An event-driven phytoplankton bloom in southern Lake Michigan observed by satellite

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[1] Sea-viewing Wide Field-of-View Sensor (SeaWiFS) images from June 1998 show a surprising early summer phytoplankton bloom in southern Lake Michigan that accounted for approximately 25% of the lake's annual gross offshore algal primary production. By combining the satellite imagery with in situ measurements of water temperature and wind velocity we show that the bloom was triggered by a brief wind event that was sufficient to cause substantial vertical mixing even though the lake was already stratified. We conclude that episodic events can have significant effects on the biological state of large lakes and should be included in biogeochemical process models. *INDEX TERMS:* 4239 Oceanography: General: Limnology; 4568 Oceanography: Physical: Turbulence, diffusion, and mixing processes; 4806 Oceanography: Biological and Chemical: Carbon cycling; 4855 Oceanography: Biological and Chemical: Plankton

1. Introduction

[2] Transient physical processes can have major effects on primary production in the oceans [*Franks and Walstad*, 1997; *Anderson and Prieur*, 2000; *Levy et al.*, 2000; *Cipollini et al.*, 2001]. Physical phenomena occurring on short time scales have not been considered as factors affecting biological production in temperate freshwaters like the Laurentian Great Lakes where seasonal processes dominate the algal primary production cycle [*Vollenweider et al.*, 1974; *Scavia et al.*, 1986]. Given the significant impact of transient phenomenon on oceanic primary production, and the current interest in the effects of episodic events on the functioning of inland seas [*Eadie et al.*, 1996], we were curious to see if we could use satellite imagery to detect and study transient events in the Great Lakes.

[3] Although some attempts have been made to use multispectral observations from earlier sensors for study of inland waters [*Mortimer*, 1988; *Bolgrein and Brooks*, 1992], only since data from SeaWiFS became available in late 1997 have we had the observations needed to study the detailed spatio-temporal dynamics of Great Lakes phytoplankton. Here we report on the first use of SeaWiFS imagery to investigate the connection between physical and biological processes in the Great Lakes. Our initial focus is on the effect of a brief storm that occurred during June 1998 on algal production in southern Lake Michigan.

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2. Data and Processing

[4] We obtained SeaWiFS High-Resolution Picture Transmission data from NASA's Goddard Distributed Active Archive Center (DAAC) and processed them to level 2 by using Version 4.0 of the NASA SeaDAS software. We limited our analysis to images recorded within 35 min of 18:20 UTC to reduce the distorting effects of extreme satellite viewing angles. Figure 1 shows a series of chlorophyll a (chl*a*) images of Lake Michigan collected between 16 May 1998 and 25 August 1998 projected onto a polyconic 1-km grid. The nine images shown were selected from 33 relatively cloud-free scenes during the period that satisfied our analysis criteria. The geographic limits of the images are 41°35.9′N, 87°59.4′W (lower left) and 46°06.2′N, 84°42.9′W (upper right).

[5] We estimated the chl*a* values shown in Figure 1 by using the Ocean Chlorophyll 2 version 2 (OC2v2) algorithm [*O'Reilly et al.*, 1998]. The OC2v2 algorithm has not been validated for inland waters like the Great Lakes. We have, however, collected limited in situ chl*a* data that compare reasonably well with the satellite estimates (see Figure 3c). These data, which were collected at one station in the southern basin of Lake Michigan during the late summer of 1998, span only a limited range of chl*a* but provide some measure of the algorithm's utility, at least at these relatively low chl*a* values. Efforts to collect more in situ data for comparison with satellite retrievals are underway, but have not yet been published.

[6] We measured water temperature profiles by using a thermistor string deployed at 42°41.77′N, 87°01.46′W in 156 m of water. The thermistors were located 17, 27, 32, 47, 77, 87, 97, 107, and 152 m below the surface. We augmented the thermistor data with water temperature measurements made 0.6 m below the surface at a nearby meteorological buoy. The meteorological buoy, designated 45007, is operated by the National Data Buoy Center and is deployed at 42°40.33′N, 87°01.32′W in 165 m of water. The buoy wind and temperature data are averages of 1-sec samples measured during an 8-min period and are reported hourly.

3. Results and Discussion

[7] The images of Lake Michigan chl*a* show that a major phytoplankton bloom occurred in June 1998. The offshore average estimated chl*a* values started to increase rapidly from about 1.5 mg m^{-3} on 2 June (day 153) to a peak level near 5.4 mg m^{-3} on 22 June (day 173). After peaking, chl*a* decreased rapidly to about 1 mg m^{-3} in mid July (day 195). The net rate of change of chl*a* between days 153 and 173 is 0.07 d^{-1}, a value that agrees closely with growth rates measured for the dominant spring phytoplankton assemblage (diatoms) in Lake Michigan [*Fahnenstiel et al.*, 2000].

