SeaWiFS and MODIS-observed multi-year seasonal and spatial dynamics in biotic and abiotic processes in Lake Michigan as obtained from a new water quality retrieval algorithm

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Abstract - Seven years of SeaWiFS and three years of MODIS observation data were used to obtain seasonal and interannual time histories of the major water color producing agents (CPAs), phytoplankton chlorophyll (*chl*), dissolved organic carbon (*doc*) and suspended minerals (*sm*) for Lake Michigan. Correlations of the retrieved CPAs with the coincident environmental observations are established. Episodic events of sediment resuspension and calcium carbonate precipitation out of the water are remotely sensed. Compared are the established time history between the CPAs spatial and temporal distributions throughout the lake from shipborne observations. The obtained results are then used to speculate on the future of Lake Michigan under climate change conditions.

Keywords: Lake Michigan, multi-year satellite observations, phytoplankton, sediments, climate change, lake ecology dynamics

1. INTRODUCTION

The amassed observational evidence of multifaceted changes that occurred over the last few decades in both the system of the Great Lakes and the atmosphere over them strongly indicates that there were serious alterations of the entire lacustrine system in general, Lake Michigan inclusive (Anonymous 2003). These documented changes are thought to arise from both anthropogenic influences and climate change.

The future climate will likely produce in the Great Lakes longer ice-free periods, higher water temperature, longer stratification periods, earlier onsets of the spring phytoplankton bloom, decline of the diatom population with a shift of the phytoplankton community to blue-green algae (Gerten and Adrian 2002).

The primary production is expected to decline because nutrient inputs to surface waters from sediments would be reduced by an earlier onset of the thermocline (Brooks and Zastrow 2002).

The anticipated changes can also affect the onset, extent and duration of the episodic events such as spring-time sediment resuspension and autumnal calcium carbonate precipitation, which are known to affect the ecosystems of water bodies such as Lake Michigan (Ji *et al*. 2002).

Given large surface dimensions of Lake Michigan, the conventional ground-based monitoring needs to be supplemented by a remote sensing component capable of providing data on water quality parameters or their proxies. As such phytoplankton chlorophyll (*chl*), suspended minerals (*sm*) and dissolved organics (*doc*) are eligible for this purpose since they are known to be involved in the aforementioned seasonal and/or episodic events. However, it requires such a bio-optical algorithm that could simultaneously retrieve these substances from satellite data.

Such an algorithm has been developed by the authors of this paper for the Great Lakes. This algorithm employs a combination of neural network emulators and the multivariate optimization technique. Its detailed description and results of validation are given elsewhere (Pozdnyakov *et al.,* 2005).

2. SEASONAL DYNAMICS OF WATER QUALITY PARAMETERS IN LAKE MICHIGAN

Figures 1 to 3 illustrate the spatial distributions of *chl*, *sm* and *doc* for several dates throughout 1998. This year is known as the year of a very strong El Niňo event, and very warm winter in the basin of Lake Michigan. There the biggest resuspension event in several years was observed. As seen from Figure 1, the SeaWiFS image taken on March 24, 1998 actually displays this event in the retrieved field of *sm*: the area of enhanced concentration of *sm* has the form of a horseshoe but with an outgrowth directed offshore and reaching westward towards the central part of southern Lake Michigan. At the same time, the field of *doc* exhibits a mirror-like pattern, but corresponding to drastically decreased concentrations of this CPA, which is a clear manifestation of scavenging of colloidal *doc* by settling particulate matter constituting the resuspension plum. The spatial distribution of *chl* displays some significantly increased concentrations within the resuspension plume area, which is because this event brings along with *sm* also ample amounts of nutrients spurring up an enhanced growth of the indigenous micro algae.

Later on in mid April the plum still persists (Figure 2 for April 17)), but obviously is appreciably depleted (the central outgrowth has been practically reduced to naught), and in the central part a considerable decrease of *sm* has formed. This area is surrounded by a vast region of high *doc* concentrations, indicating that the previously scavenged *doc* gradually regains its initial levels or regenerated *de novo* from authothonous algal cycling. Both maps for *sm* and *doc* in southern Lake Michigan resemble a donut-shaped distribution.

