Hydrodynamic and Sediment Transport Modeling of March 1998 Resuspension Event in Lake Michigan

Dmitry Beletsky[1], David J. Schwab[2], Jing Lou[2], Michael J. McCormick[2], Gerald S. Miller[2], James H. Saylor[2], and Paul J. Roebber[3]
[1]University of Michigan
[2]NOAA/Great Lakes Environmental Research Laboratory
[3]University of Wisconsin-Milwaukee

Introduction

Satellite observations of surface reflections in Lake Michigan have revealed a recurrent turbidity plume observed every spring since 1992. The resuspension plume of March 1998 was one of the largest events of record (Fig. 1). 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.

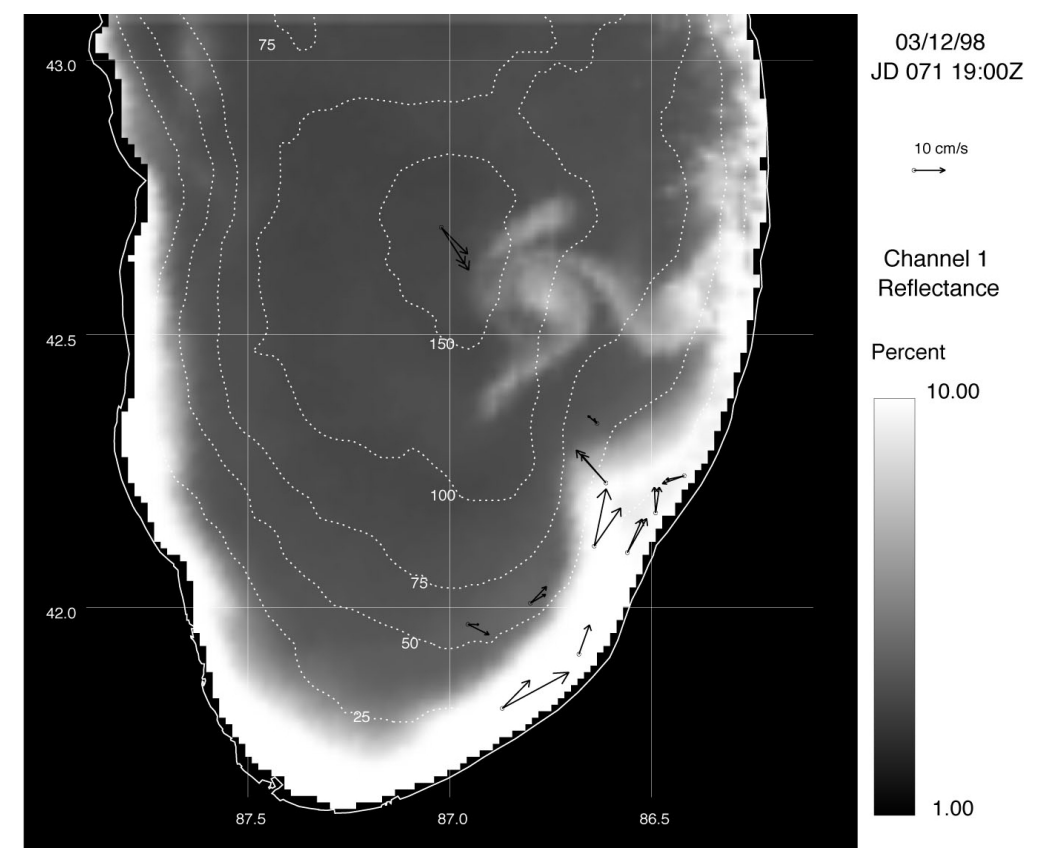

Figure 1. Satellite measurements of surface reflectance in southern Lake Michigan with observed currents.

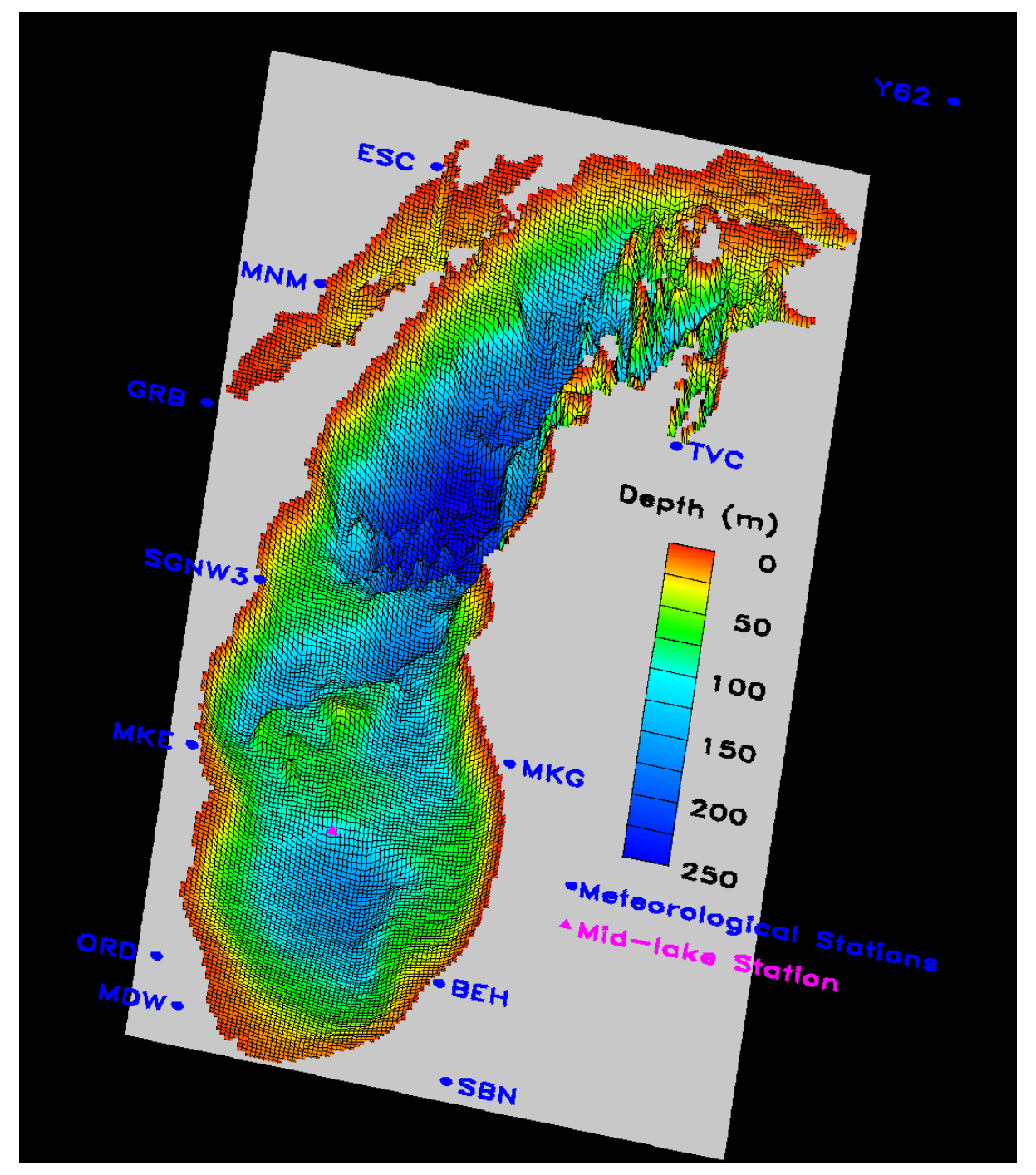

Figure 2. 2 km computational grid, meteorological stations around Lake Michigan, and location of mid-lake station in southern Lake Michigan.

