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An improved spectral optimization algorithm for atmospheric correction over turbid coastal waters: A case study from the Changjiang (Yangtze) estuary and the adjacent coast

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ABSTRACT

Remote sensing-based retrieval of the concentrations of water components relies largely on the accuracy of the atmospheric correction. Although a variety of atmospheric correction algorithms have been developed for turbid waters, the water-leaving reflectance is still underestimated in extremely turbid waters, such as in the Changjiang (Yangtze) estuary and the adjacent coast. To address this issue, this paper proposes an improved algorithm that is based on a spectral optimization algorithm (ESOA) with a coupled water-atmosphere model. The model combines an aerosol model that is constructed from Aerosol Robotic Network (AERONET) observation data and a simple semi-empirical radiative transfer (SERT) model (Shen et al. 2010) for water component retrieval. Four unknown parameters are involved in the coupled model: the relative humidity (RH), fine-mode fraction (FMF), aerosol optical thickness in the near-infrared (NIR) wavelength $\tau_a(\lambda_0)$ and suspended particulate matter (SPM) concentration (C_{spm}). These parameters are estimated by a global optimization approach that is based on a genetic algorithm (GA) without any initial inputs. Validation results of the atmospherically corrected remote sensing reflectance $R_{rs}(\lambda)$ from matchups between Geostationary Ocean Color Imager (GOCI) data and in situ data show that the algorithm has satisfactory accuracy. The root mean square error (RMSE) and the absolute percentage difference (APD) are 0.0089 and 35.12, respectively. By contrast, the $R_{rs}(\lambda)$ values retrieved from the same matchups using the GOCI data processing system (GDPS) have higher RMSE and APD of 0.0104 and 69.15, respectively. The ESOA method can be implemented conveniently within the open source code of SeaDAS (v7.1) as an alternative and operational tool for atmospheric correction of ocean color data, including GOCI, MERIS and MODIS, over highly turbid estuarine and coastal regions, such as the Yangtze estuary, the Hangzhou Bay and most of the coastal ocean in Eastern China.

1. Introduction

Approximately 90% of the radiant signals received by ocean color remote sensors is contributed by atmospheric components that are unrelated to the water components. Therefore, the accuracy of atmospheric correction critically affects the accuracy of ocean color parameter retrievals. In recent decades, due to the efforts of many researchers, the atmospheric correction for Case-1 waters has been well established. However, the atmospheric correction for turbid coastal waters is still unsatisfactory. The difficulty in atmospheric correction is how to determine the types and optical thicknesses (τ_a) of aerosols based on remote-sensing images. A classical atmospheric correction algorithm (GW94; Gordon and Wang, 1994) that is based on the near-infrared (NIR) "dark pixel" assumption infers the ratio (ε) of the aerosol scattering reflectances ρ_a at two NIR bands ρ_a (NIR). The algorithm neglects the absorption of heavily absorbing aerosols, selects the best aerosol model from 12 candidate aerosol models (M50, M70, M90, M99, C50, C70, C90, C99, T50, T80, T99, and O99) based on ε and then extrapolates ρ_a (NIR)to the visible spectrum (VIS). In the implementation of GW94 in the Sea-viewing Wide Field-of-View Sensor Data Analysis System (SeaDAS) (v7.1), the 12 candidate aerosol models are replaced with the AERONET-based aerosol model (Ahmad et al., 2010), which works well for Case-1 waters but suffers from two problems when applied to turbid waters. First, the assumption of an NIR "dark pixel" is invalid. Second, the absorption by heavily absorbing aerosols cannot be ignored because most turbid waters are located in estuaries and coastal regions. Due to the influence of continental contaminant emissions (e.g., smoke), aerosols over these regions are often absorbing. Numerous researchers have attempted to address these two problems.

