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Exploring the potential of Rayleigh-corrected reflectance in coastal and inland water applications: A simple aerosol correction method and its merits

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ABSTRACT

Atmospheric correction methods that are designed for either ocean color or land applications often result in low-quality or even no surface reflectance data for coastal and inland waters. In contrast, Rayleigh-corrected reflectance (R_{rc}) has been used in water applications, although without removing aerosol scattering. However, a systematic effort has not been made to investigate the uncertainties and applicability of R_{rc} in ocean color studies. This knowledge gap was filled in this study by using Moderate Resolution Imaging Spectroradiometer (MODIS) data covering a large area (almost the entire middle and lower reaches of the Yangtze River Basin and the Yangtze River Estuary) between 2002 and 2016. We first examined the correlation between a quality-controlled reflectance product that was generated using a shortwave-infrared (SWIR)-based atmospheric correction method (R_{rs_swir}) and R_{rc}. Improved relationships between these two products were found for all MODIS bands if a subtraction of the Rayleigh-corrected reflectance at 1240-nm was utilized as the aerosol correction for R_{rc} ($R_{rc\text{-}1240}$). The robust correlations between the two products allow for R_{rs_swir} to be replaced with $R_{rc\text{-}1240}$-converted reflectance (denoted as $R_{rs\_rrc\text{-}1240}$) in water applications. In situ validations further demonstrated that the accuracy levels between usable $R_{rs\_rrc\text{-}1240}$ and R_{rs_swir} data are comparable for most MODIS wavelengths. The most striking superiority of $R_{rs\_rrc\text{-}1240}$ over R_{rs_swir} is the pronounced increase in data coverage (especially for small water bodies), where the percentages of usable observations (PUOs) of the former are several times to more than one order of magnitude higher than those of the latter. The differences in PUOs were mostly due to perturbations related to land adjacency effects (LAEs) in the SWIR-based atmospheric correction. Such effects could also explain the reduced PUOs for smaller water bodies. Ocean color applications in the examined regions could benefit from such a dramatic increase in PUOs, which could enhance the capability of tracking short- to long-term dynamics and could create new possibilities for inland water system monitoring at the basin scale.

1. Introduction

Over the past several decades, significant progress has been made in research on coastal and inland waters by utilizing satellite ocean color remote sensing to quantitatively measure water quality parameters (such as the concentrations of total suspended sediment (TSS) and chlorophyll-a (Chl-a)) (Budhiman et al., 2012; Son and Kim, 2018) and to understand the impacts of climatic changes and/or human activities on the ecological and biogeochemical functions of water bodies. However, many challenges have remained unresolved for decades (Mouw et al., 2015), one of which is the lack of an accurate surface reflectance product, leading to a lack of data or low-quality inputs for various inversion algorithms that are used for water quality product retrievals.

The difficulties associated with atmospheric correction over optically complex coastal and inland waters are the primary reasons for this challenge. The atmospheric path radiance received by a sensor at the top-of-atmosphere (TOA) can be mainly decomposed into Rayleigh and aerosol scattering. While the Rayleigh component can be computed accurately even with the consideration of polarization effects (Gordon, 1997), the estimation of aerosol reflection is difficult. The classic

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atmospheric correction (AC) algorithm for Moderate Resolution Imaging Spectroradiometer (MODIS) imagery often fails in coastal and inland waters, yielding negative reflectance due to overcorrections and leading to large errors to the derived ocean color products (Gordon, 1997; Gordon and Wang, 1994; Hu et al., 2000; Ruddick et al., 2000). These errors mainly occur because the black-pixel assumption in the near-infrared (NIR) bands is not valid in turbid waters because of the elevated signals in the NIR bands associated with significant particle scattering. An additional challenge for the NIR-based method is signal saturation over highly reflective waters (Hu et al., 2012), which further limits the validity of R_{rs} products.

Algorithms have also been developed to tackle non-“black-pixel” issues, including but not limited to spatial extrapolation of aerosol information from nearby clear waters, assumptions of spectral shape in aerosol scattering, relationship between Chl-a concentration and NIR reflection (Hu et al., 2000; Jamet et al., 2011; Ruddick et al., 2000; Siegel et al., 2000; Stumpf et al., 2003) and the replacement of the original NIR bands with the shortwave-infrared (SWIR) wavelengths (Novoa et al., 2017; Vanhellemont and Ruddick, 2015; Wang and Shi, 2007). The last approach has been implemented as an alternative algorithm in both NASA’s and NOAA’s software package SeaDAS to derive R_{rs} products for coastal and inland productive waters (denoted as R_{rs_swir}).

Theoretically, water reflection in SWIR bands is essentially zero, even for extremely turbid waters, because the water absorption coefficients are significantly higher for these bands than for NIR bands (Hale and Querry, 1973), and the TOA signal in the SWIR wavelengths is the result of the atmospheric path radiance. Therefore, the surface reflectance estimation from the SWIR-based AC method is expected to be reliable, as long as the absorbing aerosol is not dominant in the atmosphere (Chander et al., 2009) and the SWIR bands have sufficient signal-to-noise ratios (Hu et al., 2012). Indeed, this AC approach has demonstrated promising performance in producing satisfactory remote sensing reflectance (R_{rs}, in sr^{-1}) values, even in the most turbid waters, such as the Yangtze River Estuary where the TSS concentrations reach $> 1000\ mg\ L^{-1}$ (Wang et al., 2007). The uncertainties in the resulting R_{rs} values could be significantly reduced through various radiometric calibration and noise reduction schemes for SWIR bands (Li et al., 2017).

