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MERIS satellite chlorophyll mapping of oligotrophic and eutrophic waters in the Laurentian Great Lakes

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ABSTRACT

Chlorophyll-*a* (Chl*a*) concentrations and 'water-leaving' reflectance were assessed along transects in Keweenaw Bay (Lake Superior) and in Green Bay (Lake Michigan) (two of the Laurentian Great Lakes, USA), featuring oligotrophic (0.4–0.8 mg Chl*a* m^{-3}) and eutrophic to hyper-eutrophic waters (11–131 mg Chl*a* m^{-3}), respectively. A red-to-NIR band Chl*a* retrieval algorithm proved to be applicable to Green Bay, but gave mostly negative values for Keweenaw Bay. An alternative algorithm could be based on Chl*a* fluorescence, which in Keweenaw Bay was indicated by enhanced reflectance near 680 nm. Bands 7, 8 and 9 of the Medium Resolution Imaging Spectrometer (MERIS) have been specifically designed to detect phytoplankton fluorescence in coastal waters. A quite strong linear relationship was found between Chl*a* concentration and fluorescence line height (FLH) computed with these MERIS bands. The same relationship held for observations on oligotrophic waters elsewhere, but not for Green Bay, where the FLH diminished to become negative as Chl*a* increased. The remote sensing application of the algorithms could be tested because a MERIS scene was acquired coinciding with the day of the field observations in Keweenaw Bay and one day after those in Green Bay. For Green Bay the pixel values from the red-to-NIR band algorithm compared well to the steep Chl*a* gradient *in situ*. This result is very positive from the perspective of satellite use in monitoring eutrophic inland and coastal waters in many parts of the world. Implementation of the FLH relationship in the scene of Keweenaw Bay produced highly variable pixel values. The FLH in oligotrophic inland waters like Lake Superior appears to be very close to or below the MERIS detection limit. An empirical algorithm incorporating three MERIS bands in the blue-to-green spectral region might be used as an alternative, but its applicability to other regions and seasons remains to be verified. Moreover, none of the algorithms will be suitable for mesotrophic water bodies. The results indicate that Chl*a* mapping in oligotrophic and mesotrophic areas of the Great Lakes remains problematic for the current generation of satellite sensors.

1. Introduction

Containing one-fifth of the world's surface freshwater (Wetzel, 2001), the Laurentian Great Lakes provide drinking water, food, recreation and transportation for a growing population of about 35 million presently. On both sides of the US–Canadian border their ecological state is regarded as reflecting environmental health in the heart of the continent. The three largest of these 'inland seas', Lake Superior (surface area A=83 10^3 km^2; mean depth $\bar{z}$=147 m), L. Michigan (A=58 10^3 km^2; $\bar{z}$=85 m) and L. Huron (A=60 10^3 km^2; $\bar{z}$=59 m) are also deep, and their enormous volumes involve water renewal times of decades, even up to nearly two centuries in L. Superior (EPA, 1995). Large parts of these lakes therefore appear to be unaffected by regional environmental changes even long after significant demotechnic growth in the drainage basin.

In the vicinity of land the impacts of increased nutrient loading, soil erosion and invasive species may be apparent already in an early stage. The physical, chemical and biological gradients in such regions are highly interesting for mechanistic studies, but also because they are first in signaling environmental changes. These lake areas are typically receiving riverine inputs from hinterlands with cities, industries, forestry and agriculture. Prominent examples are Green Bay, L. Michigan (Auer et al., 1986; De Stasio & Richman, 1998; Millard & Sager, 1994), and Saginaw Bay, L. Huron (Bierman et al., 1984; Budd et al., 2001).

