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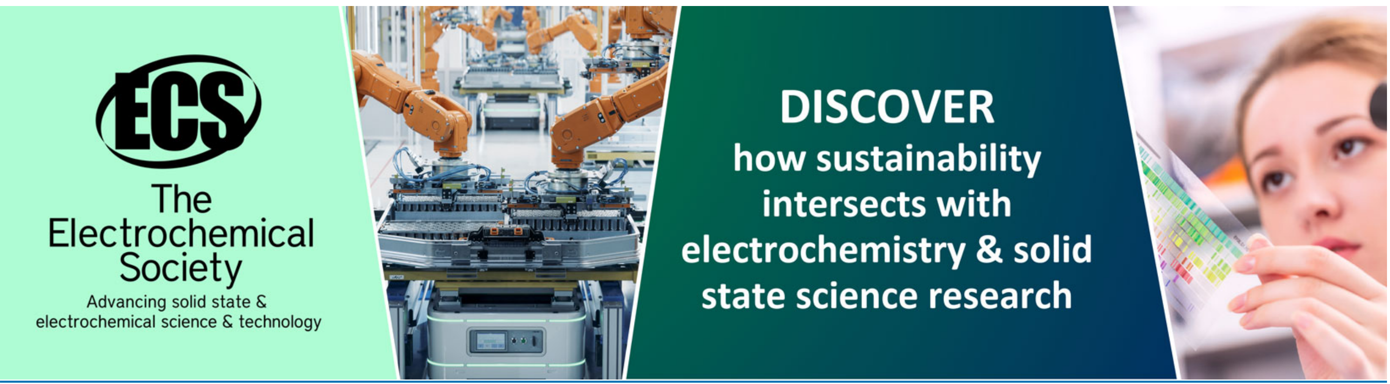

Retrieval of Secchi disk depth in the Yellow Sea and East China Sea using 8-day MODIS data

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Abstract. Secchi disk depth (SDD), is widely used as an indicator of water clarity. The traditional sampling method is not only time-consuming and labor-intensive but also limited in terms of temporal and spatial coverage. Remote sensing technology may deal with these limitations. In this paper, the applicability of 8-day MODIS-Aqua remote sensing reflectance data with 4 km spatial resolution for estimating water clarity in the Yellow Sea and the East China Sea was investigated. Field data such as Secchi depths were collected from two cruises conducted in the Yellow Sea and the East China Sea from 5 May to 7 June 2009. A three-band algorithm to retrieve SDD was developed based on remote sensing reflectance at bands of 488, 555, and 678 nm, which performed better than single-band model and band ratio algorithm, with a determination coefficient of 0.72 and a mean relative error of 19%. This suggests that 8-day MODIS-Aqua products of remote sensing reflectance could be used to assess water transparency in the study area.

1. Introduction

Secchi disk depth (SDD, m), as the earliest oceanographic measurement of water transparency[1], is an important optical measurements related to water quality, which originated from the nineteenth century and has already become a widely used tool for measuring water clarity. However, *in situ* measurements of SDD are often affected by the sea conditions. Although the traditional sampling methods provide accurate measurements, they are time-consuming, and, they can not give the spatial overview that is necessary for monitoring and measuring water clarity.

Satellite remote sensing is recognised as a valuable tool for monitoring water quality in large areas, especially for remote and inaccessible areas. For case 2 waters, the algorithms proposed to estimate water transparency are mainly empirical [2]. Satellite remote sensing technique has been found to be an important tool for monitoring Secchi disk depth [3-7].

The Yellow Sea and the East China Sea are typical case 2 waters, where concentrations of suspended matter, phytoplankton pigments, and coloured dissolved organic matter are higher than those in other open oceans, e.g., the Pacific. Large scale of green tide has occurred in this region every year since 2007 and has become one of important local ecological phenomena [8], which has brought great economic losses and influences marine ecosystems. Changes in water transparency have been widely linked to eutrophication and water quality [9]. Thus, for monitoring the status of ecological environments in the East China Seas, it is necessary to find a model that can be used to estimate

Secchi disk depth and estimate it in this area. The objective of this study is to establish a local algorithm using MODIS-Aqua remote sensing reflectance and field data for retrieving Secchi disk depth in the Yellow Sea and the East China Sea.

2. Study area and Data

2.1. In situ data
Two cruises were conducted in the Yellow Sea and the East China Sea between May and June in 2009. The main survey areas of the first one, which was carried out on the ocean research vessel "Science no.1" from 15th to31st May in 2009, were the South Yellow Sea and the East China Sea. The second one was conducted on the research ship "Science no.3" from 15th to 20th June in 2009, and the North Yellow Sea was main area of the investigation. 62 water sampling stations of water clarity were collected in the Yellow and the East China Sea.

Secchi disk transparency measurements were made with a standard Secchi disk (diameter 30 centimeters) with alternate black and white quadrants. The disk was lowered into the water body on the side of the ship as far as it is just visible, and their values were in the range of 0.0112 to 15.6 m with the mean of 6.72 m and a standard deviation of 3.18 m.

2.2. Satellite data
The Moderate Resolution Imaging Spectroradiometer (MODIS) instruments were onboard the U.S. National Aeronaautics and Space Administration (NASA) satellites, Terra and Aqua, launched in 1999 and 2002, respectively. The remote-sensing reflectance data, including channel bands centered at 412, 443, 469, 488, 531, 547, 555, 645, 667, and 678 nm respectively, were Level 3 Standard Mapped Image (SMI) products observed by MODIS-Aqua. All the data had the 8-day temporal resolution and 4×4 km spatial resolution. The MODIS data were provided by NASA Goddard Space Flight Center Ocean Bilogy Processing Group (http://oceandata.sci.gsfc.nasa.gov/MODISA/L3SMI/).

