Forecast Verification for Eta Model Winds Using Lake Erie Storm Surge Water Levels*

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ABSTRACT

This article has two purposes. The first is to describe how the Great Lakes Coastal Forecasting System (GLCFS) can be used to validate wind forecasts for the Great Lakes using observed and forecast water levels. The second is to evaluate how well two versions (40 km and 29 km) of the numerical weather prediction step-coordinate Eta Model are able to forecast winds for the Great Lakes region, using the GLCFS as a verification technique. A brief description is given of the 40- and 29-km versions of the Eta Model and their surface wind and wind stress output. A description is given of the GLCFS for Lake Erie. This includes the numerical Princeton Ocean Model (POM), observed winds from surface meteorological stations and buoys, and water level gauge data. The wind stresses obtained from both the 40-km Eta Model and the observed winds are used to force the POM for Lake Erie for several periods in 1993 when water level surges were recorded. The resulting POM water levels are then compared to observed water levels to provide an indication of the accuracy of 40-km Eta Model forecasts. The same experiments are made with the POM using wind stresses from the 29-km Eta Model and observed winds in 1997. Twin experiments are made with the GLCFS to determine: 1) how well it can predict (hindcast) water levels using observed winds as forcing, and 2) how well it can predict water levels using both the 40- and 29-km Eta Model forecast winds as forcing. The use of this forecast validation technique for other coastal forecasting systems is discussed.

1. Introduction

Environmental prediction for coastal regions has become increasingly important in recent years. Commercial and recreational boating require timely forecasts of winds, currents, waves, and water levels. Water quality and pollution transport studies require timely knowledge of the three-dimensional current and temperature structure of the water. To supply this needed information, coastal forecasting systems are being developed for several U.S. coastal regions. Any coastal forecasting system must have two components: an ocean model to predict the state of the coastal ocean, and meteorological input to this ocean model. The ocean model may be a two-dimensional or three-dimensional hydrodynamic model and/or a wind wave model. In turn, the ocean model requires accurate meteorological forcing data as input over the duration of the simulation. The output of numerical mesoscale atmospheric models can be used as forcing for the ocean model, because observed data may not be sufficiently available in time and space. The increase in computer power in recent years and advances in numerical mesoscale models of both ocean and atmosphere now make it possible to perform high-resolution prediction studies for the coastal oceans.

This coupling of atmospheric and oceanic models will be the basis of future operational prediction systems being developed at the National Centers for Environmental Prediction (NCEP, formerly the National Meteorological Center; McPherson 1994). As part of the National Oceanic and Atmospheric Administration (NOAA) Coastal Ocean Program, the output of NCEP numerical atmospheric prediction models is being used as the forcing for numerical ocean prediction models for several U.S. coastal regions. The atmospheric model in use is the step-coordinate Eta Model. The numerical ocean model being used in this endeavor is the Princeton Ocean Model (POM), which has been used to study the Gulf Stream region (Ezer and Mellor 1992; Ezer et al. 1993; Ezer 1994; Ezer and Mellor 1994a,b) as well as other coastal regions. The meteorological output from

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the Eta Model is being used to drive the POM as part of an ocean prediction system for the U.S. east coast (Aikman et al. 1996), called the Coastal Ocean Forecast System. The resulting ocean model water levels have then been compared to the observed water levels at stations along the East Coast (Aikman et al. 1996; Schmalz 1996; Kelley et al. 1997). A nowcast system is also being developed for the Straits of Florida with the POM, using meteorological input from the Eta Model (Mooers and Ko 1994). The sea level predictions from these coastal forecasting systems can subsequently be used as the open boundary conditions that drive higher-resolution models for bays and harbors (Parker 1994, 1996). Nowcast–forecast systems are presently being set up for Galveston Bay (Schmalz 1998), Tampa Bay (Hess 1994), and San Francisco Bay (Cheng and Casulli 1996). Output from the Eta Model is also being used for nowcast–forecast systems being developed for coastal regions such as Chesapeake Bay (Bosley 1996) and New York Harbor (Wei and Sun 1998).

One method of wind forecast verification is by comparison of observed water levels with those forecast by the ocean model component of the forecasting system. This is an indirect method of forecast validation, as opposed to the more direct method of comparing forecast winds with observed station and buoy winds as was done by Khandekar and Lalbeharry (1996). The indirect method of comparing water levels complements the direct method of comparing wind observations and has other advantages. The water levels of a lake, estuary, or coastline are the net result of the spatial and temporal distribution of the winds over that region. The water level comparisons give an indication of how well winds were forecast over the entire region. Furthermore, the water level forecasts are needed for marine navigation in the shallow channels to ports. As forecasting systems are applied to smaller bays and harbors, the shorter timescales of episodic events such as frontal passages become important, due to the resulting marked water level changes which affect marine navigation. This is particularly true for the nowcast–forecast systems that must forecast water levels for shipping, such as those being set up for Chesapeake Bay (Bosley 1996), New York Harbor (Wei and Sun 1998), and Galveston Bay (Schmalz 1998).

The Great Lakes Coastal Forecasting System (GLCFS) is a joint project between the NOAA/Great Lakes Environmental Research Laboratory and The Ohio State University. Its goal is to develop a real-time forecasting system for the lakes, including the water levels, wave conditions, and the three-dimensional temperature and current structure. The GLCFS includes the computer systems and visualization software, observational data networks, various atmospheric mesoscale models, and the POM for the lake circulation. A parametric wave model is used to forecast wave conditions. The observed data necessary for initializing the system and for forecast verification are obtained through the NOAA CoastWatch program. These data include winds and temperatures measured by buoys in the Great Lakes and at land stations surrounding them, NOAA National Ocean Service water level gauge data, and remotely sensed satellite thermal infrared imagery of lake surface temperature. A discussion of these CoastWatch products, especially the satellite imagery data, is given by Schwab et al. (1992) and Leshkevich et al. (1993). A description of the computer visualization capabilities is given by Bedford and Schwab (1990) and Chu et al. (1994). The present state of the GLCFS is described by Bedford and Schwab (1994, 1998) and Schwab and Bedford (1994, 1995, 1996). The first implementation of the system was for Lake Erie and it is presently being tested for Lake Ontario. The expectation is that it will eventually be applied to all five of the Great Lakes.

One of the reasons the GLCFS was implemented first for Lake Erie is that this lake has notable wind-forced water level fluctuations. This lake shows the greatest water level response to wind stress forcing of all the Great Lakes. This is because of its shallow depth and its southwest–northeast orientation along a direction of frequently strong winds. These winds usually result from the passage of a cyclone or its associated front. The time series of water levels measured at Buffalo at the east end of the lake, and Toledo at the west end, are often near–mirror images of each other (Schwab 1978; Hamblin 1987). It is not uncommon to record wind-forced water level displacements greater than 0.5 m at Buffalo and Toledo.

The GLCFS has produced nowcasts from marine observations around Lake Erie since 1992 (Yen et al. 1994) and has produced forecasts using meteorological data provided by the Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model Versions 4 and 5 (Penn State–NCAR MM4 and MM5; Kelley et al. 1994a,b; Powers et al. 1997). A detailed study of several surge events on Lake Erie in 1992–93 was made by Kelley et al. (1998) using the GLCFS forced by the Penn State–NCAR MM4 model output. Recently the 29-km Eta Model output has been used to force the POM and produce forecasts for Lake Erie (Kelley et al. 1996). The GLCFS forecasts are made available on the Internet (at the Web site http://superior.eng.ohio-state.edu).

This article has two purposes. The first is to show how the GLCFS water levels can be used as an indirect method of forecast verification for atmospheric model forecast winds. The second purpose is to evaluate the wind forecasts from two versions of the Eta Model (at 40- and 29-km resolution) using the GLCFS. Both of these purposes have application to other coastal forecasting systems under development. First we will briefly describe the Eta Model, particularly its surface output for the Great Lakes region. A detailed description is given of how the hydrodynamic model (POM) is applied to Lake Erie. The Eta Model winds and winds from coastal stations are used to force the POM to predict water levels. These model water levels are then compared with observed water level gauge data from Toledo and Buffalo. This article reports on the initial application of 40-km Eta Model output to drive the POM to simulate several surge events for Lake Erie in 1993, and application of the 29-km Eta Model forecasts to several cases in 1997. Twin experiments are made with the GLCFS to determine 1) how well it can predict (hindcast) water levels using observed CoastWatch winds as forcing, and 2) how well it can predict water levels using both the 40- and 29-km Eta Model forecast winds as forcing. Finally, the results are summarized and their application to other coastal forecasting systems is discussed.

2. Eta Model winds and observed winds

a. Eta Model description

The Eta Model is the numerical weather prediction model for the North American region that has been under continuous development at NCEP. The model development and its operation at NCEP are discussed by Black (1994). The first version became operational in June 1993 and had a horizontal grid spacing of 80 km (Black 1993). The grid spacing was reduced to 48 km in October 1995 (Rogers et al. 1996). A 40-km version of the Eta Model was run in a test mode from June 1992 through the latter part of 1995. From August 1995 to June 1998, a 29-km grid version of the model was run operationally. In June 1998, the present 32-km grid version of the Eta Model was implemented. The output of the 40-km version was used in this study for the 1993 cases and the output of the 29-km version was used for the 1997 cases.

The Eta Model vertical coordinate is a modification of the terrain-following sigma coordinate. The nondimensional Eta Model levels, like the sigma model levels, are interfaces between layers, and the distance between them generally increases with decreasing atmospheric pressure. However, it is a step-mountain coordinate where the coordinate surfaces are relatively horizontal everywhere, so that the difficulties associated with the calculation of the pressure gradient force over steep topography with the sigma coordinate model are significantly reduced (Mesinger 1982). The land surface topography coincides with the model layer interfaces. The model uses the semistaggered Arakawa E grid, with the pressure and temperature variables calculated at one set of points, and the horizontal (u, v) velocities calculated at another set of points. The (u, v) velocities are calculated at the midpoint of the layers and are zero at the vertical boundaries of the steps. Each surface horizontal grid square is designated as being over land or water. The grid is rotated in longitude and latitude to minimize convergence of the meridians in the region of interest, the continental United States.

