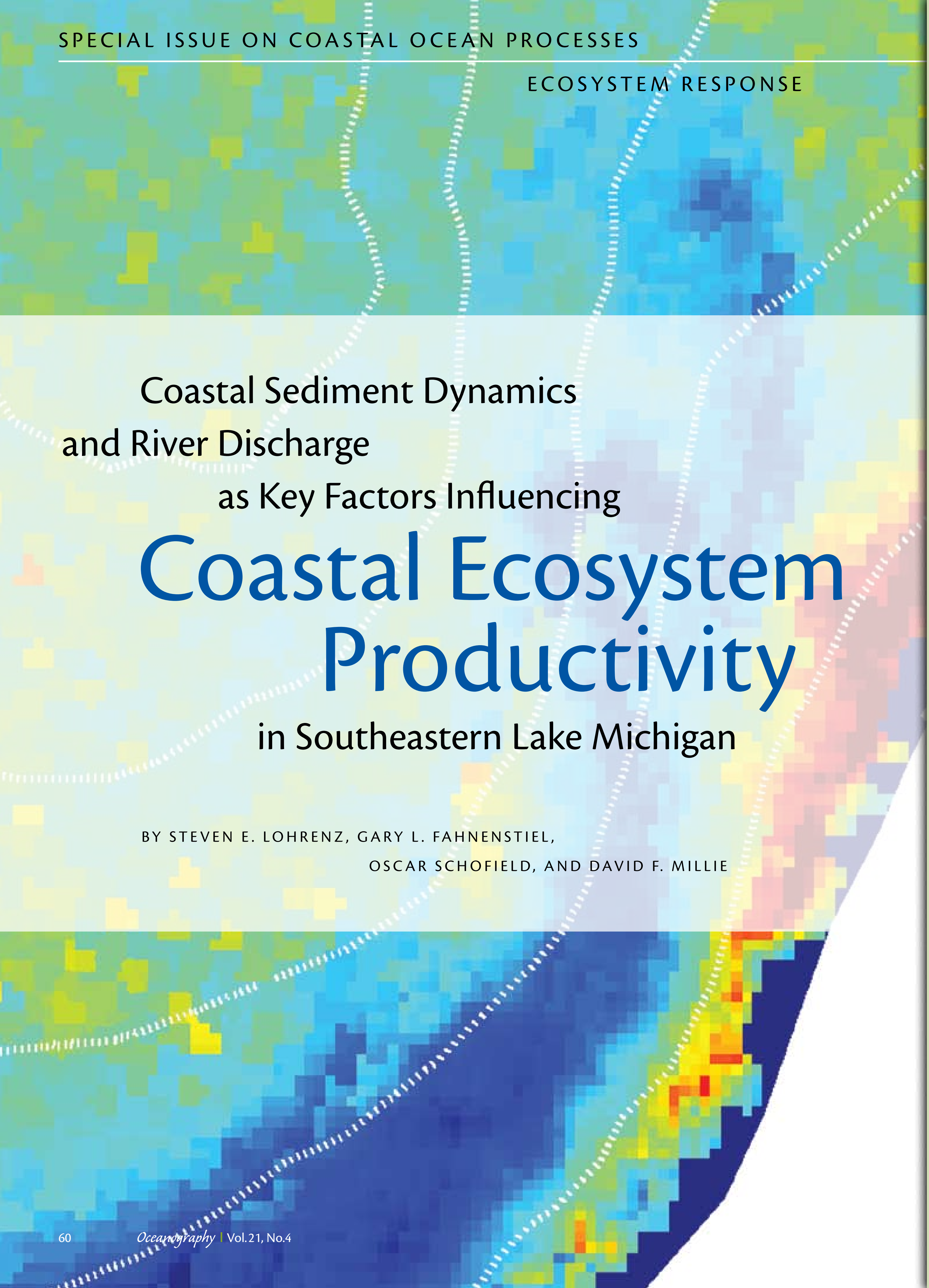

SPECIAL ISSUE ON COASTAL OCEAN PROCESSES

ECOSYSTEM RESPONSE

Coastal Sediment Dynamics and River Discharge as Key Factors Influencing Coastal Ecosystem Productivity in Southeastern Lake Michigan

BY STEVEN E. LOHRENZ, GARY L. FAHNENSTIEL, OSCAR SCHOFIELD, AND DAVID F. MILLIE

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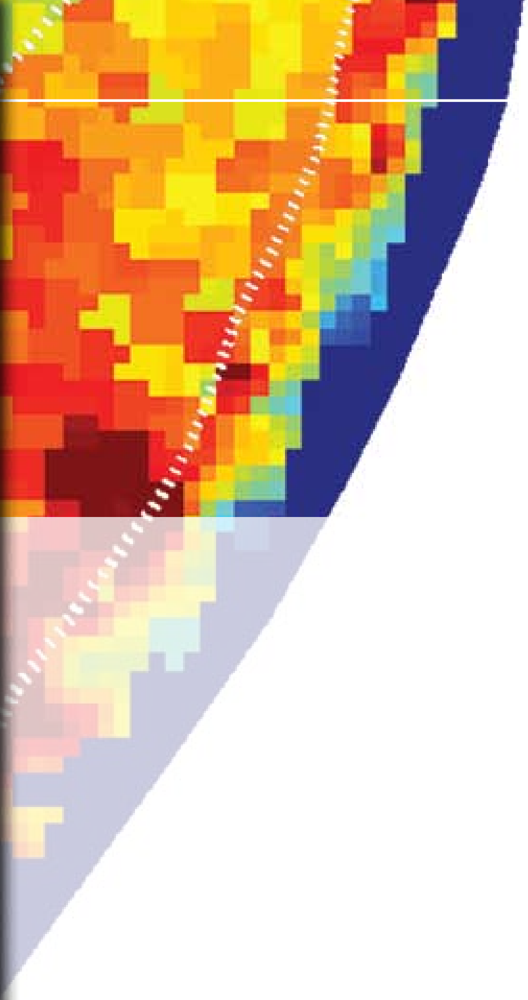

