Estimation of the diffuse attenuation coefficient $K_{d\text{PAR}}$ using MERIS and application to seabed 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 active radiation ($K_{d\text{PAR}}$). 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 $K_{d\text{PAR}}$ 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 $K_{d490}$ and $K_{d\text{PAR}}$ 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 $K_{d\text{PAR}}$ are evaluated using coincident in-situ data collected over the world in both clear and turbid waters, and by using Ecoclight simulations. Temporal means at 250 m resolution of $K_{d490}$ 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 $K_{d\text{PAR}}$ 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.

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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 at 490 nm 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 ($K_{d\text{PAR}}$). Both $K_{d\text{PAR}}$ and $K_{d490}$ increase with increasing solar zenith angle and $K_{d\text{PAR}}$ 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 $K_{d\text{PAR}}$ at large spatial scales offering a great improvement in spatial and temporal
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 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) (Esaías 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 $Ze_u$ 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:

$$Ed(\lambda) = E_0(\lambda)e^{-K_d(\lambda)z}.$$  \hspace{1cm} (1)

Here $E_0(\lambda)$ is the spectral downwelling irradiance in W.m$^{-2}$.nm$^{-1}$ at depth z and wavelength $\lambda$ and $E_d(\lambda)$ 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 $E_d(\lambda)$ using energetic (Eq. 2a) or quantum units (Eq. 2b) (Baker & Frouin, 1987; Morel & Smith, 1974):

$$\text{PAR}(z) = \int_{\lambda_{min}}^{\lambda_{max}} Ed(\lambda; z = 0), \exp^{-K_d(\lambda)z} d\lambda \left[W.m^{-2}\right]$$ \hspace{1cm} (2a)

$$\text{PAR}(z) = \frac{1}{\lambda} \int_{\lambda_{min}}^{\lambda_{max}} \lambda Ed(\lambda; z = 0), \exp^{-K_d(\lambda)z} d\lambda \left[\text{photons}.m^{-2}.s^{-1}\right].$$ \hspace{1cm} (2b)

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

$$K_{dPAR}(z) = -\frac{\ln(\text{PAR}(z + dz)) − \ln(\text{PAR}(z))}{dz}.$$ \hspace{1cm} (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 (case2, orange).](image-url)
with the sun at 30° from the zenith. For coastal water simulation (orange), [Chl-a] is set to 1 mg·m⁻², a_message to 0.05 m⁻¹ and [SPM] to 1 g·m⁻³. The instantaneous KdPAR (Fig. 1) is estimated using Eq. (3). Fig. 1 verifies that KdPAR(z) is more constant for coastal turbid waters (Wang et al., 2009).

We consider in this paper the vertical average value of KdPAR between the surface and the euphotic depth, KdPAR (Eq. 4) because KdPAR values reported in the literature or in-situ databases used for validation are estimated using Eq. (5) in this expression.

\[
\text{KdPAR} = \frac{\ln(\text{PAR}(0)) - \ln(\text{PAR}(z))}{z}
\]  

(4)

We use \( z = Z_{eu} \) in this study. Using KdPAR, instead of KdPAR(z) will lead to an accurate estimation of PAR near the surface and Zeu. Between these two depths, PAR will be slightly over-estimated. Further in this paper, KdPAR is noted KdPAR.

3. In-Situ data

3.1. Kd660, KdPAR measurements

In-situ Ed(\(\lambda, z\)) or PAR(z) measurements must be collected following a community-vetted protocol, (Werdell & Bailey, 2005a, 2005b) to avoid ship shadow and reflectance. If required (not here), PAR irradiance data expressed in W·m⁻² can be converted to molar units using the following approximation: 2.5 \times 10^{18} \text{quanta·s}^{-1}·W^{-1} or 4.2 \mu\text{E·m}^{-2}·\text{s}^{-1}·\text{W}^{-1} (Morel & Smith, 1974). In-situ data of Kd660 and KdPAR available through global datasets such as NOMAD (http://seabass.gsfc.nasa.gov/data/nomad_seabass_v2_a_2008200.txt), SeaBASS (http://seabass.gsfc.nasa.gov/) were extracted over the period 2005 to 2009.

