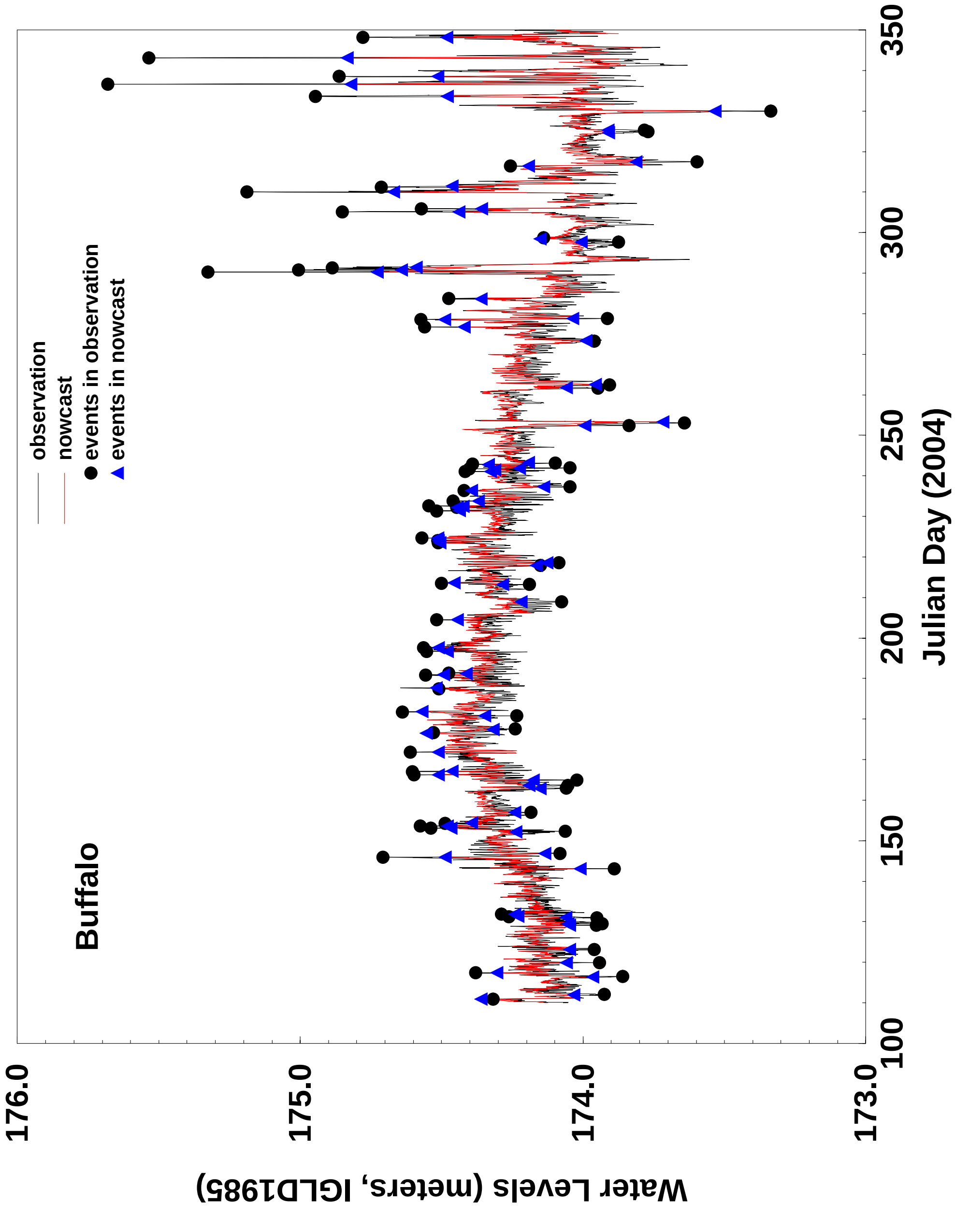

Fig. B.1. Time Series Plot of Semi-Operational Nowcasts of Water Level vs. Observations at NOS Gauge at Buffalo, NY during 2004.

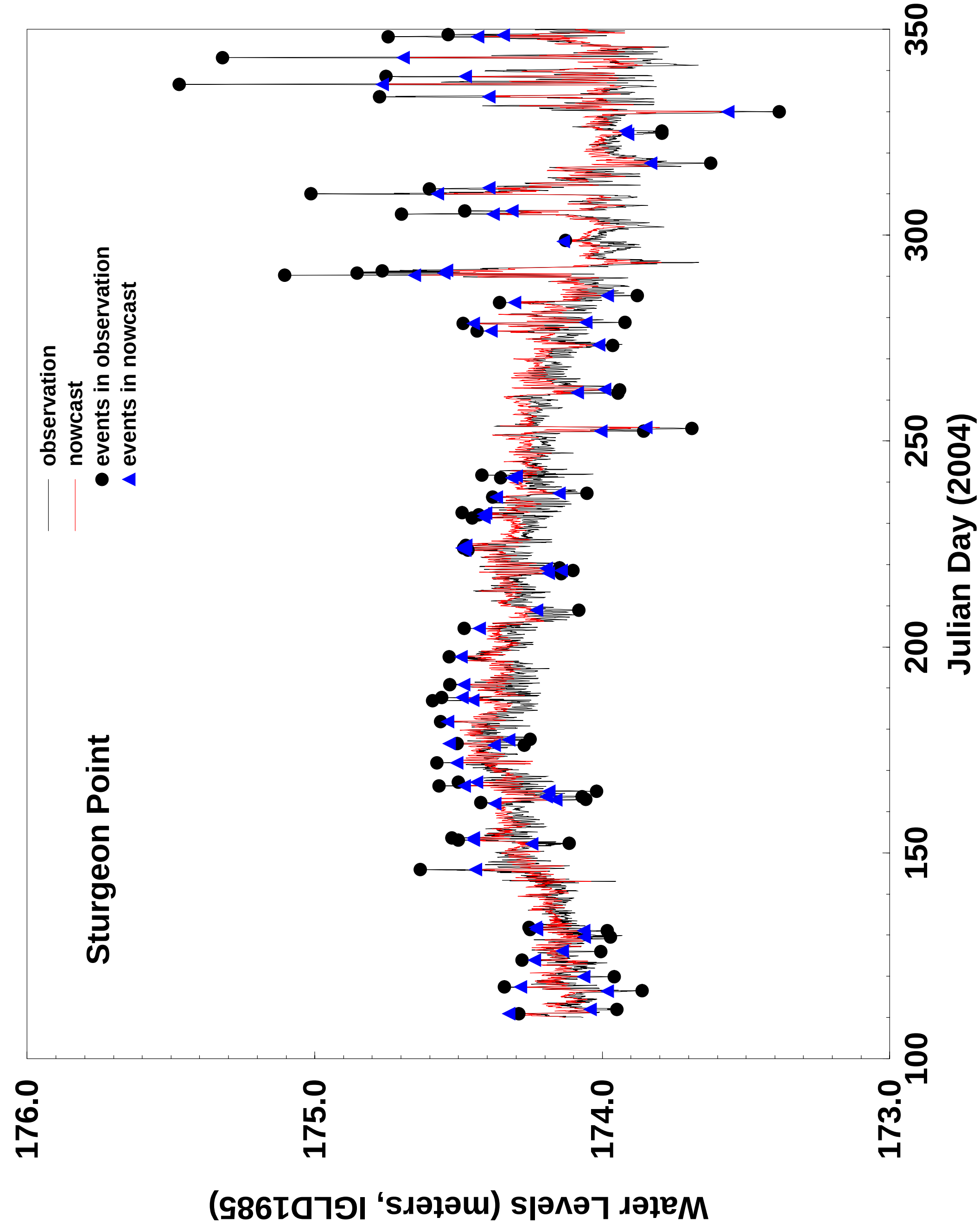

Fig. B.2. Time Series Plot of Semi-Operational Nowcasts of Water Level vs. Observations at NOS Gauge at Sturgeon Point, NY during 2004.

