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A hybrid algorithm for estimating the chlorophyll-*a* concentration across different trophic states in Asian inland waters

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ABSTRACT

The chlorophyll-*a* (Chl-*a*) concentration is one of the most important parameters for evaluating the state of water environments, which often vary markedly across both time and space. Here we propose a hybrid algorithm for retrieving the Chl-*a* values from *in situ* remote sensing data. This hybrid algorithm contains three individual Chl-*a* estimation algorithms that were previously developed for clear waters (a blue–green algorithm), turbid waters (a two-band index-based red–near infrared algorithm), and highly turbid waters (a three-band index-based red–near infrared algorithm). The MCI value (maximum chlorophyll index) was used to switch the three algorithms. To evaluate the performance of the proposed hybrid algorithm, we used the *in situ* remote sensing reflectance and Chl-*a* values collected from five Asian lakes, the trophic status of which varied from oligotrophic to hypertrophic. The results showed that the hybrid algorithm performed well for a wide variety of optical properties, with the NMAE (normalized mean absolute error) of 13.3%. Our results indicate that the proposed hybrid algorithm has the potential for use as an operational tool for monitoring Chl-*a* in waters with widely varying trophic conditions without the requirement of reparameterization.

1. Introduction

The chlorophyll-*a* (Chl-*a*) concentration is one of the most important parameters for evaluating water environments, such as the trophic status, clarity, and algal biomass of waters. Routine observations of Chl-*a* are thus requested by researchers and local governments. Compared to the conventional sampling methods (e.g., sampling from a boat), the retrieval of Chl-*a* values from remote sensing data can not only save costs and labor but also provide synoptic observations for water areas, and it is thus is considered one of the effective techniques for water-quality monitoring.

Generally, the remote sensing reflectances (R_{rs}) at blue and green wavelengths are used to estimate Chl-*a* in clear waters (e.g., open ocean waters). For example, the OC4 algorithm (oceanic chlorophyll-*a* algorithm for SeaWiFS) used the R_{rs} at the wavelengths of 443, 490, 510 and 555 nm to estimate Chl-*a* for global oceans (O'Reilly et al., 1998). This is because the R_{rs} at these wavelengths can provide a high signal-to-noise ratio (SNR) along with the first absorption peak of Chl-*a* (at the blue spectra domain) for detecting phytoplankton changes.

In contrast, the R_{rs} at longer wavelengths (e.g., red or near-infrared) cannot provide a sufficient SNR due to the strong absorption from pure waters and the relatively weak backscattering from suspended solids in clear waters. The Chl-*a* estimation algorithms based on the R_{rs} at the blue and green wavelengths are denoted hereafter as blue–green algorithms. The blue–green algorithms have often failed in optically complex waters (e.g., Case-2 waters) because the R_{rs} at these wavelengths are affected not only by phytoplankton but also by other constituents including non-algal particles (NAP) and colored dissolved organic matter (CDOM) (Gitelson et al., 2009).

Optically complex waters often have higher turbidity along with a sufficient SNR around the second absorption peak of Chl-*a* (at the red spectra domain), and thus the R_{rs} at the red and near-infrared (NIR) wavelengths became an alternative for estimating Chl-*a* in these types of waters. For example, Dall'Olmo et al. (2003) proposed a three-band index which was designed by using

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the R_{rs} at the wavelengths around 665, 709, and 754 nm (i.e., $[R_{rs}^{-1}(665) - R_{rs}^{-1}(709)] \times R_{rs}(754)$) to minimize the effects from NAP and CDOM. It was found that the Chl-*a* estimation algorithms based on this index could provide higher accuracy even for optically complex waters (Gitelson et al., 2008; Moses et al., 2009; Gilerson et al., 2010; Yang et al., 2010, 2011). However, Gurlin et al. (2011) reported that the Chl-*a* estimation algorithms based on a two-band index (i.e., $R_{rs}(709)/R_{rs}(665)$) could in some cases perform better than those based on the three-band index. The Chl-*a* estimation algorithms based on the R_{rs} at the red and NIR wavelengths are denoted hereafter as red–NIR algorithms.

