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Development, implementation, and skill assessment of the NOAA/NOS Great Lakes Operational Forecast System

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Abstract The NOAA Great Lakes Operational Forecast System (GLOFS) uses near-real-time atmospheric observations and numerical weather prediction forecast guidance to produce three-dimensional forecasts of water temperature and currents, and two-dimensional forecasts of water levels of the Great Lakes. This system, originally called the Great Lakes forecasting system (GLFS), was developed at The Ohio State University and NOAA's Great Lakes Environmental Research Laboratory (GLERL) in 1989. In 1996, a workstation version of the GLFS was ported to GLERL to generate semi-operational nowcasts and forecasts daily. In 2004, GLFS went through rigorous skill assessment and was transitioned to the National Ocean Service (NOS) Center for Operational Oceanographic Products and Services (CO-OPS) in Silver Spring, MD. GLOFS has been making operational nowcasts and forecasts at CO-OPS since September 30, 2005. Hindcast, nowcast, and forecast evaluations using the NOS-developed skill assessment software tool indicated both surface water levels and temperature predictions passed the NOS specified criteria at a majority of the validation locations with relatively low root mean square error (4–8 cm for water levels and 0.5 to 1°C for surface water temperatures). The difficulty of accurately simulating seiches generated by storms (in particular in shallow lakes like Lake Erie) remains a major source of error in water level prediction and should be addressed in future improvements of the forecast system.

Keywords Numerical modeling · Lake forecasts · Coastal nowcast/forecast lake modeling system

1 Introduction

The Great Lakes of North America is the largest fresh water body in the world with a surface area of 246,000 km^2 and a volume of 22,684 km^3. It consists of five large lakes (Lakes Superior, Huron, Michigan, Erie, and Ontario) and one small lake (Lake St. Clair), as shown in Fig. 1. It contains more than 20% of the world′s fresh water reserves, is shared by the USA and Canada, and supports a population of 30 million along its perimeter regions. It created and continues to create tremendous economic, commercial, and recreational values and at the same time is undergoing heavy stress.

The Great Lakes Forecasting System (GLFS) was developed by researchers at The Ohio State University (OSU) and NOAA′s Great Lakes Environmental Research Laboratory (GLERL) in the late 1980s to provide nowcast and forecast guidance of water levels, water temperatures, waves and currents of the five Great Lakes. The main uses for those predicted variables are (1) hazard warning and avoidance, (2) enhancement of recreational and commercial activities, (3) scenario test and risk assessment, and (4) natural resources preservation and decision making.

GLFS used the Princeton Ocean Model (POM) (Blumberg and Mellor 1987) and the GLERL–Donelan wave model (Schwab et al. 1984) to predict three-dimensional (3-D)

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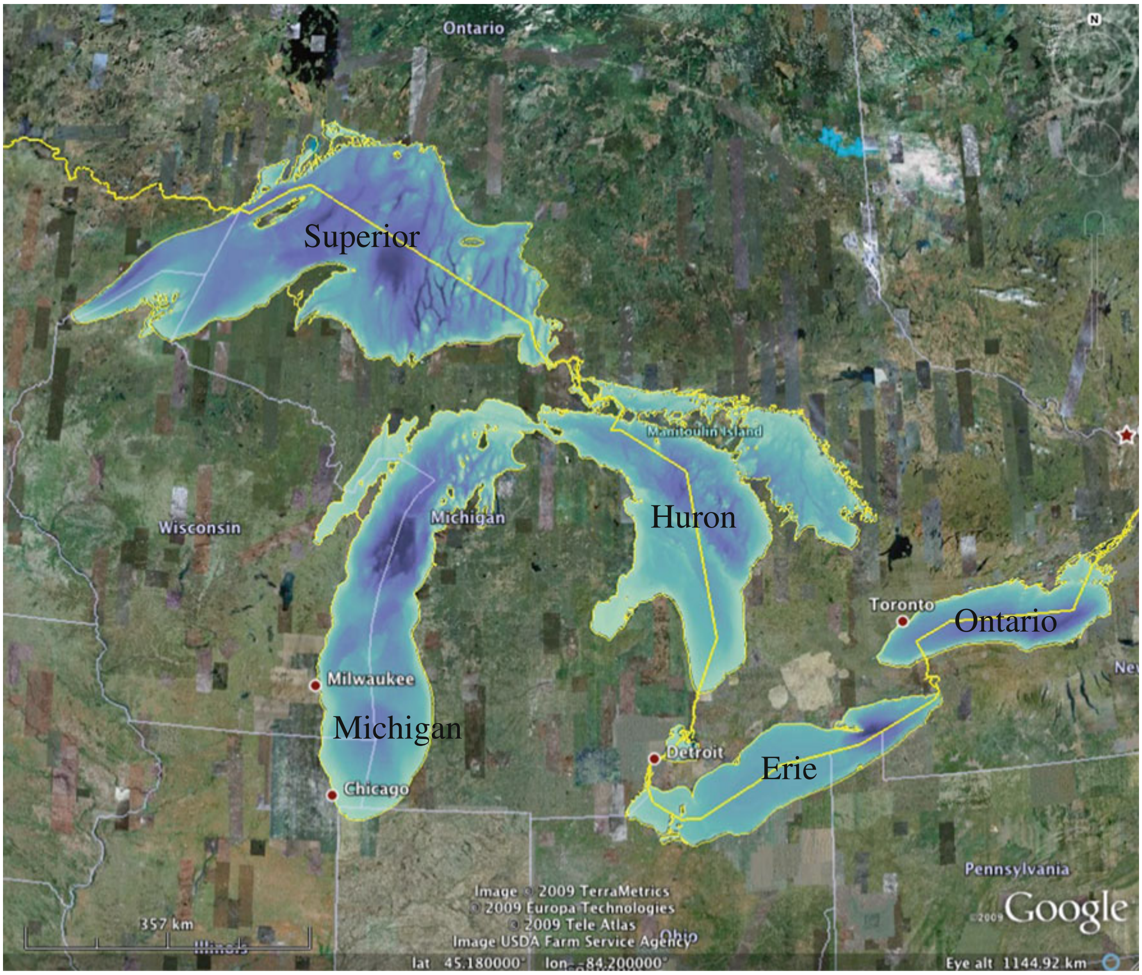

Fig. 1 Great Lakes map

temperature, currents and two-dimensional (2-D) water levels, and waves of the Great Lakes. The first 3-D nowcast for the Great Lakes was made in 1992 at the Ohio Supercomputer Center at OSU (Yen et al. 1994; Schwab and Bedford 1994). Twice per day forecasts were made for Great Lakes starting in 1995 (Schwab and Bedford 1996). In 1996, GLFS was ported to GLERL in Ann Arbor, MI, and the workstation version of the system was named the Great Lakes Coastal Forecast System (GLCFS). GLCFS generates nowcasts four times per day, and 60-h forecast guidance twice per day and has been running in a semi-operational mode since February 1997 (Schwab et al. 1999). GLFS was recognized as the first US coastal forecasting system to make routine real-time predictions of currents, temperatures, and key trace constituents in 2001 by the American Meteorological Society.