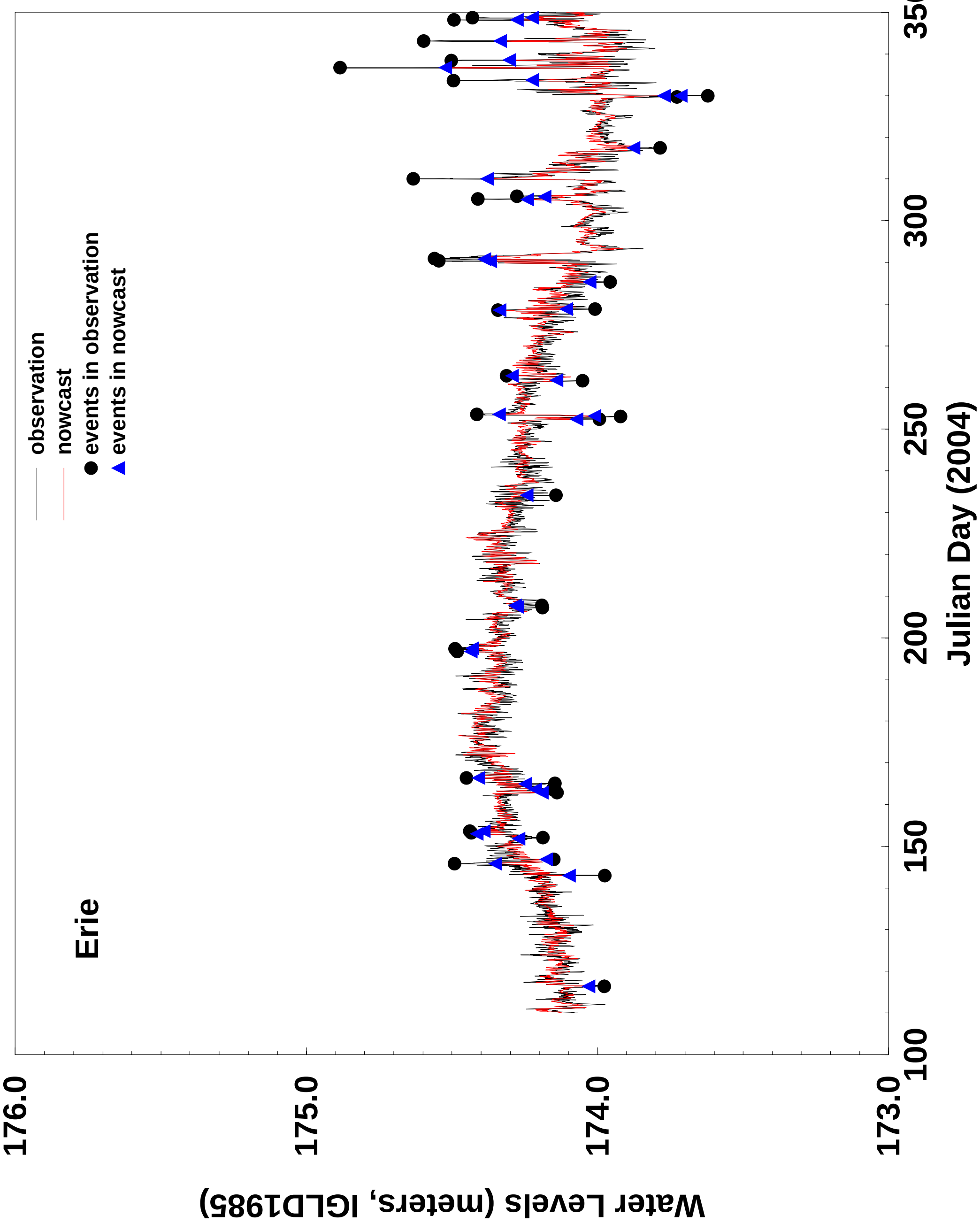

Fig. B.3. Time Series Plot of Semi-Operational Nowcasts of Water Level vs. Observations at NOS Gauge at Erie, PA during 2004.

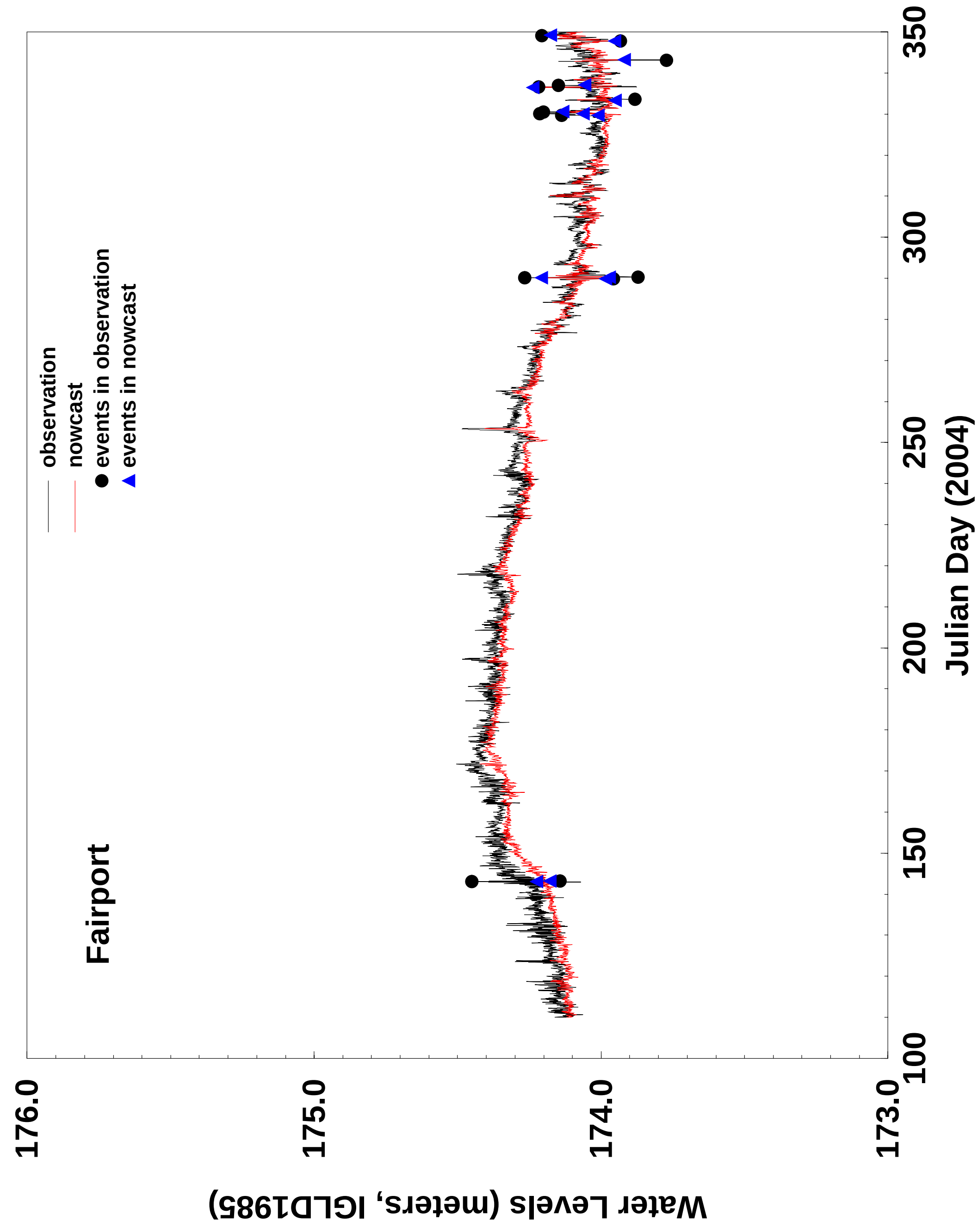

Fig. B.4. Time Series Plot of Semi-Operational Nowcasts of Water Level vs. Observations at NOS Gauge at Fairport, OH during 2004.

