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An improved atmospheric correction algorithm for applying MERIS data to very turbid inland waters

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ABSTRACT

Atmospheric correction (AC) is a necessary process when quantitatively monitoring water quality parameters from satellite data. However, it is still a major challenge to carry out AC for turbid coastal and inland waters. In this study, we propose an improved AC algorithm named N-GWI (new standard Gordon and Wang's algorithms with an iterative process and a bio-optical model) for applying MERIS data to very turbid inland waters (i.e., waters with a water-leaving reflectance at 864.8 nm between 0.001 and 0.01). The N-GWI algorithm incorporates three improvements to avoid certain invalid assumptions that limit the applicability of the existing algorithms in very turbid inland waters. First, the N-GWI uses a fixed aerosol type (coastal aerosol) but permits aerosol concentration to vary at each pixel; this improvement omits a complicated requirement for aerosol model selection based only on satellite data. Second, it shifts the reference band from 670 nm to 754 nm to validate the assumption that the total absorption coefficient at the reference band can be replaced by that of pure water, and thus can avoid the uncorrected estimation of the total absorption coefficient at the reference band in very turbid waters. Third, the N-GWI generates a semi-analytical relationship instead of an empirical one for estimation of the spectral slope of particle backscattering. Our analysis showed that the N-GWI improved the accuracy of atmospheric correction in two very turbid Asian lakes (Lake Kasumigaura, Japan and Lake Dianchi, China), with a normalized mean absolute error (NMAE) of less than 22% for wavelengths longer than 620 nm. However, the N-GWI exhibited poor performance in moderately turbid waters (the NMAE values were larger than 83.6% in the four American coastal waters). The applicability of the N-GWI, which includes both advantages and limitations, was discussed.

1. Introduction

The optical signal received by a satellite sensor, known as the top of atmosphere (TOA) reflectance, is generally a mixture of signals from the earth's surface (from land or water masses) and atmosphere as well as their interactions (Gordon and Wang, 1994; Santer et al., 1999). In most water areas, only 10% of signals recorded by the satellite sensors originate from water bodies in the visible wavelengths (IOCCG, 2000, 2010; Siegel et al., 2000). Therefore, it is necessary to remove the atmospheric effects from the TOA reflectance before applying the satellite data to quantitative estimation of the water quality parameters.

Most of the atmospheric correction (AC) algorithms for the remote sensing of water color originated from the following basic scheme proposed by Gordon and Wang (1994):

$$\rho_{\text{toa}}(\lambda) = \rho_r(\lambda) + [\rho_a(\lambda) + \rho_{\text{ra}}(\lambda)] + t(\lambda)\rho_w(\lambda) \quad (1),$$

where $\rho_{\text{toa}}(\lambda)$ is the reflectance recorded by a satellite sensor, $\rho_r(\lambda)$ is the reflectance from Rayleigh scattering, $[\rho_a(\lambda)+ \rho_{\text{ra}}(\lambda)]$ is the reflectance from the sum of aerosol scattering and the interaction between Rayleigh and aerosol scattering (i.e., aerosol multiple-scattering reflectance), $t(\lambda)$ is the diffuse transmittances of the atmospheric column, and $\rho_w(\lambda)$ is the water-leaving reflectance. In Eq. (1), the variables $[\rho_a(\lambda)+\rho_{\text{ra}}(\lambda)]$ remain as the largest uncertainty that needs to be solved for retrieving $\rho_w(\lambda)$ (Gordon and Wang, 1994; Gordon, 1997).

In the open oceans, the AC algorithm proposed by Gordon and Wang (1994) (denoted as GW94 hereafter) is widely used by exploiting the fact that water-leaving reflectance at near infrared

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(NIR) wavelengths can be neglected in this type of clear water. However, in most inland and coastal waters, the assumption of negligible water-leaving reflectances at the NIR wavelengths becomes invalid because of higher scattering values (Hu et al., 2000; Shi and Wang, 2007, 2009; Wang et al., 2009).

Numerous attempts have been made to solve the above problem. Our previous work summarized the existing AC algorithms for turbid waters and then evaluated four representative algorithms in Lake Kasumigaura, Japan (Jaelani et al., 2013). The four evaluated AC algorithms were (1) GWI (the standard Gordon and Wang algorithm with an iterative process and a bio-optical model; Bailey et al., 2010; Stumpf et al., 2003); (2) MUMM (Management Unit of the North Sea Mathematical Models; Ruddick et al., 2000); (3) SCAPE-M (self-contained atmospheric parameters estimation for MERIS data; Guanter et al., 2007, 2010); and (4) C2WP (case-2 water processor; Doerffer and Schiller, 2008). The results showed that all four of the evaluated AC algorithms had limitations in Lake Kasumigaura, and that further improvements were needed to address the issue of atmospheric correction for very turbid inland waters. This previous work gave us a good understanding of the AC algorithm limitations, and also provided two important considerations for improving the algorithms in the context of very turbid inland waters such as Lake Kasumigaura. These considerations were: (1) aerosol (and especially its concentration) over a water body should be estimated pixel by pixel (i.e., with consideration of the heterogeneous atmospheric status); and (2) water-leaving reflectance at two NIR reference wavelengths should be more accurately estimated for each pixel.