Data from the instrumented buoy BOUSSOLE located near Villefranche (France) in the Mediterranean sea were also used (http://www.upmc.fr/en/research/living_earth_and_environment_section/laboratories/villefranche_sur_mer_oceanography_laboratory_umr_7093.html). Additional data in the Chesapeake Bay, which is traditionally a turbid area (Wang & Shi, 2005), and data obtained from Ifremer and OPTIC-MED (2008) and OPTIC-PCAF (2004) cruises were also added as they provide some in-situ measurements on shores where SPM backscattering and CDOM absorption may be important.

In-situ Kd660 and KdPAR values reported in public databases are calculated using Eq. (4) and integrated over the first optical depth of Ed(\(\lambda, z\)) (\(Z_{fi, 660}/K_{d660}\)) (Morel et al., 2007). To validate either satellite-derived Kd660 or KdPAR, we produced “matchups”, i.e., data pairs of satellite-derived \(K_{d}\) and in-situ colocated in space (same pixel) and obtained during the same day. The satellite Kd660 (Figs. 2 to 6) is directly comparable to the in-situ Kd660. We estimated, using Ecrolight and the IOP available for the matchups from NOMAD and Seabass dataset, a correction for KdPAR(\(Z_{eu}\)) = 0.94 × KdPAR(\(Z_{fi, 660}\)) as we do not have the irradiance profiles to re-estimate KdPAR(\(Z_{eu}\)). This correction is applied to Figs. 7a and 9. For OPTICs (12 matchups of Fig. 7) and Ifremer dataset (18 matchups of Fig. 7), the higher values of Fig. 7, we calculated KdPAR(\(Z_{eu}\)) from the irradiance profiles and Eq. (4).

Matchups are used to produce statistical comparisons for the two fields. Bias and Pearson correlation coefficient (R) for Figs. 2 to 7 are calculated on log-transformed data.

3.2. Seagrass and kelp data

In-situ coverage of P. oceanica in Corsica and single beam sounder survey data acquired on rocky seabed covered by kelp (L hyperborea) in Brittany (Mélenèder et al., 2010), are used to compare satellite-derived residual energy observed at the macrophytes lower limits to the known minimum thresholds reported in the literature. Six sites were selected by Ifremer according to accurate knowledge of species distribution and state of conservation, and the availability of an accurate bathymetry (resolution of 100 m horizontally and 1 to 5 m vertically).

![Fig. 2. Mueller’s Kd660 vs. in-situ.](image)

![Fig. 3. Morel’s Kd660 vs. in-situ.](image)

Table 1: List of symbols and abbreviations.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Unit</th>
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<tr>
<td>(lw)</td>
<td>Water leaving radiance</td>
<td>W·m⁻²·sr⁻¹·m⁻¹</td>
</tr>
<tr>
<td>(a(\lambda))</td>
<td>Absorption coefficient at wavelength (\lambda)</td>
<td>m⁻¹</td>
</tr>
<tr>
<td>(bb(\lambda))</td>
<td>Backscattering coefficient at wavelength (\lambda)</td>
<td>m⁻¹</td>
</tr>
<tr>
<td>CDOM</td>
<td>Coloured dissolved organic matters</td>
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<tr>
<td>Chl-a</td>
<td>Chlorophyll-a</td>
<td></td>
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<tr>
<td>DTM</td>
<td>Digital terrain model</td>
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<tr>
<td>GSM</td>
<td>Garver–Siegel–Maritorena</td>
<td></td>
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<tr>
<td>Globcolour</td>
<td>Global ocean colour ESA funded project</td>
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<tr>
<td>SPM</td>
<td>Suspended particulate matter</td>
<td>W·m⁻²·m⁻¹</td>
</tr>
<tr>
<td>E((\lambda,0))</td>
<td>Spectral downwelling irradiance at depth 0</td>
<td>W·m⁻²·m⁻¹</td>
</tr>
<tr>
<td>IOP</td>
<td>Inherent optical properties</td>
<td></td>
</tr>
<tr>
<td>Kd((\lambda,0))</td>
<td>Spectral diffuse attenuation coefficient for (E(\lambda,0))</td>
<td>m⁻¹</td>
</tr>
<tr>
<td>(\delta E_z(\lambda,0))</td>
<td>Spectral diffuse attenuation coefficient for downwelling irradiance between (E(\lambda,0)) and 0.10</td>
<td>m⁻¹</td>
</tr>
</tbody>
</table>
4. Satellite data

