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Hydrodynamic modeling for the 1998 Lake Michigan coastal turbidity plume event

Dmitry Beletsky[1], David J. Schwab[2], Michael J. McCormick[2],
Gerald S. Miller[2], James H. Saylor[2], and Paul J. Roebber[3]

Abstract

A three-dimensional primitive equation numerical ocean model, the Princeton model of Blumberg and Mellor (1987), was applied to Lake Michigan to simulate hydrodynamic conditions during the 1998 coastal turbidity plume event. A massive turbidity plume in southern Lake Michigan was caused by a strong storm with northerly winds up to 17 m/s during this period. The hydrodynamic model of Lake Michigan has 20 vertical levells, and a uniform horizontal grid size of 2 km. The model is driven with surface momentum flux derived from observed meteorological conditions at 12 land stations in March 1998 and also with surface winds calculated using the mesoscale meteorological model MM5 (Dudhia, 1993) on a 6 km grid. Current observations from 11 subsurface moorings showed that while the model was able to qualitatively simulate wind-driven currents, it underestimated current speeds during strong wind events and in particular an onshore-offshore component of the flow in the area of observations. This may be due at least in part to the significant decrease of modeled current speeds with depth during strong wind events while observed currents showed almost no vertical shear. Hydrodynamic model results using MM5 winds as the forcing function were slightly better than results which were based on objectively analyzed winds.

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[1] Department of Naval Architecture and Marine Engineering, University of Michigan; Cooperative Institute for Limnology and Ecosystems Research/NOAA GLERL and University of Michigan, Ann Arbor, MI, 48105-2845

[2] NOAA Great Lakes Environmental Research Laboratory, Ann Arbor, MI, 48105-2845

[3] Department of Mathematical Sciences, University of Wisconsin-Milwaukee, Milwaukee, WI, 53201

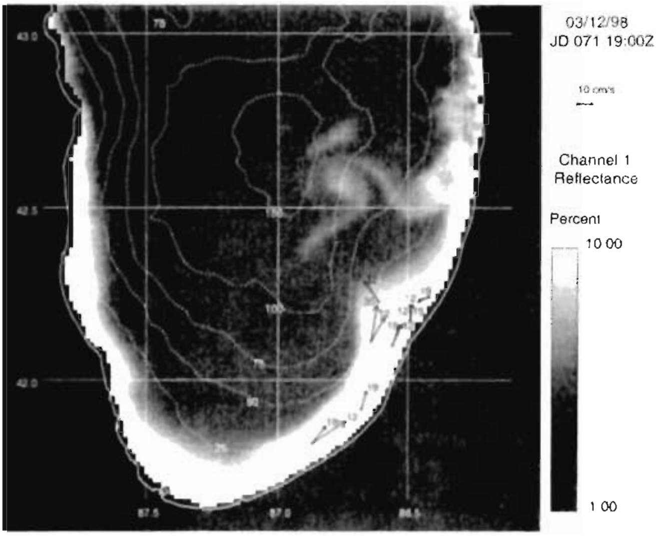


Figure 1. Satellite measurements of surface reflectance in southern Lake Michigan with currents at various depths observed at 1900 GMT, 3/12/98.

Introduction

Satellite observations of surface reflectivity in Lake Michigan have revealed a recurrent turbidity plume (Eadie et al., 1996). A 10 km wide plume of resuspended material extending over 100 km along the southern shore of the lake was first observed in satellite imagery by Mortimer (1988), and has since been observed every spring since 1992, when satellite imagery for the Great Lakes region first became available on a routine basis. The resuspension plume of March 1998 was one of the largest events of record. Satellite observations (Fig.1) reveal a well developed plume extending over 300 km of coastline from

Milwaukee, WI to Muskegon, MI with several dominant offshore features originating from the southeastern shoreline. The plume originated around March 10 following several days of intense storms that produced 17 m/s northerly winds and generated waves in the basin over 6 m high (Schwab et al., 2000). Our current understanding is that the initiation of the plume is caused by a major storm with strong northerly winds generating large waves in southern Lake Michigan. The plume appears along the entire southern coastline of the lake. It occasionally veers offshore along the eastern shore of the lake, coincidentally near the areas of highest measured long-term sediment accumulation in the lake.

