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A neural network model for remote sensing of diffuse attenuation coefficient in global oceanic and coastal waters: Exemplifying the applicability of the model to the coastal regions in Eastern China Seas

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ABSTRACT

For global oceanic and coastal waters, a multilayer back propagation neural network (MBPNN) is developed to retrieve the diffuse attenuation coefficient for the downwelling spectral irradiance at the wavelength 490 nm ($K_d(490)$). The applicability of Lee's quasi-analytical algorithm-based semi-analytical model, Wang's switching model, Chen's semi-analytical model, Jamet's neural network model, and the MBPNN model is evaluated using the NASA bio-optical marine algorithm dataset (NOMAD) and the Eastern China Seas dataset. Based on the comparison of $K_d(490)$ predicted by these five models, with field measurements taken in global oceanic and coastal waters, it is found that the MBPNN model provides a stronger performance than the Lee, Wang, Chen, and Jamet's models. The atmospheric effects on the MODIS data are eliminated using near-infrared band-based and shortwave infrared band-based combined models, and the $K_d(490)$ is quantified from the MODIS data after atmospheric correction using the MBPNN model. The study results indicate that the MBPNN model produces ~28% uncertainty in estimating $K_d(490)$ from the MODIS data. Finally, an exemplification of the applicability of the model to the coastal regions in the Eastern China Seas is carried out. Our results suggest that the $K_d(490)$ shows a large variation in the Eastern China Seas, ranging from 0.02 to 4.0 m^{-1}, with an average value of ~0.17 m^{-1}.

1. Introduction

The light available in the water column is a natural component of the irradiance reaching the Earth's surface, and its potential to influence ecological processes and biogeochemical cycles in natural waters has long been known (Robert, Alexander, & Kirill, 1995). This incoming solar light is the major energy source fueling for marine primary production in the natural world. On one hand, the penetrative solar light limits the growth of phytoplankton, and is a first order determinant of the response of phytoplankton to nutrient input in the ocean euphotic zone (Wu, Sathyendranath, & Platt, 2007); On the other hand, all benthic substrates must receive a sufficient amount of light to sustain primary production to harbor photosynthetic organisms, including both conspicuous substrates such as sea grasses, algae and corals (Delesalle, Pichon, Frankignoulle, & Gattuso, 1993), and less conspicuous such as the microflora thriving on sandy and muddy seabeds (Gattuso et al., 2006). Therefore, light, together with nutrients, is a major governing parameter controlling production and photosynthetic processes in the global oceanic and coastal ecosystems.

The diffuse attenuation coefficient for downwelling irradiance at the wavelength 490 nm, $K_d(490)$, is an important water property related to light penetration and availability in the oceanic and coastal ecosystems (Mobley, 1994). Therefore, accurate estimation of the diffuse attenuation coefficient is a critical factor to understand the ecological processes and energy cycles in the upper ocean. Recent advances in optical sensor technology have allowed scientists to utilize ocean color satellite data to synoptically investigate $K_d(490)$ over basin and global scales for ocean waters at high spatial and temporal resolutions (Lee, Du, & Arnone, 2005; Mishra, Narumalani, Rundquist, & Lawson, 2005; Schaeffer et al., 2011). These achievements greatly improved our knowledge regarding the biological processes and heat balance of the global oceanic systems. Traditionally, the in situ $K_d(490)$ had been measured by the ocean color scientific community following the primary studies carried out in the late 1970s (Smith & Baker, 1978). Since the launch of the Coastal Zone Color Scanner (CZCS) in 1973, satellite remote sensing image data has been used by the color community to map the distribution of $K_d(490)$ in the global oceans, with better spatial and temporal resolution than the in situ measurements. Currently, three main types of models are used to derive $K_d(490)$ maps from ocean color satellite sensors:

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(1) empirical relationships between the $K_d(490)$ and Apparent Optical Properties (AOP) (Austin & Petzold, 1981; Jamet, Loisel, & Dessailly, 2012; Mueller, 2000; Mueller & Trees, 1997; Sweeney, Titterton, & Leonard, 1991); (2) empirical relationships between $K_d(490)$ and chlorophyll-a, through regression analyses (Morel & Gentili, 1996; Morel et al., 2007); and (3) semi-analytical approaches based on Radiative Transfer Equation (RTE) models (Chen, Cui, Tang, & Song, 2014b; Lee et al., 2005; Wang, Son, & Harding, 2009a).

