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Impacts of suspended sediment on the ecosystem in Lake Michigan: A comparison between the 1998 and 1999 plume events

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[1] The impact of a reflective, recurrent coastal resuspension plume on the lower trophic food web system in Lake Michigan was examined using a 3-D coupled physical and biological model. Numerical experiments were conducted for the March 1998 and 1999 plume events. The comparison between modeling results of these 2 years shows that the spatial distributions of the biological fields (i.e., phosphorus, phytoplankton, detritus, etc.) were closely coupled to the physical environment associated with wind-induced three-dimensional circulation and mixing. The influence of suspended sediment plumes on the lake ecosystem was reflected in heterotrophic (secondary) production rather than in the autotrophic (primary) production. Nutrients were maintained through nutrient release from suspended sediments within the plume, while it was supplied by current advection and diffusion in the interior. The cross-shore flux of nutrients was driven by episodic wind events with a period of about 5–7 days. The flux was offshore during northerly winds and onshore during southerly winds. Comparisons between energy fluxes among biological variables suggest that the microbial loop (detritus-heterotrophic bacteria and microzooplankton) played an important role in the ecosystem dynamics during plume events. Bacteria were good competitors with phytoplankton for inorganic phosphorus and were also a key supporter for growth of microzooplankton inside and outside the plume. As a result, the lower food web system could be divided into two decoupled loops: (1) detritus-bacteria-microzooplankton-large zooplankton and (2) nutrient-phytoplankton-detritus. *INDEX TERMS:* 4255 Oceanography: General: Numerical modeling; 4804 Oceanography: Biological and Chemical: Benthic processes/benthos; 4815 Oceanography: Biological and Chemical: Ecosystems, structure and dynamics; 4817 Oceanography: Biological and Chemical: Food chains; *KEYWORDS:* ecosystem dynamics, physical and biological interaction, lower trophic level food web

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1. Introduction

[2] Highly reflective coastal suspended sediment plumes are a typical springtime event in southern Lake Michigan [*Eadie et al.*, 1996]. This plume is caused mainly by wind-driven sediment resuspension and current convergence in the coastal region [*Mortimer*, 1988; *Edgington and Robbins*, 1973; *Johengen et al.*, 1994; *Chen et al.*, 2002; *Ji et al.*, 2002]. It episodically occurs in early spring because of strong southward wind and is suppressed in early summer as the seasonal thermocline develops. Examples of plume events can be viewed in the 1998 and 1999 surface sediment maps from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and wind measurements on NOAA meteorological buoys in the lake (Figure 1 (right)). In 1998, the first plume was viewed from satellite around 9 March during a strong southward wind event. It lasted for about a week and then diminished on 15–17 March at which time the wind turned northward. Sediment resuspension reoccurred episodically during sustained strong southward wind events for about two months and finally disappeared in late April after the lake began to stratify. In 1999, the first plume appeared after 1 March coinciding with a strong southward wind. Resuspension events in the same year were subsequently suppressed by northward winds and intensified by the south-southwestward winds. The total duration of the 1999 plume event was about two months,

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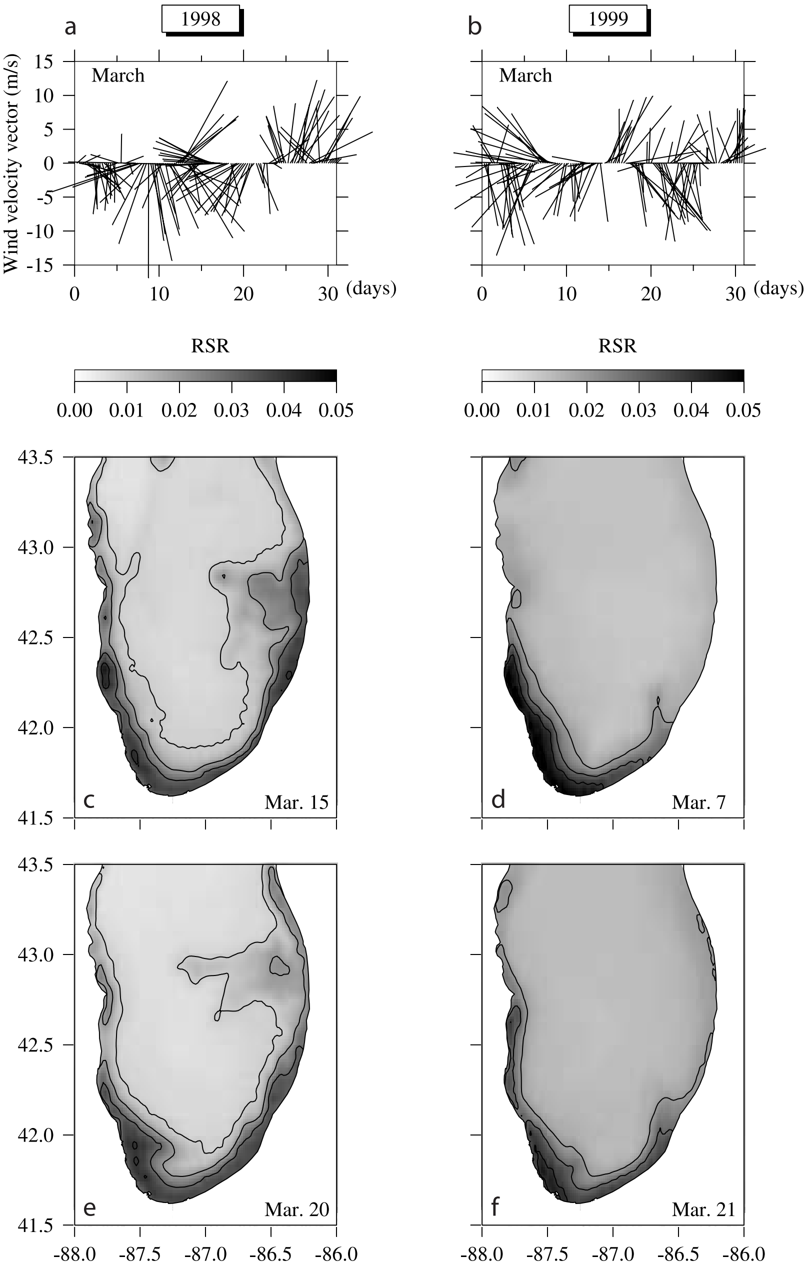

Figure 1. Time series of surface wind velocity vectors taken at center of lake basin during March of (a) 1998 and (b) 1999 and spatial distributions of remote sensing reflectance (RSR) taken on (c) 15 and (e) 20 March 1998 and (d) 7 and (f) 21 March 1999.

similar to 1998, with two large sediment resuspension events on 7 and 21 March. Although the physical processes driving the plume in 1998 and 1999 were the same, the spatial distribution of the plume significantly differed in these 2 years. In March 1998, regions of high sediment resuspension were distributed along eastern and western shores, while in March 1999, sediment was restricted to only a limited area around the southwestern shore (Figure 1 (left)).

[3] Both the 1998 and 1999 plume events were characterized by low light levels and relatively high nutrient concentrations [*Cotner*, 2000]. Because of light limitation, no significant cross-isobath gradient of chlorophyll *a* concentration was observed over a timescale of 5–7 days for these 2 years. The concentration of phosphorus in southern Lake Michigan was lower in 1999 than in 1998. A high bacterial abundance was found during plume events of these 2 years, which was thought to be associated with high decomposition rates from the detrital pool [*Cotner*, 2000]. This observational evidence implied that the microbial food web was sufficient to supply the energy required for microzooplankton growth [*Chen et al.*, 2002]. Since the observed phytoplankton within the plume showed slow growth rates during the period, the impact of episodic plumes on the Lake Michigan ecosystem was to stimulate the heterotrophic, rather than autotrophic production.

[4] As one of the modeling components of the US NSF/NOAA funded Episodic Event-Great Lakes Experiment (EEGLE) program, we used a three-dimensional (3-D)

coupled biological and physical model to examine the influence of the 1998 suspended sediment plume on the lower trophic level food web ecosystem in southern Lake Michigan [*Ji et al.*, 2002]. The model results showed that the suspended sediments in the recurrent coastal plume had a significant impact on the spatial distribution and temporal variation of nutrients and plankton in southern Lake Michigan. Phosphorus release from suspended sediments played a critical role in maintaining nutrient levels during the plume event. The growth of the phytoplankton within the plume was controlled by the available nutrients and light. Because of energetic vertical turbulent mixing, the cross-shelf distribution of the phytoplankton concentration depends on a ratio of the euphotic depth to the water depth. Energy flux estimates among biological variables suggested that the lower trophic level food web system in southern Lake Michigan might be divided into two decoupled loops: (1) a detritus-bacteria-microzooplankton-large zooplankton loop and (2) a nutrient-phytoplankton-detritus loop. These model results are consistent with 1-D modeling experiments conducted at the long-term monitoring station in Southern Lake Michigan for 1994 and 1995 [*Chen et al.*, 2002].

[5] As described above, the spatial distribution of sediments and timing of wind-driven resuspension events of the 1999 plume event significantly differed from those of the 1998 plume event. These differences raised three fundamental questions: First, how similar were the characteristics of the ecosystem dynamics detected in modeling experiments for the 1998 plume event compared to the 1999 plume event? Second, what caused the difference in the geographic locations of the 1998 and 1999 plumes? Thirdly, what were the main impacts of the wind-induced circulation and mixing on the spatial and temporal variation of nutrients and autotrophic and heterotrophic production in Lake Michigan? To our knowledge, these questions have not been addressed in previous modeling studies.

[6] As part of the EEGLE observational component, a series of interdisciplinary field measurements were conducted during the March 1998 and 1999 plume events in southern Lake Michigan. Biological measurements were conducted on 3 cross-shore transects near Muskegon, MI, St. Joseph, MI, and Gary, IN in 1998, and 5 cross-shore transects near Muskegon, St. Joseph, Gary, Chicago, IL, and Racine, WI (Figure 2) in 1999. The data included water samples and continuous records from the tow-yowed Plankton Survey System (PSS). The modeling effort simulated the observed distribution of nutrients and phytoplankton for both the 1998 and 1999 plume periods, and a process-oriented study addressing questions raised above was conducted by comparing the model results for these 2 years.

[7] The remaining sections of this paper are organized as follows: In section 2, the description of the coupled biological and physical model and the design of numerical experiments are given. In section 3, the model results for the 1998 and 1999 plume events are presented and compared. In section 4, the food web dynamics of the 1998 and 1999 plume events are discussed. Finally, a summary is given in section 5.