Models

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. All models employ uniform horizontal 2 km grid (Fig.2).

Hydrodynamic model. A 3D 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 includes the Mellor and Yamada (1982) level 2.5 turbulence model. The hydrodynamic model of Lake Michigan has 20 vertical levels. The output from the lake circulation model is used to provide estimates of horizontal advection and bottom shear stress for the sediment transport model.

Wave model. The wave model is a 2D numerical parametric model based on the wave momentum conservation equation (Schwab et. al., 1984). The output from the wave model (wave height and wave period) is used to estimate bottom shear stress in the sediment transport model.

Sediment Transport Model. The suspended sediment transport model is a quasi-3D model based on an asymptotic solution of the convection-diffusion equation. The bottom shear stress is calculated by a bottom boundary layer model. The effect of nonlinear wave-current interaction on the bottom shear stress was obtained based on the concept of Grant and Madsen (1979).

Meteorological data

A preliminary test of the linked circulation -waves-sediment transport modeling system was carried out for the period 1-30 March, 1998. Meteorological data were obtained from 12 National Weather Service stations around Lake Michigan (Fig. 2). 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, the Penn State/NCAR 5th generation mesoscale model (MM5) (Dudhia, 1993) was run for the period 7-10 March 1998. A triply nested domain configuration (54/18/6 km) with two-way interactions was employed in MM5, with the innermost nest providing 6 km grid point resolution in an area centered on Lake Michigan.

Oceanographic 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 the pilot year of the EEGLE program and only 11 moorings were deployed (Fig. 3). 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. The mid-lake station (CM1) had 4 VACM's at 20, 55, 115 and 152 m.

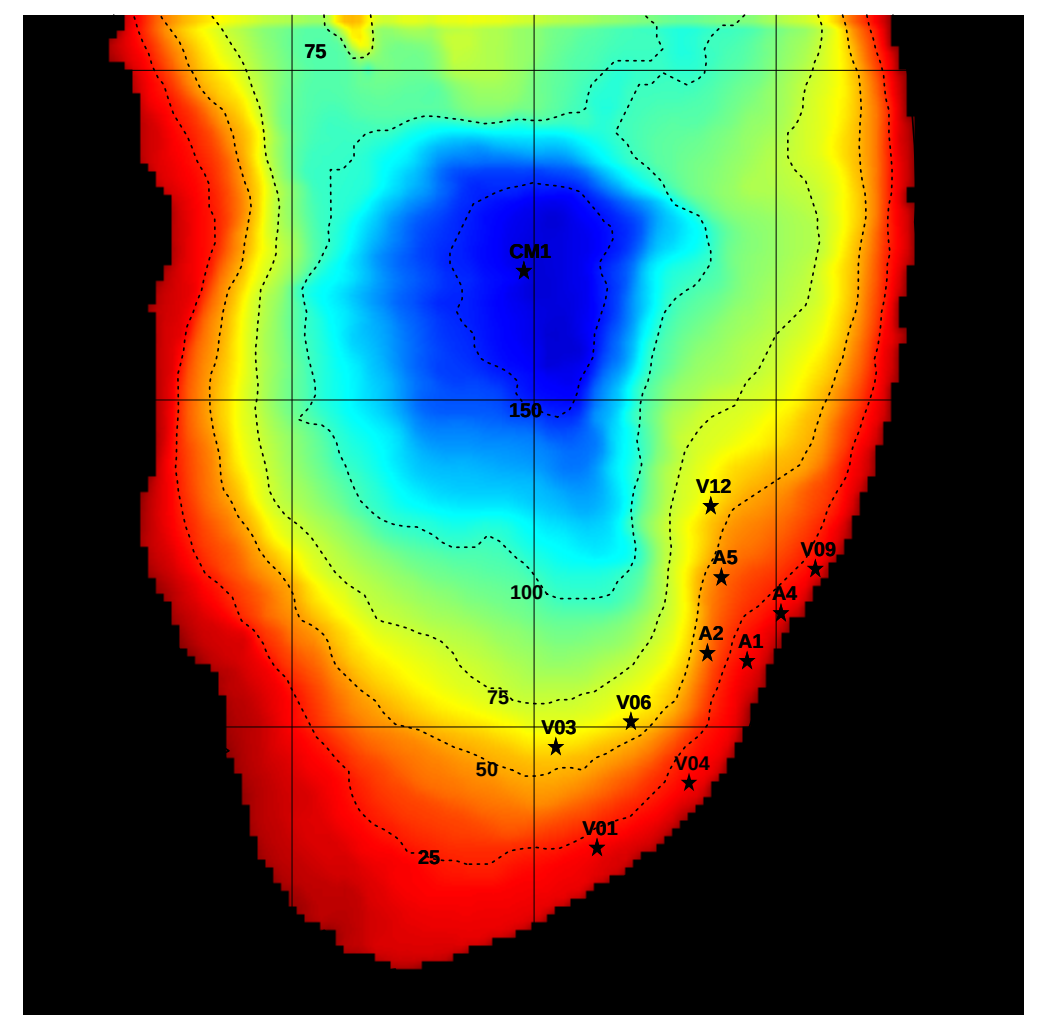

Figure 3. Current meter moorings in 1997-1998.

Results

Time series of wind speed and direction from a point in the middle of the southern basin (Fig. 2) are shown in Fig. 4. 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). Wave model results for wave height, period and direction at the same point are presented in Fig. 4. The largest wave heights (up to 5 m) in the southern basin occur during the storms with northerly winds which provide the longest overwater fetch distance. These waves caused significant sediment resuspension which is apparent in the satellite images shown in Fig.5.

Hydrodynamic 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 especially clearly seen during the two northerly wind events in March in southern Lake Michigan (Fig. 6). The first storm with northerly winds up to 17 m/s on March 9 caused strong along shore southerly currents that converged south of Benton Harbor, MI and caused massive offshore flow lasting several days.

The sediment transport model started from zero concentration over the whole lake. The dominant sediment particle size is assumed to be 15 microns, the settling velocity is set to 0.5 m/day, the critical bottom shear stress is 0.05 N/m^2, and the bottom of the lake is treated as an unlimited sediment source. Sediment concentration results showed (Fig. 7) that at least some suspended sediment was present during most days of March 1998. The strongest sediment resuspension mainly occurred in the southern lake and the shallow waters near the coastline. The two most significant sediment resuspension events were detected in the model results on 9-12 March and 20-22 March, which coincide with the strongest winds as shown in Fig. 4. Though the sediment transport model can depict the resuspension events reasonably well, it was not able to describe the detailed plume structure, particularly the spiral eddy in the central part of southern lake probably because of inaccuracies in the hydrodynamic model results.

Net erosion during storm events in March 1998 occurred mainly along the shoreline and deposition occurred offshore (Fig. 8). Overall, the deposition pattern during this event is similar to the long term sediment accumulation map shown in Figure 9. Both show an asymmetric pattern of sediment deposition, with maximum deposition occurring mainly in the eastern side of the lake in water depths of 50-100 m.