In 2004, the hydrodynamic model code of GLCFS was transitioned to the National Ocean Service (NOS) Center for Operational Oceanographic Products and Services (CO-OPS) in Silver Spring, MD. GLCFS was reconfigured to run in the NOS Coastal Ocean Modeling Framework (COMF) and to use surface meteorological observations from the NOS Operational Data Acquisition and Archive System (ODAAS). At this stage, the system went through significant improvements, upgrades, skill assessment, and documentation, and the new system was named the Great Lakes Operational Forecast System (GLOFS) to reflect its operational status. GLOFS has been making operational nowcasts and forecasts at CO-OPS since September 30, 2005 and was the first NOS forecast system to be implemented for non-tidal water bodies. This article describes the model development, implementation, and skill assessment of the Great Lakes operational forecast system.

2 System overview

This section provides a brief description of the numerical hydrodynamic model used by GLOFS. A flowchart of this forecasting system is shown in Fig. 2. Similar descriptions of the model as it has been applied to Great Lakes have been given by Kuan (1995), Kelley (1995), Kelley et al. (1998), Hoch (1997), Chu (1998), and O'Connor et al. (1999).

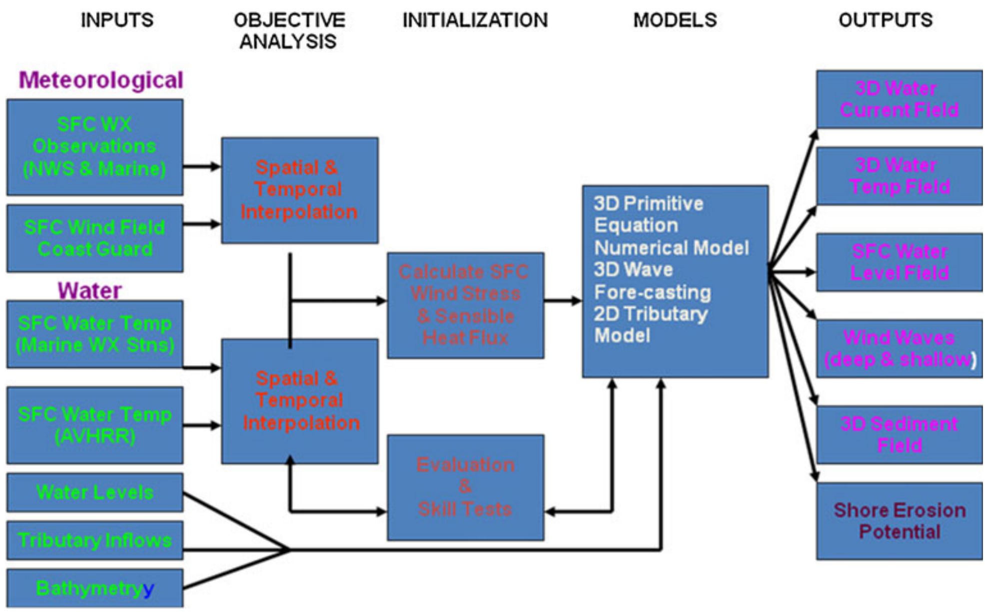

Fig. 2 GLFS flowchart

2.1 Description of model

The core numerical model in GLOFS is the POM developed by (Blumberg and Mellor 1987; Mellor 2004). 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, momentum, and conservation equations simultaneously in an iterative fashion, and the resulting predictive variables are free upper surface elevation, full three-dimensional velocity and temperature fields, turbulence kinetic energy, and turbulence macroscale. Other main features of the model include terrain following coordinate in the vertical (sigma coordinate), finite difference numerical scheme, Boussinesq and hydrostatic approximation, and mode splitting technique. Several modifications have been made by OSU and GLERL researchers for use in the Great Lakes (Bedford and Schwab 1991; O'Connor and Schwab 1993). Each of the Great Lakes is treated as an enclosed basin. Therefore, there are no inflow/outflow boundary conditions and no fluid exchange between the lake and its tributaries.

2.2 Grid domain

The model domain for Great Lakes consists of a rectangular grid with a 5 km horizontal resolution in both the x- and y-directions (except for Lake Superior, which uses 10 km). 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 noise. The Lake Erie domain has 1,944 grid points with 81 points in the x-direction and 24 points in the y-direction with a 27.33° counterclockwise rotation so that the x-coordinate is along the longitudinal axis of the lake and the y-axis is across the lake (Fig. 3). Lake Erie has 11 sigma layers in the vertical, while the other four lakes have 20 layers. Table 1 shows the grid dimensions for all five of the Great Lakes models.

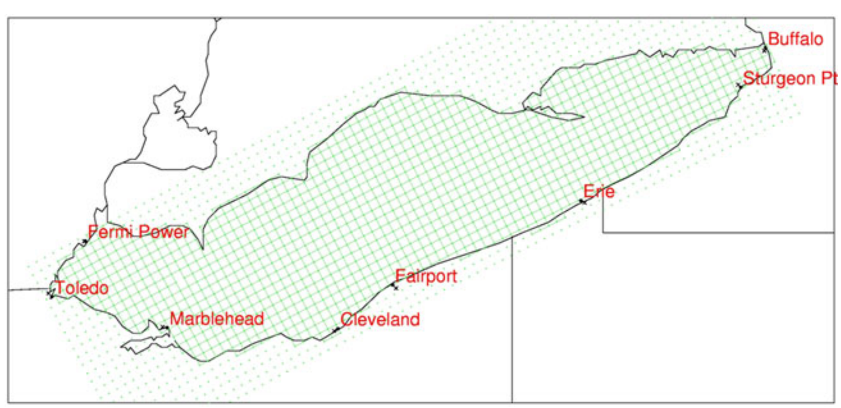

Fig. 3 Lake Erie grid and NOS gauge stations

Table 1 Configurations of numerical grid domains for each lake

Lake	Gird size (I×J)	Spatial resolution (km)	Vertical layers
Erie	81×24	5	11
Michigan	53×102	5	20
Ontario	61×25	5	20
Huron	81×75	5	20
Superior	61×30	10	20