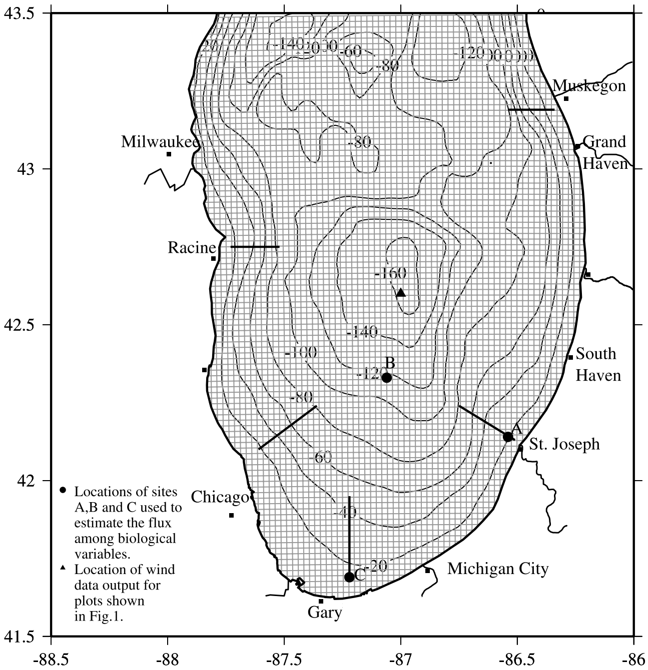

Figure 2. Bathymetry (thin solid curved lines) and model grids in southern Lake Michigan. Heavy solid straight lines represent the cross-isobath transects near the Muskegon, St. Joseph, Gary, Chicago, and Racine. Heavy solid curved lines indicate the river path terminated around the lake. Solid dots are the locations of sites A, B, and C used to estimate the flux among biological variables in the food web, and solid triangles are location of the wind data output for the plots shown in Figure 1.

2. Model and Design of Numerical Experiments

[8] The coupled biological and physical model used for this study was developed by the Marine Ecosystem Dynamics Modeling Laboratory at the University of Massachusetts-Dartmouth [*Chen et al.*, 2002; *Ji et al.*, 2002]. The physical model is the Princeton Ocean Model (POM) that was configured for Lake Michigan by D. J. Schwab's group at NOAA/GLERL [*Schwab et al.*, 2000; *Beletsky et al.*, 2003]. The biological model represents a phosphorus-controlled lower trophic level food web system with 7 state variables (Figure 3). The governing equations for the modified biological model are given as

$$\frac{dP_L}{dt} - \frac{\partial}{\partial z}\left(A_h \frac{\partial P_L}{\partial z}\right) = LP(\text{uptake}) - LP(\text{mortality}) - LZLP(\text{grazing}) - LP(\text{sinking}) \quad (1)$$

$$\frac{dP_S}{dt} - \frac{\partial}{\partial z}\left(A_h \frac{\partial P_S}{\partial z}\right) = SP(\text{uptake}) - SP(\text{mortality}) - SZSP(\text{grazing}) \quad (2)$$

$$\frac{dZ_L}{dt} - \frac{\partial}{\partial z}\left(A_h \frac{\partial Z_L}{\partial z}\right) = \varepsilon^{Z_L} LZLP(\text{grazing}) + \varepsilon^{Z_{LS}} LZSZ(\text{grazing}) - LZ(\text{mortality}) \quad (3)$$

$$\frac{dZ_S}{dt} - \frac{\partial}{\partial z}\left(A_h \frac{\partial Z_S}{\partial z}\right) = \varepsilon^{Z_S} SZSP(\text{grazing}) - LZSZ(\text{grazing}) + \varepsilon^{B} SZB(\text{grazing}) - SZ(\text{mortality}) \quad (4)$$

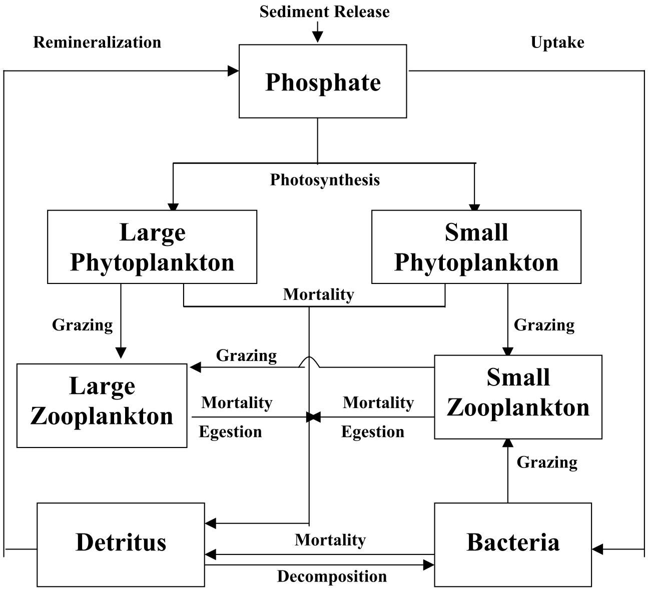

Figure 3. Schematic of the lower trophic level food web model for Lake Michigan.

$$\frac{dB}{dt}-\frac{\partial}{\partial z}\left(A_h\frac{\partial B}{\partial z}\right)=DB(\text{decomposition})+BP(\text{uptake})-SZB(\text{grazing})-B(\text{mortality}) \tag{5}$$

$$\begin{aligned}\frac{dD}{dt}-\frac{\partial}{\partial z}\left(A_h\frac{\partial D}{\partial z}\right)={}&(1-\varepsilon^{z_L})LZLP(\text{grazing})\\&+\left(1-\varepsilon^{Z_S}\right)SZSP(\text{grazing})\\&+\left(1-\varepsilon^{B}\right)SZB(\text{grazing})\\&+\left(1-\varepsilon^{Z_{LS}}\right)LZSZ(\text{grazing})\\&-DB(\text{decomposition})-DP(\text{sinking})\\&-DP(\text{remineralization})+LP(\text{mortality})\\&+SP(\text{mortality})+LZ(\text{mortality})\\&+SZ(\text{mortality})+B(\text{mortality})\end{aligned} \tag{6}$$

$$\begin{aligned}\frac{dP}{dt}-\frac{\partial}{\partial z}\left(A_h\frac{\partial P}{\partial z}\right)={}&-LP(\text{uptake})-SP(\text{uptake})-BP(\text{uptake})\\&+DP(\text{remineralization})+PQ\end{aligned} \tag{7}$$

where P_L, P_S, Z_L, Z_S, B, D and P are the large size phytoplankton (diatom from 13 to 312 μm), small sized phytoplankton (small nondiatom: flagellates smaller than 10 μm), large sized zooplankton (copepods), small sized zooplankton (ciliates and heteroflagellates), bacteria, detritus, and phosphorus, respectively. A_h is the tracer diffusion coefficient that is determined using the Mellor and Yamada level 2.5 turbulent closure scheme in the physical model. $\frac{d}{dt}=\frac{\partial}{\partial t}+u\frac{\partial}{\partial x}+v\frac{\partial}{\partial y}+w\frac{\partial}{\partial z}$ is the derivative operator; x, y and z are the eastward, northward, and vertical axes of the Cartesian coordinate, and u, v, and w are the x, y, and z components of the velocity. PQ is the phosphorus release rate from suspended sediments. LP (uptake), SP (uptake) and BP (uptake) are phosphorus uptake by large phytoplankton, small phytoplankton and bacteria, respectively; $LZLP$ (grazing) and $LZSZ$ (grazing) are grazing of large phytoplankton and small zooplankton by large zooplankton, respectively; $SZSP$ (grazing) is grazing of small phytoplankton by small zooplankton; SZB (grazing) is grazing of bacteria by small zooplankton; DB (decomposition) is decomposition of detritus to bacteria; DP (remineralization) is remineralization of detritus to phosphorus. LP (sinking), SP (sinking), and DP (sinking) are sinking fluxes of large phytoplankton, small phytoplankton, and detritus, respectively; LP (mortality), SP (mortality), LZ (mortality), SZ (mortality), and B (mortality) are the mortalities of large and small phytoplankton, large and small zooplankton, and bacteria, respectively. ε^{Z_L}, ε^{Z_s}, ε^{B}, and $\varepsilon^{Z_{LS}}$ are the assimilation efficiencies of large zooplankton on large phytoplankton, small zooplankton on small phytoplankton, small zooplankton on bacteria, and large zooplankton on small zooplankton, respectively. The definition of each term in equations (1)–(7) was described in detail by *Chen et al.* [2002].

[9] The numerical domain covered the entire southern basin of Lake Michigan with a uniform grid size of 2 km in the horizontal and 20 σ levels in the vertical (Figure 2). The coupled biological and physical model was driven by the realistic wind interpolated from the wind records on the NOAA buoys in the lake and the net surface heat flux estimated by the Bulk algorithm according to meteorological parameters of air and water temperatures, wind speed and cloud coverage recorded on NOAA buoys [*Beletsky et al.*, 2003]. For the 1998 and 1999 yearly experiments, the model was spun up over two months starting on 1 January, with uniform spatial distributions of temperature and biological variables at initial. Model-data comparisons were made over the plume period after 1 March. The initial value of temperature was 2°C everywhere for both years.

[10] The values of biological parameters used in our numerical experiments are listed in Table 1. These values were obtained either from field measurements taken in Lake Michigan or the literature. The same set of biological parameters was chosen for the 2 years' experiments to ensure that the comparison was made on the same basis. The detailed explanation and discussion of the choice of parameters and sensitivity analysis of these parameters were given by *Chen et al.* [2002]. Field measurements taken on 28 January 1998 and 15 February 1999 were used to specify the initial values of the following biological variables for the 1998 and 1999 experiments. For the 1998 experiment, the initial values of P, P_L, P_S, Z_L, Z_S, B, and D were given as 0.01 μmol P/L, 1.6 μmol C/L, 1.6 μmol C/L, 2.0 μmol C/L, 0.5 μmol C/L, 3.0 μmol C/L, and 7.7 μmol C/L, respectively, while for the 1999 experiments, they were 0.006 μmol P/L, 1.2 μmol C/L, 1.2 μmol C/L, 0.4 μmol C/L, 0.3 μmol C/L, 2.0 μmol C/L, and 4.0 μmol C/L, respectively.

