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Assessment of water constituents in highly turbid productive water by optimization bio-optical retrieval model after optical classification

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SUMMARY

Based on the bio-optical properties of highly turbid productive inland waterbody, Taihu Lake, a novel bio-optical optimization algorithm was developed to estimate chlorophyll-*a* concentration (C_{chla}) and total suspended matter concentration (C_{TSM}) after optical classification. Between 2006 and 2013, 1080 in situ samples collected from four inland lakes in China were utilized to test this optimization algorithm. All data were classified into four classes based on a new bio-optical classification method. The retrieval results of C_{TSM} and C_{chla} exhibit a good consistency with in situ measured C_{TSM} and C_{chla}. C_{TSM} retrieval accuracies (evaluated by the root mean square of percentage errors: RMSPs) of classes 1, 2, 3, and 4 were 35.77%, 16.09%, 28.42%, and 26.86% for data1 and were 32.15%, 33.14%, 47.71%, and 34.89% for data3, respectively. C_{chla} retrieval accuracies (RMSPs) of classes 1, 2, 3, and 4 were 32.49%, 20.05%, 42.01%, and 34.85% for data1, were 44.71%, 32.59%, 47.92%, and 38.11% for data2, and were 33.12%, 25.65%, 70.88%, and 23.57% for data3, respectively. The optimization algorithm was also tested by the simulated data of Medium Resolution Imaging Spectrometer, Moderate Resolution Imaging Spectroradiometer, and Sea-viewing Wide Field-of-view Sensor satellite sensors' center wavelengths. The validation shows a good correlation with the measured C_{TSM} and C_{chla}. All these examinations demonstrate that the bio-optical optimization algorithm and classification are valid and robust for both the in situ data and the simulated satellite data. The optical relationships of $a_{ph}(440)$ to C_{chla} and $b_{bp}(440)$ to C_{TSM} are reasonable and effective. In summary, the results present that the bio-optical optimization algorithm proposed in this study shows high potential application to various water types and satellite sensors. The retrieval accuracy of C_{TSM} and C_{chla} derived by bio-optical optimization algorithm was significantly improved after classification.

1. Introduction

Remote sensing reflectance of water [$R_{rs}(\lambda)$] includes the information on water optical active substances, such as chlorophyll-*a*, suspended particle matter, and colored dissolved organic matter (CDOM) (Morel, 1988). Many empirical and semi-analytical retrieval algorithms for the estimation of optical properties and water constituents' concentration have been developed (Hoge et al., 1993, 1999; Gons, 1999; Lee et al., 1998, 2002). These algorithms perform efficiently in case1 water, whose optical properties are mainly controlled by phytoplankton and its derived particulate and dissolved materials (Matsushita et al., 2012). However, their application scope and retrieval accuracy are limited duo to the significant spatial–temporal variation and extreme complexity of bio-optical properties in inland turbid water. For instance, the blue/green (B/G) band ratio algorithm can be used to estimate the chlorophyll-*a* concentration (C_{chla}) in case1 water with accepted accuracy (Gordon and Morel, 1983; O'Reilly et al., 1998). Nevertheless, in the turbid coastal water, these spectral wavelengths (B/G) are limited in retrieving C_{chla} because of the high absorption properties

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of non-algal particles (NAPs) and CDOM that are uncorrelated with phytoplankton. Thus, the B/G algorithm has been developed to near-infrared/red (NIR/R) band ratio algorithm for the low absorption of NAPs and CDOM in NIR and red spectral regions (Gitelson, 1992; Dall'Olmo and Gitelson, 2005; Dekker, 1993). Based on NIR and red spectra, Dall'Olmo and Gitelson proposed a semi-analytical model (i.e., three-band algorithm) for turbid productive water to the estimation of C_{chla} with high accuracy (Dall'Olmo et al., 2003; Dall'Olmo and Gitelson, 2005; Gitelson et al., 2007, 2008, 2009). This algorithm, nevertheless, still needs to be developed into different forms (Duan et al., 2010; Le et al., 2009; Yang et al., 2010), or changes the wavelengths' position (Zhang et al., 2009, 2011), to improve the retrieval accuracy in inland waters. The quasi-analytical algorithm (QAA) developed by Lee et al. (2002) is widely used in case1 water (QAA-version 4). Considering that the empirical estimation of absorption coefficient at reference wavelength is not highly robust, QAA-version4 was improved to QAA-version5 (Lee et al., 2009). This algorithm was also calibrated to retrieve the inherent optical properties (IOPs) in very highly turbid inland water via changing the reference wavelength (Le et al., 2009). All the above-mentioned algorithms share a common feature, i.e., to confirm the reference wavelengths' position (the most sensitive wavelength to the retrieval object). Nevertheless, the reference wavelength of each $R_{rs}(\lambda)$ is not fixed given the variation of bio-optical properties. An optimization algorithm retrieves water quality parameters via minimizing the difference between the measured and modeled $R_{rs}(\lambda)$ (Lee et al., 1999; Chami and Robilliard, 2002; Maritorena et al., 2002; Chang et al., 2007; Zhan et al., 2003). Thus, the optimization algorithm does not need to confirm the reference wavelength, although it has defects, such as losing the physical significance of the retrieved parameters led by excessive mathematical optimization.