2.3 The data

Two types of input forcing are required by the system to make water level, temperature, and current predictions: wind stress and surface heat flux. Wind stress *u*- and *v*-components are computed from surface wind speed and directions, while heat flux is estimated from wind speed, air temperature, dew point temperature, and cloud cover. The main difference between the nowcast and forecast guidance is the data source: The nowcast relies on surface meteorological observations (Fig. 4) while the forecast uses the meteorological forecasts from National Weather Service (NWS) gridded weather forecasts or forecast guidance from the NWS numerical weather prediction model. The observations consist of data from a variety of sources such as the Automated Surface Observing System, Coastal-Marine Automated Network, NOS National Water Level Observing Network (NWLON), and NDBC's and Environment Canada's buoys. The gridded surface weather forecasts are from the NWS National Digital Forecast Database (NDFD) with a 5-km spatial resolution and the NWS/National Centers for Environmental Prediction (NCEP) North American Mesoscale (NAM) Model with a 12-km resolution. Both are available from NOS' Operational Data Acquisition and Archive System (ODAAS), and NWS/NCEP observational "data tanks", located on the NOAA Central Computer Systems (CCS).

2.4 Nowcast cycle

The nowcast cycle of GLOFS is run hourly at NOS to generate updated hourly nowcasts of 3-D water temperatures and currents and 2-D water levels. The initial conditions for the nowcast cycle are provided by the end of the previous hour's nowcast cycle. The nowcast cycle is forced by gridded surface meteorological analyses valid at two times, 1 h prior to the time of the nowcast and the current time of the nowcast. The gridded surface meteorological analyses are generated by interpolating surface

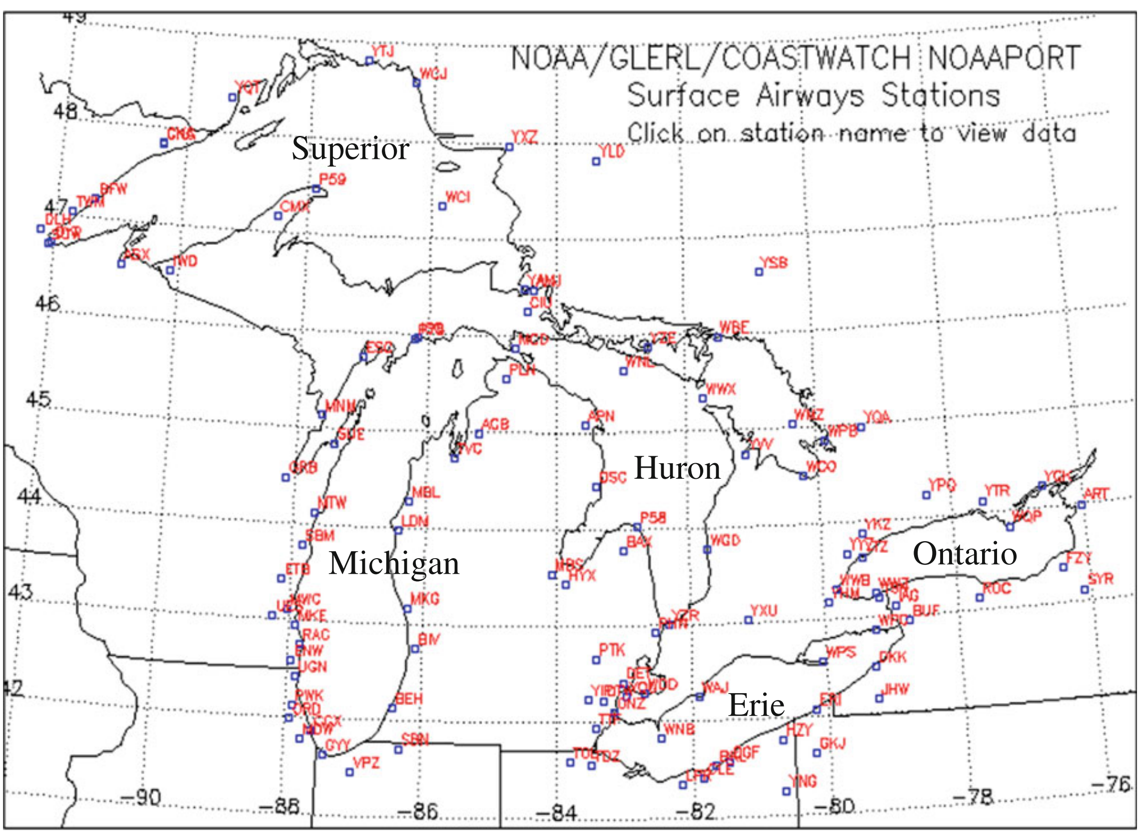

Fig. 4 Map depicting locations of Great Lakes meteorological stations

observations using the natural neighbor interpolation technique (Sambridge et al. 1995).

The surface wind, air temperature, and other meteorological parameter observations are adjusted to a 10-m height, corrected for stability and overwater conditions before being interpolated. Both adjustments use the previous day's lake average water temperature from GLERL's Great Lakes Surface Environmental Analysis (GLSEA). The GLSEA temperature analysis is generated using sea surface temperature retrievals derived from the Advanced Very High Resolution Radiometer onboard NOAA's polar-orbiter weather satellites.

The gridded surface wind fields are then used to calculate wind stress at each model grid point. The surface meteorological fields along with lake surface water temperature predictions 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. Additional information on the wind stress and heat flux implementation schemes can be found in Kelley (1995) and Chu (1998).

2.5 Forecast cycle

The forecast cycle of GLOFS is run four times per day to generate up to a 36-h forecast guidance of the 3-D and 2-D state of Great Lakes. The forecast cycle uses the most recent nowcast as its initial conditions. The surface meteorological forcing is provided by the latest forecast of surface *u*- and *v*-wind components and surface air temperature from the 00, 06, 12, or 18 UTC forecast cycles from the NDFD or the NAM model. Prior to April 2007, NAM, which uses the Weather Research and Forecast Model as its core model, was the main input for GLOFS forecast cycles. After April 2007, NDFD was the primary input and NAM served as a source of backup forcing.