The recurrent turbidity plume in southern Lake Michigan and associated nearshore-offshore water mass and material exchange is an object of intense study within a multidisciplinary research program called EEGLE (Episodic Events-Great Lakes Experiment) (http://www.glerl.noaa.gov/eegle). The program is jointly sponsored by NOAA (National Oceanic and Atmospheric Administration) and NSF (National Science Foundation). One of the goals of EEGLE is to create a suite of physical and biological models to understand the nearshore-offshore transport of biogeochemically important materials. Currently, a linked system of wave, circulation and sediment transport models is being developed at NOAA Great Lakes Environmental Research Laboratory (GLERL). Preliminary results of application of that system to the March 1998 resuspension event were described in Schwab et al. (2000). In this paper, we will investigate the dynamics of wind-induced circulation and offshore transport in March 1998 in more detail by using current observations and analyzing sensitivity of hydrodynamic model results to meteorological data. We will focus mainly on the large storm of 9-12 March 1998 because the most significant offshore transport occurred during that period.

Hydrodynamic model

A 3-dimensional circulation model for the Great Lakes (Schwab and Beletsky, 1998) is used to calculate lake circulation. The model is based on the Princeton Ocean Model (Blumberg and Mellor, 1987) and is a nonlinear, fully three-dimensional, primitive equation, finite difference model. The model is hydrostatic and Boussinesq so that density variations are neglected except where they are multiplied by gravity in the buoyancy force. The model uses time-dependent wind stress and heat flux forcing at the surface, zero heat flux at the bottom, free-slip lateral boundary conditions, and quadratic bottom friction. The drag coefficient in the bottom friction formulation is spatially variable. It is calculated based on the assumption of logarithmic bottom boundary layer using constant bottom roughness of 1 cm. Horizontal diffusion is calculated with a Smagorinsky eddy parameterization (with a multiplier of 0.1) to give a greater mixing coefficient near strong horizontal gradients.

The Princeton Ocean Model employs a terrain following vertical coordinate system (σ-coordinate). The equations are written in flux form, and the finite differencing is done on an Arakawa-C grid using a control volume formalism. The finite differencing scheme is second order and centered in space and time (leapfrog). The model includes the Mellor and Yamada (1982) level 2.5 turbulence closure parameterization for calculating the vertical mixing coefficients for momentum and heat from the variables describing the flow regime.

The hydrodynamic model of Lake Michigan has 20 vertical levels and a uniform horizontal grid size of 2 km. Model bathymetry is based on the new, high resolution bathymetric data (NGDC, 1996).

Meteorological data 1: objectively analyzed

In order to calculate momentum flux fields over the water surface for the lake circulation model, it is necessary to estimate wind and air temperature fields at model grid points. Meteorological data were obtained from 12 National Weather Service stations around Lake Michigan (Fig. 2). These observations form the basis for generating gridded overwater wind and air temperature fields. Because overland wind speeds generally underestimate overwater values we apply the empirical overland-overlake wind speed adjustment from Resio and Vincent (1977). (See Beletsky and Schwab (1998), and Schwab and Beletsky (1998) for more detail.)

In order to interpolate meteorological data observed at irregular points in time and space to a regular grid so that it can be used for input into numerical circulation model, some type of objective analysis technique must be used. For this study we first used the nearest-neighbor technique (NRST), with the addition of a spatial smoothing step (with a specified smoothing radius). In the NRST technique, we also consider observations from up to three hours before the interpolation time to three hours after the interpolation time. In the nearest-neighbor distance calculations, the distance from a grid point to these observation points is increased by the product of the time difference multiplied by a scaling speed. The interpolation scaling speed is taken as 10 km/hr. Interpolation smoothing distance is 30 km. We found that the NRST technique provided results comparable to results from the inverse power law or negative exponential weighing functions discussed in Schwab (1989).

While nearest neighbor technique was used earlier in the Lake Michigan Mass Balance Study models (Beletsky and Schwab, 1998) and Great Lakes Forecasting System (GLFS) models (http://superior.eng.ohio-state.edu), the GLFS models have subsequently adopted a new geometrically-based technique that appears to provide a more realistic representation of the 2-d wind field than NRST techniques. The approach is called 'Natural Neighbor' interpolation (NTRL) and is based on the Delaunay triangulation of the station observation network (Sibson, 1981, Watson, 1994). According to Sambridge et al. (1995), the method has the following useful properties:

1) the original function values are recovered exactly at the reference points

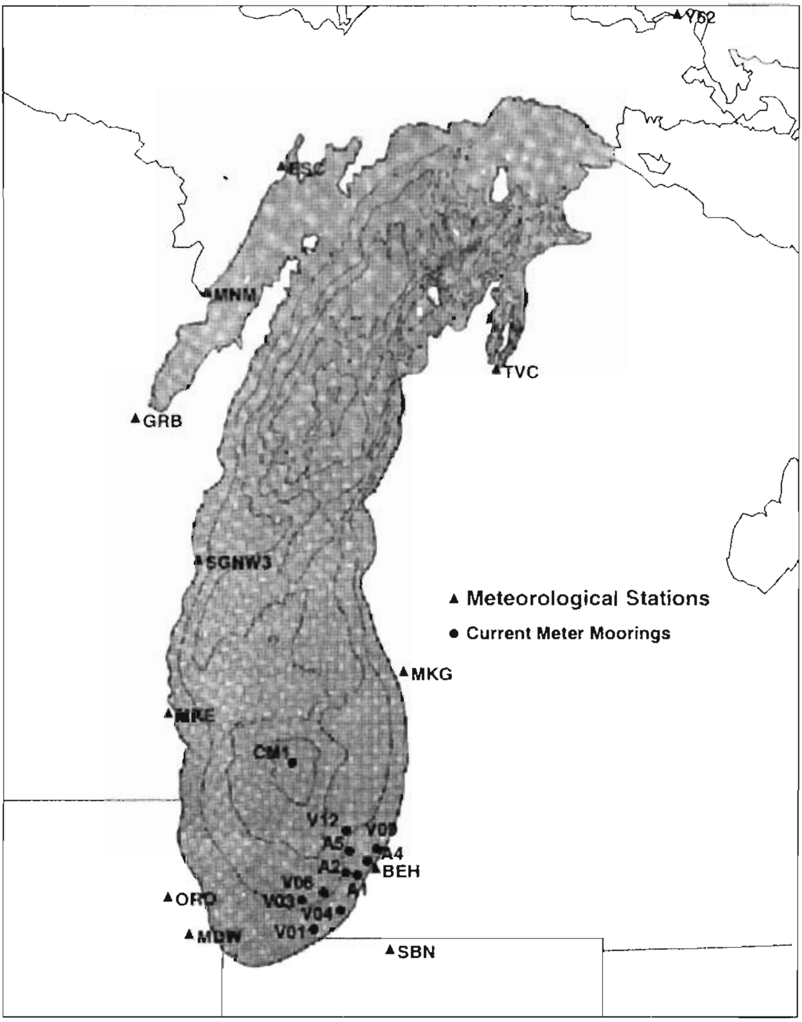


Figure 2. Observations network and 2 km computational grid.

2) the interpolation is entirely local (every point is only influenced by its natural neighbor nodes)
3) the derivatives of the interpolated function are continuous everywhere except at the reference points.
Points 1) and 2) are especially important for the type of network we deal with in the Great Lakes, i.e., not every station is available at every hour and some stations (ships) appear only intermittently. This technique is also advantageous for interpolating data fields for which the spatial autocorrelation function is not well known, such as hourly wind fields.

In this paper we will use both NRST and NTRL interpolation techniques in order to find out which method gives currents that match observations better.

Meteorological data 2: MM5 model based

In addition to objectively analyzed data, we also used meteorological model data as the forcing function in order to compare results obtained by various methods. In order to generate atmospheric forcing fields that take full advantage of the advanced capabilities of modern numerical weather prediction, the Penn State/NCAR 5th generation mesoscale model (MM5) was run for the period 7-10 March 1998. In the hydrodynamic model run, NRST winds during that 4-day period were replaced with MM5 winds. A triply nested domain configuration (54/18/6 km) with two-way interactions (such that exterior domains feel the influence of interior domains and vice versa) was employed, with the innermost nest providing 6 km grid point resolution in an area centered on Lake Michigan. Model initialization and lateral boundary conditions were determined as follows. First guess fields of atmospheric variables (wind, temperature, moisture) were obtained from the National Centers for Environmental Prediction (NCEP) historical archives of global (2.5° latitude by 2.5° longitude) mandatory-level analyses and were then adjusted using a Cressman-type objective analysis of surface and rawinsonde data for all stations within or near the grid domain. These analyses provided boundary conditions on the outermost grid domain throughout the course of the integrations and were used in the four dimensional data assimilation (FDDA) procedure described below.

Vertical sigma levels were arranged such that the model output was available on a total of 23 levels, with a relative concentration at the lowest levels in order to resolve planetary boundary layer structure. The planetary boundary layer was modeled using a high-resolution Blackadar scheme coupled with a 5-layer soil model. Physiographic and land use patterns were back interpolated from a high-resolution data set to the model grids.

The surface and upper-air meteorological analyses described above were incorporated into the simulation using the FDDA technique known as Newtonian Relaxation or nudging. In this technique, an analysis dataset that provides time continuity and dynamic coupling among the various model fields is generated by weakly forcing the model solutions toward three-dimensional gridded analyses of wind, temperature and mixing ratio. In this way, the model solution remains "bounded" by the observations and the horizontal resolution of the observations is effectively enhanced by the added time-dimension.

