Measuring Marine Suspended Sediment Concentrations from Space: History and Potential

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ABSTRACT

Advances in analysis of particle scattering and absorption have improved understanding of how suspended particles influence the light field and the resulting ocean color signature. These advances enable algorithms which uncouple the spectrum into spectral backscattering, detritus absorption, colored dissolved organic matter, and chlorophyll. Future algorithms will determine linkages between optical components beyond merely the suspended particulate matter (SPM) product, including the influence of particle size, shape, refraction, stratification, and composition. This paper examine historical progress in research on space-based SPM observations; evaluate the status of current algorithms and models; describe user community interest in SPM data products; and discuss strategies to promote publically-available SPM data products.

1.0 INTRODUCTION

In the Coastal Zone Color Scanner era (1978-1986), coastal waters were observed as "turbid" areas with high particulate concentrations. At that time, it was recognized that quantifying suspended matter (SPM) concentration posed a challenge at least as difficult as the accurate determination of chlorophyll concentration in "Case 2" (Morel and Prieur 1977) waters (turbid, coastal). The pronounced color signature from sediments suggested a future potential capability to observe coastal marine sediment transport and to quantify SPM concentrations with improved ocean radiance sensors.

With the CZCS future now transformed to the present, it has become apparent that accurate "global" determination of SPM concentrations still remains a future goal. SPM products from the Moderate Resolution Imaging Spectoradiometer (MODIS) and for the Visible and Infrared Imaging Radiometer Suite (VIIRS) slated for the National Polar Orbiting Environmental Satellite System (NPOESS) have been abandoned since "universal" SPM algorithms are not currently available. Currently, only "regional" SPM algorithms are implemented in areas with similar particle characteristics and where SPM products can be validated. Hopes for "universal" algorithms must thus be based on emerging research in particle optical properties.

Despite the abandonment of effort (at the time of this writing) to author global or universal SPM algorithms, considerable success in SPM estimation has been demonstrated with data from a variety of sensors with varying radiometric accuracy and sensitivity and various spatial and temporal resolutions. Landsat, SPOT, the Advanced Very High Resolution Radiometer (AVHRR), the Sea-viewing Wide Field-of-view Sensor (SeaWiFS)

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and MODIS have all provided data that have been used for accurate SPM estimation in specific applications and settings.

This paper briefly examines several aspects of this topic. A historical overview highlights selected research papers with the goal of illustrating progress in the determination of SPM concentration. This overview is followed by a review of the current status of SPM algorithms and models, and a description of selected applications illustrating the interest in – and need for – accurate SPM data products. Note that this paper cannot present a comprehensive treatment, and therefore any exclusion of papers from mention here does not represent a judgment of quality or appropriateness. Rather, the papers that are cited here should be viewed as illustrative of the progress of research on this important topic.

2.0 HISTORICAL OVERVIEW

Prior to the launch of CZCS in 1978, Kritikos (1974) described the use of ERTS-A, more commonly known as Landsat 1, data for SPM analysis. Munday and Afoldi (1979) discussed the use of reflectance models for Landsat data for SPM measurement. Prior to the CZCS mission, Morel and Prieur (1977) provided the widely-known Case 1 and Case 2 water classification schema, and subsequently Holyer (1978) discussed progress toward universal multispectral suspended sediment algorithms, which seems optimistic in retrospect.

The CZCS was the first satellite-borne sensor with radiometric sensitivity designed for the marine environment. CZCS thus provides the first data from which marine SPM concentrations could in theory be estimated. CZCS imagery provided several striking examples of marine suspended sediments – one of the most notable was an image of the Po River (Italy) sediment plume acquired on October 9, 1984 acquired on the same day that this region and feature were photographed by astronauts on the Space Shuttle (Figure 1). This particular image is also an excellent example of how high SPM erroneously influenced CZCS pigment retrievals in sediment-laden Case 2 waters. Initial efforts to quantify SPM with CZCS data relied on empirical regression algorithms similar in form to algorithms used to calculate chlorophyll concentration. Noteworthy in this regard are Viollier and Sturm (1984), Amos and Topliss (1985), Tassan and Sturm (1986), Stumpf and Pennock (1989), and Topliss *et al*. (1990). Clark *et al*. (1980) described a reflectance ratio sediment algorithm for CZCS data.