A discussion of the parameterization of physical processes in the Eta Model is given by Janjic (1990, 1994). The Eta Model uses the Mellor and Yamada (1982) level 2.5 turbulence closure parameterization, where the turbulent kinetic energy and turbulent length scale are prognostic variables. Although the Eta Model describes the entire three-dimensional structure of the atmosphere, here we shall consider only the surface-layer products that directly force the POM Great Lakes circulation model. Surface heat fluxes are important in determining lake stratification on timescales beyond a week. However, since we desire to model strong wind events lasting only several days, the wind stress becomes the most important meteorological input parameter to the ocean model, and the only one we shall use in this study.

The GLCFS surface forcing subroutines take the 10-m winds as input. How these winds were obtained depended on the version of the Eta Model. During the 1993 test period the lowest-level winds of the 40-km Eta Model were those of the first layer, at about 40 m above the surface of the Great Lakes region. This version used the Mellor–Yamada level 2.0 diagnostic scheme with surface bulk relationships (Lobocki 1993) to calculate the friction velocity u_*. The wind stress τ was calculated from the Eta Model friction velocity u_* by the formula $u_* = (\tau/\rho)^{1/2}$, where the air density is $\rho = 1.2$ kg m^{-3}. In order to make use of wind interpolation schemes to grid the data, the log wind profile was used to obtain 10-m wind from the friction velocity. The ocean model surface forcing subroutines then converted the 10-m wind back to stress. Because a wind profile for neutral stablity conditions was used, the calculations were reversible. The lowest-level winds were used only for wind direction, and did not enter into any wind stress calculation. Because the Eta Model used the constant flux surface-layer approximation, the wind stress direction was taken to be the same direction as the lowest-level winds (40 m for the 40-km Eta Model and 10 m for the 29-km version). Although the wind stress direction will differ from the wind direction at the 40-m level, the approximation should be acceptable for two reasons. First, we are modeling strong wind cases with more turbulence that tends to reduce the stratification. Second, work with the lake model showed that for strong winds generally along the axis of the elongated lake, the water levels at Toledo and Buffalo were not critically dependent on a few degrees change in wind direction. In the 1997 cases, the 29-km Eta Model used an improved boundary layer turbulence scheme, which diagnoses 10-m winds and surface wind stress directly.

The Eta Model was run twice per day, with forecasts that started at 0000 and 1200 UTC, and gave predictions at 3-h intervals out to 36 h. For both the 1993 and 1997 periods, the Eta Model gridded output data covering the Great Lakes region were obtained by automated remote access to NCEP. The parameters that were retrieved for use with the GLCFS were the (u, v) velocity components at 40 m and friction velocity for the 40-km Eta Model, and the 10-m winds for the 29-km Eta Model. The Eta

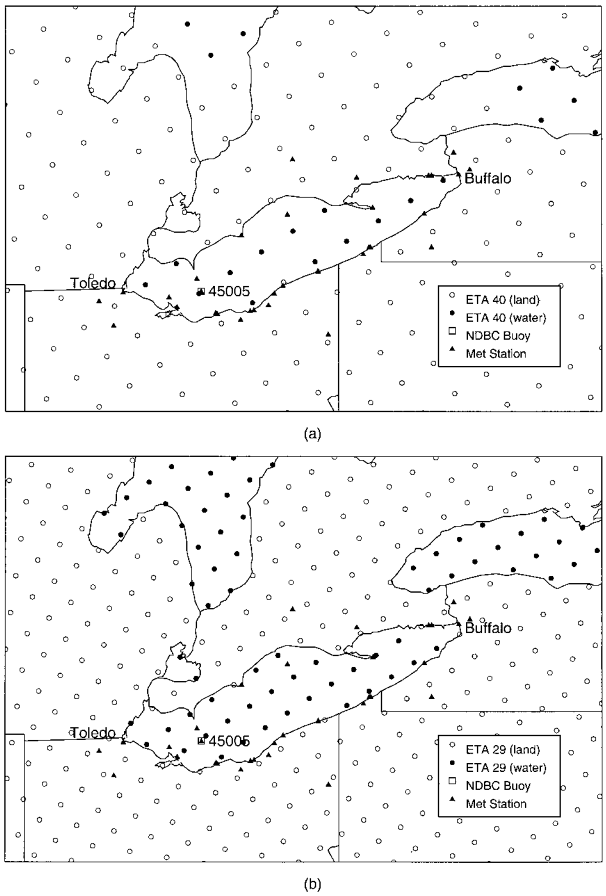

FIG. 1. The Eta Model 40-km (a) and 29-km (b) grid points near Lake Erie. The Eta Model land points are shown as open circles, water points as filled circles, the location of NOAA data buoy 45005 as a square, and surface wind station observations as triangles.

winds were rotated to give the direction from true north. Grid center points from that portion of the 40- and 29-km grids around Lake Erie are shown in Fig. 1, with those surface grid points that are over water depicted as filled circles. The data for each Eta Model water point over Lake Erie were made into a time series. Data were taken at 3-h intervals from the most recent 0000 or 1200 UTC forecast. Any data gaps due to failure of the automatic retrieval procedure were filled by the data from the previous forecasts out to 36 h. Although the 0- and 3-h forecasts were made during the data assimilation spinup period, the model results for the friction velocity and wind direction should be accurate enough to force water levels on the Great Lakes. The present 32-km version of the Eta Model completely cycles on itself with little spinup (DiMego et al. 1998).

b. The wind observations

The observed winds used for the GLCFS nowcasts were from the National Data Buoy Center buoy 45005 moored in the western basin of Lake Erie, and land stations around the lake reporting to the CoastWatch network, as indicated in Fig. 1. Since overland wind speeds underestimate the overwater wind speeds because of larger roughness over ground, the winds from land stations were adjusted to overwater speeds using the method described by Resio and Vincent (1977) and Schwab and Morton (1984). From these winds the surface stress was calculated with a quadratic resistance law. The drag coefficient is a function of wind speed and air–sea temperature difference as described by Schwab (1978). The procedure for calculating the drag coefficient uses a roughness length that increases with wind speed and uses similarity theory to account for boundary layer stability.

3. Lake model and forcing

The POM is a three-dimensional, nonlinear, primitive equation finite difference ocean model, which is described by Blumberg and Herring (1987) and Blumberg and Mellor (1987). It uses a mode-splitting technique that solves the barotropic mode for the free surface and vertically averaged horizontal currents, and the baroclinic mode for the fully three-dimensional temperature, turbulence, and current structure. The equations are written in the sigma vertical coordinate system and include a turbulence closure parameterization with an implicit time scheme for vertical mixing. Because we desire to investigate the wind-forced water level set up in the Great Lakes, we use the barotropic equations subset of the POM. These are the vertically integrated nonlinear continuity and horizontal momentum equations, which are solved for the water level and the horizontal components of velocity (u, v). These equations were used by Blumberg (1977) and Blumberg and Kantha (1985) to study barotropic flow due to tides and wind forcing in Chesapeake Bay and along the U.S. eastern continental shelf. The horizontal momentum equations consist of terms for the local time derivative and horizontal advection terms, the Coriolis deflection, sea level pressure gradient, tangential wind stress on the sea surface, and quadratic bottom friction. For the barotropic mode, we use a constant value 0.0025 for the bottom friction coefficient. The system of equations is written in flux form and solved using a finite differencing scheme that is centered in time and space on the Arakawa C grid.

The POM was applied to Lake Erie using rectangular Cartesian coordinates. The lake is 395 km long and 110 km wide, with its greater axis aligned southwest–northeast. The model domain has been rotated so that the grid has the x coordinate along the greater axis of the lake. The grid spacing is 5 km in both the x and y directions, and so there are 81 grid points in the x direction, and 24 grid points in the y direction, including a one-grid land border all around the domain. Because the lake is enclosed, there is no need to specify open boundary conditions for the model. The value of the

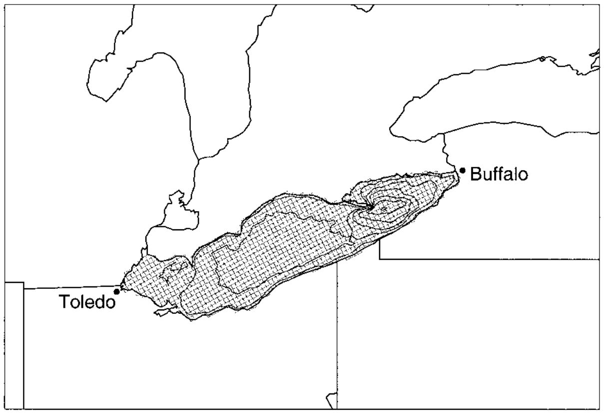

FIG. 2. POM 5-km grid bathymetry for Lake Erie. Depth contours at 10-m intervals to 60 m.

Coriolis parameter is 10^{-4} s^{-1}. Lake Erie is the shallowest of the five Great Lakes. The maximum depth is just over 60 m in the eastern basin, while the western two-thirds of the lake is shallower, generally less than 20 m deep. The model uses the GLERL digital bathymetry (Schwab and Sellers 1980). The bathymetry was filtered so that the maximum relative change in depth between adjacent grid squares was less than 0.5. This was done to avoid problems associated with the sigma coordinate hydrostatic consistency criterion described by Mesinger (1982) and Haney (1991). The model depths vary from 1 m at the western end of the lake, to a maximum of 62 m in the eastern basin. The model grid, bathymetry, and station locations are shown in Fig. 2. Both 5- and 2-km versions of the GLCFS have been developed. The 2-km grid version of the model is presently being used for the operational GLCFS. To ensure computational stability under the Courant criterion, the 5-km model uses a barotropic mode time step of 60 s. The application of the POM to Lake Erie as part of the GLCFS is further described by Kelley et al. (1994a,b) and Schwab and Bedford (1994). The barotropic model configuration of the POM described above has been used successfully by O'Connor and Schwab (1994) to model a strong 2-day wind event in Lake Erie.

The Eta wind and the CoastWatch station wind observations must be interpolated in space and time to be used as forcing for any ocean model. The GLCFS version of the POM takes hourly gridded wind fields as input, so that the model reads in a new wind field every hour, and interpolates these wind fields to every barotropic mode time step. The Eta output was interpolated from 3-h intervals to 1-h intervals. The method used to spatially interpolate the winds to the 5-km Lake Erie model grid is discussed by Schwab and Bedford (1994). The interpolation scheme is that of Barnes (1973) using a negative exponential weighting function with radius of influence set to 15 km, about one-third to one-half of the distance between station observations or Eta Model output grids.

