NOAA Technical Memorandum NOS CS 8

SKILL ASSESSMENT OF NOS LAKE MICHIGAN OPERATIONAL FORECAST SYSTEM (LMOFS)

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National Ocean Service
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LIST OF ACRONYMS

ASOS	Automated Surface Observing System
AVHRR	Advanced Very High Resolution Radiometer
AWOS	Automated Weather Observing System
C-MAN	Coastal-Marine Automated Network
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
LEOFS	Lake Erie Operational Forecast System
LMOFS	Lake Michigan Operational Forecast System
LMMBS	Lake Michigan Mass Balance Study
NAM	North America Mesoscale Model
MMAP	Marine Modeling and Analysis Programs
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 State Coast Guard
VOS	Voluntary Observing Ship

EXECUTIVE SUMMARY

This document describes the Lake Michigan Operational Forecast System (LMOFS) 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 for Lake Michigan.

LMOFS is the result of technology transfer of the Great Lake Forecasting System (GLFS) and 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 model system skill assessment of LMOFS follows scenarios required by NOS standards for operational nowcast/forecast systems (Hess et al. 2003) which are applicable to 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 results of the Hydrodynamic Modeling Project of the Lake Michigan Mass Balance Study (SB98) were used to satisfy NOS skill assessment requirements. The modeling project was conducted by Drs. David Schwab and Dmitry Beletsky of GLERL for the years 1982-1983 and 1994-1995 and used the Princeton Ocean Model adapted to the Great Lakes (POMGL). The model had a grid increment of 5 km and 20 vertical sigma levels. This is the same configuration used by LMOFS.

SB98 compared POMGL water level simulations to observations at 8 NOS gauges. Surface water temperature simulations were compared to observations at 2-3 NWS fixed buoys. Subsurface water temperature simulations were compared to observations from GLERL moorings, municipal water intakes, ship surveys, and transects. Current simulations were evaluated against observations at GLERL current moorings.

The skill statistics from the SB98 hindcast simulations are summarized below:

1) Water Levels:

POMGL did not simulate the same amount of high frequency (>0.5/hr) fluctuations with amplitudes on the order of 5 cm that was seen in the observations. The mean algebraic differences (MAD) during 1983-84 and 1994-95 were +0.28 and +0.32 cm, respectively. The root mean square differences (RMSD) for the two periods were 3.62 and 4.02 cm, respectively. The correlation coefficients (CC) were 0.42 and 0.40 for the two periods. Large RMSDs (4.6-6.0cm) but high CCs (0.49-0.62) were found at the NOS gauges located at the south and north ends of the lake. The largest amplitude wind-induced water level fluctuations on the lake are usually exhibited at these two gauges. The highest RMSD was at Green Bay, WI with a value of 12.30 cm indicating the inability of POMGL to simulate the water levels in this small bay. Overall, POMGL was able to simulate the water level in the main part of the lake but given the 5 km grid increment and lack of atmospheric pressure gradients in its forcing fields, the model could not resolve many local effects such as harbor resonance and edge waves (SB98).

2) Surface Water Temperatures:

There was good agreement between POMGL simulations and observations in terms of both horizontal distribution and time evolution of the surface water temperatures. The MADs during 1983-84 and 1994-95 were 0.0 and +0.2^{o}C, respectively. The RMSDs for the two periods were 1.2 and 1.5^{o}C, respectively. The CCs were 0.99 and 0.96 for the two periods, respectively. These positive comparisons indicated that the heat fluxes near the lake's surface were correctly inputted into the model.

3) Subsurface Water Temperatures:

POMGL subsurface temperature simulations, especially in the thermocline region were not as good as at the surface. For the epilimnion (upper layer), the MADs were -0.7 and +0.4^{o}C for the two periods, respectively. The RMSDs were 2.5 and 2.4^{o}C and the CCs were 0.87 and 0.93, respectively. For the hypolimnion (lowest layer of water), the MADs were +0.1 and +0.8^{o}C for the two periods, respectively. The RMSDs were 0.7 and 1.3^{o}C and the CCs were 0.78 and 0.87, respectively. These subsurface and surface comparisons, as well as comparisons with ship transect data, indicate that POMGL reproduced the basic features of the thermal structure evolution in the lake. However, the modeled thermocline was too diffuse and also the model did not simulate the frequent temperature fluctuations in this region.

4) Currents:

POMGL was found to properly simulate a cyclonic large-scale circulation pattern with cyclonic circulation within each subbasin, and anticyclonic circulations in ridge areas of the lake as indicated by previous observational studies. Comparisons of POMGL simulations to current observations using normalized Fourier norm resulted in values between 0.70 and 1.00 where values greater than 0 and less than 1 indicate a simulation better than no prediction at all. According to SB98, the model did the best in the southern basin (which is characterized by smooth bathymetry) and in the fall-winter months when barotropic processes are dominant. During the spring-summer months when baroclinic are dominant, the horizontal resolution (5 km) is too coarse to properly simulate these processes which have horizontal length scales comparable to the Rossby deformation radius (~ 5 km).

For the semi-operational nowcast and forecast scenarios, an evaluation of GLERL's real-time nowcast (4 times/day) and forecast (2 times/day) cycles from the Great Lakes Coastal Forecast System (GLCFS) for Lake Michigan were used to satisfy NOS evaluation standards (Hess et al., 2003). Although Hess et al. (2003) recommends conducting evaluations for 365 days in order to capture all expected seasonal conditions, GLCFS nowcasts and forecast guidance were evaluated for the ice free period from 15 April to 17 December 2004. 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 Michigan.

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 mean (SM), 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 nowcast and forecast scenarios are summarized below:

(1) Water Levels:

Nowcasts:

The hourly water nowcasts met the NOS acceptance criteria for amplitude at all 6 NOS gauges. The MAD ranged between -2.1 cm and +1.9 cm. The nowcasts under-predicted the hourly water levels at all gauges except at Port Inland, MI. The RMSE among the 6 gauges ranged between 4.8 and 7.0 cm. The hindcasts from 1982-83 and 1994-95 performed better than the nowcasts. The reason for this is not clear but could be due to the different method used to estimate mean lake-wide water level, the density and location of wind observations or some other factor.

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 nowcast predictions of high water level events passed the NOS criteria for amplitude at 2 of the 6 NOS gauges, while the predictions of low water level events passed the NOS criteria at 3 of the 6 NOS gauges. The nowcasts failed to meet NOS criteria in predicting the timing of both extreme high and low water events at all the NOS gauges.

Forecast Guidance:

The hourly forecast guidance met the NOS criteria at all 6 locations. The MAD ranged between -1.7 to + 1.3 cm and the RMSE ranged between 5.0 and 7.2 cm, very similar to the statistics for the nowcast evaluation. Similar to the nowcasts, the greatest error was at the Calumet Harbor, IL gauge located at the southern end of the lake. The forecast under-predicted the water levels at all gauges except at Port Inland, MI. There was no significant increase in the MAD, RMSE, or CF values as the forecast projection increased in time.

The forecast guidance of extreme high and low water level events passed NOS criteria at 2 and 4 of the 6 gauges, respectively. The forecast guidance failed to meet NOS criteria in predicting the timing of both extreme high and low water events at all NOS gauges.

(2) Surface Water Temperatures:

Nowcasts:

The hourly water temperature nowcasts meet the NOS criteria at the southern buoy. The nowcasts came very close to meeting NOS criteria at the northern buoy, failing to meet the CF by 7%. The MAD for the period ranged between 0.7 and 1.4^{o}C and the RMSE ranged between 1.5 and 2.2^{o}C.

Forecast Guidance:

The hourly water temperature forecast guidance at 24 hours for the southern buoy passed the NOS criteria while the southern one came very close at 87%. The MAD ranged between 0.5 and 1.2^{o}C and RMSE between 1.3 and 1.9^{o}C, which were slightly lower than for the nowcasts. The RMSE of the hourly water temperature forecasts slightly decreased as the forecast projection increased in time.

Key Words: short-term lake predictions, nowcasts, model forecast guidance, Lake Michigan, skill assessment, water levels, water currents, water temperatures, Princeton Ocean Model, North American Mesoscale weather prediction model

1. INTRODUCTION

The Great Lakes Coastal Forecasting System (GLFS) was developed by The Ohio State University (OSU) and NOAA's Great Lakes Environmental Research Laboratory (GLERL) in the late 1980s and 1990s to provide nowcasts and short-range forecasts of the physical conditions (temperature, currents, water level, and waves) of the five Great Lakes (Schwab and Bedford 1994). 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 over 36 contracts from 25 different sources. From the start, GLERL and OSU were interested in working cooperatively with NOAA 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) 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 (Bedford and Schwab 1991; Yen et al. 1994). Starting in July 1995, twice per day forecasts were made for Lake Erie. 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 GLERL workstation in Ann Arbor, MI. GLERL's workstation version of GLFS, called The Great Lakes Coastal Forecast System (GLCFS), has been running in semi-operational mode at GLERL for Lake Michigan since April 2001. GLCFS for Lake Michigan 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 Common Modeling Framework (COMF) and to use surface meteorological observations from NOS' Operational Data Acquisition and Archive System (ODAAS). The CO-OPS version of GLCFS for Lake Michigan was renamed as the Lake Michigan Operational Forecast System (LMOFS). LMOFS began making operational nowcasts and forecasts for Lake Michigan on September 30, 2005 at CO-OPS.

LMOFS along with LEOFS represents the first NOS forecast systems to be implemented for non-tidal water bodies. The predictions from LMOFS, similar to those from NOS estuarine forecast systems, must be evaluated to inform users about the skill of the nowcasts and forecasts.

In evaluating LMOFS, 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 routinely-produced nowcasts and forecasts produced by GLERL to fulfill the semi-operational nowcast 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). Brief descriptions of Lake Michigan and an overview of LMOFS are given first.

2. LAKE MICHIGAN

Lake Michigan is the third largest of the Great Lakes and the fifth largest lake in the world, with a width of 100 km and a length of 500 km. It has an average depth of 85 m and a maximum depth of 281 m. Because of its considerable depth, the lake exhibits considerably smaller short term water level fluctuations than Lake Erie, where the wind-induced water level fluctuations often exceed 1 m (Schwab 1978). In Lake Michigan, typical wind-induced water level fluctuations are only in the range of 10-20 cm (SB98). Lake Michigan, similar to other Great Lakes, has a pronounced annual thermal cycle ranging from a vertically well-mixed water body in late autumn to thermal stratification across the entire lake with a well-developed thermocline (Boyce et al. 1989; SB98).

Lake Michigan experiences three types of water level fluctuations. Short-term changes occur due to surface winds and changes in atmospheric pressure. Seasonal changes occur with the lowest levels during the winter and highest during the early autumn. The lowest levels occur during winter, when evaporation is the greatest and more water is leaving the lake than entering it. During the spring the water level begins to rise as runoff from melting snow increases and evaporation decreases, as the air above the lake becomes warm and moist and the lake is relatively cold. The highest levels occur in early to mid autumn, just before the amount of water leaving the lake due to outflows and increased evaporation exceeds the amount of water entering the lake. Long term water level changes occur over consecutive years, with wet/cold years causing water levels to rise and warm/dry years resulting in lower water levels (GLIN 2006).

3. SYSTEM OVERVIEW

This section provides a brief description of the numerical hydrodynamic model used by LMOFS. Detailed descriptions of the model as it has been applied to Lake Michigan can be found in SB98). Similar descriptions of the model as it has been applied to Lake Erie are given by Hoch (1997), Kuan (1995), and Kelley (1995).

3.1 Description of Model

The core numerical model in LMOFS is the Princeton Ocean Model (POM) developed by Blumberg and Mellor (1987). The model is a fully three-dimensional, non-linear primitive equation coastal ocean circulation model, with a second order Mellor-Yamada turbulence closure scheme to provide parameterization of vertical mixing processes. The model solves the continuity equation, momentum equations and conservation equations for temperature simultaneously in an iterative fashion. 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 coordinates in the vertical (sigma coordinate), finite difference numerical scheme, Boussinesq and hydrostatic approximation, mode splitting technique.

POM was modified by researchers at OSU and GLERL for use in the Great Lakes (Schwab and Bedford 1994; O'Connor and Schwab 1994). For the rest of this report, the modified version of the POM for the Great Lakes will be referred to as POMGL. Lake Michigan, 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 lakewide 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 POMGL domain for Lake Michigan consists of a rectangular grid with a 5-km horizontal resolution in both the x- and y-directions. The domain has a total of 2318 grid points with 53 points in the x-direction and 102 points in the y-direction (Figure 1). 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 uses 20 sigma levels in the vertical with vertical levels spaced more closely in the upper 30 m of water and near the bottom to better resolve both the seasonal thermocline and bottom boundary layer (SB98). The levels are located at sigma values of 0, -.0227, -.0454, -.0681, -.0908, -.1135, -.1362, -.1589, -.1816, -.2043, -.2270, -.2724, -.3405, -.4313, -5448, -.6810, -.7945, -.8853, -.9534, and -1.0.

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 the 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 decoded and written out to a text file for use by LMOFS and other NOS operational forecast systems. The surface observation text file is available to LMOFS within a minute of receiving the observations from the CCS.

The text file includes surface observations from a variety of observing networks on and around Lake Michigan. On land, these 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 United States Coast Guard (USCG) stations around the lake are not available in the NCEP data tanks.

Over water, the networks included 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 LMOFS or by any of the other Great Lakes forecast systems.

3.4 Nowcast Cycle

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

The initial conditions for the nowcast cycle are provided by 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 correction and overland adjustment procedure use the previous day' 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 Very 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).

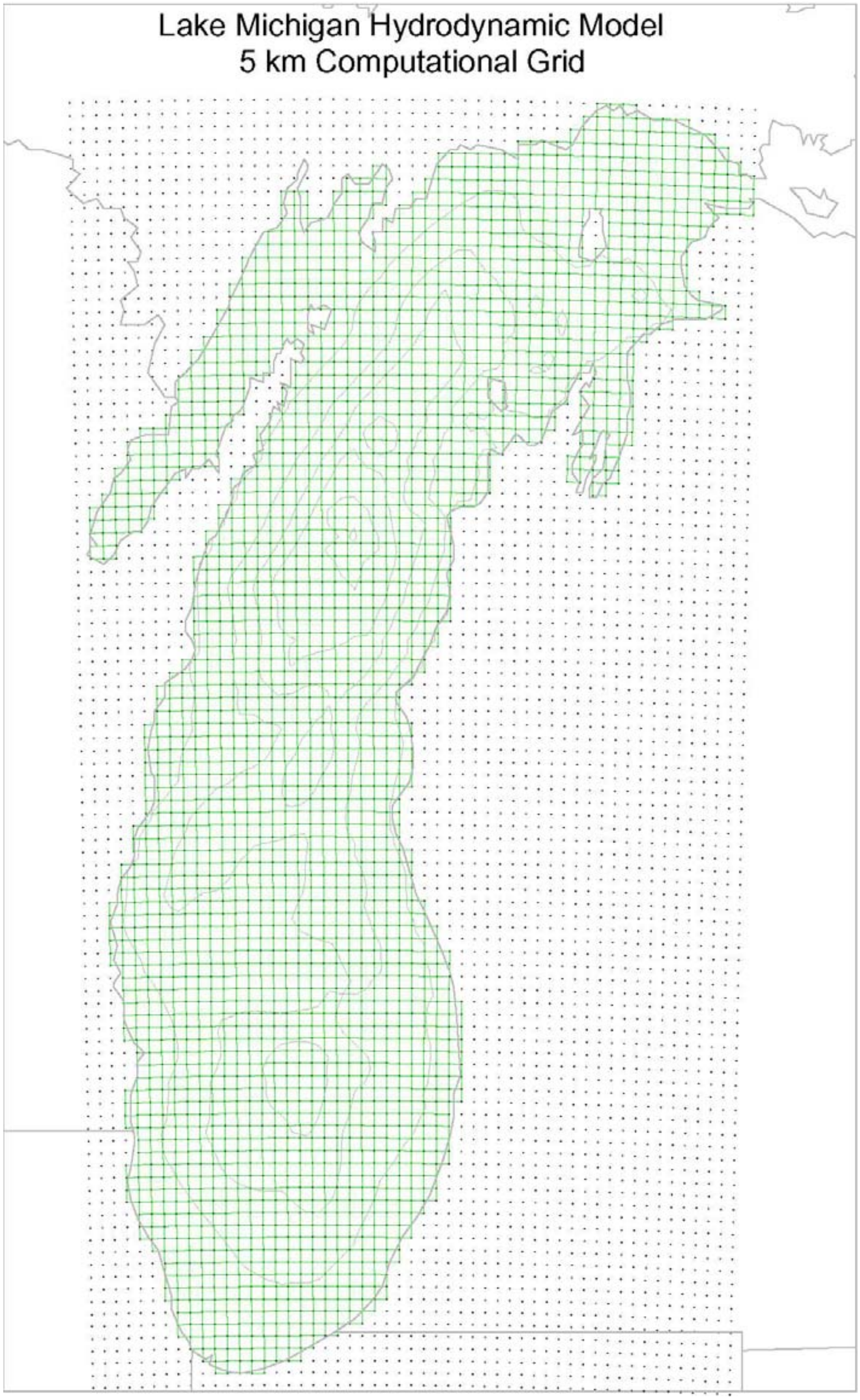


Figure 1. Map depicting the POMGL grid domain (5 km spatial resolution) used by NOS' Lake Michigan Operational Forecast System (from SB98).

3.5 Forecast Cycle

The forecast cycle of LMOFS is run four times per day to generate forecast guidance of the 3-D state of Lake Michigan. The forecast cycle uses the most recent nowcast for 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, 6, 12, or 18 UTC forecast cycles of NWS/NCEP's North American Mesoscale (NAM) model. Presently, NAM uses the Weather Research and Forecast (WRF) 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 forecast cycle does not use surface pressure guidance from NAM in forcing POMGL

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.

3.6 Operational Environment and Scheduling

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

The forecast cycle of LMOFS is run four times per hour at 0000, 0600, 1200, and 1800 UTC at 50 minutes past the top of the hour. The forecast horizon of each forecast cycle is 30 hours.

LMOFS and also the forecast system for Lake Erie were officially implemented as an operational forecast system at CO-OPS on the afternoon of September 30, 2005.

4. HINDCAST SKILL ASSESSMENT

The results of the Hydrodynamic Modeling Project conducted by Drs. David Schwab and Dmitry Beletsky SB98, hereafter SB98) of GLERL for the EPA Lake Michigan Mass Balance Study (LMMBS) serves as the basis for the NOS required hindcast scenario assessment (Hess et al. 2003). The purpose of the LMMBS (http://www.epa.gov/glnpo/lmmb) was to seek the "sources, pathways and fate of contaminants cycling through Lake Michigan." The objectives of the modeling project for the LMMBS were to 1) implement a three-dimensional hydrodynamic model for Lake Michigan, 2) calibrate the model with GLERL current meter and temperature data from the GLERL 1982-83 Lake Michigan field program, 3) use the model to simulate three-dimensional transport and thermal structure in Lake Michigan during the mass balance study field season of 1994-1995, and 4) couple the hydrodynamic model with a sediment re-suspension and transport model being developed at the EPA Large Lakes Research Station.

SB98 conducted model simulations using POMGL for Lake Michigan during 1982-1983 and also 1994-1995. They compared their model simulations to observations and their findings were published in a NOAA Technical Memorandum (SB98). A summary of their findings with respect to the NOS skill assessment requirements for the hindcast scenario (Hess et al. 2003) are presented in the following sections.

4.1 Description of Hindcast Runs

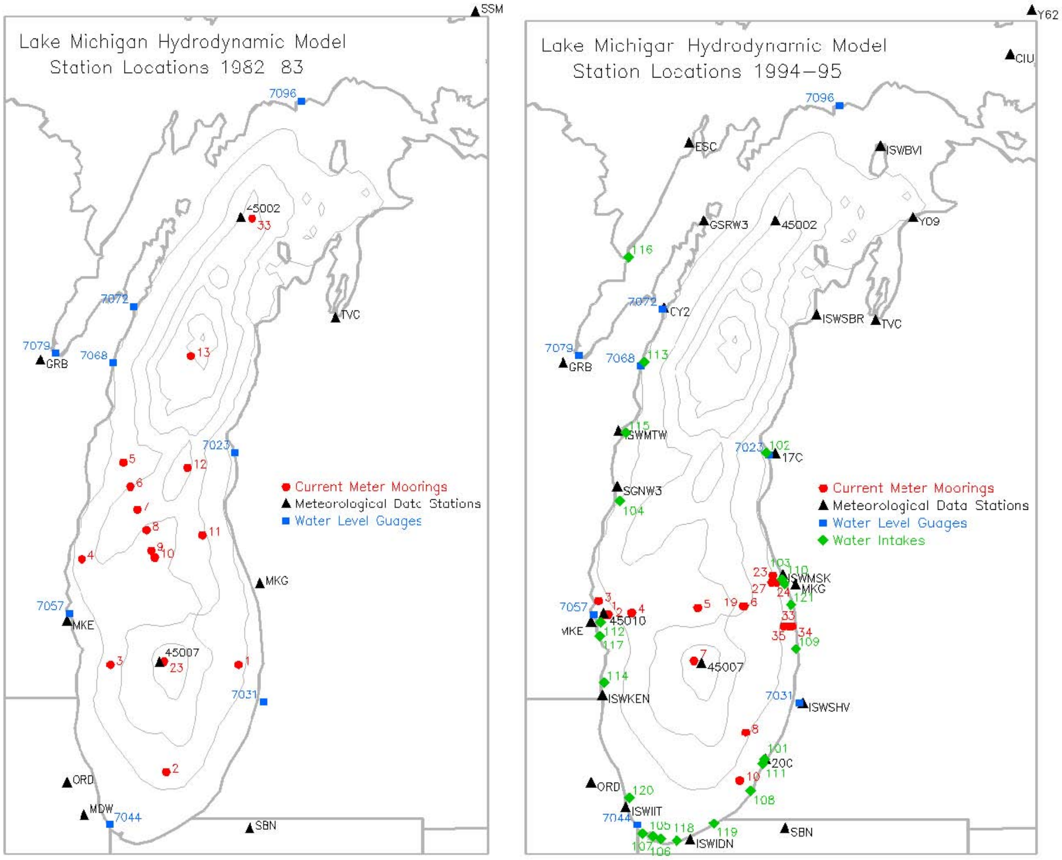
SB98 conducted model simulations for two time periods using POMGL. The first period was during 1982-1983 and used for model calibration. The second period was for 1994-1995 during the mass balance study period. Brief summaries about how the POMGL simulations were initialized and how the surface forcings were defined are given in this section.

