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Estimation of the diffuse attenuation coefficient K_{dPAR} using MERIS and application to seabed habitat mapping

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ABSTRACT

The availability of light in the water column and at the seabed determines the euphotic zone and constrains the type and the vertical distribution of algae species. Light attenuation is traditionally quantified as the diffuse attenuation coefficient of the downwelling spectral irradiance at wavelength 490 nm (K_{d490}) or the photosynthetically available radiation (K_{dPAR}). Satellite observations provide global coverage of these parameters at high spatial and temporal resolution and several empirical and semi-analytical models are commonly used to derive K_{d490} and K_{dPAR} maps from ocean colour satellite sensors. Most of these existing empirical or semi-analytical models have been calibrated in open ocean waters and perform well in these regions, but tend to underestimate the attenuation of light in coastal waters, where the backscattering caused by the suspended matters and the absorption by the dissolved organic matters increase light attenuation in the water column.

We investigate two relationships between K_{dPAR} and K_{d490} for clear and turbid waters using MERIS reflectances and the spectral diffuse attenuation coefficient $K_d(\lambda)$ developed by Lee (2005). Satellite-derived fields of K_{d490} and modelled K_{dPAR} are evaluated using coincident in-situ data collected over the world in both clear and turbid waters, and by using Ecolight simulations. Temporal means at 250 m resolution of K_{dPAR} and euphotic depth were computed over the period 2005–2009 for European coastal waters. These mean data were cross-tabulated with in-situ data of kelp (*Laminaria hyperborea*) and seagrass (*Posidonia oceanica*), respectively observed at locations on Atlantic and Mediterranean shores where the light is taken as the limiting factor to the depth distribution for these species. The minima observed for *P. oceanica*, in percent of energy, are very close to 1% of surface irradiance, the historical threshold known as euphotic depth as defined by Ryther (1956). Real estimates of the surface irradiance (Frouin, 1989) are used in conjunction with the estimated K_{dPAR} to calculate the residual energy at the lower limit of *P. oceanica* and *L. hyperborea* in mol·photons·m^{-2}·day^{-1} as a complement to the usual fraction of the surface energy. We show that the observed values, in terms of energy, for both species were equivalent to the values reported in the literature.

1. Introduction

The light available in the water column at wavelengths between 400 and 700 nm in the visible part of the spectrum, termed photosynthetically active radiation (PAR), is utilised by phytoplankton for photosynthesis (Falkowski & Raven, 1997; Kirk, 1994) and constrains the type and distribution of algae species and benthic algae, which contribute significantly to total primary production (Cahoon et al., 1993; McMinn et al., 2005; Carter et al., 2005). The estimation of the light attenuation in the water column is also critical to understand physical processes such as the heat transfer in the upper layer of the ocean (Lewis et al., 1990; Morel & Smith, 1974; Sathyendranath et al., 1991; Rocheford et al., 2001; Wu et al., 2007). From an optical perspective, in addition to pure water, light attenuation is constrained by the concentration of three components (IOCCG Report 3, 2000): pigments, expressed here as the concentration of chlorophyll-a ([Chl-a]), dissolved yellow substances (gelbstoff or CDOM) absorption a_{cdm} and suspended particulate matter concentration ([SPM]). The in-situ spectral diffuse attenuation coefficient $K_d(\lambda)$ was traditionally measured by the ocean-colour scientific community at 490 nm (K_{d490}), following the primary studies in the 1970s (Jerlov, 1976). Concurrently, biologists have focused on the PAR measurement and attenuation (K_{dPAR}). Both K_{dPAR} and K_{d490} increase with increasing solar zenith angle and K_{dPAR} is significantly depth dependent (the longer wavelength, red in this example, is rapidly attenuated in the water column relatively to the shorter wavelength blue) even for well-mixed waters.