4. Case studies

a. The 40-km Eta Model

The water level gauge data for Buffalo and Toledo for 1993 are shown in Fig. 3. We obtained the 40-km Eta Model wind data for July–December 1993, which covers the period from summer through early winter, and examined nine cases of surge events for which sufficient data were available. These are indicated by the shaded intervals in Fig. 3. The largest water level fluctuations on Lake Erie during this period were associated with autumn storms. The nine cases selected are a representative sample of surge events for the period summer through early winter, including large surges over 1 m and other lesser surges.

These cases were chosen because both observed CoastWatch winds and Eta Model output were available continuously over a 5-day period. For each of these 5-day cases, both the CoastWatch winds and Eta winds were interpolated in space and time as discussed previously, so that the POM was forced by 120 hourly wind fields on the 5-km lake model grid. The model output barotropic mode water levels were saved hourly for the grid squares closest to Buffalo and Toledo. For evaluation purposes the NOAA National Ocean Service hourly water level gauge data were obtained for locations at Toledo and Buffalo. Although these gauges are in harbors smaller than the POM grid resolution, they provide the closest available data near the ends of the lake. Twin experiments were made with the GLCFS to determine 1) how well it can predict (hindcast) water levels using observed CoastWatch winds as forcing, and 2) how well it can predict water levels using Eta Model forecast winds as forcing. The water levels at Buffalo and Toledo for the nine cases are shown in Figs. 4–12. These figures show three water level time series for each case: those observed by gauges, those hindcast by the POM forced by analyzed CoastWatch winds, and those forecast by the POM forced by Eta Model winds. The lakewide mean water level has been subtracted from the observed water levels for each case. The model output results indicated that the respective water level curves for Buffalo and Toledo are also near–mirror images of each other. The correlation coefficient and root-mean-square difference (rmsd) statistics for the comparison of observed water levels versus model output water levels for these cases are given in Table 1.

In late spring through summer the centers of surface low pressure systems tend to pass north of Lake Erie or sometimes over it. These systems are usually less intense, resulting in water level fluctuations that are lower in magnitude and more gradual in time. For lows that move over or north of the lake, the water level generally increases at Buffalo and decreases at Toledo in advance of an approaching cold front. For lows that pass south of the lake, easterly winds cause the water levels to increase at Toledo and decrease at Buffalo. Locally, water level fluctuations depend on the wind speed and

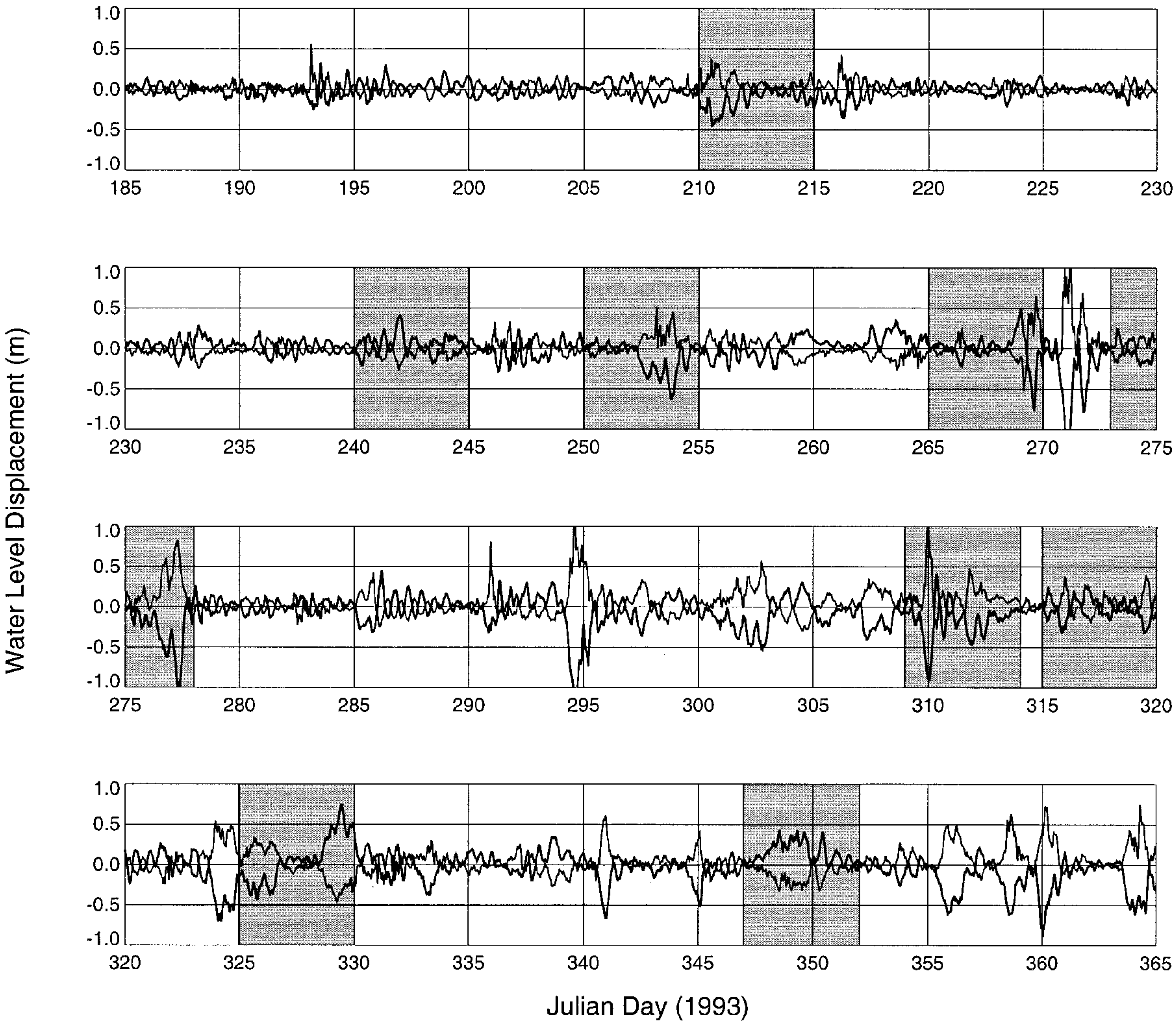

FIG. 3. Hourly NOAA/National Ocean Service water level data for Toledo gauge 906-3085 (thick) and Buffalo gauge 906-3020 (thin), 4 July–31 December 1993 (JDs 185–365). Shaded regions indicate time periods of 40-km Eta Model cases used in this study.

direction, which depend on the spacing and orientation of the surface isobars. The first two cases (Figs. 4 and 5) are for the passage of weaker systems during summer, and the water level fluctuations are comparatively small. In the first case (Fig. 4), the low pressure system developed to the northeast of the lake. Compared to the hindcast water levels for Buffalo and Toledo, the Eta-based forecasts show significant differences in the timing of maxima and minima, although forecast magnitudes are reasonable. In the second case (Fig. 5), the Eta-based forecast completely misses the peak water level setup at Toledo on Julian day (JD) 242. For these two cases the Eta-forced water level correlation coefficients (Table 1) are significantly lower than for most of the other cases. These two cases are representative of the type of weak events in summer and fall that are not forecast well with Eta Model winds.

In autumn the polar front begins to shift southward, and the cyclonic systems speed up and become more intense, so that the largest water level fluctuations tend to occur in late fall through early spring. Particularly rapid water level fluctuations can result from frontal passages, depending on the strength, speed, and orientation of the front. For strong frontal gradients and faster moving fronts, the forced water level oscillations had a more ''spike''-like appearance. The water level time series at Buffalo and Toledo for these cases of autumn and winter are shown in Figs. 6–12 and indicate some skill in the Eta-forced water level forecasts. Case 3 (Fig. 6) shows a typical positive surge at Buffalo and negative surge at Toledo. Both the hindcast and the Eta Model forecast water levels show good correlation and low rmsd. Case 4 (Fig. 7) is a good example of a low pressure system that passed south of the lake and caused

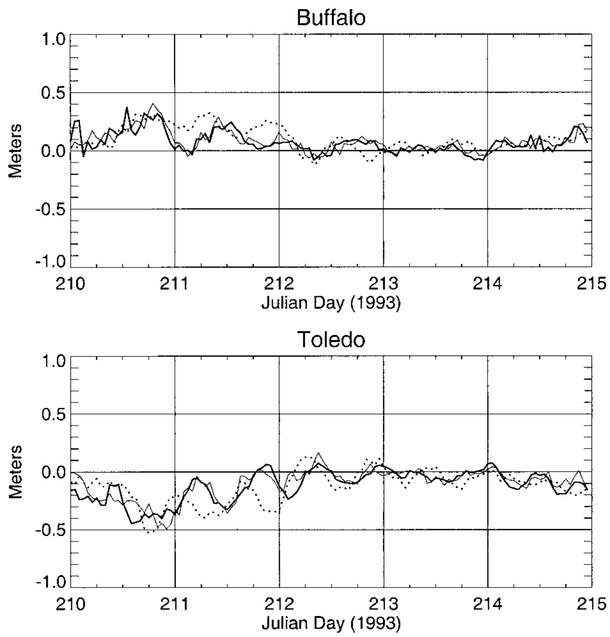

FIG. 4. Water levels for Buffalo and Toledo: observed by NOAA gauges (thick solid), hindcast output of POM forced by observed winds (thin solid), and forecast output of POM forced by 40-km Eta Model winds (dashed), for case 1, 29 July–2 August 1993 (JDs 210–214). Observed water levels at Buffalo and Toledo are relative to the lakewide mean level for each case.

TABLE 1. Rmsd and correlation coefficient (CC) statistics comparing observed water levels at Buffalo and Toledo with the hindcast water level output of the ocean model forced by observed winds, and the forecast water level output of the ocean model forced by 40-km Eta winds in 1993.