3 Skill assessments

3.1 NOS evaluation standard and skill assessment software

In order to ensure the nowcast/forecast systems developed and implemented at NOS are done so in a scientifically sound and operationally robust way, standards for evaluating such modeling systems (Hess et al. 2003) have been established and skill assessment software have been developed at Coast Survey Development Laboratory (CSDL) (Zhang et al. 2006). The skill assessment software computes various statistic measures after collecting files containing observation records, computed hindcast, nowcast, and forecast variables such as water levels, temperatures, and currents. All data are processed, and the skill assessment results are tabulated for each location. This section describes the standard, statistic metrics, and GLOFS skill assessment results.

According to NOS standards, hydrodynamic models are required to be executed and the results evaluated under three scenarios before declared operational: (1) hindcast scenario, (2) semi-operational nowcast, and (3) semi-operational forecast. In this context, the hindcast scenario, model forcing is based on historical, quality-checked, best available gap-filled data. The model result time series can be compared with the available observations. In semi-operational nowcast scenario, the model forcing is based on real-time observed values where there may be missing or incomplete records. In semi-operational forecast scenario, the model forcing is based on forecast values from weather forecast models, even though some data could be missing or delayed. In evaluating GLOFS, NOS took advantage of previous evaluations done by researchers at OSU and GLERL to fulfill the hindcast scenario requirements and utilized the nowcasts and forecasts routinely produced by GLERL to fulfill the semi-operational nowcast and forecast scenarios.

3.2 Statistic metrics

The standard NOS model assessment statistics suite include root mean square error (RMSE), mean algebraic error (MAE), series mean (SM), standard deviation (SD), central frequency (CF), negative outlier frequency (NOF), and positive outlier frequency (POF). Their definitions and formulations are given in Table 2.

In addition to the above statistical measurements, two additional indices, index of agreement (IOA) and skill score, were also computed in the hindcast evaluation. The IOA is a relative measure reflecting the degree to which the observed variable is estimated by the simulated variable (Willmott 1981). IOA is related to the RMSE and is defined as $\mathrm{IOA}=1-(n\times\mathrm{RMSE}^2)/\mathrm{PE}$, where PE is the potential error and IOA ranges from 0 to 1 with 1 being perfect agreement. Skill score is a non-parametric-based statistic developed by Dingman and Bedford (1986) to assess the model credibility.

Table 2 NOS skill assessment statistics (from Hess et al. 2003)

Variable	Equation
Mean algebraic error (e or MAE)	e=prediction − observation
Series mean (SM)	$\bar{y}=\frac{1}{N}\sum_{i=1}^{N}y_i.$
Root mean square error (RMSE)	$\mathrm{RMSE}=\sqrt{\frac{1}{N}\sum_{i=1}^{N}e_i^2}.$
Standard deviation (SD)	$\mathrm{SD}=\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(e_i-\bar{e})^2}$

The rule of the skill score for water levels is that one point is deducted from a scale of 10 for every 0.05 m difference between the observed and computed values with a minimum score of 0 when the difference is greater than 0.5 m. The same analogy is applied for the temperature where one point is deducted for every 0.5°C model-data difference.

Since the NOS skill assessment software was designed to evaluate model skills on water levels, temperature and currents in tidally dominated regions, several modifications were made for the non-tidal, fresh water Great Lakes: (1) Tidal evaluations and harmonic analysis in the water level were not computed, extreme high-low water level events were evaluated instead, and (2) the acceptance criteria for water temperature has been adjusted for the Great Lakes region. The NOS sets an acceptable error of 7.7°C and 7.5 cm (3 in.) in evaluating water temperature and water level predictions in tidal regions. Since the Great Lakes are considered non-tidal, there is no preset standard for lake temperature prediction. A 3°C criterion for water temperature was suggested by Dr. David Schwab of NOAA/GLERL based on the experience of running the Great Lakes Coastal Forecasting System and input from the Great Lakes user community (Schwab, personal communication 2004).

3.3 Hindcast skill assessment

In order to fulfill the NOS hindcast requirement, several previous research efforts and evaluations were used: for Lake Erie, a comprehensive evaluation of water levels, temperature, and currents (both surface and subsurface) performed by Kuan (1995) and Kuan et al. (1995) served as the basis for the hindcast scenario assessment, and the validation results were summarized in the NOAA technical report (Chu et al. 2007). The Lake Michigan portion of the hindcast was done using the data and modeling results from Lake Michigan Mass Balance Study (Schwab and Beletsky 1998), and the skill assessment was summarized in Kelley et al. (2007a, b). A 30-year Lake Ontario thermal structure reconstruction was used to satisfy the Lake Ontario hindcast requirement.

Lake Erie, due to its shallowness (20 m average depth) and SW–NE orientation, responds quickly to the passage of weather systems (Figs. 5 and 6). The wind-driven water level fluctuations (seiche) and thermal response (Schertzer et al. 1987) are much more significant than that of the other four lakes and hence pose a greater challenge in data-model comparison. The seiches cause a sudden opposite water level change at the two ends of the lake, as seen for most storm events in Buffalo (Fig. 5) and Toledo (Fig. 6). Therefore in this article, all the statistic analyses and plots use Lake Erie as example. Detailed skill assessment and statistics for other lakes are presented in individual skill assessment technical reports.