ABSTRACT. A central question addressed by the Episodic Events in the Great Lakes Experiment (EEGLE) was the extent to which the spring phytoplankton bloom in southern Lake Michigan is influenced by a recurrent coastal turbidity plume that results from wind-driven sediment resuspension and transport. Findings from a series of studies conducted as part of EEGLE during spring in 1998, 1999, and 2000 confirmed the importance of sediment processes as a factor influencing ecosystem productivity in southeastern Lake Michigan, but also identified interannual variability in river discharge as potentially important in regulating productivity in coastal waters. Here, we describe the application of satellite-derived and in situ optical observations to examine the impacts of the recurrent coastal turbidity plume (RCP) on light availability and phytoplankton productivity. A review and synthesis of prior work highlighted findings that sediment resuspension during the 1998 El Niño period, a time of intense winter storm activity and an unusually strong RCP, profoundly influenced optical properties in coastal waters, constraining phytoplankton growth and primary production. In contrast, in 1999, a moderate RCP coupled with relatively high discharge from the St. Joseph River led to a strong inner shelf optical signature indicative of elevated levels of dissolved organic matter and apparent enhancement of productivity. We speculate that future changes in climate are likely to alter sediment dynamics and river discharge with uncertain consequences for coastal ecosystem productivity and community structure in southeastern Lake Michigan as well as in other coastal systems.

INTRODUCTION

Light is a critical variable in the productivity of the Lake Michigan coastal ecosystem. Research conducted from 1998–2000 as part of the National Science Foundation (NSF)- and National Oceanic and Atmospheric Administration (NOAA)-funded Episodic Events in the Great Lakes Experiment (EEGLE) shed some "light" on just how much of an impact it can have and how much light can vary in response to climate-related fluctuations. Lake Michigan phytoplankton form the basis for the productivity of this important ecosystem. These single-celled microscopic organisms are the dominant form of plants in the Great Lakes, as well as in the world's ocean. Phytoplankton require light for photosynthesis and growth, but light can be in short supply at times. During what is referred to as the "isothermal period," which occurs in winter and spring, the Lake Michigan water column is generally well mixed. Deeply mixed water columns along with low sun angles and short days limit the amount of light available to phytoplankton and constrain photosynthesis and growth (Fahnenstiel et al., 2000; Vanderploeg et al., 2007). As light availability increases during the spring isothermal period, an annual, episodic diatom bloom is typically observed in southern Lake Michigan (Brooks and Torke, 1977; Fahnenstiel and Scavia, 1987). With the onset of thermal stratification later in spring and summer, nutrients in surface waters become depleted and productivity generally decreases. For this reason, the spring bloom represents an important event in the overall productivity of the southern Lake Michigan ecosystem (Brooks and Torke, 1977), and it is an important food source for invertebrates and fish (Gardner et al., 1990; Fitzgerald and Gardner, 1993).

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A central question of EEGLE was the extent to which the spring bloom in southern Lake Michigan was influenced by a recurrent coastal turbidity plume (RCP) (Mortimer, 1988; Eadie et al., 1996). The RCP is an episodic event resulting from wind-driven sediment resuspension and transport in coastal waters (Chen et al., 2004). The feature has generally been observed to occur in late winter to early spring, which coincides with development of the spring diatom bloom. Early studies of the RCP reported elevated phosphorus levels, leading to the supposition that the plume may be a significant source of nutrients and play an important role in the spring diatom bloom (Eadie et al., 1996). The EEGLE field efforts were conducted in 1998, 1999, and 2000. However, as we describe below, the RCP has a profound impact on the optical conditions of southeastern Lake Michigan coastal waters, which can negatively impact phytoplankton production.

Although the RCP is commonly observed in southern Lake Michigan during winter and early spring, the March 1998 event was especially intense. This event can be seen in a comparison of Advanced Very High Resolution Radiometer (AVHRR) reflectance images for March 1998, 1999, and 2000 (Figure 1). The intense RCP in March 1998 coincided with an unusually strong El Niño (Kerr, 1998; McPhaden, 1999), which was accompanied by reduced ice cover and strong winter storms with winds out of the north that generated large waves (Beletsky et al., 2003). A series of studies demonstrated that the resultant resuspension event that occurred in 1998 was accompanied by reduced light availability for photosynthesis (Chen et al., 2004; Lohrenz et al., 2004; Vanderploeg et al., 2007).