MERIS Level 2 Reduced Resolution (RR, 1 km resolution) data were used to match up with in-situ for the validation exercise. MERIS Full Resolution (FR) data were used to provide temporal means of Zeu and KdPAR over Europe. Coastal areas are characterised by strong gradients of Chl-a and SPM, which strongly affect the absorption and scattering of light. Therefore, the use of FR data when available is clearly relevant. The level 2 MERIS RR archive is available at ACRI-ST and MERIS FR data for Europe were downloaded from ESA facilities. Pixels flagged (MERIS Level 2 Detailed Processing Model) as CLOUD and HIGLINT were discarded. FR daily nLw were then projected on a regular grid of 250×250 m². Daily fields of Kd490 and KdPAR were subsequently calculated from nLw and temporally averaged over the period 2005 to 2009 as required by the EuseaMap project. Daily mean PAR (in mol·photons·d⁻¹·m⁻²) was evaluated using the algorithm developed by Frouin in 1989 and recently updated in 2011 for MERIS using Level 1 RR. The daily fields are averaged temporally over the period 2005 to 2009. Then the temporal averaged mean PAR is attenuated using the averaged KdPAR at 250 m resolution and (Eq. 3) to provide an estimation of residual PAR in the water column in mol·photons·m⁻²·d⁻¹.

5. Results

5.1. Evaluation of existing Kd490 model compared to our in-situ dataset

5.1.1. Mueller’s algorithm

Mueller (2000) proposed an empirical model for non-turbid waters based on the ratio of the nLw at wavelengths 490 and 555 nm, i.e.:

$$K_{d_{490}} = K_{w_{490}} + A \frac{nLw_{490}}{nLw_{555}}$$

Parameter A was set initially to 0.15645 and B to −1.5401. Werdell (2005a) updated (Eq. 5) to improve the algorithm performance for the clearest ocean waters. K_{w_{490}} was suppressed, A set to 0.1853 and B set to −1.349. Fig. 2 shows that Mueller’s Kd490 estimation is accurate for clear water (Kd490<0.2 m⁻¹). Above 0.2 m⁻¹ the algorithm saturates and the Kd490 is clearly under-estimated compared to the dataset used. ‘Other’ in Fig. 2 represents matchups not collected in the Mediterranean Sea. From this same dataset, the number of matchups may vary as we progress from Figs. 2 to 7 as the spectral bands used and the algorithms may be different.

5.1.2. Morel’s approach

An empirical Kd490 model based on chlorophyll-a concentration has been proposed by Morel in 2004. This model has been recently revised (Morel et al., 2007) using in-situ measurements from the NASA Bio-Optical Marine Algorithm Dataset (NOMAD) (Werdell & Bailey, 2005a, 2005b). The revised formula is given as:

$$K_{d_{490}} = 0.016 + 0.0773 \cdot [\text{Chl}]^{0.6715}.$$  

Fig. 3 shows that for Kd490<0.2 m⁻¹, the estimated Kd490 fits the in-situ retrievals. For turbid Kd490>0.3 m⁻¹ the model underestimates the attenuation. We recall that the Mueller and Morel’s algorithms have been calibrated and dedicated for open sea clear waters.
5.1.3. Lee's semi-analytical algorithm

Lee et al. (2005a, 2005b, 2009) proposed a semi-analytical approach to derive the mean Kd(\(\lambda\)) based on a radiative transfer model. The model has been revised recently (Lee et al., 2007), and Kd(\(\lambda, 10\%\)) i.e. integrated from the surface to the depth where \(E(z, \lambda) = 10\% E(0, \lambda)\) can be written as (Lee et al., 2005a):

\[
Kd(\lambda, E10\%) = (1 + 0.005 \cdot \theta) \cdot a(\lambda) + 4.18 \cdot (1 - 0.52 \cdot e^{-1.8 \cdot z}) \cdot b_b(\lambda). \tag{7}
\]

Where \(\theta\) is the solar-zenith angle in the air, \(a(\lambda)\) the total absorption at \(\lambda\) and \(b_b(\lambda)\) the total backscattering at \(\lambda\). It is interesting to note that the semi-analytical approach developed by Lee allows the derivation of Kd at any wavelength. In our case, at \(\lambda = 490\ nm\), Kd490 is derived from Eq. (7) and the absorption and backscattering coefficients at 490 nm, \(a(490)\) and \(b_b(490)\) are themselves calculated using Lee’s QAA model. The model has been revised recently (Lee et al., 2007), and which \(E(z, \lambda) = 10\% E(0, \lambda)\)) can be written as (Lee et al., 2005a):

\[
Kd(\lambda, E10\%) = (1 + 0.005 \cdot \theta) \cdot a(\lambda) + 4.18 \cdot (1 - 0.52 \cdot e^{-1.8 \cdot z}) \cdot b_b(\lambda). \tag{7}
\]