4.1.1 Period 1982-1983

SB98 performed model simulations for the period from March 31, 1982 to November 30, 1983, a total of 600 days. The configuration of POMGL was very similar to the version presently used at NOS, with a spatial resolution of 5 km and 20 vertical sigma layers. The model was initialized using surface water temperature observations at NWS/NDBC Fixed Buoys 45007 and 45002 located in the southern and northern parts of the lake, respectively. Since the model was started on March 31st , the time of year when vertical temperature gradients are very small, the initial vertical temperature gradients in the model were set to zero, but horizontal gradients were preserved. The horizontal temperature distribution was determined based on depth and latitude in order to represent decreasing temperatures toward shallow waters as shown by observations (SB98). The initial velocity was set to zero. Due to the strong wind-driven character of the lake circulation, the effect of the initial conditions for velocity on model simulated currents disappears within the first few weeks or even first few days if there is a strong wind event (SB98). The model was forced with analyzed surface meteorological fields based on observations from 8 coastal observing stations and two NDBC fixed buoys (Figure 2a).

4.1.2 Period 1994-1995

SB98 conducted additional numerical simulations using POMGL during the mass balance field experiment of 1994-1995 using the same model configuration. Model simulations were conducted for the period from January 1, 1994 to December 31, 1995 for a total of 730 days. For the first 3 months, the water temperature in the model was kept at a constant 2°C due to the lack of an ice module in POMGL and the presence of an extensive ice cover. On April 1, 1994, when the ice was gone from the lake, the model was switched from a diagnostic mode (constant temperature) to a prognostic mode with the same uniform temperature distribution (SB98). The model was forced during this period using analyses of surface meteorological observations from more stations then were present during 1982-1983, 21 land-based stations and 2 NDBC fixed buoys (Figure 2b).



(a) (b)

Figure 2. Map depicting locations of observing networks during (a) 1983-1984 and (b) 1994-1995 periods.

4.2 Method of Evaluation

SB98 compared the POMGL simulations of water levels, and water temperatures were compared to available observational data. For the period 1982-1983, observed data included hourly water level observations from 9 NOS/CO-OPS water level gauges in the lake, surface water temperature data from two NWS/NDBC fixed buoys, and current and water temperature data at several depths from GLERL's 15 subsurface moorings (Gottlieb et al. 1989). A GLERL subsurface mooring was collocated at each of the two NWS buoys.

During the 2nd period of 1994-1995, available data included water level observations at 9 NOS water level gauges, surface water temperature observations from three NWS/NDBC buoys, subsurface water temperature from 21 municipal water intake sites, subsurface water temperature and current observations at 15 moorings. A GLERL subsurface mooring was collocated at NWS buoy 45007. The locations of NOS gauges, NWS buoys, municipal water intakes, and GLERL moorings are depicted in Figures 2a and 2b, for the first and second periods, respectively.

SB98 used standard statistical measures to quantitatively compare the model simulations to the observed data. These included arithmetic means, root mean square value (RMSV), maximum difference, arithmetic means, mean algebraic differencs, root mean square error difference (RMSD), and correlation coefficient (CC). The specific set of measures used depended on the variables. They found that the correlation coefficient is a good measure of the agreement in the timing of events for simulated vs. observed time series. They state that a value greater than 0.5 usually indicates significant correlation in timing. In addition, SB98 also qualitatively compared the simulations to previous research studies.

4.3 Skill Assessment of Surface Hindcasts

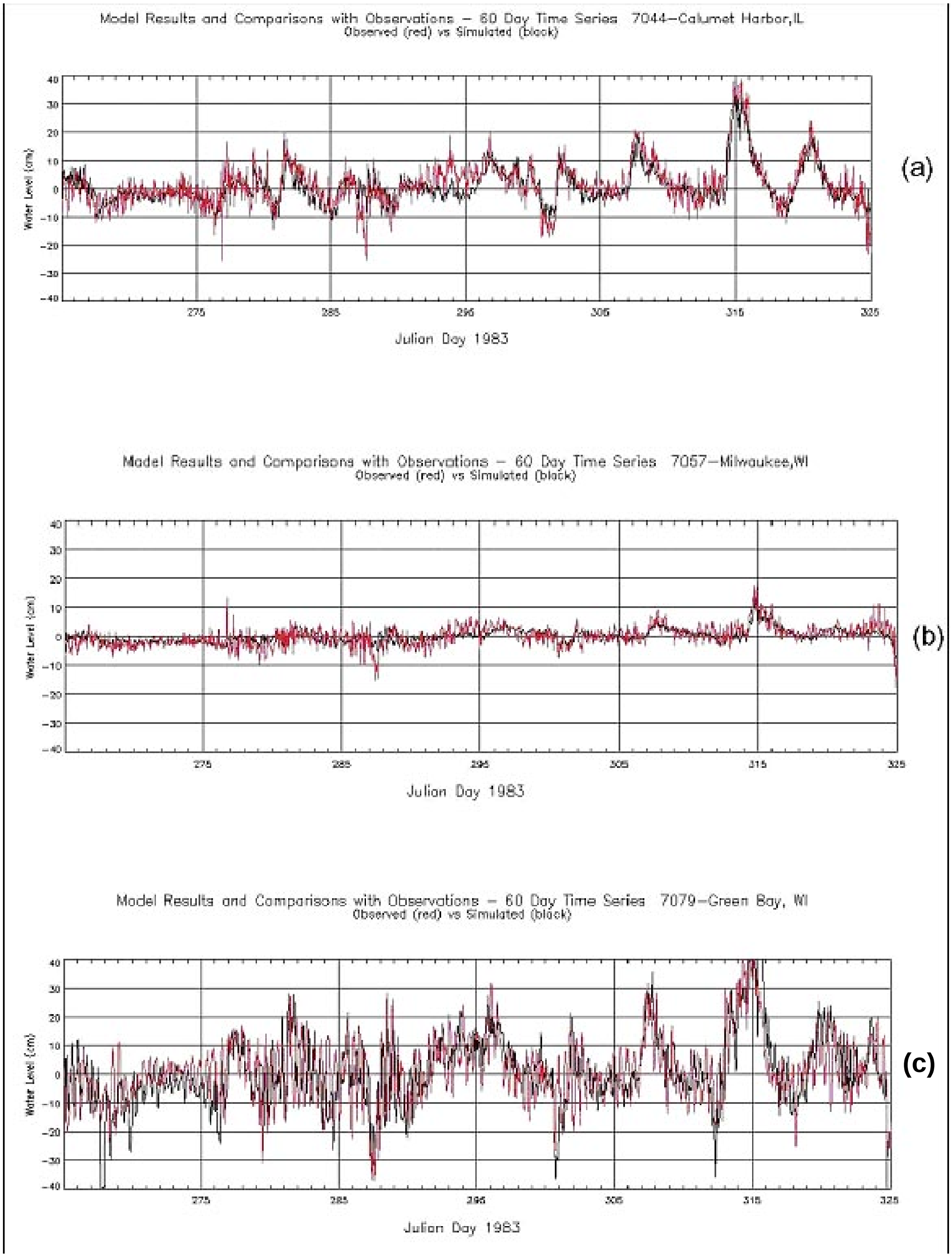
This section provides a summary of the findings by Schwab and Belesky (1998) regarding the performance of POMGL in simulating water levels and surface water temperatures during both the 1st and 2nd periods. The water level comparisons are discussed first, followed by analysis of the modeled water temperatures.

4.3.1 Water Levels during 1982-1983

SB98 compared POMGL water level simulations to observations at 9 NOS water level gauges. However, prior to comparing the simulations to observations, they removed the seasonal fluctuation of mean lake level from the individual water level records. This was accomplished in the following manner. Hourly water level data were obtained from NOS gauges and an hourly average was computed for all stations except for Green Bay, WI and Sturgeon Bay, WI due to their geographic locations and the size of POMGL grid increment. The average time series was then smoothed with a 12 hour running mean filter and subtracted from the observed hourly values at all stations. The resulting water level fluctuations represent the combined effects of wind, atmospheric pressure gradients, and local bathymetry (SB98).

A sample of the observed and computed water level fluctuations for Calumet Harbor, Milwaukee, and Green Bay for the period from October to November 1983 (JD 265-325) is shown in Figure 3. Calumet Harbor and Green Bay showed the highest fluctuations (up to 50 cm), while Milwaukee did not exhibit as high an amplitude. At all NOS gauges there was a significant amount of high frequency (> 0.5/hr) fluctuation, with amplitudes on the order of 5 cm apparent in the observed water level record. This high frequency fluctuation was not seen in the simulated water levels. SB98 speculated that this difference is due mainly to local water level fluctuations in the harbors and coastal areas where the NOS gauges are located, which cannot be simulated with POMGL using a 5 km grid increment.

The statistical comparison between observed and computed water level fluctuations is presented in Table 1. The RMSV of the observations is significantly greater than the RMSV of the computed water level fluctuations at all stations except Green Bay. They state that this was probably due to the high frequency fluctuations which are seen in the observations, but not as much in the POMGL simulations. In addition, they state that the RMSD between model results



Model Results and Comparisons with Observations – 60 Day Time Series 7044–Calumet Harbor, IL
Observed (red) vs Simulated (black)

Model Results and Comparisons with Observations – 60 Day Time Series 7057–Milwaukee, WI
Observed (red) vs Simulated (black)

Model Results and Comparisons with Observations – 60 Day Time Series 7079–Green Bay, WI
Observed (red) vs Simulated (black)

Figure 3. Times series of simulated water levels versus observed for October – November 1983 at NOS Gauge Stations, (a) Calumet Harbor, IL, (b) Milwaukee, WI, and (c) Green Bay, WI (from SB98).

Table 1. Statistical comparison of 1982-83 simulated vs. observed short-term water level fluctuations (cm) at NOS water level gauges (modified from SB98).

NOS Gauge Name and ID	No. of Obs.*	Avg (Obs.)	RMSV (Obs.)	Avg (Model)	RMSV (Model)	Mean Alg. Diff. (M-O)	RMSD	CC
Ludington 9087023	14371	-0.28	3.45	0.59	0.95	+0.87	3.32	0.39
Holland 9087031	13730	0.33	2.73	0.67	1.64	+0.35	2.39	0.51
Calumet 9087044	14253	0.63	7.03	0.58	4.67	-0.05	5.50	0.62
Milwaukee 9087057	14233	-0.27	3.46	0.12	1.64	+0.39	3.22	0.39
Kewaunee 9087068	13123	-0.07	3.42	-0.25	0.97	-0.18	3.39	0.17
Sturgeon Bay 9087072	14366	-0.13	2.97	-0.17	1.01	-0.04	2.92	0.22
Green Bay 9087079	14368	0.27	9.72	0.46	12.20	+0.18	12.30	0.39
Port Inland 9087096	14283	-0.32	5.70	0.33	2.73	+0.65	4.61	0.61
Mean (Green Bay not included)						+0.28	3.62	0.42

*Maximum number of possible observations during the period was 14,400.

and observations is also reflective of this difference. Correlation coefficients are highest at Calumet Harbor and Port Inland, which are located at the south and north ends of the main lake, respectively. They point out that the largest amplitude wind-induced water level fluctuations on the lake are usually exhibited at these NOS two gauges.

4.3.2 Water Levels during 1994-1995

SB98 compared POMGL water level simulations for the 1994-1995 period to observed data from the same 8 NOS gauges in Lake Michigan used for the 1st period. The statistical comparisons at each gauge are given in Table 2. They found similar results as for the 1st period, except that the correlation coefficients were somewhat lower for 1994-1995.

Table 2. Statistical comparison of 1994-95 simulated vs. observed short term water level fluctuations (cm.) at NOS water level gauges (modified from SB98).

NOS Gauge Name and ID	No. of Obs.	Avg (Obs.)	RMSV (Obs.)	Avg (Model)	RMSV (Model)	Mean Alg. Diff. (M-O)	RMSD	CC
Ludington 9087023	17249	2.06	3.80	0.14	1.21	-1.92	4.08	0.32
Holland 9087031	16571	0.69	2.83	0.65	1.95	-0.04	2.55	0.48
Calumet 9087044	16705	-0.29	6.95	0.81	4.23	+1.10	6.06	0.52
Milwaukee 9087057	17243	0.34	3.69	0.07	2.01	-0.27	3.45	0.39
Kewauee 9087068	15746	-0.72	3.53	-0.31	1.19	+0.41	3.42	0.28
Sturgeon Bay 9087072	17272	-0.99	3.12	-0.24	1.34	+0.74	3.04	0.34
Green Bay 9087079	16827	-0.38	10.11	-0.09	12.82	+0.29	13.58	0.32
Port Inland 9087096	16147	-2.27	5.74	0.06	3.09	+2.33	5.52	0.49
Mean (Green Bay not included)						+0.32	4.02	0.40

4.3.3 Water Temperatures during 1982-1983

SB98) compared POMGL simulations of surface water temperatures to observed temperatures at NWS fixed buoys 45007 and 45002. The comparisons are depicted in Figure 4 and indicate good agreement between the time evolution of surface water temperatures. They found that the simulation of the surface temperature is much more accurate than below the surface, which indicated the correct input of heat fluxes near the lake's surface. (Subsurface comparisons are given in Section 4.4.1) The results of the statistical evaluation of POMGL surface water temperature simulations at the two buoys are given in Table 3. They noted that the accuracy of surface temperature simulations is similar in the first and second year of simulations, which they attributed to the rapid adjustment of the surface temperature field to the model's surface boundary conditions.

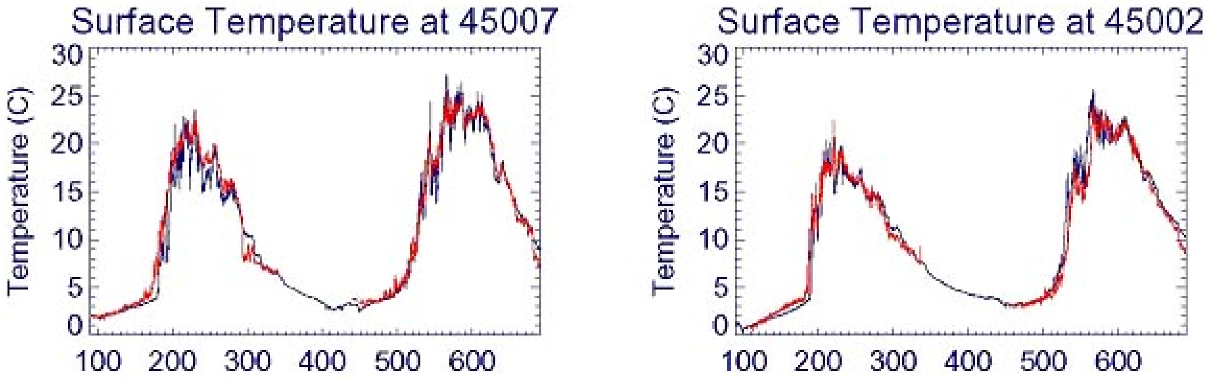


Figure 4. Comparison of simulated surface water temperatures vs. observed at NWS fixed buoys 45007 and 45002 for 1982-1983. Red line is the observation and the blue line is the model simulation (modified from SB98).

Table 3. Statistical measures of POMGL surface water temperature simulations at NWS/NDBC fixed buoys 45002 and 45007 for the periods 1982-1983 and 1994-1995 (modified from SB98).

Period	RMSD (^{o}C)	Max. Error (^{o}C)	Average Obs (^{o}C)	Average Model (^{o}C)	Mean Alg. Difference (Model-Obs)	CC
1982-1983	1.2	6.6	12.1	12.1	0.0	0.99
1994-1995	1.5	6.1	13.1	13.3	+0.2	0.96

4.3.4. Water Temperatures during 1994-1995

During the 2nd period, SB98 compared simulations of surface water temperatures to observed temperatures at NWS' permanent fixed buoys 45007 and 45002, and also at NWS' temporary buoy 45010 located in the coastal zone off Milwaukee, WI (Figure 5). The results of the statistical comparisons at the three NWS buoys are given in Table 3. They noted that the accuracy of surface temperature predictions is similar in the first and second year of the simulations, in agreement with the 1982-1983 findings.

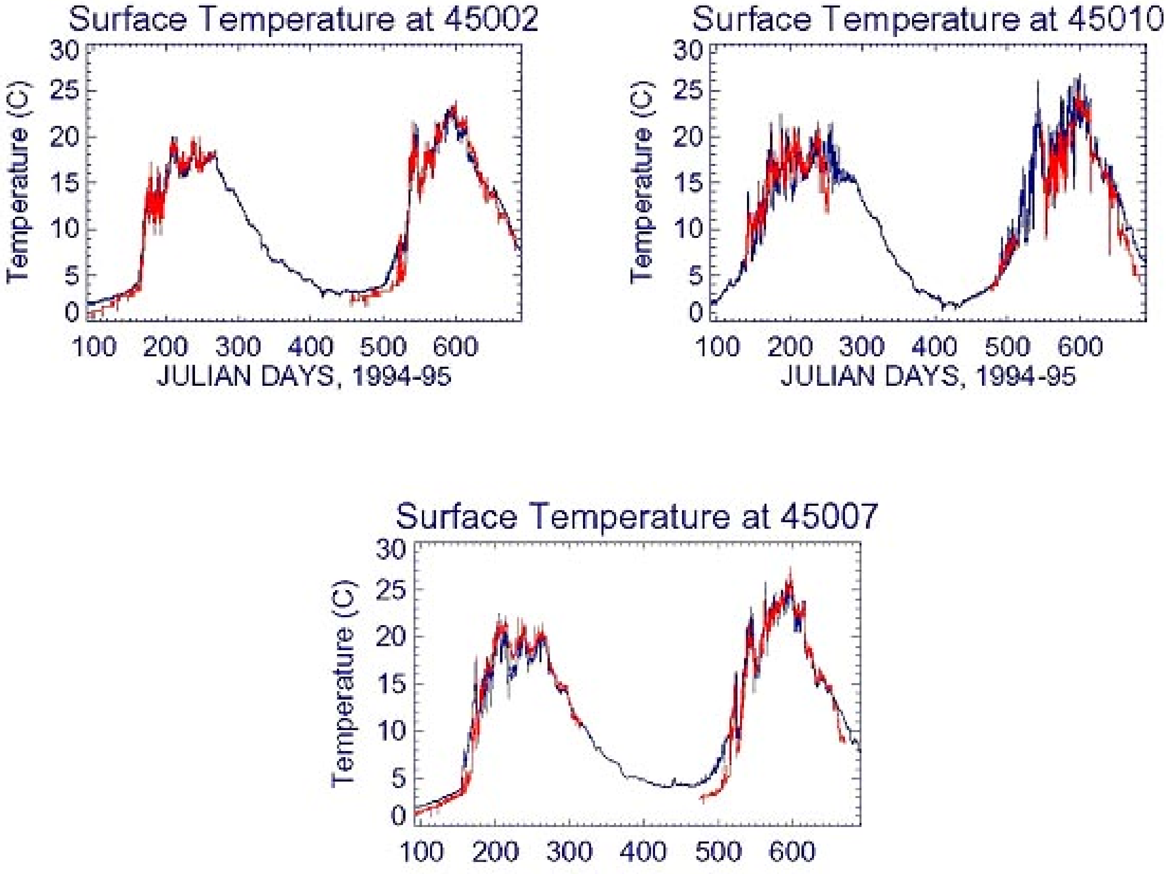


Figure 5. Comparison of simulated vs. observed surface water temperatures at NWS fixed buoys 45002, 45010, and 45007 for 1994-1995. Red line is observation and blue is model simulation (modified from SB98).

4.4 Skill Assessment of Subsurface Hindcasts

This section provides a summary of the findings by Schwab and Belesky (1998) regarding the performance of POMGL in simulating subsurface water temperatures and currents during both the 1st and 2nd periods. The water temperature comparisons are discussed first, followed by the analysis of the modeled currents.

4.4.1 Water Temperatures during 1982-1983

SB98 compared observed subsurface temperatures from GLERL's moorings to model output at several depths. A comparison of POMGL simulations to observations at several depths at the GLERL moorings, collocated at NWS buoys, is given in Figure 6. The results of a statistical comparison of POMGL subsurface temperature simulations to observations are given in Table 4. To insure comparability with the 1994-95 period, they only used temperature and current observations longer than 300 days. No subsurface temperatures were taken for the second summer (1983) during this first period.

SB98 found good agreement between the horizontal distribution and time evolution of the surface and bottom temperatures. However, they found a worse agreement in the thermocline area (depth 15m), where internal waves are also much less pronounced in the POMGL simulations than in observations. They speculated that because the model tends to generate excessive vertical diffusion, the modeled thermocline is too diffuse and hence temperature fluctuations are decreased.

They concluded that POMGL was able to reproduce all of the basic features of thermal structure of Lake Michigan during the 600 days of the 1st period, including the spring thermal bar, full stratification, deepening of the thermocline during the autumn cooling, and finally an overturn in the late fall (Figure 7).

Table 4. Statistical measures of POMGL surface water temperature simulations at GLERL subsurface current moorings for the periods 1982-1983 and 1994-1995 at different layers in the water column (modified from SB98).