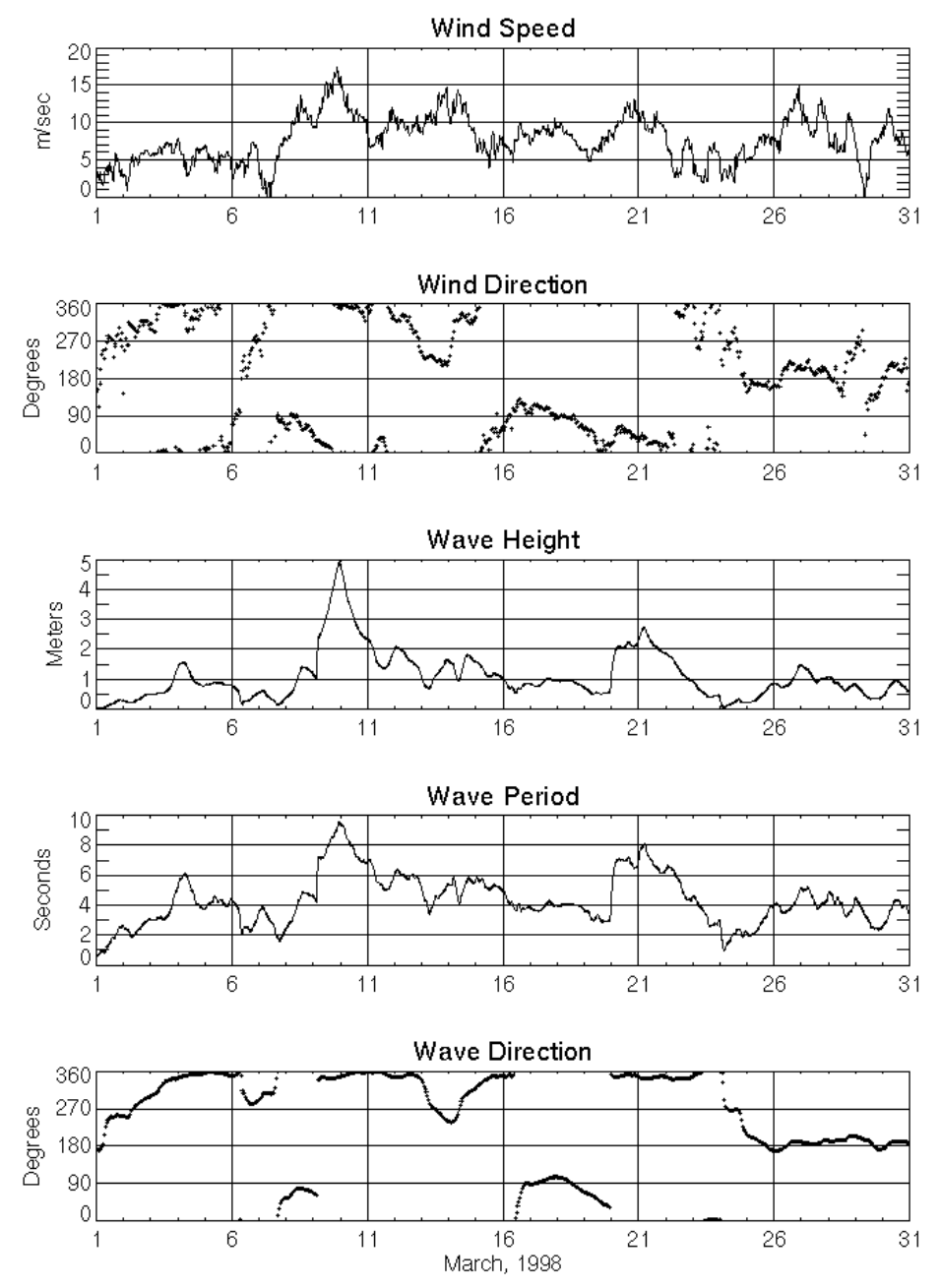

Figure 4. Time series of interpolated wind and modeled waves at a location in the center of southern Lake Michigan for 1-30 March, 1998.

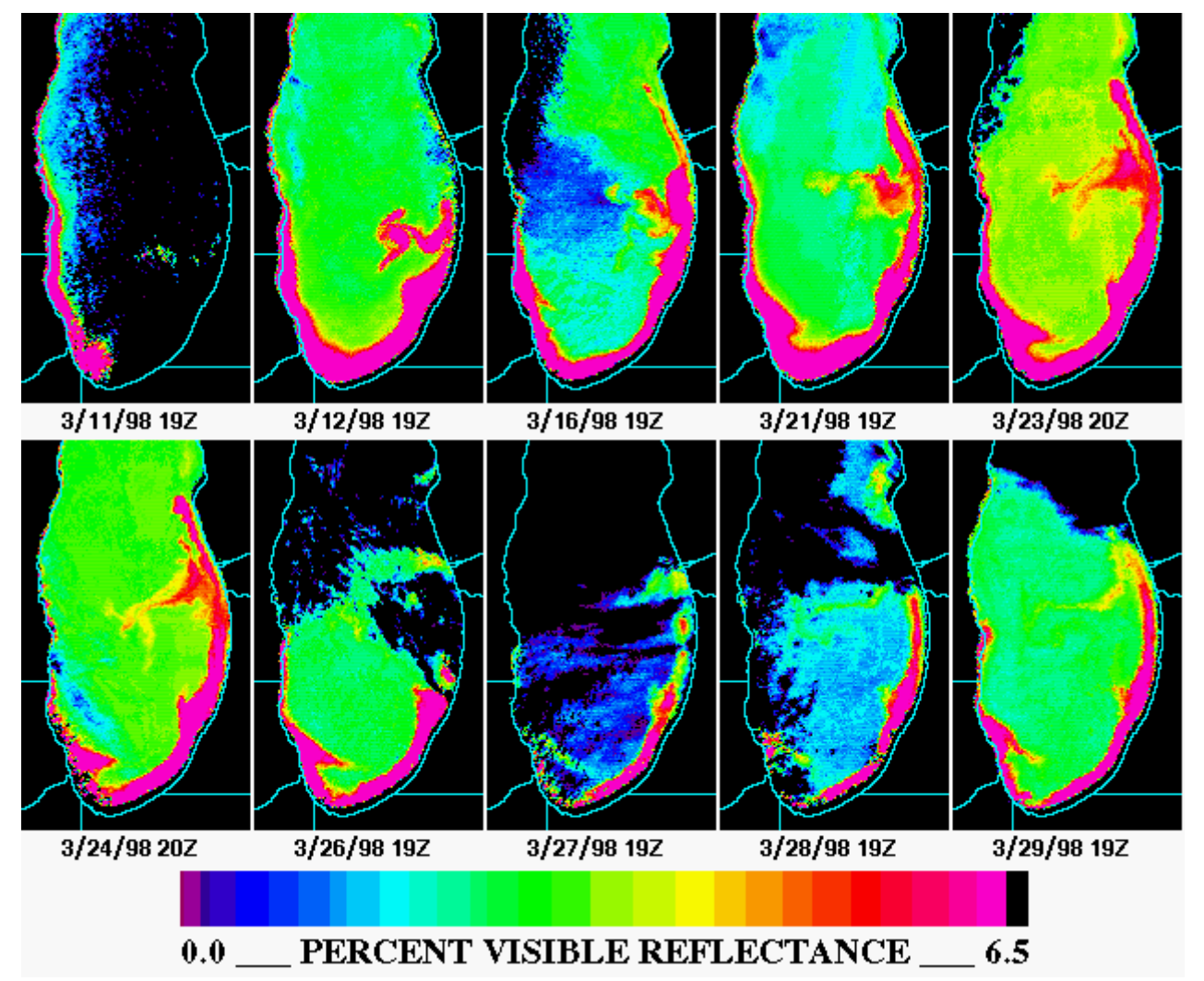

Figure 5. Satellite measurements of surface reflectance in southern Lake Michigan.