Two relationships were derived between \(E_\text{u}\) and the depth at which \(E(z, 490) = 13E(0, 490)\), Z490, using the Lw observed at the in-situ matchups (Fig. 5). The two relationships between \(K_{\text{PAR}}\) and Kd490 are directly derived from the two relationships between \(E_\text{u}\) and \(Z_{\text{PAR}}\). Relating \(K_{\text{PAR}}\) to Kd490 was not absolutely necessary as we could have integrated the spectral Kd provided by Lee using Eq. (2b). Nevertheless, we decided to propose a relationship between \(K_{\text{PAR}}\) and Kd490 as this link is meaningful and useful to derive \(K_{\text{PAR}}\) from several Kd490 in-situ datasets that are available. The threshold of 40 m for Z490 (Kd490 = 0.115 m\(^{-1}\)) was set arbitrarily to separate clear from turbid waters.

An exponential model is fitted for turbid waters (Z490 < 40 m) and a linear model for clear waters (Z490 ≥ 40 m). The proposed equations between \(K_{\text{PAR}}\) and Kd490 are shown in Fig. 6 (Eqs. 9a in blue and 9b in red).

\[
K_{\text{PAR}} = 4.6051 \cdot K_{\text{490}}/(0.0700 \cdot K_{\text{490}} + 3.200), \text{ for } K_{\text{490}} < 0.115\text{m}^{-1} \tag{9a}
\]

\[
K_{\text{PAR}} = 0.8100 \cdot K_{\text{490}}^{0.8256}, \text{ for } K_{\text{490}} > 0.115\text{m}^{-1}. \tag{9b}
\]

Morel et al. (2007) expressed \(K_{\text{PAR}}\) as a function of Kd490 for clear waters:

\[
K_{\text{PAR}} = 0.0665 + 0.874 \cdot K_{\text{490}} - 0.00121 / K_{\text{490}}. \tag{10}
\]

Similar approaches to Eq. (9b) have been recently developed by Wang & Son (Eq. 11, 2009) and Pierson & Kratzer (Eq. 12, 2008) for respectively the Chesapeake Bay turbid waters and Baltic Sea, where CDOM absorption is important.

\[
K_{\text{PAR}} = 0.8045 \cdot K_{\text{490}}^{0.9170} \tag{11}
\]

\[
K_{\text{PAR}} = 0.6677 \cdot K_{\text{490}}^{0.6763} \tag{12}
\]

Relationships between \(K_{\text{PAR}}\) and Kd490 directly depend on [Chl-a], \(a_{\text{cdom}}\) and [SPM]. In clear waters Kd490 Values are less than \(K_{\text{PAR}}\) values as the attenuation is greatest in the red with a resulting stronger PAR attenuation (which includes the red). In coastal areas, Pierson (2007)
suggests that increasing acdom has the result of increasing more rapidly Kd490 than KdPAR.

Fig. 7 shows the scatterplot of the estimated KdPAR (Fig. 7a) and the Globcolour (Fig. 7b) vs. in-situ data. The estimated KdPAR is higher than the case 1 Globcolour standard algorithm for values greater than 0.3 (Fig. 6). Although the number of matchups available is small for KdPAR > 0.3 m$^{-1}$ we can observe the saturation effect on the standard KdPAR. The number of available KdPAR matchups is too small (Fig. 7, 7 matchups) and we propose therefore an alternative validation using Ecolight simulations (Fig. 8). The Ecolight configuration is provided in Appendix A. To obtain a realistic distribution of the IOPs we start from those gathered in the NOMAD dataset. The NOMAD dataset does not provide [SPM] and an estimation of this concentration was done using Babin et al. (2003):

$$[\text{SPM}] = 1.73/0.015 \cdot b_{bp443}.$$  

$B_{bp443}$ is the particular backscattering measured at 443 nm. The sun zenith angle, $\Theta_s$, a required input parameter for Ecolight, was estimated for each in-situ data using the date, time, longitude and latitude. Finally the satellite-derived KdPAR is compared to the KdPAR estimated using Ecolight (KdPAR is calculated from the PAR provided in the Ecolight output files and averaged using Eq. (4) and the depth at which $E(z) = 1\% E_0$).