		Observed wind forcing		Eta wind forcing	
Case	Dates (JD)	Rmsd (m)	CC	Rmsd (m)	CC
Buffalo water levels forced by					
1	210–215	0.06	0.75	0.10	0.48
2	240–245	0.06	0.76	0.10	0.29
3	250–255	0.08	0.74	0.08	0.76
4	265–270	0.09	0.86	0.11	0.79
5	273–278	0.10	0.92	0.16	0.76
6	309–314	0.10	0.89	0.16	0.63
7	315–320	0.06	0.89	0.12	0.78
8	325–330	0.07	0.96	0.12	0.91
9	347–352	0.08	0.82	0.11	0.50
Avg		0.08	0.84	0.12	0.66
Toledo water levels forced by					
1	210–215	0.07	0.84	0.13	0.55
2	240–245	0.07	0.83	0.14	0.30
3	250–255	0.06	0.93	0.10	0.82
4	265–270	0.08	0.92	0.11	0.82
5	273–278	0.11	0.91	0.18	0.73
6	309–314	0.10	0.94	0.17	0.66
7	315–320	0.08	0.89	0.11	0.76
8	325–330	0.11	0.97	0.15	0.90
9	347–352	0.09	0.84	0.14	0.49
Avg		0.09	0.90	0.14	0.75

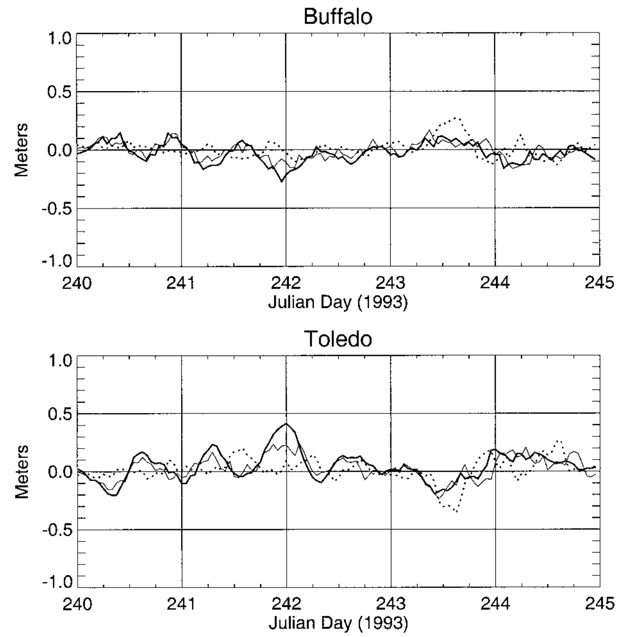

FIG. 5. Same as Fig. 4 but for case 2, 28 Aug–1 Sep 1993 (JDs 240–244).

a positive surge at Toledo and a negative surge at Buffalo. Even though the negative surge at Buffalo was somewhat underpredicted, the overall water level forecast is quite good. Cases 5 and 6 (Figs. 8 and 9) are both positive surges at Buffalo and correspond to well-developed low pressure systems passing north of the lake. In case 5, on JD 276 there was an upper-air low

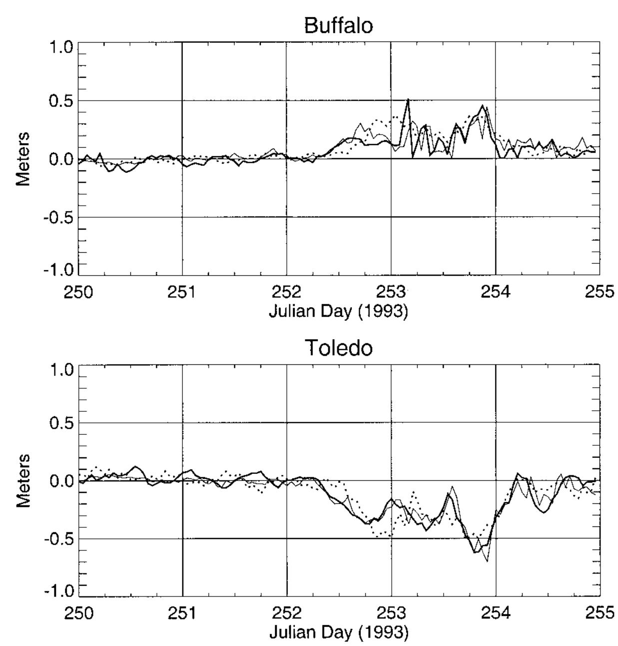

FIG. 6. Same as Fig. 4 but for case 3, 7–11 Sep 1993 (JDs 250–254).

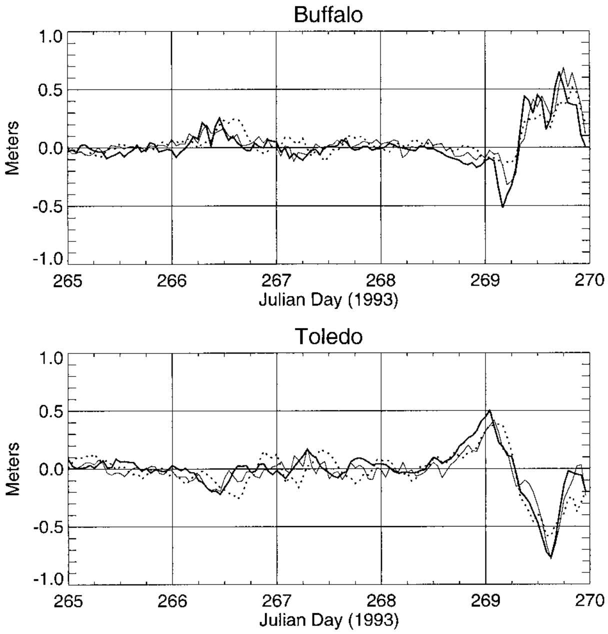

FIG. 7. Same as Fig. 4 but for case 4, 22–26 Sep 1993 (JDs 265–269).

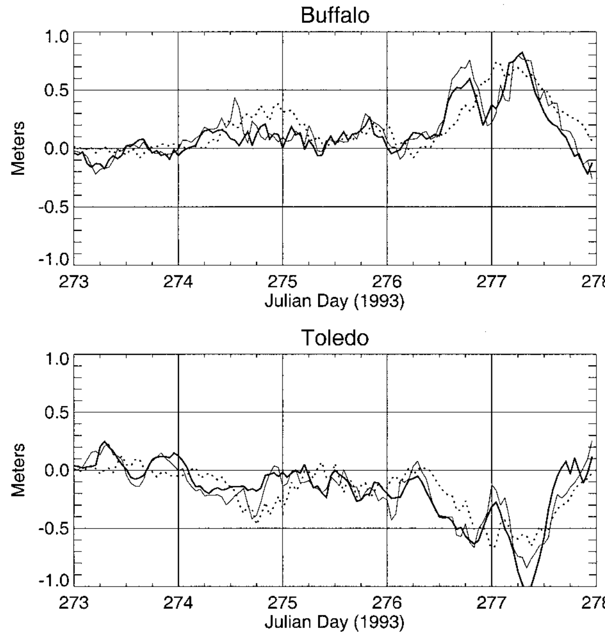

FIG. 8. Same as Fig. 4 but for case 5, 30 Sep–4 Oct 1993 (JDs 273–277).

centered over Hudson Bay with a trough extending SE over the eastern Great Lakes region. The center of the surface low pressure was also over southern Hudson Bay. After 1200 UTC on JD 276 a surface low pressure trough rapidly deepened and by 1200 UTC on JD 277 a cold front was aligned SW–NE, nearly parallel to the axis of Lake Erie. The surface winds were about 10 kt (5 m s^{-1}) from the SW over Lake Erie, causing a setup at Buffalo of 0.8 m (Fig. 8). Comparison with weather maps indicated that the Eta Model winds for this time adequately represented the surface wind field with respect to the front. With the passage of the cold front, the water levels relaxed to their normal values. Case 6 (Fig. 9) is a second case of strong wind forcing during a frontal passage. The 500-mb low was centered over northern Hudson Bay with a trough extending SE to the eastern Great Lakes. At 1200 UTC on JD 310 the surface low was north of Maine with a trough and cold front extending SW along the St. Lawrence to just east of the Great Lakes. Winds from the SW in advance of the cold front had increased the water levels at Buffalo to just over 1 m (Fig. 9). The diminishing winds as the front approached, and their shift to the NW after passage caused the rapid relaxation of the water levels at Buffalo. Again, comparison with weather maps indicated that the Eta Model winds for this time adequately depicted the position of the surface winds with respect to the frontal position. Comparisons with weather maps also showed that for cases with poor correlations, the Eta Model missed the timing of the cyclonic system or frontal passage. Case 7 (Fig. 10) includes two typical positive surges at Buffalo with good Eta-based forecasts of both surges. Case 8 (Fig. 11) corresponds to a large, slow-moving low pressure system in Canada, which causes the winds to gradually shift from westerly to easterly over the 5-day period. The Eta-based forecasts are good for both the positive and negative surges. Case 9 (Fig. 12) is a weaker disturbance and is not well predicted by the Eta-based forecast.

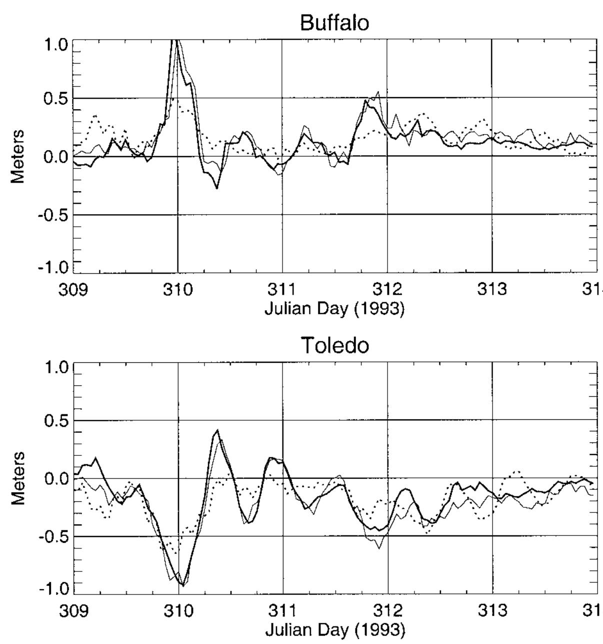

FIG. 9. Same as Fig. 4 but for case 6, 5–9 Nov 1993 (JDs 309–313).