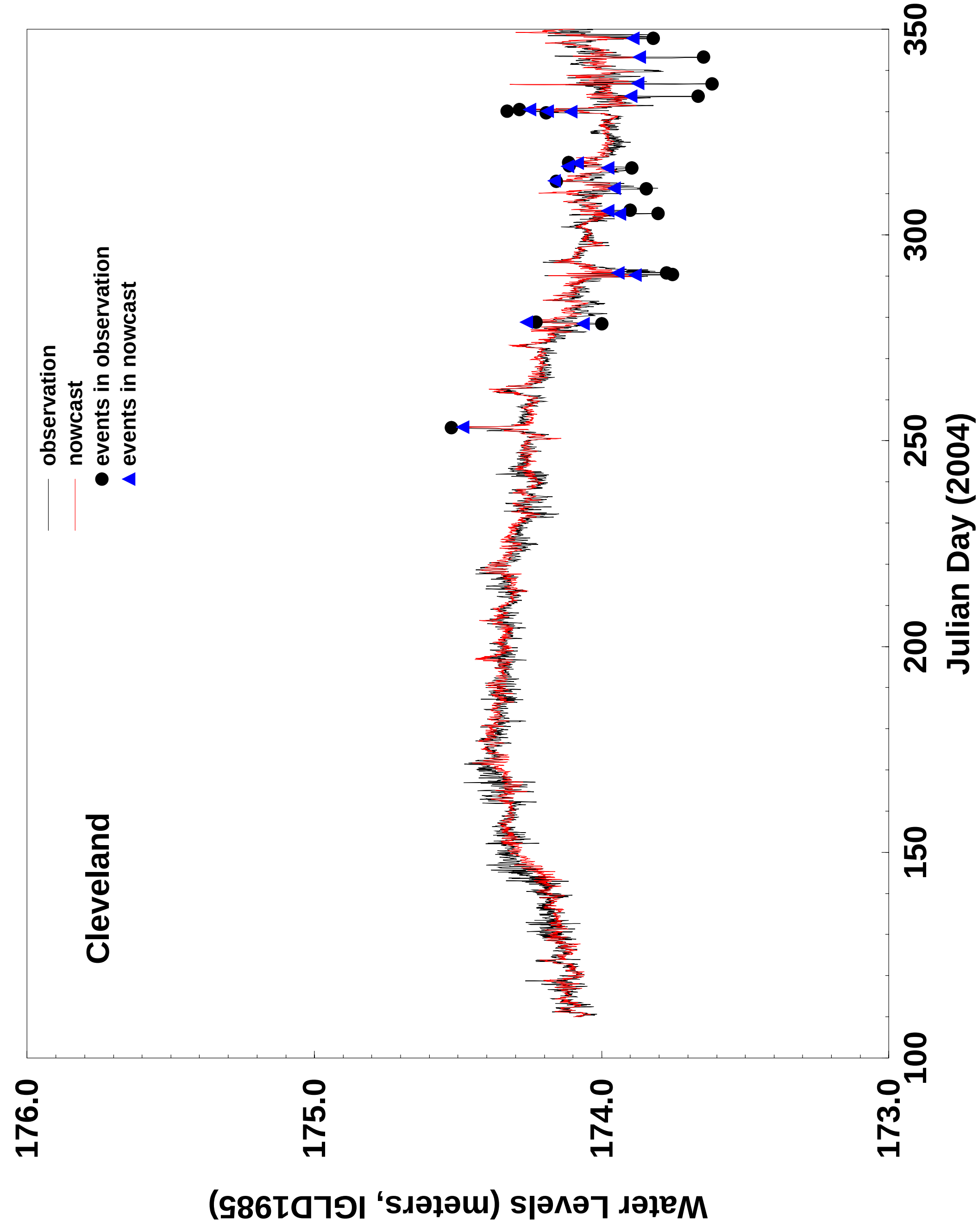

Fig. B.5. Time Series Plot of Semi-Operational Nowcasts of Water Level vs. Observations at NOS Gauge at Cleveland, OH during 2004.

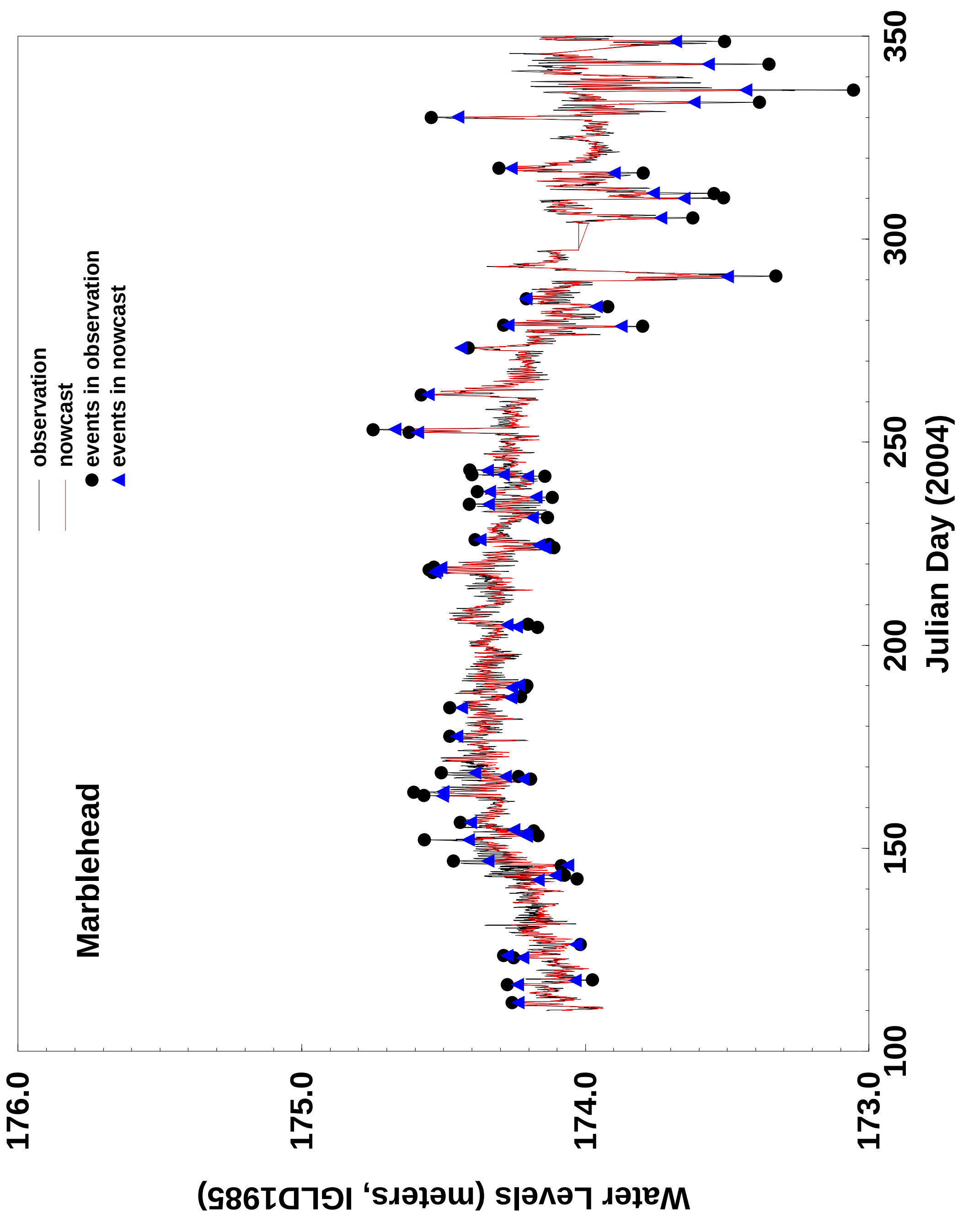

Fig. B.6. Time Series Plot of Semi-Operational Nowcasts of Water Level vs. Observations at NOS Gauge at Marblehead, OH during 2004.

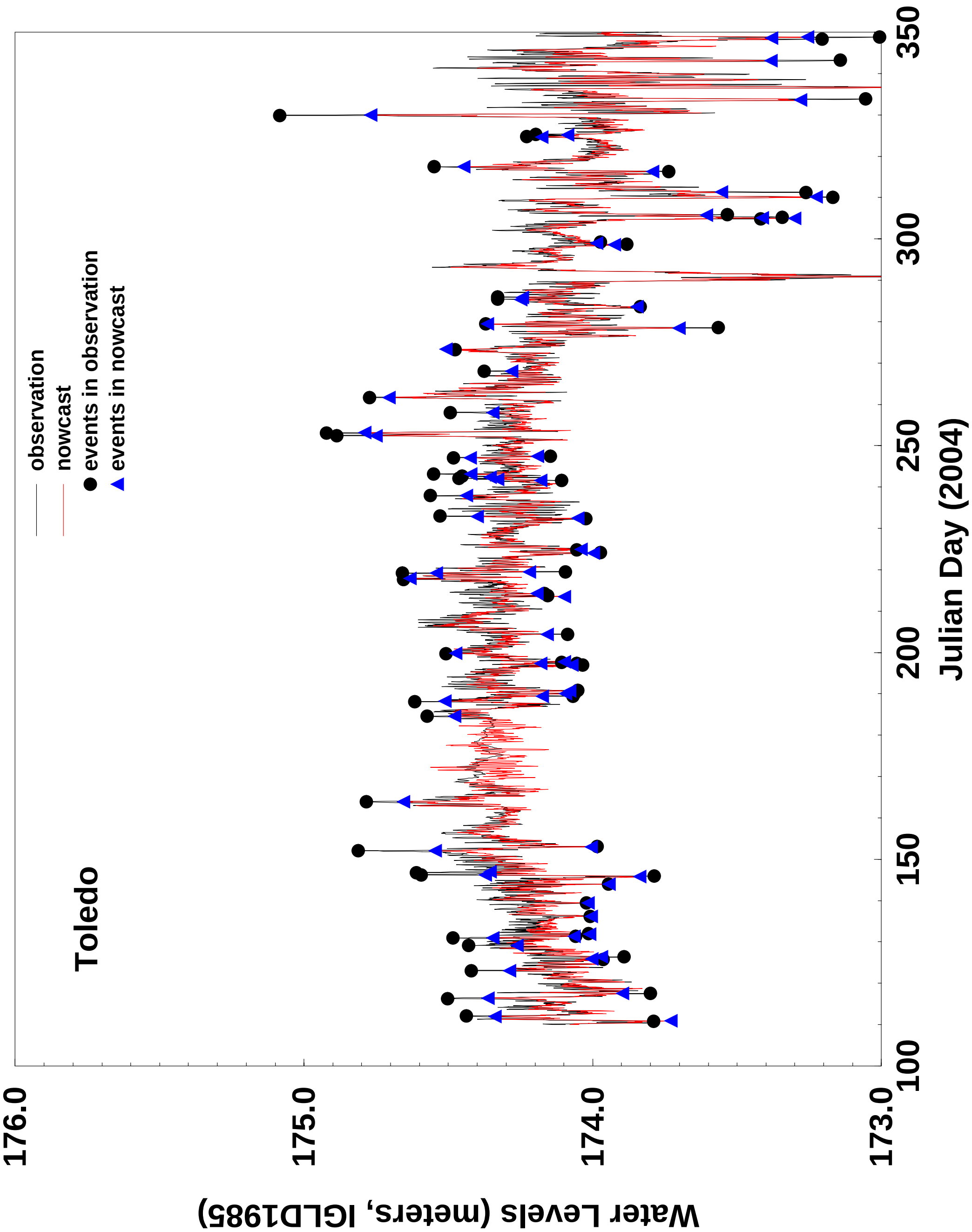

Fig. B.7. Times Series Plot of Semi-Operational Nowcasts of Water Level at NOS Gauge at Toledo, OH during 2004.