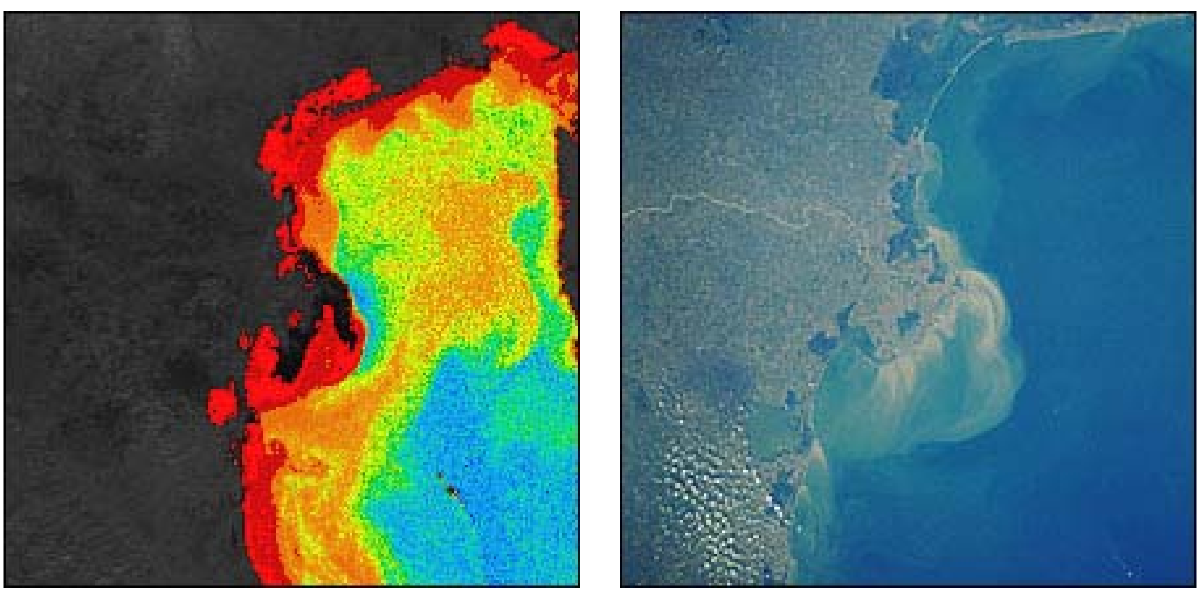

Figure 1. The Po River sediment plume entering the northern Adriatic Sea, acquired on October 9, 1984. (left) CZCS image (right) Astronaut photograph from the Space Shuttle. In the CZCS image, note that the brightest part of the plume is interpreted as land (black mask). Red indicates high pigment concentration, likely erroneous here due to high SPM concentration.

SeaWiFS, launched in 1997, provided a long-awaited improved radiometric capability for marine remote sensing, and also provided near-daily ocean coverage. Empirical algorithms utilizing reflectance ratios were proposed for SPM estimation using SeaWiFS data, in particular Wernand *et al*. (1998) and Doxaran *et al*. (2003). The launch of MODIS on the Terra satellite in 1999 and on the Aqua satellite in 2002, the latter following the launch of the Medium Resolution Imaging Spectroradiometer (MERIS) on Envisat by two months, gave advanced radiometric capability to oceanographic remote-sensing scientists (Figure 2). In the late 1990s and the first years of the 21st century, India, China, Korea, and Taiwan also launched satellites with ocean color sensors capable of providing data for SPM determination. With the current plethora of sensors, the ability to accurately determine SPM concentrations should be enabled. The following section discusses the primary approaches under research for SPM determination.

