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A regional remote sensing algorithm for total suspended matter in the East China Sea

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ABSTRACT

The East China Sea (ECS) is well known for its high concentration of total suspended matter (TSM). Some regions of the ECS have concentrations higher than 5000 g m^{-3}, exceeding the valid ranges of many TSM remote sensing algorithms. To overcome the limitation of the existing algorithms, a new TSM model, the "complex proxy TSM model" (CPTSM), is developed in this study. The model is established on the basis of a complex proxy of remote sensing reflectance. The proxy is designed to convert the non-linear relationship between reflectance and TSM to a quasi-linear function over the entire range of TSM concentrations. This proxy is deduced from four indices defined by combinations of the reflectance at different bands. The four indices take advantage of the different relationships between the band combinations of the reflectance and total TSM concentrations. The band selections and model parameters are based on correlation coefficients and regression analysis between the indices and TSM. The results show that the correlation coefficient of 0.912 between the proxy and TSM is higher than that between any individual index and TSM. To validate the CPTSM model, TSM, turbidity, and reflectance data were collected in the ECS during 4 cruises in 2006 and 2007. The actual TSM concentration was measured by weighing the samples collected on filter papers. Turbidity was measured by a Seapoint Turbidity Meter. The turbidity data with values higher than 750 FTU were re-calibrated using an empirical equation. All turbidity values were converted to TSM concentrations using a linear equation. The in situ reflectance was measured using the above-water method at 459 stations and the in-water method at 146 stations. A total of 87 pairs of reflectance measured by both methods were used for inter-comparison with a relative difference of 4.5%. The reflectance values were used to retrieve TSM concentrations using the CPTSM model. A comparison with in situ measurements gave a mean relative error of 23%. Applying the CPTSM model to the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) data and analyzing the errors from a match-up dataset of SeaWiFS and in situ data, we found that the average relative error was 24.5%. We propose to use the CPTSM model to map TSM concentrations from satellite data in the ECS.

1. Introduction

The East China Sea (ECS) is one of the largest marginal seas in the world. It receives approximately 486 million tons of sediments annually from the Changjiang (Yangtze) River and other rivers. As a result, large amounts of sediment as well as other particulate matter have accumulated on the seabed. Fine particles can be easily re-suspended from the bottom to the surface under the influence of tides, winds, ocean currents and other forces. In the coastal areas of the ECS, the concentration of total suspended matter (TSM) can be very high with values over 5000 g m^{-3} in some regions. In contrast, TSM concentrations are very low in the eastern part of the ECS, less than 0.1 g m^{-3}. The high concentrations can be due to the presence of suspended sediments or phytoplankton cells, or a mixture of both. Meanwhile, the colored dissolved organic matters (CDOM) vary from high in coastal areas to low over the outer shelf. The variety of water constituents in the ECS gives rise to very complicated optical properties of waters.

Suspended sediment has always been a great concern for coastal engineering management. It is an important consideration in the cost of port maintenance and the decision to develop new port sites. Suspended sediment is a good proxy for water quality in coastal waters due to its close relationship with other water quality parameters. It plays a key role in the ecological system of coastal waters because of its impact on phytoplankton productivity, nutrient concentration and pollutants (Doxaran et al., 2009). Sediment transport also plays an important role in the global carbon cycle since half of the terrestrial organic carbon exported by rivers is ultimately buried in marine sediment (Schlunz & Schneider, 2000).

Mapping TSM from satellite data is a useful way to investigate the distribution and variation of suspended sediment and chlorophyll concentration at the sea surface. In turbid waters, owing to the strong absorption and backscattering of sunlight by particles in waters,

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suspended particles have a dominant influence on the optical properties of waters, resulting in the poor performance of remote sensing algorithms for chlorophyll (Sathyendranath et al., 1989). The presence of TSM in coastal areas can lead to overestimates of chlorophyll concentration by 20–500% (Ahn et al., 2001). However, with improved knowledge of the optical properties of water constituents and more reliable observations of TSM concentrations, the effects of suspended sediment may be removed from remote sensing reflectance and the performance of the algorithms for chlorophyll concentration in Case 2 waters can be improved.

Many models of TSM have been developed using empirical methods or semi-analytical approaches. These models can be used to process satellite data efficiently, but some problems are encountered when they are applied to the ECS. For example, when the TSM algorithm developed by Tassan (1994) was used to process satellite data in the ECS, the values of the retrieved TSM concentrations were all less than 3 g m^{-3}. The two algorithms of Neukermans et al. (2009) gave the maximum concentrations of TSM in the ECS as 32 and 45 g m^{-3}, respectively. However, field measurements indicate a much wider range of TSM concentrations in the ECS, from <0.1 to >5000 g m^{-3}. The discrepancies indicate that the algorithms developed for other regions must be modified before they can be applied to the ECS.