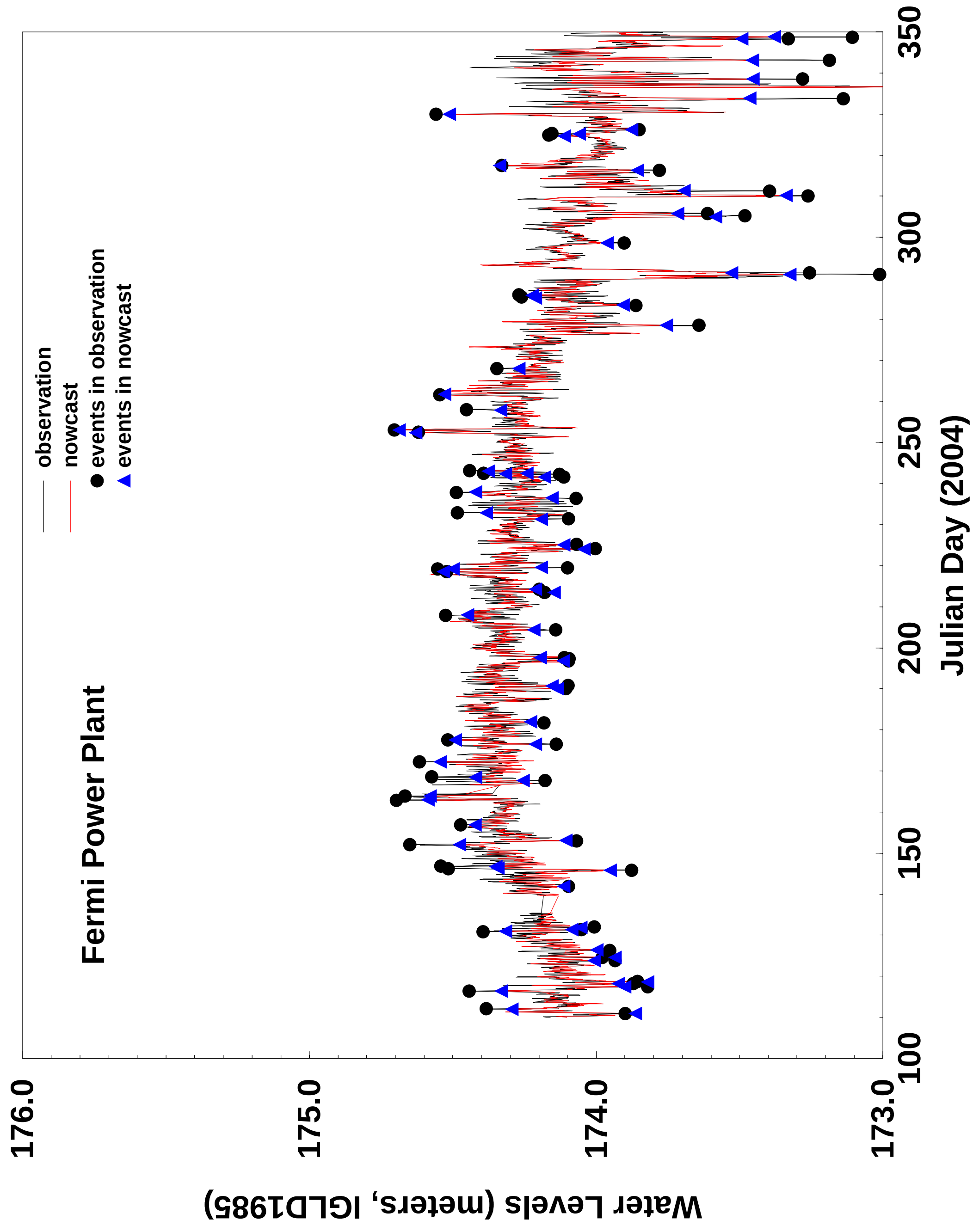

Fig. B.8. Times Series Plot of Semi-Operational Nowcasts of Water Level at NOS Gauge at Fermi Power Plant, MI during 2004.

APPENDIX C. Time Series Plots of Semi-Operational Water Level Forecast Guidance vs. Observations from 15 April to 17 December 2004 at eight NOS Gauges in Lake Erie.

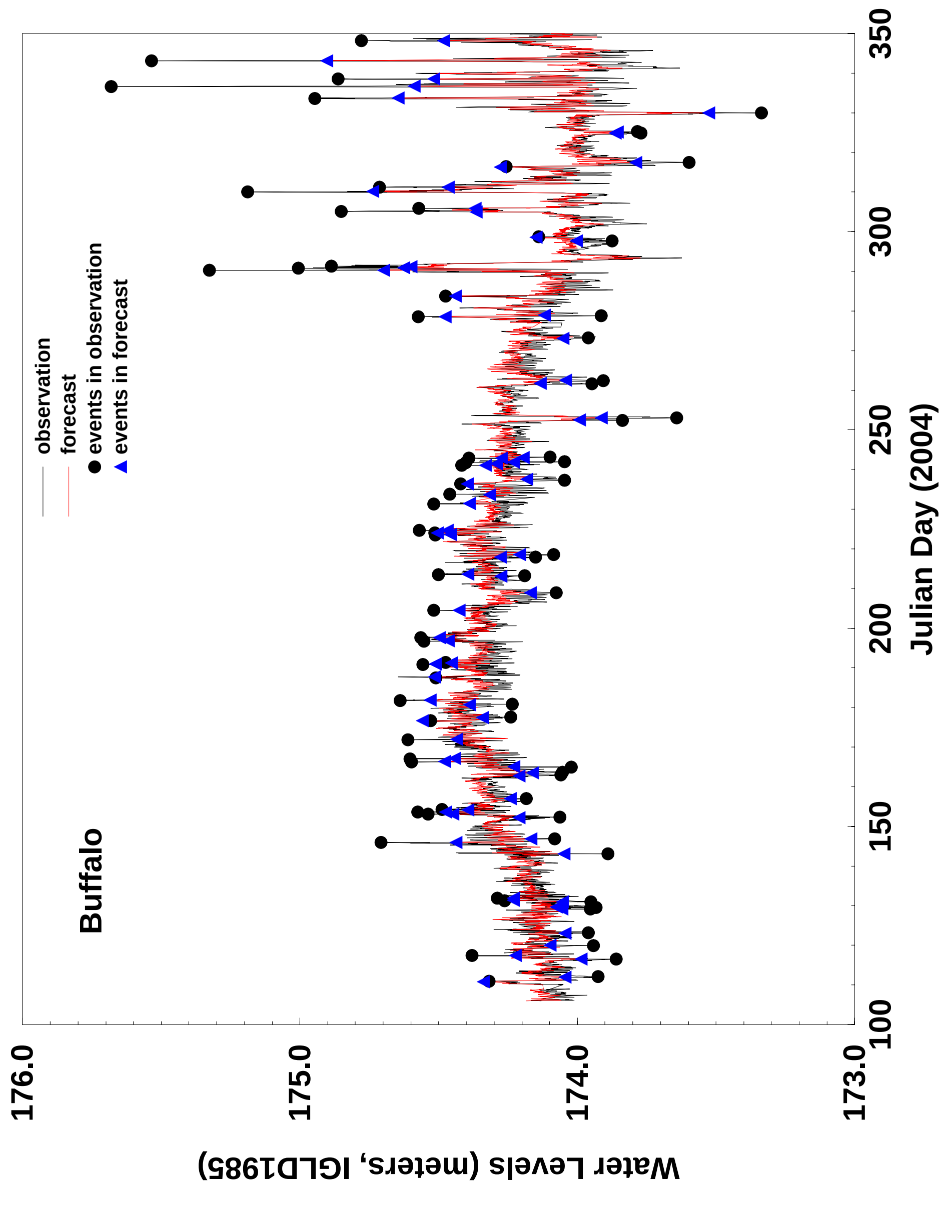

Fig. C.1. Times Series Plot of Semi-Operational Forecast Guidance of Water Level vs. Observations at NOS Gauge at Buffalo, NY during 2004.