Here, we review and synthesize findings using remote and in situ optical approaches to examine the influence of episodic environmental forcing on light availability and phytoplankton

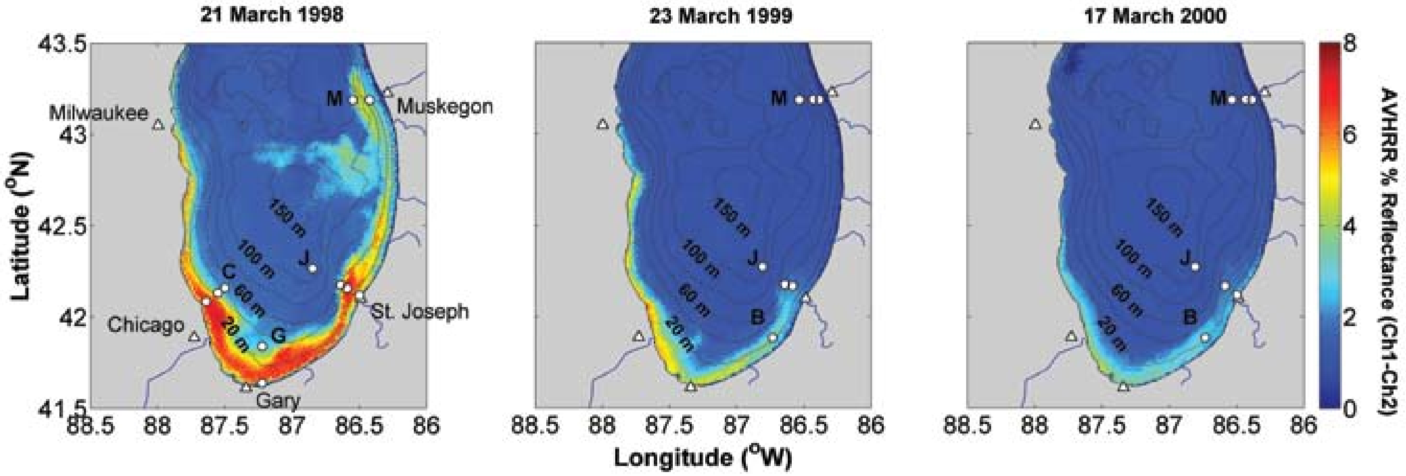

Figure 1. Percent reflectance determined from Advanced Very High Resolution Radiometer (AVHRR) imagery (channel 1 minus channel 2) during March in 1998–2000. Imagery was acquired from the NOAA Comprehensive Large Array-data Stewardship System (CLASS) and processed and mapped using the Coastwatch Data Analysis Tool v3.2.2 and MATLAB v7.6.0.

productivity. Specifically, we examine the utility of optical measurements and analyses using available algorithms to characterize temporal and spatial variations in sediment distributions and their impact on lake optical properties, and we trace inputs of river-borne materials in coastal waters; we also assess changes in lake autotrophic productivity related to these impacts. We summarize results from a combined approach using in situ optical measurements and remote sensing to characterize sediment distributions and properties during resuspension events, we track algal distributions, and we assess basin-scale temporal and spatial patterns in primary production. Our synopsis reinforces findings presented in numerous prior publications that identify both sediment processes and river discharge as important environmental variables regulating interannual variability in ecosystem productivity. We conclude with a discussion of how projected changes in climate and associated consequences for sediment dynamics and river discharge may alter the lake ecosystem through impacts on autotrophic productivity, phytoplankton community structure, and terrestrial inputs of materials.

THE IMPACT OF THE RCP ON OPTICAL CONDITIONS

Satellite observations revealed substantial year-to-year variability in AVHRR reflectance (Figure 1), which was representative of suspended sediment distributions (Chen et al., 2004; Lee et al., 2007; Vanderploeg et al., 2007). A more comprehensive illustration of the interannual variability in AVHRR reflectance can be viewed online (NOAA/GLERL, 2002). High sediment concentrations have a profound impact on light availability in the coastal zone. This relationship can be seen by examining AVHRR reflectance and the diffuse attenuation coefficient for downwelling irradiance, K_d (m^{-1}), which provides a useful index for characterizing light availability. The value of K_d at 490 nm, corresponding to the blue region of the visible light spectrum, is commonly used as an index of light attenuation. We observed a strong relationship between AVHRR reflectance and diffuse attenuation at 490 nm (Figure 2, right). Consistent with our findings, various other studies documented correlations between increased light attenuation and suspended sediment concentrations (Millie et al., 2003; Bergmann et al., 2004; Chen et al., 2004; Vanderploeg et al., 2007).

Light attenuation can be related to the inherent optical properties of scattering and absorption (Kirk, 1994). In situ measurements with optical instrumentation (WETLabs, Inc. *ac*-9 absorption and attenuation meter; c.f. Bergmann et al., 2004) during March 1999 provided evidence that the spatial patterns evident in AVHRR reflectance were associated with intense light scattering by suspended particles. Vertical profiles of light scattering due to particles at a wavelength of 532 nm (i.e., $b_p[532]$), were characterized by high values in the coastal waters, consistent with the AVHRR imagery (Figure 3). We chose here to use 532 nm as a representative wavelength of scattering, because there is less influence of