For example, using iterative schemes, Siegel et al. (2000) and Bailey et al. (2010) estimated chlorophyll-*a* (Chla) concentrations by

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establishing a semi-analytical model of the water-leaving radiance L_w and the Chla concentration. Shi et al. (2012) derived the diffuse attenuation coefficient at 490 nm (K_d_490) by developing an empirical relationship between L_w and the water diffuse attenuation coefficient K_d, deriving L_w in the NIR using a bio-optical model, and gradually decreasing L_w in the NIR using an iterative scheme. Atmospheric correction algorithms that are based on iterative schemes have improved the accuracy of atmospheric correction for turbid waters. However, these iterative schemes are fundamentally based on the NIR "dark pixel" assumption, which overestimates $\rho_a(\lambda)$ at the beginning of the iteration, which will likely result in negative L_w values in the blue region. To address the issue that the L_w values of turbid waters for short-wavelength infrared (SWIR) spectra are close to 0, Wang and Shi (2005) and Wang et al., 2009 proposed the assumption of a SWIR "dark pixel" for MODIS atmospheric correction. This method has been validated over western Pacific turbid waters. However, most current ocean color remote sensors, such as the Sea-viewing Wide Field-of-View Sensor (SeaWiFS), Medium Resolution Imaging Spectrometer (MERIS) and Geostationary Ocean Color Imager (GOCI), do not include SWIR bands, which limits the application of this method. He et al. (2012) proposed an atmospheric correction algorithm based on the assumption of an ultraviolet (UV) "dark pixel" (UV-AC)·The UV-AC algorithm produces good corrections for turbid waters, but the UV "dark pixel" assumption is still invalid for highly turbid waters (He et al., 2012; Knaeps et al., 2012). In addition to the "dark pixel" assumption, Ruddick et al. (2000) proposed an atmospheric correction algorithm that assumes that the ratios between ($\rho_a(765)/\rho_a(865)$, $\rho_w(765)/\rho_w(865)$) are homogenous over a study area. Due to the large temporal and spatial variabilities of turbid estuaries and coastal regions (for example, the Yangtze estuary and Hangzhou Bay), the assumption of a homogenous ρ_w ratio is always invalid. Mao et al. (2013, 2014) suggested that using ε between two infrared bands to extrapolate ρ_a (VIS) would amplify the errors. Thus, they proposed a new method to determine the aerosol type by matching measured $R_{rs}(\lambda)$ data with aerosol models. This method requires a large amount of measurements to build a remote-sensing reflectance database. On the one hand, if the volume of measured data is not sufficient, it is difficult to fully represent all of the water's spectral characteristics; on the other hand, if the volume of measured data is too large, it will take a long time to perform searches, which reduces the practicality of the algorithm.

The atmospheric correction algorithms described above are all based on the 12 classical types of aerosol models, which use ε to determine the aerosol types and extrapolate ρ_a (VIS). This method is highly reliable for non-absorbing or weakly absorbing aerosol models but causes large errors when considering the absorption of heavy-absorbing aerosols (Gordon et al., 1997). Gordon et al. (1997) proposed an atmospheric correction algorithm based on spectral matching (SMA), and Chomko and Gordon (1998) proposed an atmospheric correction algorithm based on spectral optimization (SOA). These two algorithms build a coupled water-atmosphere model that simultaneously establishes $\rho_w(\lambda)$ and the aerosol type. By finding the optimal combination of the water spectral reflectance and aerosol reflectance, these methods simultaneously derive the water's bio-optical and aerosol model parameters. The difference between the methods is that the former searches the discrete aerosol models one-by-one, whereas the latter uses the traditional nonlinear optimization method. The SOA model assumes that a simple single-parameter model represents the particle size distribution of the aerosol, uses a series of complex refractive indices to represent the aerosol absorptivity within a certain range and then calculates the aerosol optical properties using Mie scattering theory. This method also selects a semi-analytical bio-optical model based on the Chla concentration C_{phy} and the particle scattering coefficient b_0 as the water-leaving radiance model. This coupled model includes six parameters (m_r, m_i, ν, τ, C_{phy}, and b_0) to be optimized. With the NIR "dark pixel" assumption, these are reduced to four parameters (ν, τ, C_{phy}, and b_0). Lastly, it uses a constrained nonlinear optimization method to simultaneously retrieve the four parameters. Chomko and Gordon (1998) applied the SOA algorithm to the atmospheric correction of SeaWiFS imagery over open ocean waters and validated the retrieved aerosol parameters and water bio-optical parameters. Chomko et al. (2003) improved the SOA algorithm by combining it with a globally tuned version of the Garver and Siegel (1997) bio-optical model (GSM01) and conducting an initial estimation of parameters using the NIR "dark pixel" assumption. Because the NIR "dark pixel" assumption is invalid for Case-2 waters, Kuchinke et al. (2009) used an iterative method to make an initial estimation of the parameters based on the NIR "dark pixel" assumption and proposed an improved SOA algorithm (SOA2009) so it could be applied to the atmospheric correction for Case-2 waters. Comparisons between the correction and modeling results and measurements in Chesapeake Bay showed that the algorithm performed very well.