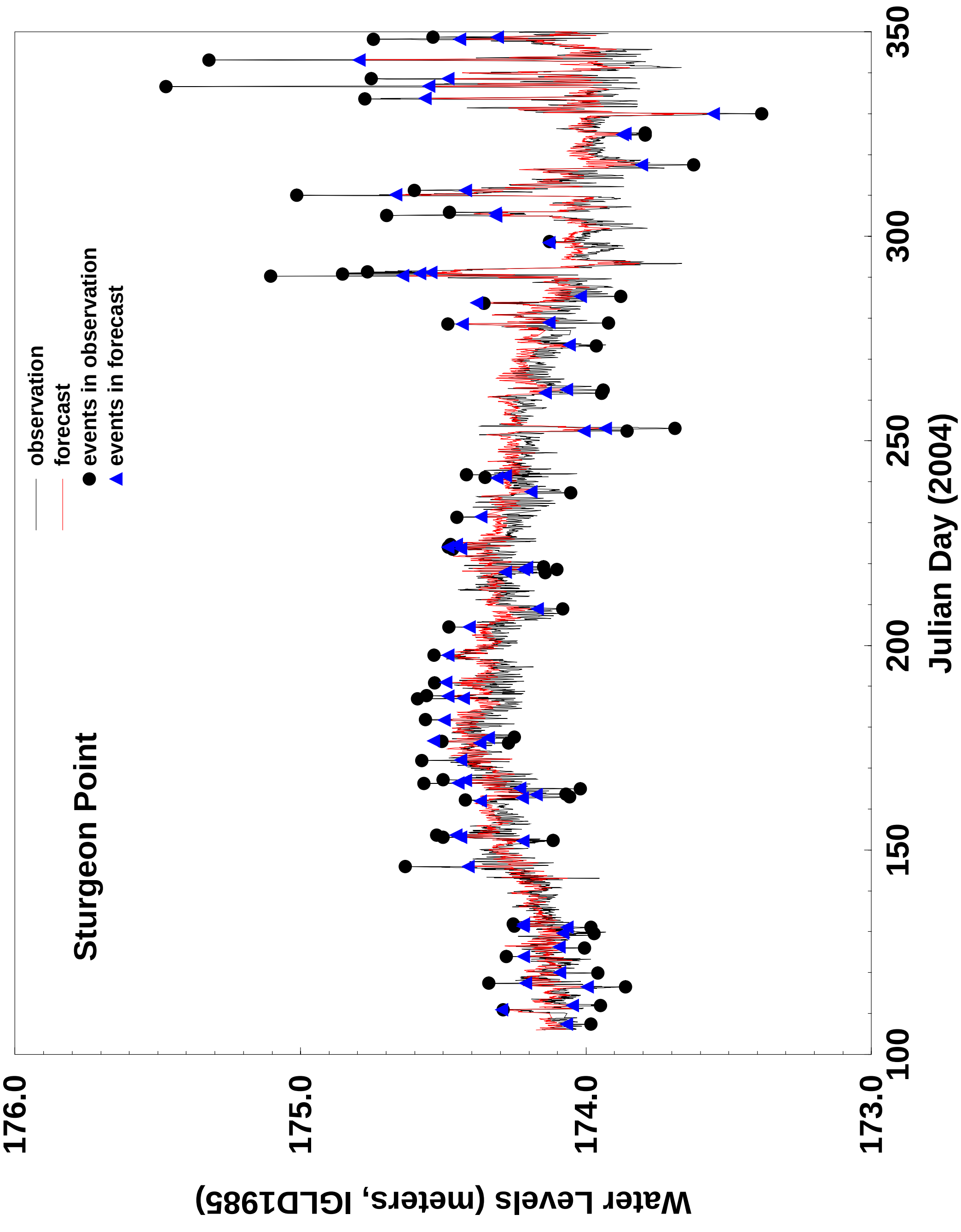

Fig. C.2. Times Series Plot of Semi-Operational Forecast Guidance of Water Level vs. Observations at NOS Gauge at Sturgeon, NY during 2004.

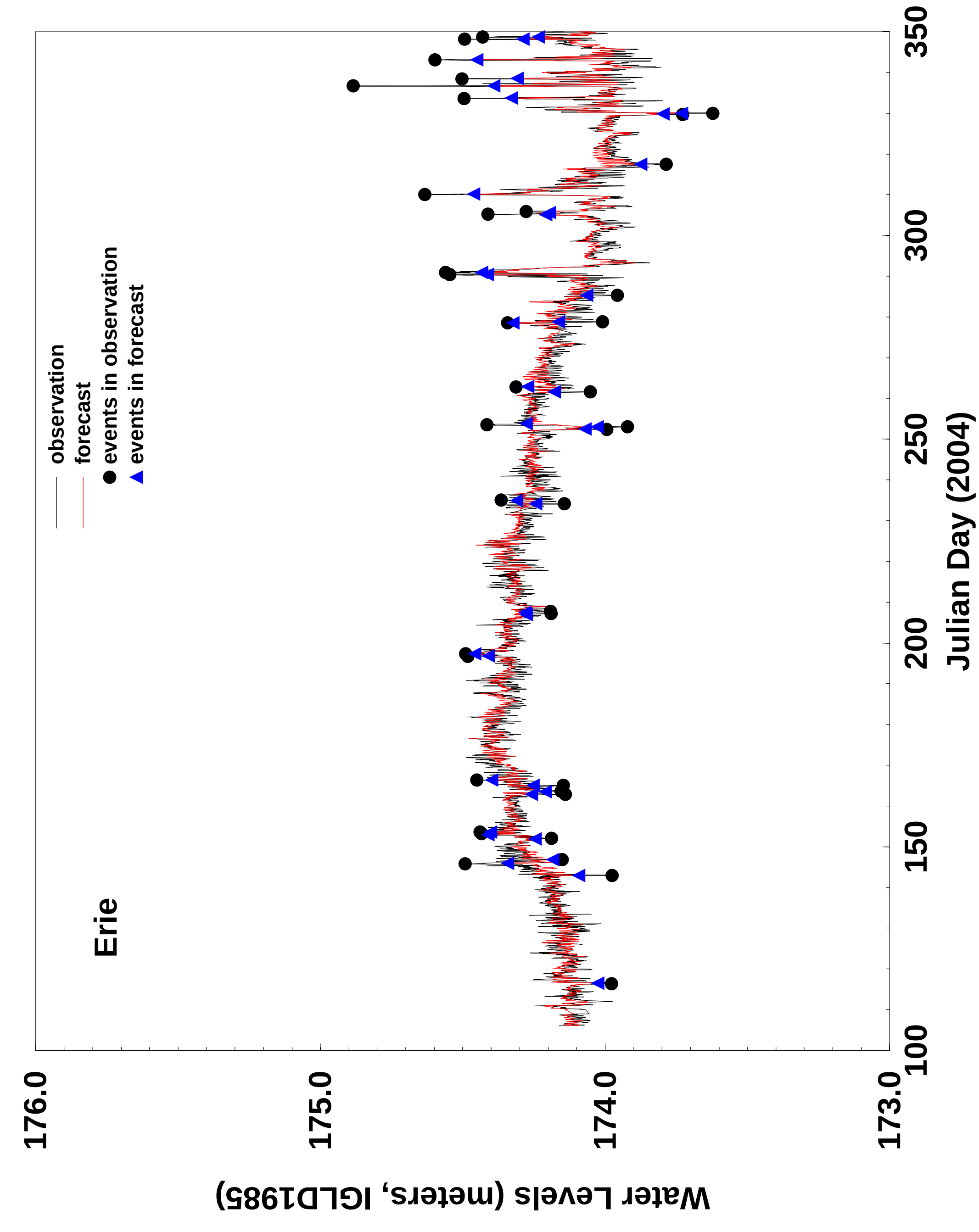

Fig. C.3. Time Series Plot of Semi-Operational Forecast Guidance of Water Level vs. Observations at NOS Gauge at Erie, PA during 2004.

