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Remotely sensed seasonality in the spatial distribution of sea-surface suspended particulate matter in the southern North Sea

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ABSTRACT

An algorithm is presented for estimating near-surface SPM concentrations in the turbid Case 2 waters of the southern North Sea. The single band algorithm, named POWERS, was derived by parameterising Gordon's approximation of the radiative transfer model with measurements of Belgian and Dutch inherent optical properties. The algorithm was used to calculate near-surface SPM concentration from 491 SeaWiFS datasets for 2001. It was shown to be a robust algorithm for estimating SPM in the southern North Sea. Regression of annual geometric mean SPM concentration derived from remote sensing (SPM_{rs}), against in situ (SPM_{is}) data from 19 Dutch monitoring stations was highly significant with an r^2 of 0.87. Further comparison and statistical testing against independent datasets for 2000 confirmed the consistency of this relationship. Moreover, time series of SPM_{rs} concentrations derived from the POWERS algorithm, were shown to follow the same temporal trends as individual SPM_{is} data recorded during 2001. Composites of annual, winter and summer SPM_{rs} for 2001 highlight the three dominant water masses in the southern North Sea, as well as their winter–fall and spring–summer variability. The results indicate that wind induced wave action and mixing cause high surface SPM signals in winter in regions where the water column becomes well mixed, whereas in summer stratification leads to a lower SPM surface signal. The presented algorithm gives accurate near-surface SPM concentrations and could easily be adapted for other water masses and seas.

1. Introduction

Understanding the spatial and temporal distribution and variability of suspended particulate matter (SPM) is of great scientific interest since SPM plays a major role in controlling the penetration of light into the sea and hence has a huge impact on primary productivity and ecology. It can also transport chemicals and resuspend pollutants, and its organic component is an important constituent of the carbon cycle (Laane et al., 1999; Turner and Millward, 2002). Finally, SPM is of interest to engineers dealing with dredging, maintenance of safe navigation routes and harbour access (De Kok, 1992).

Many coastal environments worldwide are characterised by the presence of large amounts of fine-grained cohesive and non-cohesive sediments (Healy et al., 2002; Winterwerp and Van Kesteren, 2004). This paper is concerned with suspended sediments in the southern North Sea, one of the most tidally energetic and turbid areas of shallow shelf sea in the world (Fig. 1a). Suspended particulate matter (SPM) – also known as seston, total suspended matter (TSM) and total suspended solids (TSS) – that causes this turbidity, can be defined as all matter (organic and inorganic) that stays on a Whatman GF/F glass fibre filter with an approximate pore size of 0.7 μm. The suspended particles in the North Sea have a relatively low organic fraction and their optical properties are mainly dominated by the mineral fraction (Babin et al., 2003).

The outflow of rivers, such as the Rhine–Meuse–Scheldt region of fresh water influence (hereafter referred to as the Rhine ROFI) affects instantaneous surface SPM concentrations mainly because of its role in stratification and mixing, as sediment concentrations from direct fluvial supply are often low compared to the coastal North Sea background signal (Milliman and Meade, 1983). The ROFI itself is affected by the strong tidal currents (Van der Giessen et al., 1990; De Kok, 1996). It can switch from well-mixed to stratified with the spring-neap tidal cycle, while tidal straining can cause the ROFI to switch from strongly stratified to vertically homogeneous during a tidal cycle (Simpson et al., 1990; Simpson et al., 1993; Simpson and Souza, 1995; De Boer et al., 2006).

Additionally, wind-induced waves can reach the bottom boundary layer and seabed leading to the resuspension of

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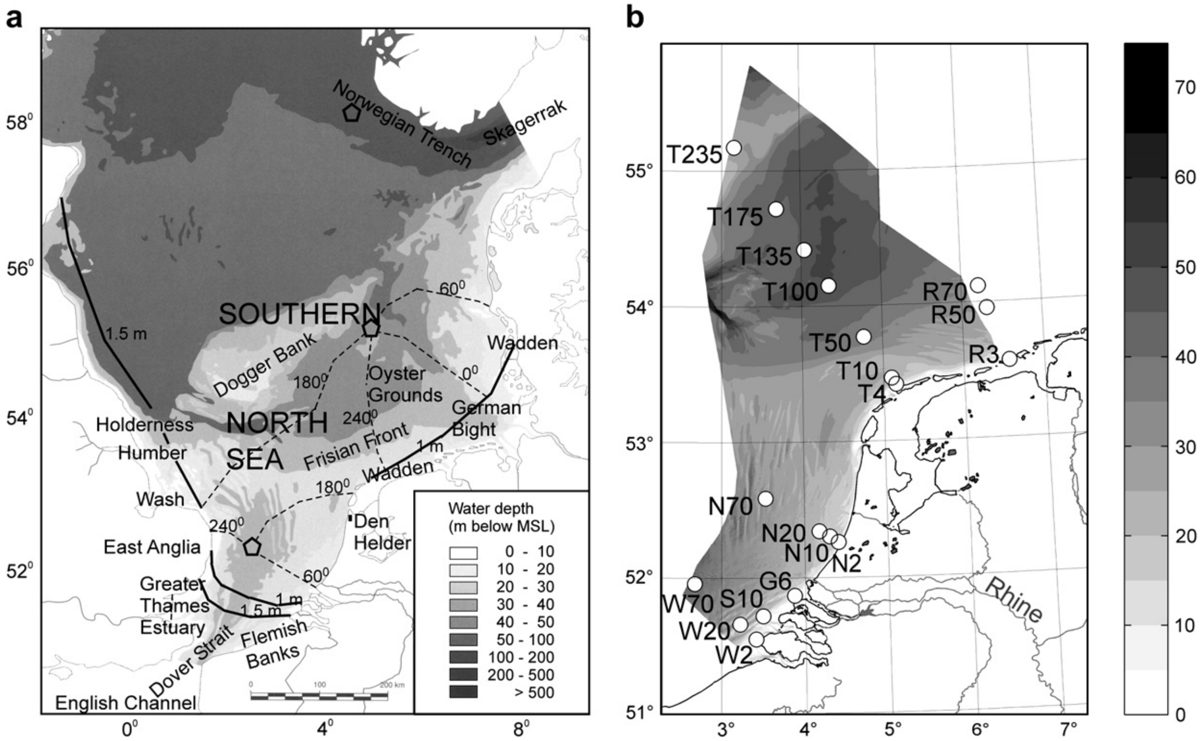