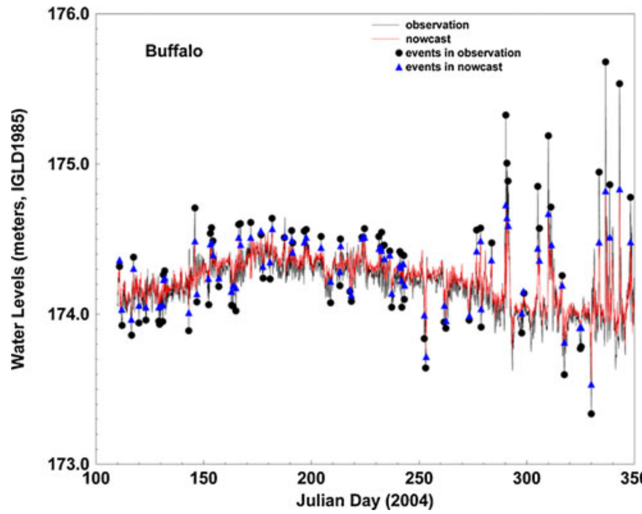

Fig. 5 Observed vs. simulated water levels at NOS NWLON stations in Buffalo, NY during the period 1 April to 31 December 2004

Hindcasts of Lake Erie water levels at Buffalo, NY; Cleveland, OH; and Toledo, OH were compared with observed values at corresponding NOS water level gauges. RMSE and the amplitude skill scores are summarized in Table 3. The average RMSE for water elevations during the evaluation period (May 29 to October 26, 1979) at Buffalo, Cleveland, and Toledo were 4.82, 3.0, and 6.18 cm, respectively. The amplitude skill scores for the entire test period were 9.73, 9.91, and 9.52 for Buffalo, Cleveland, and Toledo, respectively.

An evaluation of water levels on a seasonal basis was also performed during the heating, stratified, and cooling seasons (Table 4). Heating season was defined from May 29 to July 23. The stratified season began on July 24 and ended on September 6, and the cooling season began at the end of stratified season.

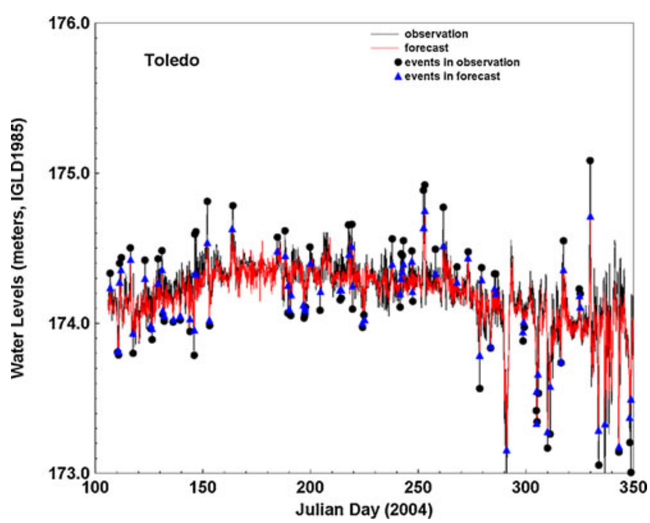

Fig. 6 Observed vs. simulated water levels at NOS NWLON stations in Toledo, OH during the period 1 April to 31 December 2004

Table 3 Summary of Lake Erie water level hindcast evaluation statistics by NOS gauge station for five time periods in 1979

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

The amplitude skill scores and IOA indicate that the water level simulations are good for all seasons. However, both tables show higher RMSE in the cooling season and Toledo tends to have larger errors than other two stations. The average RMSE between the computed and observations were 4.01, 4.23, and 5.61 cm at Buffalo, Cleveland, and Toledo, respectively, with the corresponding average skill scores of 9.97, 9.76, and 9.60 for the heating, stratified, and cooling seasons, respectively.

To evaluate model performance of lake surface temperatures, field measurements at six Canada Centre for Inland Water (CCIW) meteorological buoys were used for comparison. RMSE, IOA, and skill scores during May through October 1979 are summarized in Table 5.

Table 4 Seasonal evaluation statistics for Lake Erie water level simulations during heating, stratified, and cooling seasons in 1979

Season	NOS station	RMSE (cm)	IOA (0–1.0)	Skill score (0–10)
Heating	Buffalo	3.95	0.89	9.83
Heating	Cleveland	2.79	0.72	9.93
Heating	Toledo	5.28	0.92	9.62
Stratified	Buffalo	4.27	0.96	9.77
Stratified	Cleveland	2.74	0.88	9.92
Stratified	Toledo	5.69	0.94	9.58
Cooling	Buffalo	6.01	0.95	9.58
Cooling	Cleveland	3.41	0.94	9.87
Cooling	Toledo	7.41	0.96	9.35

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

CCIW buoy ID	RMSE (°C)	IOA	Skill score
NWRI19A	1.16	0.97	8.66
NWRI24A	1.07	0.97	8.65
NWRI26A	0.92	0.98	8.98
NWRI42A	1.06	0.97	8.69
NWRI46A	0.90	0.98	9.04
NWRI47A	0.87	0.98	9.02

Throughout the entire evaluation period, the Lake Erie temperature simulations matched well with the observed data at all six buoys. Slight differences existed between the observed and computed values. From Table 5, the average skill score was 8.84 and the average IOA was 0.97; both indices showed good agreement between the predicted and observed values. The average RMSE was less than 1°C which is also an indication that the model simulated lake surface temperature very well. Statistics due to the seasonal variations are summarized in Table 6.

In general, water surface elevation hindcasts matched well in magnitude with the corresponding observed data by picking up almost every single significant peak appearing in the observed water levels. The small RMSE and high IOA indicated that the model is accurate in simulating water surface elevation. The modeling system performed equally well in simulating surface water temperature. The computed values followed the trend of the observed data closely. The performance for the cooling season was a bit worse than the other two seasons and depended upon buoy locations. During the cooling season, surface water temperatures were consistently over predicted by 1.1°C. As seen in Table 6, the model had better skill, in terms of RMSE and skill scores, for the heating and stratified seasons than the cooling season.

3.4 Semi-operational nowcast skill assessment

The skill assessment of the GLOFS semi-operational nowcasts was performed using GLERL's archived nowcasts. Time series of hourly water levels and surface temperature nowcasts were compared to observations from NOS NWLON water

Table 6 Average seasonal analysis for surface water temperature simulations

Heating season			Stratified season			Cooling season		
RMSE (°C)	IOA	Skill score	RMSE (°C)	IOA	Skill score	RMSE (°C)	IOA	Skill score
1.05	0.97	8.81	0.80	0.88	9.20	1.10	0.95	8.55

Table 7 Summary of skill assessment statistics of semi-operational nowcasts of hourly water levels at eight NOS NWLON stations in Lake Erie for the period 15 April to 17 December 2004