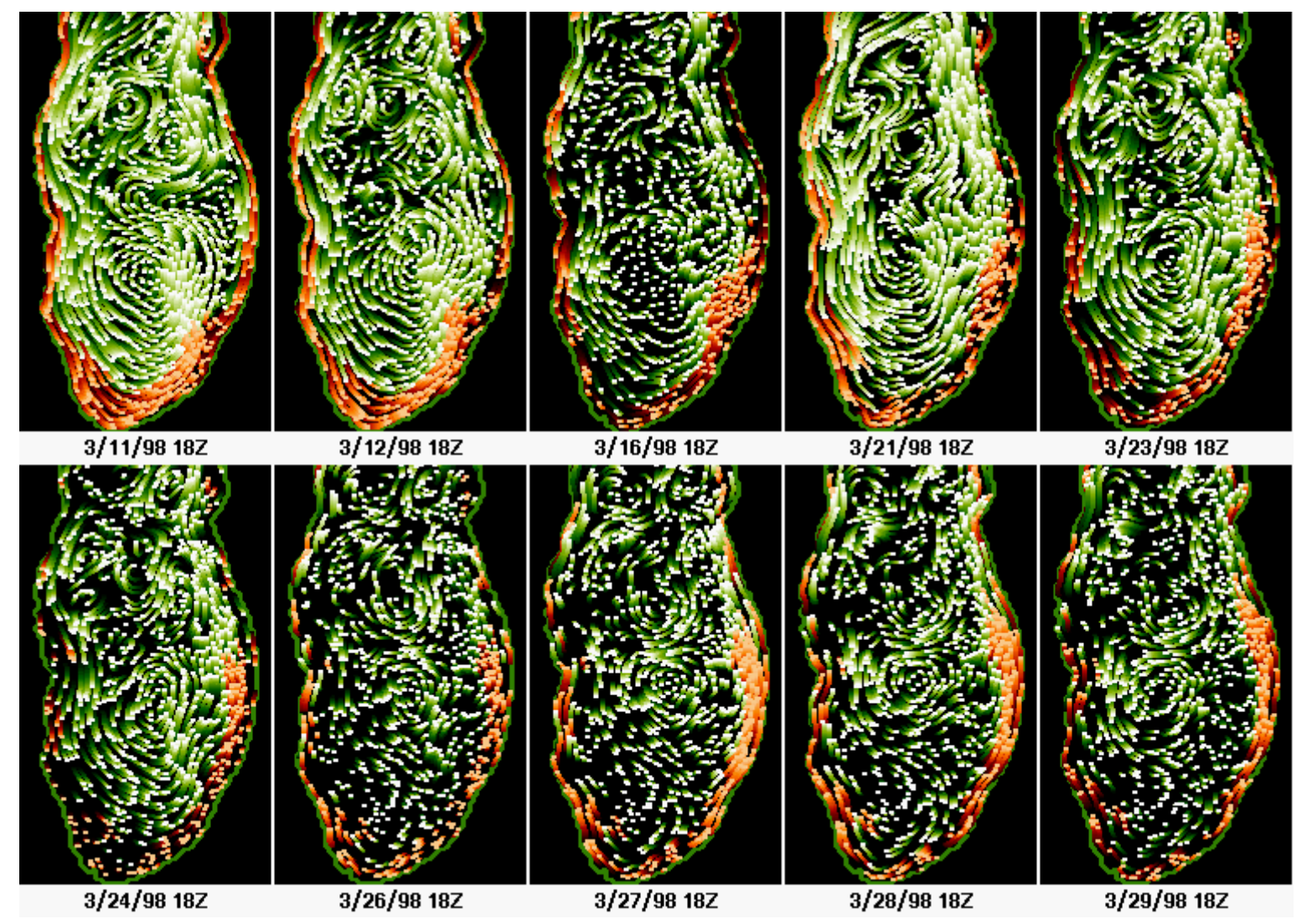

Figure 6. Snapshots of particle trajectory animation at times corresponding to satellite images in Figure 5.