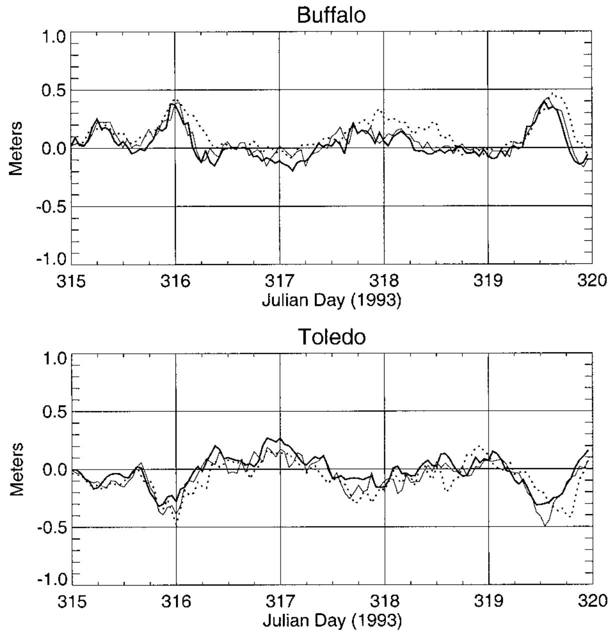

FIG. 10. Same as Fig. 4 but for case 7, 11–15 Nov 1993 (JDs 315–319).

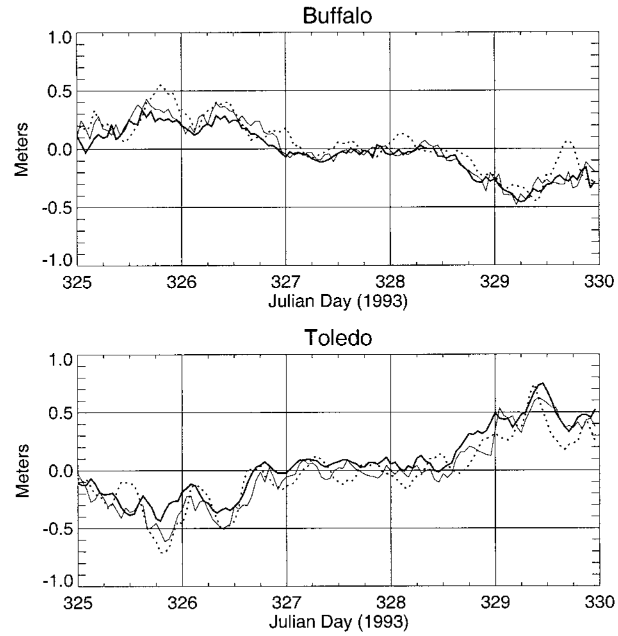

FIG. 11. Same as Fig. 4 but for case 8, 21–25 Nov 1993 (JDs 325–329).

Generally, the correlation coefficients shown in Table 1 for water levels forced by observed winds at Buffalo (0.74–0.96) and Toledo (0.83–0.97) are higher than for those forced by Eta Model winds at Buffalo (0.29–0.91) and Toledo (0.30–0.90). Similarly, the rmsd for water levels forced by observed winds at Buffalo and Toledo (0.06–0.11 m) are lower than for those forced by Eta Model winds (0.08–0.18 m). In both case 5 and case 6, the initial peak surge at Buffalo and corresponding minimum at Toledo are underforecast by as much as 0.5 m, which is reflected in the higher rmsd values for these two cases. The lowest correlation coefficients for water levels forced by Eta Model winds occurred during the summer simulations (cases 1 and 2). The correlation coefficients generally increased throughout the fall and the winter (cases 3–7), with a slight decline in late winter (cases 8 and 9). These comparisons indicate qualitatively that the weather systems of autumn and winter of 1993 were better represented by the 40-km Eta Model than the weaker summer systems.

When the polar front is shifted farther south, sometimes the centers of surface low pressure systems pass south of the lake. In this case there is usually not a frontal passage, and easterly winds increase (decrease) the water level at Toledo (Buffalo) as the low passes south of the lake. Such a case of easterly wind-forced water levels on Lake Erie was studied by O'Connor and Schwab (1994) in a similar manner using the POM and observed winds. The capacity for large surges can be reduced if the lake surface becomes substantially ice covered; however the lake was ice free for all the cases selected for this study.

b. The 29-km Eta Model

In 1997, the 29-km Eta Model forecasts were being used in the Great Lakes Coastal Forecasting System. We selected six cases in 1997 to compare water level forecast results based on the 29-km Eta Model to hindcasts based on observed winds. The water level gauge data from Buffalo and Toledo for 1997 are shown in Fig. 13.

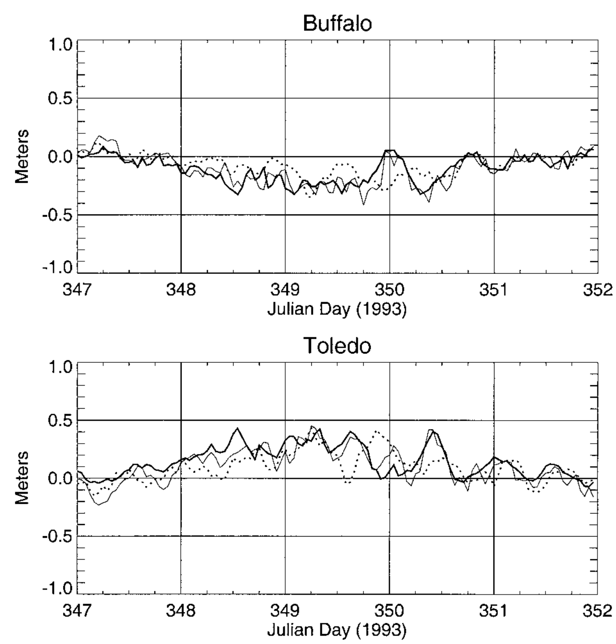

FIG. 12. Same as Fig. 4 but for case 9, 13–17 Dec 1993 (JDs 347–351).

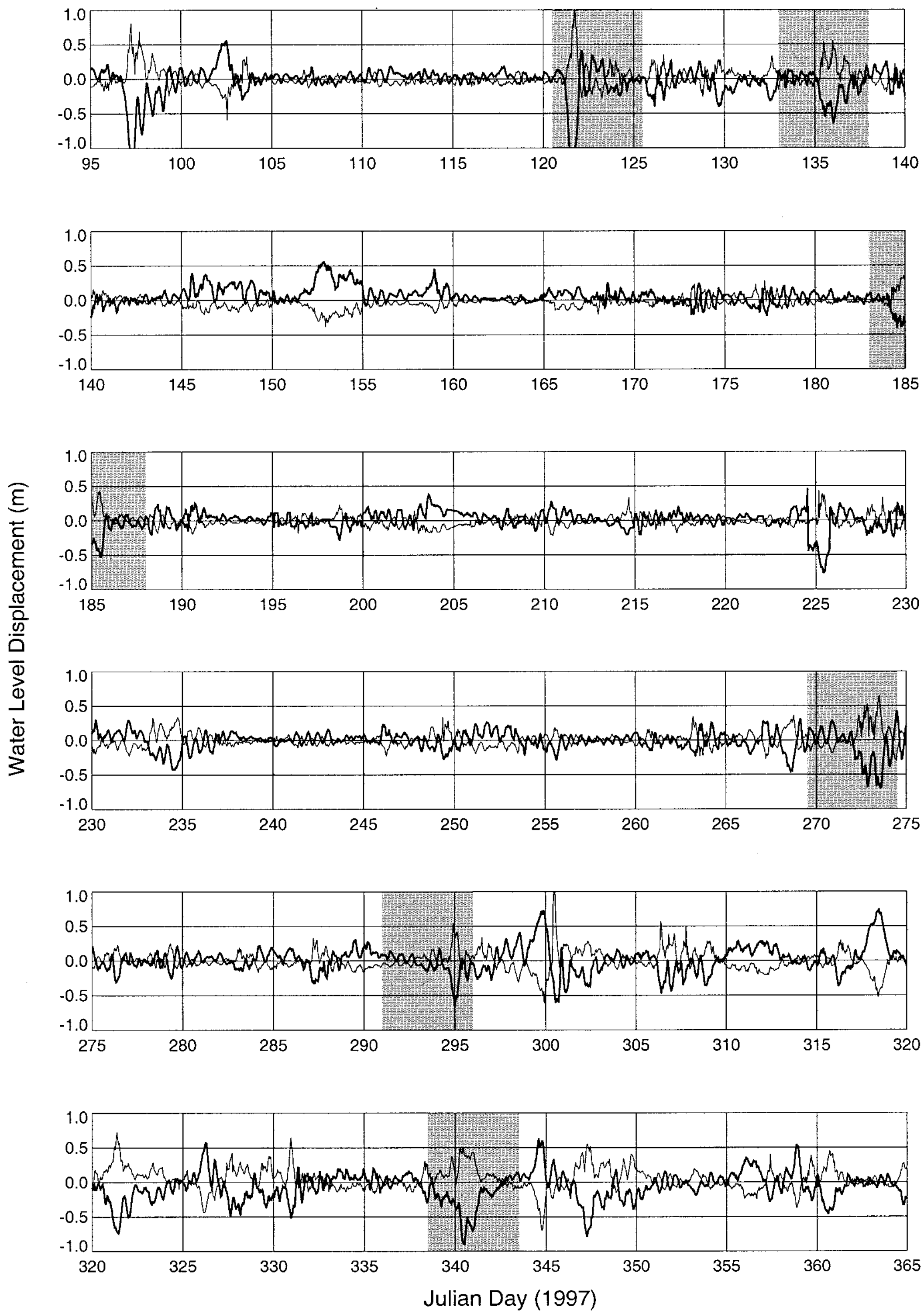

FIG. 13. Hourly NOAA/National Ocean Service water level data for Toledo gauge 906-3085 (thick) and Buffalo gauge 906-3020 (thin), 5 Apr–31 Dec 1997 (JDs 95–365). Shaded regions indicate time periods of 29-km Eta Model cases used in this study.