[11] In this modeling study, the impact of the suspended sediment on the ecosystem in southern Lake Michigan was assumed to function through two processes: (1) increasing the downward light attenuation coefficient and (2) releasing nutrients. Because the lake water was vertically well-mixed in March 1998 and 1999, the suspended sediment concentration in the water column can be determined using the surface sediment concentration converted directly from cloud-free SeaWiFS $R_{rs}(555)$ imagery. The cloud-free

Table 1. Biological Parameters

Parameter	Definition	Value Used	Ranges	Sources
$V_{\max}^{P_L}$	maximum growth rate for P_L	1.6 d^{-1}	0.8–6 d^{-1}	*Bieman and Dolan* [1981] *Scavia et al.* [1988]
$V_{\max}^{P_S}$	maximum growth rate for P_S	0.8 d^{-1}	0.8–2 d^{-1}	*Bieman and Dolan* [1981] *Scavia et al.* [1988]
$V_{\max}^{S}$	maximum Si uptake rate by P_L	1.2 d^{-1}	0.8–6 d^{-1}	various sources
$V_{\max}^{B}$	maximum P uptake rate by *B*	0.3 d^{-1}	?	
$V_{\max}^{DOP}$	maximum DOP uptake rate by *B*	5 d^{-1}	23–144 d^{-1}	*Bentzen et al.* [1992]
k_{P_L}	half-saturation constant for the *P* uptake by P_L	0.03 μmol P/L	0.07–0.4 μmol P/L	*Tilman et al.* [1982] *Bieman and Dolan* [1981]
k_{P_S}	half-saturation constant for the P uptake by P_S	0.03 μmol P/L	0.015–? μmol P/L	*Bieman and Dolan* [1981]
k_S	half-saturation constant for the Si uptake by P_L	5.0 μmol Si/L	3.5–3.57 μmol Si/L	*Bieman and Dolan* [1981] *Jorgensen et al.* [1991]
k_B	half-saturation constant for the P uptake by B	0.2 μmol P/L	0.02–0.2 μmol P/L	*Cotner and Wetzel* [1992]
k_{DOP}	half-saturation constant for the DOP uptake by B	0.1 μmol P/L	0.005–0.02 μmol P/L	*Bentzen et al.* [1992]
$G_{\max}^{Z_L}$	maximum P_L grazing rate by Z_L	0.2 d^{-1}	0.2–0.86 d^{-1}	*Jorgensen et al.* [1991] *Scavia et al.* [1988]
$G_{\max}^{Z_S}$	maximum P_S grazing rate by Z_S	0.2 d^{-1}	0.1 d^{-1}	*Bieman and Dolan* [1981]
$G_{\max}^{B}$	maximum B grazing rate by Z_S	3.5 d^{-1}	3.5 d^{-1}	*Hamilton and Preslon* [1970]
$G_{\max}^{Z_{LS}}$	maximum Z_S grazing rate by Z_L	1.0 d^{-1}	?	
k^{Z_L}	Ivlev constant for Z_L grazing	0.06 μmol^{-1}	0.001–1 μmol^{-1}	*Jorgensen et al.* [1991] *Scavia et al.* [1988]
k^{Z_S}	Ivlev constant for P_s grazing by Z_s	0.02 μmol^{-1}	0.011 μmol^{-1}	*Bieman and Dolan* [1981]
k^{B}	Ivlev constant for the B grazing by Z_s	0.03 μmol^{-1}	0.022 μmol^{-1}	*Hamilton and Preslon* [1970]
$k^{Z_{LS}}$	Ivlev constant for the Z_s grazing by Z_L	0.07	?	
ε^{Z_L}	assimilation efficiency of Z_L	0.35	0.15–0.5	*Jorgensen et al.* [1991]
ε^{Z_S}	assimilation efficiency of Z_s	0.3	?	
ε^{B}	assimilation efficiency of B grazing by Z_s	0.3	?	
$\varepsilon^{Z_{LS}}$	assimilation efficiency of the Z_s by Z_L	0.6	?	
α^{P_L}	mortality rate of P_L	0.003 d^{-1}		
α^{P_S}	mortality rate of P_S	0.003 d^{-1}		
α^{Z_L}	mortality rate of Z_L	0.02 d^{-1}	0.01–0.05 d^{-1}	*Jorgensen et al.* [1991] *Bieman and Dolan* [1981]
α^{Z_S}	mortality rate of Z_s	0.06 d^{-1}	0.1 d^{-1}	*Bieman and Dolan* [1981]
$V_{\max}^{P_L}$	mortality rate of B	0.5 d^{-1}	0.5–5.9 d^{-1}	*Jorgensen et al.* [1991]
$V_{\max}^{S}$	proportionality of DOP from the detrital P	0.02	0.1–0.58	*Valiela* [1995]
$V_{\max}^{B}$	sinking velocity of P_L	0.6 m d^{-1}	0.5–9 m d^{-1}	*Jorgensen et al.* [1991] *Scavia et al.* [1988]
$V_{\max}^{DOP}$	sinking velocity of P_s	0.2 m d^{-1}	0.01–3 m d^{-1}	*Fahnenstiel and Scavia* [1987b]
k_{P_L}	sinking velocity of D	0.6 m d^{-1}	0.5–1 m d^{-1}	*Jorgensen et al.* [1991]
e_P	remineralization rate of detrital P	0.01 d^{-1}	0.05 d^{-1}	*Fasham et al.* [1990]
k_S	remineralization rate of detrital Si	0.03 d^{-1}	?	
$G_{\max}^{B}$	temperature dependence coefficient	0.069	0.069	*Parsons et al.* [1983]
$\lambda_{C:Chl_i}$	ratio of carbon (C) to chlorophyll	35	23–79	*Parsons et al.* [1983]
$\lambda_{C:P}$	ratio of C to P	80	?	*Parsons et al.* [1983]

SeaWiFS $R_{rs}(555)$ images are available almost daily in southern Lake Michigan in March 1998 and 1999 [*Budd et al.*, 1999; J. W. Budd et al., Episodic events and trophic pulses: Seasonal and interannual chlorophyll variability in southern Lake Michigan, submitted to *Journal of Geophysical Research*, 2004, hereinafter referred to as Budd et al., submitted manuscript, 2004]. In March 1998, total suspended sediment samples were taken at the Muskegon, St. Joseph, Gary, and Chicago transects, and a regression relationship between SeaWiFS $R_{rs}(555)$ and TSS was developed as

$$C_s(x,y,t) = 1.0888e^{84.739RSR(x,y,t)} \tag{8}$$

where $C_s(x, y, t)$ is the suspended sediment concentration in units of mg/L. The correlation coefficient was $R = 0.88$ (Figure 4a). In March 1999, suspended sediment water samples were taken on Muskegon, St. Joseph, Gary, Chicago, and Racine, and a regression function relating SeaWiFS $R_{rs}(555)$ to TSS was developed as

$$C_s(x,y,t) = 0.1693e^{139.66RSR(x,y,t)}, \tag{9}$$

with a correlation coefficient of $R = 0.90$ (Figure 4b).

[12] Sediment concentration in the computational domain for the 1998 and 1999 experiments were determined by (8) and (9), respectively, in which SeaWiFS $R_{rs}(555)$ data were converted to $C_s(x, y, t)$ over a time interval of one day. The phosphorus release rate from suspended sediment was assumed to be proportional to the suspended sediment concentration. A rate of 0.5×10^{-3} μmol P mg^{-1} d^{-1} was specified for the 1998 experiment, while 0.15×10^{-3} μmol P mg^{-1} d^{-1} was used for the 1999 experiment. These two different rates are determined through experiments with the best matching of the model-predicted phosphorus concentration to water samples taken on transects.

[13] The relationship between the light attenuation coefficient [$k_{ext}(x, y, t)$] and sediment concentration was linear in March 1998 and 1999. In March 1998, $k_{ext}(x, y, t)$ was estimated using a linear fitting function as

$$k_{ext}(x,y,t) = 0.0742C_s(x,y,t) + 0.1786, \tag{10}$$

with a correlation coefficient of $R = \pm0.99$. In March 1999, $k_{ext}(x, y, t)$ was calculated using the linear function

$$k_{ext}(x,y,t) = 0.0716C_s(x,y,t) + 0.0236 \tag{11}$$

with a correlation coefficient of $R = \pm0.98$.

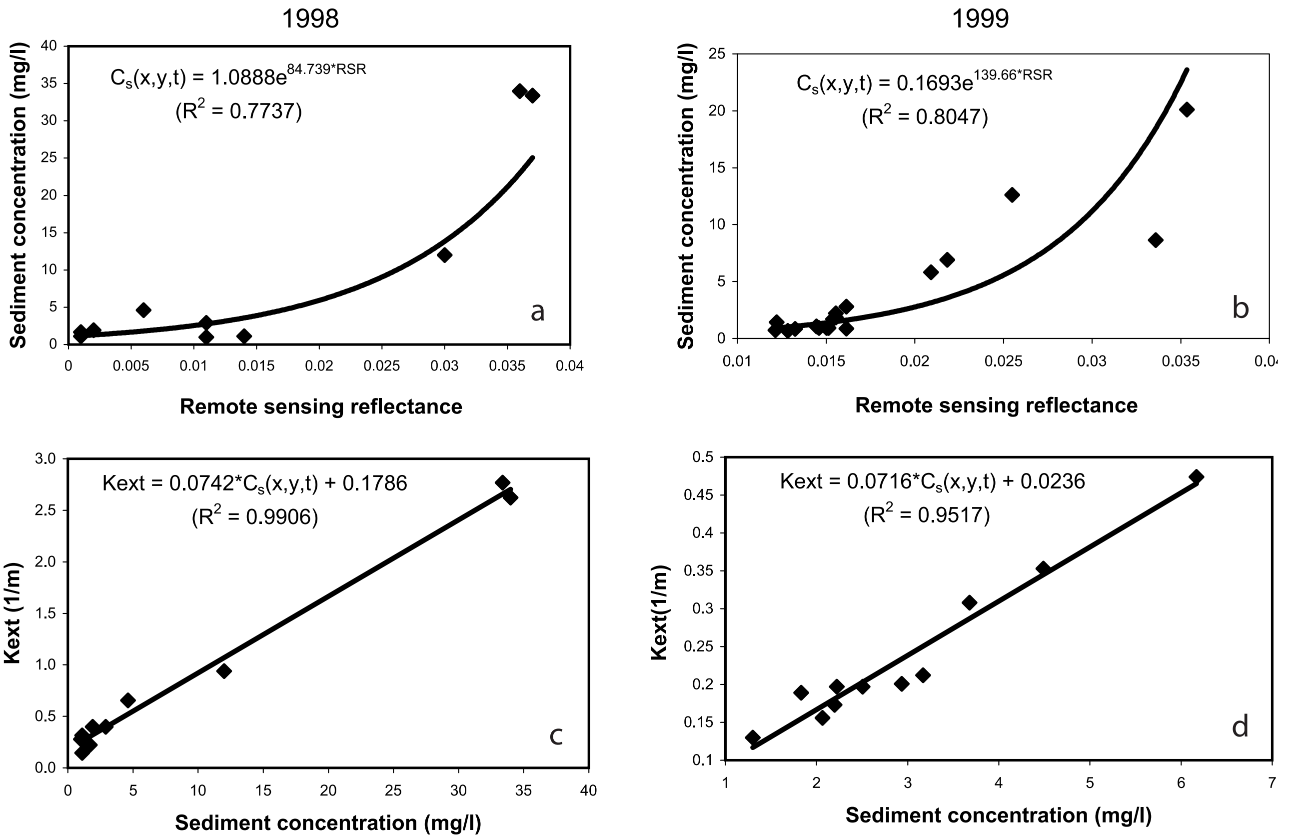

Figure 4. The regression fittings of sediment concentration with respect to remote sensing reflectance and light attenuation coefficient with respect to sediment concentration in March (left) 1998 and (right) 1999. Solid squares represent water samples collected on the transects shown in Figure 2 during the March 1998 and 1999 interdisciplinary plume cruises.

[14] Discharges from eighteen rivers flowing into Lake Michigan were included in the numerical experiments. River discharge rates at these sources were specified using the climatologically averaged values, which were the same as those used in our previous studies [*Ji et al.*, 2002]. A uniform value of 0.1 μmol P/L was specified for phosphorus concentration in all the rivers for both the 1998 and 1999 experiments, with the understanding that this value is only meaningful for process-oriented qualitative studies of the impact of river discharges on the level of nutrients and phytoplankton in southern Lake Michigan.

3. Comparison Between the 1998 and 1999 Model Results

3.1. Physical Fields

[15] In March 1998 and 1999, the wind measurements taken on the NOAA buoys showed that the meteorological field in southern Lake Michigan was mainly characterized by atmospheric frontal passages with a timescale of 2–7 days (Figure 1). In March 1998, 4 cold air fronts swept by the southern lake. The suspended sediment plume first occurred around 9 March because of strong southward wind. In March 1999, 6 cold air fronts passed over the southern lake. The plume first appeared on 1 March and was enhanced significantly on 6 March because of reoccurrence of strong southwestward wind.