Current meter data

Current meters were deployed along the east coast of southern Lake Michigan in order to capture nearshore-offshore flow in the vicinity of Benton Harbor, MI (BEH in Fig. 2) during significant northerly wind events. The 1997-98 installation was carried out during a pilot year of the EEGLE program and only 11 moorings were deployed. The 4 central moorings (A1, A2, A4, and A5) were equipped with Acoustic Doppler Current Profilers (ADCP) deployed at 18 (A1 and A4) and 38 m (A2 and A5) depths while the remaining moorings (V01, V03, V04, V06, V09 and V12) deployed at 20 and 60 m depths had 2 Vector Averaging Current Meters (VACM) each at 12m and at 1 m above the bottom (Fig. 1). Observations lasted from October 1997 to June 1998. The mid-lake station (CM1) is a part of an ongoing GLERL monitoring program and had 3 VACM's at 20, 115 and 152 m.

Base model run and comparison with observations

The base model run employs NRST data, and all other runs (NTRL and MM5 data based) will be compared against it. Hourly meteorological data from the 12 stations shown in Fig. 2 were obtained for the period 1-30 March, 1998. Overwater wind and air temperature fields were interpolated to the 2 km grid. Time series of wind speed and direction from a point in the middle of the southern basin (near station CM1 in Fig. 2) are shown in Fig. 3. There are four major wind events in March, two storms with northerly winds (on the 9th and 21st) and two with southerly winds (on the 13th and 27th). In early spring, the lake is thermally homogeneous and density gradients are negligible. Therefore, the circulation model was applied in a barotropic mode with uniform (2°C) water temperature.

Observation data and model results showed that circulation in Lake Michigan is highly episodic since it is almost entirely wind-driven in early spring. The characteristic wind-driven circulation pattern in a lake consists of two counter-rotating gyres, a counterclockwise-rotating (cyclonic) gyre to the right of the wind and a clockwise-rotating (anticyclonic) gyre to the left (Bennett, 1974). The gyres are separated by a convergence zone along the downwind shore with resulting offshore flow and a divergence zone along the upwind shore with onshore flow. This two-gyre circulation pattern was clearly seen during the two northerly wind events in March in southern Lake Michigan. The computed circulation is illustrated through the use of a snapshot of a computer animation which gives an indication of current magnitude and direction over the previous 48

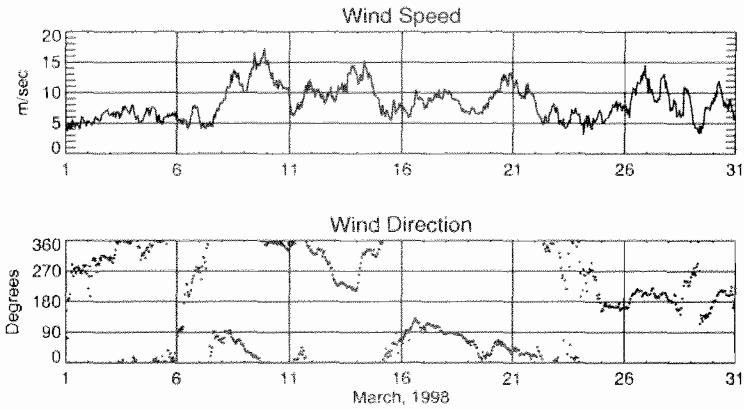
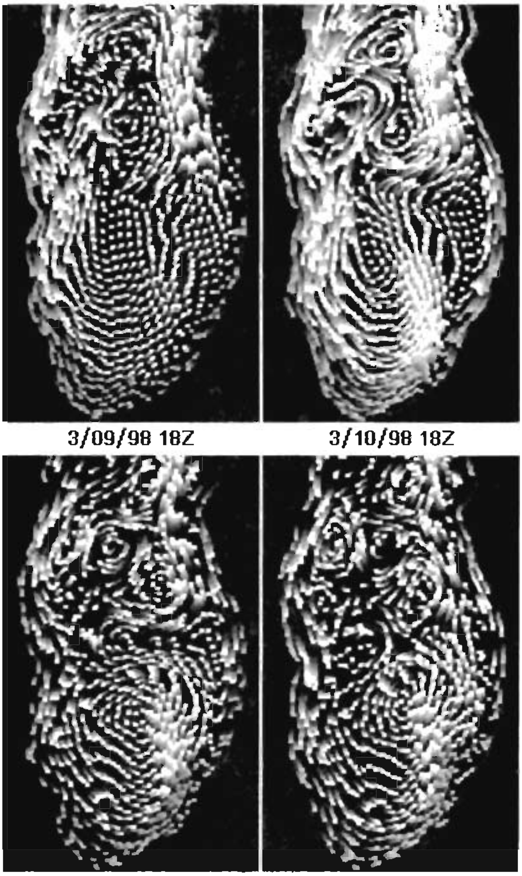


Figure 3. Time series of interpolated wind near station CM1 in southern Lake Michigan for 1-30 March, 1998.

hours (Schwab et al., 2000). The animation depicts the trajectories of passive tracer particles which were introduced into the computed depth-averaged velocity field on 1 March and are traced through the 30 day computational period. The first storm with northerly winds up to 17 m/s on March 9 caused strong along shore southerly currents that converged south of BEH and caused massive offshore flow lasting several days (Fig. 4).