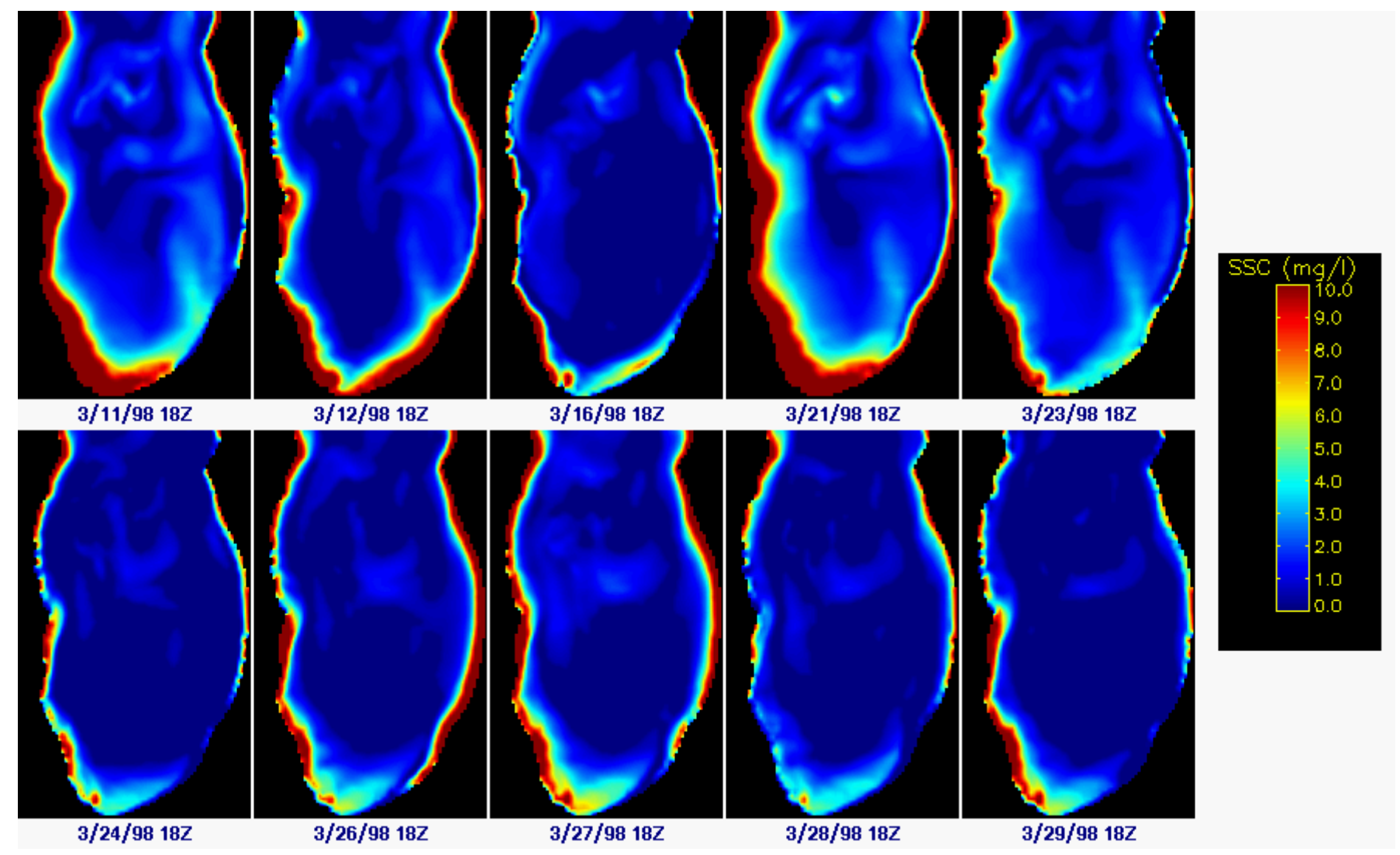

Figure 7. Snapshots of suspended sediment concentration at times corresponding to satellite images in Figure 5.

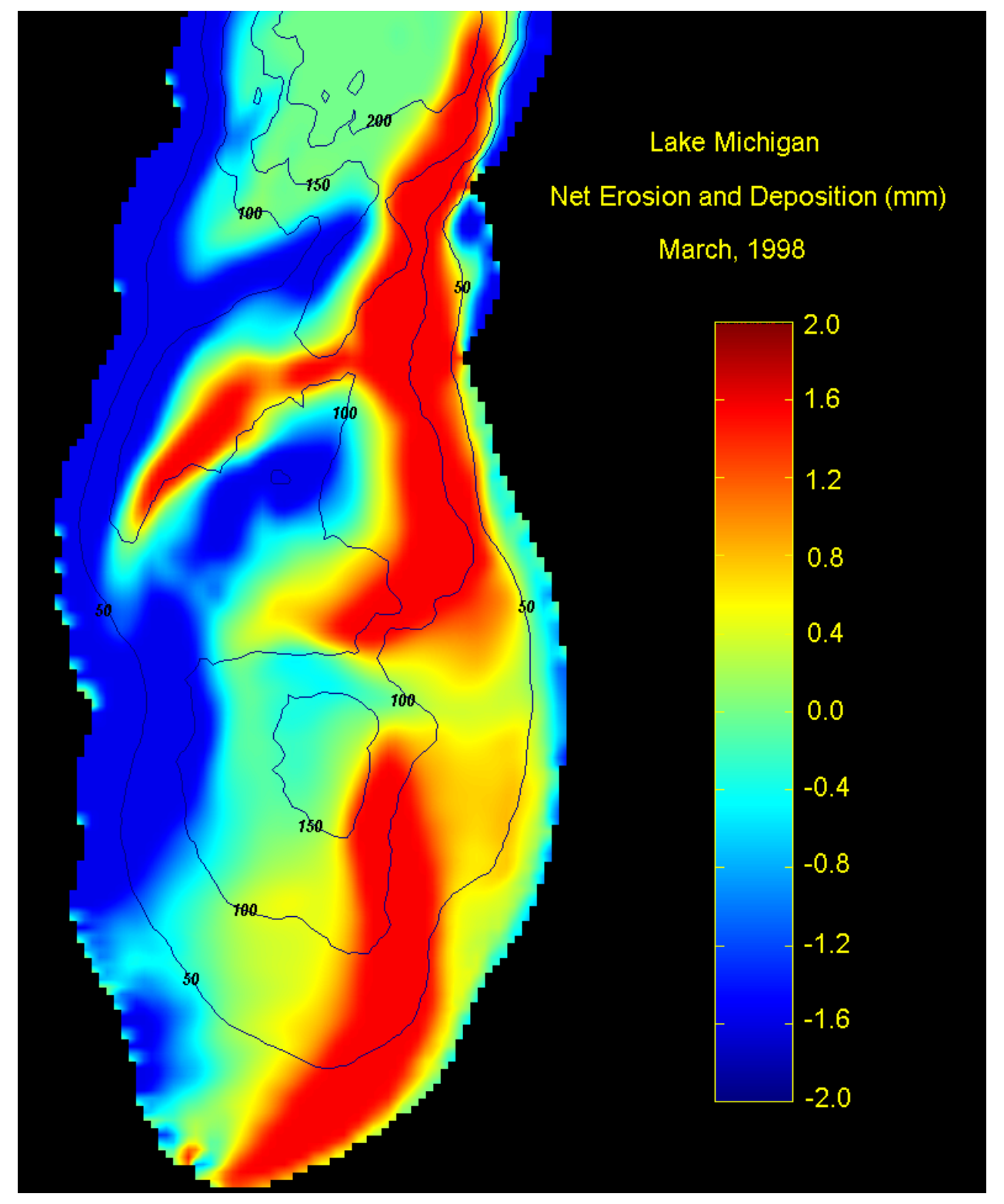

Figure 8. Net sediment erosion (blue) and deposition (red) in March 1998 from the sediment transport model.