[16] These observational events were reproduced by the model, which showed that the distributions and variations of water circulation and sediment suspension in southern Lake Michigan were mainly controlled by the wind field. In 1998, a strong southward wind prevailed in southern Lake Michigan on 8–11 March, during which the maximum wind speed reached about 10–15 m s^{-1}. This southward wind produced strong alongshore southward flows on both the eastern and western shores, as well as two cyclonic circulation gyres in the interior on 10 March (Figure 5 (left)). Two convergence zones formed along the eastern coastal area, the first of which was located at the southeastern nearshore region between St. Joseph and Michigan City and the second near Grand Haven between two cyclonic gyres. Correspondingly, significant sediment suspension occurred along the coast in this region. The distribution of suspended sediment concentration was coherent with the wind field: high concentration zones were detected along the eastern and western coast where strong southward currents existed and also in an offshore extended area near Grand Haven where convergence-induced offshore water transport was significant (Figure 1 (left)).

[17] In 1999, a strong southwestward wind of about 10–15 m s^{-1} swept over southern Lake Michigan on 2–6 March. This southwestward wind caused westward/southwest or northwestward offshore currents on the eastern coast and westward currents in the lake interior. These currents

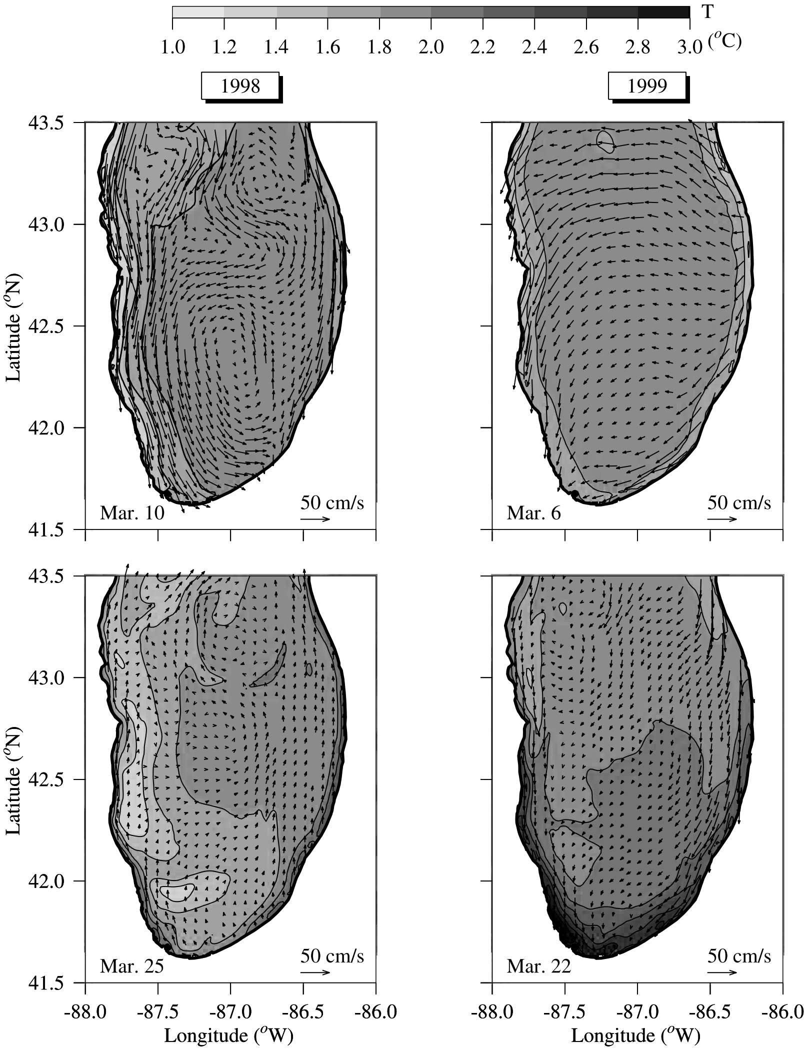

Figure 5. Distributions of surface water current vectors and temperature in southern Lake Michigan (left) on 10 and 25 March 1998 and (right) on 6 and 22 March 1999.

converged toward the western coast, leading to a strong southward transport in the nearshore region of the western coast and thus forming a convergence zone along the southwestern coast near Gary (Figure 5 (right)). Correspondingly, significant sediment suspension occurred along the western and southwestern coasts. The distribution of suspended sediment concentrations also coincided with the wind field, with higher values along the western coast where a strong southward wind was observed and highest in the southwestern nearshore region where the convergence zone was located (Figure 1 (right)).

[18] The lake water gradually warmed up as solar heat flux increased. A remarkable temperature gradient formed in late March, but the distribution of this gradient significantly differed in 1998 and 1999. In 1998, for example, the northward wind prevailed on southern Lake Michigan in late March. On 25 March, the nearshore currents reversed northward on both the eastern and western coasts, forming anticyclonic and cyclonic eddies on the north and south of 43°N in the interior, respectively. Correspondingly, the water temperature increased relatively faster on the eastern coast than on the western coast. The warm water core, which occurred in the cyclonic eddy, was the result of the offshore advection near Grand Haven. The heat flux was relatively uniform in southern Lake Michigan during the entire period of March 1998. An asymmetric heating tendency on the eastern and western coasts resulted from wind-induced advection. A strong southwestward wind of about 10 m s^{-1} prevailed over southern Lake Michigan during 15–21 March, which tended to push the relatively cold interior water toward the western coast. A relatively cold water band formed on the western coast as a result of wind-induced westward advection. Since the heat flux was uniformly distributed on the eastern and western coasts, the tendency toward higher temperatures on eastern coast remained unchanged as significant warming occurred during the northward wind event in late March.

[19] In late March 1999, the water circulation in southern Lake Michigan was controlled predominantly by southeastward and northward winds (Figure 5). Significant warming occurred during the northward wind event after 19 March, with a high water temperature band forming along the south and southwestern coasts. These nonuniform water temperatures were caused by the advection-induced water redistri-

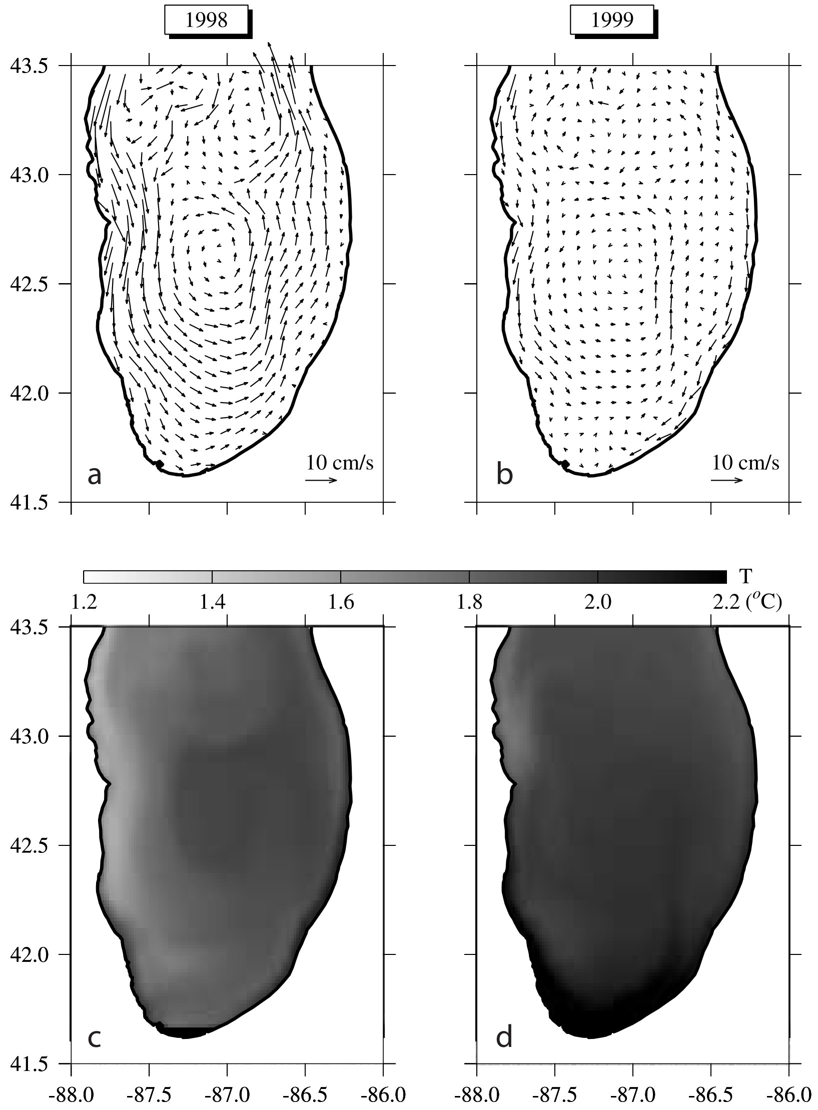

Figure 6. Distribution of monthly averaged surface water current vectors and temperature in southern Lake Michigan for March 1998 and 1999.

bution, similar to that observed in March 1998. Strong southeastward winds appeared episodically during 17–22 March 1999, which tended to push the relatively cold interior waters northeastward toward the eastern coast. When the lake was heated uniformly during the northward wind event, the water temperature remained higher on the south and southwestern coasts than the interior and eastern coast.

[20] The role of wind-induced advection in the spatial distribution of water temperature in southern Lake Michigan in March 1998 and 1999 can be clearly seen from the model-derived average monthly distribution of vertically averaged currents and water temperature. In March 1998, the wind-induced monthly averaged currents in southern Lake Michigan were characterized by a relatively strong southward flow of about 10 cm s^{-1} along the western coast (Figure 6a). This flow rotated counterclockwise in the southern end of the lake to form a cyclonic circulation gyre in the interior. Correspondingly, a cold water band formed along the western coast as a result of the alongshore southward advection and a relatively warm water patch appeared in an offshore region between Grand Haven and South Haven in association with the cyclonic gyre (Figure 6c). Although there was a southward flow along the western coast, its magnitude was much weaker in March 1999 (Figure 6b). This weaker southward coastal flow turned eastward at 42°N to form a relatively large scale cyclonic recirculation gyre in the interior. On the eastern coast, the mean flow was also southward. This flow extended southward along the coast to Michigan City and then turned clockwise to join the cyclonic circulation gyre. As a result, a nearly motionless zone formed on the southwestern coast off Gary. The distribution of monthly averaged water temperatures matched well with the circulation: two cold water bands forming on the eastern and western coast in the northern part of southern Lake Michigan as a result of the southward advection; a warmer water area appearing in the interior where the cyclonic circulation gyre was located; and the highest water temperature zone existing in the nearly motionless southwestern coastal zone (Figure 6d).