[8] To create time series for analysis, we averaged the individual pixel values over adjacent spatial blocks. These averages are shown as temporal anomalies in Figure 2. We limited the averaging to those images in which at least 40% of the pixels in each spatial block were classified as cloud-free by using the

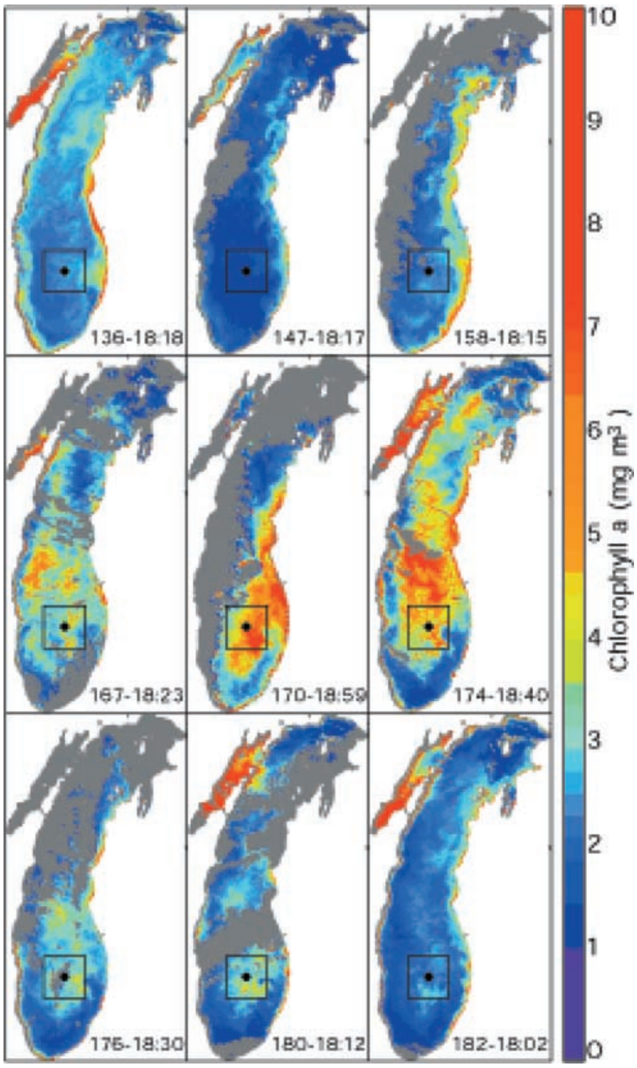

Figure 1. Images of Lake Michigan chl*a* from SeaWiFS showing the June 1998 phytoplankton bloom. The dot and solid box in the southern basin indicate the location of the thermistor string and the area enclosed by the 60-km by 60-km box we used to compute the spatially averaged chl*a* values.

standard SeaDAS cloud mask. The chl*a* anomalies, $\overline{\Delta c_{i,j}}$, were calculated as

$$\overline{\Delta c_{i,j}}(\%) = 100\left[\frac{\overline{c}_{i,j} - \overline{c}_j}{\overline{c}_j}\right], \quad \text{where}$$

$$\overline{c}_{i,j} = \frac{1}{n_{i,j}}\sum_{k=1}^{n_{i,j}} c_{i,j,k}, \text{ and } \overline{c}_j = \frac{1}{m_j}\sum_{i=1}^{m_j} \overline{c}_{i,j}.$$

We use i, j, k to represent the image, block, and pixel indices respectively. We denote the number of cloud-free pixels within block j, image i, as $n_{i,j}$; $c_{i,j,k}$ is the pixel chl*a* value and m_j is the number of images that satisfy our analysis criterion for block j.

[9] We used a multiple regression model [*Morin et al.*, 1999] to estimate gross primary production (mg C m^{-2} d^{-1}) from our measurements of water temperature and the satellite retrievals of chl*a* integrated over the estimated optical depth, that depth at which the surface photosynthetically active radiation (PAR) would be attenuated by a factor of *e* assuming exponential extinction. We estimated the optical depth by converting the bulk extinction coefficient in the blue band (k_490) calculated by SeaDAS to extinction of PAR (kPAR) with a linear relationship appropriate for Lake Michigan [*Bukata et al.*, 1995]. We fitted a simple smoothing model to the satellite estimates to calculate daily values for chl*a* and kPAR and used these to produce daily estimates of primary production. Our peak production value of 422 mg C m^{-2} d^{-1} occurred on day 173 and compares well with sample in situ measurements that range from 250 to 648 mg C m^{-2} d^{-1} [*Fahnenstiel and Scavia*, 1987]. We used the satellite-derived estimates to calculate the total carbon fixation in the southern basin by multiplying the integrated production by the area of the off-shore blocks shown in Figure 2 (~11,000 km^2). We estimate that the total amount of algal carbon fixed in the off-shore epilimnion of the lake's southern basin from day 153 to day 195 was 0.14 Tg. For comparison, the annual total (from day 56 to day 288) of carbon fixed in the same region was 0.57 Tg.