Period	No. of Instruments	Layer	RMSD (°C)	Max. Error (°C)	Average Obs (°C)	Average Model (°C)	Diff. (M-O)	CC
1982-1983	28	Epilimnion	2.5	10.6	7.1	6.4	-0.7	0.87
		Hypolimnion	0.7	3.3	4.2	4.3	+0.1	0.78
1994-1995	10	Epilimnion	2.4	9.2	7.3	7.7	+0.4	0.93
		Hypolimnion	1.3	5.2	4.5	5.3	+0.8	0.87

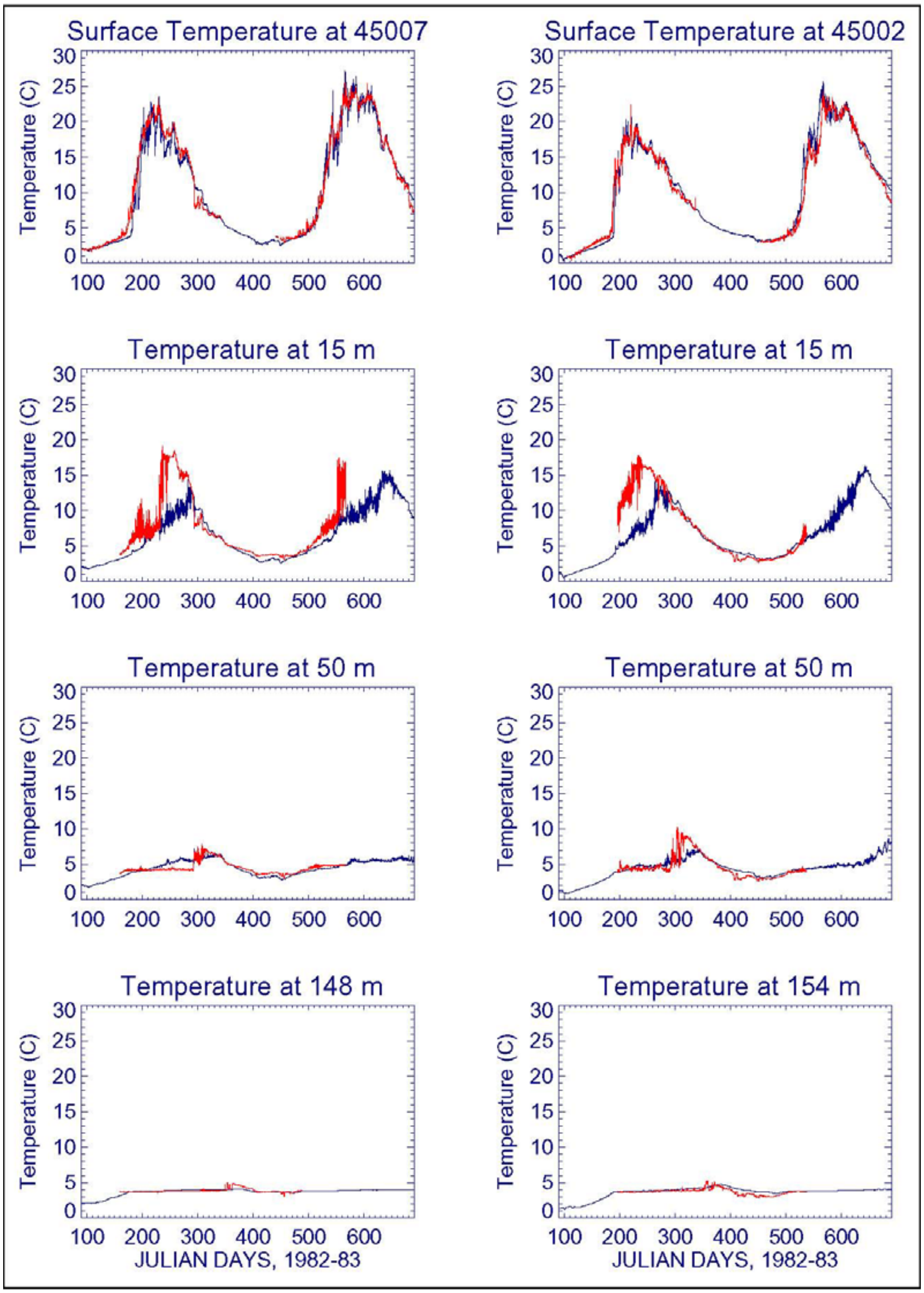


Figure 6. Time-series of POMGL simulated versus observed subsurface water temperatures at GLERL current moorings collocated near 45007 and 45002 during 1982-1983. Also shown are the simulated vs. observed surface water temperatures at the two buoys. Red line is the observation, blue is the model simulation (from SB98).

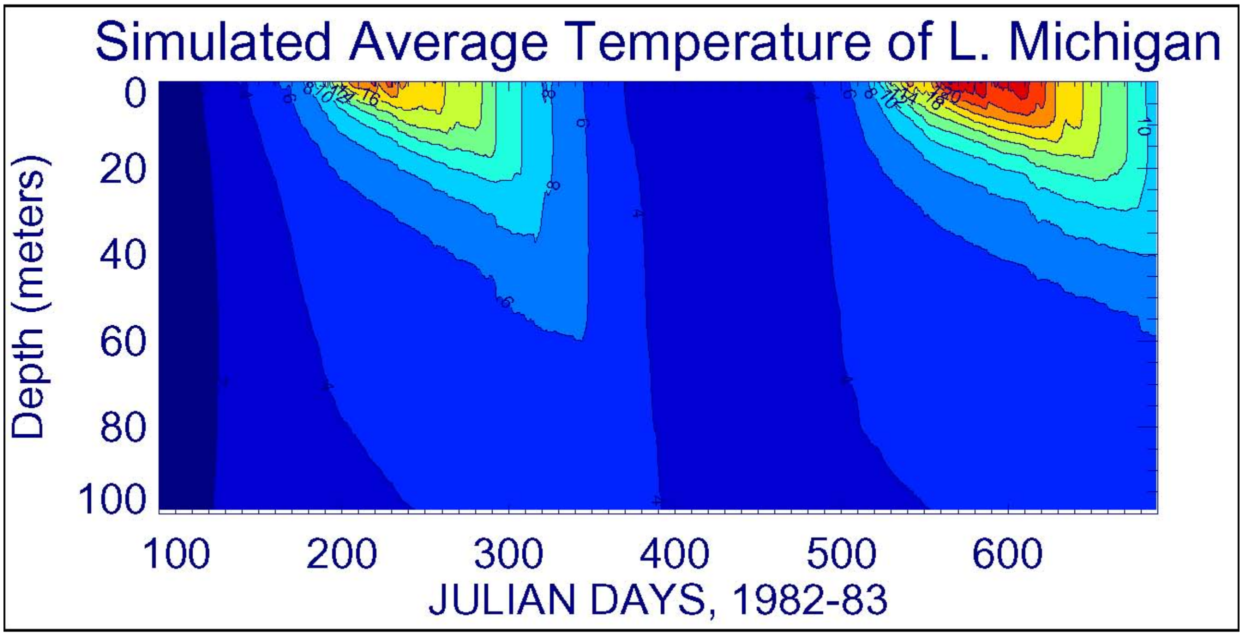


Figure 7. POMGL's simulated mean temperature profile for the period 1982-1983 (from SB98). The color contours are in ^{o}C.

4.4.2 Water Temperatures during 1994-1995

SB98 compared POMGL subsurface temperature simulations to observations from GLERL moorings. Statistical comparisons of POMGL simulations vs. observations at these moorings are presented in Table 4. As with the 1st period, only time series longer than 300 days were used in the statistical comparisons. A time series of POMGL simulations vs. observations at the GLERL mooring collocated at NWS buoy 45007 is given in Figure 8. Similar to the findings during the 1982-1993 period, the POMGL simulations were found to compare better for surface and bottom temperatures but worse in the thermocline area.

SB98 also examined the performance of POMGL in simulating the nearshore thermal structure by comparing POMGL temperatures against temperature data from 23 municipal water intakes around Lake Michigan. They used these data mostly for qualitative assessment (Figure 9), because unlike typical in-situ measurements, water temperature is measured at the municipal water plants and not in the lake itself.

In addition, they also compared observed vs. simulated temperature profiles or soundings at 20 locations from seven large-scale GLNPO temperature surveys of Lake Michigan during the 1994-95 (one example is shown in Figure 10). They also compared POMGL simulations to several nearshore transects made by the United States Geological Survey (USGS), two examples of which are shown in Figure 11.

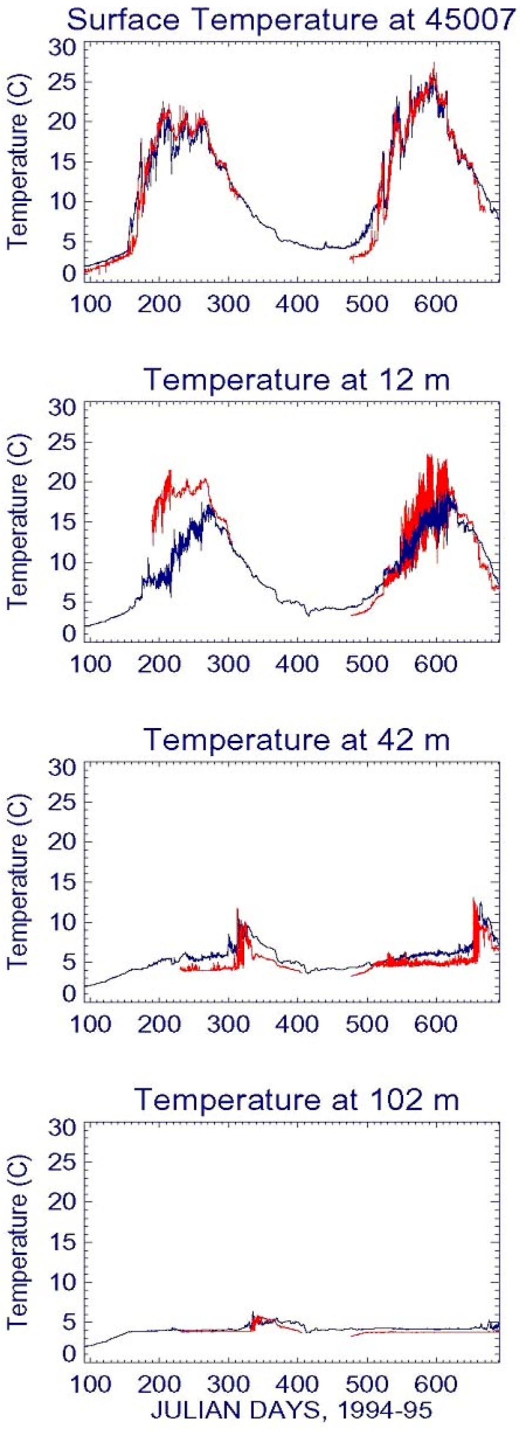


Figure 8. **Time-series of POMGL simulated vs. observed water temperatures at GLERL current mooring near NWS buoy 45007 for 1994-1995. Also shown are the simulated vs. observed water temperatures at buoy 45007. Red line is the observation, blue is the model simulation (from SB98).**

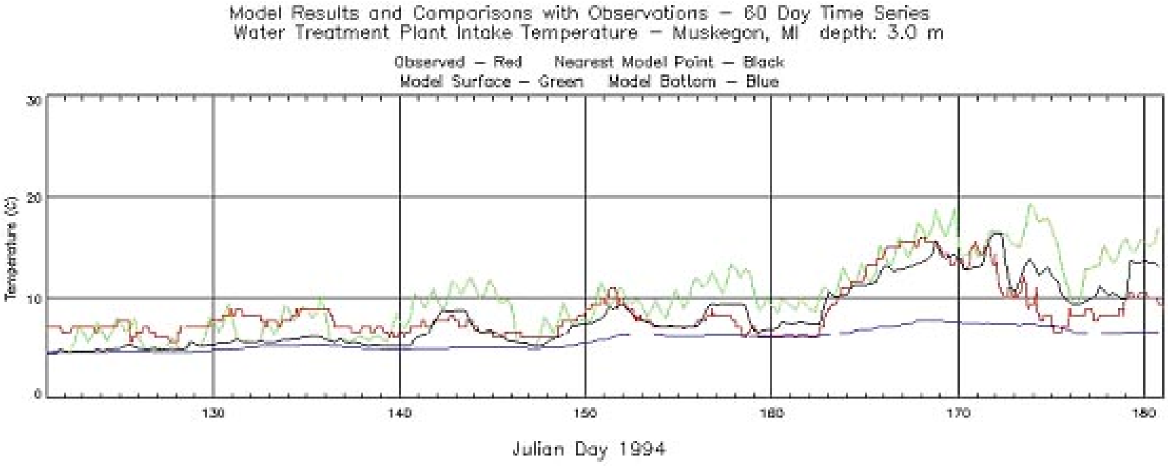


Figure 9. Time series of POMGL simulated versus observed water temperatures at the Muskegon, MI municipal water intake for May-June 1994 (from SB98).

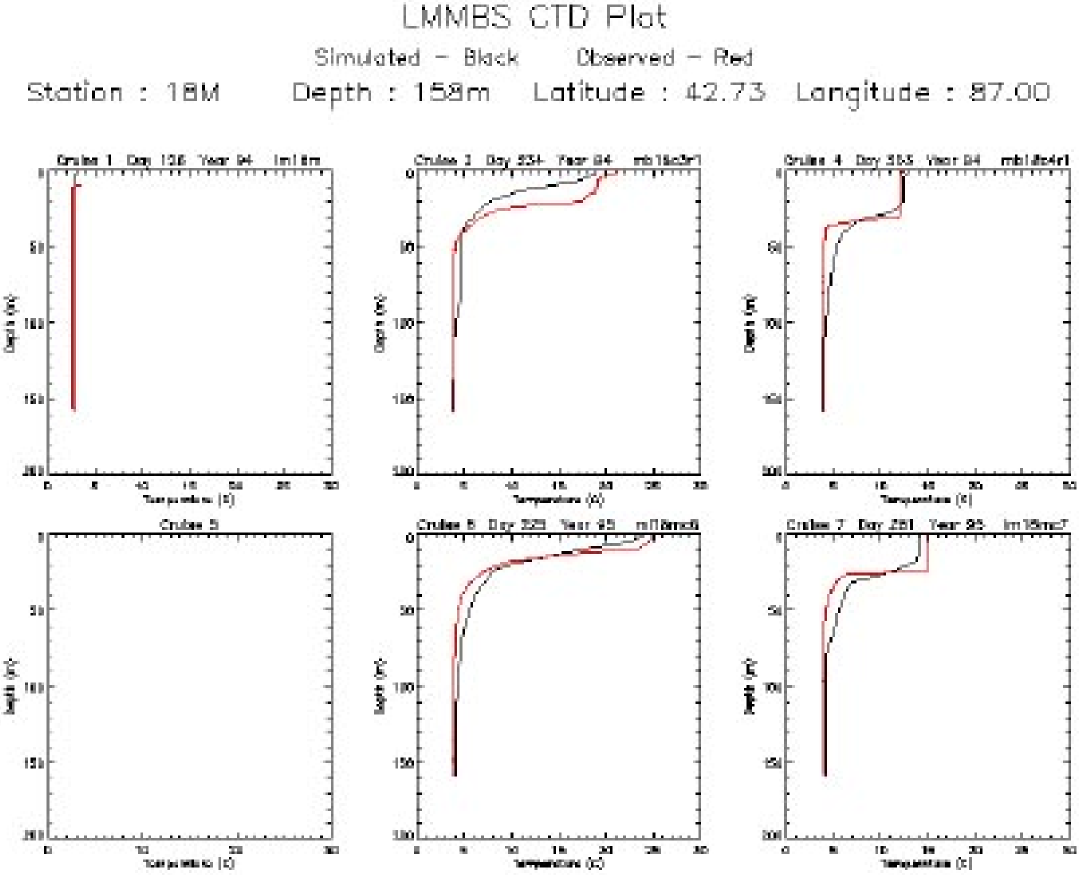


Figure 10. POMGL simulated vertical water temperature profiles vs. observations on four days in 1994-1995 at Station 18M in southern Lake Michigan near NWS buoy 45007 (modified from SB98).

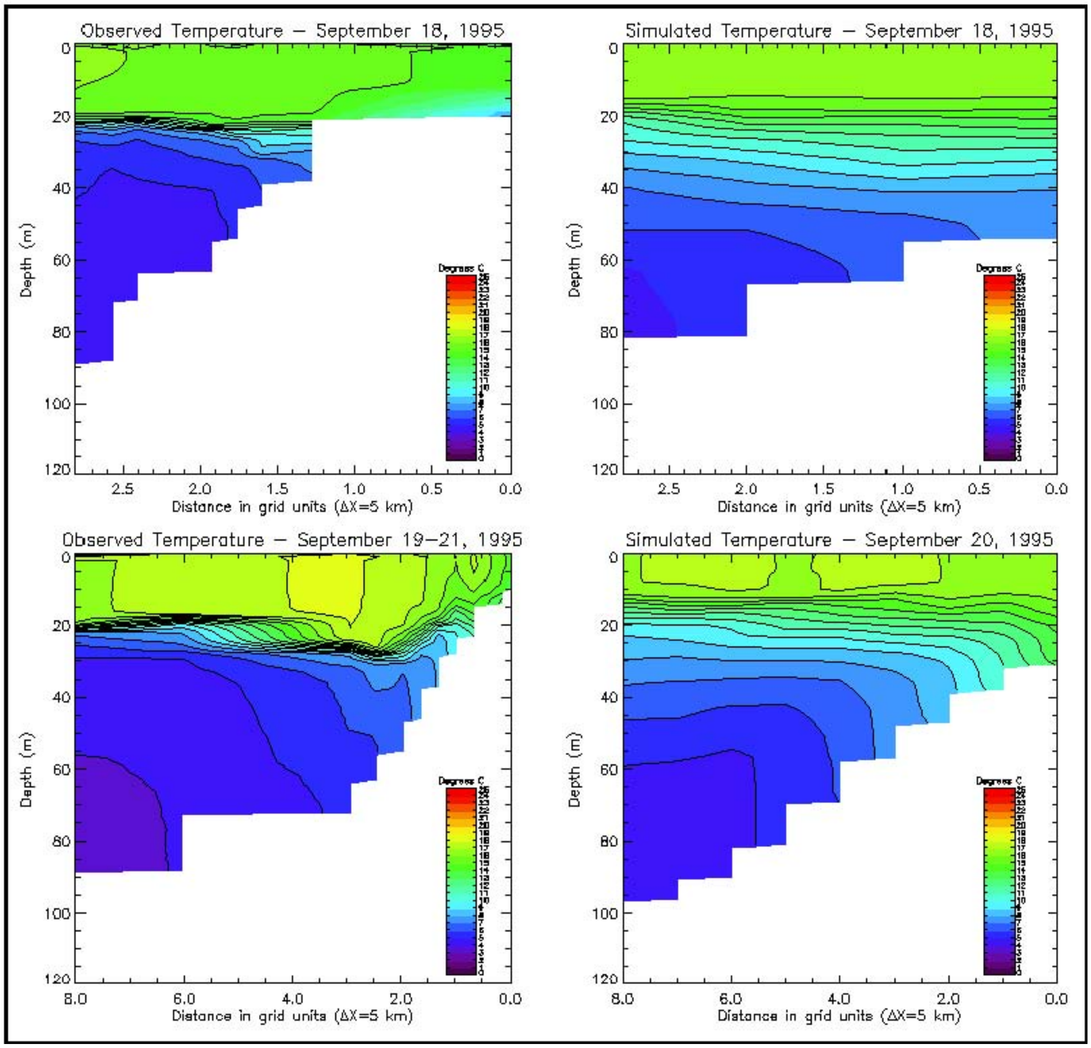


Figure 11. POMGL simulated versus observed temperature, transects offshore of Ludington, MI (upper panel) and Holland, MI (lower panel) (from SB98).

4.4.3 Water Currents during 1982-1983

In order to examine seasonal changes in lake circulation patterns, SB98 averaged model results over two 6-month periods: from May to October (summer period), and from November to April (winter period). Their selected averaging periods roughly correspond to the thermal stratified and non-stratified periods. They found that POMGL properly simulated a cyclonic large-scale circulation pattern, with cyclonic circulation within each subbasin, and anticyclonic circulations in ridge areas as shown by previous observational studies. Furthermore, they found that the simulated circulation was more organized and more cyclonic in winter than in summer, which is in agreement with Gottlieb et al. (1989) and earlier findings of Saylor et al. (1980).

SB98 also compared POMGL current simulations to observations at GLERL current moorings.

They found that the model simulations matched observed currents best in the southern basin and during the fall-winter months. However, the simulated current speeds were approximately 10-30% higher than observed speeds. Progressive vector diagrams of simulated vs. observed currents at 15 m depth for four GLERL moorings located in the southern basin (i.e. at and south of Buoy 45007) are given in Figure 12.

They state that the model did better in the southern basin probably due to the smooth bathymetry in this region. The better performance in the fall and winter months is likely due to the horizontal model resolution of the model being too coarse for proper simulation of baroclinic processes with horizontal length scales comparable to the Rossby deformation radius (approximately 5 km for summer months).

SB98 compared POMGL current simulations vs. observations using a normalized Fourier norm (root mean square difference). A value of 0 indicates a perfect prediction (simulation is identical to observation) and a value greater than 0 but less than one implies that the simulation is better than no prediction at all (zero currents). For the 1982-83 period, they found that the normalized Fourier norm was between 0.70 and 0.98. They state that the normalized Fourier norm can be interpreted as a relative percentage of variance in the observed currents that is unexplained by the simulated currents. For the 1982-83 period, the hourly POMGL simulations account for 2-30% of the total variance observed in the hourly observed currents (SB98).

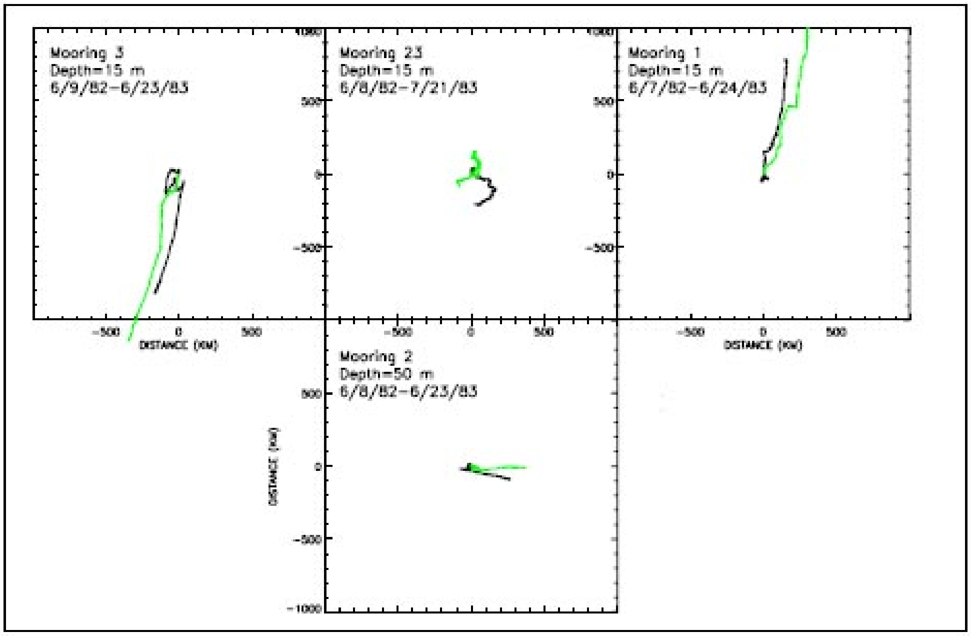


Figure 12. Progressive vector diagrams of POMGL simulated vs. observed currents at 15 m depth at GLERL moorings in the southern basin (#1, 2, 3, and 23) for 1982-83. Black line is observations, green is model simulation. (from SB98).

4.4.4 Water Currents during 1994-1995

S98 compared POMGL current simulations to observations at GLERL moorings during the 2nd period. However, the GLERL current observation data set was not as comprehensive as in the 1st period. They found that the normalized Fourier norm ranged between 0.80 and 1.08, which was slightly worse than for the 1st period.

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."

LMOFS, as described in Chapter 2, is based on NOAA/GLERL's Great Lakes Coastal Forecast System (GLCFS) for Lake Michigan. Both LMOFS and GLCFS for Lake Erie have a spatial grid increment of 5 km and 20 sigma layers and use similar surface meteorological forcing. Neither of the systems employed any river inflow or assimilated any limnological data. Unlike LSOFS, GLCFS used surface observations from United States Coast Guard (USCG) stations and cooperative marine weather observations (MAREPS). However, this difference was not expected to cause a significant difference in the nowcasts.