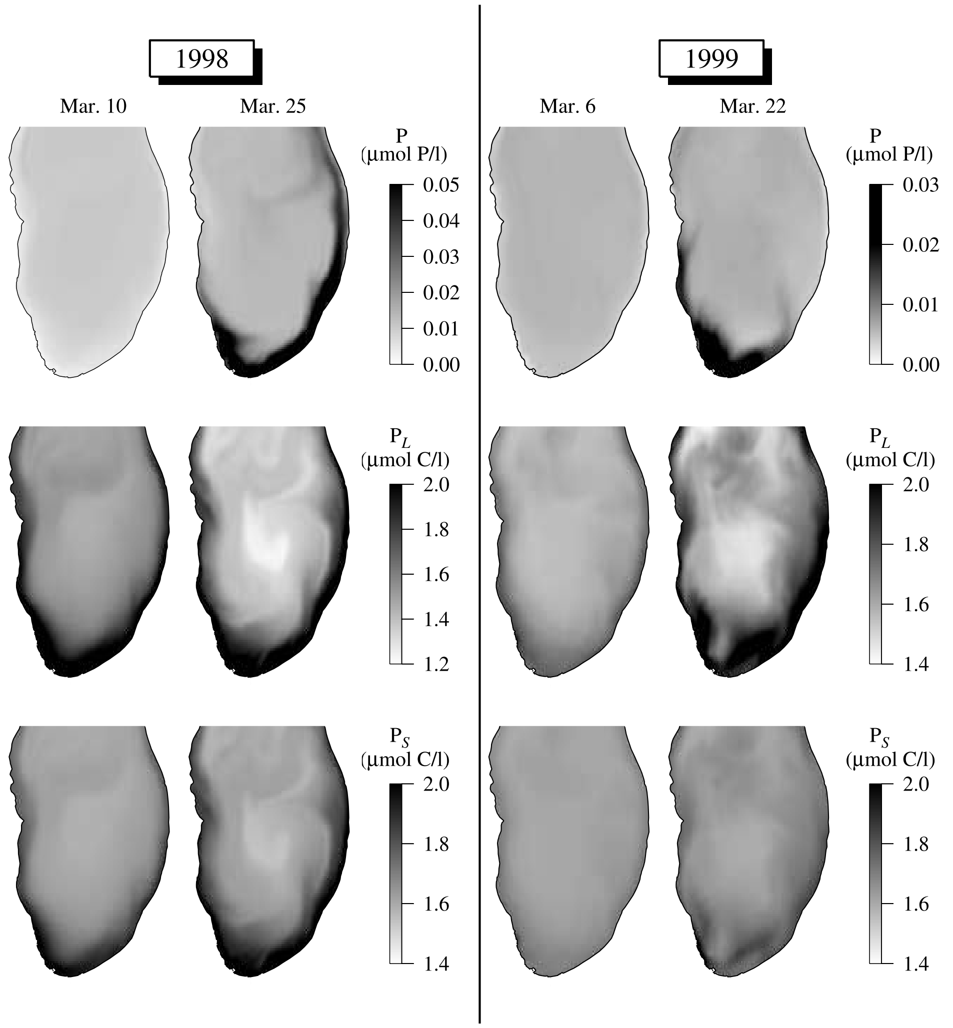

Figure 7. Distributions of phosphorus, large phytoplankton, and small phytoplankton in southern Lake Michigan (left) on 10 and 25 March 1998 and (right) on 6 and 22 March 1999, respectively.

[21] In summary, the spatial distribution and temporal variation of water circulation in southern Lake Michigan in March 1998 and 1999 were controlled by the wind field. The lake warmed up gradually as solar heat increased, but the nonuniform distribution of water temperature was caused mainly by water redistribution driven by wind-induced current advection. The differences in the distribution of water circulation and temperature predicted for 1998 and 1999 was a result of the distinct variation of the wind field observed in these 2 years.

3.2. Biological Fields

[22] In March 1998 and 1999, for a given uniform initial condition of phosphorus, the phytoplankton grew under suitable light condition and formed a distinguishable cross-isobath band as a result of relatively strong vertical mixing. After the plume occurred, light penetration was significantly reduced because of sediment suspension. Although the reduction in light penetration limited the growth of the phytoplankton within the plume area, concentrations of phytoplankton were lower offshore because of strong vertical mixing. The detrital pool developed in late March as a result of the accumulation of dead plankton, which directly contributed to growth of bacteria and micozooplankton.

[23] The difference in the spatial distributions and temporal variations of biological variables found in March 1998 and 1999 were due to the distinctly different characteristics of water circulation and sediment suspension in these 2 years. In 1998, although phosphorus, zooplankton, bacteria and detritus still remained relatively uniform in space on 10 March, when the plume was developing, a distinct cross-shore gradient of phytoplankton had already formed along the coast of the lake (Figure 7 (left)). A region of high phosphorus concentration appeared along the eastern-southwestern coast after 12 March, and intensified significantly after the subsequent southward wind event that occurred on 17–21 March. This high phosphorus concentration zone persisted throughout the countervalent northward wind event in late March. Offshore transport of phosphorus was clearly evident near Grand Haven after 15 March, which was consistent with the distribution of the circulation and temperature shown in Figure 5. Because of light limitation imposed by sediment suspension, no significant growth of the phytoplankton was found after the plume appeared (Figure 7 (left)). The large-sized phytoplankton were advected offshore near Grand

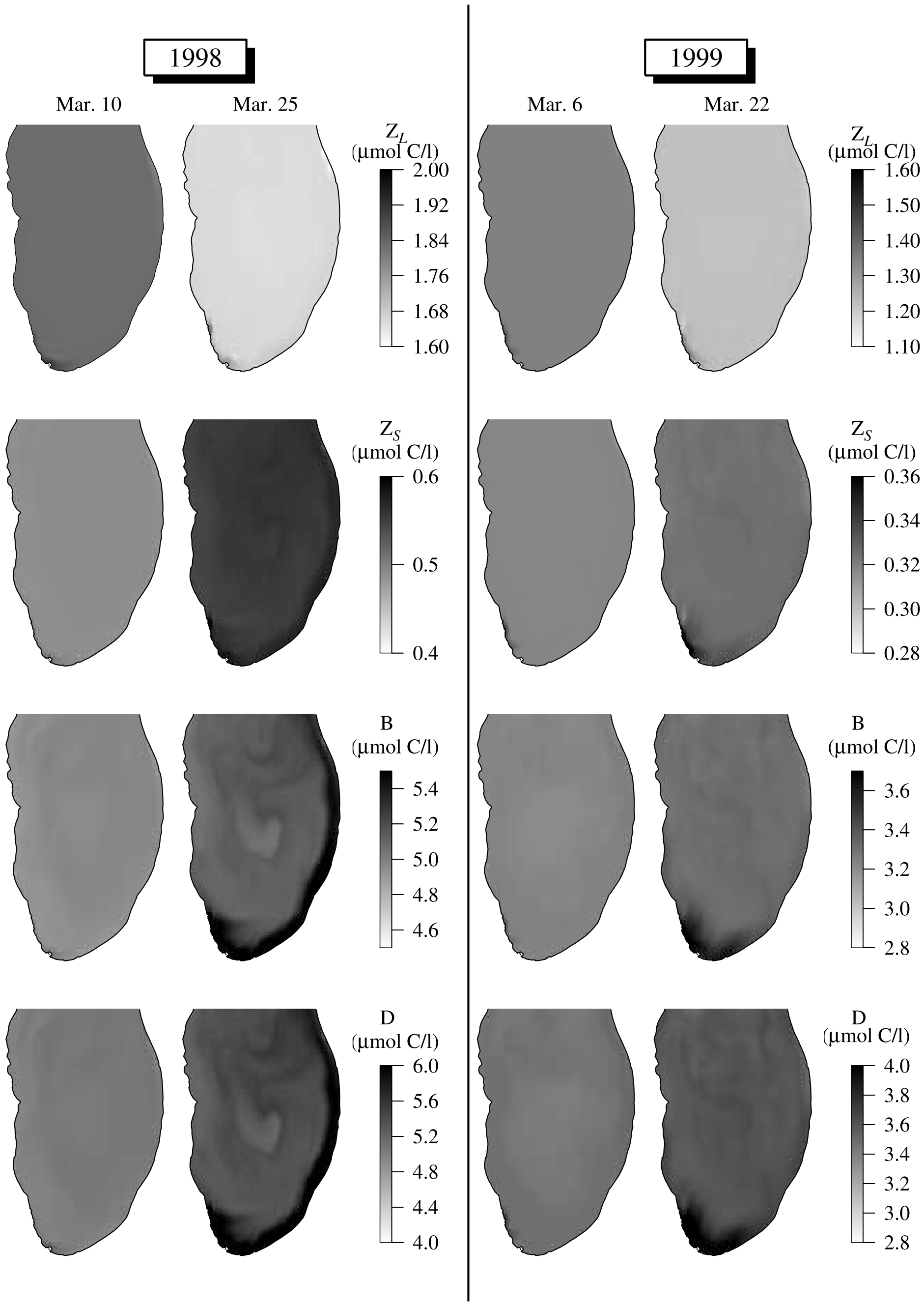

Figure 8. Distributions of large zooplankton, small zooplankton, bacteria, and detritus in southern Lake Michigan (left) on 10 and 25 March 1998 and (right) on 6 and 22 March 1999, respectively.

Haven and circulated following a cyclonic eddy in the interior, forming a donut-like structure in the offshore area of the southern part of the lake (Budd et al., submitted manuscript, 2004). The spatially distinct distribution of detritus developed during the southward wind event on 17–21 March. The growth and distribution of bacteria and small-sized zooplankton were coherent with the detrital pattern (Figure 8 (left)). Zones of high concentrations of detritus, bacteria, and even of small-sized zooplankton were clearly evident on 25 March in the donut area, and this spatial pattern was very similar to that of large-sized phytoplankton. Although there was no significant spatial gradient of large-sized zooplankton in March, the model predicted a gradual decrease in biomass.