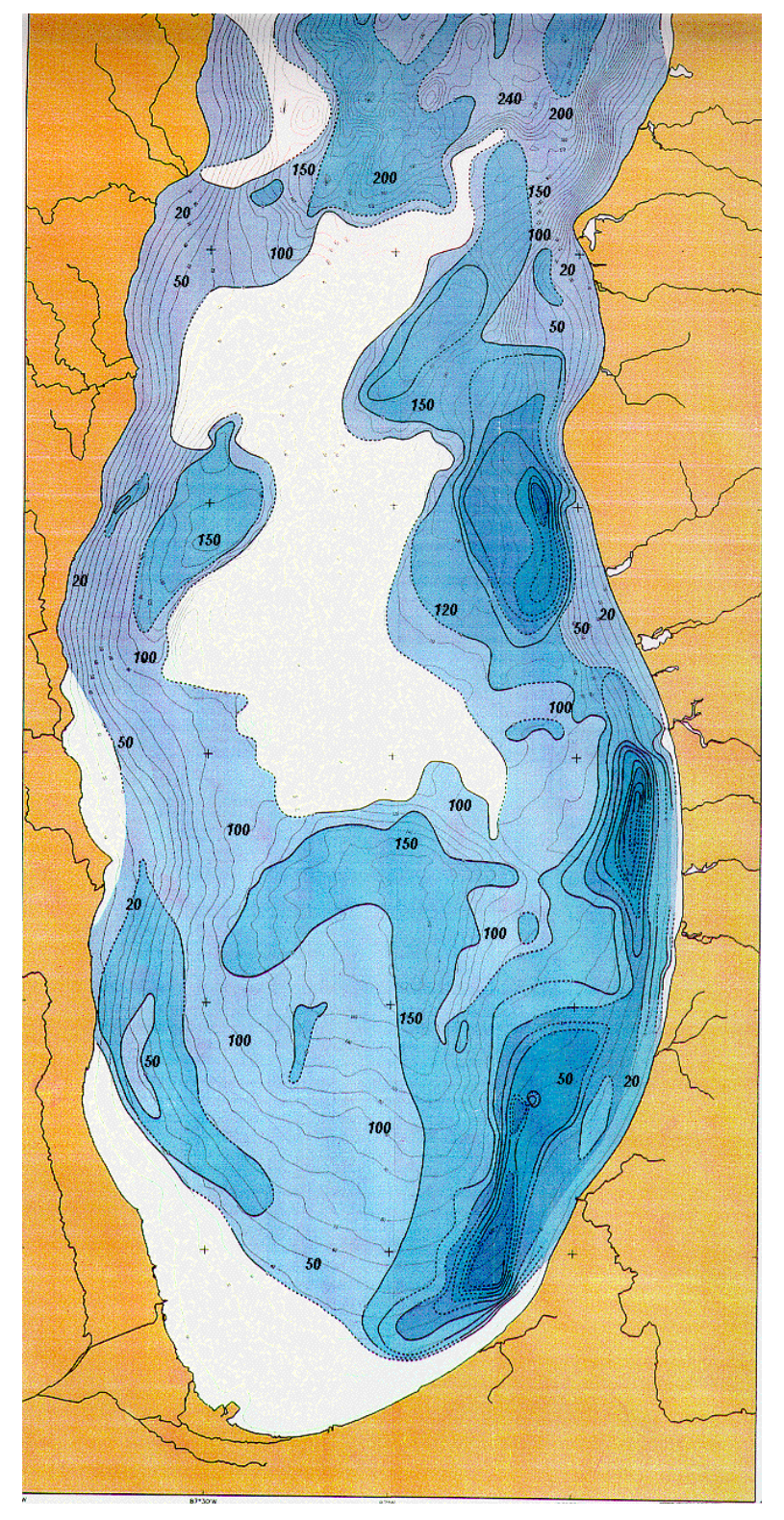

Figure 9. Long term sediment accumulation in southern Lake Michigan (Foster and Colman, 1992). The five ranges of sediment thickness depicted in the map are (from lightest to darkest): 1-2 m, 2-6 m, 6-10 m, 10-14 m, and > 14 m.

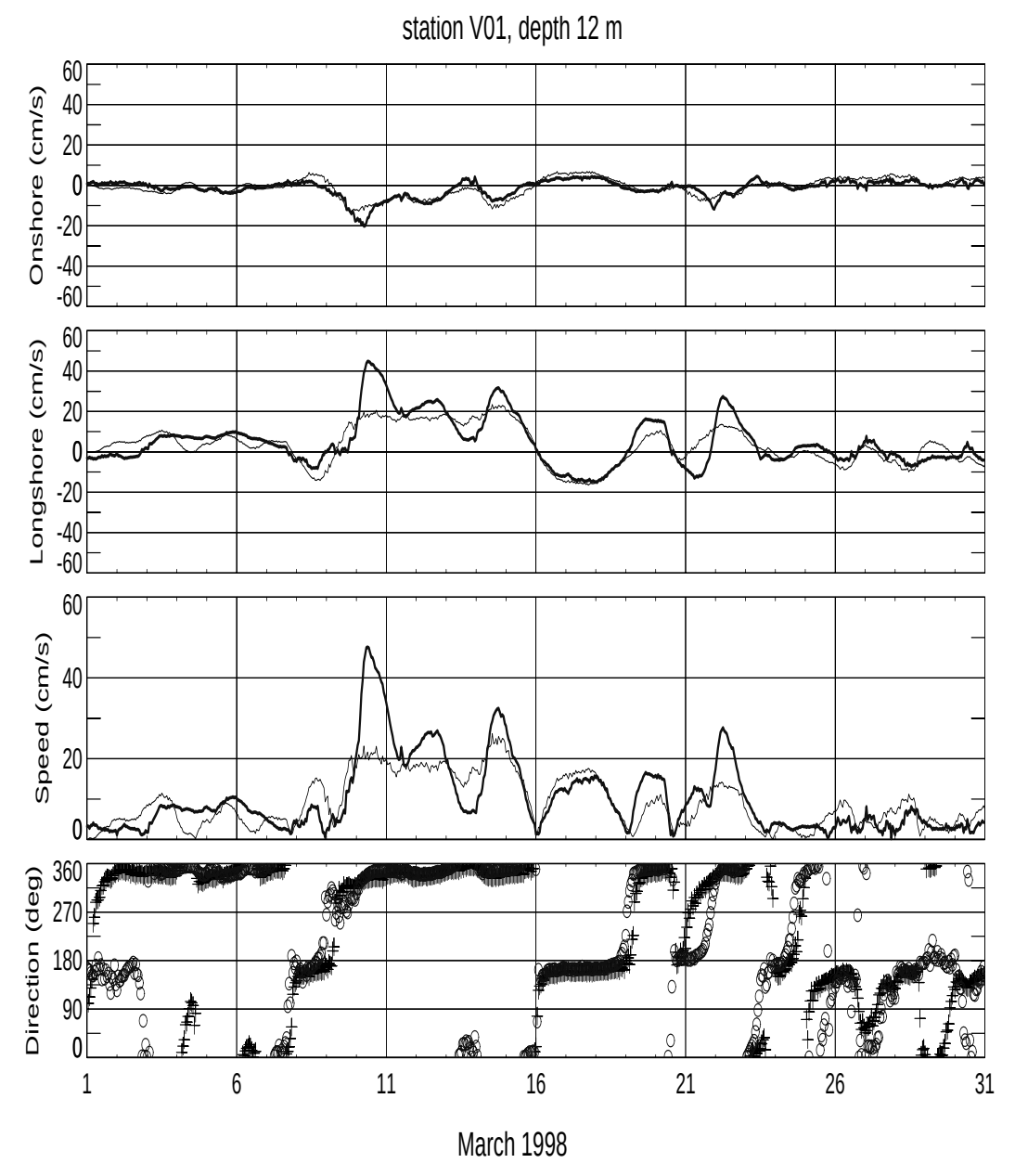

Figure 10. Time-series of modeled (thin line) versus observed (thick line) currents at station V01