Due to the similar characteristics of LMOFS and GLCFS, the assessment of the LMOFS semi-operational nowcasts was performed using archived nowcasts from GLCFS four times/day nowcast cycles.

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

5.1 Description of Nowcast Cycles

GLCFS performs four times/day nowcast cycles for Lake Michigan and the other four Great Lakes. The POMGL used by each forecast system are not reinitialized each spring. 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 NDBC C-MAN stations to be received at GLERL via NOAAPORT. Hourly model output from the four nowcast cycles is archived at GLERL.

5.2 Method of Evaluation

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

The evaluation used the standard suite of assessment statistics as defined in Hess et al. (2003). The standard suite of statistics is given in Table 5. The target frequencies of the associated statistics are the following:

$CF(X) \geq 90\%$, $POF(2X) \leq 1\%$, $NOF(2X) \leq 1\%$,
$MDPO(2X) \leq L$, $MDNO(2X) \leq L$

Table 5. 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.

There are three types of data sets (Table 6): 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 variables applied to LMOFS are presented in Table 7.

Table 6. 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 7. 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,	3oC*	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, the output was reformatted to meet the text format requirements of the skill assessment code.

Nowcasts of Water Levels

The evaluation of GLCFS nowcasts of water levels were based on time series of observed and modeled water levels at 6 NOS NWLON stations along the Lake Michigan shoreline(Table 8). Data from NOS stations at Mackinaw City, MI, Green Bay, WI, and Sturgeon Bay, WI were not used in the evaluation due to their locations between two lakes, in a small bay, and at the entrance to a canal. A map depicting the locations of the 6 NOS gauges in the lake is given in Figure 13.

Since water level nowcasts and forecasts generated by GLCFS were vertical displacements relative to the flat lake, further adjustment was necessary to bring the water levels relative to the mean lake level. An offset value based on a dynamic 7-day average mean lake water level was computed and added to the model nowcasts of water level displacement from the model's mean. The mean based on a 7-day average may or may not truly represent the instantaneous mean lake wide water level. This is the same method used by CO-OPS prior to displaying the LMOFS 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 Michigan 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 several of the Great Lakes, especially 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. This is the first attempt at evaluating the ability of a NOS prediction 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 implemented in the future.

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 levels, pick all high and low values. A data point is selected if either it is higher than its two neighboring (both sides) values or it is lower than its two neighboring points.

Step 2. For each selected peak from Step 1, a 7 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 7 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 statistical 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.

Table 8. Information on NOAA/NOS NWLON stations whose observations were used to evaluate the semi-operational nowcasts and forecasts of water levels.

Station Name	State	NOS Station ID Number	NWS Station ID	Station		Corresponding I and J Model Coordinates	
				Latitude (deg N)	Longitude (deg W)	I	J
Port Inland	MI	9087096	PNLM4	45.97	85.87	35	98
Ludington	MI	9087023	LDTM4	43.95	86.44	26	53
Holland	MI	9087031	NS	42.76	86.20	30	27
Calumet Harbor	IL	9087044	CMTI2	41.73	87.54	9	4
Milwaukee	WI	9087057	NS	43.00	87.89	4	32
Kewaunee	WI	9087068	KWNW3	44.46	87.50	10	65

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

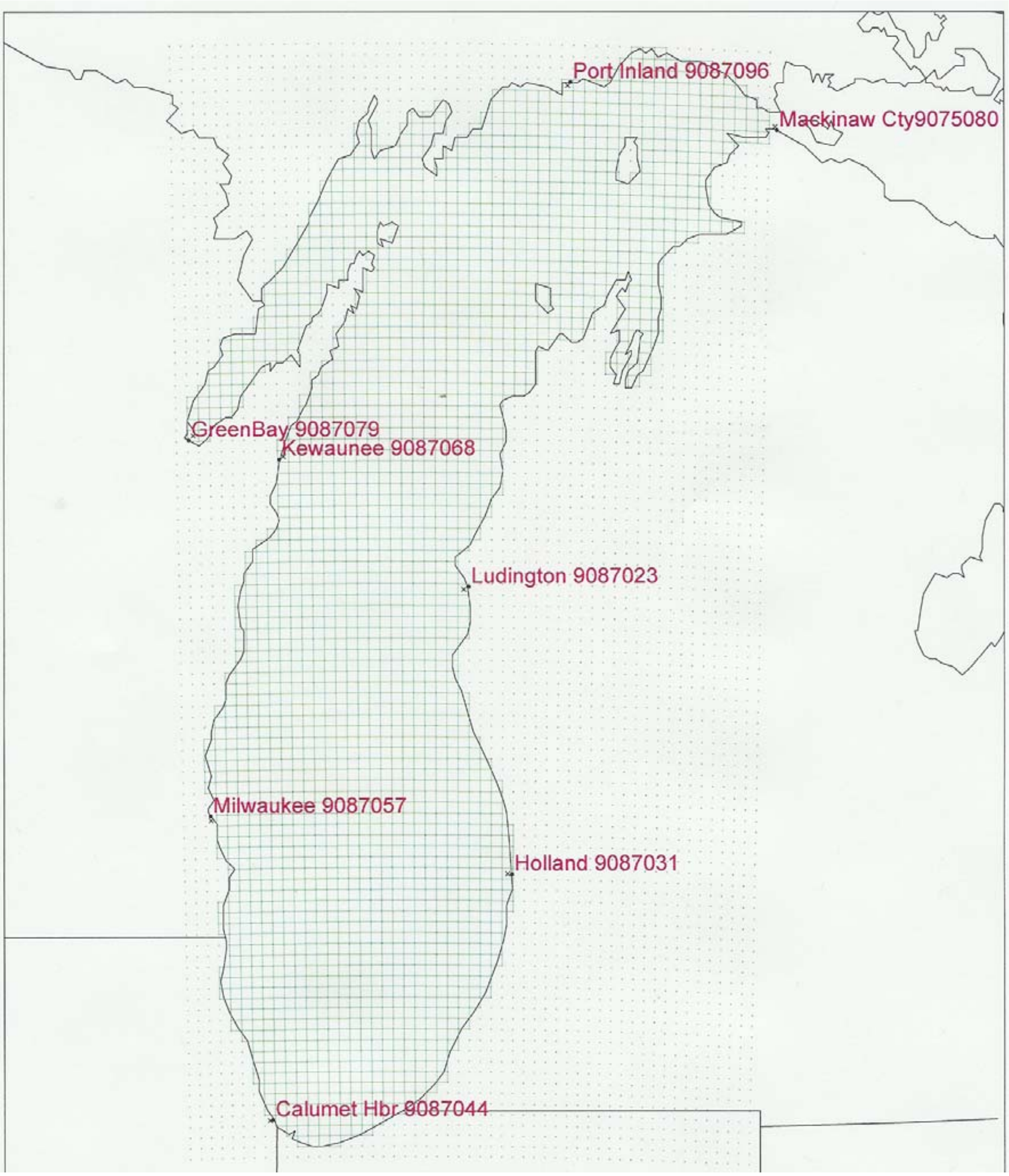


Figure 13. Map depicting locations of NOS NWLON gauges in Lake Michigan.

Nowcasts of Surface Water Temperatures

The evaluation of GLCFS surface water temperature nowcasts were based on time series comparisons of observed and predicted temperatures at two 3-m fixed disk buoy locations in the lake. A map depicting the locations of these NWS fixed buoys is given in Figure 14. The buoys are operated by NOAA/National Data Buoy Center (NDBC). Information on the two NWS buoys is given in Table 9. The lake surface temperatures at the buoys are measured using a Yellow-Springs thermistor sealed with 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.

The evaluation of GLCFS surface water temperature nowcasts for the lake was done by comparing time series differences using the SM, RMSE, SD, NOF, POF, MDPO, and MDNO statistics described in Hess et al. (2003). No attempt was made to assess the nowcast/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 fresh water bodies and non-tidal, there is no present standard for a lake temperature prediction. Based on experience of running the Great Lakes Forecasting System and input from the 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 a 3^{o}C criteria.

Table 9. Information of NWS/NDBC fixed buoys whose observations were used to evaluate the semi-operational nowcasts and forecasts of surface water temperatures.

Buoy Name	Agency	Prov. or State	WMO Buoy ID	Buoy		Corresponding LMOFS Grid Point Coordinates	
				Lat. (deg N)	Long. (degW)	I	J
45007 – South Michigan	NWS/ NDBC	MI	45007	42.68	87.03	17	25
45002 – North	NWS/	MI	45002	45.33	86.42	27	84

Michigan NDBC

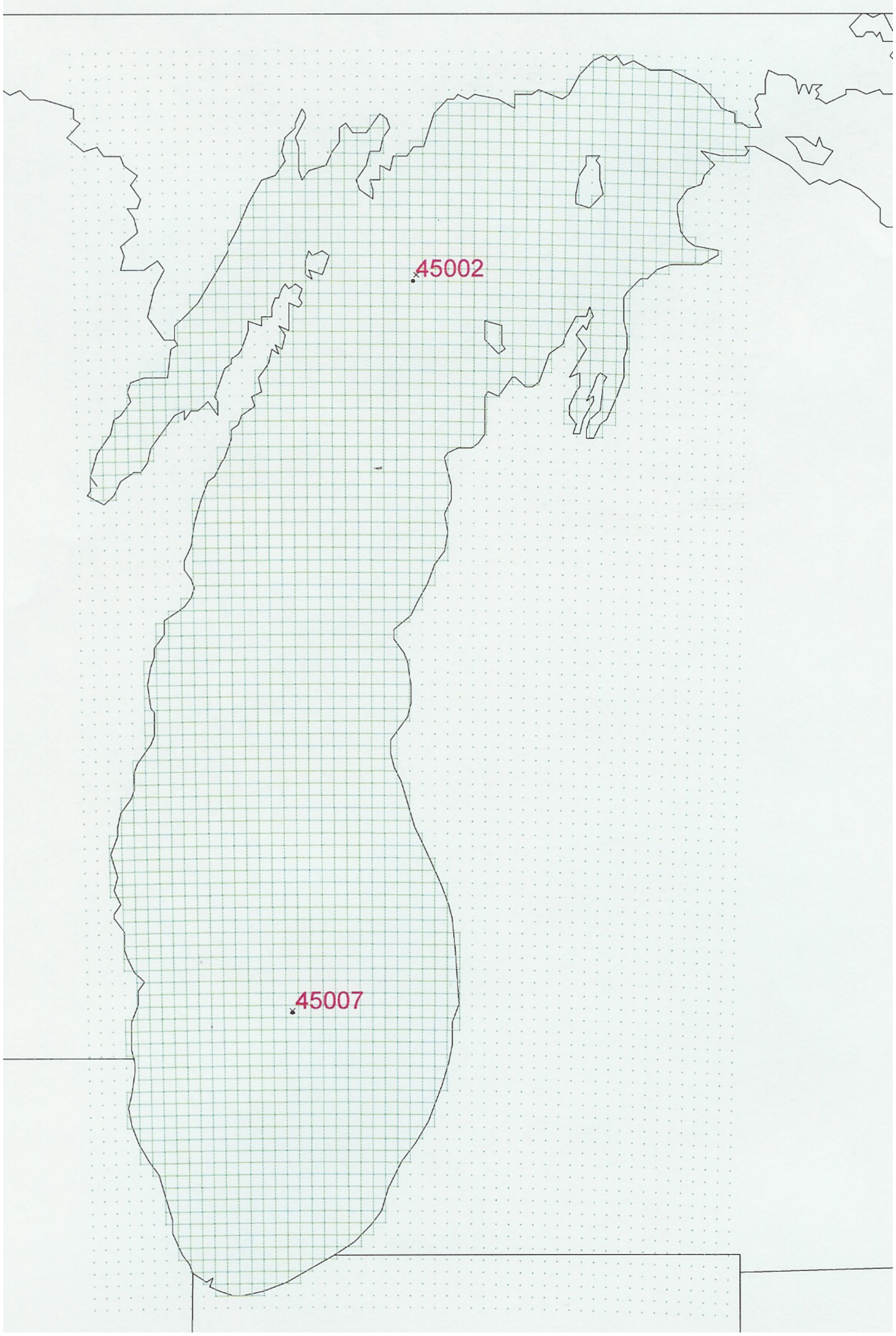


Figure 14. Map depicting the locations of NWS/NDBC fixed buoys in Lake Michigan along with the POMGL grid.

5.3 Assessment of Water Level Nowcasts

The standard suite of skill assessment statistics evaluating the ability of semi-operational nowcasts to predict hourly and extreme water levels at 6 NOS gauges from 15 April to 20 December 2004 are given in Appendix A. Time series plots of the nowcast results and observations at the gauges are given in Appendix B.

For the convenience of the reader, the skill statistics assessing the ability of the nowcasts to predict hourly water levels at the 6 NOS gauges are presented together in Table 10 along with the NOS acceptance criteria. The hourly nowcasts passed the criteria for amplitude at all 5 locations. The mean algebraic differences ranged between ± 2 cm, and the RMSE ranged between 4.8 and 7.0 cm. The greatest errors were at the Calumet Harbor, IL and Port Inland, MI gauges located at the extreme southern and northern ends of the lake, respectively (Figure 2). These sites also show the greatest hourly water level variability. The nowcasts under-predicted the water levels at all gauges except Port Inland.

A comparison of the RMSE values for 2004 and those presented in the hindcast section (Tables 1 and 2) indicate the POMGL performed worse in 2004. For example, at the northern and southern ends of the lake, the Port Inland RMSE was 4.6, 5.5, and 5.2 cm for 1982-1983, 1994-1995, and 2004, respectively. RMSE at Calumet Harbor was 5.5, 6.1, and 7.0 cm for the same time periods. However, the largest difference between the RSMEs for the hindcasts and nowcasts were on the western and eastern lake shores. For example at Ludington, the RMSE were 2.4, 2.6, and 4.8 cm and at Kewaunee, the values were 3.39, 3.42, and 5.1 cm. The reason for the worse performance in 2004 may be due to differences in 1) the density and location of wind observations, 2) the methods used for calculating mean lakewide water level, and/or 3) how POMGL was applied.

The skill statistics assessing the ability of nowcasts to predict extreme high water level events at the 6 NOS gauges during 2004 are given together in Table 11. The nowcast simulations of high water level passed the NOS acceptance criteria for amplitude at Port Inland and Holland, but not at Ludington, Calumet Harbor, Milwaukee and Kewaunee. The nowcasts ability to simulate the timing of these extreme events did not pass NOS acceptance criteria for NOF, CF, and POF at any of the 6 gauges.

Table 10. Summary of Skill assessment Statistics of *Semi-Operational Nowcasts* of Hourly Water Levels at six NOS NWLON Stations in Lake Michigan for the Period 15 April to 20 December 2004. A total of 5785 nowcasts were used in the assessment. Red indicates that the statistic did not pass the NOS acceptance criteria. Green indicates that it did meet the criteria.

Statistic, Acceptable Error [ ], and Units ( )	Port Inland MI	Luding-ton MI	Holla-nd MI	Calumet harbor IL	Milwa-kee WI	Kewau-nee WI	NOS Accept. Criteria
Mean Alg. Diff. (m)	0.019	-0.010	-0.007	-0.019	-0.021	-0.006	na
RMSE (m)	0.052	0.053	0.048	0.070	0.057	0.051	na
SD (m)	0.048	0.052	0.048	0.068	0.053	0.050	na
NOF (2x15cm) (%)	0.0	0.0	0.0	0.1	0.0	0.0	≤ 1%
CF [15 cm] (%	98.8	98.0	98.9	95.5	98.2	98.7	≥ 90%
POF [2x15 cm] (%)	0.0	0.0	0.0	0.0	0.0	0.0	< 1%
MDPO [2x15 cm] (hour)	0.0	0.0	0.0	0.0	0.0	0.0	≤ 24 hours
MDNO [2x15 cm] (hour)	0.0	0.0	0.0	0.0	0.0	0.0	≤ 24 hours

Table 11. Summary of Standard Statistics Evaluating the Ability of the *Semi-Operational Nowcasts* to Predict Extreme High Water Level Events at the NOS NWLON stations in Lake Michigan during the Period 15 April to 17 December 2004. Red indicates that the statistic did not pass the NOS acceptance criteria. Green indicates that it did meet the criteria.

Statistic, Acceptable Error [ ], and Units ( )	Port Inland MI N=19		Ludington MI N=24		Holland MI N=19	
	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Diff. (m) (min)	-0.080	1.0	-0.147	2.875	-0.088	0.895
RMSE (m) (min)	0.086	3.532	0.159	4.495	0.100	4.298
SD (m) (min)	0.032	3.480	0.061	3.530	0.050	4.319
NOF [2x15cm] (90min) %	0.0	10.5	0.0	4.2	0.0	15.8
CF [15 cm or 90 min] (%)	100.0	36.8	54.2	16.7	94.7	47.4
POF [2x15 cm or 90 min] (%)	0.0	21.1	0.0	45.8	0.0	26.3
MDPO [2x15 cm or 90 min] (#)	0.0	0.0	0.0	0.0	0.0	0.0
MDNO [2x15 cm or 90min] (#)	0.0	0.0	0.0	0.0	0.0	0.0

Table 11. (cont.).

Statistic, Acceptable Error [ ], and Units ( )	Calumet Harbor IL N=28		Milwaukee WI N=21		Kewaunee WI N=16		NOS Accept. Criteria
	Amplitude	Time	Amplitude	Time	Amplitude	Time	
Mean Alg. Diff. (m) (min)	-0.151	-0.286	-0.134	0.333	-0.152	1.500	na
RMSE (m) (min)	0.166	5.043	0.149	5.568	0.161	5.148	na
SD (m) (min)	0.071	5.127	0.068	5.695	0.056	5.086	na
NOF [2x15cm] (90min) %	3.6	32.1	0.0	19.0	0.0	18.8	≤ 1
CF [15 cm or 90 min] (%)	50.0	17.9	66.7	38.1	56.3	6.3	≥ 90
POF [2x15 cm or 90 min] (%)	0.0	28.6	0.0	23.8	0.0	50.0	≤ 1
MDPO [2x15 cm or 90 min] (#)	0.0	0.0	0.0	0.0	0.0	0.0	≤ 24 hours
MDNO [2x15 cm or 90min] (#)	0.0	0.0	0.0	0.0	0.0	0.0	≤ 24 hours

The skill statistics to predict extreme low water level events at the 6 NOS gauges during 2004 are given together in Table 12. The nowcast simulations of extreme low water level passed NOS acceptance criteria for amplitude at Holland, Milwaukee and Kewaunee, but not at Port Inland, Ludington and Calumet Harbor. The nowcasts' ability to simulate the timing of these events did not pass NOS acceptance criteria for NOF, CF, and POF at any of the 6 gauges.

Table 12. Summary of Standard Statistics Evaluating the Ability of *Semi-Operational Nowcasts* to Simulate <u>Extreme Low Water Level Events</u> at the NOS NWLON Stations in Lake Michigan for the Period 15 April to 17 December 2004. Red indicates that the statistic did not pass the NOS acceptance criteria. Green indicates that it did meet the criteria.

Statistic, Acceptable Error [ ], and Units ( )	Port Inland MI N=33		Ludington MI N=28		Holland MI N=10	
	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Diff. (m) (min)	0.114	0.758	0.094	-0.250	0.089	1.200
RMSE (m) (min)	0.120	2.928	0.100	3.942	0.094	2.608
SD (m) (min)	0.036	2.873	0.033	4.006	0.031	2.441
NOF [2x15cm] (90min) %	0.0	9.1	0.0	35.7	0.0	0.0
CF [15 cm or 90 min] (%)	78.8	36.4	89.3	17.9	90.0	30.0
POF [2x15 cm or 90 min] (%)	0.0	15.2	0.0	25.0	0.0	20.0
MDPO [2x15 cm or 90	0.0	0.0	0.0	0.0	0.0	0.0

min] (#)						
MDNO [2x15 cm or 90min] (#)	0.0	0.0	0.0	0.0	0.0	0.0

Table 12 (cont.).

Statistic, Acceptable Error [ ], and Units ( )	Calumet Harbor IL N=38		Milwaukee WI N=25		Kewaunee WI N=25		NOS Accept. Criteria
	Amplitude	Time	Amplitude	Time	Amplitude	Time	
Mean Alg. Diff. (m) (min)	0.091	0.105	0.064	-1.000	0.080	-0.480	na
RMSE (m) (min)	0.110	3.026	0.073	2.878	0.088	3.394	na
SD (m) (min)	0.063	3.065	0.035	2.754	0.038	3.429	na
NOF [2x15cm] (90min) %	0.0	15.8	0.0	20.0	0.0	24.0	≤ 1
CF [15 cm or 90 min] (%)	84.2	39.5	96.0	52.0	92.0	28.0	≥ 90
POF [2x15 cm or 90 min] (%)	0.0	13.2	0.0	8.0	0.0	20.0	≤ 1
MDPO [2x15 cm or 90 min] (#)	0.0	0.0	0.0	0.0	0.0	0.0	≤ 24 hours
MDNO [2x15 cm or 90min] (#)	0.0	0.0	0.0	0.0	0.0	0.0	≤ 24 hours

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 2 NWS/NDBC fixed buoys from mid-April to early December 2004 are given in Appendix D. Time series plots of the nowcasts (1^{st} sigma level) compared with observations at the buoys are given in Appendix E. The time series plots clearly indicate that the nowcast values are 2 degrees higher than observations starting in mid-April, but then begin to close the gap approaching mid- to late-August. After that, the nowcasts differ from observations by +1-2^{o}C until the end of the period. The wide temperature gap in the beginning of the simulation could be due to continuous simulation of the GLFS over the winter season, thus accumulating heat in the water body. This problem may be resolved by reinitializing the model at the beginning of the simulation period by using a isothermal condition based on the satellite-derived SST.

The skill statistics to predict hourly surface water temperatures at the two NDBC buoys are given together in Table 13 along with the NOS acceptance criteria. The hourly water temperature nowcasts at the southern buoy passed the NOS skill assessment criteria. The hourly nowcasts at the northern Michigan buoy came close to passing the criteria, failing primarily in regards to CF by only 7%. The MAD for the period ranged between 0.7-1.4^{o}C and the RMSE ranged between 1.5-2.2^{o}C at the two buoys.

Table 13. Summary of Skill Assessment Statistics of the Semi-Operational Nowcasts of Hourly Surface Water Temperatures at two NWS/NDBC fixed buoys in Lake Michigan for the Period from mid-April to early November 2004. Red indicates that the statistic did not pass the NOS acceptance criteria. Green indicates that it did meet the criteria.