Many TSM models based on empirical methods have been used in operational satellite remote sensing systems. These models were established on the basis of statistical relationships between TSM concentrations and single-channel or multi-channel reflectance. The band selection is critical for the establishment of a robust model. The Landsat Thematic Mapper (TM) images at Band 1 (0.45–0.52 μm) is sensitive to various concentrations of suspended solids (Baban, 1993), and has been used to map fluvial sediment discharge based on a linear relationship between suspended solid concentrations and digital number (Baban, 1995). Eleveld et al. (2008) used the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Band 5 (0.545–0.565 μm) for monitoring suspended particulate matters. Miller and Mckee (2004) established a robust linear relationship between the Moderate resolution Imaging Spectroradiometer (MODIS) Terra Band 1 (0.62–0.67 μm) data and in situ measurements of TSM. Ahn et al. (2001) argued that the best wavelength for suspended sediment was 0.625 μm while Ouillon et al. (2008) considered the reflectance at 0.681 μm as the best choice for remote sensing turbidity using a one-band polynomial relationship. These studies suggest that the reflectance at many different bands can be used to retrieve TSM. As the sensitivity of remote sensing reflectance is related to the wavelengths and the range of TSM concentrations, the combination of the reflectance at different bands may improve the performance of TSM models.

The sensitivity of the reflectance at a given band varies significantly with TSM distributions from clear ocean waters to very turbid coastal waters. It is thus difficult to apply one TSM model for all water types. To overcome this limitation, some models include two algorithms, and the computation is switched between the two algorithms according to the ranges of TSM concentrations (Neukermans et al., 2009; Pradhan et al., 2005; Tassan, 1994). These models can improve the accuracy of retrievals, but they may also introduce some pseudo-features in TSM imagery. Therefore, to develop a robust TSM model, it is necessary to find a proxy which has a linear relationship over the entire range of TSM concentrations.

Semi-analytical models have been established by many authors based on the relationship between the inherent optical properties (IOP) and water constituents (e.g. Gordon et al., 1988). The IOP parameters include absorption and scattering properties (coefficients and scattering phase function) of pure seawater, suspended sediments, phytoplankton and CDOM. There are several different approaches to retrieve TSM based on different IOP parameters. Since light scattered from suspended particles is generally the first-order determinant for variability in reflectance in coastal waters, the backscattering coefficients can be used to derive TSM (Babin et al., 2003; Volpe et al., 2011). Similarly, if the absorption coefficient of particles can be deduced from the reflectance spectra using an analytical inversion model, it can then be used to derive TSM distributions. TSM concentrations can also be derived from the reflectance spectra using simple bio-optical models (Fettweis et al., 2007; Nechad et al., 2010). Dekker et al. (2001) developed algorithms based on an analytical optical model in conjunction with the in situ IOP parameters. Doerffer and Fischer (1994) developed an inversion modeling technique using a two-flow radiative transfer approximation including the aerosol path radiance.

The performance of a TSM model is expected to improve if empirical and semi-analytical approaches are combined. In this study, the TSM model is established in two steps: Firstly, four indices are constructed from different combinations of the reflectance signal. One of these indices is derived from a simplified semi-analytical model, while the others are obtained using empirical methods. These four indices are then used to derive the complex proxy. In the second step, the relationship between the complex proxy and TSM concentrations is analyzed. Based on the results of the analyses, a new TSM model is established. The performance of the model is evaluated using both SeaWiFS imagery and in situ reflectance data. In the following sections, band selections and parameters in the TSM model are discussed, together with the sensitivity of the indices to the satellite imagery.

2. Measurements and data analysis

Four cruises were carried out to measure TSM concentrations and water-leaving reflectance for the development of the TSM algorithm. The cruises were conducted in the summer and winter of 2006 and in the spring and autumn of 2007. Each cruise employed two ships (Haijian 46 and Haijian 49) and took about 2 months to complete 514 pre-planned stations in the ECS (Fig. 1).

2.1. Measurements of TSM concentrations and turbidity

TSM concentrations were carried out using the weighing method, following the Chinese National Standard protocols (SAC, 2007). Briefly, water samples were collected at a depth of 1 m using a rosette Niskin sampler and filtered immediately onto 47 mm diameter dried and pre-weighed Sartorius™ acetate fiber filters on board. The filters were stored in a −20 °C refrigerator until processed in the laboratory where they were repeatedly dried (>4 h) in a thermal infrared dryer at 40 °C and weighed until the difference between the last two measurements was less than 0.01 mg. The inorganic fraction was separated by burning the filters in a muffle furnace at 450 °C for about 2 h and weighing the inorganic remains carefully. The organic fraction was then calculated from the difference between TSM concentrations and the inorganic fraction. During the operations, the adsorbed sea salts and the associated water of hydration were not removed from the filters. This may introduce some errors in measurements of sea water (Stavn et al., 2009).

The turbidity data were measured using a Seapoint Turbidity Meter (STM) equipped with a water quality instrument manufactured by Richard Brancker Research Ltd (RBR). This RBR instrument was installed on a conductivity–temperature–depth (CTD) package. The instrument is easy to operate and can log a large amount of data automatically. In addition to turbidity, the RBR instrument can also incorporate other sensors, such as sensors for chlorophyll fluorescence and yellow substance fluorescence. The RBR instrument is very useful for measuring the vertical distribution of water constituents. Some pertinent information about the four cruises and in situ measurements is given in Table 1.

TSM concentrations were estimated using the weighing technique, while the Seapoint Turbidity Meter (STM) was used to measure turbidity in Formazan Turbidity Units (FTU). A total of 964 stations of TSM and 515 stations of STM turbidity data were included in the in situ dataset, of which 170 stations had both measurements. Some statistics of TSM concentrations and STM turbidity are listed in Table 2.