[24] In 1999, the cross-isobath gradient of phytoplankton appeared on 6 March, just after a relatively strong southward wind event, though phosphorus, detritus, bacteria, and zooplankton still remained uniform in space (Figures 7 (right) and 8 (right)). Significant sediment resuspension occurred during the southward wind event after 8 March. As a result, a zone of high phosphorus concentrations formed around the nearshore area of the southwestern lake, which was consistent with the SeaWiFS sediment map shown in Figure 1. This high-phosphorus zone intensified

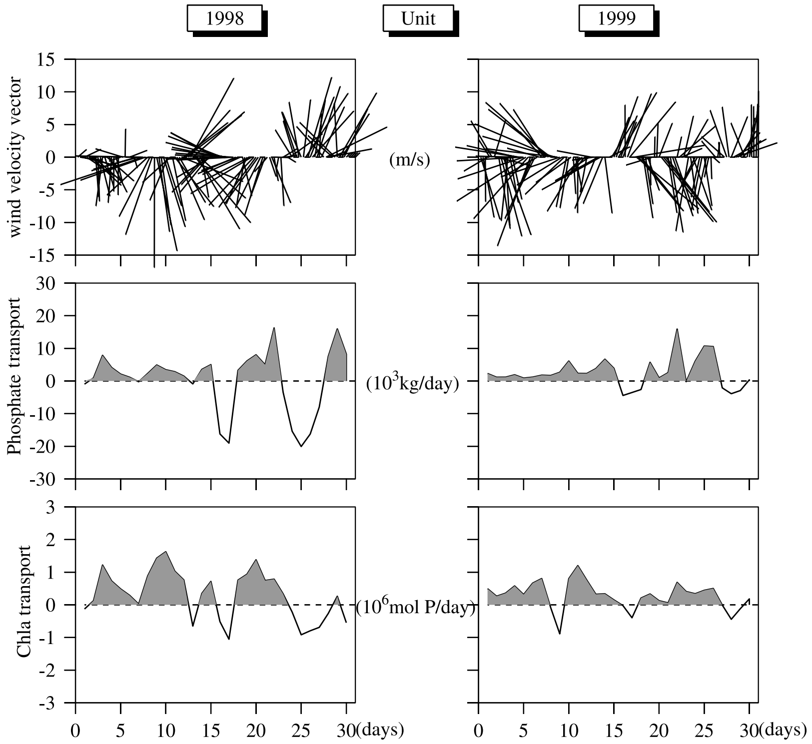

Figure 9. Time series of (top) surface wind velocity vectors and (middle) cross-plume fluxes of phosphate and chlorophyll *a* around the 20-m isobath during March (left) 1998 and (right) 1999. Positive: offshore flux, and negative: onshore flux.

significantly in late March because of intermittent southward wind events. Noticeable growth of the phytoplankton occurred in the southwestern nearshore area of the lake. The shoreward intrusion of interior waters (donut hole) coincided with a relatively low biomass zone of phytoplankton in the southwestern lake in late March, and persisted even during the northward wind event after 15 March. A significant increase in detritus was found in the sediment suspended area in the southwestern lake after 16 March, which led to the growth of bacteria and small-sized zooplankton around the same area in late March. Similar to 1998, no significant spatial gradient in large-sized zooplankton was found in March 1999 (Figure 8 (right)).

3.3. Cross-Shore Fluxes of Phosphorus and Phytoplankton

[25] To understand the influence of the suspended sediment plume on the interior of Lake Michigan, we estimated the offshore fluxes of biological variables across a 20-m isobath around southern Lake Michigan. The cross-shore fluxes varied significantly with time during March of 1998 and 1999. Although the features of the 1998 and 1999 suspended sediment plumes differed considerably, the cross-shore fluxes of phosphorus and phytoplankton were coherent with wind magnitude and direction (Figure 9). The fluxes increased with wind speed and changed sign as the wind turned its direction. Offshore fluxes resulted from southward, southwestward or southeastward winds, whereas, onshore fluxes resulted from northward, northwestward or northeastward wind. These results suggest that in southern Lake Michigan the cross-shore fluxes of biological variables were mainly driven by the wind-induced water circulation. The spatial distributions of nutrients, phytoplankton and bacteria, to a certain extent, are controlled by physical processes associated with water circulation and turbulent mixing.

3.4. Model-Data Comparison

[26] Model-predicted phosphorus was in reasonable agreement with water samples collected on the three transects at Gary, St. Joseph, and Muskegon in 1998 and the five transects at Gary, St. Joseph, Muskegon, Racine and Chicago in 1999 (Figure 10). Phosphorus concentration within the plume was significantly higher in 1998 than 1999. For example, at the Gary transect, phosphorus concentration was 0.05 μmol P/L in March 1998, but it was only 0.01 μmol P/L in 1999. This raises a fundamental question regarding the annual variation of nutrients in southern Lake Michigan. In the 1998 experiment, the model without nutrients released from suspended sediment failed to capture the high concentration of phosphorus within the plume, which suggests that benthic flux played a critical role in supplying nutrients in the sediment suspension area. When sediment resuspension occurred, detritus in the benthic layer was carried up into the water column where it was converted to inorganic nutrients through the remineralization process. In the 1998 numerical experiments, the benthic flux was unknown in the field measurement, so as a first step, we simply assumed that the suspended detritus-generated nutrient was proportional to the total concentration of suspended sediment. For a given release rate of 0.5×10^{-3} μmol P mg^{-1} d^{-1}, the model provided a reasonable simulation of phosphorus within the plume. This success implies a linear relationship between detritus and sediment

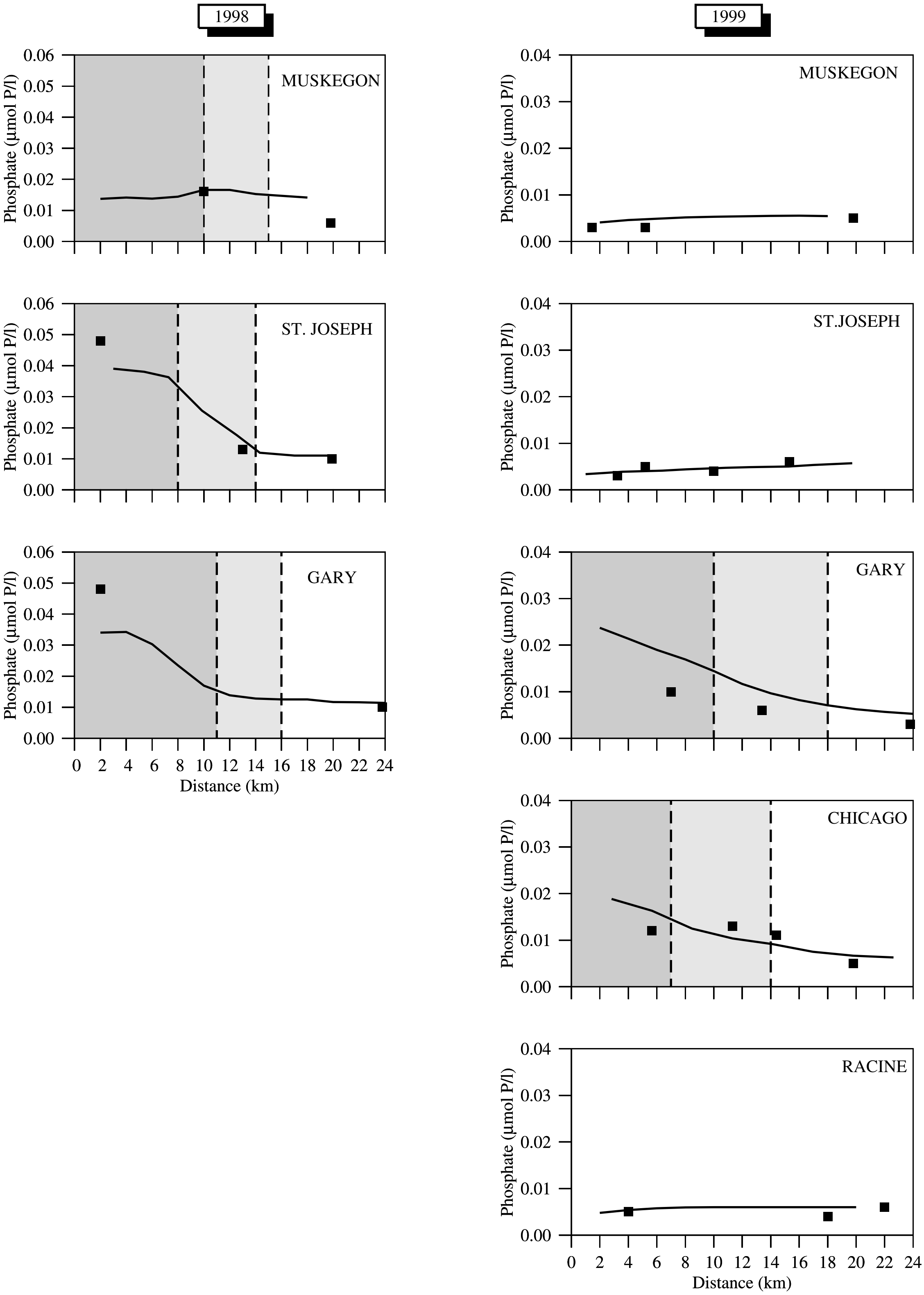

Figure 10. Comparison between model-computed and observed phosphorus concentrations on the Gary, St. Joseph, and Muskegon transects in March 1998 and on Gary, St. Joseph, Muskegon, Chicago, and Racine transects in March 1999. Solid squares are water samples, and curvature lines are model results.

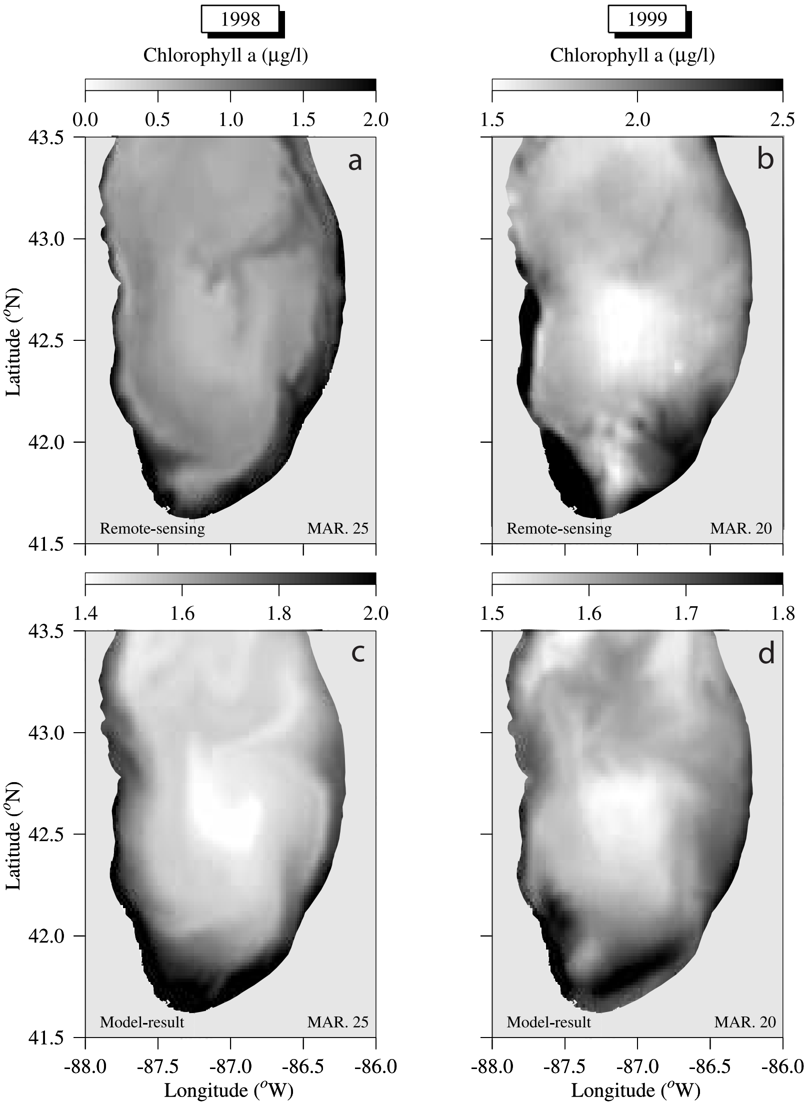

Figure 11. Comparison of the surface distributions of satellite-derived and model-computed chlorophyll *a* concentrations in southern Lake Michigan on 25 March 1998 and 20 March 1999.

concentration in the nearshore region of southern Lake Michigan in March 1998. If this relationship did not change with time, the model should capture the spatial distribution of nutrients in 1999. However, even if the nutrient rate was dropped to 0.15×10^{-3} μmol P/mg, the model still overestimated the concentration of phosphorus within the plume for the March 1999 experiment. This fact suggests that there was a significant annual or spatial variability of detritus concentration and/or the release of inorganic nutrients from suspended sediments in the nearshore region of southern Lake Michigan. Moreover, this finding is consistent with previous sediment trap measurements conducted by *Eadie et al.* [1984].