Since the launch of the Coastal Zone Color Scanner (CZCS) in 1978, the ocean-colour community has provided maps of K_{d490} or K_{dPAR} at large spatial scales offering a great improvement in spatial and temporal

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resolution compared to in-situ data. Space based sensors measure top-of-atmosphere radiances at different wavelengths and the Medium Resolution Imaging Spectrometer (MERIS) sensor has 15 bands between 412 and 865 nm. The contribution from the atmosphere is firstly removed from the top-of-atmosphere radiance, through a process known as atmospheric correction (Gordon & Wang, 1994), to obtain the water-leaving radiance (Lw). The Lw values are normalised, i.e. expressed in standard solar conditions (sun at zenith) in the absence of the atmosphere, and corrected for bidirectional effects (viewing angle dependence and effects of seawater anisotropy, Morel et al., 2002) to obtain the normalised water-leaving radiance (nLw). Today, several empirical and semi-analytical models of K_{d490} and K_{dPAR} are commonly used to derive K_{d490} maps from satellite-derived nLw.

Mueller (2000) defines an empirical relationship between K_{d490} and the ratio between blue and green water-leaving radiances from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) (McClain et al., 2004), and the Moderate Resolution Imaging Spectroradiometer (MODIS) (Esaias et al., 1998). Morel et al. (2007) proposes an empirical relationship between the K_{d490} and the Chl-a concentration. Lee et al. (2002, 2005a, 2005b, 2007) provided a semi-analytical model for K_{d490} with dedicated versions for SeaWiFS, MERIS and MODIS nLw.

K_{dPAR} has historically been expressed as a function of [Chl-a] (Morel, 1988) for clear open ocean waters. This latest approach is routinely used in the open ocean where phytoplankton is the main contributor to attenuation (Claustre & Maritorena, 2003). In coastal waters however, the determination of K_{dPAR} is complicated by increased light attenuation by CDOM and SPM(Case 2 waters). In coastal areas regional approaches express K_{dPAR} as a function of the [Chl-a], and [SPM] (Devlin et al., 2009; Gohin et al., 2005). More recently, K_{dPAR} is more often related to K_{d490} using empirical approaches and the relationship between K_{d490} and K_{dPAR} has quite large regional variations (Barnard et al., 1999; Pierson, 2008; Morel et al., 2007; Pierson et al., 2008; Wang et al., 2009; Zaneveld et al., 1993).

In this paper, we show the performance of three models of K_{d490} (Lee et al., 2005a, 2005b; Morel et al., 2007; Mueller, 2000), routinely used as standard MERIS, SeaWiFS and MODIS Level 3 products, compared to an in-situ dataset collected near shore and in clear open ocean waters. We then derive two relationships between K_{dPAR} and K_{d490}, estimated by integrating the spectral irradiances over the euphotic depth and the visible spectrum using $K_d(\lambda)$ as estimated using Lee et al. (2005a, 2005b).

Our aim is to provide an estimation of K_{dPAR} for values greater than 0.06 m^{-1} and lower than 1 m^{-1}. For more turbid waters, dedicated algorithms may be used, and for oligotrophic waters (K_{dPAR}<0.06 m^{-1}), standard K_{dPAR} estimations (Morel et al., 2007; Mueller, 2000) are freely available at 4 km resolution on the Globcolour website (www.globcolour.info), and the oceancolor webpage (http://oceancolor.gsfc.nasa.gov/).

Secondly, temporal means of satellite derived K_{dPAR} and Z_{eu} were calculated for the European waters, from 2005 to 2009, to characterise a reference state for light and marine coastal fauna and flora in the intertidal zone at 250 m resolution.

Finally, six sites where selected by Ifremer in Corsica (Mediterranean Sea) and in Brittany (English Channel and Atlantic Ocean) to compare the satellite derived minimum light threshold values for *P. oceanica* and *L. hyperborea* to the literature. The threshold of 1% used to define Z_{eu} as the minimum light requirement for benthic primary production, was historically determined from in-situ observations of *P. oceanica* in the Mediterranean Sea. We therefore compare the satellite-derived 1% to the deepest depth at which *P. oceanica* is observed at the Corsican site. Nevertheless, some species can survive at lower light levels and the evaluation of the light available in fraction of the surface irradiance is biologically meaningless (Gattuso et al., 2006) as the fraction of moonlight is the same than the fraction of sunlight. Therefore, we propose the use of daily integrated PAR (Frouin et al., 1989) attenuated into the water column using K_{dPAR}, to arrive at an estimation of the PAR in the water column in mol·photons·m^{-2}·d^{-1}. This provides a more meaningful estimation of energy in the water column than fraction of the surface energy, generally used by the community.