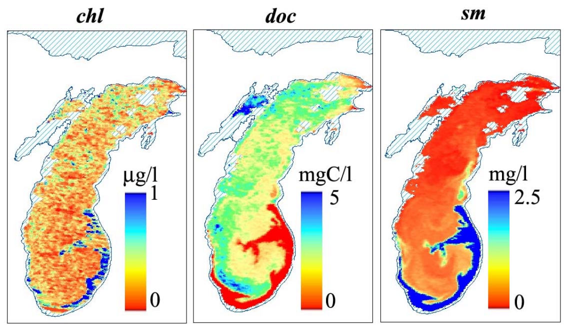

Fig. 1. CPA spatial distributions in Lake Michigan, 24.03.1998

As to the mid summer situation (not illustrated here) the nutrients provided by the spring resuspension become exhausted, the phytoplankton are either nearly completely depleted being consumed by zooplankton or died off, and the bacterial decomposition produced enhanced concentrations of *doc*. The field of *sm* is rather homogeneous and its levels are fairly low. The biological activity in the lake appreciably ebbs down for a while in expectation of the forthcoming resuscitation.

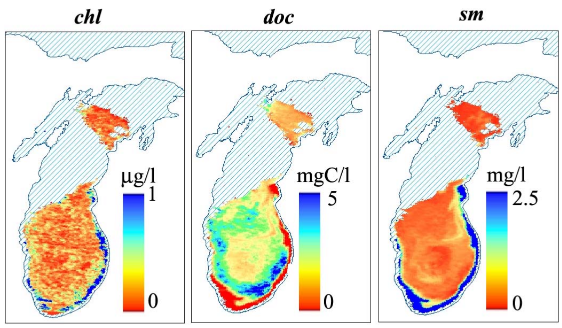

Fig. 2. CPA spatial distributions in Lake Michigan, 17.04.1998

In late July the first signs of the second episodic event appear, but they become especially pronounced in mid to late August. As illustrated in Figure 3 for August 25, extensive areas in southern and central Lake Michigan exhibit high concentrations of *sm*: high water temperature attained at this time of year results in massive precipitation of calcium carbonate. Again, the *doc* spatial distribution becomes a mirror-like reflection of the *sm* field: *doc* levels drop down due to the scavenging effect discussed above in relation to the spring resuspension event. The *chl* field shows a slight enhancement of *chl* levels within the boundaries of the chalk plum. This is thought to be a result of endogenous recovery of nutrients due to the lake metabolic processes.

In November the primary production still continues but in December phytoplankton ends their vegetation activity.

The results presented in this section relate to a single year. But the onset and duration of various stages of the ecosystem dynamics vary from year to year, and those variations could be traced down in a time series of satellite images.

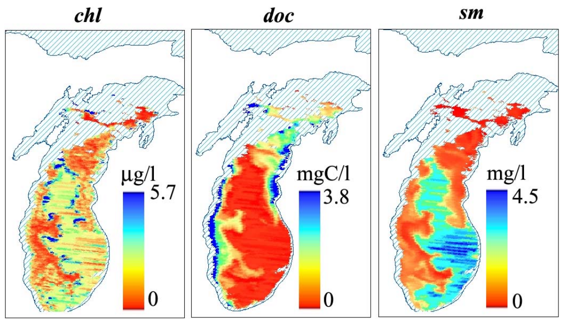

Fig. 3. CPA spatial distributions in Lake Michigan, 4.08.1998

3. A SEVEN YEAR SERIES OF SeaWiFS IMAGES

When averaged over the seven-year period (1999-2004) for southern Lake Michigan, the concentrations of *sm*, *doc* and *chl* exhibit distinct patterns in seasonal variations. As is illustrated in Figure 4 *a,* the plot of seasonal fluctuations of *chl* content has two distinct maxima occurring in early spring and autumn with a pronounced minimum in July. As discussed in the previous section, the spring maximum is initiated by the episodic resuspension event. The autumn maximum has a two peak/saddle-like structure. The first rise in *chl* content is coincident/associated with the second episodic event. The second peak is obviously associated with the autumnal regular development of the indigenous phytoplankton apparently spurred up by the autumnal overturn.

The described causal mechanisms driving the *chl* time variations also explain the specific features of the *sm* plot in Figure 4 *b*. Also bi-modal, the *sm* plot exhibits the obvious prevalence of the second episodic event over the spring-time resuspension, which is thought to be due to the fact that “milky” waters generally cover vast areas of southern Lake Michigan, and hence the cumulative effect should be very significant.

