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Remote sensing of spatio-temporal relationships between the partitioned absorption coefficients of phytoplankton cells and mineral particles and euphotic zone depths in a partially mixed shelf sea

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ABSTRACT

Absorption coefficients for mineral particles and phytoplankton cells in the 488 nm waveband, $a_{MSS}(488)$ and $a_{CHL}(488)$, and euphotic zone depths, $z_{1\%PAR}$, were determined for the Irish Sea and St. George's Channel from 8 years of MODIS remote sensing reflectance observations. The results are presented as composite maps of the entire region for the months of January, April, July and October and as time series averaged over 2 week intervals for three selected locations representing different mixing regimes. Annual cycles in $a_{MSS}(488)$ were observed in most areas, with maximum values occurring in winter when increased vertical mixing brought fine sediments to the surface. Euphotic depths were strongly influenced by $a_{MSS}(488)$ cycles, but sharp reductions were superimposed wherever phytoplankton blooms occurred. A key hydrographic feature of this region is the formation of a front in St. George's Channel between mixed and seasonally stratified water bodies. On the mixed side of the front, single peaks in $a_{CHL}(488)$ were observed in summer when the euphotic zone was at its deepest. On the stratified side, double peaks in $a_{CHL}(488)$ occurred in spring and autumn while low summer values of $a_{CHL}(488)$ coincided with high values of $z_{1\%PAR}$. The remote sensing evidence indicates, therefore, that phytoplankton growth (as reflected by net accumulation at the surface) in summer was limited by light availability in mixed waters, and nutrient availability in the stratified region. We conclude that observations of spatio-temporal patterns in phytoplankton and mineral particle absorption coefficients and euphotic depths derived from ocean colour sensors can provide insights into the processes determining the depth of penetration of solar radiation, and also the factors limiting near-surface primary production, in optically complex and spatially heterogeneous shelf seas.

1. Introduction

The patterns of primary production observed in shelf seas exhibit a challenging degree of dynamical complexity (Simpson & Sharples, 2012). It is important to understand the mechanisms which generate this complexity if we are to develop realistic numerical models of shelf sea ecosystems, and to gain insights into the likely response of these ecosystems to anthropogenic disturbance and climate change (Guenette, Araujo, & Bundy, 2014; Holt et al., 2014). Positive rates of net primary production, which require adequate light levels, are achieved in the euphotic zone which is often assumed to extend from the surface to the depth ($z_{1\%PAR}$) at which spectrally-integrated photosynthetically active radiation (PAR) falls to 1% of its surface value (Kirk, 2011). If phytoplankton growth is to be sustained, however, there is also a requirement for a supply of inorganic nutrients which are usually derived from the remineralisation of organic material in benthic sediments (Schultz & Zabel, 2006). Consequently, physical mixing of the water column plays an important role in determining rates of primary production by transporting inorganic nutrients towards the surface from deeper water while simultaneously circulating phytoplankton cells through a light field which decreases exponentially with depth (Howarth, Simpson, Sundermann, & van Haren, 2002). Mathematical models which quantify this interdependence of light availability, nutrient supply and vertical mixing are capable in themselves of generating a rich variety of dynamic behaviour (Ryabov, Rudolf, & Blasius, 2010; Greenwood & Craig, 2014), but in a real water column there are additional complicating factors. These include (i.) the possible presence of non-phytoplankton modifiers of subsea light fields, such as coloured dissolved organic matter and suspended mineral particles (Vantrepotte et al., 2007) and (ii.) processes of advection and stratification which can introduce significant spatial and temporal decoupling between mixing events and phytoplankton growth (Peeters, Kerimoglu, & Straile, 2013). In a given region, therefore, observation of the timing and geographical distribution of phytoplankton blooms, and the degree to which they are correlated with euphotic zone depths, is an important key to understanding the

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fundamental processes which sustain shelf sea ecosystems (van Ruth, Ganf, & Ward, 2010; Capuzzo et al., 2013; Jin et al., 2013). However the high degree of heterogeneity in many shelf sea areas makes it difficult to adequately capture this spatial and temporal variability using in-situ sampling techniques (Gohin, 2011).

Optical remote sensing from polar orbiting satellites appears to offer an attractive solution to this problem (Robinson, 2008; Blondeau-Patissier, Gower, Dekker, Phinn, & Brando, 2014). Obvious advantages include synoptic spatial mapping, daily overpasses for many shelf sea locations and, thanks to extensive existing infrastructure, relatively low resource requirements at the level of individual projects. There are also disadvantages, which include the possibility of significant primary production occurring below the remote sensing penetration depth (Gholamalifard, Esmaili-Sari, Abkar, Naimi, & Kutser, 2013; Frolov, Ryan, & Chavez, 2012) and biases arising from the fact that observations are always made around noon under cloud-free conditions (Eleveld, van der Wal, & van Kessel, 2014). A greater obstacle, however, arises from the uncertain performance of traditional, empirically-derived algorithms in shelf sea environments (Cui et al., 2010; Shang et al., 2014; Zhao et al., 2014). The approach to algorithm development adopted here is based on the Quasi-Analytical Algorithm (QAA) developed by Lee, Carder, and Arnone (2002), which aims to retrieve two inherent optical properties, the spectral absorption coefficients $a(\lambda)$ and backscattering coefficients $b_b(\lambda)$ from subsurface remote sensing reflectance $r_{rs}(\lambda)$. Once these inherent optical properties have been determined, they can be incorporated into secondary algorithms to generate values for irradiance attenuation coefficients (Lee et al., 2013), euphotic depths (Shang, Lee, & Wei, 2011; Soppa, Dinter, Taylor, & Bracher, 2013; Mitchell, Cunningham, & McKee, 2014a) and in specific cases concentrations of optically significant seawater constituents (Le & Hu, 2013; Mishra, Mishra, Lee, & Tucker, 2013). Moreover, in waters where the optical contribution of CDOM is constant (or so low that its variability can be neglected) particulate absorption coefficients recovered by the QAA can be resolved into separate components for phytoplankton cells and mineral particles (Mitchell, Cunningham, & McKee, 2014b).