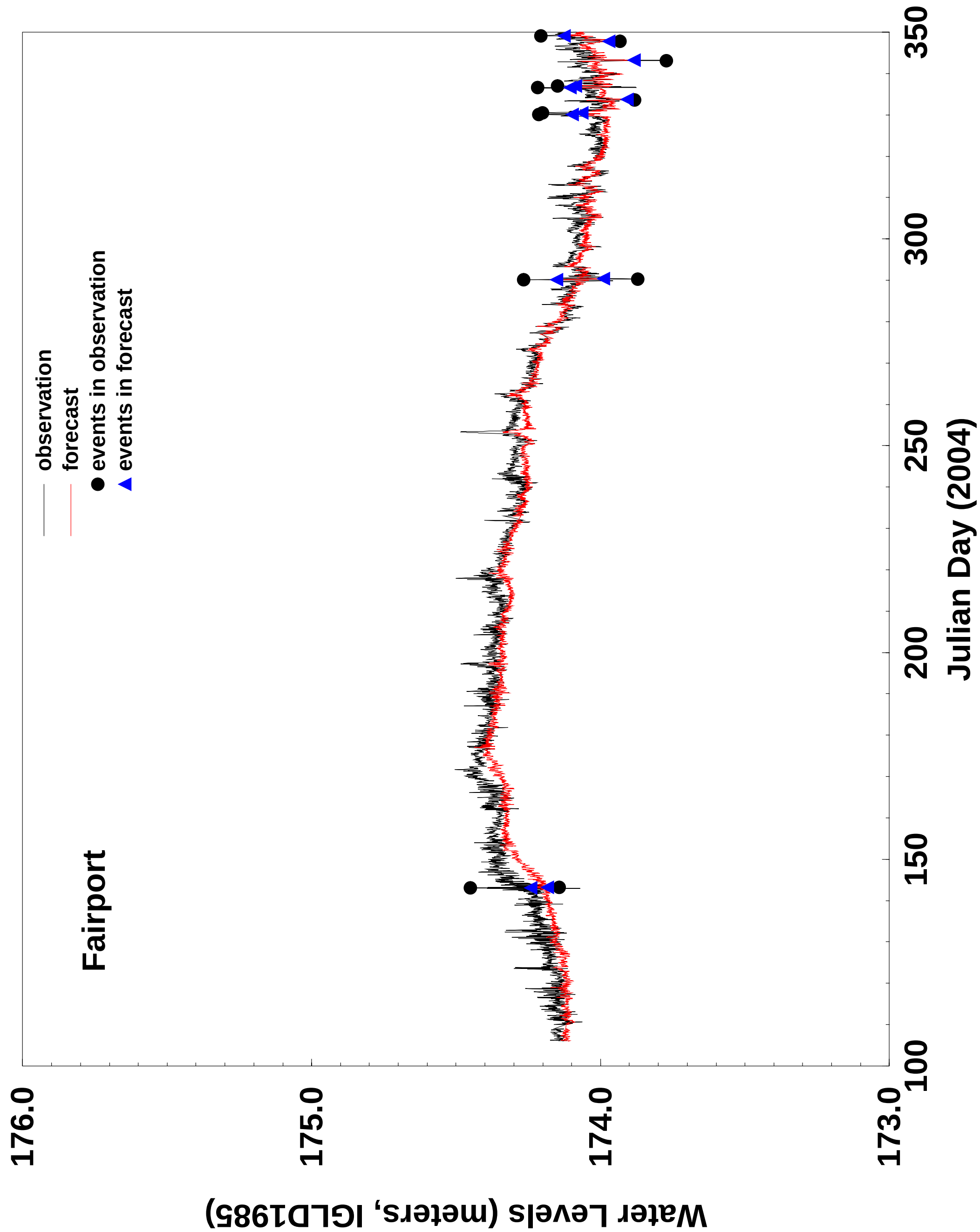

Fig. C.4. Time Series Plot of Semi-Operational Forecast Guidance of Water Level vs. Observations at NOS Gauge at Fairport, OH during 2004.

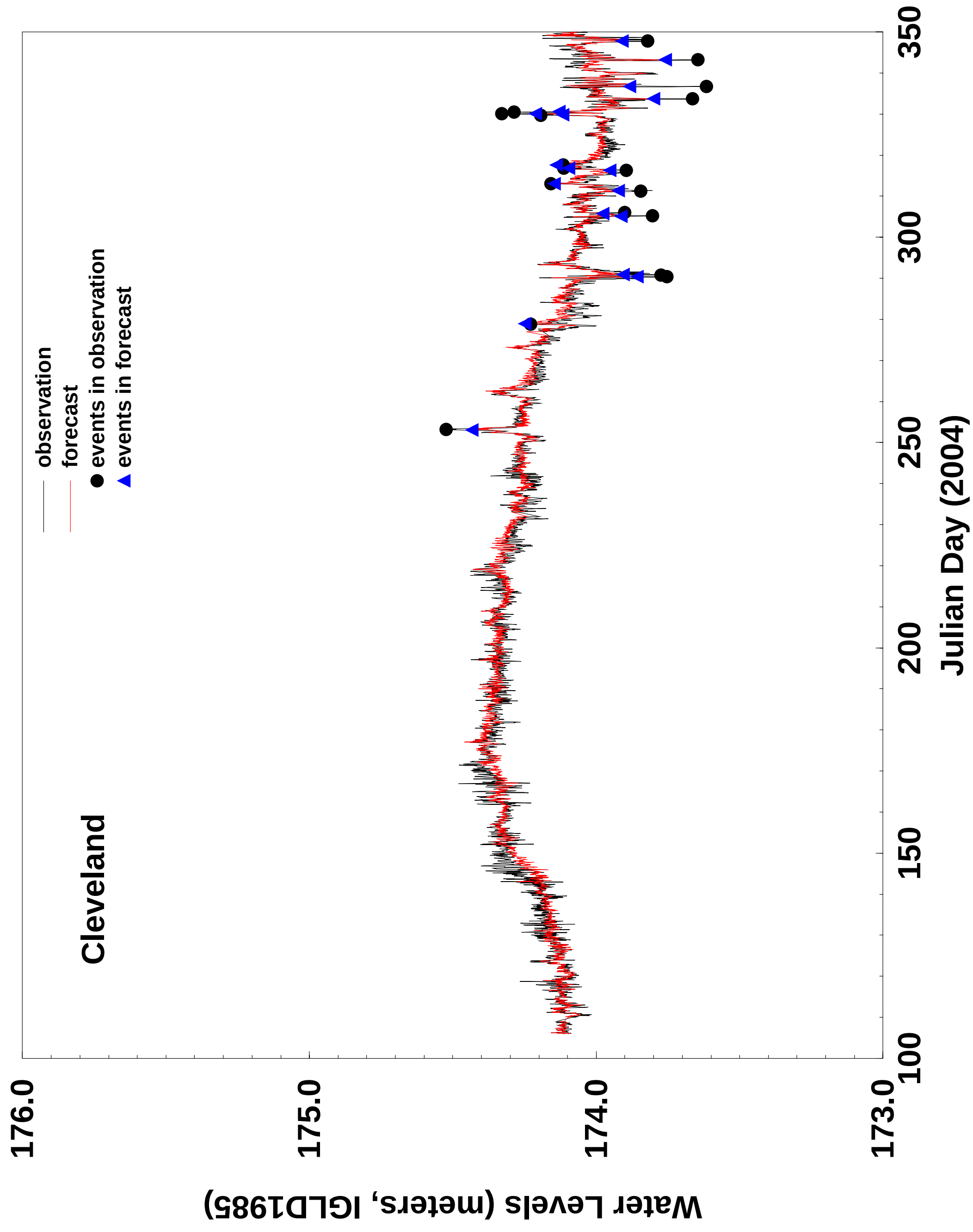

Fig. C.5. Time Series Plot of Semi-Operational Forecast Guidance of Water Level vs. Observations at NOS Gauge at Cleveland, OH during 2004.