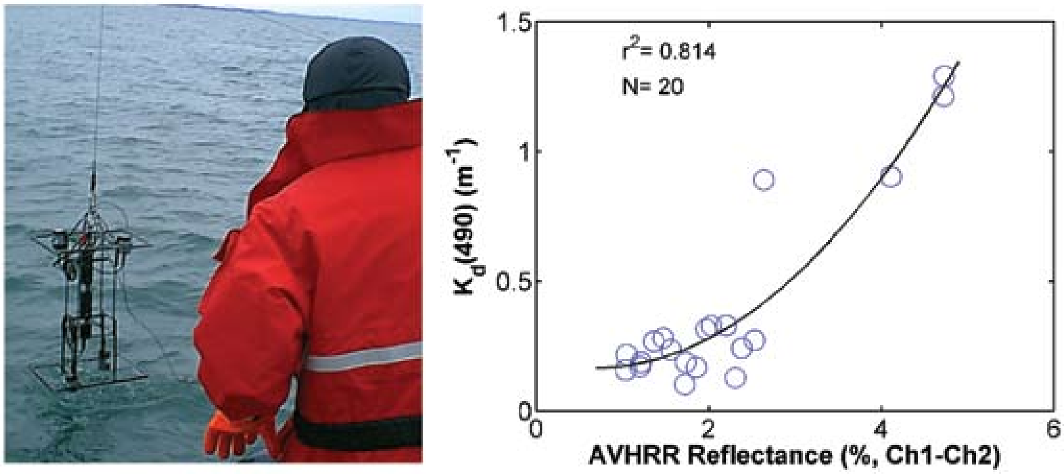

Figure 2. (Left) Photograph showing the lowering of a Satlantic profiling radiometer (Bergmann et al., 2004) during March 1999 for measuring diffuse spectral attenuation. (Right) Relationship between satellite-derived AVHRR reflectance and diffuse attenuation at 490 nm, $K_d(490)$. The outlier point is from station J10, which was influenced by outflow from the St. Joseph River.

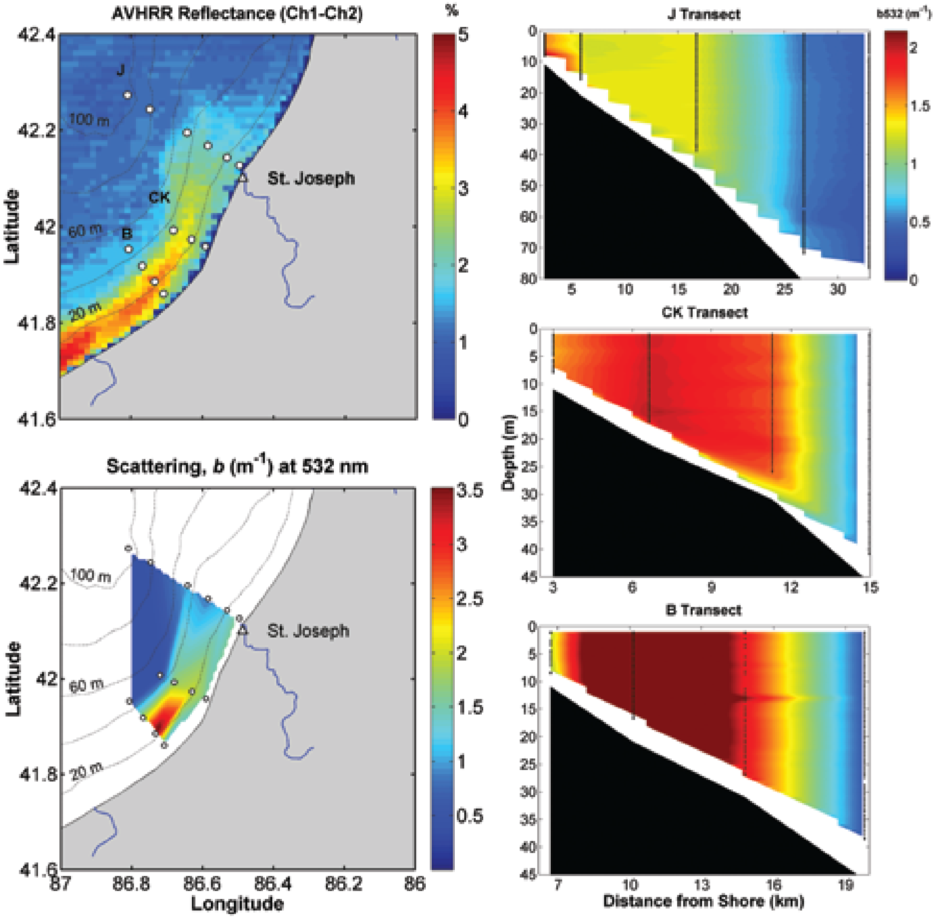

Figure 3. The RCP was evident as high AVHRR reflectance in the St. Joseph region of southeastern Lake Michigan (upper left). In situ instrumentation (WETLabs, Inc. *ac*-9) revealed a consistent pattern of high scattering by particles at 532 nm, $b_p(532)$ (lower left). Profiles of particulate scattering (at right) showed uniform vertical distributions of scattering and strong cross-shelf and along-shelf gradients.

absorption by water and other substances at this wavelength. From examination of the vertical profiles of $b_p(532)$, it was evident that particles were generally uniformly distributed vertically in the water column and showed strong gradients in concentrations both across and along the southeastern Lake Michigan shelf. The high values of scattering and reflectance could be largely attributed to elevated sediment concentrations. Indeed, for the 1999 field season, we observed a strong relationship between $b_p(532)$ and total suspended matter concentrations as determined by filtration (Figure 4, upper right). Such an observation was consistent with prior work showing high correlation between beam attenuation at 630 nm and suspended particulate matter concentration (Bergmann et al., 2004). The beam-attenuation measurement includes effects of both light scattering and absorption.