Quasi-analytical algorithm (QAA)-based semi-analytical model (Lee's model) is an effective model in open ocean waters and some coastal waters, but produces poor performance in highly turbid coastal waters (Chen, Cui, Tang, & Song, 2014b; Wang, Son, & Harding, 2009a). In open oceanic waters, the total backscattering coefficient, $b_b(\lambda)$, is usually much smaller in comparison to the total absorption coefficient, $a(\lambda)$, and may thus be safely removed from $a(\lambda) + b_b(\lambda)$. Therefore, the $a(\lambda)$ may be accurately derived using QAA model in open oceanic waters. However, the QAA model may produce poor performance when deriving $a(\lambda)$ from productive and/or turbid coastal waters, due to the fact that the $b_b(\lambda)$ cannot be neglected in these waters (Chen, Cui, Tang, & Song, 2014b). As a result, Lee's model may be violated in these waters, due to the fact that this model is a QAA model-derived $a(\lambda)$-based model. The performance of Lee's model in turbid coastal waters is expected to be improved using Chen's model, because a semi-analytical model is used to isolate the $a(\lambda)$ from the remote sensing reflectance. However, since Chen's model relies strongly on the remote sensing reflectance in the red region, some specific difficulties are to be expected. The strong absorption by water in the red region greatly reduces the magnitude of the recorded signal in the red region, thus reducing the signal-to-noise ratio (SNR) values and enhancing the effects of the inherent noise in the recorded signal (Chen, Cui, & Lin, 2013a). Regardless of what the source is, such inherent noise has a greater proportional effect in clear waters, due to the lower reflectance magnitudes, thus affecting the models' output. Therefore, Chen's model may be violated in the clearly waters due to its lower magnitude of remote sensing reflectance at 667 nm in these waters.

In order to accurately derive $K_d(490)$ from a global marine system, a switching model was proposed by Wang, Son, and Harding (2009a) for improving the performance of the currently used global $K_d(490)$ model. By comparison with the field measurements, the limitations of Lee's model in turbid coastal waters and those of Chen's model in open oceanic waters appear to be improved by Wang's model. However, the backscattering coefficient is derived using the conceptual model of $b_b(490) \propto R_{rs}(667)$. It is well known that $R_{rs}(667)$ is not only related to $b_b(667)$ but also related to $a(667) + b_b(667)$ (Chen, Yao, & Quan, 2013b; Gordon et al., 1988). In Wang's model, the effects of $a(667) + b_b(667)$ are ignored, and are instead approximated using a constant. This may be true when the bio-optical conditions are similar to those used during the development of Wang's model, but the model may be violated in some complex cases (Chen, Cui, Tang, & Song, 2014b). As a result, the applicability of Wang's model may be limited in terms of application to some turbid coastal waters, where the bio-optical properties are very complex. Therefore, the accurate assessment of $K_d(490)$ in global oceanic and coastal waters by means of remote sensing remains a challenging task, due to the complicated and widely varied optical properties found in natural oceanic waters. For the estimation of $K_d(490)$, which is important for studies regarding heat budgets and photosynthesis (Chen, Yao, & Quan, 2013b; Gordon et al., 1988), a model which is capable of providing a higher level of accuracy remains desired.