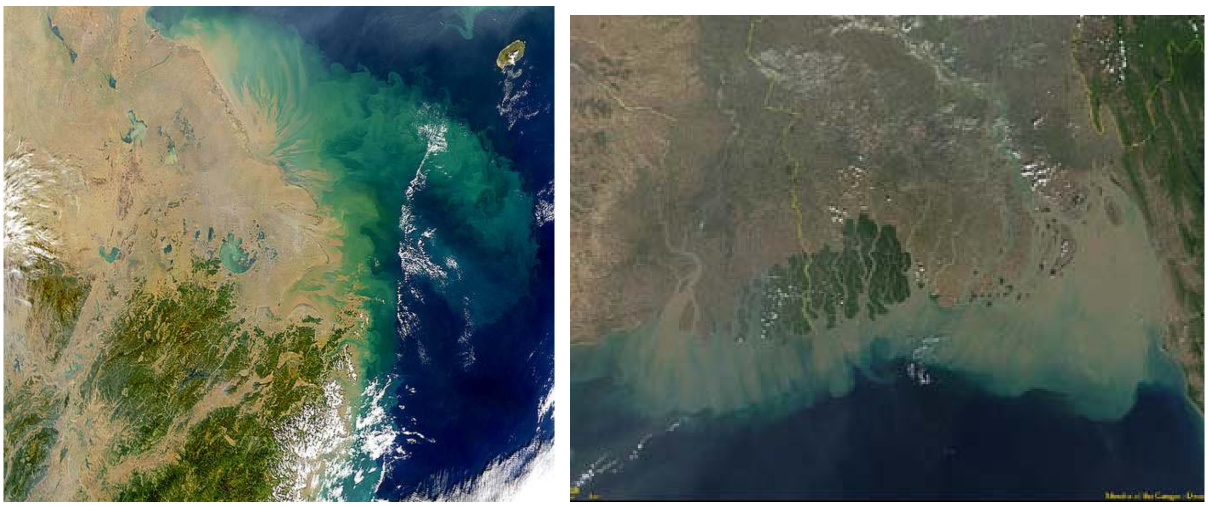

Figure 2. (left) SeaWiFS image of sediments in the East China Sea, stemming in part from the Yangtze and Qianliang rivers. (right) MODIS image of the outflow of the Ganges River into the Bay of Bengal.

3.0 EVOLUTION AND STATUS OF SPM ALGORITHMS

There are two varieties of SPM algorithm under examination: empirical models and semi-analytical models.

3.1 EMPIRICAL ALGORITHMS

Two empirical regression methods have been employed to convert remote sensed data into SPM data in the coastal zone:

- the direct calibration method, which consists in comparing remotely sensed data and SPM experimental data (e.g. Baban 1995),
- the indirect calibration method, consisting in a comparison of *in situ* reflectances (or normalized water-leaving radiances, nLw) measured by a field radiometer, and SPM experimental data.

The indirect method is based on relationships between SPM and single-channel or multi-channel remote-sensing reflectance (R_{rs}). The equivalent reflectance, equivalent to that which is estimated from satellite measurements, is obtained by integration of the reflectance spectral values weighted by the sensor sensitivity function.

Regressions between equivalent reflectances and SPM were thus proposed for CZCS, TM or MSS by Viollier and Sturm (1984), Ritchie and Cooper (1988), Lathrop and Lillesand (1989), Stumpf and Pennock (1989), and You and Hou (1992); for NOAA/AVHRR by van Raaphorst *et al.* (1998); for SPOT XS by Forget and Ouillon (1998), Froidefond *et al*. (2002), and Doxaran *et al*. (2002); and for SeaWiFS by Robinson *et al*. (1998), Ahn *et al*. (2001), and van der Woerd and Pasterkamp (2004).

At the smallest wavelengths (around 550 nm), the remotely-sensed signal saturates at high turbidity: around 60 mg/l at 450 and 650 nm (Larouche *et al*. 2003), around 30 mg/l at 550 nm (van der Woerd and Pasterkamp 2004), and around 60 mg/l at 650 nm (Lehner *et al.* 2004).