2. Methods

The spectral diffuse attenuation coefficient $K_d(\lambda)$ is the coefficient of the exponential attenuation of the spectral downwelling irradiance:

$$Ed(\lambda) = E0(\lambda).e^{-Kd(\lambda)z}. \quad (1)$$

Here $E_d(\lambda)$ is the spectral downwelling irradiance in W.m^{-2}.nm^{-1} at depth z and wavelength λ and $E_0(\lambda)$ is the energy just beneath the surface). All symbols and acronyms cited in the text are summarized in Table 1 for a better understanding. If the visible spectral domain is considered, the PAR at depth z can be related to $K_d(\lambda)$ and E_d (λ) using energetic (Eq. 2a) or quantum units (Eq. 2b.) (Baker & Frouin, 1987; Morel & Smith, 1974):

$$\mathrm{PAR}(z) = \int_{400\mathrm{nm}}^{700\mathrm{nm}} \mathrm{Ed}(\lambda; z=0).\exp^{-\mathrm{Kd}(\lambda).z} d\lambda \left[\mathrm{W.m}^{-2}\right] \quad (2a)$$

$$\mathrm{PAR}(z) = \frac{1}{h.c}\int_{400\mathrm{nm}}^{700\mathrm{nm}} \lambda.\mathrm{Ed}(\lambda; z=0).\exp^{-\mathrm{Kd}(\lambda).z} d\lambda \left[\mathrm{photons.m}^{-2}.\mathrm{s}^{-1}\right]. \quad (2b)$$

An expression of the instantaneous $K_{dPAR}(z)$ is:

$$\mathrm{KdPAR}(z) = -\frac{\ln(\mathrm{PAR}(z+dz)) - \ln(\mathrm{PAR}(z))}{dz}. \quad (3)$$

K_{dPAR} changes with depth as the red photons are absorbed in the top layers. The spectral diffuse attenuation coefficient of downwelling irradiance $K_d(\lambda)$ also changes with depth, but its magnitude of variation is significantly smaller than that of K_{dPAR} (Lee, 2009; Zaneveld et al., 1993). The Hydrolight/Ecolight (© Curtis D. Mobley, 2008) is a radiative transfer model that computes radiance distributions and related quantities (irradiance, reflectances, diffuse attenuation functions, etc.) in any water body starting from the Chl-a and SPM concentration and CDOM absorption. Fig. 1 shows two Ecolight simulations of K_{dPAR} for clear (blue plot) and coastal turbid waters (orange plot). In this simulation the water is assumed to be well mixed and scattering of particulates is based on the model of Gordon and Morel (1983). The sky is assumed to be cloudless

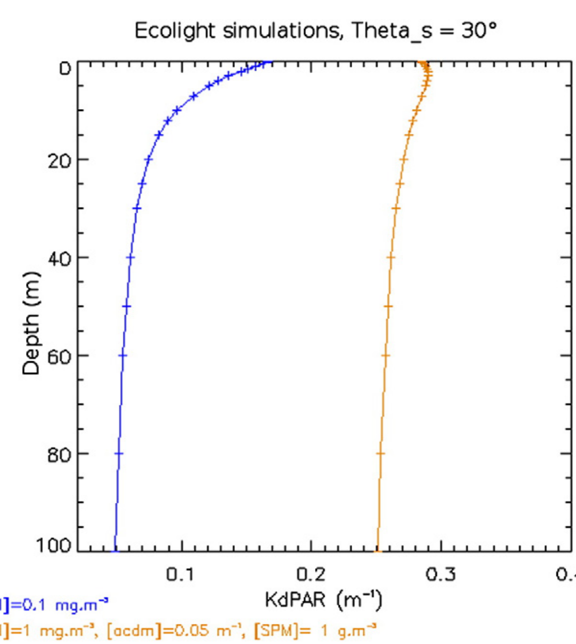

Fig. 1. Simulated $K_{dPAR}(z)$ in the water column using Ecolight for clear water with low [Chl-a] (case1, blue) and coastal water (case 2, orange).