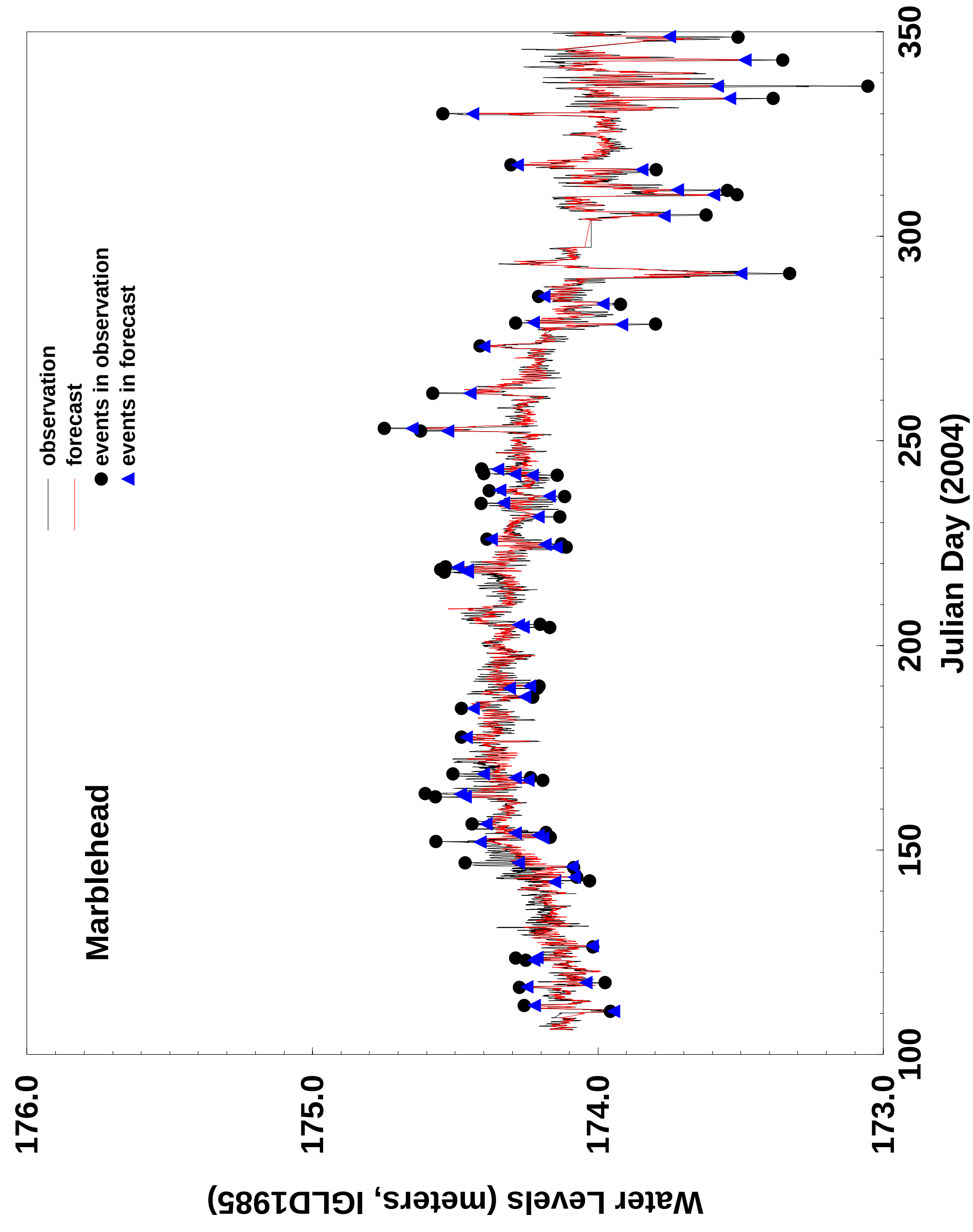

Fig. C.6. Time Series Plot of Semi-Operational Forecast Guidance of Water Level vs. Observations at NOS Gauge at Marblehead, OH during 2004.

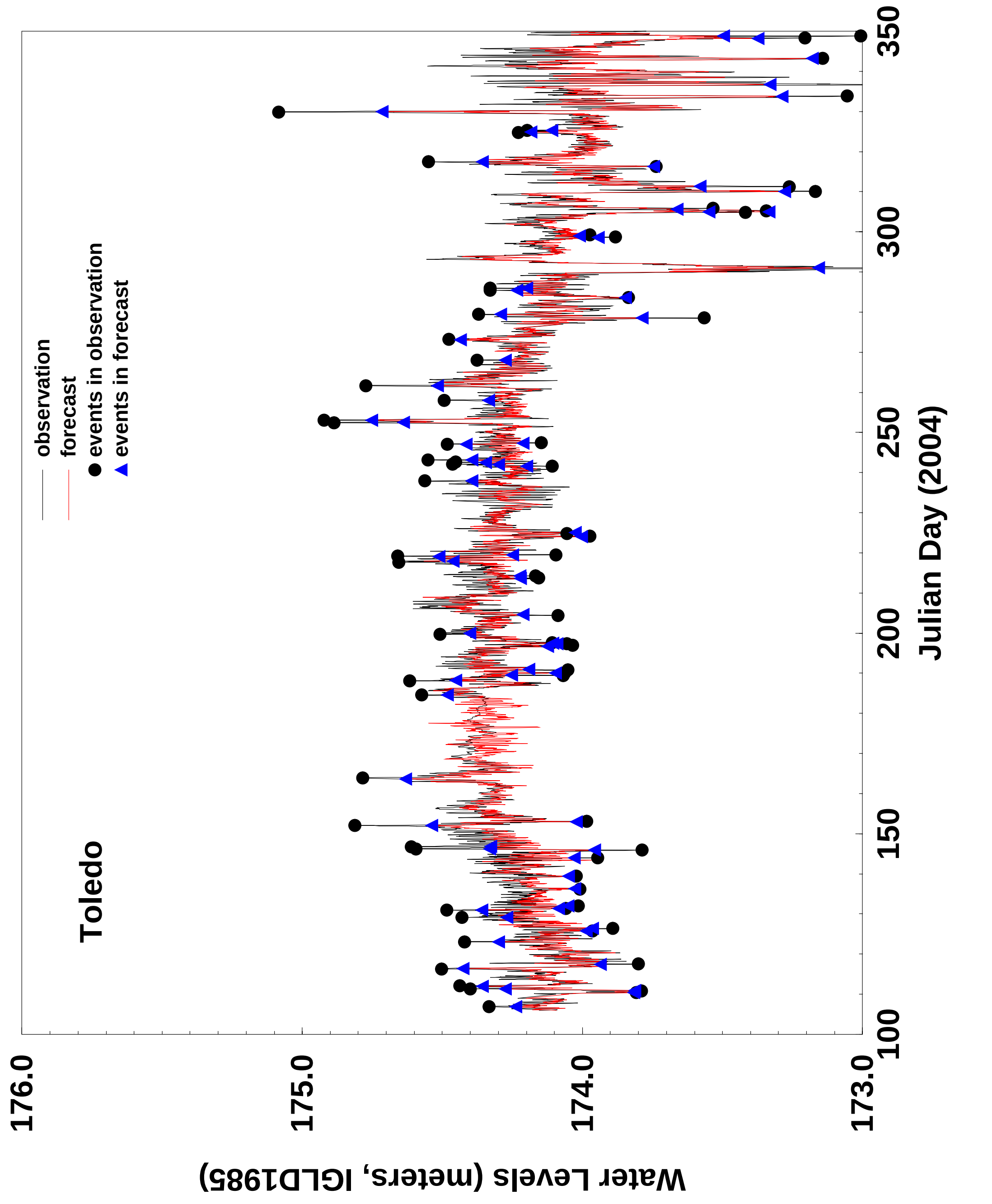

Fig. C.7. Time Series Plot of Semi-Operational Forecast Guidance of Water Level vs. Observations at NOS Gauge at Toledo, OH during 2004.