Neural networks are good candidates for modeling inverse functions in geophysical and remote sensing applications (Ceyhun & Yalçın, 2010; González Vilas, Spyrakos, & Torres Palenzuela, 2011; Gross, Thiria, & Frouin, 1999). A neural network model, if properly parameterized, can yield retrievals that are accurately and relatively insensitive to reasonable noise levels, because noise is introduced and accounted for during the training process (Ioannou, Gilerson, Gross, Moshary, & Ahmed, 2013; Jamet et al., 2012). For example, Jamet et al. (2012) reported that as the six visible MODIS remote sensing reflectance at the wavelengths ranging from 412 to 667 nm are used as input parameters, $K_d(490)$ can be accurately retrieved using a neural network model from both oceanic and coastal waters. However, from the perspective of statistics, the increasing number of inputting parameters would result in an increase of the "degree-freedom" of the model (Chen, Yu, & Jin, 2003), which in turn may decrease the stability and accuracy of the neural network model (Chen, 2013). Moreover, the success of the application of Jamet's model to satellite data may depend heavily on the accuracy of the atmospheric correction procedure and the retrieval of accurate reflectance at the shortest blue wavelength of MODIS. Unfortunately, all optical instruments have calibration problems in the blue range and the performance of atmospheric correction is worse in the shortest blue part of the spectrum (Chen, Cui, & Lin, 2013a; Gordon & Voss, 1999; Wang, Son, & Shi, 2009b). Therefore, to improve the stability and accuracy of the Jamet's model, it is necessary to optimize the inputting parameters of the neural network model.

The objectives of this study are to validate the respective performances of Lee, Wang, Chen, and Jamet's models, and to further improve these for application to the global oceanic and coastal waters using an MBPNN model. The specific goals of the study are as follows: (1) to evaluate the performance of Lee, Wang, Chen, and Jamet's models for the accurate estimation of $K_d(490)$ in the global oceanic and coastal waters; (2) to improve the accuracy of Lee, Wang, Chen, and Jamet's models by proposing the MBPNN model with the spectral bands of the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor; (3) to compare the accuracy of Lee, Wang, Chen, and Jamet's models and the MBPNN model in deriving $K_d(490)$ from global oceanic and coastal waters; and (4) to carry out a special case study on the applicability of the MBPNN model in the Eastern China Seas.

2. Data, methods and techniques

2.1. Datasets and field measurements

The SeaBASS in situ data have been continuously used to support SeaWiFS and MODIS ocean color product validation (Chen, Zhang, & Quan, 2013c; Werdell & Bailey, 2002). Therefore, the SeaBASS data are appropriate for the new global model calibration and evaluations. In order to evaluate the accuracy of Lee, Wang, Chen, and Jamet's models and the MBPNN model in predicting $K_d(490)$, a large ($n = 1811$) global evaluation dataset (Fig. 1), consisting of measured $R_{rs}(\lambda)$ at MODIS wavelengths and $K_d(490)$, was achieved by the National Aeronautics and Space Administration (NASA) SeaWIFS Project, known as the NASA Optical Marine Algorithm Dataset (NOMAD) (Werdel & Bailey, 2005). These data originate from various researchers around the United States and Europe, and contain mostly subsurface values of $R_{rs}(\lambda)$ and $K_d(490)$. In addition to these data, we have received 125 data points from the Bohai Sea and 245 data points from the Yellow Sea and East China Sea, consisting of $R_{rs}(\lambda)$ and $K_d(490)$ measurements above the surface; we also collected additional above-water datasets

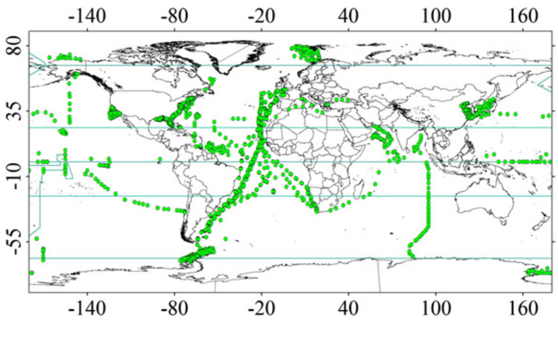

Fig. 1. Field measurements.