ISPRS Journal of Photogrammetry and Remote Sensing 91 (2014) 85–97

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

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

A simple two-band semi-analytical model for retrieval of specific absorption coefficients in coastal waters

Jun Chen [a,b], Tingwei Cui [c], Zhongfeng Qiu [d], Changsong Lin [a,*]

[a] School of Ocean Sciences, China University of Geosciences, Beijing 100083, China
[b] Key Laboratory of Marine Hydrocarbon Resources and Environmental Geology, Qingdao Institute of Marine Geology, Qingdao 266071, China
[c] First Institute of Oceanography, State Oceanic Administration, Qingdao 266071, China
[d] School of Marine Sciences, Nanjing University of Information Science and Technology, Nanjing 210000, China

ARTICLE INFO

Article history:
Received 17 October 2012
Received in revised form 7 January 2014
Accepted 13 January 2014
Available online 15 March 2014

Keywords:
Remote sensing
Absorption coefficient
Semi-analytical model
Spectral slope technique
Bohai Sea
West Florida Shelf

ABSTRACT

A non-linear iterative method is used to replace the traditional spectral slope technique in initializing the total absorption decomposition model. Based on comparison of absorption coefficient by QAA and two-band semi-analytical model (TSAA) models with field measurements collected from the West Florida Shelf waters and Bohai Sea, it is shown that both models are effective in estimating absorption coefficients from the West Florida Shelf waters, but the TSAA model is superior to the QAA model. Use of the TSAA model in estimating absorption coefficient in the West Florida Shelf and Bohai Sea decreases the uncertainty of estimation by 1.3–74.7% from the QAA model. The TSAA model's sensitivity to the input parameters was evaluated by varying one parameter and keeping the others fixed at their default values. Our results indicate that the TSAA model has quite a strong noise tolerance to addressing the field data of the total absorption coefficient.

1. Introduction

Recent advances in optical sensor technology have opened new opportunities for the study of biogeochemical processes in aquatic environments at spatial and temporal scales (Clavano et al., 2007). These advances have allowed scientists to utilize ocean color satellite images to synoptically investigate large-scale surface features in the world's oceans (Chang and Gould, 2006). Over the past 25 years, ocean color data have primarily been used to investigate absorption related to particulate matters in open ocean waters, and several ocean color algorithms have been developed for this type of environment. Empirical algorithms generally employ waveband ratios of upwelling or normalized water-leaving radiance, or remote sensing reflectance $R_{rs}(\lambda)$ (Gould and Arnone, 1997). Quasi-analytical and semi-analytical algorithms are based on the $b_b(\lambda)/[a(\lambda)+b_b(\lambda)]$ to remote sensing reflectance relationship (Lee et al., 2002; Smyth et al., 2006), where $b_b(\lambda)$ is the backscattering coefficient, and $a(\lambda)$ is the absorption coefficient.

It is essential to improve our understanding of coastal ocean processes, due to the fact that the majority of the world's primary production occurs on continental shelves, and coastal oceans are the areas which are most utilized and affected by humans. Reliable interpretation of satellite measurements of water color is dependent on a thorough understanding of the absorption coefficients pertinent to the water body under consideration (Binging et al., 2008). In order to address these issues, many recent oceanographic studies performed throughout the world have shifted from open oceans to coastal oceans (Chen and Quan, 2013; Gordon and Franz, 2008; Matthews et al., 2012; Moses et al., 2012a). Furthermore, algorithms to infer total and partitioned spectral absorption for optically active constituents (containing colored dissolved organic matter (CDOM), detrital matter and phytoplankton) for ocean color data have also been developed (Lee et al., 2002). Satellite estimation of absorption associated with particulate matter concentration in coastal oceans may be used to develop new optical water mass classification schemes, and to track water masses and river discharge plumes. In addition, spectral particulate and phytoplankton absorption data are essential for ecological studies, including those concerning algal bloom monitoring and mitigation (Chang and Gould, 2006), due to the fact that these inherent optical properties may be converted to the concentration of particulate matters (Moses et al., 2012b).

Although considerable attention has been given to the subject of accurate remote sensing of absorption coefficients related to

---

* Corresponding author. Tel.: +86 0532 85777429.
E-mail address: cugb_lcs@163.com (C. Lin).

http://dx.doi.org/10.1016/j.isprsjprs.2014.01.002

optically active constituents in coastal waters (Chen et al., 2013b; Lee et al., 2002; Smyth et al., 2006), there remains a gap between theory and actual measurement. This gap is attributed to both instrumental limitations and simplification assumptions used in analytical, semi-analytical, quasi-analytical, and empirical models (Clavano et al., 2007). For example, Hoge and Lyon (1996) developed a linear matrix inversion of ocean radiance to obtain colored dissolved organic matters (CDOM), as well as detrital absorption $a_g(\lambda)$, phytoplankton $a_p(\lambda)$, and total scattering coefficients. They found that the $a_p(\lambda)$ which aircraft retrieved using the matrix inversion method was quite similar to the retrieved results of the laser methods. Strong agreement was also found using a limited number of in situ measurements. Carder et al. (1999) developed a semi-analytical technique to derive $a_g(\lambda)$ and $a_p(675)$ using the spectral reflectance ratios ranging between 412:443 and 443:551. Compared to the limited in situ dataset, they found an acceptable agreement with $a_p(675)$ retrievals from the Moderate Resolution Imaging Spectroradiometer (MODIS). However, poor retrievals from optically complex waters have also been reported (Astoreca et al., 2012; Chang and Gould, 2006; Chen et al., 2013b; Darecki and Stramski, 2004), due to the fact that the variations in the shape and magnitude of $a(\lambda)$ and $b_b(\lambda)$ are poorly documented. Therefore, an accurate semi-analytical retrieval model is still under development.