The main factors explaining reflectance sensitivity to changes in SPM are particle size (Holyer 1978, Han and Rundquist 1996), particle shape (Ferrier 1995), sediment type (Novo *et al*. 1989) and concentration range (proceedings papers quoted by Novo *et al.* 1991; Bhargava and Mariam 1991). The optimum wavelength for SPM quantification (whatever the sediment size or type) is likely to depend on the concentration range.

3.2 SEMI-ANALYTICAL ALGORITHMS

The semi-analytical algorithm approach consists in connecting reflectance (R) to the SPM concentration via a simplified optical model by which R is expressed according to the inherent optical properties (IOPs) of absorption (a) and backscattering (b_b) such as, at the first order: $R = f X$ with $X = b_b/a+b_b$. Gordon (2002) presents a review of the simplified models. Kirk (1984) and Gordon (1989) show that f varies with the conditions of illumination (i.e. primarily with the position of the sun by clear sky). Morel and Gentili (1991) demonstrate that f also depends on the IOPs. Gordon *et al*. (1988) introduce the relation between R_{rs} ($R_{rs} = R/Q$) and X whose correlation appears better between measurements and models that between R and X. This best correlation is justified *a posteriori* by Zaneveld (1995) which shows that f is directly proportional to Q and that these two parameters follow similar tendencies when the sun angle changes. Morel and Gentili (1996) show by modeling that f/Q varies less with the conditions of illumination than f and Q.

When R is measured instead of R_{rs}, the problem of the transformation from R to R_{rs} lies in the estimate of Q, which is a variable parameter whose value is between 0.3 and 6.5 sr in theory (Morel and Gentili 1993). The value of Q is estimated near to 3.5 sr for turbid waters (Bukata *et al*. 1988, Morel and Gentili 1993). Lee *et al*. (1998) proposed an alternative to the model of Gordon *et al*. (1988) better adapted to turbid coastal waters: $R = \pi\,(0.070 + 0.155\,X^{0.752})\,X$. R is generally expressed under water and R_{rs} above. Thus by combining the simple models resulting from works by Morel and Prieur, Gordon *et al*. or Lee *et al*., and the relationships at the interface (e.g. Morel 1980), one can express R_{rs} and R according to X (see e.g. Ahn *et al.* 2001).

a and b_b can be expressed as the absorption due to water, chlorophyll, and colored dissolved organic matter (CDOM): $a = a_w + a_{chl} + a_y$, and backscattering can be expressed in terms of water, chlorophyll, and SPM: $bb = b_{bw} + b_{bchl} + b_{bs}$ (Prieur and Sathyendranath 1981, Sathyendranath *et al.* 1989, Roesler *et al.* 1989). To determine the concentration in chlorophyll or in suspended sediment from this decomposition and from a simplified optical model thus requires knowledge of the specific IOPs. A simplified optical model, including the formulation of some IOPs, can be used to determine parameters of water quality (see a review in Zhan *et al*. 2003). To build semi-analytical models specific to a site, authors performed field measurements of IOPs and sometimes simplified the basic semi-analytical models by neglecting some IOPs on the basis of assumptions. They can alternatively use generic formulations or measurements taken on other sites to express ignored IOPs and to supplement a model (e.g. Bowers *et al.* 1998, Li *et al*. 1998, Forget *et al*. 1999, Lahet *et al*. 2000). Alternatively, remotely sensed dated can be used to derive inherent optical properties rather than the content of chlorophyll, CDOM, and SPM. This approach is described in Gould and Arnone (1997a, 1997b) and Gould *et al*. (2001).

3.3 ALGORITHM REFINEMENT

Benefiting from improvements in optical modeling and knowledge of the IOPs, empirical models are evolving into semi-empirical models. Indeed, the form of the empirical relationship is selected on the basis of simplified optical models and assumptions (e.g. Moore *et al*. 1999, Vasilkov *et al*. 1999, Zhan *et al*. 2003). Moreover, inversion methods are not only used to describe the surface parameters, but also to describe the surface layer in three dimensions (Arnone and Gould 1997b, Gould *et al*. 2001).