Although SOA2009 provides a good model for atmospheric correction over turbid waters, its application in regional waters with complex optical properties, such as the Yangtze estuary and the adjacent coast, is limited for several reasons. (1) The particle size distribution of the aerosol model in SOA2009, which is based on a Junge power law (see Chomko and Gordon (1998) and Kuchinke et al. (2009) for a description), cannot explain the appearance of large particles in the observed particle size distribution (Davies, 1974), especially in coastal regions. (2) The GSM01-based SOA2009 relies on the chlorophyll-specific absorption spectra a^*_{ph}, the colored dissolved organic matter (CDOM) spectral slope S and the particle backscattering spectra n, which vary strongly in waters with regionally complex optical properties. In addition, in highly turbid waters, L_w is mainly determined by the backscattering of suspended particulate matter (SPM). The GSM01 model, which synthesizes the effects of Chla, CDOM and total suspended matter (TSM), is too complicated. (3) SOA2009 uses a traditional constrained nonlinear optimization algorithm, such as the quasi-Newton algorithm, that strongly relies on parameter initialization and can only find an optimum near the initial values. However, it is difficult to accurately estimate the initial values of the parameters.

This study proposes an improved SOA atmospheric correction algorithm for turbid waters (ESOA). To address the three limitations described above, we made the following improvements: (1) In ESOA, the aerosol model is based on the AERONET observation data; thus, it can accurately reflect the actual conditions of the coastal aerosols (Ahmad et al., 2010). Additional details about this model are given in Section 2.1. (2) ESOA replaces the GSM01 model with a simple semi-empirical radiative transfer (SERT) model that has fewer parameters and works well with turbid coastal waters (Section 2.2). By combining (1) and (2), we derive a set of nonlinear equations based on radiative transfer (Section 3). (3) ESOA replaces the traditional optimization methods with a global-optimization genetic algorithm that does not rely on parameter initialization (Section 3). In Section 4, we validate ESOA with the simulated data and measurements separately. The measurements that are used for the validation include measured $R_{rs}(\lambda)$ data, fixed station SPM datasets and GOCI images over the Yangtze estuary and the adjacent coast. Finally, this study discusses the operational satellite image processing approach based on ESOA.

2. Aerosol and water models

In this study, we replace the top of atmosphere (TOA) radiance L with the planetary reflectance, which is defined as:

$$\rho = \frac{\pi L}{F_0\ \cos\theta_0}, \tag{1}$$

where F_0 is the extraterrestrial solar irradiance, and θ_0 is the solar zenith angle. Thus, the TOA reflectance of the ocean-atmosphere system at wavelength λ is $\rho_t(\lambda)$, and $\rho_m(\lambda)$ is the calibrated $\rho_t(\lambda)$ with Rayleigh scattering $\rho_r(\lambda)$ correction, white cap reflectance $\rho_{wc}(\lambda)$ and flare