Statistic, acceptable error [], and units ()	Buffalo, NY	Sturgeon Point, NY	Erie, PA	Fairport, OH	Cleveland, OH	Marblehead, OH	Toledo, OH	Fermi Power Plant, MI	NOS acceptance criteria
Mean algebraic error (m)	0.026	0.034	0.008	−0.031	0.008	0.000	−0.029	−0.005	0.075
RMSE (m)	0.080	0.076	0.045	0.044	0.040	0.050	0.080	0.065	na
SD (m)	0.076	0.068	0.044	0.031	0.040	0.050	0.075	0.065	na
NOF [2×15cm] (%)	0.8	0.5	0.0	0.0	0.0	0.0	0.3	0.1	≤ 1%
CF [15 cm] (%)	95.6	96.4	98.9	99.7	99.1	98.4	94.0	96.6	≥ 90%
POF [2×15 cm] (%)	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.1	< 1%

A total of 5,832 nowcast records were used in the assessment

level stations and NDBC buoy temperature records along the Great Lakes for the period from April to December 2004. Time series plots of the water level nowcasts vs. observations at Buffalo and Toledo are given in Figs. 5 and 6. Both figures clearly show the drawdown at Toledo and high setup at Buffalo (the result of wind-driven lake seiches dynamics) during the strong storm events between Julian day 290 and 350. The skill statistics for the Lake Erie water level nowcasts to at eight NOS gauges during 2004 are presented together in Table 7 along with the NOS acceptance criteria. The hourly nowcasts passed NOS acceptance criteria at all eight NOS gauge locations.

The MAE differences ranged between −2.9 and +3.4 cm and the RMSE ranged between 4 and 8 cm. The largest RMSE were at Toledo, OH and Buffalo, NY (Fig. 3) where nowcasts under predicted at Toledo and over predicted at Buffalo. Toledo and Buffalo, located at the extreme SW and NE ends of the lakes, respectively, experience the greatest water level variability and are the most difficult locations to predict. The differences at gauge locations to the north (Erie, PA) and south (Cleveland, OH) of the lake were less than 1 cm.

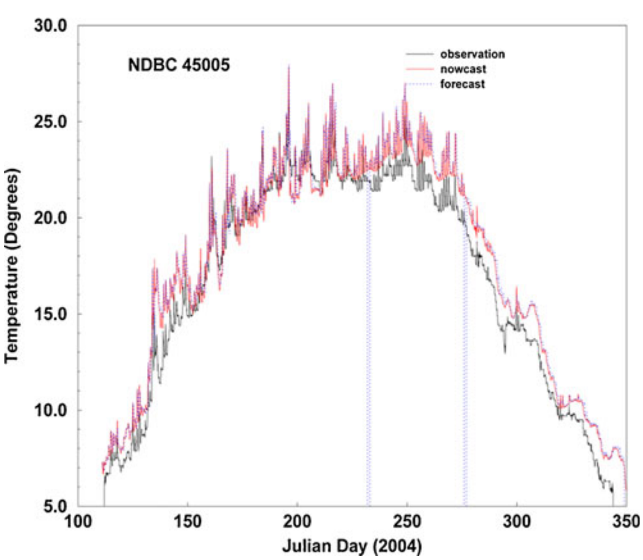

Fig. 7 Time series plot of semi-operational nowcast and forecast guidance of surface water temperatures (degrees Celsius) vs. observations at NDBC buoy 45005 (Western Lake Erie) for the period 21 April to 8 December 2004

The evaluation of surface water temperatures nowcasts was based on comparisons of time series of NOAA/NDBC buoy data vs. model-predicted temperatures from April to December 2004. A time series plot of the nowcasts vs. observations at the buoy 45005 is given in Fig. 7. The time series plot indicates that the nowcasts were in close agreement with observations (+0.5 to +1°C) from mid-April until early May, but then began to deviate from the observations by +1 to +2°C until late May (JD150). After that, the nowcasts differ from observations by +0.5°C until mid-August (JD230). The nowcasts then deviated by +1 to +2°C until early October (JD280). During the remaining days of autumn through the mid-December, the nowcasts generally differed from observations by +0.5°C.

The skill statistics for predicted hourly surface water temperature at NDBC buoy 45005 are given in Table 8 along with the NOS acceptance criteria. The hourly water temperature nowcasts at the buoy did pass the NOS

Table 8 Summary of skill assessment statistics of the semi-operational hourly nowcasts of surface water temperatures at the NDBC buoy 45005 in Lake Erie for the period from mid-April to early December 2004

Time period, statistic, acceptable error [], and units ()	45005 West Erie (N=5566)	NOS acceptance criteria
Time Period (days)	202	365
Mean Difference (°C)	0.951	na
RMSE (°C)	1.292	3°
SD (°C)	0.875	na
NOF [2×3°C] (%)	0.0	≤1%
CF [3°C] (%)	98.7	≥90%
POF [2×3°C] (%)	0.0	≤1%

Table 9 Summary of skill assessment statistics of semi-operational 24-hr forecast guidance of hourly water levels at NOS NWLON stations in Lake Erie for the period 15 April to 17 December 2004

Statistic, acceptable error [], and units ()	Buffalo, NY (*N*=490)	Sturgeon Point, NY (*N*=490)	Erie, PA (*N*=490)	Fairport, OH (*N*=490)	Cleveland, OH (*N*=490)	Marblehead, OH (*N*=473)	Toledo, OH (*N*=489)	Fermi Power Plant, MI (*N*=477)	NOS acceptance criteria
Mean algebraic error (m)	0.036	0.044	0.017	−0.030	0.006	−0.008	−0.034	−0.016	0.075
RMSE (m)	0.088	0.084	0.052	0.044	0.041	0.065	0.107	0.086	na
SD (m)	0.080	0.072	0.050	0.032	0.041	0.065	0.102	0.084	na
NOF [2×15 cm] (%)	0.4	0.4	0.2	0.0	0.0	0.4	1.4	0.8	≤1%
CF [15 cm] (%)	95.9	96.1	98.6	99.4	99.4	97.3	**87.7**	93.9	≥90%
POF [2×15 cm] (%)	0.4	0.6	0.0	0.0	0.0	0.2	0.2	0.2	<1%

Number in bold indicates that the statistic did not pass the NOS criteria

acceptance criteria for all the assessment statistics. The MAE was 0.95°C, and the RMSE was 1.29°C.

3.5 Semi-operational forecast skill assessment

For the assessment of the semi-operational forecast scenario for GLOFS, archived GLCFS semi-operational 24-h forecast guidance was compared to water level observations from NOS NWLON stations from April to December 2004, and to NDBC buoy data from April to November 2004 for the surface water temperature forecasts. Water level skill assessment statistics for the semi-operational forecast guidance at eight NWLON stations along with the NOS acceptance criteria are given in Table 9.