To further examine the relationship between inherent optical properties and water column environmental conditions, we compared the magnitude of particulate scattering at three different stations, including one in the RCP (Station B20), one influenced by both the RCP and the outflow of the St. Joseph River (J20), and an offshore station in relatively clear water (J110) (Figure 4, upper left). Scattering was highest at B20 in the core of the RCP, and decreased sequentially from J20 to J110. The three different stations also showed distinct differences in the magnitudes of absorption due to particles (a_p) and colored dissolved organic matter (a_{CDOM}) (Figure 4, lower left). Measurements of a_{CDOM} were made with the *ac*-9 equipped with a 0.2-µm pore size filter on the inlet. Values of a_p were determined by subtracting a_{CDOM} from unfiltered measurements of total absorption (excluding absorption due to water). The highest levels of a_p were observed in the RCP at Station B20, while the lowest values were seen offshore at Station J110. Distinct peaks in a_p spectra were evident at 676 nm and could largely be attributed to absorption by chlorophyll associated with phytoplankton. Indeed, a strong correlation was evident between $a_p(676)$ and measurements of chlorophyll (Figure 4, lower right). Highest a_{CDOM} was observed at the river-influenced Station J20, an indication of river inputs of terrestrially derived dissolved organic matter. These results illustrate the strong influence of sediment dynamics and biological materials on optical properties.

IMPACTS ON PHYTOPLANKTON GROWTH AND PHOTOSYNTHESIS

A consequence of the strong attenuation of light in the RCP was to reduce the light available for photosynthesis and growth of phytoplankton. For a given wavelength of light (e.g., 490 nm), the rate at which light decreases with depth can be described by the following equation:

$$E_d(z,490) = E_d(0^-,490)e^{-K_d(490)z}$$

where $E_d(z,490)$ is the downwelling irradiance at depth z, and $E_d(0^-,490)$ is the downwelling irradiance just below the water surface. During the spring isothermal period, we can reasonably assume that attenuation at a given wavelength is constant with depth, allowing us to use the simple expression above to model light fields.

Prior work examining the relationship of phytoplankton growth rates to available irradiance provided evidence of light limitation of growth at low irradiance levels (Fahnenstiel et al., 2000; Lohrenz et al., 2004). Using modeled estimates of light conditions in the RCP, Lohrenz et al. (2004) inferred that growth rates would have been light limited in waters as shallow as 5.4 m at Station J30 during March 1998. In contrast, at the same location, saturating light levels for growth extended to depths of 20 m during 1999 and 15.5 m during 2000. Vanderploeg et al. (2007) estimated photic depths (depth of 1% of surface irradiance) of 1–2 m in the plume region and concluded that such conditions would limit phytoplankton growth.

To examine the impact of the RCP on phytoplankton primary production, we applied a wavelength-resolved primary production model as described by Lohrenz et al. (2004). Model performance was previously shown to be most sensitive to chlorophyll and diffuse attenuation (Lohrenz et al., 2004). Here, we used satellite-derived chlorophyll estimates (Figure 5) as input to the model along with estimates of $K_d(490)$ derived from AVHRR reflectance, using the relationship given in Figure 2. Other inputs to the model included average values of photosynthetic parameters (Table 1), including the light-saturated rate of photosynthesis (P^B_{max}, g C g Chl^{-1} h^{-1}) and the maximum photosynthetic quantum yield (ϕ^C_{max} mol C fixed mol quanta^{-1}). More information about the implementation of the model can be found in Lohrenz et al. (2004).

The model relied on satellite-derived estimates of chlorophyll and, as was the case for AVHRR reflectance, chlorophyll distributions estimated from SeaWiFS ocean color imagery showed distinct differences among years (Figure 5, left column). Satellite-derived distributions of chlorophyll showed strong cross-shelf gradients with generally higher values nearshore. The satellite-derived distributions were generally comparable in magnitude to determinations of chlorophyll in discrete water samples (Figure 5, left column), including analyses by high-pressure liquid chromatography (Millie et al., 2002), fluorometric assay (Lohrenz et al., 2004), or as derived from measurements of absorption using the relationship given in Figure 4 (lower right). There were differences, and the complex