Recent studies focusing on different aspects of the SPM influence on the upwelling sea radiance will be of help to improve the inversion methods regarding, for example:

- the derivation of indirect parameters that are more suitable than the mass concentration of SPM in the inversion procedure, such as the projected surface area of particles (Mikkelsen 2002) or several optical parameters derived related to SPM, such as the turbidity (backscattering in the red or near-IR region), the extinction coefficient, or even the "old" Secchi disk depth;

- the use of multispectral data to retrieve a profile of sediment concentration over superimposed surface layers, using the property of wavelength-dependency of absorption by water (Ouillon 2003);
- the use of a color classification for coastal waters, so as to determine specific algorithms for each color class, more suitable than a generic algorithm (Lahet *et al.* 2001a, 2001 b); and
- the use of optical data to retrieve the bulk refractive index of particles (Twardowski *et al*. 2001) or the grain size distribution (Boss *et al*. 2001), and the introduction of known refractive indices of rocks and minerals in the inversion procedure (e.g. Kerr 1977).

4.0 APPLICATIONS OF SPM DATA PRODUCTS

Figure 3. SeaWiFS image of the Mid-Atlantic coast of the United States, acquired September 23, 1999. Sediments generated by inland flooding caused by Hurricane Floyd are being transported into the Gulf Stream. In addition, high sediment concentrations and discolored water are visible in the Pamlico and Albemarle Sounds. The blackish-blue color of the coastal waters to the north of the sediment plume is due to light absorption by chlorophyll in this pseudo-true color image.

The preceding discussion of the evolution of remotely-sensed SPM data products from the CZCS era to the present day invites the dual questions: <u>why is there interest in remotely-sensed SPM data products, and what could these products be used for</u>? The following discussion is a subset of current and/or potential applications of SPM data products in the marine environment.

Perhaps foremost among applications is the potential capability of accurate SPM estimation to allow improved deconvolution of the components of the remotely-sensed signal in Case 2 waters, leading to significant improvements in the quantification of chl *a* concentration in the coastal zone. Coastal zone chl *a* concentrations are commonly higher than in Case 1 waters (characteristic of the open pelagic ocean), and can be greater by orders of magnitude. Since a large amount of primary productivity in the global ocean occurs in the difficult-to-quantify coastal zone, improved estimation of chl *a* in Case 2 waters is a paramount goal of ocean color research.

Improved estimation of chl *a* in coastal waters is relevant to interest in the detection of harmful algal blooms (HABs) and planktonic disease vectors, as in the case of cholera. There has been particularly high interest in this application for countries adjoining the Yellow, East China, and South China Seas. In this region, the coastal zone is highly turbid (Figure 2), and there has been an increased frequency of HABs, perhaps due to higher nitrogen availability due to changing agricultural and land-use practices (Jeong 2003). The National Oceanic and Atmospheric Administration (NOAA, USA) recently initiated a HAB monitoring and reporting system for the Gulf of Mexico utilizing a chl *a* algorithm specifically tailored for the high SPM characteristics of this region (Stumpf 2003).

SPM concentration is a fundamental water quality parameter that is related to land-use practices and water resource conservation, particularly for freshwater resources. The USA's Clean Water Act has established total maximum daily loads (TMDLs) for a large number of pollutants, one of which is SPM or turbidity. Ritchie and Cooper (2001) describe the use of satellite data for TMDL monitoring of SPM. The availability of high-quality radiometric data at spatial resolutions greater than 1 km (i.e., spatial resolution at scales between 10-100 and 100-1000m) makes SPM determination in inland lakes and waterways increasingly feasible, with a direct impact on water quality (Miller *et al*. 2005, this conference). At the 1km resolution common to SeaWiFS and MODIS, the generation of coastal SPM plumes by inland flooding can be easily distinguished (Figure 3).