Time Period, Statistic, Acceptable Error [ ], and Units ( )	45002 Northern Michigan N=5083	45007 Southern Michigan N=5574	NOS Acceptance Criteria
Time Period	21 April to 17 Nov. 2004	20 April to 8 Dec. 2004	365 days
Mean Alg. Difference (^{o}C)	1.428	0.735	na
RMSE (^{o}C)	2.213	1.565	na
SD (^{o}C)	1.692	1.381	na
NOF [2x3^{o}C] (%)	0.0	0.0	≤ 1%
CF [3^{o}C] (%)	83.7	91.5	≥ 90%
POF [2x3^{o}C] (%)	1.8	0.0	≤ 1%
MDPO [2x3^{o}C] (hours)	0.0	0.0	≤ 24 hours
MDNO [2x3^{o}C] (hours)	36.0	0.0	≤ 24 hours

(Note na = not applicable, NA=not available).

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.”

For the assessment of the semi-operational forecast scenario for LMOFS, archived forecast guidance from GLCFS twice per day forecast cycles (0000 and 1200 UTC) were compared to available observations in Lake Michigan. This chapter provides a description of the GLCFS forecast cycles, the method of evaluation including time period and assessment statistics, and the results of the evaluation.

6.1 Description of Forecast Cycles

GLCFS performs twice/day forecast cycles for Lake Michigan. The two forecast cycles are initialized at 0000 and 1200 UTC each day and generate forecast guidance 60 hours into the future. 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 forecast input data. For example, 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 consists of the 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 GLCFS forecast guidance at 1 hour increments out to 30 hours were compared to observations from coastal observing platforms in the Lake Michigan region from 15 April to 17 December 2004. This was a period when there was no significant ice cover on Lake Michigan.

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 modeled water levels at the same six NOS stations used in the evaluation of the nowcasts as described in 5.2

The evaluation of semi-operational forecast guidance of surface water temperatures was based on time series comparisons of observed and modeled temperatures at the same two NWS fixed buoys used in the nowcast evaluation. There are a few gaps in the record of forecast guidance due to computer and/or network problems or incomplete surface forcing from the NAM model for a particular forecast cycle.

6.3 Assessment of Water Level Forecast Guidance

The standard suite of skill assessment statistics for the semi-operational forecast guidance and the nowcasts' ability to predict hourly and extreme water levels at 6 NOS gauges from 15 April to 20 December 2004 are given in Appendix A. Time series plots of the forecast guidance from the 0000 UTC model forecast cycle compared with observations at the gauges are given in Appendix C.

The skill statistics assessing the ability of the forecast guidance to predict hourly water levels at the 6 NOS gauges are presented together in Table 14 along with the NOS acceptance criteria. The hourly forecast guidance passed the criteria at all six locations. The mean algebraic differences ranged between -1.7 to + 1.3 cm, and the RMSE ranged between 5.0 and 7.2 cm, very similar to the statistics for the nowcast evaluation. Similar to the nowcasts, the greatest errors were at NOS gauges in Calumet Harbor, IL and Port Inland, MI, located at the southern and northern ends of the lake, respectively. The forecasts underpredicted the water levels at all gauges except Port Inland. There was no significant increase in MAD, RMSE values, or CF as forecast projection time increased (Appendix A).

Table 14. Summary of Skill assessment Statistics of *Semi-Operational Forecast Guidance* of Hourly Water Levels at six NOS NWLON Stations in Lake Michigan for the Period 15 April to 17 December 2004. A total of 481 forecasts were used in the assessment. **Red indicates that the statistic did not pass the NOS acceptance criteria. Green indicates that it did meet the criteria.**

Statistic, Acceptable Error [ ], and Units ( )	Port Inland MI	Ludington, MI	Holland, MI	Calumet Harbor, IL	Milwaukee, WI	Kewaunee, WI	NOS Accept. Criteria
Mean Alg. Diff. (m)	0.013	-0.009	-0.004	-0.011	-0.017	-0.007	na
RMSE (m)	0.050	0.055	0.051	0.072	0.057	0.051	na
SD (m)	0.049	0.055	0.051	0.071	0.054	0.050	na
NOF (2x15cm) (%)	0.0	0.0	0.0	0.0	0.0	0.0	≤ 1%
CF [15 cm] (%)	99.0	97.1	98.2	95.5	98.2	98.4	≥ 90%
POF [2x15 cm] (%)	0.0	0.0	0.0	0.0	0.0	0.0	≤ 1%
MDPO [2x15 cm] (hour)	0.0	0.0	0.0	0.0	0.0	0.0	≤ 24 hours
MDNO [2x15 cm] (hour)	0.0	0.0	0.0	0.0	0.0	0.0	≤ 24 hours

The skill statistics to assess the ability of the forecast guidance to predict extreme high water level events at the six NOS gauges during 2004 are given together in Table 15. The forecasts of extreme high water level passed NOS acceptance criteria for amplitude at Port Inland and Holland, but not at Ludington, Calumet Harbor, Milwaukee and Kewaunee. The forecasts' ability to simulate the timing of these events did not pass NOS acceptance criteria for NOF, CF, and POF at any of the six gauges.

Table 15. 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 Michigan during the Period 15 April to 17 December 2004. Red indicates that the statistic did not pass the NOS acceptance criteria. Green indicates that it did meet the criteria.

Statistic, Acceptable Error [ ], and Units ( )	Port Inland MI N=19		Ludington MI N=24		Holland MI N=16	
	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Diff. (m) (min)	-0.061	0.474	-0.153	0.625	-0.075	1.063
RMSE (m) (min)	0.073	4.020	0.171	4.287	0.087	4.085
SD (m) (min)	0.040	4.101	0.077	4.332	0.045	4.074
NOF [2x15cm] (90min) %	0.0	21.1	0.0	20.8	0.0	12.5
CF [15 cm or 90 min] (%)	100.0	31.6	45.8	16.7	93.8	6.3
POF [2x15 cm or 90 min] (%)	0.0	21.1	0.0	25.0	0.0	25.0

Table 15 (cont.)

Statistic, Acceptable Error [ ], and Units ( )	Calumet Harbor IL N=30		Milwaukee WI N=21		Kewaunee WI N=12		NOS Accept. Criteria
	Amplitude	Time	Amplitude	Time	Amplitude	Time	
Mean Alg. Diff. (m) (min)	-0.137	-0.500	-0.141	-0.143	-0.177	-1.083	na
RMSE (m) (min)	0.159	5.648	0.155	6.751	0.184	5.867	na
SD (m) (min)	0.081	5.722	0.064	6.916	0.052	6.022	na
NOF [2x15cm] (90min) %	3.3	30.0	0.0	38.1	8.3	33.3	≤ 1
CF [15 cm or 90 min] (%)	56.7	20.0	61.9	9.5	41.7	25.0	≥ 90
POF [2x15 cm or 90 min] (%)	0.0	23.3	0.0	33.3	0.0	33.3	≤ 1

The skill statistics to assess the ability of the forecast guidance to predict extreme low water level events at the five NOS gauges during 2004 are given together in Table 16. The forecasts of extreme low water level passed NOS acceptance criteria for amplitude at Port Inland, Holland, Milwaukee and Kewaunee, but not at Ludington and Calumet Harbor where the CF was 85.7 and 83.8%, respectively. The forecasts' ability to simulate the timing of these events did not pass NOS acceptance criteria for NOF, CF, and POF at any of the six gauges.

Table 16. 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 Michigan during the Period 15 April to 17 December 2004. Red indicates that the statistic did not pass the NOS acceptance criteria. Green indicates that it did meet the criteria.

Statistic, Acceptable Error [ ], and Units ( )	Port Inland MI N=33		Ludington MI N=28		Holland MI N=10	
	Amp.	Time	Amp.	Time	Amp.	Time
Mean Alg. Diff. (m) (min)	0.099	0.000	0.095	-1.107	0.079	0.091
RMSE (m) (min)	0.103	3.266	0.101	4.145	0.083	3.398
SD (m) (min)	0.028	3.317	0.035	4.067	0.027	3.562
NOF [2x15cm] (90min) %	0.0	21.2	0.0	39.3	0.0	18.2
CF [15 cm or 90 min] (%)	97.0	27.3	85.7	17.9	100.0	27.3
POF [2x15 cm or 90 min] (%)	0.0	12.1	0.0	21.4	0.0	18.2

Table 16 (cont.).

Statistic, Acceptable Error [ ], and Units ( )	Calumet Harbor IL N=38		Milwaukee WI N=25		Kewaunee WI N=25		NOS Accept. Criteria
	Amplitude	Time	Amplitude	Time	Amplitude	Time	
Mean Alg. Diff. (m) (min)	0.080	-0.973	0.054	0.200	0.080	-0.923	na
RMSE (m) (min)	0.104	3.661	0.063	3.317	0.089	4.132	na
SD (m) (min)	0.068	3.578	0.033	3.379	0.039	4.108	na
NOF [2x15cm] (90min) %	0.0	24.3	0.0	16.0	0.0	38.5	≤ 1
CF [15 cm or 90 min] (%)	83.8	27.0	100.0	36.0	96.2	15.4	≥ 90
POF [2x15 cm or 90 min] (%)	0.0	13.5	0.0	24.0	0.0	23.1	≤ 1

Notes: na=not applicable

6.4 Assessment of Water Temperature Forecast Guidance

The standard suite of skill assessment statistics evaluating the ability of the semi-operational forecast guidance to predict hourly lake surface water temperatures at two NWS/NDBC fixed buoys from mid-April to early December 2004 are given in Appendix D. The table provides skill statistics at the forecast projection times of 0, 6, 12, 18, and 24 hours. Time series plots of the forecasts (1st sigma level) from the 0000 UTC forecast cycle compared with buoy observations are given in Appendix E. The time series plots indicate 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 does 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 values are 2°C higher than observations beginning in mid-April, but then begin to close the gap towards mid- to late-August. After that, the nowcasts differed from observations by +1-2°C until the end of the period. The wide temperature gap in the beginning of the simulation could be due to continuous simulation of the GLFS over the winter season, thus accumulating heat in the water body.

The skill statistics assessing the ability of the semi-operational forecast guidance to predict surface water temperatures 24 hours in advance at the 2 NDBC buoys are given in Table 17 along with the NOS acceptance criteria. The hourly forecast guidance at the Southern Michigan buoy (45007) passed all the criteria while the hourly forecast guidance at the northern Michigan buoy (45002) came close to passing all the criteria (failing to meet the CF criteria by only 3%). The MAD ranged between 0.5 and 1.2°C and the RMSE ranged between 1.3 and 1.9°C at the two buoys. The MAD and RMSEs for the forecast guidance were slightly lower than for the nowcasts.

It is interesting to note that mean differences, RMSE, and the CF and POF values decreased as forecast projection increased in time. For example, at the northern buoy, the RMSE was 2.2°C at the 0-hr projection and 1.9°C by the 24-hr projection (see Table D.3). This suggests that the surface heat flux is being overestimated during the nowcast cycle.

Table 17. Summary of Skill Assessment Statistics for Semi-Operational Forecast Guidance in Predicting Surface Water Temperatures 24 hours in advance at NWS/NDBC fixed buoys during the period from mid-April to early-November 2004. Red indicates that the statistic did not pass the NOS acceptance criteria. Green indicates that it did meet the criteria.

Time Period, Statistic, Acceptable Error [ ], and Units ( )	45002 Northern Michigan N=420	45007 Southern Michigan N=461	NOS Acceptance Criteria
Time Period	20 April to 17 November 2004	20 April to 8 December 2004	365 days
Mean Alg. Difference (°C)	1.252	0.517	na
RMSE (°C)	1.988	1.397	na
SD (°C)	1.545	1.299	na
NOF [2x3°C] (%)	0.0	0.0	≤ 1%
CF [3°C] (%)	87.1	94.1	≥ 90%
POF [2x3°C] (%)	1.0	0.0	≤ 1%
MDPO [2x3°C] (hours)	0.0	0.0	≤ 24 hrs
MDNO [2x3°C] (hours)	24.0	0.0	< 24 hrs

Notes: na=not applicable

7. SUMMARY

NOS' Lake Michigan Operational Forecast System (LMOFS) 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.

LMOFS became operational at CO-OPS on 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 LMOFS predictions was conducted according to the NOS evaluation standards (Hess et al. 2003). To comply with the NOS standards, the results of the numerical modeling component of the Lake Michigan Mass Balance Study (SB98) of 1983-84 and 1994-95 was used for the hindcast scenario and are summarized below.

To comply with the NOS required semi-operational nowcast and forecast scenarios, the evaluation used archived output from NOAA/GLERL's GLCFS semi-operational nowcast and forecast cycles for the ice free period from15 April to 17 December 2004. The semi-operational nowcasts and forecast guidance were compared to water level observations at six NOS NWLON stations and surface temperature temperatures at two NWS/NDBC fixed buoys in the lake. Due to the lack of subsurface water temperatures and current observations, no assessment of these variables could be conducted for LMOFS.

Water Levels

The POMGL for Lake Michigan was able to simulate the water level in the main part of the lake but could not resolve many local effects such as edge waves or resonance in harbors and small . The mean algebraic differences (MAD) at the northern and southern ends of the lake where the largest wind-induced water level fluctuations occur ranged from 0.65 to -0.05 cm in 1983-84 and 2.33 to 1.10 cm in 1994-95, respectively. In Green Bay, the RMSE was over 12 cm in both time periods, while the RMSE at other locations ranged between 3 and 6 cm.

The hourly nowcasts of water levels met the NOS acceptance criteria at all six NOS gauges. The MAD ranged between -2.1 cm and +1.9 cm. Thus, the nowcasts underpredicted the hourly water levels at all gauges except at Port Inland, MI. The RMSE among the six gauges ranged between 4.8 and 7.0 cm. One can not distinguish the amount of error due to the ability of POMGL to predict the water level or the potential error caused by the method used to estimate the lake wide water level which was added to POMGL water level predictions The ability of the nowcasts to predict extreme high and low water level events was also assessed using a proposed evaluation procedure to the NOS standards. The nowcast predictions of high water level events passed the NOS criteria for amplitude at two of the six NOS gauges, while the predictions of low water level events passed the NOS criteria at three of the six NOS gauges. The nowcasts failed to meet NOS criteria in predicting the timing of both extreme high and low water events at all the NOS gauges.

The hourly forecast guidance met the NOS criteria at all six locations. The MAD ranged between -1.7 to + 1.3 cm and the RMSE ranged between 5.0 and 7.2 cm, very similar to the statistics for the nowcast evaluation. Similar to the nowcasts, the greatest error was at the Calumet Harbor gauge located at the southern end of the lake. The forecast underpredicted the water levels at all gauges except at Port Inland. There was no significant increase in the mean algebraic differences,RMSE, or CF as forecast projection time increased.

The forecast guidance of extreme high and low water level events passed NOS criteria at two and four of the six gauges, respectively. The forecast guidance failed to meet NOS criteria in predicting the timing of both extreme high and low water events at all NOS gauges.

Water Temperatures

POMGL simulated well the surface water temperatures in terms of both horizontal distribution and time evolution, indicating that the model was initialized properly and that the correct amount of heat flux was inputted into the lake. The MAD were less than +0.5°C. The modeled sub-surface temperatures, especially in the thermocline, were not as good as the surface temperatures. The model reproduced the basic features of the evolution of the three-dimesional thermal structure of the lake, but the model produced a thermocline that was too diffuse and failed to capture the frequent temperature fluctuations.

The hourly surface water temperature nowcasts meet the NOS criteria at the southern buoy. The nowcasts came very close to meeting NOS criteria at the northern buoy, failing to meet the CF by 7%. The MAD for the period ranged between 0.7 and 1.4°C, and the RMSE ranged between 1.5 and 2.2°C.

The hourly surface water temperature forecast guidance at 24 hours for the southern buoy passed the NOS criteria while the southern one came very close at 87%. The MAD ranged between 0.5 and 1.2°C and RMSE between 1.3 and 1.9°C, which were slightly lower than for the nowcasts. The RMSE of the hourly water temperature forecasts slightly decreased as the forecast projection increased in time.

WaterCurrents

POMGL simulated properly the cyclonic large-scale circulation pattern in the lake, with cyclonic circulation within each sub-basin and anticyclonic in ridge areas. The model did the best in the southern basin, which is characterized by smooth bathymetry, and in the fall-winter months when barotropic processes are dominant. During the spring-summer months when baroclinic processes are dominant, the horizontal resolution (5 km) is too coarse to properly simulate these processes which have horizontal length scales comparable to the Rossby deformation radius (~5 km).

There was no current data in the lake to evaluate the water current nowcasts and forecast guidance.

8. RECOMMENDATION FOR FUTURE WORK

Recommendation #1

The comparisons of the semi-operational nowcasts and forecast guidance of surface water temperature to observations at buoys in the lake indicate a problem with surface water temperature predictions, especially during the Spring and Summer. This could be caused by the inaccuracy in the model's depiction of the three dimensional thermal structure at the start of spring warming. It is recommended that sensitivity runs be conducted to determine impacts of 1) re-initializing early spring the three-dimensional thermal structure on the surface water temperature predictions based on the historical mean temperature profile and 2) the use of an ice module in POMGL. GLERL is presently testing an ice module in POMGL for Lakes Erie and Michigan.

Recommendation #2

The comparisons of the semi-operational nowcasts and forecast guidance of surface water temperature to observations indicate a potential overestimation of the surface heat flux during the nowcast cycle. An examination of the surface heat flux algorithm and/or its meteorological inputs should be conducted to identify the potential cause.

Recommendation #3

SB98 found poor agreement between POMGL and observed water temperatures in the thermocline area where internal waves are also much less pronounced in the model simulations than in the observations. SB98 speculated that model predicted thermocline is too diffuse due to the model excessive vertical diffusion. The study to determine the cause and solution for this excessive diffusion is needed.

Recommendation #4

A study is needed to determine the reason why POMGL was unable to better forecast the timing of water level of extreme high and low water level events and the water level amplitudes at the northern and southern ends of the lakes in order to meet NOS standards. This would likely involve sensitivity tests with POMGL using higher grid resolution and incorporating atmospheric pressure forcing. GLERL is presently running a 2 km resolution version of POMGL for Lake Erie and Michigan.

Recommendation #5

The NWS Weather Forecast Office in Detroit, MI has requested that NOS use gridded surface wind direction and speed forecasts from the NWS' National Digital Forecast Database (NDFD) instead of forecast guidance from the NAM model as surface forcing for the forecast cycles of LMOFS and the other Great Lakes forecast systems. CO-OPS is now obtaining an experimental

NDFD surface windand air temperature forecast composites for the Great Lakes from the NWS Weather Forecast Office in Cleveland, OH and is running a parallel version of GLOFS forced by these gridded forecasts. An comparison is need of water level and temperature forecast guidance generated by LMOFS forced by NDFD forecasts vs, guidance produced by LMOFS forced by NAM modelpredictions.

Recommendation #6

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. If this is the case, alternative methods to estimate the mean lake wide water level may be explored. 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.

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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 Technologies Inc. In particular, we acknowledge the hard work of Greg Mott, Mark Vincent, Zack Bronder, and others at CO-OPS.

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REFERENCES

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, 206-264.

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

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

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

Great Lakes Information Network, 2006: Water Levels on the Great Lakes. Great Lakes Information Network (http://www.great-lakes.net/teach/envt/levels/lev_2.html).

Gottlieb, E.S., J.H. Saylor, and G.S. Miller, 1989: Currents and temperatures observed in Lake Michigan from June 1982 to July 1983. NOAA Technical Memorandum ERL GLERL-71, 45 pp.

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 from 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 Lake Erie. Ph.D. Dissertation, Ohio State University, 376 pp. [Available from Atmospheric Sciences Program, 1049 Derby Hall, 154 N. Oval Mall, Ohio State University, Columbus, OH 43210-1361.]

Kuan, C.-F., 1995: 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.

O'Connor W. P. and D.J. Schwab, 1993: Sensitivity of Great Lakes Forecasting System Nowcasts to Meteorological Fields and Model Parameters. *Proceedings, 3rd International Conference on Estuarine and Coastal Modeling,* ASCE Waterways, Port, Coastal and Ocean Division, 149-157.

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

Saylor, J. H, J. C. K. Huang, and R. O. Reid, 1980: Vortex modes in Lake Michigan. *J. Phy. Oceanography,* **10**, 1814-1823.

Schwab, D. J., 1978: Simulation and forecasting of Lake Erie storm surges**.** *Mon. Wea. Rev*., *106,* 1476-1487.

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***.,** **89**, no. C3, 3586-3592.

Schwab, D. J. and D. Beletsky, 1998: Lake Michigan Mass Balance Study: Hydrodynamic Modeling Project. NOAA Technical Memorandum ERL GLERL-108, 53 pp.

Schwab, D. J. and D. L. Seller, 1980: Computerized bathymetry and shorelines of the Great Lakes. NOAA Data Report, ERL GLERL-16, 13 pp.

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. Canada*, **29**, 203-220.

Schwab, D. J., and D. Beletsky, 1998: Lake Michigan Mass Balance Study: Hydrodynamic Modeling Project. NOAA Technical Memorandum ERL GLERL-108, 53 pp. [Available from NOAA/Great Lakes Environmental Research Laboratory, Publications Office, 2205 Commonwealth Blvd., Ann Arbor, MI 48105-2945.]

Schwab, D. J. Personal communication of May 2006.

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

Zhang, A., K. W. Hess, E. Wei, and E. Myers, 2006: Implementation of Model Skill Assessment Software for Water Level and Current. NOAA Technical Report NOS CS 24, 61 pp.

APPENDIX A. Skill Assessment Scores of Semi-Operational Water Level Nowcasts and Forecasts of Water Levels from six NOS NWLON gauges in Lake Michigan for 2004.