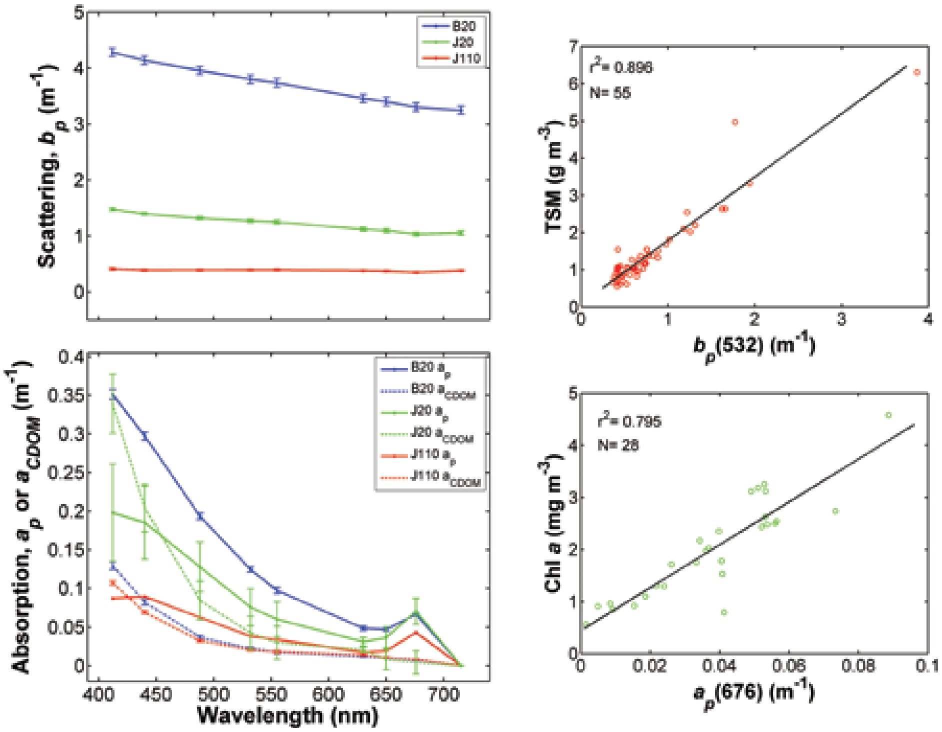

Figure 4. Magnitudes of spectral particulate scattering (b_p) (upper left) varied from highest in the RCP (Station B20), to moderate in the vicinity of the St. Joseph River outflow (Station J20), to relatively low offshore (Station J110). A strong correlation was evident between particulate scattering at 532 nm, $b_p(532)$ and total suspended matter determined as in Millie et al. (2002) (upper right). Differences were also evident between stations in magnitudes of spectral particulate absorption (a_p) and absorption due to colored dissolved organic matter (a_{CDOM}) (lower right). Highest values of a_p were observed in the RCP at Station B20, while highest a_{CDOM} was associated with Station J20, which was influenced by outflow from the St. Joseph River. An absorption peak was evident in the a_p spectra at 676 nm, which was largely due to chlorophyll in phytoplankton. This relationship was evidenced by a strong correlation between $a_p(676)$ and chlorophyll determined by fluorometric analyses on filtered samples (lower right).