The *doc* plot (Figure 4 *c*) displays a drastic decrease of *doc* during the second episodic event, but not during the spring-time resuspension. This will be discussed in more detail below.

Revealing the generalized patterns in *sm*, *chl* and *doc* seasonal variations, these data, being averaged over time and space, understandably conceal *intra-annual* fluctuations. A closer look at the times of onset and duration of the aforementioned seasonal and episodic changes in the ecosystem of Lake Michigan reveals significant excursions. When averaged over southern Lake Michigan, concentrations of *sm*, *doc*, and *chl* exhibit very pronounced inter-annual variations in the moments of attaining maximal and minimal values and the time-periods, during which those increases and decreases unfold.

The seven-year spaceborne data indicate that the spring episodic events occur in the lake through out the time-period from January to May. Although they might also arise in summer, but their effect must be mitigated due to the strong thermal stratification precluding lake waters from vertical mixing. The correlation coefficient between the concentration of *sm* in the vernal plum and number of days with high winds having a strong northern component in the years 2000-2004 amounts to 0.95. Data on wind speed and wind direction were derived from the SAR data at a 25 km resolution generated by the QuikSCAT satellite sensor SeaWinds (htpp://poet.jpl.nasa.gov/).

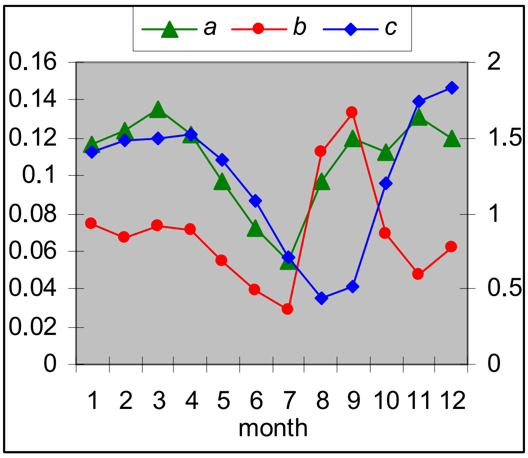

Fig. 4. Seasonal variations of concentrations of *chl* (*a, µg/l, left axis*), *sm* (*b, mg/l, right axis*) and *doc* (*c, mgC/l, right axis*) as retrieved from satellite images and averaged over southern Lake Michigan and over each year within the time period 1998-2004.

The correlation coefficient of surface water temperature averaged over the entire area of southern Lake Michigan for August and the maximum *sm* concentration in the calcium carbonate precipitation plum for each of the years within the time period 1998-2003 amounts to 0.85. To generate this dependence, the NOAA AVHRR Oceans Pathfinder sea surface monthly-averaged temperature data were derived for the above years.

The SeaWiFS and MODIS images processed with the developed algorithm allow one not only visualizing the spatial inhomogeneity of the *sm* flux within the resuspension plum as it propagates along the shore line of southern Lake Michigan but also assessing the total amount of *sm* in the plum strip neighboring the shoreline and separately in the off-shore line outgrowth: the total amount of *sm* in the plume thus estimated mounts up to one million tons, which is consistent with the reported assessments (Anonymous, 2000).

The pattern of the spatial distribution of voluminal content of *sm* in the resuspension plume (not indicated here) closely follows the contours of bottom sediments accumulations reported by Schwab *et al*. (2000).

The obtained spaceborne images also faithfully reflect the correlation between the river runoff, episodic events impacts and CPA temporal variations in the river mouth neighboring areas in Lake Michigan. When comparing the remotely sensed *doc* values and the Grand River flow rate, a distinct coincidence in time of enhanced *doc* concentrations with the maxima of river flow rate/river discharge has been revealed with some exception which are thought to be due to the *doc* depletions associated with the spring and autumn episodic events, the onset, duration and intensity of which vary strongly from year to year. Thus, the spaceborne data in the visible processed by the developed algorithm and synergistically linked with data from satellite sensors operating in the IR and microwaves can be a powerful aid in attaining a more adequate insight into many in-water processes and their driving mechanisms.