[10] The temperature data Figure 3b show a sudden deepening of the developing thermocline on 2 June (day 153). The concurrent wind data (Figure 3a) show that this deepening was associated with a brief wind event that also occurred on 2 June. The maximum wind speed 5 m above the surface was 14.2 m s^{-1} during this event, but the speed exceeded 10 m s^{-1} for only 4 hr. In that 4-hr period, however, the surface water temperature dropped from 12.4°C to 11.3°C, and the temperature gradient from 1 m to 27 m below the surface was reduced from −0.26 °C m^{-1} to −0.13 °C m^{-1}.

[11] The number of occurrences of wind events of this magnitude varies greatly from year to year [*Parsons and Lesht*, 1996]. We reviewed the 20-year (1981–2000) record of wind observations made at buoy 45007 and found that the average number of times that the wind speed exceeded 10 m s^{-1} continuously for 4 hr between days 136 and 235 was 2.4. Seven of the 20 years had no such events and one (1999) had 6. Only 1 wind event of this magnitude occurred during this 100-day period in 1998: at the onset of the June event.

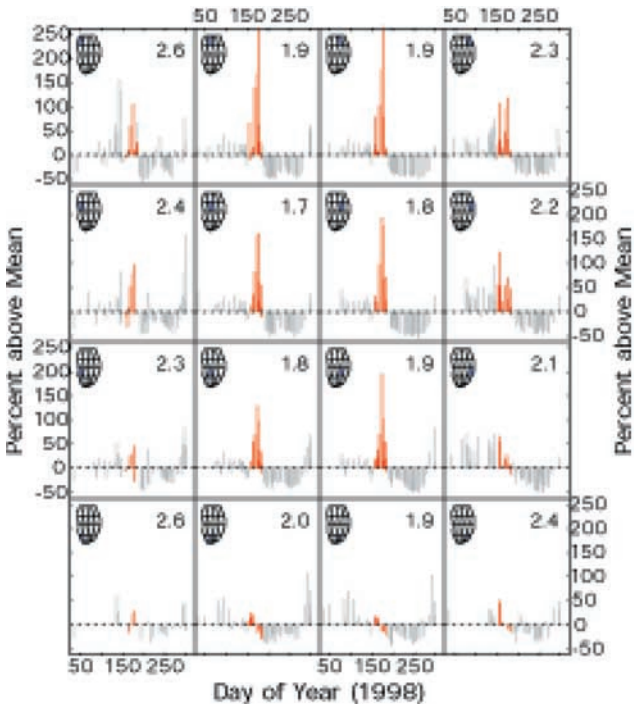

Figure 2. Temporal anomalies in satellite-derived chl*a* concentrations for the southern basin of Lake Michigan. The geographic location of each block is shown in the map inset, and the annual average chl*a* concentration (mg m^{-3}) for the block is printed at the upper right.