2.3. Data processing
We matched 8-day remote sensing reflectance data (Julian days 137-144, 145-152, and 169-176 in 2009) with *in situ* Secchi disk depth by temporal-spatial matching, and then analyzed the correlation between Secchi depths and different band combinations. Determination coefficient and mean relative error were applied to assess the precision of models. Three types of Secchi disk depth retrieval algorithm were evaluated, including single-band model, band ratio model and three-band model.

3. Results and Discussion

3.1. Single-band model
The correlation analysis was performed between Secchi depths and remote sensing reflectance of all 10 bands. The best correlation was found at 678 nm, which reached -0.604 (Table 1). According to this, a single-band model of power function type was established , as in equation (1).

$$SDD = 0.3589 \times R_{rs}(678)^{-0.377} \quad (1)$$

The coefficient of determination of the single-band model was 0.42, and the mean relative error was 31.5%.

Table 1. The correlation between remote sensing reflectance and SDD

Wavelength （nm）	412	443	469	488	531	547	555	645	667	678
Correlation Coefficients	0.077	0.013	-0.034	-0.191	-0.582	-0.522	-0.541	-0.507	-0.569	-0.604

3.2. Band ratio model

The advantage of using band ratios but not absolute values of reflectance (or radiance) is that this method can correct some of the effects of atmosphere and measurement geometry [10]. Dekker *et al.*[11] showed that band ratios performed high correlation coefficients for several water quality parameters.

In our analysis, the best band ratio algorithm with the highest R^2 was found empirically by regression analysis. A simple linear regression model, as in equation (2), for retrieving Secchi disk depth was developed when a channel ratio with channel centered at 488 and 555 nm is used.

$$SDD = 0.071 + 5.818 \times \left[\frac{R_{rs}(488)}{R_{rs}(555)} \right] \tag{2}$$

The coefficient of determination of this model was 0.68, and the mean relative error was 24.3%. Both of them were higher than that in the single-band model.

3.3. Multiple-band model

Multiple-band models link two or more different bands to water constituents in ocean colour remote sensing. The multiple-band model was applied to retrieve phytoplankton pigments, suspended sediment, and yellow substance in the Mediterranean Sea by Tassan [12]. Wang *et al*. modified the Tassan model of estimating suspended sediment and applied it to retrieve Secchi disk depth using bands of 490, 555, and 670 nm in the Yellow Sea and the East China Sea [13]. A three band model with MODIS bands centered at 488, 555, and 678 nm was found in this study, as in equation (3).

$$SDD = 0.921 - 342.766 \times R_{rs}(678) + 5.346 \times \left[\frac{R_{rs}(488)}{R_{rs}(555)} \right] \tag{3}$$

The coefficient of determination of above model was 0.72, and the mean relative error was 19%. Both of them were higher than that in the band ratio model. Figure 2 presents Secchi disk depth estimated using the three-band model, with 8 days MODIS-Aqua remote sensing reflectance during sampling collection, versus the measured and distribution of it in the Yellow Sea and the East China Sea.

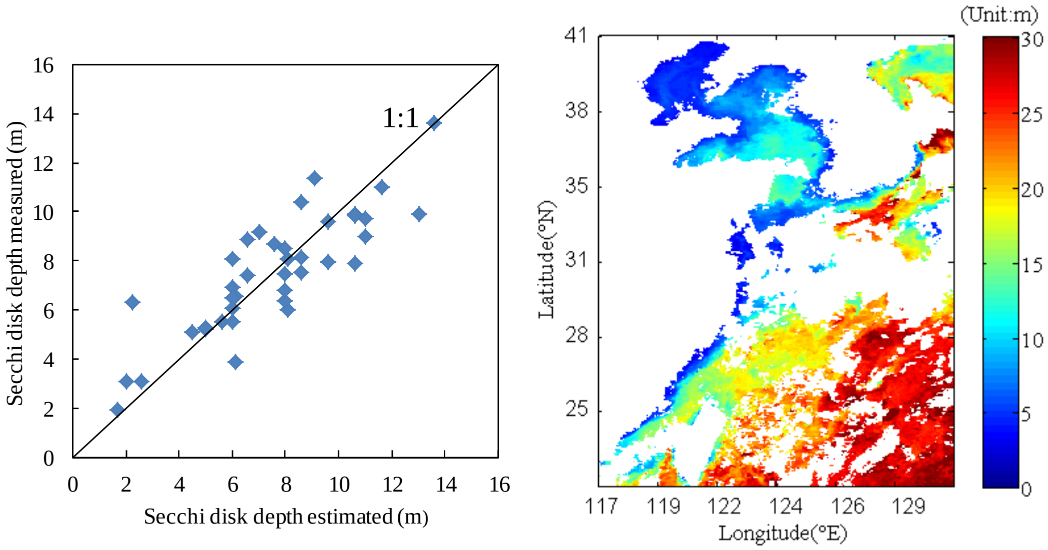

Figure 2. Left: Secchi disk depth estimated versus measured. Right: Distribution of Secchi disk depth in the study area.

4. Summary

Two cruises were carried out between May and June in 2009 in the Yellow Sea and the East China Sea. *In situ* measurements of Secchi disk depth matched with the 8-day MODIS-Aqua remote sensing reflectance data were used for further analysis. Analysis of correlation between all the 10 bands and

Secchi depths suggested that red spectral region should not be neglected when retrieving water clarity in case 2 waters, especially for the East China Seas. Bands centered at 488, 555, and 678 nm were employed to develop a three-band model with better performance than the others for estimating Secchi disk transparency. Finally, distribution of Secchi disk depth in the study area was presented using the three-band model.

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