Monitoring of water quality in the Great Lakes of course is strongly facilitated by optical remote sensing, certainly in combination with the study of processes *in situ* and numerical modeling (Ji et al., 2002; Lathrop et al., 1990; Mortimer, 1988; Shuchman et al., 2006). One of the parameters most quickly responding to environmental change is the ubiquitous phytoplankton pigment chlorophyll *a* (Chl*a*), which

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exhibits a unique spectral absorption signature with marked peaks in the blue and red wavebands. In oceanography great progress has been made in the retrieval of this pigment from blue-to-green ratios of remote sensing reflectance, paving the way to estimates of global carbon fixation (Campbell et al., 2002; O'Reilly et al., 1998). In contrast to the clear oceanic waters (case-1 waters), serious Chl*a* retrieval problems have arisen for coastal and inland waters in which the optics are not closely related to phytoplankton (case-2 waters); see Morel et al. (2006) for a recent discussion of case-1 and case-2 marine waters, Bukata et al. (1991) for the example for Ladoga lake, the largest lake in Europe, and Budd and Warrington (2004) and Li et al. (2004) for L. Superior. Indeed, L. Superior, the clearest of the Great Lakes, can be classified as oligotrophic case-2 rather than case-1 (Budd & Warrington, 2004; Gons & Auer, 2004).

Hence, whereas Chl*a* in case-1 waters can be accurately estimated on the basis of the pigment's absorption peak in the blue, the approach does not work for case-2 waters because of high and variable absorption by chromophoric dissolved organic matter (CDOM; otherwise known as Gelbstoff, dissolved humic substances or gilvin) and detritus particles in this spectral region. In oligotrophic case-2 waters, estimation on the basis of the Chl*a* absorption peak in the red can be no alternative due to the overwhelming absorption by water of the red and near-infrared (NIR) wavelength bands. However, this spectral region also features the emission of Chl*a* fluorescence, which may be detected by dedicated satellite sensors (Babin et al., 1996; Gower & Borstad, 2004). The same spectral region is important with regard to eutrophic case-2 waters, where the Chl*a* absorption in the red becomes so strong that Chl*a* can be estimated from reflectance in the vicinity of the Chl*a* absorption peak in the red and in the NIR wavelength band (Dall'Olmo & Gitelson, 2005; Gons et al., 2002).

The Medium Resolution Imaging Spectrometer (MERIS) provides imagery for the spectral radiance in bands centred at 665, 681 and 709 nm. The aim here is to derive the enhancement of reflectance associated with Chl*a* fluorescence in seawater. Fluorescence could be detected with shipboard measurements of spectral reflectance in the oligotrophic Keweenaw Bay, L. Superior (Gons & Auer, 2004). MERIS imagery might therefore be suitable to map Chl*a* in the oligotrophic parts of the Great Lakes. In the present article an empirical relationship between fluorescence line height (FLH) and Chl*a* concentration of the shipboard data is described. The actual MERIS application could be tested for a scene covering part of the Keweenaw Bay at the day where observations were made *in situ*.

The same MERIS bands used to derive FLH, together with the 779 nm spectral band, are expected to provide reasonably accurate estimates of Chl*a* in eutrophic water (Gons et al., 2002). A previously derived semi-analytic algorithm mainly for European inland and coastal waters (Gons et al., 2002, 2005) was applied to shipboard spectral reflectance in Green Bay, L. Michigan, as well as oligotrophic to eutrophic waters of the Finger Lakes (New York). The results are reported in this paper. The above-mentioned MERIS scene fully included Green Bay, thus a MERIS application for eutrophic Great Lakes waters could be evaluated, even though in this case field observations were made a day earlier.

2. Materials and methods

2.1. Study sites

2.1.1. Keweenaw Bay

Keweenaw Bay is located on the southern shore of L. Superior, south-east of the Keweenaw Peninsula. The bay is 36 km in length and varies in width from 3 km at its southern end to 18 km where it joins the main body of L. Superior. Water depths range from 30 to 170 m over much of the bay. Almost the entire riverine input originates from the Sturgeon River flowing into Portage L. on the Keweenaw Peninsula. Part of the river water is delivered to Keweenaw Bay through the Keweenaw Waterway's South Entry. The river water is highly stained, and may be expected to influence optical conditions in the bay. Phytoplankton biomass in Keweenaw Bay is similar to that of other sites adjacent to the Keweenaw Peninsula, where Chl*a* concentrations of 0.5–1.5 mg m^{-3} are typical (Auer & Bub, 2004). See Gons and Auer (2004) and references therein for more details on the physical and chemical environment.