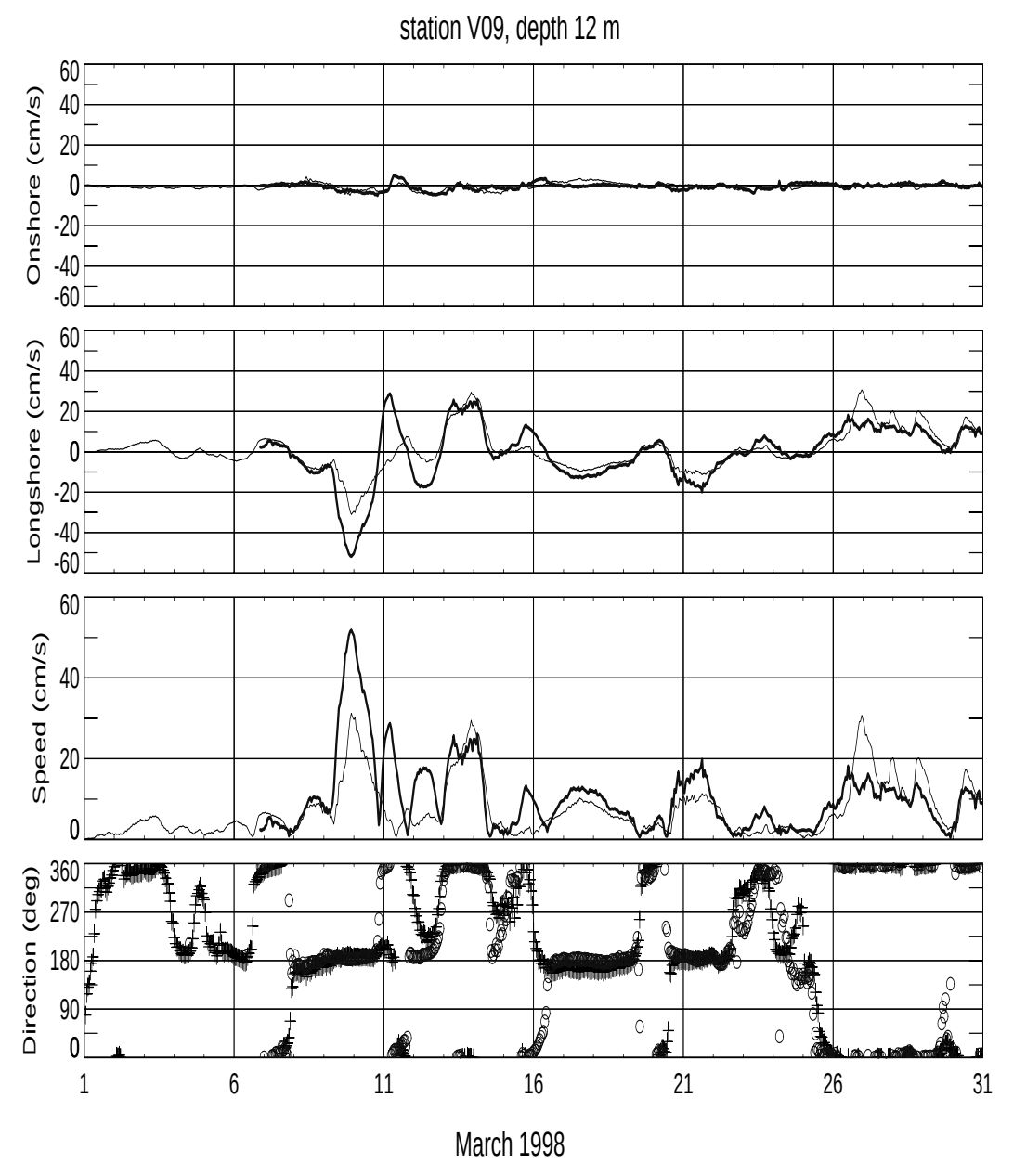

Figure 11. Time-series of modeled (thin line) versus observed (thick line) currents at station V09

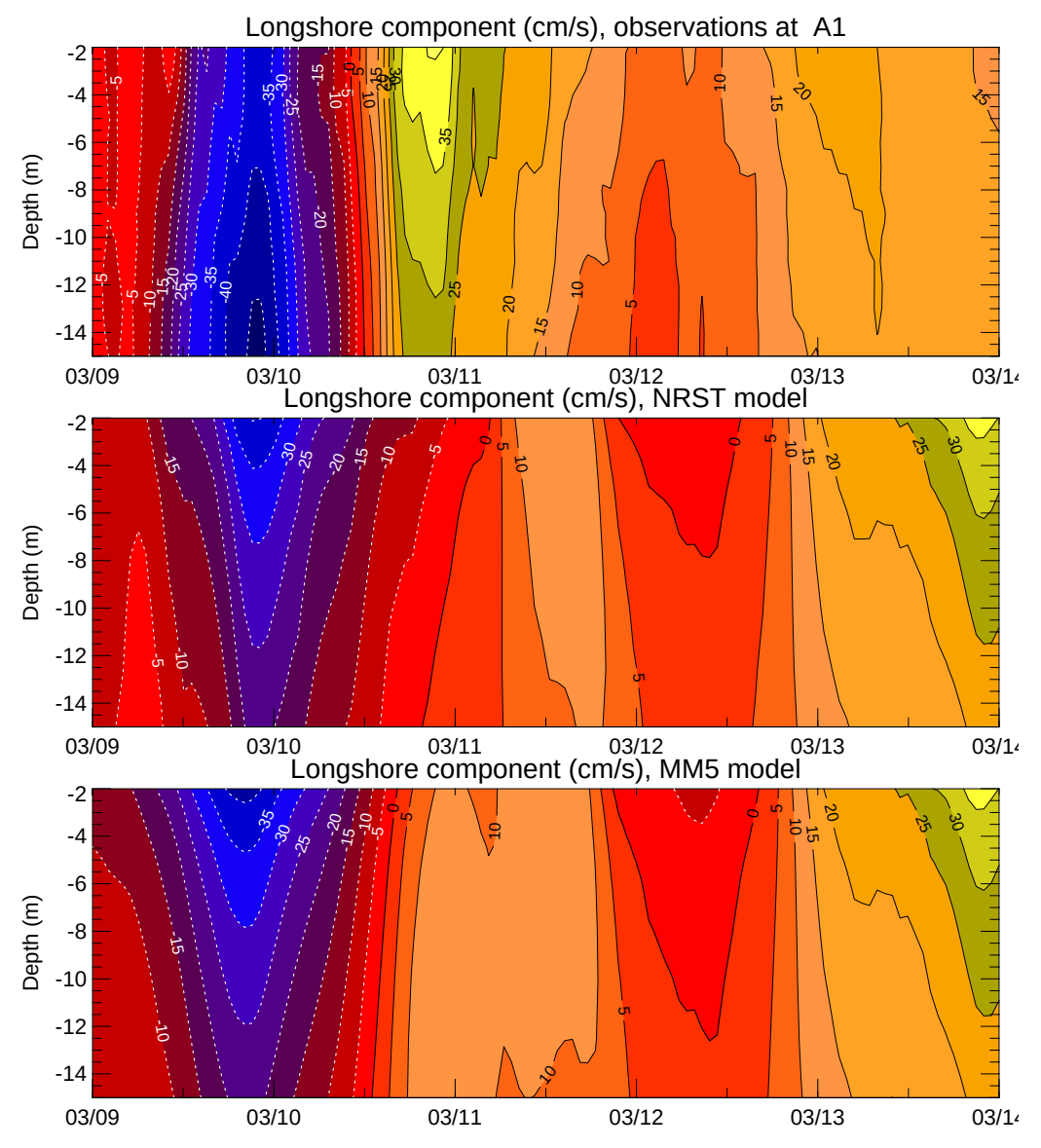

Figure 12a. Time-series of modeled versus observed longshore currents at station A1. NRST model run employs objectively analyzed winds, MM5 – modeled winds.