Lee et al. (2002) developed a multi-band quasi-analytical algorithm (QAA) for deriving $a_g(\lambda)$ and $a_p(\lambda)$ from the remote sensing reflectance of coastal areas, further analyzed the influential factors of the model, and suggested a method for optimizing the reference positions. This QAA model is composed of two empirical models, three semi-analytical models, and two analytical models (Lee et al., 2005). The model has been well validated using in situ observations from a variety of oceanic and coastal environments with a wide range of water types, covering waters such as the Gulf of Mexico (Lee et al., 2002), Bering Sea, Arabian Sea, Sargasso Sea, area near Key West (Lee and Carder, 2004), and Bohai Sea (Xiu et al., 2009). These results have demonstrated that the QAA model may be used to produce retrieval absorption coefficients from various coastal waters without re-parameterization. However, in the QAA model, the total absorption coefficient and backscattering coefficient at 551 nm are estimated by empirical models, then extrapolated to the “unknown” shorter wave bands using a semi-analytical model. It is well known that empirical models are generally only suitable for application to waters with optical characteristics similar to those used in the development of the model. As a result their applicability may be quite limited, possibly resulting in significant errors. Ivey (2009) applied the QAA algorithm to derive the respective $b_b(\lambda)$ from coastal waters of Puget Sound, Washington State, Stocking Island, the Bahamas, and the West Florida Shelf, indicating that the QAA algorithm produces poor performance in $b_b(\lambda)$ predictions, the estimation uncertainty of which is >50%. Zheng et al. (2010) also demonstrated that the QAA-derived $b_b(\lambda)$ generally leads to overestimation of both the backscattering and absorption at wavelengths shorter than 551 nm, and may yield negative chl*a* absorption coefficients in the Arctic waters and many coastal locations. Therefore, it is of utmost necessity to validate the applicability of the QAA model in coastal waters, and to improve the performance of the QAA model by means of remodeling absorption coefficient estimation models.

The objectives of this study are to validate the performance of QAA model, and to further improve it for application in coastal waters, using an innovative two-band semi-analytical algorithm (TSAA). The specific goals are as follows: (1) to evaluate the accuracy of the QAA model for accurately estimating the absorption coefficients in the West Florida Shelf waters; (2) to evaluate the accuracy of the TSAA model with the spectral bands of MODIS; and (3) to compare the accuracy of the QAA and TSAA models in estimating absorption coefficients in the coastal waters of the West Florida Shelf.

2. Material and methods

2.1. Accuracy assessment

In this study, the mean normalized bias (MNB) is used to assess the accuracy of the ch*a* concentration estimation. This statistic was previously described by Zibordi et al. (2004), Darecki and Stramski (2004), and Gitelson et al. (2008), as follows:

$$\mathrm{MNB} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{x_{mod,i} - x_{obs,i}}{x_{obs,i}}\right| \times 100\% \tag{1}$$

where $x_{mod,i}$ is the modeled value of the i^{th} element, $x_{obs,i}$ is the observed value of the i^{th} element, and n is the number of elements.

2.2. Dataset description

Satellite ocean color missions require an abundance of high quality in situ measurements for bio-optical and atmospheric algorithm development, post-launch product validation, and sensor calibration (Werdell and Bailey, 2002). In order to facilitate the assembly of a global dataset, through various projects programs created since 1997, NASA has funded the collection of ocean in situ data for data product validation, algorithm development, satellite data comparison and inter-calibration, as well as data merger studies and time series analyses (Wang et al., 2009). The SeaWiFS Bio-optical Archive and Storage System (SeaBASS) maintains a local repository of in situ ocean optical and bio-optical data to support and sustain regular scientific analyses. Specifically, the database includes in situ ocean optical, biological, and other related oceanographic data (for details see http://seabass.gsfc.nasa.gov). These data were constructed by various researchers around United States and Europe, using various instrumentation, with all measurements closely following rigorous, community-defined deployment and data processing protocols (Mueller and Fargion, 2002). The SeaBASS in situ data have been continuously used in support with SeaWiFS and MODIS ocean color product validation and algorithms (Wang et al., 2009; Werdell and Bailey, 2002). Therefore, the SeaBASS data are appropriate for the new algorithm calibration and evaluations.

Until recently the SeaBASS only contained a relatively small amount of data which could be referred to as “coastal” in the sense that the measurements were carried out at a small distance from the coastline. From the optical point of view most of these measurements were still very clear oceanic waters if compared with the “actual” optically complex turbid coastal and inland waters. Therefore, in order to evaluate the accuracy of the TSAA and QAA models in predicting the absorption coefficients associated with optically active constituents, in this study only three independent datasets containing the spectral optical properties and inherent optical properties of water columns were collected from SeaBASS. These datasets were taken during the period of 1999–2003 in the West Florida Shelf by HL Carder from 19 independent cruises during the period of 1999–2002 (Fig. 1A) (Carder et al., 2003). In order to calibrate and validate the performances of the QAA and TSAA models, the calibration and validation datasets must contain nearly simultaneously observations of the remote sensing reflectance and water constituent absorption coefficients for a given water mass. There are a total of 194 samples which meet that requirement. In this study, the data in the calibration dataset ($n = 108$, Fig. 2A and Table 1a) were retrieved from 11 independent cruises in the West Florida Shelf during the period of 2001–2002, and two validation datasets were taken from eight independent cruises in the