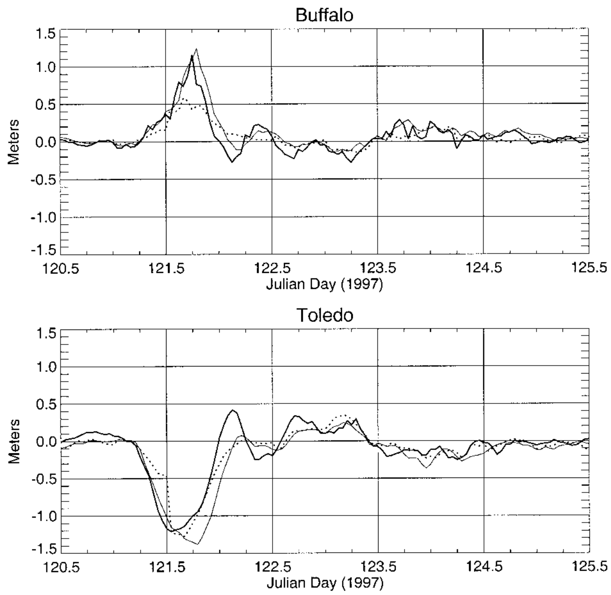

FIG. 14. Water levels for Buffalo and Toledo: observed by NOAA gauges (thick solid), hindcast output of POM forced by observed winds (thin solid), and forecast output of POM forced by 29-km Eta Model winds (dashed), for case 10, 31 Apr–5 Jul 1997 (JDs 120–125). Observed water levels at Buffalo and Toledo are relative to the lakewide mean level for each case.

TABLE 2. Rmsd and CC statistics comparing observed water levels at Buffalo and Toledo with the hindcast water level output of the ocean model forced by observed winds, and the forecast water level output of the ocean model forced by-29 km Eta winds in 1997.

		Observed wind forcing		Eta wind forcing	
Case	Dates (JD)	Rmsd (m)	CC	Rmsd (m)	CC
Buffalo water levels forced by					
10	120.5–125.5	0.11	0.91	0.13	0.86
11	133–138	0.17	0.86	0.11	0.71
12	183–188	0.06	0.90	0.09	0.66
13	269.5–274.5	0.10	0.91	0.13	0.76
14	291–296	0.06	0.89	0.09	0.70
15	338.5–343.5	0.08	0.88	0.10	0.75
Avg		0.10	0.89	0.11	0.74
Toledo water levels forced by					
10	120.5–125.5	0.18	0.90	0.18	0.87
11	133–138	0.15	0.92	0.11	0.84
12	183–188	0.09	0.87	0.12	0.67
13	269.5–274.5	0.13	0.92	0.16	0.82
14	291–296	0.07	0.91	0.10	0.80
15	338.5–343.5	0.20	0.92	0.11	0.91
Avg		0.14	0.91	0.13	0.82

The six 5-day cases during which significant storm surge events occurred have been identified by shaded areas in the figure. These particular events were chosen because they have the most complete forecast and hindcast coverage. The hindcast procedure was the same as for the 1993 cases. The results from the hindcasts (using observed winds) and forecasts (using 29-km Eta winds) are identified as cases 10–15 and shown in Figs. 14–19. Again, the observed water level fluctuation from the mean lake level is shown as the thick line, the hindcast water level as a thin line, and the forecast water level as a dotted line. The correlation coefficient and rmsd between modeled and observed water levels for the six cases are given in Table 2.

In 1997, two of the cases (10–11; Figs. 14 and 15) occurred in the springtime, three cases (13–15; Figs. 17–19) occurred in the fall, and one case (12; Fig. 16) is an unusual example of a summer storm surge. The observed water level fluctuations at Buffalo and Toledo during case 10 (Fig. 14) are the largest of all the cases, reaching 1.1 m at Buffalo and −1.2 m at Toledo. The hindcast peak water level deviations are within 0.2 m of the observed deviation at both Buffalo and Toledo. For this case, the forecast peak is significantly underestimated at Buffalo (by 0.5 m) but is within 0.1 m of the observed peak deviation at Toledo. At both Buffalo and Toledo there is a difference in the timing of the initial surge in case 10 between the observed water levels and both the forecast and hindcast water levels, but the forecast and hindcast water levels are similar to each other. In case 11 (Fig. 15), the timing and amplitude of the multiple water level peaks on JDs 135–137 are matched quite well by the Eta-based forecasts. The hindcasts in this case tend to overestimate peak fluctuations at both Buffalo and Toledo. The unusual summer case, case 12 (Fig. 16), shows a more gradual buildup in the storm surge amplitude than most of the spring and fall cases. The winds during this case were associated with a large, slow-moving low pressure system passing well north of the lake. This case had the poorest correlation between forecast and observed water levels of all the

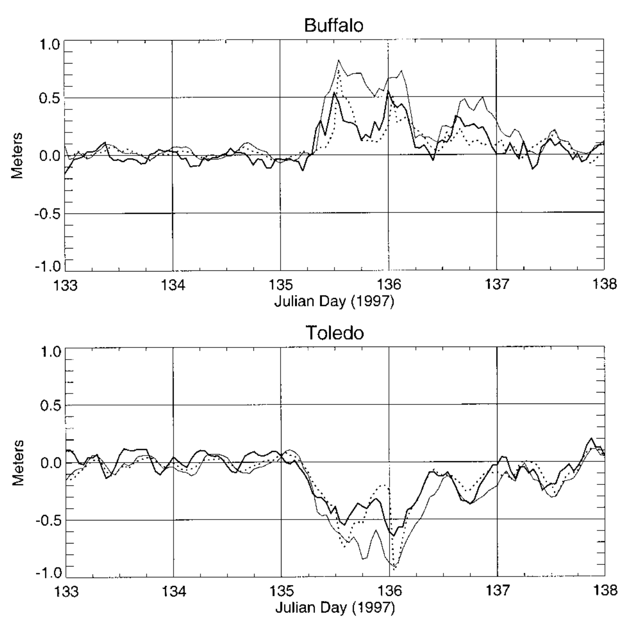

FIG. 15. Same as Fig. 14 but for case 11, 13–17 May 1997 (JDs 133–137).

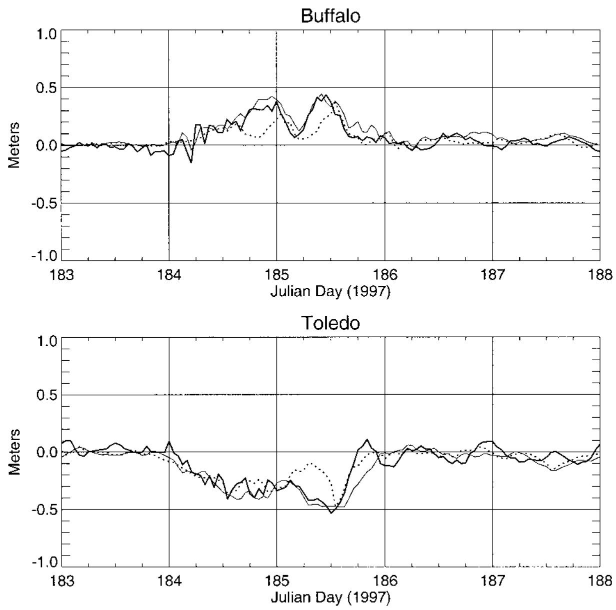

FIG. 16. Same as Fig. 14 but for case 12, 2–6 Jul 1997 (JDs 183–187).

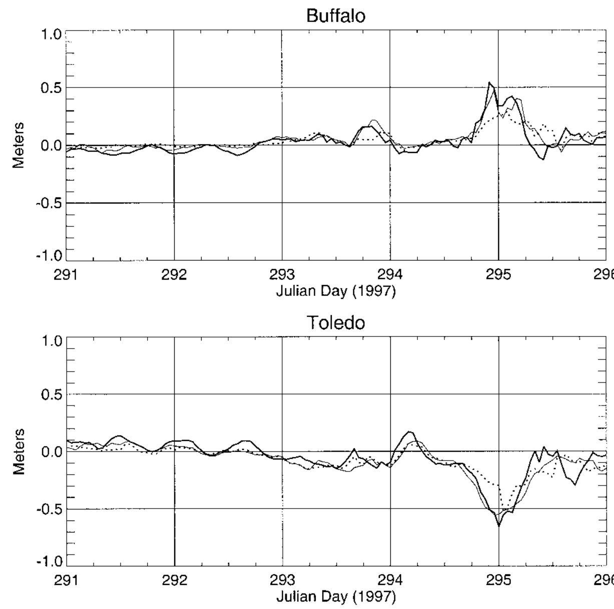

FIG. 18. Same as Fig. 14 but for case 14, 18–22 Oct 1997 (JDs 291–295).

29-km Eta Model cases. Cases 13–15 (Figs. 17–19) are all typical fall storm surge cases, with a moderate rise in water level at Buffalo and a moderate depression at Toledo. In case 13 (Fig. 17), the Eta-based forecast underestimates the first peak water level deviation on JD 272 but captures the second peak on JD 273 a little better. In case 14 (Fig. 18), the single peak on JD 295 is underforecast by the 29-km Eta winds. Case 15 (Fig. 19) has multiple peaks in the recorded water levels, and the Eta-based forecasts again tend to underestimate observed fluctuations. The rmsd and correlation coefficients for the 29-km Eta-based forecasts in Table 2 appear to show more consistency from case to case than the 40-km Eta-based forecasts. The highest rmsd values are for cases 10 and 13 where peak water levels at Buffalo and corresponding minima at Toledo were underforecast by as much as 0.5 m. The average rmsd was slightly lower for the 29-km Eta-based forecasts at both

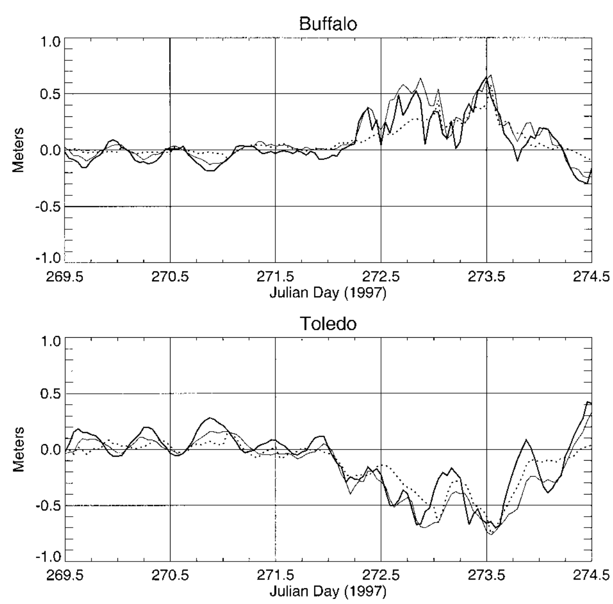

FIG. 17. Same as Fig. 14 but for case 13, 26 Sep–1 Oct. 1997 (JDs 269–274).