The hourly forecasts passed the criteria at seven of the eight gauges, failing only at Toledo for central frequency by a small margin. The MAE values ranged between −3 and +4.4 cm, and the RMSE ranged between 4.1 cm at Cleveland and 10.7 cm at Toledo. Similar to the nowcasts, the greatest errors were at Buffalo and Toledo, located at the extreme ends of the lake. The forecasts under predicted the water levels at Toledo and over predicted the levels at Buffalo. There was some increase in the RMSE values as forecast projection increased.

Skill assessment statistics for semi-operational forecast guidance to predict hourly lake surface water temperatures at NDBC buoy 45005 along with the NOS acceptance criteria are tabulated in Table 10, and the time series plots are given in Fig. 7. Similar to the nowcasts, the semi-operational forecast guidance was in close agreement to observations (+0.5 to +1°C) from mid-April until early May, but then began to deviate from the observations by +1 to +2°C until late May. After that, the forecast guidance differed from observations by +0.5°C until mid-August. The guidance then deviated by +1 to +2°C until early October. During the remaining days of autumn through mid-December, the forecast guidance generally differed from observations by +0.5°C. The hourly forecast guidance at the buoy passed all NOS criteria. The MAE was 0.7°C, and the RMSE was 1.3°C. The MAE and RMSE for the forecast guidance were slightly lower than for the nowcasts (Table 8). It is interesting to note that MAE and RMSE values decreased as forecast projection increased in time. The MAE was 1.07°C at the 0-h projection and reduced to 0.71°C by the 24-h projection. Both statistics suggest that the surface heat flux is being overestimated during the nowcast cycle and that temperature prediction is cooling off during the forecast cycle when there is no surface heat flux input.

For water levels, both hindcast and nowcast/forecast statistics show large error at the far ends of Lake Erie (Toledo and Buffalo). Although model grid resolution and the lack of tributary input (Maumee and Niagara Rivers) could be potential sources of error, we believe the seiche effect is the main source as RMSE in both locations are also higher during the cooling season when storms occur frequently.

For lake surface temperature, both nowcasts and forecasts indicated a warm bias. Possible errors are (1) overestimation of surface heat flux, (2) lack of ice module,

Table 10 Summary of skill assessment statistics for semi-operational forecast guidance to predict surface water temperatures 24 h in advance at NDBC buoy 45005 in Lake Erie during the period from mid-April to early November 2004

Time period, statistic, acceptable error [], and units ()	45005 (*N*=460)	NOS acceptance criteria
Time period	202	365 days
Mean algebraic error (°C)	0.713	na
RMSE (°C)	1.306	3°
SD (°C)	1.095	na
NOF [2×3°C] (%)	0.0	≤1%
CF [3°C] (%)	98.7	≥90%
POF [2×3°C] (%)	0.0	≤1%

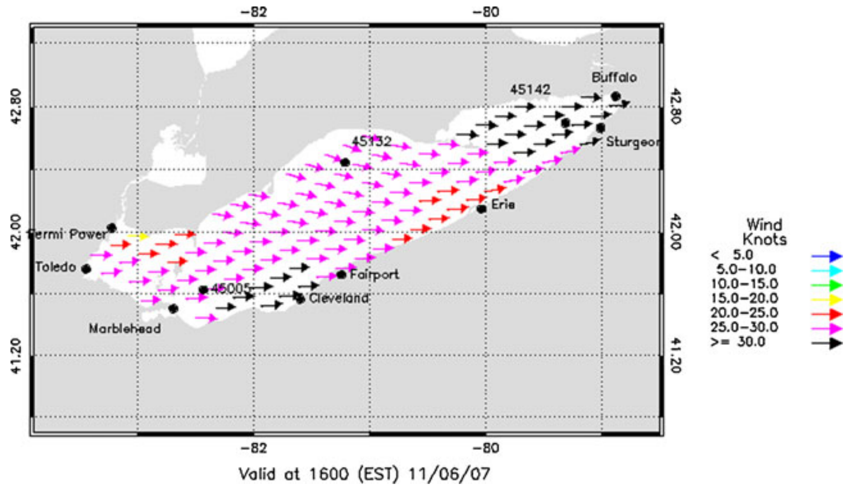

Fig. 8 Example of LEOFS map wind fields

and (3) inadequate model vertical resolution. Potential solutions include: (1) improve the surface heat flux formulation, especially the cloud cover parameterization in the shortwave and longwave radiation components, (2) incorporate an ice module with better thermodynamics to better account for the total lake heat content and distribution, and (3) increase the vertical resolution to better resolve the thermocline.

3.6 Improvements during the transition stage

During the evolution of GLFS to GLCFS and the transition into GLOFS, every component of the system has been upgraded or improved to a certain degree, except the main POM ocean circulation model code. The initial project goals included maintaining the model accuracy, enhancing the system robustness and reliability, setting a standard for the future NOS operational oceanographic forecast modeling systems while maintaining a consistent "look-and-feel" of GLOFS products, and dissemination procedures for end users. Significant improvements include: (1) automate scripts to streamline data ingestion and output, (2) modify forecast system requirements of NOS' Coastal Ocean Modeling Framework (COMF) to enhance system reliability, (3) complete unified netCDF-based file I/O, and (4) add new error checking, gap filling procedures, and extend the forecast period to 60 h.

4 Summary and conclusion

This article describes the historical background, development, implementation, transition, and skill assessment of the NOAA Great Lakes Operational Forecast System (GLOFS). GLOFS is the result of technology transfer of the Great Lakes Forecasting System (GLFS) and the Great Lakes Coastal Forecasting System (GLCFS) from The Ohio State University (OSU) and NOAA's Great Lakes Environ-