Observations in Keweenaw Bay were made on the 14th of August 2003 at 12 stations along a transect running from 47°10′N 88°12′W near the interface with the main body of L. Superior (Station 1) to 46°46′N 88°28′W near the head of the bay (Station 12; see Fig. 1 in Gons & Auer, 2004). The weather was calm, with surface water wave heights <0.2 m. During the measurements of the first half of the transect, the sky was clear, but thereafter considerable cloudiness developed. Water temperatures near the surface and at 6 m depth ranged 19–23 °C and 18–22 °C, respectively. Except for two stations near the head of the bay around solar noon, the temperature difference between these depths was ≤0.8 °C, indicating that the upper water layer was well mixed. Secchi-disk depth varied from 16 m near the main body of L. Superior to 8 m near the head of the bay. The 40 km long transect exhibited small variations in Chl*a* and CDOM (Table 1).

2.1.2. Green Bay

Green Bay is a major gulf located in north-western L. Michigan. The bay is 160 km in length along its NE–SW axis, has a mean width of 22 km and a mean depth of 16 m. The mouth of the bay permits substantial water exchange with the main lake, yielding a mean water retention time of about 6 years. The main tributary for Green Bay, and for L. Michigan as well, is the Fox River, entering the system at the head of the bay at the city of Green Bay. Agricultural runoff, discharges from pulp and paper mills, and wastewater treatment facilities

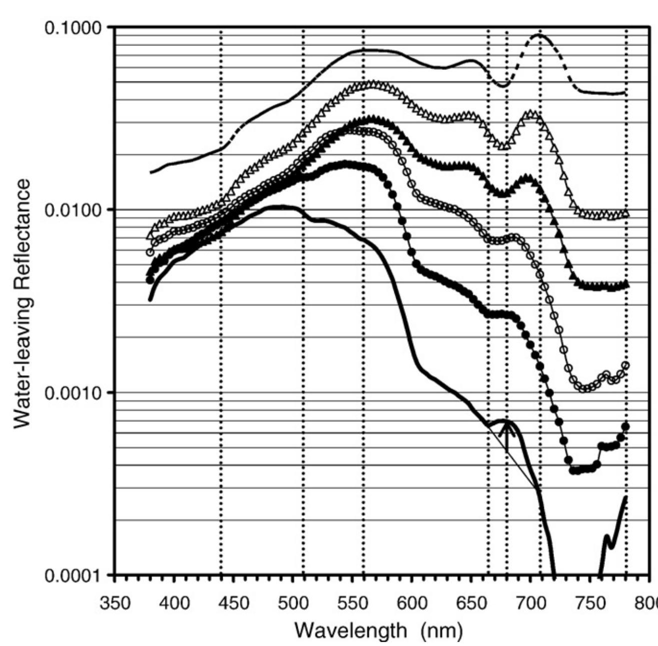

Fig. 1. Spectra of water-leaving reflectance in this study selected for incremental chlorophyll-*a* concentrations (solid line without symbols: Keweenaw Bay, Station 1, Chl*a* = 0.49 mg m^{-3}; solid circles: Canandaigua Lake, Chl*a* = 1.1 mg m^{-3}; open circles: Otisco Lake, northern basin, Chl*a* = 4.2 mg m^{-3}; solid triangles: Green Bay, Station 4, Chl*a* = 17 mg m^{-3}; open triangles: Green Bay, Station 9, Chl*a* = 31 mg m^{-3}; broken line without symbols: mouth of the Fox River, Chl*a* = 131 mg m^{-3}). The vertical dotted lines indicate positions of MERIS wavebands 2, 4, 5, 7, 8, 9 and 12 centred at approximately 443, 510, 560, 665, 681, 709, and 779 nm, respectively. The arrow pointing at the Keweenaw Bay spectrum indicates the fluorescence line height above the reflectance baseline drawn between the values at 665 nm and 709 nm.