In this study, a bio-optical optimization algorithm was developed to retrieve C_{chla} and total suspended matter concentration (C_{TSM}) after optical classification. This bio-optical algorithm includes two main optimization steps. The genetic algorithm is used to calibrate the influence of the uncertainty in the in situ measurement caused by surrounding environment and calculation parameters. The water optical and quality parameters obtained from the first step was set as the initial value and was introduced to the second optimization step. In the second step, we use non-linear quadratic programming to retrieve the water quality parameters. The non-linear quadratic programming allows embedding water optical and qualitative conditions, which are from the optical classification results, to ensure that the retrieval results must not be excessively optimized. Finally, a large number of in situ data, which include significant spatial – temporal variation of bio-optical properties, were used to check the performance of this optimization algorithm.

2. Sampling and methods

2.1. Study area

Four study areas were selected, namely, Taihu Lake, Chaohu Lake, Dianchi Lake, and Three Gorges Reservoir (Fig. 1). The Taihu Lake is located in Jiangsu Province. This lake ranks third among the five largest freshwater lakes in China, with an area of 2428 km^2 (the water surface area is 2338 km^2; the island's area is 90 km^2) and a mean depth of 1.9 m. The Chaohu Lake is located in Anhui Province, with an area of 820 km^2 and a mean depth of 4.5 m. The Dianchi Lake is located in Yunnan Province and is the source of drinking water for Kunming City. This lake has an area of 298 km^2 and a mean depth of 6.5 m. The Three Gorges Reservoir is located in Hebei Province. The water level of this reservoir is 175 m (Qin et al., 2004; Dai et al., 2008; Feng et al., 2010).

2.2. Data acquisition

The validation data in this study includes three portions. The first part (noted as Taihu data1) is 10 cruises during 2006–2011 in the Taihu Lake. The second part (noted as Taihu data2) is 19 cruises during 2003–2006 (from March to October) in the Taihu Lake. The third part (noted as other area data3) includes one cruise in the Dianchi Lake (25 points), one cruise in the Chaohu Lake (30 points), and one cruise in the Three Gorges Reservoir in 2009 (23 points). Some anomalous data were removed because of floating algae, as well as the measurements collected beyond the range of instruments. The details information on each data set is listed in Table 1.

(1) Measurement of water constitutes' concentration

The water samples were collected in the surface layer (20 cm) and stored in a cooler with ice. Then, they were transported to a laboratory for analyzing C_{TSM} and C_{chla} within 24 h. C_{TSM} was obtained by measuring the difference between the weight of the pre-combusted (550 °C for 4 h) and the dried (105 °C for 4 h) 0.7 μm Whatman GF/F glass fiber filters before and after the filtration of the water samples. The filters were re-combusted at 550 °C for 4 h to remove the organic suspended matter (OSM) and weighed again to obtain the inorganic suspended matter concentration (C_{ISM}) (Mueller et al., 2003). By subtracting C_{ISM} from C_{TSM}, the OSM concentration (C_{OSM}) was obtained. The samples of chlorophyll-*a* were filtered on GF/C filters (Whatman). Chlorophyll-*a* was extracted with ethanol (90%) at 80 °C and then analyzed spectrophotometrically at 750 and 665 nm with a correction for phaeopigments by Shimadzu UV-3600 (Chen et al., 2006).

(2) Measurement of $R_{rs}(\lambda)$

$R_{rs}(\lambda)$ measurements were conducted with ASD FieldSpec spectroradiometer (spectral range 350–1050 nm with 1 nm sampling interval). The dark current measurement and instrument optimization were conducted before measuring the objects (water, standard reflectance panel, and sky). $R_{rs}(\lambda)$ is the ratio of the upward radiance that emerged from water body [$L_w(\lambda)$] to the downwelling irradiance incident onto the water surface [$E_d(\lambda, 0^+)$]. This ratio can be expressed as follows (Lee et al., 2010a):

$$R_{rs}(\lambda) = L_w(\lambda)/E_d(\lambda, 0^+), \tag{1}$$

where $E_d(\lambda, 0^+)$ was calculated by the reflected radiance from the standard lambert gray board [$L_g(\lambda)$] and the calibration parameter (reflectivity at each wavelength) of the gray board (ρ_g). The calculation equation is

$$E_d(\lambda, 0^+) = L_g(\lambda)^* \pi/\rho_g, \tag{2}$$

where $L_w(\lambda)$ was calculated by subtracting the sky radiance reflected by water surface from the water surface measured radiance. The calculation equation is

$$L_w(\lambda) = L_{wm}(\lambda) - r^* L_{sky}(\lambda) \tag{3}$$

where $L_{wm}(\lambda)$ is the water surface radiance measured by ASD FieldSpec spectroradiometer directly, $L_{sky}(\lambda)$ is the diffusion radiance of sky, r is the reflectivity of air–water interface to the sky light and depends on the wind speed (in this paper, it was set as 2.2%). The parameters $L_g(\lambda)$, $L_{wm}(\lambda)$, and $L_{sky}(\lambda)$ were measured by ASD field spectrometer (Jiao et al., 2006).