Eqs. (9a, 9b) can also be used to derive an estimate of KdPAR from Kd490. Fig. 9 shows a comparison for the NOMAD dataset between the KdPAR estimated from the in-situ Kd490 and the corresponding in-situ KdPAR, i.e. a validation of Eqs. (9a, 9b) and Fig. 6.

Fig. 9 shows an overestimation for the very clear waters. As Lee’s algorithm slightly overestimated Kd490 for clear waters (Fig. 4) and KdPAR is derived from satellite data and Lee’s spectral Kd, this slight overestimation occurs for KdPAR < 0.1 m$^{-1}$, i.e. Zeu > 46 m. For KdPAR greater than 0.1 m$^{-1}$ the estimated value fits to the in-situ data (Fig. 9).

5.3. High resolution maps of Zeu and KdPAR

Fig. 10 shows the temporal mean of KdPAR and Zeu for Brittany and the Gulf of Lions at 250 m resolution. The covered area (Europe) by the EuSeaMap project was divided in 25 zones (not shown).

5.4. Application to seabed habitat mapping

5.4.1. P. oceanica in Corsica

In Corsica three sites where P. oceanica meadows are known to be in a natural state were selected for comparison. Fig. 11 shows the distribution of P. oceanica at two sites in north-west (Calvi) and north-east (south Bastia) Corsica. The orange line shows Zeu (1% E0) estimated from MERIS 250 m over the period 2005–2009. It is interesting to note that the lower extension for P. oceanica follows the satellite-derived Zeu.

Gattuso et al. (2006) proposed a light range of 0.1 to 2.8 mol photons $\cdot$ m$^{-2} \cdot$ d$^{-1}$ for the minimum requirements of P. oceanica. Table 2 shows for the 3 selected sites the observed value in percentage of the surface irradiance and energy at the lower limit of the Posidonia beds. Using GIS software, in-situ points (black dots, Fig. 11) were selected manually on fine scale Posidonia maps at locations representing the deep boundary of the meadows. Statistics (Table 2) were computed for depth, percentage of the surface irradiance and energy by retrieving at these locations the values of pixels from respectively a 100 m resolution DTM, the temporal mean at 250 m resolution of KdPAR and the temporal mean at 1 km resolution of PAR. The observed mean values, weighted means for the 3 sites by the number of observations, are 0.94% and 0.26 mol photons $\cdot$ m$^{-2} \cdot$ d$^{-1}$ for P. oceanica. These values are very close to the 1% threshold and in the lower part of the energy range proposed by Gattuso et al. (2006).

5.4.2. Kelp in Brittany

In the same manner as the previous analysis, we have evaluated the minimum light requirements for kelp using single beam sounder acoustic data acquired in 2006 and 2007 at three sites in Brittany (les Abers in North Brittany, îles de Glénan and Île de Groix in South Brittany). The bathymetry used here is calculated from the
hydrographic zero, which in France corresponds to the lowest observed sea level. While in the Mediterranean Sea the tide range is very small, a tidal range of several metres in Brittany is normal. Therefore the half of the annual mean tide value at Brest \((0.5 \times 6.1 \text{ m})\) was added to the bathymetry (Table 3).

Fig. 12 shows the distribution of *L. hyperborea* in the French Abers. Kelp forest presence was obtained by echo-integrating the acoustic signal (Méléder et al., 2010), which enables distinguishing dense kelp forest from sparse kelp or bare rock. The sounder also provided in-situ depth measurements that account for the effect of tide, resulting in a relatively accurate estimate of the depth (with an uncertainty of 0.5 m). The values observed for the minimum in les Abers (mean of 2.3%) is significantly higher for the two other sites. This can be explained by the hydrodynamic energy regime at the seabed, which differs greatly between the North and South Brittany. Kain (1971, 1976) proposed a minimum percentage of incidental light ranges from 1% to 1.9% for *L. hyperborea* and Lüning (1979, 1990), 0.7% and 70 mol·m\(^{-2}\)·year\(^{-1}\) for this species, i.e. 0.19 mol·photons·m\(^{-2}\)·d\(^{-1}\).