Table A.1. Skill Assessment Statistics of Semi-Operational Predictions at NOS Port Inland, MI (NOS ID 9087096) Gauge.

```
Station:           Port Inland, Lake Michigan, MI
Observed data-longest continuous time segment from:  8/10/2004  to 11/26/2004
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                     5726 176.236
h                     5726 176.217
H-h        15 cm 24h  5726   0.019  0.052  0.048   0.0  98.8   0.0    0.0  0.0
AHW-ahw    15 cm 24h    19  -0.080  0.086  0.032   0.0 100.0   0.0    0.0  0.0
ALW-alw    15 cm 24h    33   0.114  0.120  0.036   0.0  78.8   0.0    0.0  0.0
THW-thw  1.50 hr 25h    19   1.000  3.532  3.480  10.5  36.8  21.1    0.0  0.0
TLW-tlw  1.50 hr 25h    33   0.758  2.928  2.873   9.1  36.4  15.2    0.0  0.0

     SCENARIO: SEMI-OPERATIONAL FORECAST
H00-h00    15 cm 24h   485   0.011  0.050  0.049   0.0  98.4   0.0    0.0  0.0
H06-h06    15 cm 24h   479   0.028  0.053  0.044   0.0  99.2   0.0    0.0  0.0
H12-h12    15 cm 24h   481   0.012  0.047  0.046   0.0  99.0   0.0    0.0  0.0
H18-h18    15 cm 24h   479   0.026  0.051  0.044   0.0  99.4   0.0    0.0  0.0
H24-h24    15 cm 24h   481   0.013  0.050  0.049   0.0  99.0   0.0    0.0  0.0
AHW-ahw    15 cm 24h    19  -0.061  0.073  0.040   0.0 100.0   0.0
ALW-alw    15 cm 24h    33   0.099  0.103  0.028   0.0  97.0   0.0
THW-thw  1.50 hr 25h    19   0.474  4.020  4.101  21.1  31.6  21.1
TLW-tlw  1.50 hr 25h    33   0.000  3.266  3.317  21.2  27.3  12.1
```

Table A.2. Skill Assessment Statistics of Semi-Operational Predictions at NOS Ludington, MI (9087023) Gauge for 2004

```
Station:             Ludington, Lake Michigan, MI
Observed data-longest continuous time segement from: 4/23/2004  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                     5785 176.239
h                     5785 176.248
H-h        15 cm 24h  5785  -0.010  0.053  0.052   0.0  98.0   0.0    0.0  0.0
AHW-ahw    15 cm 24h    24  -0.147  0.159  0.061   0.0  54.2   0.0    0.0  0.0
ALW-alw    15 cm 24h    28   0.094  0.100  0.033   0.0  89.3   0.0    0.0  0.0
THW-thw  1.50 hr 25h    24   2.875  4.495  3.530   4.2  16.7  45.8    0.0  0.0
TLW-tlw  1.50 hr 25h    28  -0.250  3.942  4.006  35.7  17.9  25.0    0.0  0.0

     SCENARIO: SEMI-OPERATIONAL FORECAST
H00-h00    15 cm 24h   490  -0.008  0.052  0.051   0.0  98.4   0.0    0.0  0.0
H06-h06    15 cm 24h   486  -0.011  0.056  0.055   0.0  97.5   0.0    0.0  0.0
H12-h12    15 cm 24h   486  -0.008  0.054  0.053   0.0  97.3   0.0    0.0  0.0
H18-h18    15 cm 24h   486  -0.012  0.057  0.056   0.0  97.5   0.0    0.0  0.0
H24-h24    15 cm 24h   486  -0.009  0.055  0.055   0.0  97.1   0.0    0.0  0.0
AHW-ahw    15 cm 24h    24  -0.153  0.171  0.077   0.0  45.8   0.0
ALW-alw    15 cm 24h    28   0.095  0.101  0.035   0.0  85.7   0.0
THW-thw  1.50 hr 25h    24   0.625  4.287  4.332  20.8  16.7  25.0
TLW-tlw  1.50 hr 25h    28  -1.107  4.145  4.067  39.3  17.9  21.4
```

Table A.3. Skill Assessment Statistics of Semi-Operational Predictions at NOS Holland, MI (9087031) Gauge for 2004

```
Station:               Holland, Lake Michigan, MI
Observed data-longest continuous time segment 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 176.237
h                     5832 176.244
H-h        15 cm 24h  5832  -0.007  0.048  0.048   0.0  98.9   0.0    0.0  0.0
AHW-ahw    15 cm 24h    19  -0.088  0.100  0.050   0.0  94.7   0.0    0.0  0.0
ALW-alw    15 cm 24h    10   0.089  0.094  0.031   0.0  90.0   0.0    0.0  0.0
THW-thw  1.50 hr 25h    19   0.895  4.298  4.319  15.8  47.4  26.3    0.0  0.0
TLW-tlw  1.50 hr 25h    10   1.200  2.608  2.441   0.0  30.0  20.0    0.0  0.0

     SCENARIO: SEMI-OPERATIONAL FORECAST
H00-h00    15 cm 24h   494  -0.001  0.047  0.047   0.0  99.0   0.0    0.0  0.0
H06-h06    15 cm 24h   490  -0.014  0.049  0.047   0.0  99.0   0.0    0.0  0.0
H12-h12    15 cm 24h   490  -0.003  0.049  0.049   0.0  98.8   0.0    0.0  0.0
H18-h18    15 cm 24h   490  -0.013  0.054  0.052   0.0  98.0   0.0    0.0  0.0
H24-h24    15 cm 24h   490  -0.004  0.051  0.051   0.0  98.2   0.0    0.0  0.0
AHW-ahw    15 cm 24h    16  -0.075  0.087  0.045   0.0  93.8   0.0
ALW-alw    15 cm 24h    11   0.079  0.083  0.027   0.0 100.0   0.0
THW-thw  1.50 hr 25h    16   1.063  4.085  4.074  12.5   6.3  25.0
TLW-tlw  1.50 hr 25h    11   0.091  3.398  3.562  18.2  27.3  18.2
```

Table A.4. Skill Assessment Statistics of Semi-Operational Predictions at NOS Calumet Harbor, IL (9087044) Gauge for 2004.

```
Station:        Calumet Harbor, Lake Michigan, IL
Observed data-longest continuous time segment 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 176.237
h                     5832 176.256
H-h        15 cm 24h  5832  -0.019  0.070  0.068   0.1  95.5   0.0    2.0  0.0
AHW-ahw    15 cm 24h    28  -0.151  0.166  0.071   3.6  50.0   0.0    0.0  0.0
ALW-alw    15 cm 24h    38   0.091  0.110  0.063   0.0  84.2   0.0    0.0  0.0
THW-thw  1.50 hr 25h    28  -0.286  5.043  5.127  32.1  17.9  28.6    0.0  0.0
TLW-tlw  1.50 hr 25h    38   0.105  3.026  3.065  15.8  39.5  13.2    0.0  0.0

     SCENARIO: SEMI-OPERATIONAL FORECAST
H00-h00    15 cm 24h   494  -0.008  0.068  0.068   0.0  96.0   0.0    0.0  0.0
H06-h06    15 cm 24h   490  -0.031  0.071  0.064   0.2  96.5   0.0    0.0  0.0
H12-h12    15 cm 24h   490  -0.010  0.069  0.069   0.0  96.3   0.0    0.0  0.0
H18-h18    15 cm 24h   490  -0.029  0.078  0.072   0.2  94.5   0.0    0.0  0.0
H24-h24    15 cm 24h   490  -0.011  0.072  0.071   0.0  95.5   0.0    0.0  0.0
AHW-ahw    15 cm 24h    30  -0.137  0.159  0.081   3.3  56.7   0.0
ALW-alw    15 cm 24h    37   0.080  0.104  0.068   0.0  83.8   0.0
THW-thw  1.50 hr 25h    30  -0.500  5.648  5.722  30.0  20.0  23.3
TLW-tlw  1.50 hr 25h    37  -0.973  3.661  3.578  24.3  27.0  13.5
```

Table A.5. Skill Assessment Statistics of Semi-Operational Predictions at NOS Milwaukee, WI (9087057) Gauge for 2004.

```
Station:             Milwaukee, Lake Michigan, WI
Observed data-longest continuous time segment 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 176.229
h                     5832 176.250
H-h        15 cm 24h  5832  -0.021  0.057  0.053   0.0  98.2   0.0    0.0  0.0
AHW-ahw    15 cm 24h    21  -0.134  0.149  0.068   0.0  66.7   0.0    0.0  0.0
ALW-alw    15 cm 24h    25   0.064  0.073  0.035   0.0  96.0   0.0    0.0  0.0
THW-thw  1.50 hr 25h    21   0.333  5.568  5.695  19.0  38.1  23.8    0.0  0.0
TLW-tlw  1.50 hr 25h    25  -1.000  2.878  2.754  20.0  52.0   8.0    0.0  0.0

     SCENARIO: SEMI-OPERATIONAL FORECAST
H00-h00    15 cm 24h   494  -0.015  0.055  0.053   0.0  98.2   0.0    0.0  0.0
H06-h06    15 cm 24h   490  -0.028  0.058  0.051   0.0  98.8   0.0    0.0  0.0
H12-h12    15 cm 24h   490  -0.017  0.057  0.054   0.0  98.2   0.0    0.0  0.0
H18-h18    15 cm 24h   490  -0.027  0.060  0.054   0.0  98.0   0.0    0.0  0.0
H24-h24    15 cm 24h   490  -0.017  0.057  0.054   0.0  98.2   0.0    0.0  0.0
AHW-ahw    15 cm 24h    21  -0.141  0.155  0.064   0.0  61.9   0.0
ALW-alw    15 cm 24h    25   0.054  0.063  0.033   0.0 100.0   0.0
THW-thw  1.50 hr 25h    21  -0.143  6.751  6.916  38.1   9.5  33.3
TLW-tlw  1.50 hr 25h    25   0.200  3.317  3.379  16.0  36.0  24.0
```

Table A.6. Skill Assessment Statistics of Semi-Operational Predictions at NOS Kewaunee, WI (9087068) Gauge for 2004.

```
Station:              Kewaunee, Lake Michigan, WI
Observed data-longest continuous time segment 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 176.226
h                     5832 176.233
H-h        15 cm 24h  5832  -0.006  0.051  0.050   0.0  98.7   0.0    0.0  0.0
AHW-ahw    15 cm 24h    16  -0.152  0.161  0.056   0.0  56.3   0.0    0.0  0.0
ALW-alw    15 cm 24h    25   0.080  0.088  0.038   0.0  92.0   0.0    0.0  0.0
THW-thw  1.50 hr 25h    16   1.500  5.148  5.086  18.8   6.3  50.0    0.0  0.0
TLW-tlw  1.50 hr 25h    25  -0.480  3.394  3.429  24.0  28.0  20.0    0.0  0.0

     SCENARIO: SEMI-OPERATIONAL FORECAST
H00-h00    15 cm 24h   494  -0.007  0.048  0.048   0.0  99.0   0.0    0.0  0.0
H06-h06    15 cm 24h   490  -0.006  0.052  0.052   0.0  98.8   0.0    0.0  0.0
H12-h12    15 cm 24h   490  -0.007  0.050  0.049   0.0  99.0   0.0    0.0  0.0
H18-h18    15 cm 24h   490  -0.007  0.052  0.052   0.0  98.8   0.0    0.0  0.0
H24-h24    15 cm 24h   490  -0.007  0.051  0.050   0.0  98.4   0.0    0.0  0.0
AHW-ahw    15 cm 24h    12  -0.177  0.184  0.052   8.3  41.7   0.0
ALW-alw    15 cm 24h    26   0.080  0.089  0.039   0.0  96.2   0.0
THW-thw  1.50 hr 25h    12  -1.083  5.867  6.022  33.3  25.0  33.3
TLW-tlw  1.50 hr 25h    26  -0.923  4.132  4.108  38.5  15.4  23.1
```

APPENDIX B. Time Series Plots of Semi-Operational Water Level Nowcasts vs. Observations at Six NOS Gauges during 2004.

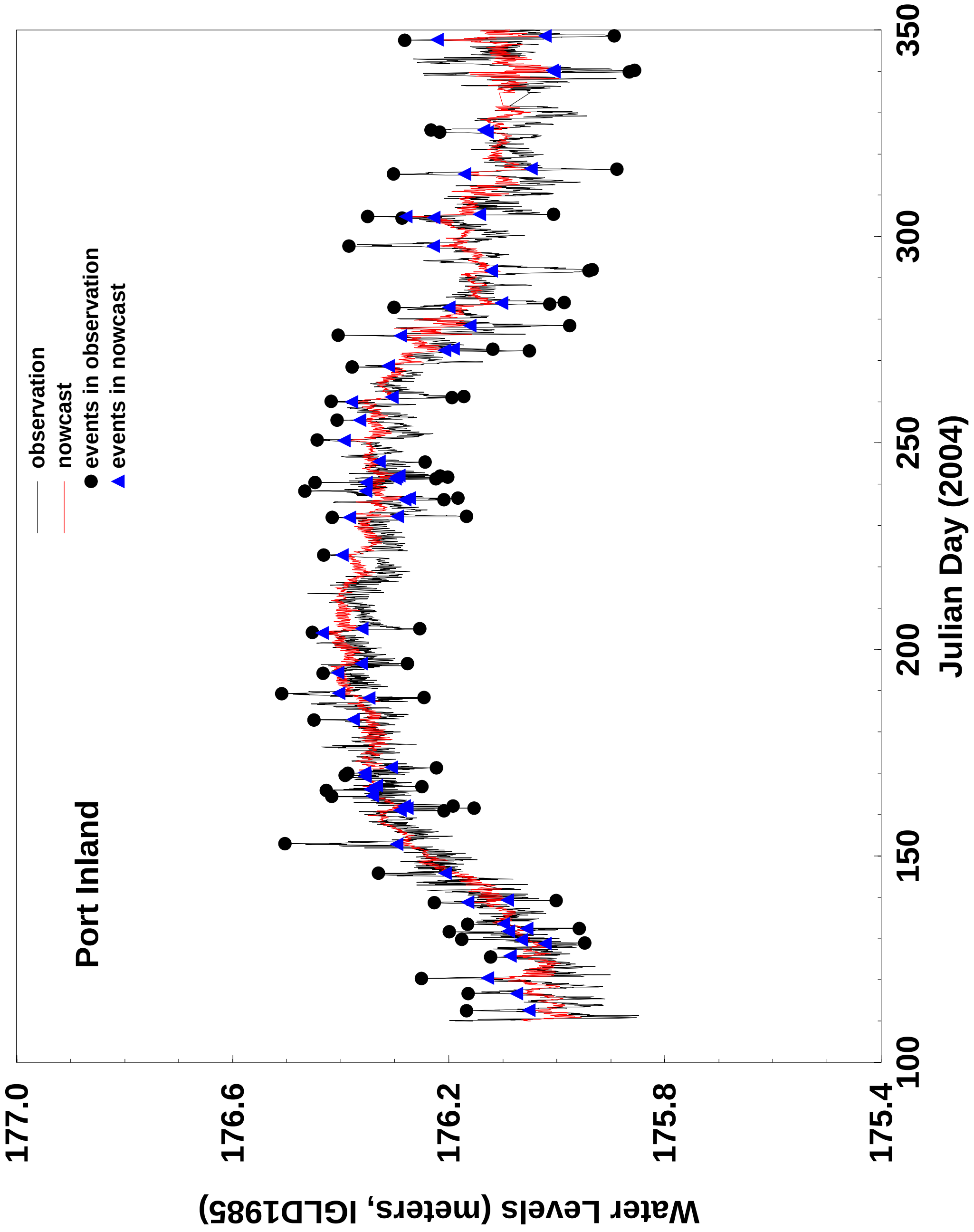

Figure B.1. Time Series Plot of Semi-Operational Nowcasts vs. Observations at NOS Gauge at Port Inland, MI.

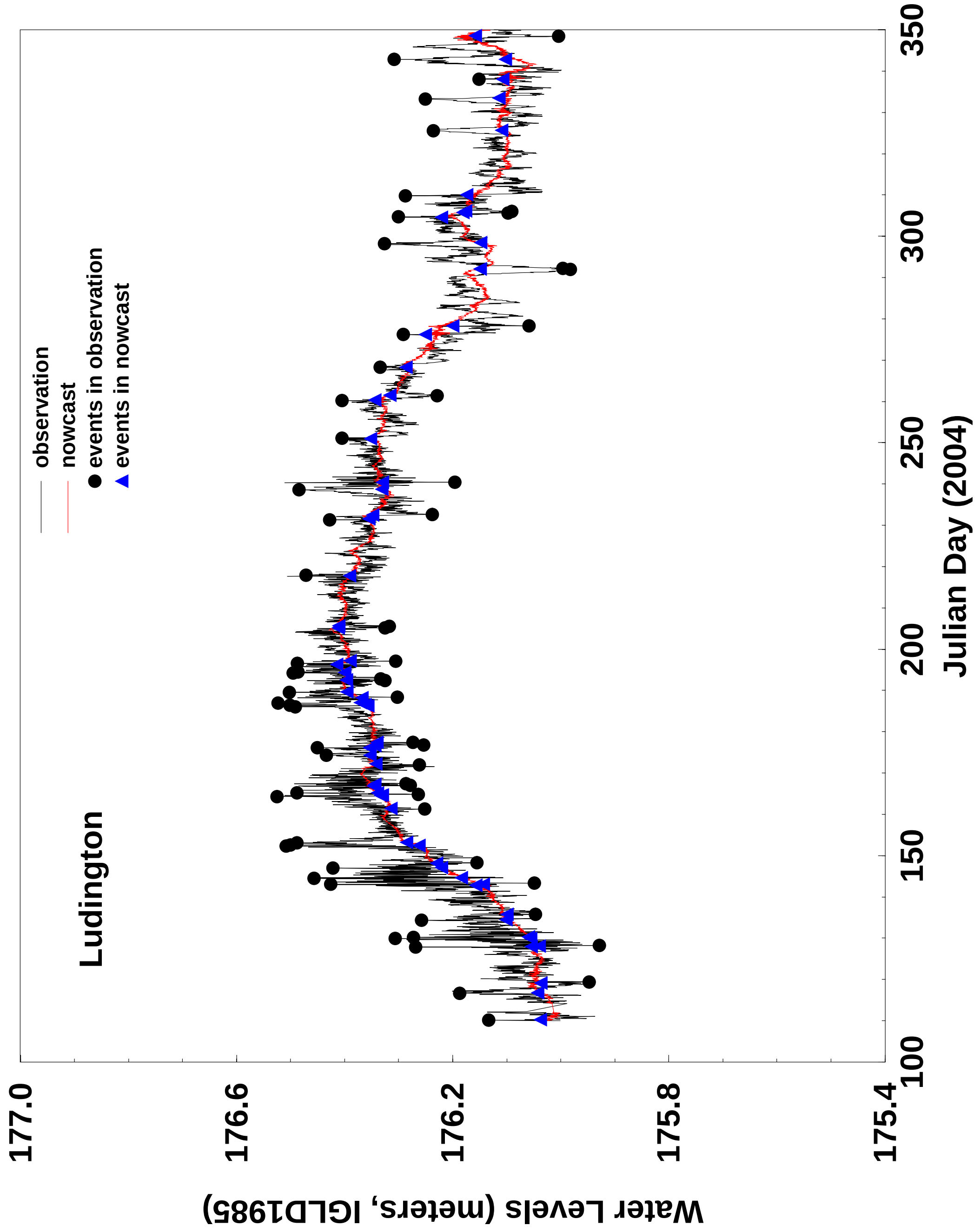

Figure B.2. Time Series Plot of Semi-Operational Nowcasts vs. Observations at NOS Gauge at Ludington, MI.

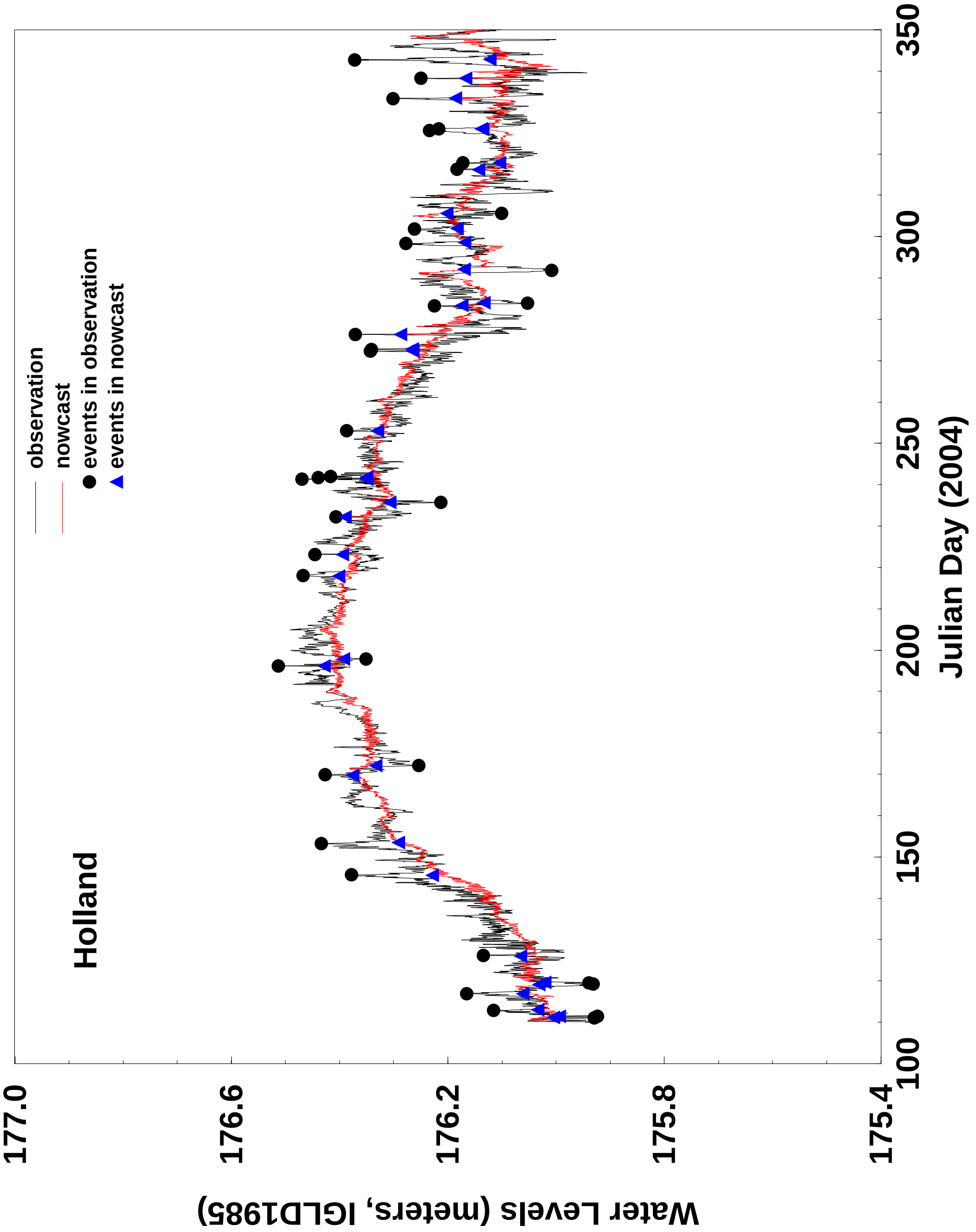

Figure B.3. Time Series Plot of Semi-Operational Nowcasts vs. Observations at NOS Gauge at Holland, MI.