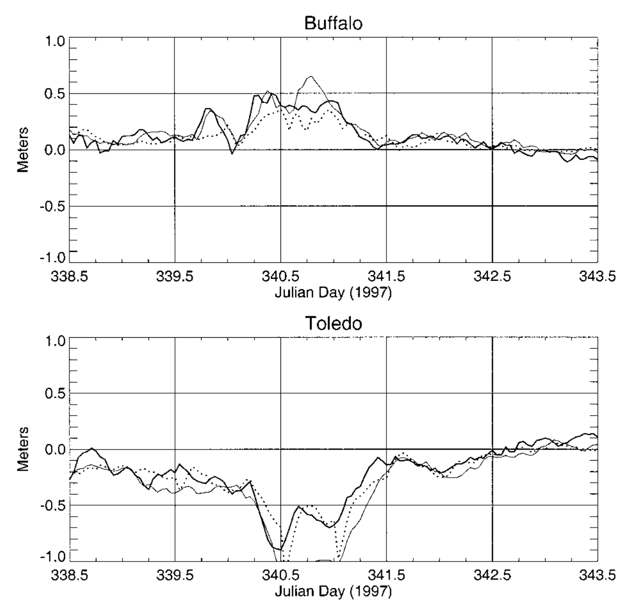

FIG. 19. Same as Fig. 14 but for case 15, 4–9 Dec 1997 (JDs 338–343).

Buffalo and Toledo, and the average correlation coefficients were somewhat higher. We speculate that these correlation coefficients may be most dependent on how well the Eta Model depicts the timing of the frontal passage, while the rmsd may be more dependent on the low-level Eta Model winds and boundary layer turbulence parameterization.

In this article we are emphasizing the method of indirect forecast verification by comparing observed and forecast water levels, and so we do not show direct comparisons of model wind output with weather map observations. Some comparisons of this nature were made by Kelley et al. (1998).

5. Summary and discussion

The first purpose of this article is to describe how the GLCFS can be used to validate wind forecasts for the Great Lakes using observed and forecast water levels, as was demonstrated for Lake Erie. This forecast verification technique can be used with any observed or forecast wind field. The second purpose of this article is to evaluate the Eta Model wind forecasts for Lake Erie using the GLCFS. Nine cases of strong winds over the Great Lakes during 1993, and six cases during 1997, were chosen to study water level forecasts and hindcasts. These were 5-day periods when the 40-km (1993) or 29-km (1997) Eta winds and observed winds were available simultaneously. Twin experiments were performed. For the first part of the experiment, observed winds from stations around Lake Erie were interpolated to the 5-km POM grid for the lake. These were used to drive the ocean model and obtain model water levels for grid points closest to Toledo and Buffalo. The results were compared with the observed water level gauge data for these locations. This test shows how well the coastal forecasting system can hindcast lake conditions. Results indicate that water levels forced by the observed winds compare favorably with the observed water level data. In 1993, the average rmsd was 0.08 m at Buffalo and 0.09 m at Toledo. The corresponding average correlation coefficients were 0.84 and 0.90. In 1997, the average rmsd was similar, 0.10 m at Buffalo and 0.14 m at Toledo. The corresponding average correlation coefficients were also similar, 0.89 and 0.91. For the second part of the experiment, the 40-km (1993) and 29-km (1997) Eta Model forecast winds were interpolated to the 5-km grid for Lake Erie. These fields were used to drive the POM and the resulting water level output was also compared to the observed water level gauge data at Toledo and Buffalo. This gives an indication of the skill of the Eta Model forecasts that give rise to surge conditions. Results indicate that model forecast water levels compare best with observed water levels when the Eta Model accurately predicts frontal passages. In the 1993 cases with 40-km Eta Model forecasts, the average rmsd for the water level forecasts was 0.12 m at Buffalo and 0.14 m at Toledo. The corresponding average correlation coefficients were 0.66 and 0.75. In the 1997 cases with 29-km Eta Model forecasts, the average rmsd for the water level forecasts was similar to the 40-km forecasts, 0.11 m at Buffalo and 0.13 m at Toledo. The corresponding average correlation coefficients, however, were somewhat higher than for the 40-km forecasts, 0.74 and 0.82 at Buffalo and Toledo respectively. The Eta Model has been under continuous development at NCEP for several years, and the 29-km version appears to have given improved surface output over the 40-km version for the GLCFS cases studied here. The 29-km Eta Model was discontinued in June 1998 and has since been replaced with a 32-km version.

The Great Lakes represent a unique opportunity to see how well a coastal forecasting system can predict water levels based on observed and predicted wind fields. For the problem of short-term wind-forced water level fluctuations, each of the Great Lakes may be treated as a closed domain, and the difficulties associated with specifying open boundary conditions are not encountered. The size of the enclosed domains and strong bathymetric control of wind forced currents ensure a deterministic model regime, where the water levels can be adequately modeled with the known wind forcing and without the need of data assimilation. This is in contrast to the coastal oceans where water level fluctuations over several days can result from synoptic-scale atmospheric pressure forcing over the continental shelf. This setup or setdown of water level conditions on the shelf can greatly influence the water level of a local region of specialized interest, such as Chesapeake Bay or New York Harbor. Timely water level forecasts for harbors are important for marine navigation.

Furthermore, it is noted by Bosley (1996) that in order to obtain accurate water levels even in Chesapeake Bay, a semienclosed domain, it is also necessary to spatially resolve the local wind field (the wind field for the bay cannot be inferred from only one or two stations). While Lake Erie is larger than the domain used to study a coastal region such as Chesapeake Bay, the GLCFS obtains winds from stations all around the lake. We have used the GLCFS as a research tool with the 40- and 29-km Eta Model output, and have shown that if the winds are known sufficiently well in time and space, the water levels for an enclosed region can be forecast with some success. By implication, any coastal forecasting system such as the Coastal Ocean Forecast System for the U.S. east coast (Aikman et al. 1996) must know the winds sufficiently well in time and space to forecast water levels. This is especially important for episodic events such as the passage of fronts and weather systems over bays and semienclosed coastal regions. The resultant water levels forced by Eta Model winds can be used with some skill in forecasting periods of high and low water, although these may be off in magnitude by tens of centimeters and in time by a number of hours. Knowing the degree of error will allow for the issue of warnings within some levels of uncertainty. These potential errors do not make the forecasts less valuable, but indicate the extra level of caution that is needed.

The results presented in this article can be useful to coastal and lake modelers and marine forecasters. As was stated in the introduction, coastal forecasting systems are being developed for several U.S. coastal regions. This indirect method of wind forecast validation by comparing observed and predicted water levels is applicable to these other forecasting systems. In particular, the Coastal Ocean Forecast System for the East Coast (Aikman et al. 1998), as well as the forecasting systems for the Port of New York and New Jersey (Wei and Sun 1998) and Galveston Bay (Schmalz 1998), all use some version of the POM for the ocean model and some interpolation of the Eta Model winds as the forcing. When model and observed water levels are compared for the larger Coastal Ocean Forecast System, the emphasis has been on the comparison of the subtidal water levels. For smaller bays and harbors the tidal oscillation and shorter timescale wind forecasts become important for water levels in support of marine navigation. The GLCFS, including the POM, Eta Model winds, and statistical and visualization software, has been set up for Lake Erie and is now being tested for Lake Ontario. It will eventually be applied to all the Great Lakes. Technically, the GLCFS is as relocatable as the POM, which has now been applied to over 100 coastal and ocean areas around the world. The GLCFS model verification has been used for both the 40- and 29-km Eta Model wind forecasts, but is not limited to the Eta Model wind input. The GLCFS has been used to investigate the forcing of Lake Erie with MM4 and MM5 model winds (Kelley et al. 1994a; Kelley et al. 1994b; 1998). The wind forcing output from any atmospheric model (or buoy and station observations) can be used as input to the ocean model, as long as the data can be interpolated temporally and spatially to the ocean model grid. The use of forecast winds to predict water levels for ports and coastal regions, and the indirect method of wind forecast verification using observed and ocean model–predicted water levels, are becoming useful tools for coastal modelers and marine forecasters. The GLCFS is now developing and performing these techniques for the Great Lakes. The GLCFS serves as a benchmark for the accuracy of water level predicitons under the best conditions, and should continue to be improved, because conditions are much easier to document and models easier to validate than in the coastal oceans.

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REFERENCES

Aikman, F., III, G. L. Mellor, T. Ezer, D. Sheinin, P. Chen, L. Breaker, K. Bosley, and D. B. Rao, 1996: Towards an operational nowcast/forecast system for the U.S. east coast. *Modern Approaches to Data Assimilation in Ocean Modeling,* P. Malanotte-Rizzoli, Ed., Elsevier Oceanographic Series, Vol. 61, 347–376.

——, E. J. Wei, and J. R. Schultz, 1998: Water level evaluation for the Coastal Ocean Forecast System. Preprints, *Second Conf. on Coastal Atmospheric and Oceanic Prediction and Processes,* Phoenix, AZ, Amer. Meteor. Soc., 1–6.

Barnes, S. L., 1973: Mesoscale objective analysis using weighted time-series observations. NOAA Tech. Memo ERL NSSL-62, National Severe Storms Laboratory, 60 pp. [NTIS COM-73-10781.]

Bedford, K. W., and D. J. Schwab, 1990: Preparation of real-time Great Lakes forecasts. *Cray Channels,* **12,** 14–17.

——, and ——, 1994: The Great Lakes forecasting system: An overview. *Proc. 1994 Hydraulic Engineering Conf.,* Buffalo, NY, American Society of Civil Engineers, 197–201.

——, and ——, 1998: Recent developments in the Great Lakes Forecasting System (GLFS)—Performance evaluation. Preprints, *Second Conf. on Coastal Atmospheric and Oceanic Prediction and Processes,* Phoenix, AZ, Amer. Meteor. Soc., 45–50.