The model qualitatively reproduces the observed large-scale circulation pattern (Fig. 5) although the offshore flow in the model is located somewhat south of the observed convergence zone. This may be explained by the sensitivity of the large-scale lake circulation pattern to the direction and vorticity of the wind field. We were not able to reproduce the spectacular spiral eddy observed in the middle of the lake on March 12 (Fig. 1) which is probably either a result of meandering of the strong offshore jet or direct atmospheric forcing. The last argument seems to be more convincing since there is a strong evidence based on National Weather Service radar data that on March 11 a mesoscale atmospheric vortex was present in southern Lake Michigan. That vortex is almost missing in objectively analyzed winds because of the lack of overlake observations. Monthly mean modeled currents match observed currents very accurately (Fig. 6).

For the purposes of comparison, modeled and observed currents were decomposed into longshore and onshore components. Comparison at nearshore stations at southern (V01) and northern (V09) boundaries of the array of moorings



3/09/98 18Z

3/10/98 18Z

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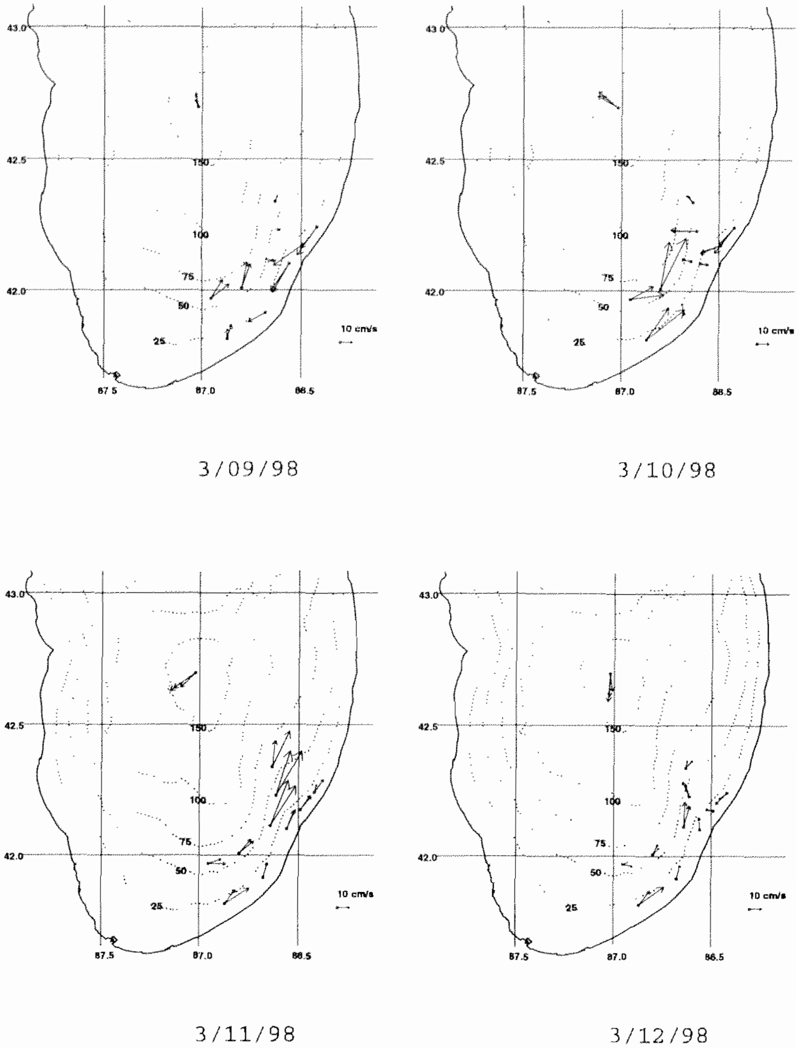
Figure 4. Modeled circulation in southern Lake Michigan, March 9-12 (see text for more explanation).



3/09/98

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Figure 5. Observed daily averaged currents on March 9-12. Currents experience predominantly counterclockwise rotation toward the bottom.