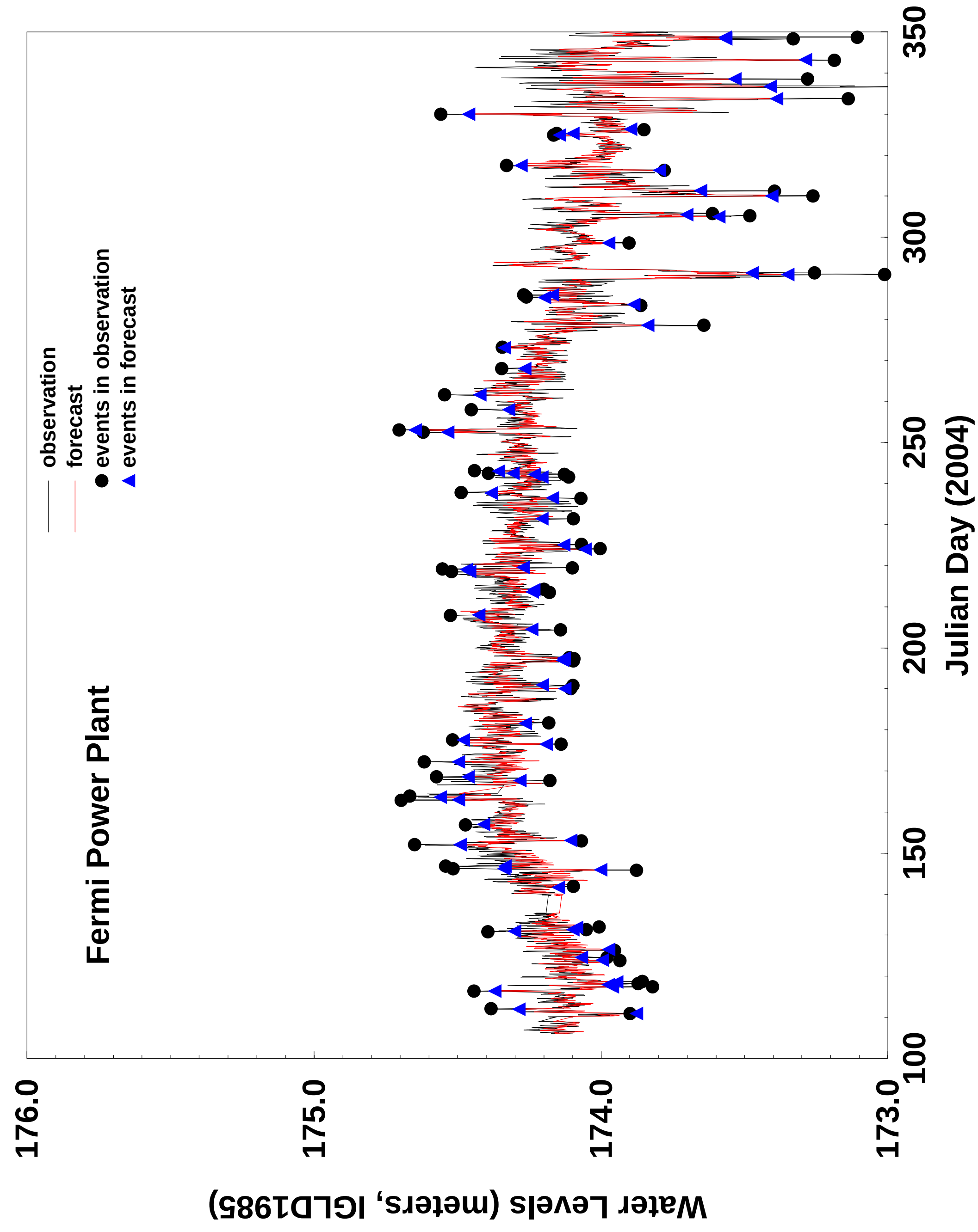

Fig. C.8. Time Series Plot of Semi-Operational Forecast Guidance of Water Level vs. Observations at the NOS Gauge at Fermi Power Plant, MI during 2004.

APPENDIX D. Skill Assessment Scores of Semi-Operational Nowcasts and Forecast Guidance of Surface Water Temperatures from 21 April to 8 December 2004 at a NDBC fixed buoy in Lake Erie.

Table D.1. Skill Assessment Statistics of Semi-Operational Nowcasts and Forecast Surface Water Guidance at the NWS/NDBC Fixed Buoy 45005 (Western Erie) for the Period 21 April to 8 December 2004.

Station: NDBC Buoy 45005 in Lake Erie
Longest continuous data time period from: 4/21/2004 to 12/8/2004
Data gap is filled using SVD method
Data are filtered using 3.0 Hour Fourier Filter

VARIABLE	X	N	IMAX	SM	RMSE	SD	NOF	CF	POF	MDNO	MDPO
CRITERION	-	-	-	-	-	-	<1%	>90%	<1%	<N	<N
SCENARIO: SEMI-OPERATIONAL NOWCAST											
T		5566	17.800								
t		5566	16.850								
T-t	3.0 c 24h	5566	0.951	1.292	0.875	0.0	98.7	0.0	0.0	0.0	
SCENARIO: SEMI-OPERATIONAL FORECAST											
T00-t00	3.0 c 24h	464	1.070	1.400	0.904	0.0	98.1	0.0	0.0	0.0	
T06-t06	3.0 c 24h	460	0.871	1.406	1.105	0.0	97.4	0.0	0.0	0.0	
T12-t12	3.0 c 24h	460	0.824	1.446	1.190	0.0	97.8	0.0	0.0	0.0	
T18-t18	3.0 c 24h	460	0.703	1.279	1.070	0.0	99.1	0.0	0.0	0.0	
T24-t24	3.0 c 24h	460	0.713	1.306	1.095	0.0	98.7	0.0	0.0	0.0	

APPENDIX E. Time Series Plots of Semi-Operational Nowcasts and Forecast Guidance of Surface Water Temperatures vs. Observations from 15 April to 17 December 2004 at a NDBC fixed buoy in Lake Erie.

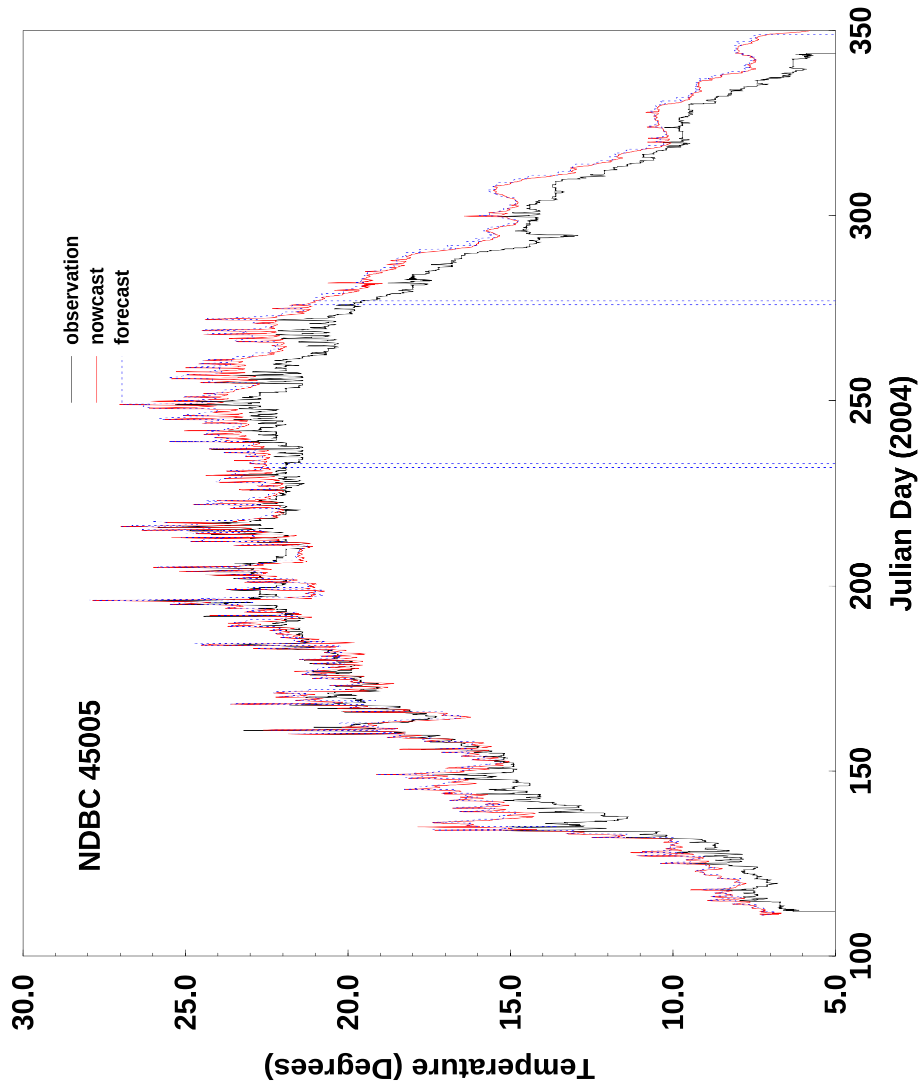

Fig. E.1. Time Series Plot of Semi-Operational Nowcasts and Forecast Guidance of Surface Water Temperatures (°C) vs. Observations at the NWS/NDBC Fixed Buoy 45005 (Western Lake Erie) for the Period 21 April to 8 December 2004. The forecast values depicted on the plot are from the 0000 UTC forecast cycle.

APPENDIX F. Description of NWS Water Level Criteria for Lakeshore Flood Warnings and Low Water Statements for Lake Erie.

For the Michigan shore of Lake Erie, the NWS WFO in Detroit, MI issues coastal flood warnings when the water level is expected to be 72 inches above NOS chart datum. The WFO Detroit issues low water statements for this area when water levels are expected to fall 10 inches or more below chart datum or in coordination with WFO Cleveland as appropriate. These general guidelines were developed over the years in collaboration with U.S. Coast Guard personnel and user groups (Richard Wagenmaker, 2006, personal communication).

For the Ohio and Pennsylvania shores of Lake Erie, the NWS WFO in Cleveland, OH issues flood warnings when the water level is expected to be 60 inches above NOS charge. The WFO issues low water statements for this area when water levels are forecast or observed to be below the critical mark for safe navigation. This threshold is determined by subtracting 24 inches from the bi-weekly forecast level issued by the U.S. Corps of Engineers, Detroit District (http://www.lre.usace.army.mil/greatlakes/hh/datalinks/PrinterFriendly/channeldepth.pdf) . "This value can be determined by using the lowest value in line 4 or line 5. Using the latest forecast level on the web site, the lowest value is 22 inches above chart datum. Subtracting 24 from 22, you get 2 inches below chart datum. So, in this example anytime the water level is forecast or observed to be 2 inches below chart datum or below, we would issue a low water statement/advisory" (Michael Dutter, 2006, personal communication).

For the New York shore of Lake Erie, the NWS WFO in Buffalo, NY issues flood warnings when the water level is observed or expected to reach 8 feet above low water datum (Thomas Niziol, 2006, personal communication). The Buffalo WFO does not issue low water statements since it so rare to have a low water event on the eastern shore of the lake.