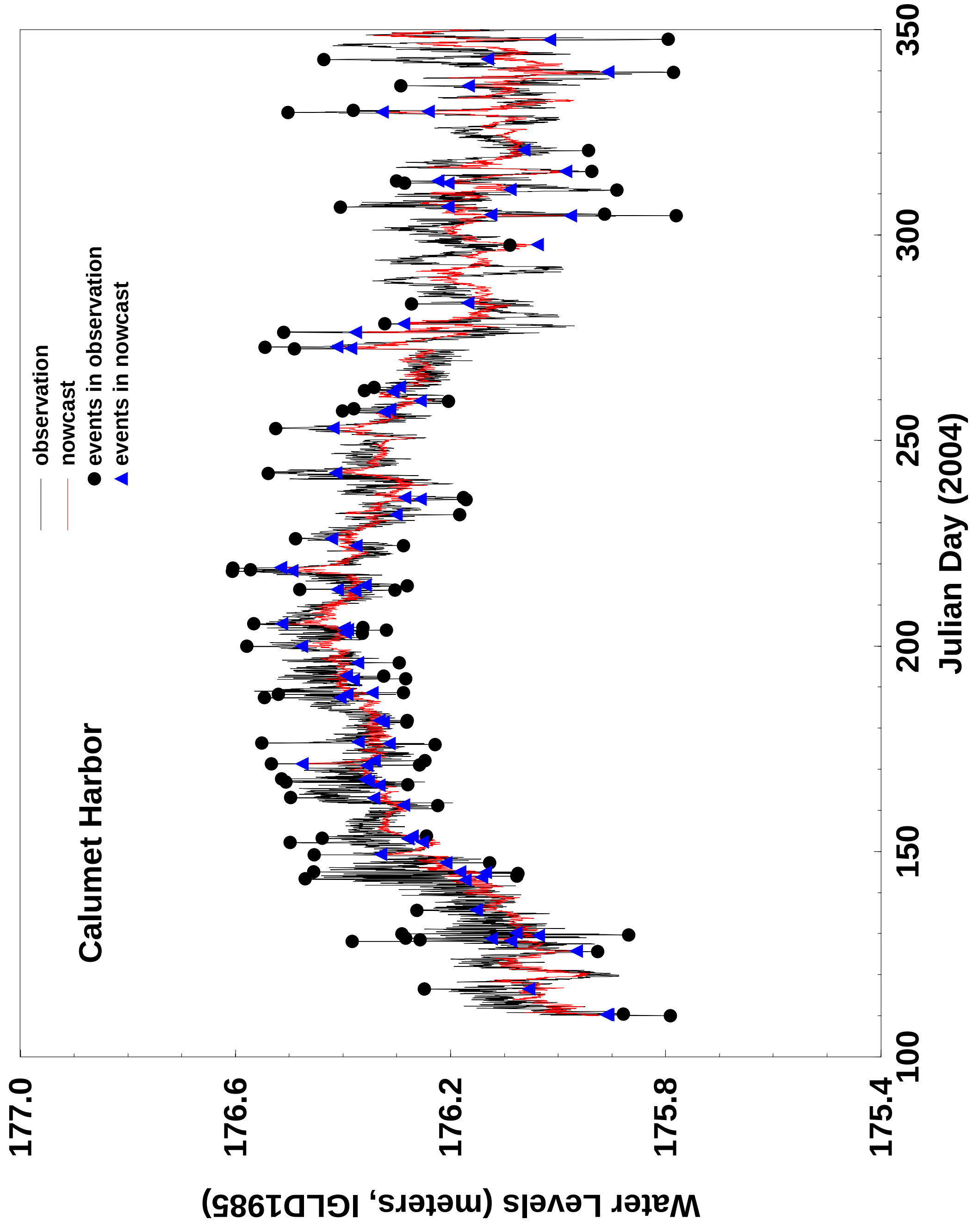

Figure B.4.Time Series Plot of Semi-Operational Nowcasts vs. Observations at NOS Gauge at Calumet Harbor, IL.

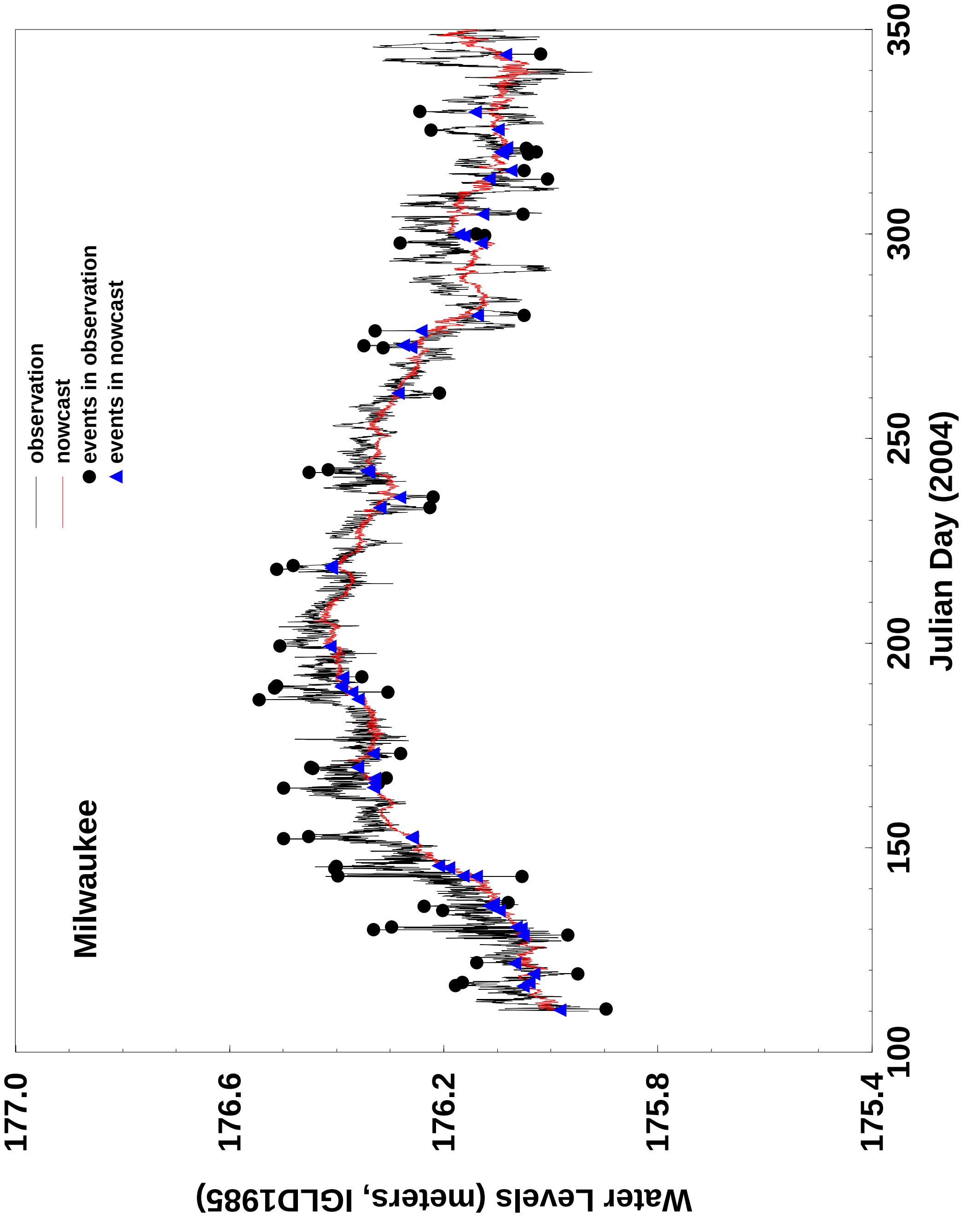

Figure B.5. Time Series Plot of Semi-Operational Nowcasts vs. Observations at NOS Gauge in Milwaukee, WI.

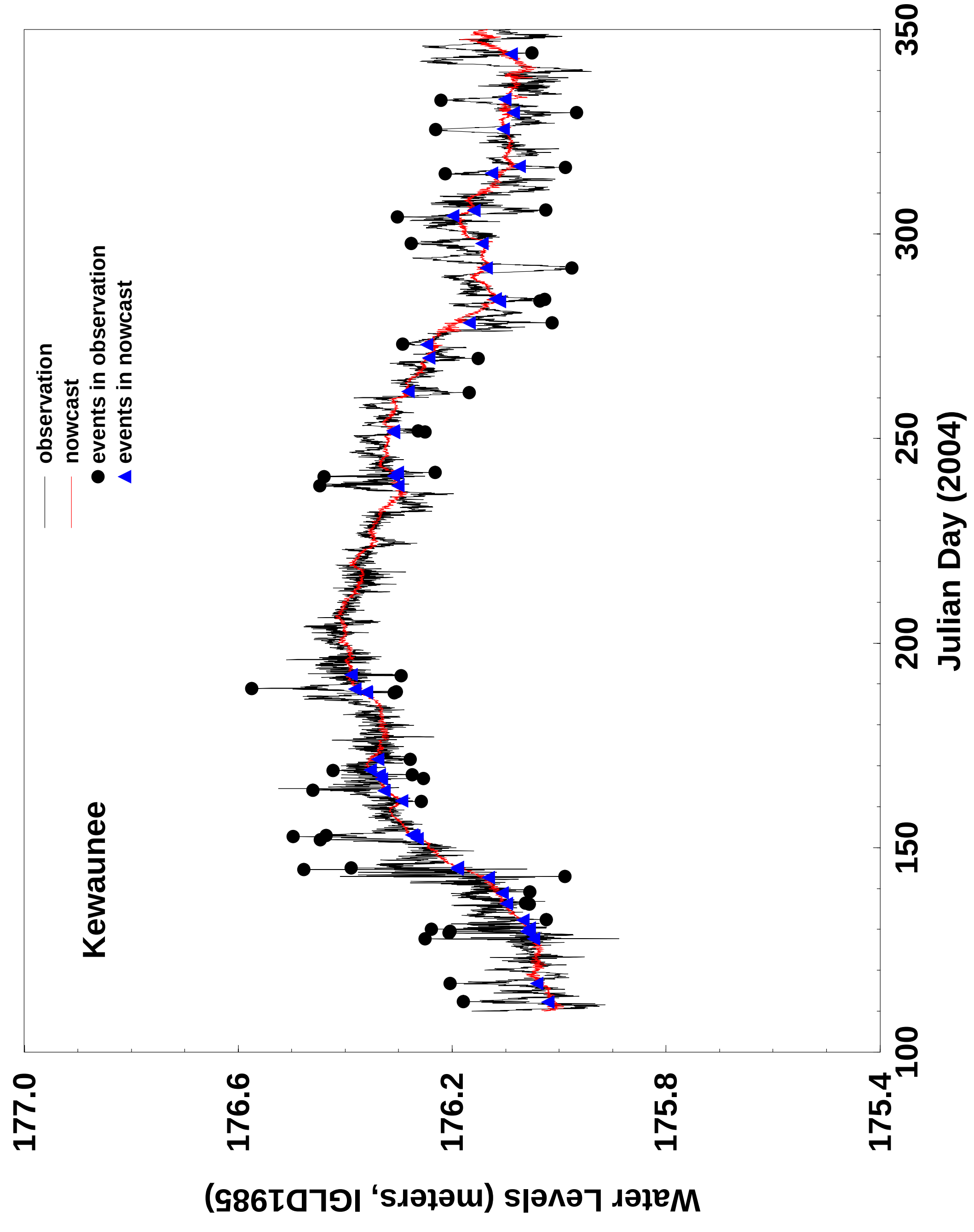

Figure B.6. Time Series Plot of Semi-Operational Nowcasts vs. Observations at NOS Gauge in Kewaunee, WI.

APPENDIX C. Time Series Plots of Semi-Operational Water Level Forecast Guidance vs. Observations at Six NOS Gauges in Lake Michigan during 2004.

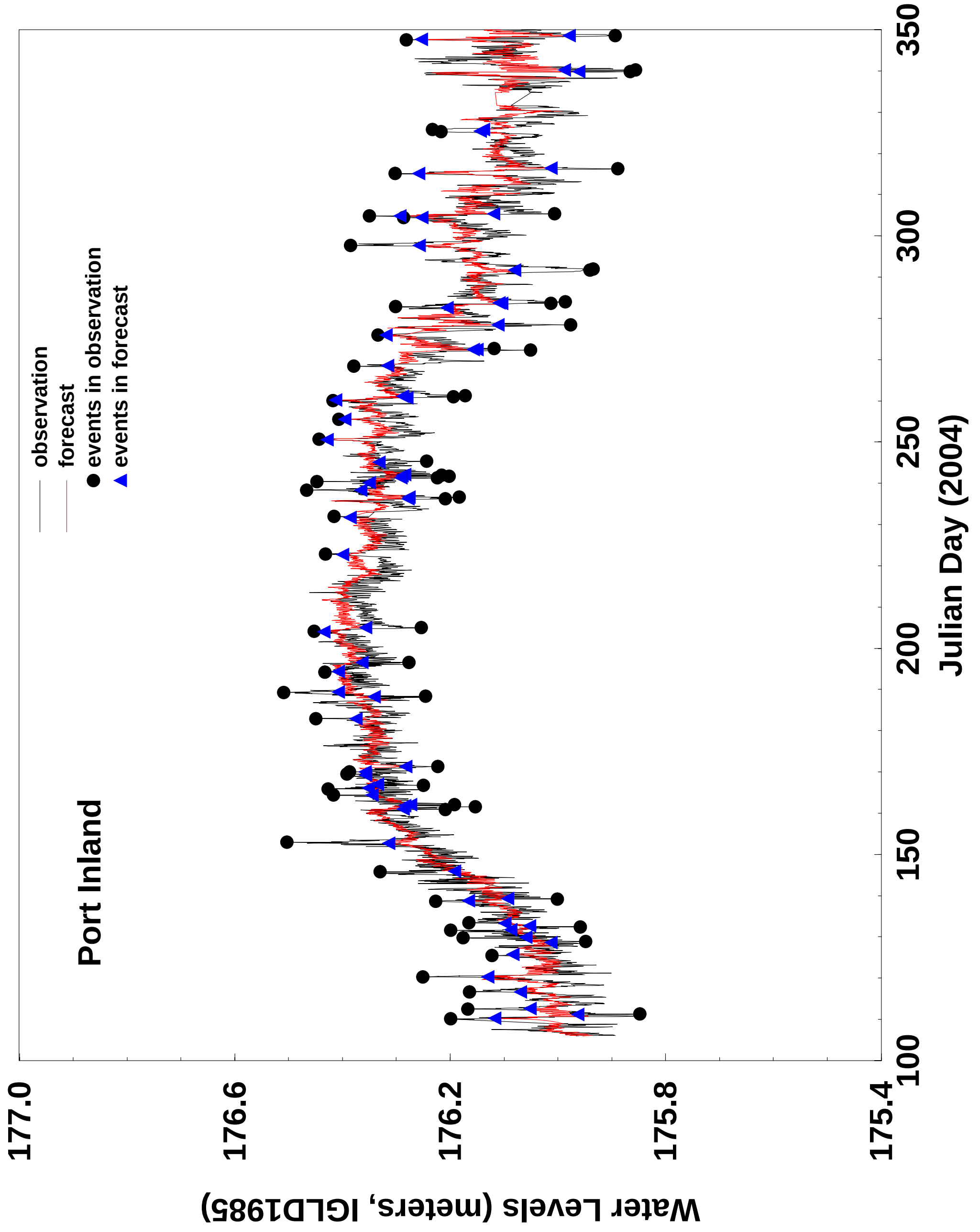

Figure C.1. Time Series Plot of Semi-Operational Forecast Guidance vs. Observations at the NOS Port Inland, MI Gauge.

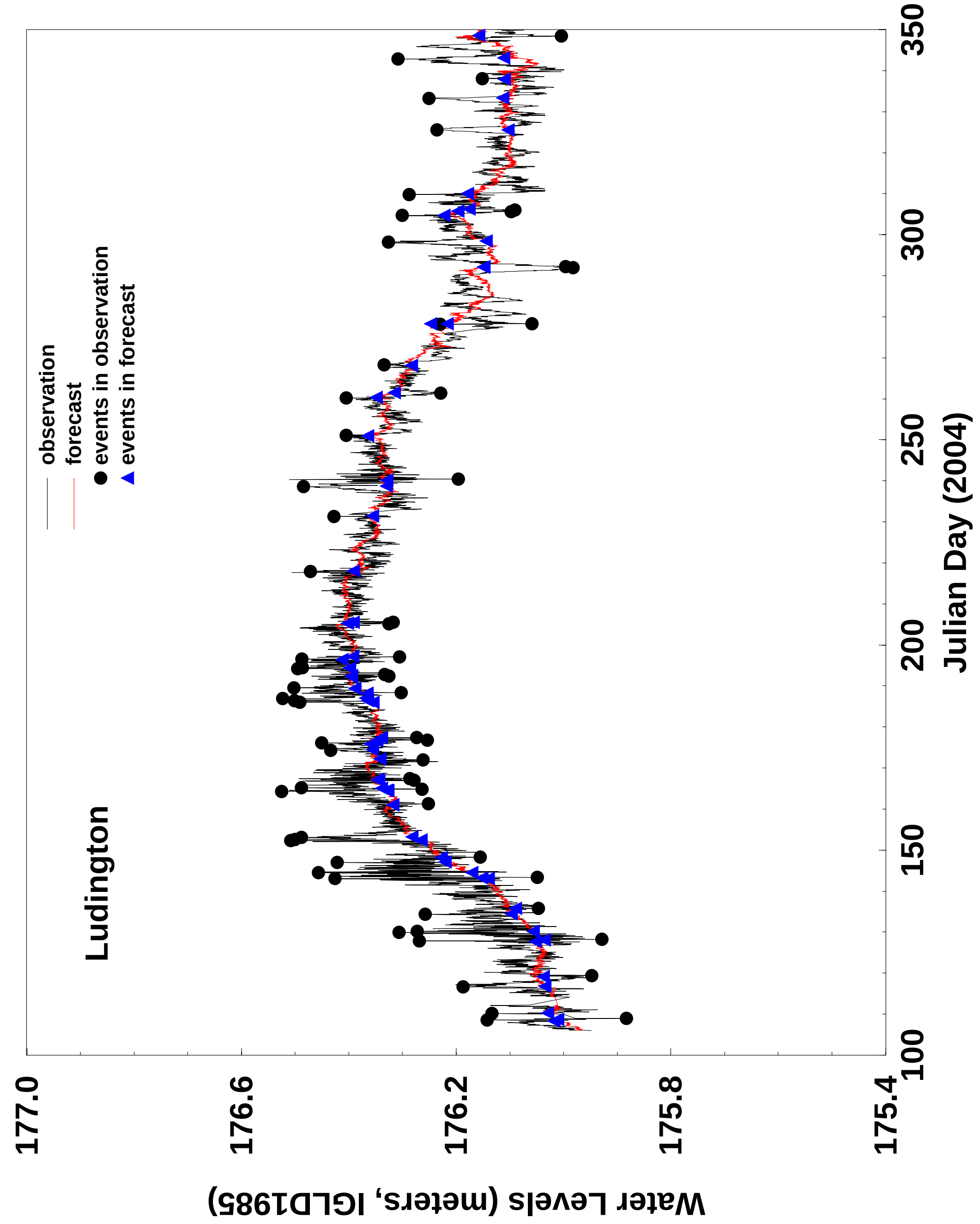

Figure C.2. Time Series Plot of Semi-Operational Forecast Guidance vs. Observations at the NOS Ludington, MI Gauge.

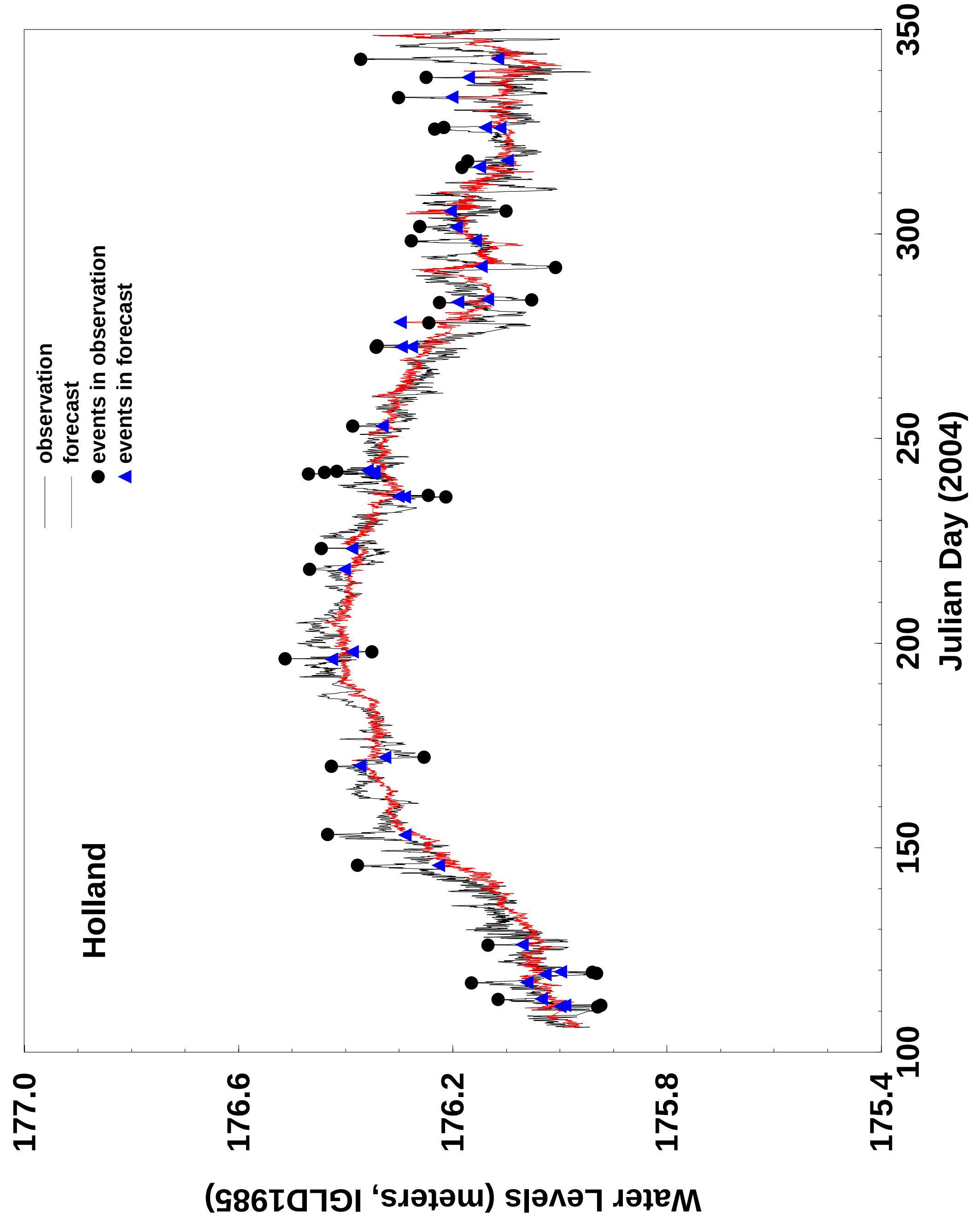

Figure C.3. Time Series Plot of Semi-Operational Forecast Guidance vs. Observations at the NOS Holland, MI.