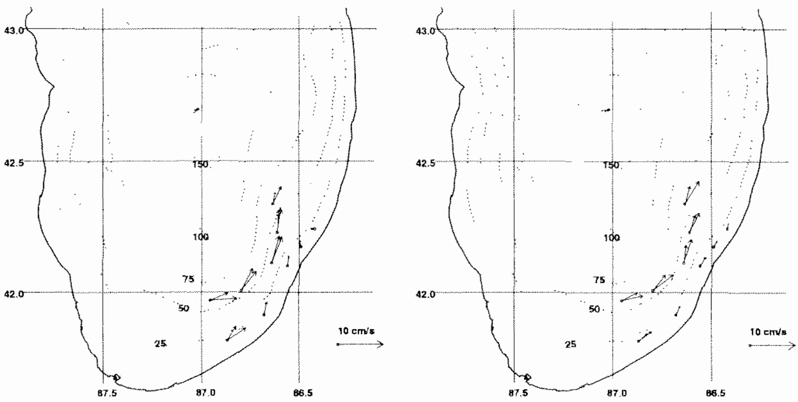


Figure 6. Observed (left) and modeled (right) monthly averaged currents. Currents experience predominantly counterclockwise rotation toward the bottom.

shows good prediction by the model of an offshore flow at 12 m depth but significant underestimation of the longshore flow (Fig. 7). ADCP data (station A1) provided valuable information on vertical current distributions. Observations during March 9-14 (Fig. 8a) showed strong southerly longshore currents (up to 45 cm/s) around March 10 followed by current reversal on March 11 (with northerly currents up to 35 cm/s) and persisting northerly currents for the rest of the period. Model longshore currents also peaked on March 10 at this location although reversed currents were not as strong (up to 10 cm/s). There is also an increase in model current speed around March 14 not seen in observations. The onshore component was also calculated qualitatively correctly (Fig. 8b) but its magnitude was significantly less than in observations. It is interesting to note that while observed currents posess almost no vertical shear, modeled currents showed significant reduction (almost twice) in speed with depth during strong wind events. This demands further investigation of the influence of both bottom friction and vertical turbulent viscosity on model results.

A statistical comparison of modeled and observed currents is presented in the form of the Fourier norms (rms difference). The Fourier norm of time-series of observed current vectors $\mathbf{v}_0$ and computed $\mathbf{v}_c$ is defined as