[27] The model-predicted total phytoplankton abundance (a sum of small and large phytoplankton abundances) was compared with the remote sensing-derived chlorophyll *a* concentration on the surface in 1998 and 1999. In 1998, the SeaWiFS chlorophyll a ($C_{OC\text{-}2}$) satellite image on 25 March showed a relatively high concentration zone of chlorophyll *a* along the eastern and western coasts of the southern basin. The high chlorophyll *a* concentration was advected offshore around Grand Haven and flowed following a cyclonic circulation to form a donut-like distribution pattern in the interior (Figure 11a). The model-predicted chlorophyll *a* was characterized by a high concentration zone around the eastern and western coasts, an offshore extension of the immediate high concentration around Grand Haven, noticeably high chlorophyll *a* concentration zone following a cyclonic circulation gyre, and a lower concentration in the center (Figure 11c). This model-predicted spatial distribution of chlorophyll *a* concentration was robustly consistent with the remote sensing chlorophyll *a* image. In 1999, the satellite image on 20 March showed a relatively high concentration zone of chlorophyll *a* around the southern coast. A tongue-like lower concentration area of chlorophyll *a* was found east of Gary, which was consistent with a southward intrusion of the interior water found in the distribution of currents and temperature shown in Figure 5. These spatial distributions of the chlorophyll *a* concentration were reproduced by the model (Figure 11d), though model-predicted concentration

of chlorophyll *a* was relatively lower than satellite-derived chlorophyll *a* observations.

[28] The model-predicted chlorophyll *a* concentration also was in reasonable agreement with water samples taken on cross-shore transects around the coast in southern Lake Michigan in 1998 and 1999 (Figure 12). In 1998, water samples were taken on different days on three cross-shore transects at Gary, St. Joseph, and Muskegon: 16 March on St. Joseph transect, 17 March on Gary transect, and 19 March on Muskegon transect. On the Gary transect, the model showed no significant cross-plume gradient of chlorophyll *a* concentration, which was consistent with the cross-shore distribution of observed chlorophyll *a* concentration. At the St. Joseph and Muskegon transects, water samples showed a relatively high concentration of chlorophyll *a* in the plume, which failed to be resolved by the model. Mismatching between model-computed and observed chlorophyll *a* concentration on these two transects was thought to be due in part to river fluxes, which were not accurately simulated in the 1998 numerical experiment [*Ji et al.*, 2002]. In 1999, water samples were collected along the Racine transect on 10 March, the Chicago transect on 11 March, the Gary transect on 12 March, the St. Joseph transect on 13 March, and the Muskegon transect on 14 March. Gary and Chicago transects were across the plume, while Muskegon, St. Joseph, and Racine were outside the plume. Water samples clearly showed that chlorophyll *a* concentrations decreased shoreward on the cross-plume Gary and Chicago transects. There was no significant cross-shore gradient on the Muskegon and Racine transects outside of the plume, and chlorophyll *a* concentrations increased gradually shoreward on the St. Joseph transect. The model reproduced relatively uniform distributions of chlorophyll *a* concentrations on the cross-shore Muskegon and Racine transects, but failed to capture the shoreward decrease or increased chlorophyll *a* concentrations at the Gary and Chicago transects and St. Joseph transect, respectively.

[29] Synthetic analysis of controlling terms in growth of phytoplankton suggests that the failure to reproduce the cross-shore distribution of chlorophyll *a* concentration observed in March 1999 was due to inaccurate determination of the light attenuation coefficient within the plume. In 1998, the dissolved phosphorus concentration within the plume was at a saturation level. Light reduction and phosphorus increase within the plume led to a relatively uniform cross-shore distribution of chlorophyll *a* in the nearshore region. In 1999, the dissolved phosphorus concentration within the plume was a slightly lower than the saturation level ($0.7 \sim 0.8$ μmol L^{-1}). If the cross-plume light attenuation coefficient was the same as that in 1998, then the chlorophyll *a* concentration should have decreased toward the shore because of the increase of sediment suspension. Without including the river flux, our model seemed to overestimate the concentration of chlorophyll *a* within the plume for both 1998 and 1999. Light attenuation coefficients used in the model experiments were determined by a regression function between sediment concentration and water samples, which might not resolve the spatial variation of the light attenuation coefficient. In addition, a constant phosphorus flux was specified for all the rivers. This assumption ignored the variability in nutrient concentrations among rivers, which might be directly related to the spatial distribution of the chlorophyll *a* in the nearshore region.

[30] Recently Vanderploeg examined the impact of flocculation of phytoplankton in the very high sediment concentration area on the spatial distribution of chlorophyll *a* concentration in southern Lake Michigan (H. Vanderploeg, personal communication). His studies suggest that the high shear rates in some nearshore areas may increase collisions between sediment and phytoplankton. He also found that zebra mussels, which were highly abundant in the Chicago area, may be responsible for a low concentration of phytoplankton there. The failure to resolve the nearshore low concentration of chlorophyll *a* in our model experiment seemed to support the turbulence and biological cases suggested by Vanderploeg.

3.5. Fluxes Within the Food Web

[31] The monthly averaged fluxes of biological variables within the food web were estimated at selected sites A, B, and C for the March 1998 and 1999 experiments, respectively (Figure 13). Without accounting for the effects of advection and diffusion, the temporal variation of phosphorus, phytoplankton, zooplankton, detritus and bacteria at these selected sites were controlled by the net flux of each variable. Phosphorus was maintained through phosphorus release from suspended sediments (external loading) and detritus remineralization $D \rightarrow P$ (internal recycling). Growth of large or small phytoplankton was determined by flux of $P \rightarrow P_L$ or P_S minus flux of $P_L \rightarrow Z_L$ and $P_L \rightarrow D$ or flux of $P_S \rightarrow Z_S$ and $P_S \rightarrow D$. Growth of large zooplankton was supported by flux of $P_L \rightarrow Z_L$ and $Z_S \rightarrow Z_L$ minus flux of $Z_L \rightarrow D$, while growth of small zooplankton depends on flux of $P_S \rightarrow Z_S$ and $B \rightarrow Z_S$ minus flux of $Z_S \rightarrow D$ and $Z_S \rightarrow Z_L$. The source of detritus came from death of phytoplankton and zooplankton through fluxes of $P_L \rightarrow D$, $P_S \rightarrow D$, $Z_L \rightarrow D$, $Z_S \rightarrow D$ and $B \rightarrow D$. Growth of bacteria was controlled by flux of $D \rightarrow B$, $P \rightarrow B$ minus flux of $B \rightarrow D$ and $B \rightarrow Z_S$.

[32] At the nearshore sites A (for the 1998 plume) and C (for the 1999 plume) of southern Lake Michigan where recurrent plumes developed, the phosphorus supply in March was dominated by external loading. The model-predicted monthly averaged net increase of phosphorus was 0.22 μmol C/L in 1998 while it was only about 0.09 μmol C/L in 1999, suggesting that phosphorus in the nearshore region increased at a much higher rate in 1998 than in 1999. The model-predicted monthly averaged net increase of phytoplankton (a sum of large and small phytoplankton) was 0.96 μmol C/L in 1998 while it was only about 0.77 μmol C/L in 1999. In both 1998 and 1999, the flux contributed to growth of large zooplankton was supplied comparably from small zooplankton and large phytoplankton. The monthly averaged net increase of large zooplankton was about 0.42 μmol C/L in 1998 and 0.12 μmol C/L in 1999. Phosphrous was consumed by both bacteria and phytoplankton in 1998 but was taken up by mostly phytoplankton in 1999. The monthly averaged net increase of bacteria was 1.19 μmol C/L in 1998 and 0.6 μmol C/L in 1999. Similarly, growth of small zooplankton was mainly supported by the flux from bacteria and its monthly averaged net increase was 0.19 μmol C/L in 1998 and 0.15 μmol C/L in 1999. Detritus also showed a net increase of 0.44 μmol C/L in 1998 and 0.21 μmol C/L in 1999.

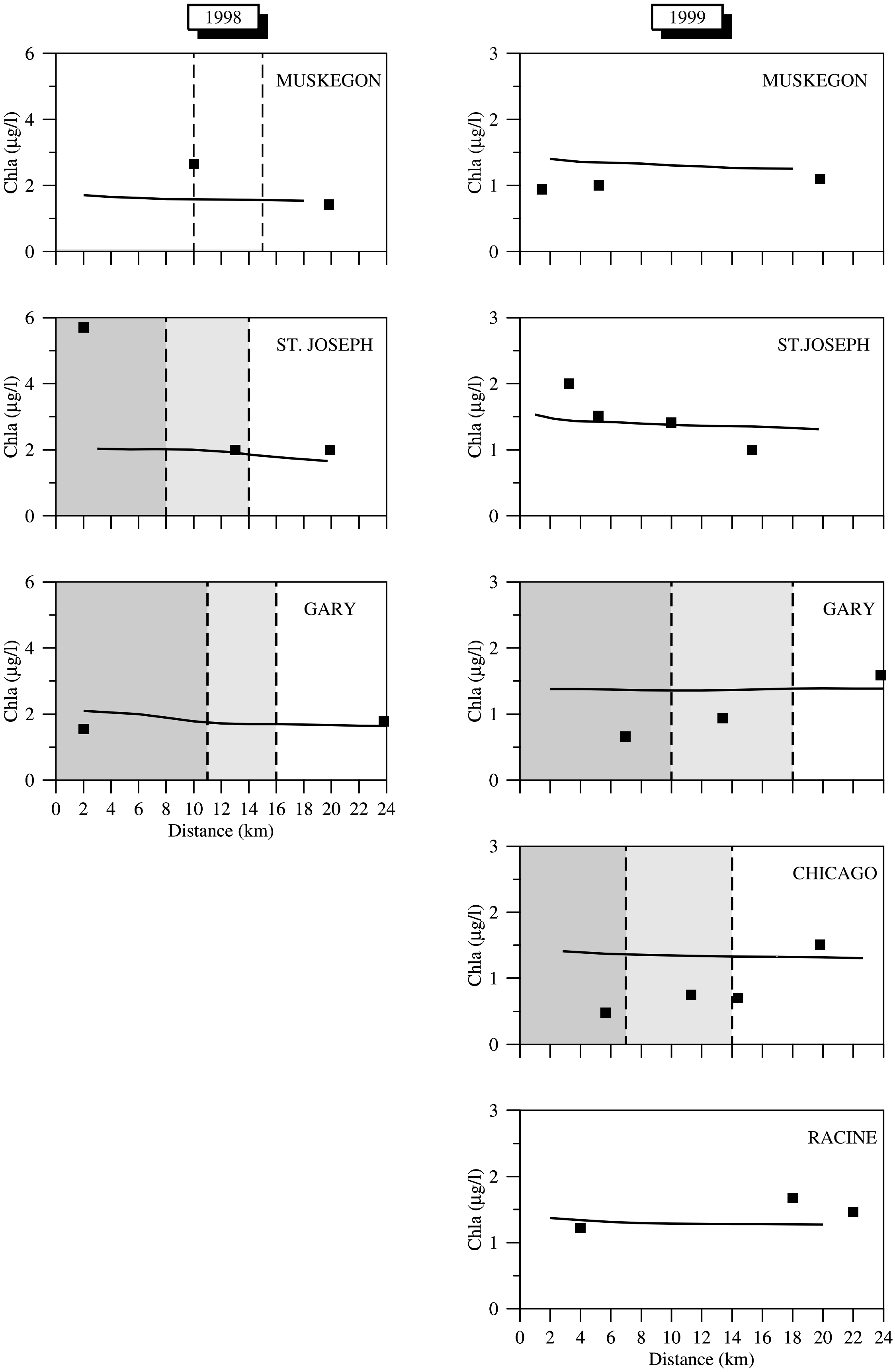

Figure 12. Comparison between model-computed and observed chlorophyll *a* concentrations on the Gary, St. Joseph, and Muskegon transects in March 1998 and on Gary, St. Joseph, Muskegon, Chicago, and Racine transects in March 1999. Solid squares are water samples, and curvature lines are model results.