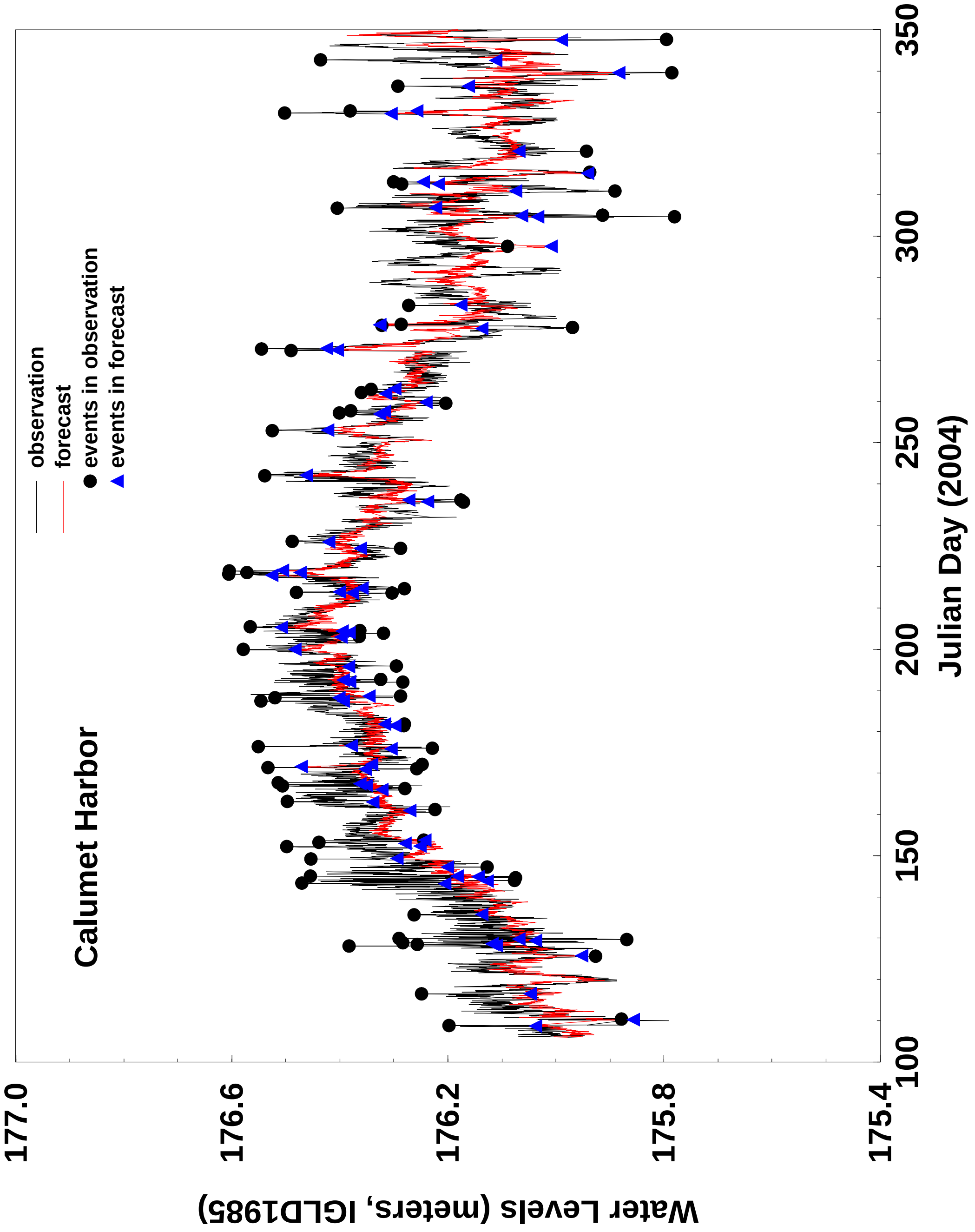

Figure C.4. Time Series Plot of Semi-Operational Forecast Guidance vs. Observations at the NOS Calumet Harbor, IL.

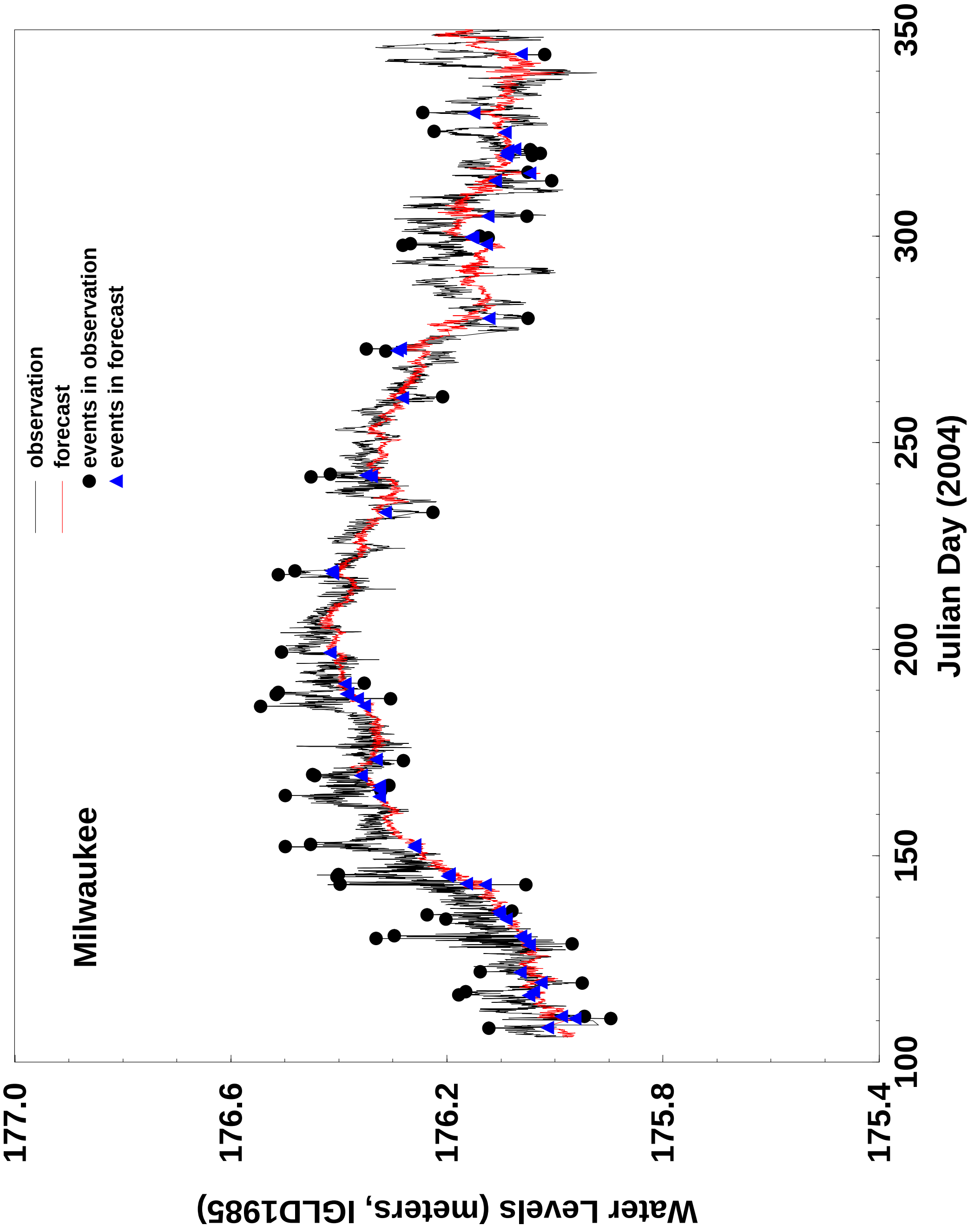

Figure C.5. Time Series Plot of Semi-Operational Forecast Guidance vs. Observations at the NOS Milwaukee, WI Gauge.

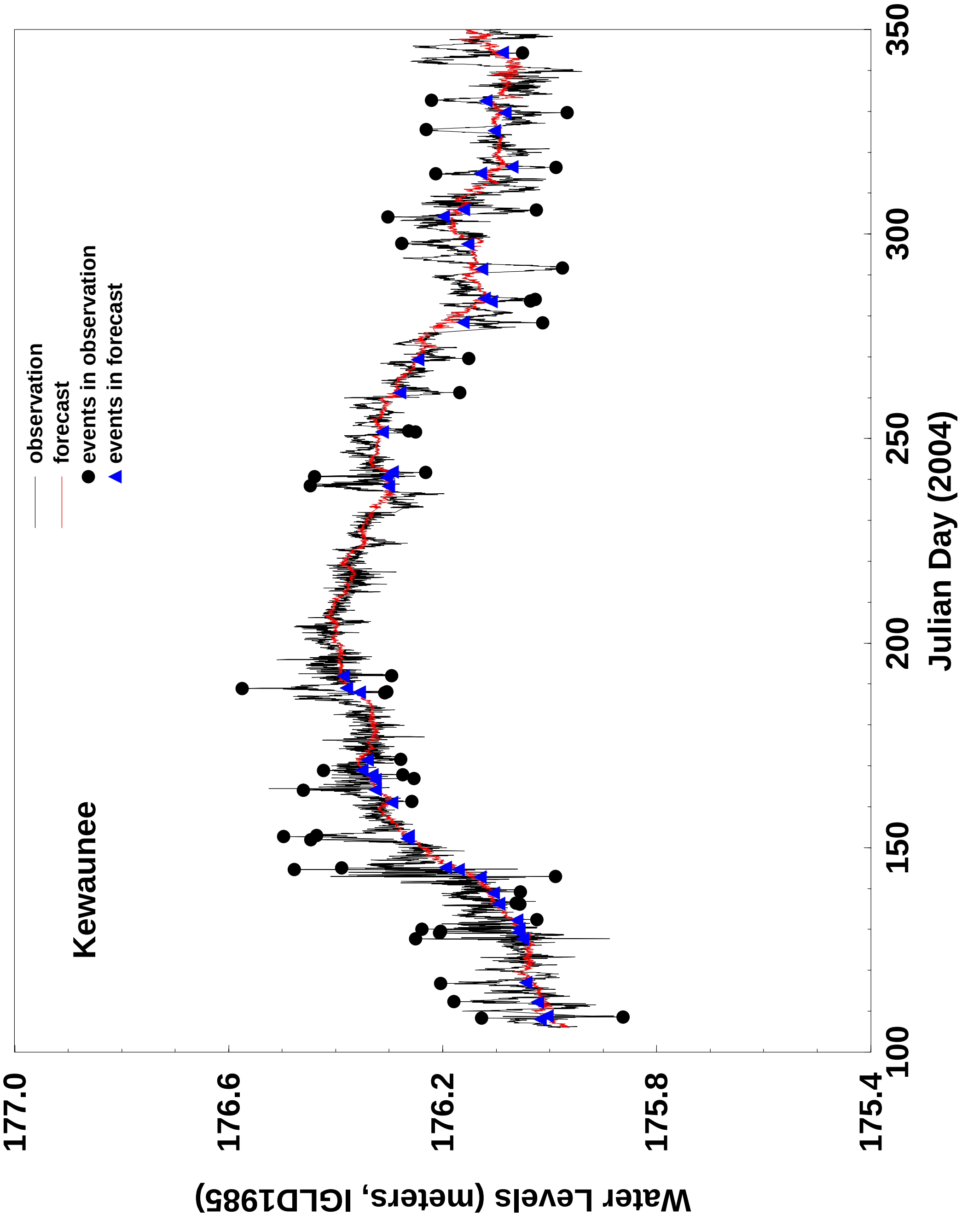

Figure C.6. Time Series Plot of Semi-Operational Forecast Guidance vs. Observations at the NOS Kewaunee, WI Gauge.

APPENDIX D. Skill Assessment Scores of Semi-Operational Water Level Nowcasts and Forecasts of Surface Water Temperatures at Two NWS/NDBC fixed buoys in Lake Michigan for 2004.

Table D.1. Skill Assessment Statistics of Semi-Operational Nowcasts and Forecast Guidance of Surface Water Temperature at the NWS/NDBC Fixed Buoy 45002 (Northern Michigan) from mid April to mid November 2004.

```
Station:         NDBC Buoy 45002 in Lake Michigan
Observed data-longest continuous time segment from:  4/20/2004  to 11/17/2004
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                     5083  12.832
t                     5083  11.404
T-t        3.0 c 24h  5083   1.428  2.213  1.692   0.0  83.7   1.8    0.0 36.0

     SCENARIO: SEMI-OPERATIONAL FORECAST
T00-t00    3.0 c 24h   424   1.468  2.252  1.710   0.0  84.0   1.9    0.0 24.0
T06-t06    3.0 c 24h   420   1.385  2.149  1.645   0.0  84.0   1.0    0.0  0.0
T12-t12    3.0 c 24h   420   1.355  2.153  1.674   0.0  84.8   1.2    0.0  0.0
T18-t18    3.0 c 24h   420   1.284  2.013  1.552   0.0  86.4   0.7    0.0  0.0
T24-t24    3.0 c 24h   420   1.252  1.988  1.545   0.0  87.1   1.0    0.0 24.0
```

Table D.2. Skill Assessment Statistics of Semi-Operational Nowcasts and Forecast Guidance of Surface Water Temperature at the NWS/NDBC Fixed Buoy 45007 (Southern Michigan) from mid April to early December 2004.

```
Station:         NDBC Buoy 45007 in Lake Michigan
Observed data-longest continuous time segment from: 4/20/2004 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                     5574  14.357
t                     5574  13.622
T-t        3.0 c 24h  5574   0.735  1.565  1.381   0.0  91.5   0.0    0.0  0.0

     SCENARIO: SEMI-OPERATIONAL FORECAST
T00-t00    3.0 c 24h   465   0.765  1.593  1.399   0.0  91.4   0.0    0.0  0.0
T06-t06    3.0 c 24h   460   0.707  1.535  1.364   0.0  91.1   0.0    0.0  0.0
T12-t12    3.0 c 24h   461   0.646  1.559  1.421   0.0  92.4   0.0    0.0  0.0
T18-t18    3.0 c 24h   460   0.601  1.420  1.288   0.0  94.6   0.0    0.0  0.0
T24-t24    3.0 c 24h   461   0.517  1.397  1.299   0.0  94.1   0.0    0.0  0.0
```

APPENDIX E. Time Series Plots of Semi-Operational Nowcasts and Forecast Guidance of Surface Water Temperature vs. Observations at Two NWS/NDBC fixed buoys during 2004.

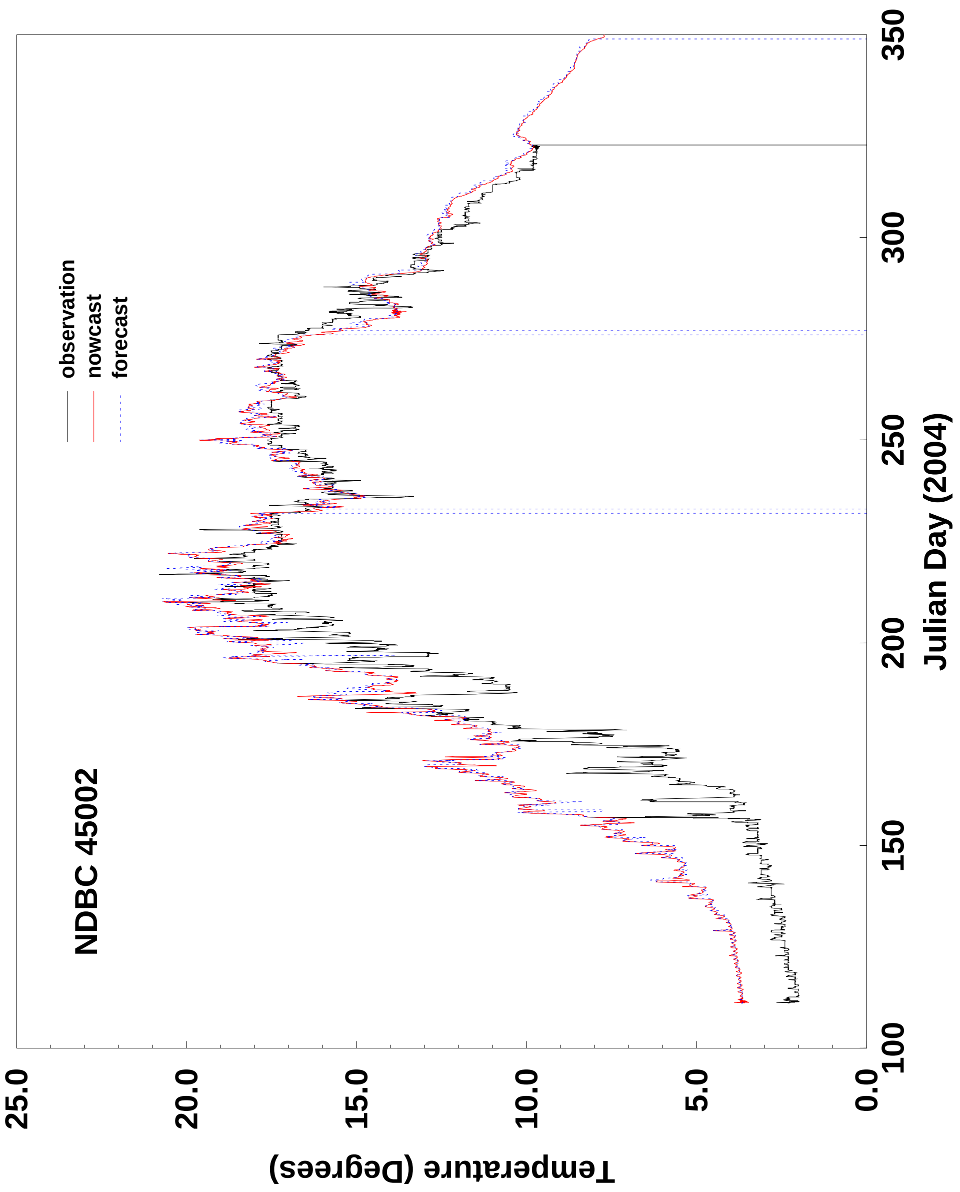

Figure E.1. Semi-Operational Surface Water Temperature Nowcasts and Forecast Guidance of Surface Water Temperatures (^{o}C) vs. Observations at NWS/NDBC Fixed Buoy 45002 (Northern Michigan) for the Period mid-April to mid-December 2004. The forecast values depicted on the plot are from the 0000 UTC forecast cycle.

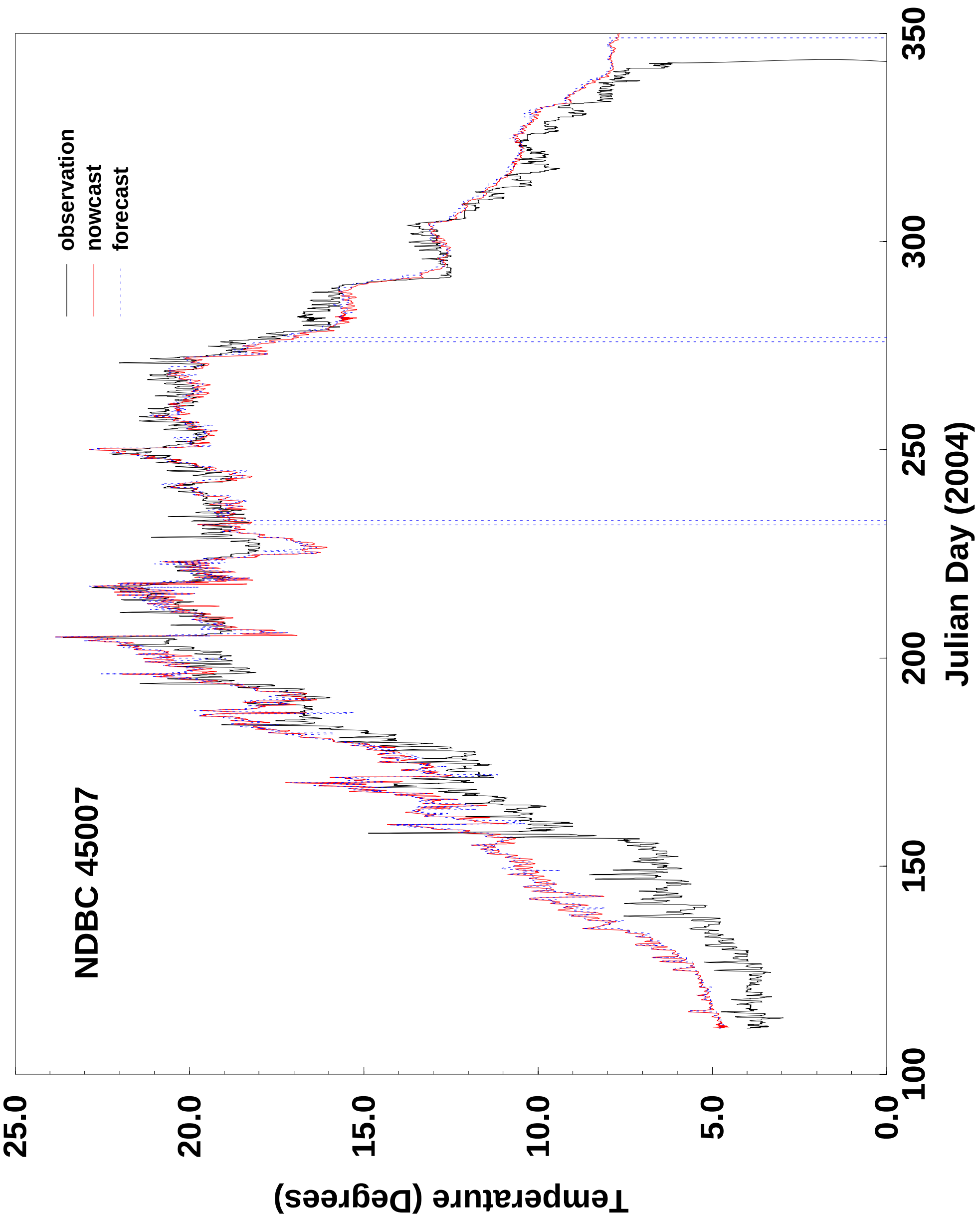

Figure E.2. Semi-Operational Surface Water Temperature Nowcasts and Forecast Guidance of Surface Water Temperatures (^{o}C) vs. Observations at NWS/NDBC Fixed Buoy 45007 (Southern Michigan) for the Period mid-April to mid-December 2004. The forecast values depicted on the plot are from the 0000 UTC forecast cycle.