Remote Sensing of Environment 175 (2016) 109–119

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Retrieval of the diffuse attenuation coefficient from GOCI images using the 2SeaColor model: A case study in the Yangtze Estuary

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ARTICLE INFO

Article history:
Received 29 May 2015
Received in revised form 29 November 2015
Accepted 31 December 2015
Available online 11 January 2016

Keywords:
Diffuse attenuation coefficient
2SeaColor
GOCI
Yangtze Estuary

ABSTRACT

The 2SeaColor model (Salama & Verhoef, 2015) was proposed to analytically retrieve the diffuse attenuation coefficient (K_d) from remote sensing reflectance (R_{rs}), but its parameterization was based on approximations and subjected to large uncertainties. In this study, we present an improvement on the parameterization equations in the inverse scheme of the 2Seacolor model. The improved model is then validated with three *in-situ* datasets and compared with the Zhang model (Zhang & Fell, 2007) and the Lee model (Lee, Darecki et al., 2005). Validation with radiometric data shows that the 2SeaColor model provides the best estimates of K_d for the full range of observations, with the largest determination coefficient ($R^2 = 0.935$) and the smallest root mean squared error (RMSE $= 0.078$ m^{-1}). For clear waters, where $K_d(490) < 0.2$, the Zhang model provides the most accurate K_d estimations, but results from the Lee model and the 2SeaColor are rather comparable. For turbid waters, where $K_d(490) > 0.2$ m^{-1}, the 2SeaColor model is found to be more accurate, with an RMSE of 0.186 m^{-1}, compared to RMSEs of 0.279 m^{-1} and 0.388 m^{-1} for the Zhang model and the Lee model, respectively.
The 2SeaColor model is finally applied to the GOCI (Geostationary Ocean Color Imager) level 2 product (L2P) to produce K_d maps over the Yangtze Estuary, resulting in a reasonable distribution and expected range of K_d, as for example $K_d(490)$ was varying from 0.04 to 9.82 m^{-1} for the image acquired at 02:16 UTC, on March 8th 2013.
The analytical 2SeaColor model is able to provide consistently stable and fairly accurate K_d estimates in both clear and turbid waters without the need of tuning empirical coefficients from field measurements, and thus has great potential for estimating K_d over optically complex waters.

1. Introduction

The diffuse attenuation coefficient (K_d, in m^{-1}) is an important optical property of water bodies that describes the penetration of incident solar radiation in the water column. K_d is classified as a quasi-inherent optical property (QIOP), since it depends on both the optically active water constituents and the distribution of the ambient light field (Kirk, 1984, 1991; Mobley, 1994; Smith & Baker, 1978).

Based on the fact that 90% of the diffusely reflected light from a water body comes from a surface layer of water within a depth of $1/K_d$ m, the diffuse attenuation coefficient shows potential effects on the functioning of ecological processes and biogeochemical cycles in oceanic and coastal ecosystems. Previous researches have shown that K_d can be an effective indicator for turbidity in water (Kirk, 1994) and sediment transportation and resuspension (Majozi, Salama, Bernard, Harper, & Habte, 2014; Zhang et al., 2006). Meanwhile, K_d is a key parameter in studies such as heat transfer in the upper water layer (Stramska & Zuzewicz, 2013; Wu, Tang, Sathyendranath, & Platt, 2007), phytoplankton photosynthesis and photobleaching (Loiselle et al., 2009; McClain, Arrigo, Tai, & Turk, 1996), and the estimation of primary production in natural waters (Bergamino et al., 2010; Lee et al., 2011).