These two considerations have potential to improve the existing GWI algorithm for very turbid inland waters. The GWI algorithm is based on the basic AC scheme in the GW94, but estimates the water-leaving reflectance at two NIR reference bands by a bio-optical model rather than by assuming them to be zero. After removing the two estimated water-leaving reflectance values from the corresponding TOA reflectance, the GW94 algorithm can be used to calculate the aerosol effects at shorter wavelengths. This algorithm adopts an iterative procedure to make the estimated water-leaving reflectance by the bio-optical model gradually close to the actual water-leaving reflectance. The big challenge in the GWI algorithm is that the bio-optical model used in the algorithm usually underestimates the water-leaving reflectance at the two NIR reference bands in very turbid waters such as Lake Kasumigaura, Japan, even though the iterative procedure is adopted (Jaelani et al., 2013).

Consequently, the objectives of the present study were (1) to improve the existing GWI algorithm for application to very turbid inland waters; and (2) to evaluate the performance of the improved

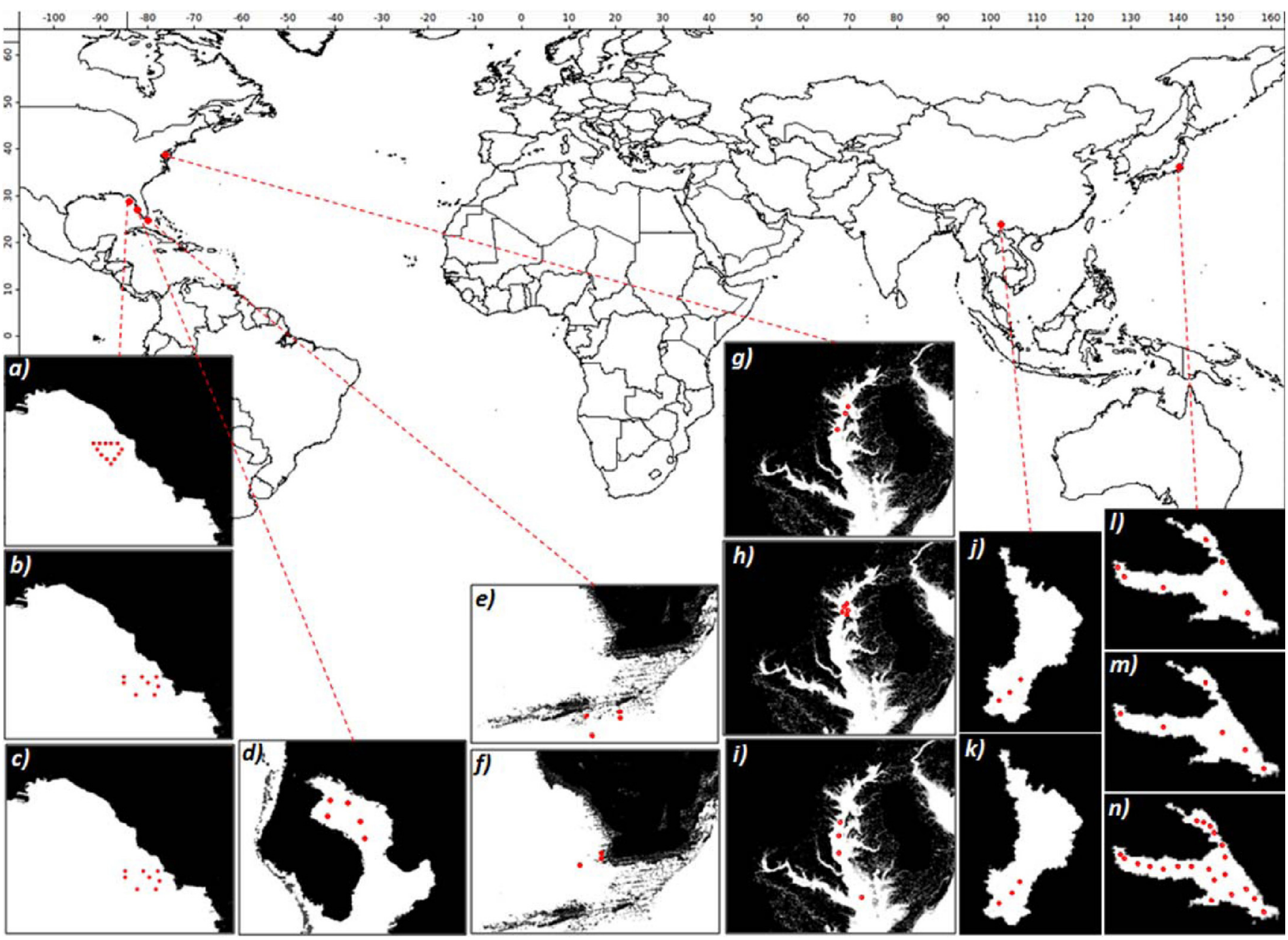

Fig. 1. The location and sampling sites at each water area. (a) Deadman Bay on March 13, 2011, 12 sites; (b) Deadman Bay on September 25, 2011, 8 sites; (c) Deadman Bay on November 21, 2011, 8 sites; (d) Tampa Bay on June 16, 2011, 5 sites; (e) coasts of South Florida on February 28, 2012, 4 sites; (f) coasts of South Florida on March 1, 2012, 3 sites; (g) Chesapeake Bay on July 11, 2012, 3 sites; (h) Chesapeake Bay on July 14, 2012, 5 sites; (i) Chesapeake Bay on July 17, 2012; 4 sites; (j) Lake Dianchi, China on October 24, 2007, 3 sites; (k) Lake Dianchi, China on March 13, 2009, 3 sites; (l) Lake Kasumigaura, Japan on February 18, 2006, 7 sites; (m) Lake Kasumigaura, Japan on August 07, 2008, 6 sites; and (n) Lake Kasumigaura, Japan on May 18, 2010, 21 sites. Red dots represent the sampling sites.