Currently, the use of R_{rs_swir} in coastal and inland waters suffers from several limitations. The first limitation is the contamination of land adjacency effects (LAEs). Due to the significant reflectance contrast between land and water, the radiance of the nearby “bright” land pixels scatter into the field of view of the satellite instruments, enhancing the signals of water pixels. The LAEs tend to increase with increasing wavelength, leading to large uncertainties in the two candidate SWIR AC bands and thus providing problematic R_{rs_swir} retrievals. Indeed, these effects could extend several kilometers from the coastline, resulting in erroneous surface reflectance results within this distance. The second limiting factor is that the SWIR AC approach embedded in SeaDAS often fails without valid R_{rs} outputs, especially when applied to relatively small water bodies (see results below). Even after adjustments to the default processing options (e.g., turning off the masks for land, shallow water, and sunglint and raising the default thresholds for aerosol optical thickness and cloud albedo), this data loss problem is still prominent.

Due to the lack of R_{rs} produced with the ocean color-based AC algorithms (either NIR- or SWIR-based AC methods), other reflectance products are often selected for coastal and inland waters applications. For example, MODIS land surface reflectance products (MYD09 for Aqua and MOD09 for Terra, denoted as R_Land), which are generated using the land-oriented AC approach (Kaufman et al., 1997), have been proven to be applicable to water turbidity mapping in many estuaries and inland lakes (Hou et al., 2017; Li et al., 2016; Petus et al., 2010, 2014; Zhang et al., 2014). A recent study by Feng et al. (2018) also demonstrated the high accuracies of R_Land(645) and R_Land(645/555). However, spatial patchiness over water surfaces has been observed in R_Land products, largely because a 10 × 10 pixel (1-km resolution) moving window is utilized during aerosol correction (Kaufman et al., 1997). Although a spatial and temporal binning scheme has been recommended to minimize the patchiness noise in R_Land images (Feng et al., 2018), it sacrifices the original spatial and temporal resolutions.

Surface reflectance products that are derived using AC processes designed for either ocean color (based on NIR or SWIR) or land applications are very sensitive to environmental disturbance (such as LAEs), leading to low-quality data (e.g., noisy or negative) or even no data coverage in coastal and inland waters. As the interferences generally occur in the aerosol correction procedures, a natural question would be whether the Rayleigh-corrected reflectance (R_{rc}, dimensionless) is sufficiently accurate without an aerosol removal step for ocean color studies. Indeed, R_{rc} has been proven to be useful for estuaries and inland water investigations in a number of pioneering studies (Duan et al., 2014; Feng et al., 2014b; Markham et al., 2008; Zhang et al., 2016), and R_{rc} even produced higher quality images with less noise and spatial patchiness than the R_Land and R_{rs_swir} products (Feng et al., 2018).

However, to date, a systematic effort has not been made to assess the consistency between R_{rc} and different reflectance products, and the uncertainties and general applicability of R_{rc} in water applications are generally unknown, not to mention the fidelity of the derived water properties. The current study is thus designed to fill this knowledge gap and to provide a general guideline for the use of R_{rc} in coastal and inland water studies. In detail, this study has the following objectives:

(1) Examine the consistency between R_{rc} and R_{rs_swir}, where the quality of R_{rs_swir} is assessed using an objective quality assurance system.
(2) Identify the relationships between the two different products for various MODIS bands and demonstrate the superiority of R_{rc}-converted reflectance in data coverage.
(3) Assess the impacts of land adjacency on the data coverage of R_{rc}-converted reflectance and discuss the limitations of this method and its implications for ocean color applications.

2. Datasets and preprocessing

2.1. Remote sensing datasets

MODIS Aqua Level-1A Local-Area-Coverage (LAC) data were downloaded from the NASA Goddard Space Flight Center (GSFC, https://oceancolor.gsfc.nasa.gov/). To allow full coverage of different weather (aerosol) conditions, water characteristics, and solar/viewing geometries, all available data between July 2002 and December 2016 that covered all of region 1 (the lower reaches of Yangtze River Basin, the Yangtze River Estuary and adjacent ocean areas) and region 2 (the middle reaches of the Yangtze River Basin) (see locations in Fig. 1) were obtained. Both regions contain many lakes, river channels and/or coastal ocean areas, while the water bodies in region 1 are generally larger than those in region 2. The MODIS data were then processed with the l2_gen module of the SeaDAS software (version 7.3) to generate two reflectance product types.

The first reflectance product is the Rayleigh-corrected reflectance (R_{rc}, dimensionless) (Hu, 2009), where the Rayleigh (molecular) scattering effects are removed, leaving the aerosol contributions in the data products. This partial AC can be expressed as:

$$R_{rc} = \pi L_t^{*}/(F_0 \times \cos\theta_0) - R_r \qquad (1)$$

where F_0 is the extraterrestrial solar irradiance, θ_0 is the solar zenith angle, L_t^{*} is the radiometrically calibrated at-sensor radiance after removing the gaseous absorption, and R_r is the reflectance due to Rayleigh (molecular) scattering.

The second product is the fully atmospherically corrected remote sensing reflectance (i.e., R_{rs}), where the contributions of both Rayleigh