Algorithms for the remote retrieval of K_d have been developed for clear waters (Austin & Petzold, 1981; Mueller, 2000), but they always generate huge errors in turbid waters due to the complexity in optical properties and limitations in the algorithms (IOCCG, 2000, 2006; Salama, Melin, & Van der Velde, 2011; Zibordi et al., 2009). To retrieve K_d in optically complex waters, several methods were adopted. The empirical models were developed by statistical fitting based on *in-situ* measurements (Werdell & Bailey, 2005; Zhang & Fell, 2007). The semi-analytic models usually calculated the K_d from remotely retrieved inherent optical properties (IOPs) of water constituents (Doron, Babin, Mangin, & Hembise, 2007; Lee, Du, & Arnone, 2005; Lee, Darecki, Carder, Davis, Stramski and Rhea, 2005; Morel & Loisel, 1998; Wang, Son, & Harding, 2009). Additionally, Salama and Verhoef (2015) developed the analytical 2SeaColor model to estimate K_d at different spectral bands and depths, based on the solution of the radiative transfer equation using the two-stream approximation. The two-stream approximation was previously adopted in the retrieval of suspended matter (Ambarwulan, Verhoef, Mannaerts, & Salama, 2012; Shen, Verhoef, Zhou, Salama, & Liu, 2010). However, the assumption in the original

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http://dx.doi.org/10.1016/j.rse.2015.12.053
0034-4257/

2SeaColor model that only water molecules contribute to the total absorption in the near-infrared (NIR) bands may not work for highly turbid waters, which leads to large uncertainties for observations from turbid waters. Therefore, improvement on the 2SeaColor model is strongly desired for K_d estimation over turbid waters. The objective of this study is to improve the 2SeaColor model and validate the respective performance of the 2SeaColor model and other empirical and semi-analytical models. We first improve the parameterizations in the inversion scheme of the 2SeaColor model. Then the 2SeaColor model is validated with three *in-situ* datasets and compared with empirical and semi-analytic models. At last, we produce K_d maps over the Yangtze Estuary by operating the 2SeaColor model on the level 2 product (L2P) of the Geostationary Ocean Color Imager (GOCI).

2. Material and methods

2.1. Data sets

Three *in-situ* datasets are employed in this study for model validation and inter-comparison, which are collected from a variety of waters covering from open ocean to coastal regions. They are the NOMAD (NASA Bio-Optical Marine Algorithm Data set) (Werdell & Bailey, 2005), the COASTLOOC (Coastal Surveillance through Observation of Ocean Color) (Babin, Morel, Fournier-Sicre, Fell, & Stramski, 2003) and *in-situ* measurements in Yangtze estuarine and coastal water, hereafter denoted as the Yangtze dataset. Fig. 1 presents the locations of the *in-situ* observations of these three datasets. Solar zenith angle (SZA, in degree) of each observation is calculated according to location (latitude and longitude and time zone), date and time (C++ code is available at http://www.psa.es/sdg/sunpos.htm). The percentage distribution of SZA for each dataset is presented in Fig. 2.

2.1.1. NOMAD dataset

The NOMAD dataset (Werdell & Bailey, 2005) contains 4459 observations of bio-optical parameters collected worldwide from open ocean to coastal waters. Observations were selected where the upwelling water radiance (L_w) and the spectral downwelling irradiance (E_s) in the bands at 411, 443, 489, 510, 555, and 665 nm are all valid, as well as the diffuse attenuation coefficient at 443 and 489 nm. As a result, 1518 concomitant observations were selected (sampled sites are shown in Fig. 1a). The diffuse attenuation coefficient at 489 nm, $K_d(489)$, of the selected observations ranges from 0.0085 m^{-1} to 0.9113 m^{-1} with an average value of 0.0852 m^{-1} and a standard deviation of 0.105 m^{-1}. Remote sensing reflectance (R_{rs}) is calculated as the ratio of upwelling water radiance L_w to the downwelling irradiance E_s, and $K_d(489)$ is considered equivalent to $K_d(490)$ for model validation and inter-comparison in this study.

