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Specific absorption coefficient of phytoplankton off the Southwest coast of the Iberian Peninsula: A contribution to algorithm development for ocean colour remote sensing

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ABSTRACT

The variability in coefficients of absorption for phytoplankton was assessed for an area off the Southwest coast of Portugal. This area included three sites at 2, 10 and 18 km perpendicular to the coast, sampled at surface, mid-Secchi and Secchi depths at each site. Phytoplankton absorption coefficients were transformed into specific coefficients ($a^*_{ph}(\lambda)$) by normalizing them with respect to chlorophyll *a* (Chl*a*) concentrations determined by High Performance Liquid Chromatography. The influence on the variability of the absorption coefficient of phytoplankton was assessed for physico-chemical and biological parameters such as nutrients or Chl*a* levels, as well as size structure and abundance of the phytoplankton community. The results showed that the phytoplankton absorption coefficients decreased from inshore to offshore, but were relatively constant within the water column, revealing a well-mixed column. The $a^*_{ph}(\lambda)$ varied inversely with Chl*a* content, with minima in Autumn and Spring, matching phytoplankton blooms. The effects of the size structure of the community and pigment composition on the variability of phytoplankton absorption coefficient were studied and results showed that size structure had a greater influence on the variability of the phytoplankton absorption, although the pigment contribution was also important.

1. Introduction

Remote sensing of ocean colour is an increasingly important tool to monitor coastal and oceanic productivity. However, its effectiveness depends on the accurate assessment of the parameters used for bio-optical models, such as the absorption and scattering properties of a water body. Absorption processes explain much of the behaviour of light in the water medium, and are indispensable for characterizing an optical medium for all model studies on radiative transfer (Prieur and Sathyendranath, 1981).

Three groups of substances are generally considered responsible for significant modifications to the absorbing properties of seawater (Prieur and Sathyendranath, 1981): phytoplankton, non-algal (or non-chlorophyllous) particles of biological or terrestrial origin, and coloured dissolved organic matter (CDOM-also known as yellow substances). A simple classification (Morel and Prieur, 1977) separates oceanic and coastal waters into Case 1 where the optical properties co-vary with phytoplankton and their derivatives, whilst Case 2 waters are dominated by non-algal particles and CDOM. However, there are increasing arguments for a classification based on a *continuum* of optical properties (Berthon et al., 2008).

1.1. Background to the hypothesis

The phytoplankton contribution is assumed to have a more preponderant role in the total absorption in coastal regions where there are no significant terrestrial inputs. Therefore, there is a need to understand phytoplankton absorption at a regional scale

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to avoid under- or over- estimation of satellite ocean colour products relative to in situ data; several studies have been published on this subject (Barocio-Léon et al., 2008; Bricaud et al., 1998; Ferreira et al., 2009; Lorenzoni et al., 2011; Suzuki et al., 1998). The phytoplankton absorption spectra and, thereby, the specific absorption coefficient (a^*_{ph}), has been assumed to be constant (Platt and Sathyendranath, 1988), but in more recent studies it is generally recognized as variable (Millán-Núñez et al., 2004; Pérez et al., 2007; Suzuki et al., 1998). This variability can be understood as a function of the local dynamics of the community, the effects of cell size, and intracellular pigment concentration and composition (Morel and Bricaud, 1981; Babin et al., 1993). In addition, the information about the shape of the phytoplankton absorption spectra is useful, not only for accurate configuration of algorithms for retrieval of ocean colour, but also for primary production models and for the possibility of predicting community abundance (Moberg et al., 2002).

Differentiation of phytoplankton communities by satellite is a major challenge for ocean optics, particularly, as the in situ data required to validate regional algorithms are sparse (Brewin et al., 2011). As part of a general effort to validate images from the Medium Resolution Image Spectrometer (MERIS) of the European Space Agency (ESA) off the SW coast of Iberia, the current study assesses the phytoplankton absorption spectral shape and dynamics as well as the local range of a^*_{ph}, relative to differences in season, depth and distance from the coast. These in situ data should contribute to the development of more accurate bio-optical algorithms for this region.

1.2. Hypothesis

Based on earlier studies (e.g., Morel and Bricaud, 1981; Babin et al., 1993) factors affecting unpackaged in vivo phytoplankton absorptions a_{sol} are described by Eq. (1) and (2) for the wavelengths 440 and 678 nm, respectively:

$$a_{sol}(440) = a_{\mathrm{Algal\ I}}[\mathrm{Algal\ I}] + a_{\mathrm{TChlb}}[\mathrm{TChlb}] + a_{\mathrm{TChlc}}[\mathrm{TChlc}] + a_{\mathrm{PPC}}[\mathrm{PPC}] + a_{\mathrm{PSC}}[\mathrm{PSC}] \quad (1)$$

$$a_{sol}(678) = a_{\mathrm{Algal\ I}}[\mathrm{Algal\ I}] + a_{\mathrm{TChlb}}[\mathrm{TChlb}] + a_{\mathrm{TChlc}}[\mathrm{TChlc}] \quad (2)$$

where $a_{sol}(\lambda)$ is the unpackaged absorption; Algal I is the notation used in MERIS Validation Protocols for total Chl*a* index used for Case 1 waters; the terms TChlb, TChlc, PPC and PSC stand for total chlorophyll *b*, total chlorophyll *c*, the sum of photoprotective carotenoids, and the sum of photosynthetic carotenoids, respectively.

