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Variability in specific-absorption properties and their use in a semi-analytical ocean colour algorithm for MERIS in North Sea and Western English Channel Coastal Waters

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ABSTRACT

Coastal areas of the North Sea are commercially important for fishing and tourism, and are subject to the increasingly adverse effects of harmful algal blooms, eutrophication and climate change. Monitoring phytoplankton in these areas using Ocean Colour Remote Sensing is hampered by the high spatial and temporal variations in absorption and scattering properties. In this paper we demonstrate a clustering method based on specific-absorption properties that gives accurate water quality products from the Medium Resolution Imaging Spectrometer (MERIS). A total of 468 measurements of Chlorophyll a (Chla), Total Suspended Material (TSM), specific- (sIOP) and inherent optical properties (IOP) were measured in the North Sea between April 1999 and September 2004. Chla varied from 0.2 to 35 mg m^{-3}, TSM from 0.2 to 75 g m^{-3} and absorption properties of coloured dissolved organic material at 442 nm ($a_{CDOM}(442)$) was 0.02 to 0.26 m^{-1}. The variation in absorption properties of phytoplankton (a_{ph}) and non-algal particles (a_{NAP}) were an order of magnitude greater than that for a_{ph} normalized to Chla (a_{ph}^*) and a_{NAP} normalized to TSM (a_{NAP}^*). Hierarchical cluster analysis on a_{ph}^*, a_{NAP}^* and a_{CDOM} reduced this large data set to three groups of high a_{NAP}^*–a_{CDOM}, low a_{ph}^* situated close to the coast, medium values further offshore and low a_{NAP}^*–a_{CDOM}, high a_{ph}^* in open ocean and Dutch coastal waters. The median sIOP of each cluster were used to parameterize a semi-analytical algorithm to retrieve concentrations of Chla, TSM and $a_{CDOM}(442)$ from MERIS data. A further 60 measurements of normalized water leaving radiance (nL_w), Chla, TSM, $a_{CDOM}(442)$ and $a_{NAP}(442)$ collected between 2003 and 2006 were used to assess the accuracy of the satellite products. The regionalized MERIS algorithm showed improved performance in Chla and $a_{CDOM}(442)$ estimates with relative percentage differences of 29 and 8% compared to 34 and 134% for standard MERIS Chla and $a_{dg}(442)$ products, and similar retrieval for TSM at concentrations >1 g m^{-3}.

1. Introduction

Information on marine environmental parameters, such as Chlorophyll a (Chla), is becoming increasingly important as it describes key parameters for monitoring climate change, water quality and the effects of pollution in the marine environment (Beaugrand et al., 2009; Yunev et al., 2005). Large scale spatial and temporal information on these parameters can be obtained by means of satellite remote sensing which can aid our understanding of biogeochemical cycles (Bousquet et al., 2006; Mohr & Forsberg, 2002). Long term time series of satellite ocean colour have shown an increase in Chla by 20% in sub-tropical regions over the past two decades but a decrease in Chla in oligotrophic gyres (Antoine et al., 2005), which are related to multi-decadal changes in ocean physics (Martinez et al., 2009). Primary production has decreased in the northern hemisphere (Tilstone et al., 2009) and at low latitudes, which is tightly coupled to increases in temperature and a reduction in nutrients as the result of enhanced stratification events (Behrenfeld et al., 2006). It is however, more difficult to accurately determine Chla from satellite in coastal regions due to their optical complexity (IOCCG, 2000). Despite their relatively

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small area, accounting for just 7% of the world ocean's surface, coastal zones play an important part in the global carbon cycle and in buffering human impacts on marine systems. They support 10–15% of the world ocean net annual productivity and may be responsible for >40% of the annual carbon sequestration (Muller-Karger et al., 2005). Coastal areas of the North Sea are commercially important for fishing and tourism, yet are subject to the increasingly adverse effects of harmful algal blooms (Aanesen et al., 1998; Davidson et al., 2009), eutrophication (Lancelot et al., 1987) and climate change (Reid et al., 2001; Stige et al., 2006). There is therefore an obvious need to develop accurate Chla algorithms in coastal regions to monitor these environmental changes.