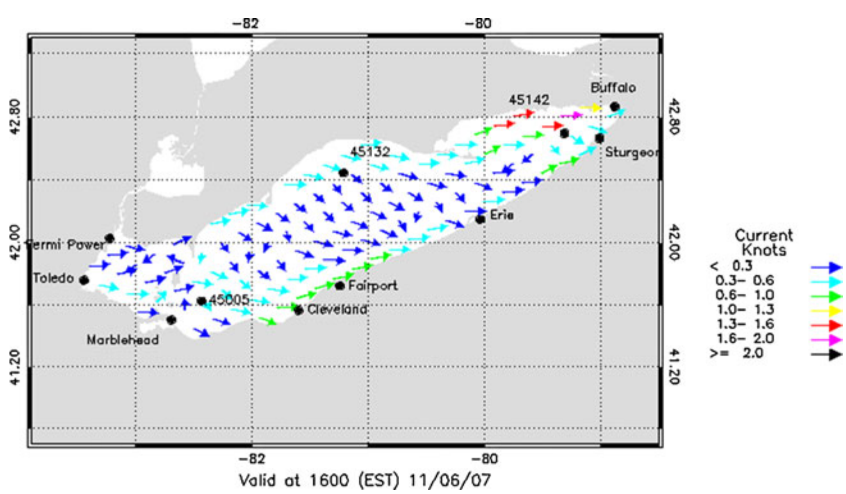

Fig. 9 Example of LEOFS map current fields

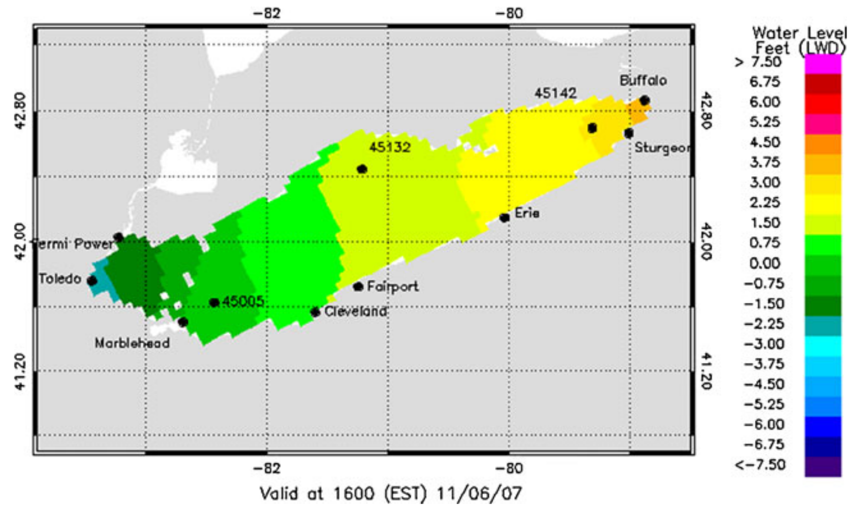

Fig. 10 Example of LEOFS map water levels

mental Research Laboratory (GLERL). GLOFS has gone through vigorous testing, skill assessment, and thorough documentation as it has been transitioned from research to operations at NOS. GLOFS was officially implemented and declared operational at NOS/CO-OPS on September 30, 2005.

The NOS in-house developed skill assessment software was used to evaluate the water level and temperature skill performance of the GLOFS. A suite of statistics was computed for water levels and lake surface temperatures for hindcast, semi-operational nowcast, and forecast scenarios. Skill assessment results indicated that GLOFS passed the NOS 7.5 cm for water level and 3°C for water temperature acceptance criteria most of the time for majority of the validation locations. Water level nowcasts tend to have better passing rates than the forecast guidance; however, surface temperature forecasts have slightly lower RMSE than that of the nowcast.

During the transition process, the model code and associated programs were integrated into the NOS COMF modeling framework and run on Linux clusters located at the NOAA CO-OPS division. All the GLOFS products, including data plots and maps as well as netCDF files containing formatted model results, are available to the general public at http://tidesandcurrents.noaa.gov. Examples of Lake Erie Operational Forecast System (LEOFS) map products are given in Figs. 8, 9, 10, and 11.

Recently, GLOFS went through another transition when it ported to NOAA's Centralized Computing System operated by NCEP to provide a robust operational computational environment and to extend its forecast horizon from 36 to 60 h. GLOFS became operational on the CCS on December 7, 2010. Future improvements of the GLOFS include increasing the spatial model resolution from 5 to 2 km, incorporating an ice modeling component, adding tributary information, running all five lakes as a single modeling system by connecting all the channels, and possibly using data assimilation approach to improve the surface heat flux estimation and water temperature predictions.

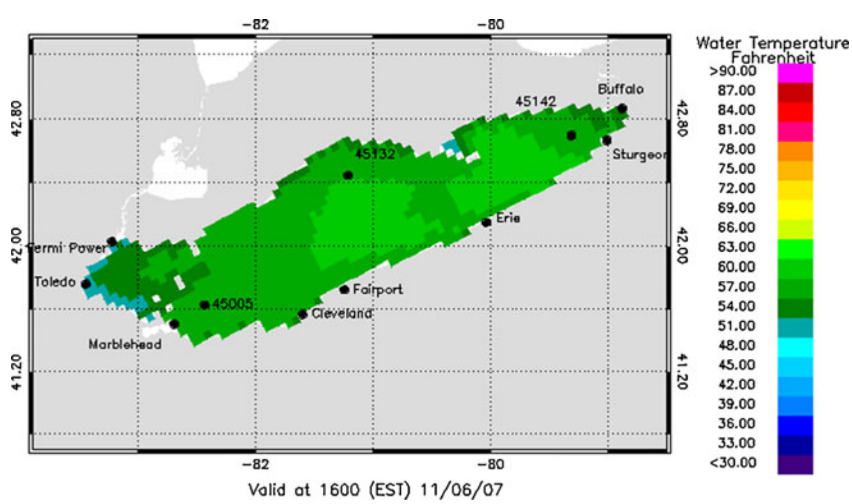

Fig. 11 Example of LEOFS map surface temperature

Acknowledgments The development of the Great Lakes Forecasting System was a joint effort of The Ohio State University (OSU) and NOAA's Great Lakes Environmental Research Laboratory under the direction of Drs. Keith Bedford and David Schwab. Fifteen graduate students, seven faculty, six postdocs, and seven research scientists from OSU have been associated with the development of the system. The transition of the GLCFS from OSU and GLERL to NOS was conducted by the GLOFS System Development and Implementation Team consisting of scientists from GLERL, OSU, CO-OPS, CSDL, and Aqualinks Inc. In particular, the authors would like to thank Drs. Frank Aikman and Mark Vincent at NOS for their support in this project. The archived GLCFS nowcast and forecast used in the skill assessment to fulfill the semi-operational nowcast and forecast scenarios were provided by Greg Lang and David Schwab at NOAA/GLERL. The authors would also like to thank the reviewers for their comments and suggestions.

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