Many studies have been conducted to retrieve Chl-*a* values from remote sensing data in waters with different optical properties (Matthews, 2011; Odermatt et al., 2012). It has gradually become clear that the blue–green ratios are limited to oligotrophic waters, whereas the red–NIR ratios are only suitable for waters with Chl-*a* concentrations >10 mg m^{-3} (Odermatt et al., 2012). This finding indicates that a hybrid algorithm that can be applied to global waters is required for operationally retrieving Chl-*a* values under a wide range of optical properties. Several studies attempted to address this issue. For example, Gomez et al. (2011) proposed two normalized difference indices (i.e., bands 705 and 665 nm, bands 560 and 442 nm) to separate Mediterranean Lakes of European Union into two types, and different Chl-*a* retrieval algorithm was used for each water type. Matthews et al. (2012) developed a maximum peak-height (MPH) algorithm, which uses a baseline subtraction procedure to calculate the height of the dominant peak across the red and NIR wavelengths, for estimating Chl-*a* in inland and coastal waters with a wide range of trophic status. Two Chl-*a* retrieval algorithms were developed for eukaryote-dominant and cyano-dominant waters respectively, and two baseline subtraction indices were used to switch the two algorithms (Matthews et al., 2012). Moore et al. (2014) suggested the use of an optical water type (OWT) framework for selecting and blending two Chl-*a* retrieval algorithms. However, this kind of study is still very limited. In addition, although the proposed Chl-*a* retrieval algorithms have been validated in some inland waters, further validation is necessary to show both the advantages and potential limitations of these algorithms in other waters, especially some Asian inland waters, which have different optical properties but are less included in the previous studies.

Consequently, the objectives of the present study were to (1) further test the performances of recently developed red–NIR algorithms as well as a blue–green algorithm, using the independent data collected from several Asian lakes with a wide range of trophic states; (2) propose a simple remote sensing-based classification method for selecting the most appropriate Chl-*a* retrieval algorithm; and (3) develop a hybrid method for estimating Chl-*a* concentrations across different trophic states in inland waters.

2. Methods

2.1. Study areas and data collection

The data used in this study were collected from five Asian lakes: Lakes Biwa (Shiga Prefecture, Japan), Suwa (Nagano Prefecture, Japan), Kasumigaura (Ibaraki Prefecture, Japan), Erhai (Yunnan Province, China), and Dianchi (Yunnan Province, China). The basic information about the lakes during the field surveys is summarized in Table 1.

In limnology, the average Chl-*a* concentration will generally be <1 mg m^{-3} in ultra-oligotrophic waters, <2.6 mg m^{-3} in oligotrophic waters, between 2.6 mg m^{-3} and 7.2 mg m^{-3} in mesotrophic waters, between 7.2 mg m^{-3} and 20 mg m^{-3} in eutrophic

Table 1
Basic information and statistical description of water constituent concentrations for Lakes Erhai and Dianchi (China) and Lakes Biwa, Suwa and Kasumigaura (Japan).

	Japanese Lakes			Chinese Lakes	
	Biwa	Suwa	Kasumigaura (western)	Erhai	Dianchi
Location	35.33°N 136.17°E	36.05°N 138.08°E	36.03°N 140.40°E	25.82°N 100.18°E	24.83°N 102.72°E
Area (km^2)	670	13.3	171	249	300
Average depth (m)	41.0	4.7	4.0	11.0	4.3
Maximum depth (m)	104	7.2	7.3	21	11.3
Chl-a (mg m^{-3})					
Min	1.8	9.8	36.6	9.7	30.3
Max	2.9	11.4	95.0	36.1	153.9
Mean	2.2	10.7	66.5	19.6	87.7
Stdv	0.4	0.6	19.5	5.9	29.2
CV	19.3	5.9	29.3	30.2	33.2
TSS (g m^{-3})					
Min	0.8	4.8	11.7	3.5	24.5
Max	2.0	6.1	47.9	11.3	55.0
Mean	1.0	5.4	24.5	5.8	37.4
Stdv	0.4	0.4	8.2	1.7	7.8
CV	36.6	8.0	33.7	29.5	20.9
ISS (g m^{-3})					
Min	0.5	1.2	3.1	0.2	0.5
Max	1.5	2.2	37.3	1.6	42.3
Mean	0.6	1.7	16.3	0.8	12.4
Stdv	0.3	0.4	7.3	0.4	11.8
CV	49.2	24.4	44.7	51.5	95.1
CDOM (m^{-1})					
Min	0.15	0.41	0.51	0.33	0.41
Max	0.26	0.48	1.78	0.56	3.98
Mean	0.21	0.44	0.90	0.41	1.25
Stdv	0.03	0.02	0.29	0.06	0.84
CV	15.6	5.4	32.0	13.5	66.9

Chl-*a*: Chlorophyll-*a* concentration; TSS: total suspended solids; ISS: inorganic suspended solids; CDOM: colored dissolved organic matters; stdv: standard deviation; CV: coefficient of variation in % and calculated as the ratio of stdv to average.