The hypotheses which are tested in this paper are (i) that recently developed algorithms based on the QAA approach can significantly extend the capability of optical remote sensing in shelf seas, (ii) that these algorithms allow the mapping of spatial and temporal patterns of variability in euphotic depth and in the absorption coefficients for phytoplankton and mineral particles in the surface layer, and (iii) that relationships between these variables can be interpreted in terms of the interaction of physical factors (light penetration depth and the degree of water column mixing) in determining the magnitude and timing of phytoplankton blooms. The Irish Sea was selected as a test location because it provides a wide range of water types in a relatively restricted area, and its optical and hydrological properties have been the subject of a large number of previous studies: see for example Brown et al. (2003) for physical structure; Tilstone, Smyth, Gowen, Martinez-Vicente, and Groom (2005) and McKee and Cunningham (2006) for inherent optical properties and primary production; Gowen et al. (2008) for trophic status; Bowers, Roberts, White, and Moate (2013) for coloured dissolved organic matter; Smith, Stewart, and McDonald (2003) for suspended particles; and Holt, Proctor, Blackford, Allen, and Ashworth (2004) for physical/biological modelling. There are, however, striking gaps in the coverage of the region provided by ship based surveys. Studies of the south and west are fewer in number and tend to be concentrated at the junction with the Celtic Sea, and there is a marked absence of information regarding conditions in winter.

2. Methods

2.1. Geographical context

The work presented in this paper covers the Irish Sea and St. George's Channel (Fig. 1), whose bathymetric characteristics include a deep (90 m–120 m) central trough bounded by broad shallow (20 m–50 m) shelves. In winter, the entire region is mixed by a combination of wind and tidal stirring (Bowers, 2003), but in summer stratified regions form in eastern bays, in deeper waters to the west of the Isle of Man, and in the south where St. George's Channel forms a link between the Irish and Celtic Seas (Simpson & Bowers, 1981). The approximate location of the front which forms between mixed and stratified waters in St. George's Channel is indicated by the change in sea surface temperature from 13 °C to 15 °C in Fig. 2.

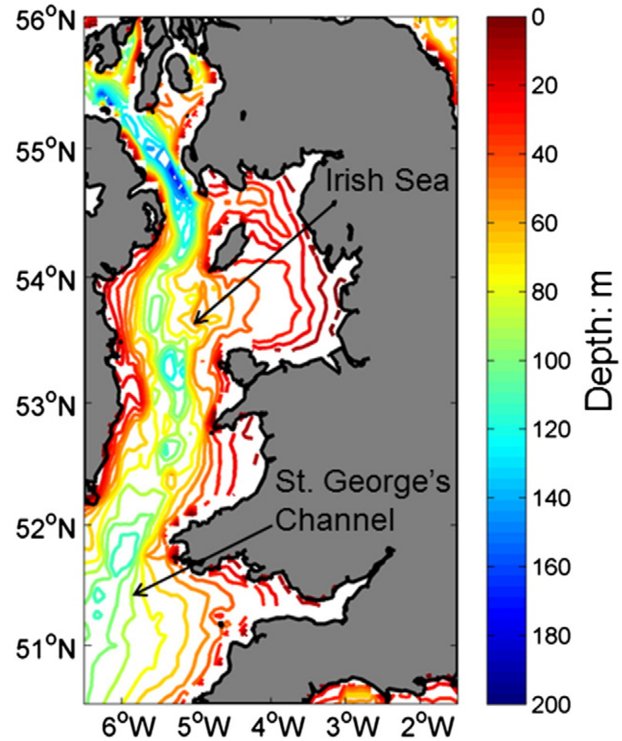

Fig. 1. Bathymetric contours for the Irish Sea and St. George's Channel.

This figure also shows the positions of three 11 × 11 pixel patches (each corresponding to an area at the sea surface of 8.5 km × 12 km) that were used to construct remote sensing time series, and two hydrographic stations from which optical profiles were obtained. Patch A (51.6°N, 6.16°W; depth 75 m) was located in the southern stratified zone, Patch B (52.8°N, 5.44°W; depth 60 m) in deep mixed water and Patch C (53.5°N, 4.71°W; depth 45 m) in shallower water with very strong tidal mixing (Ellis, Binding, Bowers, Jones, & Simpson, 2008). Station 50 (51.53°N, 6.33°W) was positioned near patch A and Station 43 (52.32°N, 5.94°W) mid-way between patches A and B.

2.2. Remote sensing data

MODIS (Moderate Resolution Imaging Spectroradiometer) Aqua data for the eight-year period from January 2005 to December 2013 were downloaded from the NASA Goddard Distributed Active Archive Center. Level-1A data were processed in SeaDAS 6.4, using the default 2-band aerosol model with an iterative near infra-red correction, to obtain remote sensing reflectance $R_{rs}(\lambda)$ at 1 km resolution in the visible wavebands. Pixels that were not masked by cloud or by proximity to the coastline were converted to subsurface reflectances, $r_{rs}(\lambda)$, using the relationship given in Lee et al. (2002):

$$r_{rs}(\lambda) = \frac{R_{rs}(\lambda)}{0.52 + 1.7R_{rs}(\lambda)} \tag{1}$$