An additional application of SPM determination addresses the potential quantification of the contribution of sediments to the marine carbon cycle. Coastal sediments can trap or otherwise sequester large amounts of organic carbon, which can be released by sediment resuspension. Ongoing research by Gould and Arnone (described at http://www.nrl.navy.mil/content.php?P=03REVIEW199) has investigated the cycling of particulate organic matter and particulate inorganic matter along with CDOM and detritus on the northern Gulf of Mexico coast via optical water mass classification. Gong *et al*. (2003) notes the necessity of improving chl *a* determination for the East China Sea's turbid shelf waters to improve estimates of annual primary production. Acker *et al*. (2002, 2004) discussed the use of SPM determination using SeaWiFS data to quantify the hurricane-induced transport of carbonate sediments produced on carbonate banks to the deep sea, where they will dissolve in deep ocean waters.

Military interests, particularly naval operations in the littoral zone, also have considerable interest in accurate SPM determination with satellite remote sensing, but this interest may not be fully represented by publications in the scientific literature. As an example, *Oceanography and Mine Warfare* (NAS Ocean Studies Board, 2000) discusses one aspect of the use of remote-sensing for the detection of mines in shallow and turbid waters. Other military applications include changes to shallow-water bathymetry due to nearshore sediment transport, alteration of channel morphology in estuaries and harbors, and detection of natural or man-made hazards to navigation.

Interest in SPM determination is also found in the commercial sector for a variety of applications. Recent research (described at this conference) has investigated the use of remote-sensing data to observe transport and deposition of sediments generated by dredging operations (Sipelgas *et al*. 2005, Odunsi 2005, this conference). Remote sensing of varying spatial resolution from the kilometer-scale to the meter-scale has been used to examine coastal erosion and beach alteration due to storm impact – while this has been commonly done with change detection analysis, Waters *et al*. (1997) described the use of the AVHRR reflectance product to assess turbidity levels following hurricane landfall on the southeastern coast of the United States. The U.S. Geological Survey has also maintained an ongoing monitoring program observing reflectance changes in Florida Bay, and has documented high reflectance events following the passage of hurricanes and strong winter cold fronts likely due to sediment resuspension. This program demonstrates the feasibility of utilizing an operational SPM product for monitoring sediment transport in other locations where sediment mobility could impact commercial and recreational activities. The routine use of SPM data by the commercial sector, however, is precluded for the most part by the absence of an accurate, readily-available SPM data product.

5.0 CONCLUSIONS

This paper has discussed the historical progression of interest in satellite remote-sensing SPM data products, and has provided a brief evaluation of the algorithm methods that have been used to create such products. Interest in SPM data products remains high, as evinced by the disappointment of users who have queried the Goddard Earth Sciences Data and Information Services Center (GES DISC) regarding the status of the provisional MODIS SPM data product, which was never validated. Several research groups have created regional SPM data products with high degree of accuracy (on the order of 25% error) – examples are described by Ruddick et al. (1998) and Gohin *et al*. (2002). The research groups associated with these authors have operationally produced SPM products utilizing SeaWiFS and MODIS data for Belgian coastal waters and the Bay of Biscay (France), respectively, and other research groups around the world are involved in similar endeavours (e.g. Ouillon et al. 2004 with ETM+ data in a lagoon). As noted in Section 2.0, India, China, Taiwan, and Korea have all orbited an ocean color sensor capable of providing SPM data products.

The implementation of "universal" (global) SPM algorithms will rely on further advances in analysis of particle scattering and absorption, leading to improved understanding of how suspended particles influence the light field and the resulting ocean color signature (as discussed in Section 3.3). These advances enable algorithms which uncouple the spectrum into spectral backscattering, detritus absorption, CDOM, and chlorophyll. Future algorithms will determine linkages between optical components beyond merely the SPM product, including the influence of particle size, shape, refraction, stratification, and composition. It should also be noted that it is desirable to couple the creation of an accurate global SPM data product with open and efficient data distribution, to allow the potential user community the opportunity to apply and test such a data product. This model has been successful for the refinement of remotely-sensed chlorophyll algorithms, and emulation of this model would encourage development of the next generation of SPM algorithms.

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