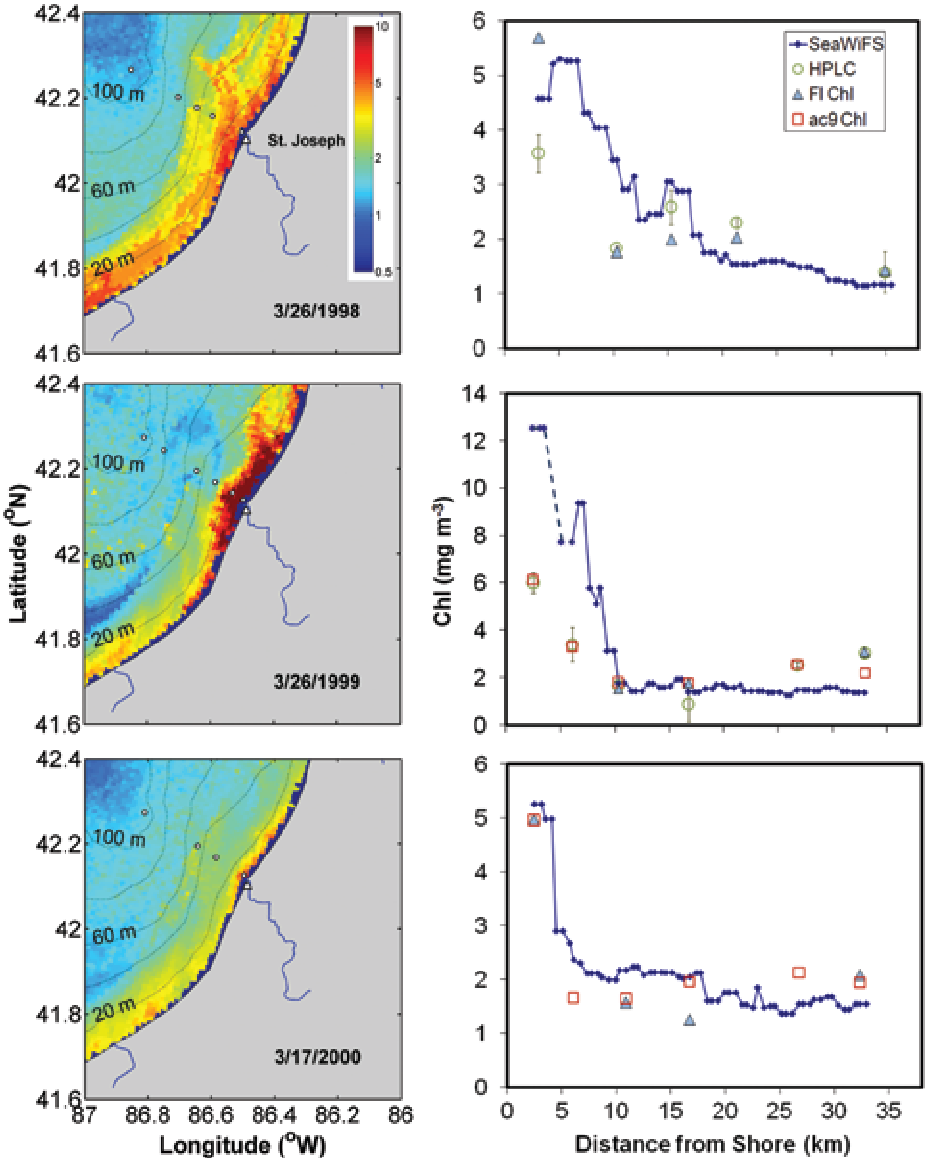

Figure 5. Distributions of phytoplankton chlorophyll were evident in ocean color images acquired by the Sea-viewing Wide Field of View Sensor (SeaWiFS) for southeastern Lake Michigan during March 1998, 1999, and 2000 (left column). Satellite chlorophyll was derived using the ocean color chlorophyll 2 (OC2) algorithm (O'Reilly et al., 1998). Values greater than 15 mg m^{-3} were excluded in 1999 (dashed line in middle right panel). In the panels to the right of each image, estimates of SeaWiFS chlorophyll were compared to determinations on discrete samples, including high-pressure liquid chromatography (HPLC; Millie et al., 2002), fluorometric assay (Fl Chl; Lohrenz et al., 2004), and as derived from relationships to $a_p(676)$ determined with the *ac*-9 as in Figure 4.

optical environment in coastal Lake Michigan posed significant challenges for ocean color algorithms (e.g., Mortimer, 1988; Bergmann et al., 2004; Darecki and Stramski, 2004). Differences were particularly evident in nearshore waters during March 1999. These differences coincided with a period of relatively high river discharge (see Lohrenz et al., 2004) and, as noted in Figure 4, our observations confirmed the presence of high colored dissolved organic matter (CDOM) in nearshore waters. High CDOM will interfere with the ocean color chlorophyll 2 algorithm (OC2) and was likely responsible for the anomalously high chlorophyll values observed at inshore locations (Figure 6). Indeed, as Mortimer (1988) so aptly pointed out:

> *This discussion and the results presented here lead to the conclusion that simultaneous presence of Chl [chlorophyll], SM [suspended minerals], and DOC [dissolved organic carbon] in many coastal waters is the central barrier to development of universal as opposed to local, empirically derived algorithms for full exploitation of remote sensing as a quantitative tool.*

In addition to overestimation in nearshore waters close to the river outflow, the OC2 algorithm tended to underestimate chlorophyll in offshore waters in 1999 and 2000. Bergmann et al. (2004) noted that, due to their unique optical properties, the presence of high abundances of cryptophytes (microscopic unicellular algae that occur in freshwater and marine habitats) introduced bias into estimates of chlorophyll using the OC2 algorithm. Consistent with this argument, Millie et al. (2002, 2003) observed higher relative abundance of cryptophytes in March 1999 as compared to March 1998, and also observed an increasing trend in the relative fraction of total chlorophyll associated with cryptophytes going from nearshore to offshore in 1999. In contrast, in 1998, diatom taxa generally accounted for the largest fraction of chlorophyll. Such interannual differences in phytoplankton community structure provide further evidence of the profound impact of the RCP on the ecosystem. Sensitivity of other trophic levels to the effects of the RCP has also been reported

(Vanderploeg et al., 2007).

Despite the inconsistencies between in situ and satellite-derived assessments of chlorophyll distributions, the satellite-derived estimates were nonetheless representative of trends in chlorophyll distributions. Such findings were consistent with those of other studies that have found satellite estimates of chlorophyll to correctly represent spatial and temporal trends in coastal waters despite bias in absolute accuracy (Harding et al., 2005).

Acknowledging the potential biases in satellite-derived estimates of biomass, we elected to use satellite observations as input to the primary production model to assess the impacts of the RCP on regional patterns in primary production. The modeled estimates of primary production illustrated the profound impact of the RCP on ecosystem productivity in southeastern Lake Michigan (Figure 6). Distinctly different patterns were evident for the three different years, and we argue that these differences were largely attributable to the following major factors: the intensity and extent of the RCP and the magnitude of river discharge. During the intense 1998 RCP event, a region of low productivity along the coastal margin of southeastern Lake Michigan was evident and coincided with the RCP (Figure 6, upper panel). In 1999, there was again a moderate suppression of primary production by the less-extensive RCP during that period. However, the model yielded much higher productivity inshore of the RCP event (Figure 6, middle panel). In 2000, which coincided with the weakest RCP event, the effect of the RCP was limited only to the southern portion of the lake, and no strong cross-shelf gradient in primary production was evident as was the case in 1998 and 1999.

Our satellite values of primary production were comparable in range to those reported in Lohrenz et al. (2004), which were derived using a similar model but with ship-based observations as input at individual stations. For example, primary production modeled from ship-based observations for Station J30 in March 1998 was 0.08 g C m^{-2} d^{-1} (Lohrenz et al., 2004), while the satellite-derived value for this location was 0.13 g C m^{-2} d^{-1}. In 1999, the range of ship-based estimates at individual stations in the southeastern region of the lake was 0.18–0.48 g C m^{-2} d^{-1} compared to 0.18–0.24 g C m^{-2} d^{-1} for satellite-derived estimates. In 2000, ship-based