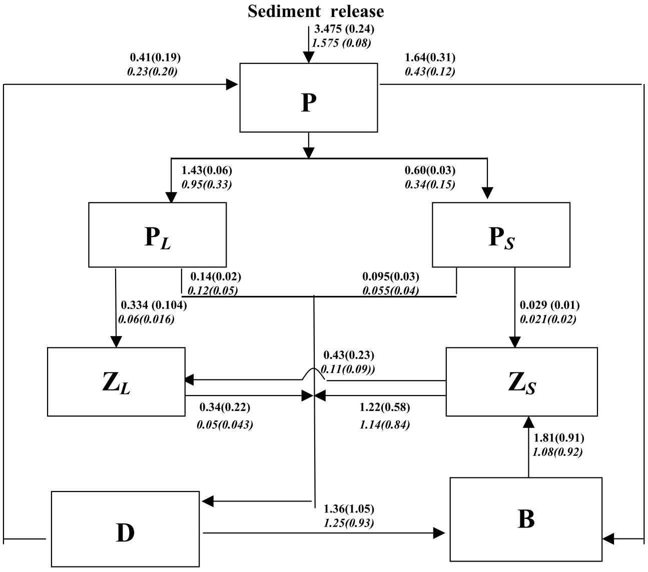

Figure 13. The model-predicted monthly averaged fluxes of biological variables among the food web inside and outside the plume for March of 1998 and 1999. The flux outside the plume was written within the brackets. The flux unit was μmol C L^{-1} d^{-1}.

[33] At site B in the interior of southern Lake Michigan, the phosphorus was maintained equally by external loading and internal recycling. The monthly averaged net flux to phosphorus was 0.03 μmol C/L in 1998 and −0.32 μmol C/L in 1999. This suggests that phosphorus in the interior was mainly supplied through physical processes of advection and diffusion. The monthly averaged net fluxes to phytoplankton, large zooplankton and small zooplankton were −0.07, 0.04, and 0.11 μmol C/L in 1998 and −0.01, −0.03, and 0.01 μmol C/L in 1999. Unlike in the nearshore region where the phosphorus was consumed by bacteria and phytoplankton, phosphorus in the interior was primarily taken up by bacteria in 1998 and by phytoplankton in 1999. Similar to those found in the nearshore region, growth of bacteria and small zooplankton were attributed to the flux of D→B and B→Z_S, respectively.

[34] Although the fluxes probably were not accurate because there were no data to calibrate them, the relative large flux values of phosphorus, phytoplankton, zooplankton, bacteria and detritus in the nearshore region agreed well with previous field measurements and modeling efforts [*Fahnenstiel and Scavia*, 1987a, 1987b; *Fahnenstiel et al.*, 1998; *Cotner*, 2000]. This pattern remained the same in 1998 and 1999, which also was consistent with our previous 1-D simulation of phosphorus and chlorophyll *a* in 1994 and 1995.

[35] Our model experiments show that regardless of region (i.e., nearshore or interior), bacteria were a key element controlling the growth of microzooplankton in early spring in southern Lake Michigan. A useful first-order approximation of the lower trophic level food web system in southern Lake Michigan is that of two decoupled loops: (1) detritus-bacteria-microzooplankton-large zooplankton and (2) nutrient-phytoplankton-detritus, based on our results that indicate fluxes of P_L→Z_L and P_S→Z_S are one order of magnitude smaller than fluxes of Z_S→Z_L and B→Z_S. This finding is similar to our results from previous 1-D and 3-D modeling experiments.

4. Discussion

[36] Our numerical experiments suggest that bacteria played an important role in the food web balance in early spring in southern Lake Michigan, and growth of bacteria was mainly supported by the detrital pool. This feature remained unchanged from 1998 to 1999, although the sediment resuspension frequencies, spatial distributions and intensities of plumes between these 2 years were significantly different. The role of bacteria in freshwater ecosystems has received a great deal of attention in recent field measurements [*Toolan et al.*, 1991; *Coveney and Wetzel*, 1992; *Morris and Lewis*, 1992; *Cotner*, 2000]. Moreover bacteria are important competitors with phytoplankton for dissolved inorganic phosphorus (DIP) [*Currie and Kalff*, 1984; *Cotner and Wetzel*, 1992; *Vadstein et al.*, 1993]. As one component of the EEGLE field measurement program, *Cotner* and his coworkers estimated the bacterial production and biomass in the March 1998 and 1999 plume event in southern Lake Michigan [*Cotner et al.*, 1999; *Cotner*, 2000; *Biddanda et al.*, 2001]. Their estimates revealed a high bacterial productivity and also a rapid increase in bacterial biomass in the plume in early spring of 1998 and 1999. On the basis of evidence from field measurements, they suggested that bacterial production in early spring in southern Lake Michigan was decoupled from primary production, consistent with model results presented here.

[37] A large DIP flux to bacteria and a net increase of bacterial biomass found in the nearshore region in early spring of 1998 and 1999 were consistent with previous field measurements done in other freshwater lakes and were in agreement with bacterial measurements in southern Lake Michigan described above. This further supports our contention that the influence of the resuspended sediments on the lower trophic level food web dynamics affected secondary production primarily related to heterotrophic bacteria rather than primary production related to the autotrophic processes.

[38] Flux estimates of phosphorus for March 1998 and 1999 suggest that phosphorus in the interior of the basin was supplied mainly through physical processes of current advection and diffusion. This was consistent with our finding of wind-induced cross-shore fluxes of nutrients, which showed significantly episodic offshore fluxes of nutrients driven by southward or southwestward winds during plume events. This result also implies that the ecosystem in the interior of Lake Michigan was maintained or controlled by the nearshore physical and biological processes, which could not be dynamically separated one from another.

[39] Our numerical experiments have raised a fundamental issue regarding the role of sediment suspension. Because there was no suspended sediment model available during our modeling efforts, the suspended sediment was included into the lower trophic level food web model by satellite-derived surface sediment concentration related empirically to satellite-derived sediment maps. This approach, however,

was only applicable in early spring when the water is vertically well mixed, and is one reason why our 3-D modeling experiments during the EEGLE program were focused on the early spring plume events in March for 1998 and 1999. In addition, because no benthic flux was included in our simulation, the external loading of nutrients into the system also was simplified and assumed to be proportional to suspended sediment concentration. This assumption was only true if the detritus concentration suspended from the bottom benthic layer during the plume events was proportional to suspended sediment concentration. Because the particle size distribution likely varied in 1998 and 1999 because of varying intensities of resuspension, this assumption may not hold. When the plume occurred, strong southward winds should cause a significant benthic flux of detritus into the water column. The remineralization rate of detritus to phosphorus probably was very high inside the plume. Our model experiments have shown that nutrients must be supplied from an external source since the recycling of nutrients in the water column was not sufficient to compensate for the loss of nutrients through uptake by phytoplankton and bacteria. One of the possible external sources was nutrients remineralized from suspended detritus. If this was the case, nutrients released from suspended sediments used in our model should belong to internal recycling rather than external loading. Since there were no data on nutrient release rates from suspended sediment, our modeling results are only meaningful for process studies on the driving mechanism of the ecosystem in early spring in southern Lake Michigan.

[40] Including the benthic flux seems to be critically important if one attempts to simulate the seasonal variability of the lower trophic level food web in Lake Michigan, especially for summer when stratification develops. To do this, we must provide the quantitative estimate of the role of benthic flux of detritus to heterotrophic production and nutrient supply in Lake Michigan. This estimation was made in our recent modeling efforts by including wave model to drive the benthic flux in our ecosystem model. This work was written in a separate paper [*Chen et al.*, 2004].

5. Summary

[41] The influence of a reflective, recurrent coastal plume on the lower trophic level food web system in Lake Michigan was examined using a 3-D coupled physical and biological model. The coupled model was driven by real-time wind and heat fluxes, initialized with wintertime climatologic, physical, and biological fields, and run prognostically with the input of the real-time suspended sediment concentration derived directly from temporally and spatially interpolated satellite images. Numerical experiments were conducted for the March 1998 and 1999 plume events. The comparison between results of these 2 years shows that the spatial distribution of the biological field was closely related to the physical environment of wind-induced 3-D circulation and mixing. The influence of suspended sediment plumes on the lake ecosystem is mainly reflected in heterotrophic production rather than in autotrophic production.

[42] Inside the plume, nutrient levels were maintained through nutrient release from suspended sediments, while in the interior, nutrients were supported by physical processes of current advection and diffusion. The cross-shore fluxes of nutrients were mainly driven by episodic wind events with a period of about 5 to 7 days. Fluxes were offshore during northerly winds and onshore during southerly winds.

[43] Flux estimation among biological variables suggests that the microbial loop played an important role in the ecosystem balance during plume events in early spring in southern Lake Michigan. Bacteria were competitors with phytoplankton for DIP and also a key food source for growth of microzooplankton inside and outside the plume. The lower trophic levels could be divided into two decoupled loops: (1) detritus-bacteria-microzooplankton-large zooplankton loop and (2) nutrient-phytoplankton-detritus loop.

[44] The model-predicted spatial distributions of nutrients and phytoplankton were in reasonable agreement with observations taken during the 1998 and 1999 EEGLE interdisciplinary cruises. The characteristics of the food web system revealed in our model experiments were consistent with observations made from previous field studies. All of these indicate that our model was robust enough to capture the basic seasonal variation of the ecosystem in Lake Michigan.

[45] Our modeling efforts in southern Lake Michigan have provided a higher level of understanding of the impact of suspended sediments on the food web system in freshwater lakes. Numerical approaches in this work could be directly applied to the ecosystem in high-turbidity coastal oceans and other freshwater lakes.

[46] It should be pointed out that the biological model shown in this work cannot be extended to simulate the seasonal variability of the lower trophic levels in Lake Michigan because benthic fluxes of detritus are unconstrained in the biological model. The 3-D structure of suspended sediments could be critically important in simulating summer conditions as stratification develops. One effort has been made to estimate quantitatively the relative importance of benthic flux in the ecosystem balance in southern Lake Michigan. A detailed discussion of this work is provided by *Chen et al.* [2004].

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