Algal I includes the following derivates for Chl*a*, as in Eq. (3):

$$Alg\ all = [MVChla] + [DVChla] + [Clidea] + [Phpba] + [Phpta], \quad (3)$$

where *MVChla*, *DVChla*, *Clidea*, *Phpba*, and *Phpta* stand for Monovinyl Chl*a*, Divinyl-Chl*a*, chlorophyllide*a*, phaeophorbide*a*, phaeophytin*a*, respectively.

Individual pigments are used for modelling of the in vivo absorptions although, for simplicity, the algal pigments are grouped into their major classes. As the pigments are packaged within phytoplankton cells, absorption is depressed according to the package index, $Q^*_a(\lambda)$, which is a function of the size distribution of the phytoplankton and their relative shape and refractive index (Morel and Bricaud, 1981). This packaging function is described by Eq. (4):

$$a_{\mathrm{ph}}(l) = Q_a{}^*(\mathrm{size})a_{sol}(\lambda). \quad (4)$$

Taking into account Eqs. (1)–(4), the blue: red ratio is described by Eq. (5):

$$\frac{a_{ph,sol}(440)}{a_{ph,sol}(678)} = \frac{Q_a{}^*(size)a_{sol}(440)}{Q_a{}^*(size)a_{sol}(678)} \quad (5)$$

On the basis of these equations, the dominant effects on this ratio are likely to be size structure of the communities, chlorophyll and carotenoids types, which are ultimately affected by nutrient availability, species composition and seasonality. Consequently, the hypothesis for this study is that the variability in phytoplankton absorption properties in the study area is the result of the variability in size structure and pigment composition of the phytoplankton community.

2. Materials and methods

The study region (Fig. 1) is located at the extreme Southwest of continental Europe, and includes both coastal and oceanic sites off Sagres, Portugal. It is an upwelling area (Ambar and Dias, 2008; Fiúza, 1982; Relvas and Barton, 2002), where favourable north westerly and westerly winds stimulate an increase in nutrient levels and primary productivity that culminate in blooms of diatoms and dinoflagellates (Loureiro et al., 2005, 2011; Nykjaers and Van Camp, 1994; Sousa and Bricaud, 1992), especially from spring to late summer. There are no river plumes in the vicinity and drainage from the coastal region is restricted to occasional rainstorms between late September and early June (Peliz and Fiúza, 1999).

2.1. Field sampling

As part of the validation effort for the products from the MERIS sensor, sampling campaigns were planned to match overpasses of the study area by the ENVISAT satellite, under clear skies with calm seas. Three sampling Stations were selected at 2 (37°00′39″N and 8°53′58″W), 10 (36°56′06″N and 8°52′48″W) and 18 km (36°51′33″N and 8°50′16″W) off the coast from Cape Sagres at Stations A, B and C, respectively (Fig. 1). The semi-rigid inflatable boat "Kogia" enabled deployment of the instruments required to obtain in situ data within the time frame considered appropriate for comparison with satellite products (Doerffer, 2002; Muller et al., 2003); up to 30 min for coastal stations (e.g., A at Sagres) and up to 3 h for more oceanic stations (e.g., B, C at Sagres).

At each Station, water leaving reflectances were obtained from a hyper-spectral radiometer, together with estimates for turbidity from a Secchi disk, and the determination of temperature and salinity profiles from a CTD (SEACAT SBE 19) deployed down to depths of approximately 40, 100 and 160 m at Stations A–C, respectively. Water samples were collected from surface, mid-Secchi and Secchi depths, using a Niskin bottle. The samples were stored in 10 l Nalgene® and 500 ml glass containers and transferred to the field laboratory for further processing within three hours of arrival onshore.

At the field laboratory, the samples in each Nalgene® container were treated to a protocol where duplicates of 2–3 l of water were filtered through Whatman® 47 mm glass-fibre filters (GF/F),with 0.7 μm pore size, which were then wrapped in aluminium foil and stored in liquid nitrogen for pigment analysis; duplicates of 500 ml were filtered through Whatman® 25 mm GF/F filters, also with 0.7 pore size, stored in tissue capsules and preserved in liquid nitrogen to determine particle absorption; 500 ml were frozen in a plastic bottle at −19 °C for nutrient analysis; finally, 300 ml were filtered through a 200 μm mesh to remove the larger organisms and preserved in lugol iodine for community analysis of plankton.