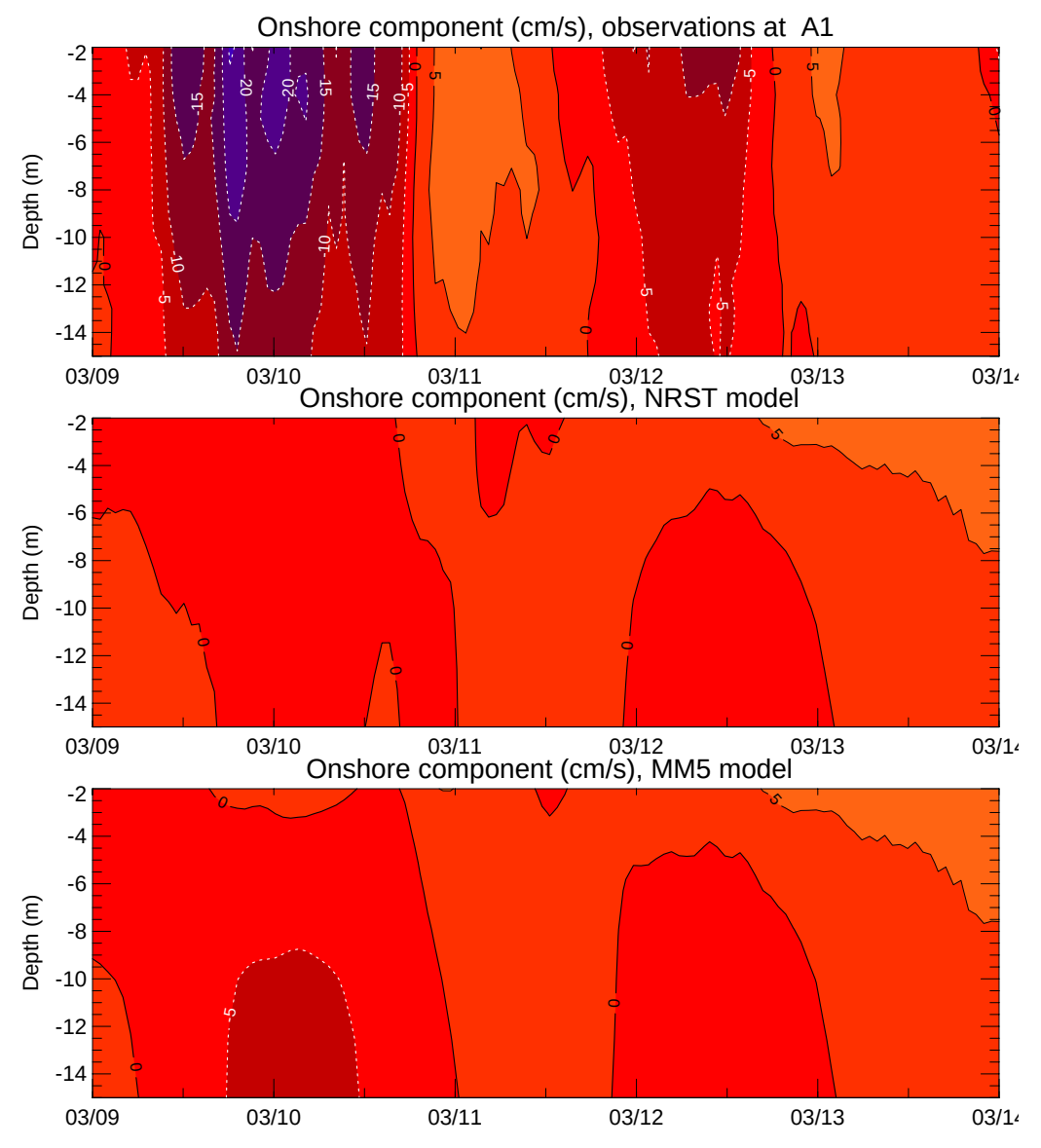

Figure 12b. Time-series of modeled versus observed onshore currents at station A1. NRST model run employs objectively analyzed winds, MM5 – modeled winds.

Hydrodynamic model evaluation and sensitivity to meteorological data

The model qualitatively reproduces the observed large-scale circulation pattern (Fig. 1) 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 both objectively analyzed and MM5 winds because of the lack of overlake observations.

Comparison of modeled and observed currents at the nearshore stations V01 and V09 shows good prediction by the model of an offshore flow at 12 m depth but significant underestimation of the longshore flow (Fig. 10-11). ADCP data (station A1) provided valuable information on vertical current distributions. Observations during March 9-14 (Fig. 12a) 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). The onshore component (Fig. 12b) was also calculated qualitatively correctly but its magnitude was significantly less than in observations. It is interesting to note that while observed currents possess almost no vertical shear, modelled currents showed significant reduction (almost twice) in speed with depth during strong wind events. The MM5 data showed some improvement in model results. Figure 12, for example, shows better timing of nearshore current reversal on March 10-11 and stronger longshore and onshore currents during wind events.

Conclusions

A system of linked wave, circulation and sediment transport models was applied to Lake Michigan to simulate hydrodynamic, wave and suspended sediment conditions during the 1998 coastal turbidity plume event. Comparison with observations showed that models were able to qualitatively simulate resuspension event but some important details of nearshore-offshore flow were missing. More experiments are underway to study the effects of wind field interpolation, grid resolution, and turbulence parameterization on hydrodynamics in Lake Michigan.

Products/Publications

Beletsky, D., D.J. Schwab, M.J. McCormick, G. S. Miller, J.H. Saylor, and P.J. Roebber, 2000. Hydrodynamic modeling for the 1998 Lake Michigan coastal turbidity plume event. Estuarine and Coastal Modeling, Proceedings of the 6th International Conference, November 2-5, 1999, New Orleans, LA. (submitted)

Schwab,D.J., D. Beletsky, and J. Lou, 2000. Modeling a coastal turbidity plume in Lake Michigan. Estuar., Coast. and Shelf Sci. (in press)

Lou J., D.J. Schwab and D. Beletsky. 1999. Suspended sediment transport modeling in Lake Michigan. The 1999 Canadian Coastal Conference, May 19-22, 1999, Victoria, B.C., p. 391-405.

Eadie, B.J., D.J. Schwab, G.L. Leshkevich, T.H. Johengen, R.A. Assel, R.E. Holland, N. Hawley, M.B. Lansing, P. Lavrentyev, G.S. Miller, N.R. Morehead, J.A. Robbins, and P.L. Van Hoof, 1996. Anatomy of a recurrent episodic event: a winter-spring plume in southern Lake Michigan. EOS, Trans. Amer. Geophys. Union., 77. 337-338.

References

Bennett, J.R., 1974. On the dynamics of wind-driven lake currents. J. Phys. Oceanogr. 4(3), 400-414.

Blumberg, A.F. and G.L. Mellor, 1987. A description of a three-dimensional coastal ocean circulation model. Three dimensional Coastal Ocean Models, Coastal and Estuarine Sciences, 5, N.S. Heaps [ed.] Amer. Geophys. Union, Washigton, D.C., pp 1-16.

Dudhia, J., 1993. A nonhydrostatic version of the Penn State-NCAR mesoscale model: validation tests and simulation of an Atlantic cyclone and cold front. J. Atmos. Sci., 46,3077- 3107.

Grant, W. D., and O. S. Madsen, 1979, Combined wave and current interaction with a rough bottom, J. Geophys. Res., 84(C4), 1797-1808, 1979.

Mellor, G.L., and T. Yamada, 1982: Development of a turbulence closure model for geophysical fluid problems. Rev. Geophys. Space Phys., 20(4), 851-875.

Schwab, D.J. and D. Beletsky, 1998. Lake Michigan Mass Balance Study: Hydrodynamic modeling project. NOAA Tech. Memo. ERL GLERL-108. NOAA Great Lakes Env. Res. Lab., Ann Arbor, MI, 53pp.

Schwab, D.J., J.R. Bennett, P.C. Liu, and M.A. Donelan, 1984. Application of a simple numerical wave prediction model to Lake Erie. J. Geophys. Res., 89(C3), 3586-3589.