Black, T. L., 1993: The ''early'' and the mesoscale versions of NMC's Eta Model. Preprints, *13th Conf. on Weather Analysis and Forecasting,* Vienna, VA, Amer. Meteor. Soc., 62–65.

——, 1994: The new NMC Mesoscale Eta Model: Description and forecast examples. *Wea. Forecasting,* **9,** 265–278.

Blumberg, A. F., 1977: Numerical tidal model of Chesapeake Bay. *J. Hydraul. Div., ASCE,* **103,** 1–10.

——, and L. H. Kantha, 1985: Open boundary conditions for circulation models. *J. Hydraul. Eng., ASCE,* **111,** 237–255.

——, and H. J. Herring, 1987: Circulation modelling using orthogonal curvilinear coordinates. *Three-Dimensional Models of Marine and Estuarine Dynamics,* J. C. J. Nihoul and B. M. Jamart, Eds., Elsevier, 55–88.

——, and G. L. Mellor, 1987: A description of a three-dimensional coastal ocean circulation model. *Three-Dimensional Coastal Ocean Models, Coastal and Estuarine Sciences,* N. S. Heaps, Ed., Vol. 4, Amer. Geophys. Union, 1–16.

Bosley, K. T., 1996: Research aimed at prediction of water levels in the Chesapeake Bay. Preprints, *Conf. on Coastal Oceanic and Atmospheric Prediction,* Atlanta, GA, Amer. Meteor. Soc., 268–271.

Cheng, R. T., and V. Casulli, 1996: Modeling the periodic stratification and gravitational circulation in San Francisco Bay, California. *Proc. Fourth Int. Conf. on Estuarine and Coastal Modeling,* San Diego, CA, American Society of Civil Engineers, 240–254.

Chu, Y.-F. P., C.-C. J. Yen, and K. W. Bedford, 1994: GLFSVIEW-GLFS product viewing application. *Proc. 1994 Hydraulic Engineering Conf.,* Buffalo, NY, American Society of Civil Engineers, 207–211.

DiMego, G., and Coauthors, 1998: Enhancements to the operational ''early'' Eta analysis and forecast system at the National Centers for Environmental Prediction. Preprints, *16th Conf. on Weather Analysis and Forecasting*, Phoenix, AZ, Amer. Meteor. Soc., 245–246.

Ezer, T., 1994: On the interaction between the Gulf Stream and the New England seamount chain. *J. Phys. Oceanogr.,* **24,** 191–204.

——, and G. L. Mellor, 1992: A numerical study of the variability and the separation of the Gulf Stream, induced by surface atmospheric forcing and lateral boundary flows. *J. Phys. Oceanogr.,* **22,** 660–682.

——, and ——, 1994a: Continuous assimilation of Geosat altimeter data into a three-dimensional primitive equation Gulf Stream model. *J. Phys. Oceanogr.,* **24,** 832–847.

——, and ——, 1994b: Diagnostic and prognostic calculations of the North Atlantic circulation and sea level using a sigma-coordinate ocean model. *J. Geophys. Res.,* **99** (C7), 14 159–14 171.

——, ——, D. S. Ko, and Z. Sirkes, 1993: A comparison of Gulf Stream sea surface height fields derived from Geosat altimeter data and those derived from sea surface temperature data. *J. Atmos. Oceanic Technol.,* **10,** 76–87.

Hamblin, P. F., 1987: Meteorological forcing and water level fluctuations on Lake Erie. *J. Great Lakes Res.,* **13,** 436–453.

Haney, R. L., 1991: On the pressure gradient force over steep topography in sigma coordinate ocean models. *J. Phys. Oceanogr.,* **21,** 610–619.

Hess, K. W., 1994: Tampa Bay Oceanographic Project: Development and application of the numerical circulation model. NOAA Tech. Rep. NOS OES 005, 90 pp.

Janjic, Z. I., 1990: The step-mountain coordinate: Physical package. *Mon. Wea. Rev.,* **118,** 1429–1443.

——, 1994: The step-mountain Eta coordinate model: Further developments of the convection, viscous sublayer, and turbulence closure schemes. *Mon. Wea. Rev.,* **122,** 927–945.

Kelley, J. G. W., C.-C. J. Yen, K. W. Bedford, J. S. Hobgood, and D. J. Schwab, 1994a: Coupled Lake Erie air–sea storm resolving forecasts and predictions, the Viento Project. *Proc. Third Int. Conf. on Estuarine and Coastal Modeling,* Oak Brook, IL, American Society of Civil Engineers, 202–215.

——, ——, J. S. Hobgood, D. J. Schwab, and K. W. Bedford, 1994b: Short-term forecasts for Lake Erie. *Proc. 1994 Hydraulic Engineering Conf.,* Buffalo, NY, American Society of Civil Engineers, 227–231.

——, D. J. S. Welsh, K. W. Bedford, D. J. Schwab, J. S. Hobgood, and B. Hoch, 1996: High-resolution short-term lake forecasts for Lake Erie. *Proc. Fourth Int. Conf. on Estuarine and Coastal Modeling,* San Diego, CA, American Society of Civil Engineers, 367–378.

——, F. Aikman III, L. C. Breaker, and G. L. Mellor, 1997: Coastal ocean forecasts. Real-time forecasts of physical state of water level, 3-D currents, temperature, salinity for the U.S. east coast. *Sea Technol.,* **38,** 10–17.

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

Khandekar, M. L., and R. Lalbeharry, 1996: An evaluation of Environment Canada's operational ocean wave model based on moored buoy data. *Wea. Forecasting,* **11,** 137–152.

Leshkevich, G. A., D. J. Schwab, and G. C. Muhr, 1993: Satellite environmental monitoring of the Great Lakes: A review of NOAA's Great Lakes CoastWatch Program. *Photogramm. Eng. Remote Sens.,* **59,** 371–379.

Lobocki, L., 1993: A procedure for the derivation of surface-layer bulk relationships from simplified second-order closure models. *J. Appl. Meteor.,* **32,** 126–138.

McPherson, R. D., 1994: The National Centers for Environmental Prediction: Operational climate, ocean, and weather prediction for the 21st century. *Bull. Amer. Meteor. Soc.,* **75,** 363–373.

Mellor, G. L., and T. Yamada, 1982: Development of a turbulence closure model for geophysical fluid problems. *Rev. Geophys. Space Phys.,* **20,** 851–875.

Mesinger, F., 1982: On the convergence and error problems of the calculation of the pressure gradient force in sigma coordinate models. *Geophys. Astrophys. Fluid Dyn.,* **19,** 105–117.

Mooers, C. N. K, and D.-S. Ko, 1994: Nowcast system development for the Straits of Florida. *Proc. Third Int. Conf. on Estuarine and Coastal Modeling,* Oak Brook, IL, American Society of Civil Engineers, 158–171.

O'Connor, W. P., and D. J. Schwab, 1994: Sensitivity of Great Lakes Forecasting system nowcasts to meteorological fields and model parameters. *Proc. Third Int. Conf. on Estuarine and Coastal Modeling,* Oak Brook, IL, American Society of Civil Engineers, 149–157.

Parker, B. B., 1994: Real-time oceanographic data for ports. *Mar. Wea. Log,* **38** (3), 12–16.

——, 1996: Monitoring and modeling of coastal waters in support of environmental preservation. *J. Mar. Sci. Technol.,* **1,** 75–84.

Powers, J. G., M. T. Stoelinga, and W. S. Boyd, 1997: Distributed numerical weather prediction via satellite. *Bull. Amer. Meteor. Soc.,* **78,** 2755–2770.

Resio, D. T., and C. L. Vincent, 1977: Estimation of winds over the Great Lakes. *Amer. Soc. Civil Eng. Waterways, Port, Coastal Ocean Div.,* **102,** 265–283.

Rogers, E., T. L. Black, D. G. Deaven, G. J. DiMego, Q. Zhao, M. Baldwin, N. W. Junker, and Y. Lin, 1996: Changes to the operational ''early'' Eta analysis/forecast system at the National Centers for Environmental Prediction. *Wea. Forecasting,* **11,** 391–413.

Schmalz, R. A., 1996: Southern boundary experimental forecasts with the NOAA East Coast ocean model. *Proc. Fourth Int. Conf. Estuarine and Coastal Modeling,* San Diego, CA, American Society of Civil Engineers, 442–453.

——, 1998: Design of a nowcast/forecast system for Galveston Bay. Preprints, *Second Conf. on Coastal Atmospheric and Oceanic Prediction and Processes,* Phoenix, AZ, Amer. Meteor. Soc., 15–22.

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

——, and D. L. Sellers, 1980: Computerized bathymetry and shorelines of the Great Lakes. NOAA Data Report ERL GLERL-16, Great Lakes Environmental Research Laboratory, 13 pp. [NTIS PB80-218308.]

——, and J. A. Morton, 1984: Estimation of overlake wind speed from overland wind speed: A comparison of three methods. *J. Great Lakes Res.,* **10,** 68–72.

——, 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 Pollut. Res. J. Canada,* **29,** 203–220.

——, and ——, 1995: Operational three-dimensional circulation modeling in the Great Lakes. *Computer Modeling of Seas and Coastal Regions II,* C. A. Brebbia, L. Traversoni, and L. C. Wrobel, Eds., Computational Mechanics, Inc., 387–395.

——, and ——, 1996: GLCFS—A coastal forecasting system for the Great Lakes. Preprints, *Conf. on Coastal Oceanic and Atmospheric Prediction,* Atlanta, GA, Amer. Meteor. Soc., 9–14.

——, G. A. Leshkevich, and G. C. Muhr, 1992: Satellite measurements of surface water temperature in the Great Lakes: Great Lakes Coastwatch. *J. Great Lakes Res.,* **18,** 247–258.

Wei, E. J., and C. L. Sun, 1998: Development of a New York/New Jersey Harbor water level and current nowcaste/forecast system. Preprints, *Second Conf. on Coastal Atmospheric and Oceanic Prediction and Processes,* Phoenix, AZ, Amer. Meteor. Soc., 11–14.

Yen, C.-C. J., J. G. W. Kelley, and K. W. Bedford, 1994: Daily procedure for GLFS nowcasts. *Proc. 1994 Hydraulic Engineering Conf.,* Buffalo, NY, American Society of Civil Engineers, 202–205.