Understanding the optical variability in the marine environment is important since it aids the development of satellite algorithms, especially in optically complex coastal areas. In most oceanic waters, which occupy approximately 60% of the global ocean (Lee & Hu, 2006), light absorption by phytoplankton dominates and is modified by the 'pigment package effect' (Bricaud et al., 2004), which is a function of cell size, species type and pigment concentration within the cell. Low pigment concentrations are predominantly associated with small phytoplankton cells, and high pigment concentrations with large cells (Yentsch & Phinney, 1989). In these waters, the absorption coefficient of coloured dissolved organic material (a_{CDOM}) is coupled with variations in phytoplankton biomass and can be modified by microbial and photochemical degradation (Del Vecchio & Blough, 2002; Hedges et al., 1997). In coastal regions, where the presence of Coloured Dissolved Organic Material (CDOM) and Total Suspended Material (TSM) also modify the light field (IOCCG, 2000), accurate estimation of Chla from satellite is more difficult. CDOM and TSM originating from riverine run-off and re-suspension of bottom sediment, are highly variable and on a global basis, the combined absorption of coloured dissolved organic and detrital material (a_{dg}) contribute up to 40% of the non-water absorption at 440 nm in the subtropical gyres and 60% at high latitudes (Siegel et al., 2005a). To facilitate algorithm development, Morel and Prieur (1977) classified optical water types into either Case 1 waters, where the optical properties are governed by phytoplankton, or Case 2 waters which are additionally affected by absorption properties of coloured dissolved organic material (a_{CDOM}) and TSM that do not co-vary with phytoplankton. A plethora of algorithms were developed to detect Chla in Case 1 waters and the most successful was an empirical, band switching ratio, which is accurate to 25% for Chla concentrations up to 35 mg m^{-3}. This algorithm was adopted by NASA as the standard Sea-viewing Wide Field of view Sensor (SeaWiFS) open ocean algorithm (O'Reilly et al., 1998). It often fails in Case 2 waters because the optical signature of CDOM or TSM can mask phytoplankton absorption at 442 nm (Sathyendranath et al., 2001). Prieur and Sathyendranath (1981) suggested seven water types based on the relative importance of the absorption coefficients of phytoplankton (a_{ph}), non-algal particles or detrital material (a_{NAP}) and a_{CDOM} to the total absorption in the water column. From these a number of algorithms were developed to retrieve inherent optical properties (IOP) and biogeochemical parameters from optically complex Case 2 waters (Carder et al., 1999; Doerffer & Schiller, 2007; Lee et al., 2002; Maritorena et al., 2002), which also provide additional parameters other than Chla (IOCCG, 2006). A number of semi-analytical approaches have been used in which water constituent concentrations are derived from the IOP, through a knowledge of the specific-inherent optical properties (sIOP) i.e. the IOP normalised to its biogeochemical concentration (Lee et al., 2002; Smyth et al., 2006; van der Woerd & Pasterkamp, 2008). These methods have advantages over conventional band ratio algorithms in that multiple ocean properties can be retrieved simultaneously from a single water-leaving radiance spectrum. The availability of data from satellite sensors such as Moderate Resolution Imaging Spectroradiometer (MODIS-Aqua) and Medium Resolution Imaging Spectrometer (MERIS), which have more spectral bands, a higher spatial resolution than SeaWiFS and novel atmospheric correction models, have also facilitated the development of a new range of satellite products for coastal waters. The current diversity of IOP models, however, exhibits large differences in performance when retrieving total absorption, backscatter or decomposing these into individual optically active components (IOCCG, 2006), primarily because they are trained on a limited IOP data set (Claustre & Maritorena, 2003; Cota et al., 2003; Sathyendranath et al., 2001). This is also compounded by the fact that with inverse modeling techniques, several combinations of IOP can lead to the same reflectance spectrum (Defoin-Platel & Chami, 2007).

There have been few studies of variations in IOP and sIOP in the optically complex coastal waters of the North Atlantic and the implementation of this data in ocean colour algorithms for Case 2 waters. North Sea and English Channel coastal areas have high absorption and scattering properties (Hommersom et al., 2009), and can switch seasonally between Cases 1 and 2 water types (Groom et al., 2009). The variability in a_{CDOM} in these areas is strongly linked to seasonal cycles of riverine run off and water column mixing (Garver & Siegel, 1997). The most comprehensive analysis of the optical properties of European waters, which included the North Sea, was conducted by Babin et al. (2003a, 2003b). From over 350 stations, they found that there were significant departures from the general trend between $a_{ph}(\lambda)$ and Chla reported for oceanic waters due to a different pigment composition and cell size under the influence of varying a_{CDOM} and a_{NAP}, and that that low light scattering at 555 nm was principally due to minerals with a low clay and silt content that occur along the European shelf. Due to its optical complexity, the North Sea has been a site for satellite algorithm development: A Chla atlas of the region was published using NASA-Coastal Zone Color Scanner (CZCS) global algorithm as a qualitative proof of concept (Holligan et al., 1989). More recently, a neural network algorithm was developed, firstly calibrated on North Sea data and then globally, to give standard global coastal products of Chla, TSM and a_{dg} from MERIS data (Doerffer & Schiller, 2007). Directional water leaving radiance is input into the algorithm and it outputs Chla, TSM and a_{dg} based on the conversion of scattering and absorption coefficients using non linear multiple inversion solutions and regional conversion factors to give concentrations. Regionally tuned algorithms for the North Sea have also been developed to retrieve Chla (Høkedal et al., 2005; Peters et al., 2005) and TSM (van der Woerd & Pasterkamp, 2004) based on either radiative transfer solutions using the numerical model HYDROLIGHT to estimate concentrations of optically active substances from modeled reflectance spectra or regionally tuned spectral shapes and slope inputs to empirical solutions.

In this paper we addressed the following questions: What are the temporal and spatial variations in absorption and specific-absorption properties in the North Sea and Western English Channel? What are the principal absorption and specific-absorption properties in this area? Can trends in specific-absorption properties alone be used to develop accurate ocean colour regional algorithms? The variation in specific-absorption properties in the North Sea and Western English Channel is analysed using hierarchical clustering to characterise the principal optical types. Representative sIOP groups are then used, in conjunction with a semi-analytical model HYDROPT, to retrieve water quality parameters Chla, TSM and CDOM. To demonstrate the benefits of this method, the products from this regionally tuned model are compared to standard MERIS Case 2 water products.

2. Methods

2.1. Study area characteristics and sampling regime

Seven research institutes measured the bio-optical properties and associated biogeochemical concentrations of 468 stations on 22 cruises from 1998 to 2004 in the North Sea, Western English Channel (WEC) and Celtic Sea (Table 1a, Fig. 1A). A further 61 stations were sampled on 15 further cruises to measure Chla, TSM, $a_{CDOM}(\lambda)$ and