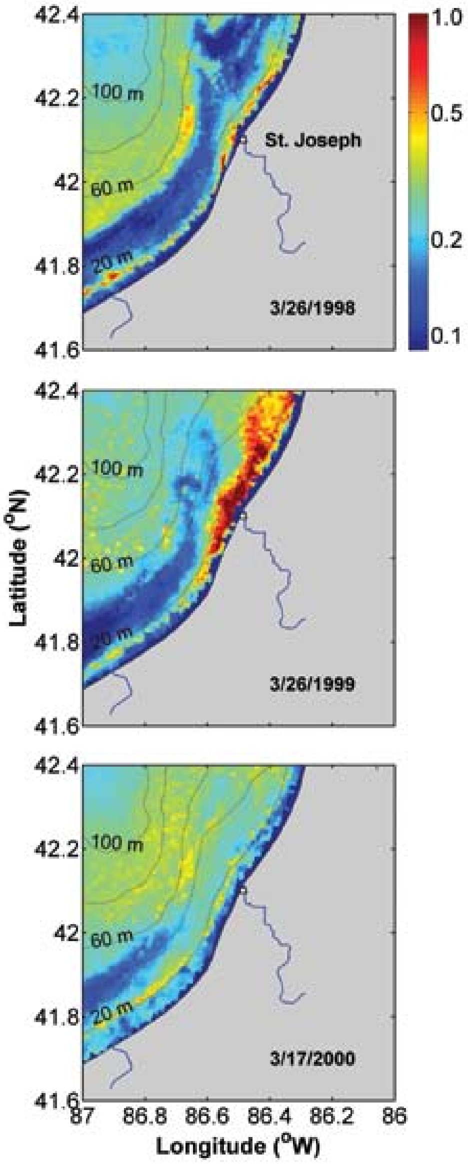

Figure 6. Satellite-derived primary production in units of g C m^{-2} d^{-1} was determined for southeastern Lake Michigan during March 1998, 1999, and 2000 using a wavelength-resolved primary production model (Lohrenz et al., 2004). A clear impact of the RCP was evident, especially in March 1998 (top panel). An influence of inputs from the St. Joseph River can be seen in the inner shelf region during March 1999.

Table 1. Averages (and standard deviations) of photosynthetic parameters used in the wavelength-resolved model for satellite-derived estimates of primary production during March.

Year	P^B_{max} g C g Chl^{-1} h^{-1}	ϕ^C_{max} mol C fixed mol quanta^{-1}
1998	2.0 (0.6)	0.036 (0.16)
1999	1.3 (0.3)	0.034 (0.10)
2000	1.5 (0.2)	0.042 (0.009)

measurements in the southeastern region of the lake ranged 0.19–0.37 g C m^{-2} d^{-1} compared to 0.15–0.46 g C m^{-2} d^{-1} for satellite-derived values.

Unfortunately, no ship-based measurements of primary production were made at river-influenced stations J10 and J20 during 1999, where satellite-derived values were 0.51 and 0.72 g C m^{-2} d^{-1}, respectively. It is very likely that these high estimates of inshore primary production in March 1999 were to some extent an artifact of the anomalously high chlorophyll values derived from the satellite imagery (Figure 6). Even so, an enhancement of inshore production due to river inputs is a reasonable supposition. Lohrenz et al. (2004) reported that lake water enriched with water from the St. Joseph River exhibited elevated levels of chlorophyll, photosynthetic parameters, and phytoplankton growth rates. Other investigators have also argued that the rivers are a potential source of nutrients, dissolved organic matter, sediments, and chlorophyll (Schelske et al., 1980; Mortimer, 1988; Cotner et al., 2000; Biddanda and Cotner, 2002; Lohrenz et al., 2004). The overall importance of river influence on coastal ecosystem productivity is a subject that deserves further study.

CONCLUSIONS

In summary, we used a combination of satellite-derived and in situ optical observations to examine how weather- and climate-sensitive phenomena, such as sediment resuspension and river discharge, influence the coastal ecosystem in southeastern Lake Michigan. Our synthesis highlights the findings from a large body of work that suggests the intense sediment resuspension event observed during the 1998 El Niño period profoundly influenced optical properties in coastal waters, constraining phytoplankton growth and primary production. Projected changes in climate may lead to reduced ice cover in the Great Lakes (e.g., Magnuson et al., 1997) and increased frequency and intensity of extratropical storms (Trenberth et al., 2007). Such a scenario could lead to more intense and extensive RCP events, with profound consequences for ecosystem productivity. Climate assessments also documented increases in precipitation in regions north of 30°N latitude (Trenberth et al., 2007), which would presumably lead to increases in river discharge and delivery of terrestrial materials into the coastal regions. We observed that river discharge exhibited a more localized influence on optical conditions, and presumably biogeochemical conditions, apparently resulting in an enhancement of phytoplankton primary production during periods of high discharge and moderate RCP intensity. However, the extent of river impact on primary production remains unclear given the uncertainties in application of satellite-derived ocean color algorithms in complex coastal waters. Our results highlight the need for improved regional algorithms coupled with in situ observations. Further study is needed to evaluate whether increased precipitation, such as could occur in a warmer climate, may enhance coastal productivity in southeastern Lake Michigan and other river-impacted margins.

The combination of light limitation by the RCP and river enhancement of coastal productivity will result in a complex interaction between key factors driving climate-related change in the southeastern Great Lakes ecosystem. As is undoubtedly true for regions elsewhere in the Great Lakes as well as other coastal ecosystems, competing factors make it difficult to predict the outcome of climate-related change on the coastal ecological and net community productivity. Understanding and managing these precious systems will require vigilance and continued study as we traverse an uncertain path into the future.

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