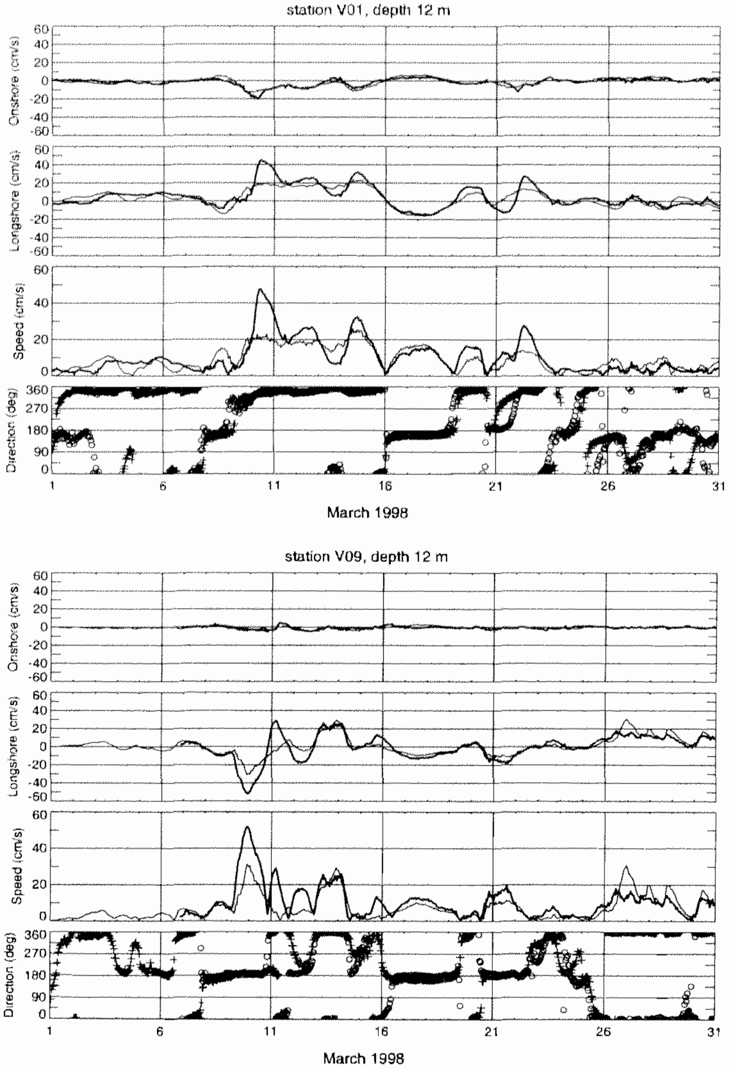
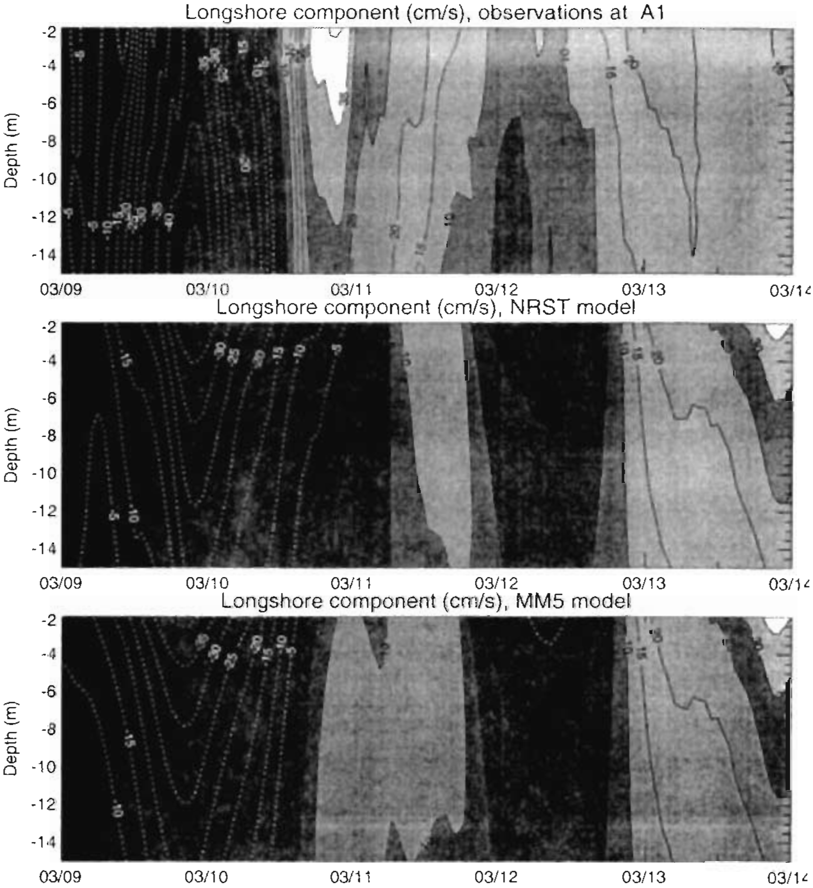


Figure 7. Time-series of modeled (thin line, crosses) versus observed (thick line, open circles) currents at stations V01 and V09.



Longshore component (cm/s), observations at A1

Longshore component (cm/s), NRST model

Longshore component (cm/s), MM5 model

Figure 8a. Time-series of modeled versus observed longshore currents at station A1