Fig. 1. Research area, with (a) selected co-tidal lines (degrees) and co-range lines (amplitudes in m) for the semi-diurnal tide shown on a bathymetric backdrop. Due to the friction of the shallow southern North Sea, the mean semi-diurnal tidal amplitude decreases from 3.8 m at Walcheren to 1.6 m at Noordwijk and exhibits a marked diurnal inequality as the tidal wave propagates. (b) Location of the in situ stations in the Dutch part of the North Sea on a backdrop of detailed bathymetry. White dots represent monitoring stations. They are labelled with the first letter of the transect name (R for Rottumerplaat, T for Terschelling, N for Noordwijk, G for Goeree, S for Schouwen, W for Walcheren) and a number representing the distance offshore in kilometres.

sediments, which generally consist of sands with intercalated mud laminae (Eisma, 1981; Eisma and Kalf, 1987; McCandliss et al., 2002). A familiar turbid zone known as the East Anglian Plume (McManus and Prandle, 1997; Dyer and Moffat, 1998) crosses the North Sea from southeast England and extends north of the Dutch Wadden Sea in the Southern Bight to east of the Danish Wadden coast (Holligan et al., 1989; Van Raaphorst et al., 1998; Eleveld et al., 2004). Holt and James (1999), Pleskachevsy et al. (2005) and Souza et al. (2007) showed the importance of erosion from the English cliffs, in particular from Holderness, in supplying the plume with sediment, with the majority of the erosion taking place in the winter months due to the increased intensity of storms and waves. Pleskachevsy et al. (2005) showed that this increased wind and wave activity is also responsible for mixing the water column in shallow regions and resuspending sediment from the bed.

SPM concentrations derived from remote sensing may be used to track turbid river plumes, or to study resuspension of bottom sediments in shallow waters due to tidal action, wind and waves. Interpretations of satellite data were mainly qualitative (Holligan et al., 1989) because of validation problems resulting from the scarcity of match-ups (sea-truth measurements at times of clear image data acquisition), and because many problems of quantitative interpretation of reflectance signatures for coastal waters still had to be solved (e.g., Gordon and Wang, 1994; Ruddick et. al., 2000). Nowadays, ocean colour data from sensors such as SeaWiFS, an instrument that has multiple narrow spectral bands (10 and 20 nm in the VIS, 40 nm in the NIR) from the blue (412 nm) to NIR (815 nm), have the potential to provide quantitative information on the spatial and temporal distribution of surface SPM in coastal waters. They allow the retrieval of SPM, phytoplankton chlorophyll-*a* pigments (CHL) and coloured dissolved organic matter (CDOM) (Sathyendranath et al., 1989) from the water-leaving radiance (L_w) if the pathway of sunlight into the sea and back to the sensor is modelled and subsequently inverted. Forward simulation studies by Tassan (1994) showed that the SPM signal is most pronounced and easily detected in the L_w 555 nm band. This was confirmed by Kirk (1994), and studies with SPOT (Doxaran et al., 2002) and SeaWiFS (Gohin et al., 2005; Morel and Bélanger, 2006).

The main influence of the SPM concentration on the reflectance spectrum lies in the backscatter coefficient (b_b). An increase of suspended sediments will augment b_b and thus increase the reflectance (R). Because the spectral shape of the backscattering coefficient is nearly flat compared to that of chlorophyll absorption, the effect on the spectral shape of the reflectance spectrum is relatively small. Therefore, the use of ratios is less suitable for SPM retrieval algorithms. However, ratios using bands that are spectrally close might reduce inaccuracies because of atmospheric correction errors and variations in the ratio of upwelling radiance to upwelling irradiance just below the water surface. Binding et al. (2005) show that single band reflectance can be used for the derivation of suspended sediment concentrations, but that algorithms are sensitive to variations in scattering behaviour that result from variations in particle size and type.

In this paper, we show how to derive a regional single band algorithm that relates SPM (suspended particulate matter concentration) to R_{555} (subsurface irradiance reflectance $R(0)$ at 555 nm), band 5 in the atmospherically corrected Level 2 data based on a physical, bio-optical approach. In particular, we use inherent optical properties (IOPs) for the Dutch and Belgium coast to parameterise and calibrate a single band SPM algorithm, and independently collected in situ SPM data to validate this simple single band algorithm. We demonstrate that remote sensing data can be used to supplement in situ measurements for characterising large-scale SPM patterns and in highlighting the location of water masses in the southern North Sea.