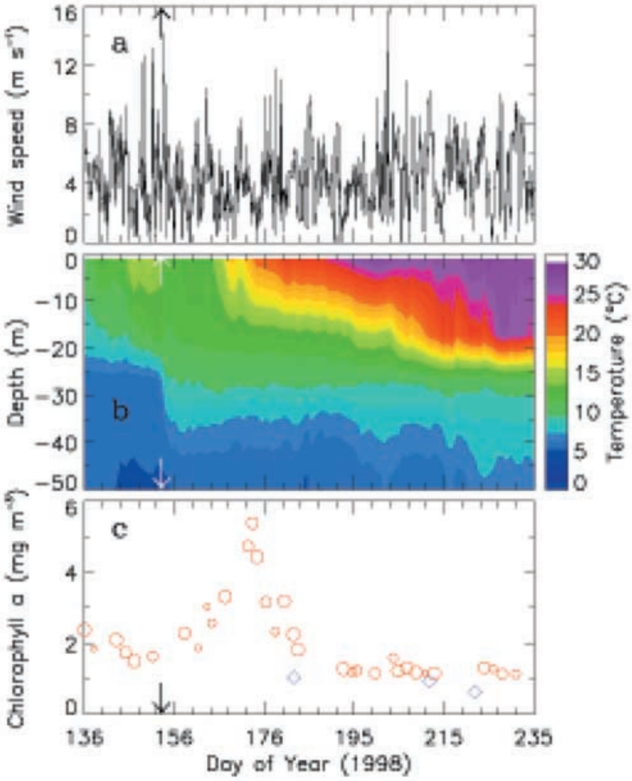

Figure 3. Time series of (a) wind speed 5 m above the water surface at buoy 45007, (b) water temperature profiles at the thermistor string, and (c) chl*a* concentrations from satellite (circles) and in situ measurements (diamonds). The arrows in each panel point to 12:00 UTC on 2 June 1998. The circle size in panel (c) is proportional to the number of cloud-free pixels contributing to the chl*a* value.

[12] Wind-forced deepening of the mixed layer can occur very quickly in the middle latitudes [*McCormick and Meadows*, 1988]. Because the mixed layer deepens by entraining water from below the thermocline, we believe the June 2 wind event resulted in an infusion of deeper, nutrient-rich water into the epilimnion. No longer nutrient starved and with more than adequate light, the relict epilimnetic diatom population bloomed until the rapidly warming surface water again became isolated from the hypolimnion. The rate at which the estimated chl*a* declined after the bloom peak is 0.15 d^{-1}. This value also agrees with field determinations of chl*a* loss by zooplankton grazing and particle settling during stratified conditions [*Fahnenstiel and Scavia*, 1987].

[13] Changes in the depth of the mixed layer result from changes in the dynamic balance between wind-forced mixing and buoyancy forces. When stratification first develops, the water column is already well mixed, and brief wind events do little to increase the epilimnion-mesolimnion exchange. As solar irradiation and sensible heat flux warm the surface water, the vertical temperature distribution becomes more stable and resistant to mixing. Thus, wind events of magnitude similar to the 2 June event, but occurring later in the year when the vertical temperature gradient is stronger (e.g., 21 July), do not result in mixed layer deepening and nutrient exchange. We used a one-dimensional mixed layer model [*Thompson*, 1979] appropriate for the Great Lakes [*McCormick and Meadows*, 1988] to estimate the mixed layer depth that would result from a steady 10 m s^{-1} wind continuing for 4 hr given the initial vertical temperature distributions measured at (day 153) and after (day 188) the 2 June event. The ratios of the modeled mixed layer depths to the measured mixed layer depths at the start of the simulations were 1.6, and 1.0 respectively. Thus, it appears that this particular wind event could have entrained water below the existing mixed layer only when the thermal stratification was at the intermediate strength observed around 2 June.

4. Summary and Conclusions

[14] The annual algal production cycle in the Great Lakes is typical of many temperate freshwater systems. Phytoplankton growth and chl*a* concentrations are low in the winter when sunlight and water temperatures are low. As solar irradiation increases in March and April, phytoplankton growth and biomass increase steadily until the available supply of nutrient silica is depleted in the epilimnion. Warming at the surface during May and June progressively isolates the epilimnion from the hypolimnion by thermal stratification. After stratification begins, the mixing of nutrient-depleted surface water with nutrient-rich deeper water is inhibited, ending the spring bloom. Particle sinking, respiration, and grazing by zooplankton quickly reduce the algal biomass above the thermocline. There is a period of time, however, when the water column has stratified enough to inhibit mixing across the thermocline and end the spring bloom but has not stratified sufficiently to maintain the isolation of the epilimnion against the action of moderate wind events.

[15] Analysis of SeaWiFS imagery along with in situ observations show that a brief, moderately intense wind event caused sufficient vertical mixing to initiate an unusual early summer phytoplankton bloom in southern Lake Michigan. Understanding the complexity of the physical and biological interactions in the Great Lakes is critical for modeling and managing this unique resource. Detailed analysis of frequent satellite images of water color is a promising way to assess the ecological significance of transient physical events in the Great Lakes and other large bodies of fresh water.

[16] **Acknowledgments.** We thank the SeaWiFS Project and the DAAC at the Goddard Space Flight Center, for the production and distribution of the SeaWiFS data, respectively. NOAA's Coastal Ocean Program supported work at ANL and at GLERL as part of the Episodic Events-Great Lakes Experiment (EEGLE) Program. We also received funding from NOAA/NESDIS. The NSF supported work at The University of Chicago under Group Infrastructure Grant 97-09696, a Graduate Research Participant Fellowship, and grant DMS 99-71127.

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