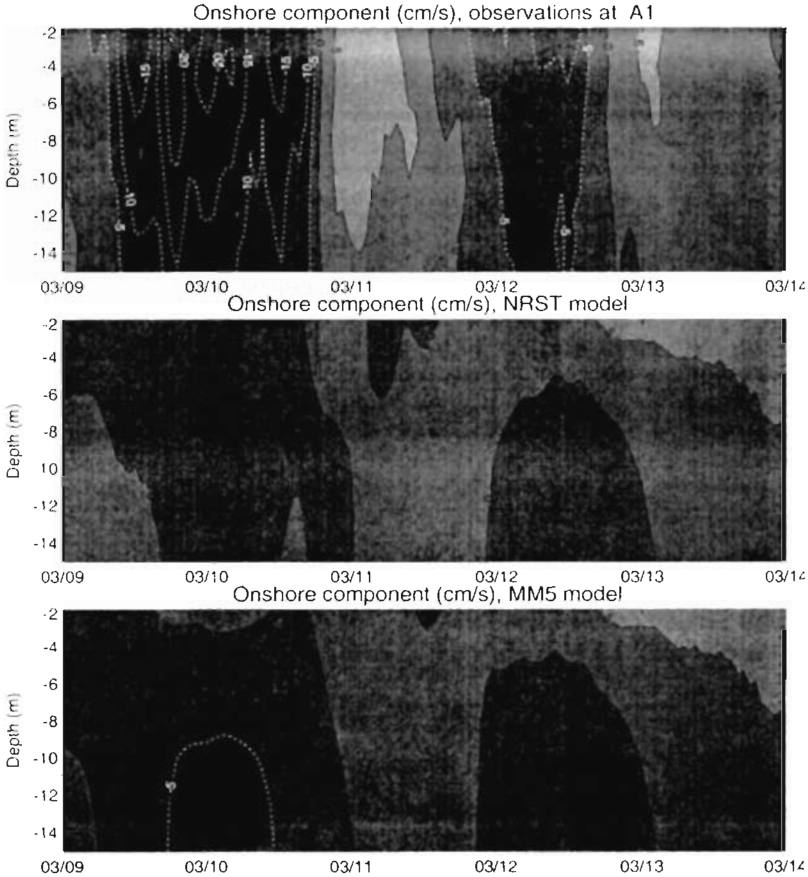


Figure 8b. Time-series of modeled versus observed onshore currents at station A1

$$\|v_o, v_c\| = \left(\frac{1}{M} \sum_{t=\Delta t}^{M\Delta t} |v_o - v_c|^2 \right)^{1/2}$$

We use a normalized Fourier norm:

$$F_n = \|\mathbf{v}_c, \mathbf{v}_o\| / \|\mathbf{v}_o, \mathbf{0}\|$$

In the case of perfect prediction $F_n=0$. In the case $0 < F_n < 1$, model predictions are better than no prediction at all (zero currents). Using F_n not only allows us to use one number for characterization of model skills in predicting vector entities, but also to compare our model results more objectively with previous model results. For example, in one of the earlier modeling exercises, Schwab (1983) calculated $0.79 < F_n < 1.01$ for a comparable barotropic simulation of Lake Michigan circulation on the 5 km grid. Our numbers show significant improvement over this result, from 0.45 to 0.76 (Table 1).

	F_n, range	F_n, mean	CC longshore	CC onshore
NRST	0.45-0.76	0.64	0.77	0.79
NTRL	0.41-0.76	0.63	0.80	0.82
MM5	0.43-0.74	0.58	0.81	0.84

Table 1. Statistical comparison of March 8-10 observed and computed currents (Fourier norm and correlation coefficient).

Sensitivity to meteorological data

Hydrodynamic model runs with NTRL winds yielded currents similar to NRST runs (Table 1 presents only 3-day comparison results but NRST and NTRL numbers were similar for the whole 30-day long comparison). Therefore, NTRL technique can be used now as a reliable alternative to NRST in the EEGLE study (there is evidence that it provides better wind wave predictions with models developed at GLERL). On the other hand, the MM5 data showed some improvement in model results (Table 1). Figure 8, for example, shows better timing of the nearshore current reversal on March 10-11 and stronger longshore and onshore currents during wind events. The spiral eddy on March 12 is absent in both NTRL and MM5-based results (MM5 runs were recently extended to cover

11-12 March period but showed no indication of the atmospheric vortex).

Although MM5 winds yielded slightly better currents than ones calculated with objectively analyzed winds, there is still room for improvement. Unfortunately, accurate modeling of over-lake atmospheric dynamics can present significant challenges during the early spring period. Analysis shows that there were two important events during the March 9-12 episode: strong winds on March 9-10 that caused the initial sediment resuspension event, and the mesoscale atmospheric vortex that apparently formed on March 11. The first event is a strong cold front with air temperature dropping from 0°C to -10°C. With water temperatures around 2°C this should cause significant instability of atmospheric boundary layer and thus increased wind stress. Unfortunately, as was mentioned earlier, there were no overlake wind observations in southern Lake Michigan during that period. It is possible that the FDDA in the MM5 results is driving the winds towards a low bias in magnitude (since it is based on the available observations, which are practically all land observations) during the storm. Problems with the second event (mesoscale vortex) can be also caused by lack of over lake data. Currently, work is underway to improve MM5 results by experimenting with alternatives to FDDA and also incorporation of radar observations into MM5 runs.

Conclusions

The Princeton ocean model was applied to Lake Michigan to simulate hydrodynamic conditions during the 1998 coastal turbidity plume event. The model is driven with objectively analyzed winds (NRST and NTRL techniques) and also with surface winds from the meteorological model MM5. Comparison with observations showed that the model was able to qualitatively simulate wind-driven currents but underestimated current speeds during strong wind events and in particular the onshore-offshore component of the flow in the area of observations. This may be due at least in part to the significant decrease of modeled current speeds with depth during strong wind events while vertical shear was almost absent in observed currents. Model results with MM5 winds were slightly better than the ones that used objectively analyzed winds (NRST and NTRL). The difference between NRST and NTRL results was minimal. More experiments are underway to study the effects of wind field interpolation, grid resolution, and friction on hydrodynamics in Lake Michigan.

Acknowledgements

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