2.1.2. COASTLOOC dataset

The COASTLOOC dataset (Babin et al., 2003) consists of 422 observations of bio-optical parameters collected from European coastal waters. The irradiance reflectance just below the sea surface $R(0^-)$ is available in the COASTLOOC data set instead of R_{rs}. Therefore, the $R(0^-)$ was converted to R_{rs} using the formulation used in Zhang and Fell (2007): $R_{rs} = 0.133R(0^-)$. It is worthy to mention that this formulation uses a constant value for the upwelling irradiance-to-radiance ratio ($Q = 4$),

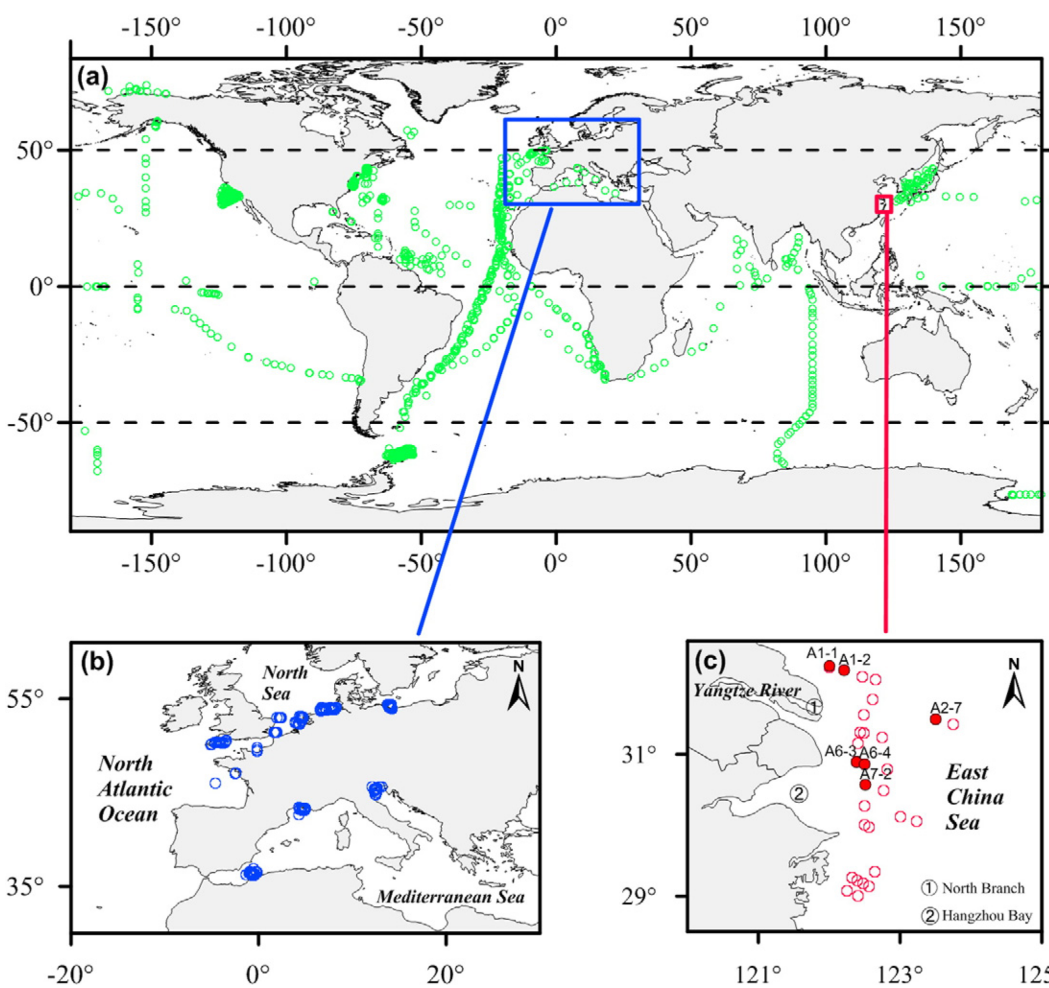

Fig. 1. Location of the field data sets. (a) The NOMAD, (b) the COASTLOOC and (c) the Yangtze data set (solid circles are matchups sites within 1 h overpass of GOCI).