4. CLIMATE CHANGE IMPLICATIONS

Notwithstanding the intricacy of climate change processes and forcing factors neither the uncertainties arising in this context as to what will happen to the Great Lakes in general and Lake Michigan in particular, the resultant consequences will certainly entrain some changes in the lake ecosystem state, and hence, in the water quality parameters. The latter are insolubly related to the content and spatial distributions of *chl*, *sm*, *doc*, which can serve as traces of ongoing in-water processes.

The major purpose of the information presented in Table 1 is to trace down the sequence of alterations that could be expected in the aquatic system of Lake Michigan should ***one*** of the considered climatic parameters drastically change. The obtained long-term correlations between (*i*) the northerly wind speed and *sm* content in this vernal plum, (*ii*) water temperature and chalky water event intensity, (*iii*) river runoff and coastal *doc* variations, (*iv*) massive *sm* resuspention/generation events and *doc* scavenging as well as the major features of the CPA inter-annual variations of the major CPAs were then used to show how those changes would be reflected in the content as well as spatial and temporal variations of *sm*, *chl* and *doc* as retrieved from satellite data. Thus, the presented concept is based on the experience gained from the above analyses of the seven year series of spaceborne images as well as the body of evidence provided in the literature (e.g. Lohrentz *et al*. 2004). Leaving alone other ramifications of ecological alterations reflected in Table 1, it can be suggested that a judicious employment of this table alongside with a synergistic use of satellite data in the visible as well as results of both shipborne measurements and numerical simulations can be instrumental in early detection and surveillance of the changes, which might take place in the Lake Michigan system under external forcing.

5. CLOSING REMARKS

The *chl*, *sm* and *doc* spatial distributions and their seasonal and inter-annual variations obtained in this study from SeaWiFS and MODIS images accurately reflect both the major cycles in the lake hydrodynamic and biological activity and the alterations of them ensuing from two major types of episodic events annually occurring in Lake Michigan. The quantitative volumetric assessments from satellite images of *sm* contained in the vernal resuspention plum proved to be in close agreement with the available independent estimations.

A synergistic use of satellite data in the visible, infrared and microwave spectral regions provided by such sensors as SeaWiFS, MODIS, AVHRR, and SeaWinds (on QuikSCAT) allowed to establish very strong correlations between the extent of the lacustrine phenomena residing in two annual episodic events and the weather/climate change forcing.

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TABLE 1. Climate change scenarios for Lake Michigan: major ecological consequences and potentials of their identification and surveillance from space

Climate change scenario	*Changes in observed CPAs*	*Major ecologic consequence*
Increase of mean annual air temperature	*A*. Earlier onset of spring resuspension events, increase in *sm* concentration, decrease of *doc* content within the plum zone *B*. Earlier onset and increase of duration of autumnal calcium carbonate precipation event, decrease of *doc* content	*A*. Increase of nutrients availability in spring, intensification of vernal phytoplankton growth, alterations of heterotrophic bacterial activity, increase of water toxicity *B*. Increase of nutrients availability, intensification of phytoplankton growth/increase of blue-green algae, alterations of heterotrophic bacterial
Decrease of mean annual atmospheric precipitation	Coastal zone: decrease of *sm* and *doc* concentrations, increase of photic depth	Alterations of *chl* vertical profile, intensification of *chl* in deeper parts of photic zone, alterations of bacterial activity in coastal zone
Increase of mean annual atmospheric precipitation	Coastal zone :increase of *sm* and *doc* concentrations, decrease of photic depth	Coastal zone: alterations of *chl* vertical profile, depletion of *chl* in lower parts of photic zone, alterations of bacterial
Increase of mean annual wind force	Intensification of spring to early summer resuspension events, increase in *sm* concentration, decrease of *doc* content in the plum,	Increase of nutrients availability in spring to early summer, intensification of vernal phytoplankton growth, alterations of bacterial
Decrease of mean annual cloudiness	Increase of *chl* and autochtonic *doc* during spring and fall episodic events, decrease of *chl* in-between these events	Increase of blue-greens in summer phytoplankton, decrease of net primary productivity, increase of algae-driven water toxicity
Increase of mean annual cloudiness	Decrease of *chl* and autochtonic *doc* during spring and fall episodic events, but less pronounced decrease of *chl* in-between these events	Stabilization of the extant phytoplankton composition, and less significant loss of primary production