The calculated mean weighted values are 1.73% and 0.42 mol·photons·m\(^{-2}\)·d\(^{-1}\) in the range proposed by Kain (in fraction of surface energy) and slightly higher than the threshold approach proposed by Lüning.

6. Conclusions

We propose two relationships between the mean \(K_{\text{PAR}}\) integrated over the euphotic layer, and the \(K_{\text{PAR}}\) estimated according to Lee et al. (2005a, 2005b), for very clear waters (\(K_{\text{PAR}}<0.115 \text{ m}^{-1}\)) and turbid waters (\(K_{\text{PAR}} \geq 0.115 \text{ m}^{-1}\)). The empirical relationship for coastal areas suggests a correction to the underestimation of \(K_{\text{PAR}}\) by the standard Globcolour case 1 algorithm, and also provides an estimation of the \(K_{\text{PAR}}(Z_{\text{eu}})\) from the in-situ \(K_{\text{PAR}}\). Satellite derived \(K_{\text{PAR}}\) and \(K_{\text{PAR}}\) have been validated using available matchups between the MERIS data, in-situ measurements and Ecolight simulations. Evaluation results suggest that the Lee et al. (2005a, 2005b) algorithm derived for MERIS is valid for estimation of \(K_{\text{PAR}}\) and the subsequent \(K_{\text{PAR}}\) in coastal areas.
The mean values of the observed threshold for the three selected sites in Corsica were 0.94% and 0.13 mol·photons·m$^{-2}$·d$^{-1}$ for *P. oceanica*. These estimates are very close to the 1% definition of $Z_{eq}$ and in the lower limit of the energy range proposed by Gattuso et al. (2006). For *L. hyperborea* surveys in Brittany, our estimated values from the satellite data were 1.73% and 0.42 mol·photons·m$^{-2}$·d$^{-1}$, in the range (1–1.9%) proposed by Kain (1971, 1976) and slightly higher than the energy threshold proposed by Lüning (0.7%, 0.19 mol·photons·m$^{-2}$·d$^{-1}$ 1979, 1990). The bathymetry used in this work is calculated from the hydrographic zero, which in France corresponds to the lowest observed level of the sea. The influence of the tide has been considered in Brittany by adding the half of the mean tidal level. Bowers and Brubaker (2010) showed also that because of tide and non-linearity of the light attenuation, the light gained at low tide exceeds the loss at high tide leading to a deeper colonisation of the species in such areas. Therefore, future works will integrate accurate local estimations of annual mean tide values.

The estimation of minimum light requirements in mol·photons·m$^{-2}$·d$^{-1}$, a true physical quantity, is meaningful compared to an estimation expressed in fraction of surface energy. This residual energy reaching the bottom at high resolution is also a good candidate as input parameter in the predictive modelling of seabed habitats such as proposed by Méléder et al. (2010).

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Appendix A. Hydrolight/Ecolight settings

Inherent optical properties
- Pure water absorption coefficient for 400–720 nm from (Pope and Fry, 1997)
- [Chl-a] constant with depth with values extracted from NOMAD
- Default Hydrolight Chl-a absorption coefficient
- Default Hydrolight Chl-a backscattering coefficient
- $A_{\text{cdm}443}$ from NOMAD
- CDOM γ coefficient $= -0.0176 \text{ nm}^{-1}$
- [SPM] from NOMAD and Eq. (13)
- Mineral particles specific scattering coefficient at 555 nm $= 0.51 \text{ m}^2\text{g}^{-1}$
- Mineral particles specific absorption coefficient at 443 nm $= 0.041 \text{ m}^2\text{g}^{-1}$
- Wavelengths similar to MERIS
- Chlorophyll fluorescence effects not included

Geometry
- Solar zenith angle of 40°
- Nadir viewing

Atmospheric and air–sea interface
- Surface wind speed of 5 m·s$^{-1}$
- Real index of refraction of water $= 1.34$

### Table 2
Statistics of fraction of the surface light and the corresponding energy in mol·photons·m$^{-2}$·d$^{-1}$ observed at the lower limit of $P$. oceanica beds.

<table>
<thead>
<tr>
<th>Location</th>
<th>Min</th>
<th>Mean</th>
<th>Max</th>
<th>St. dev.</th>
<th>Nb points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aléria, depth DTM accuracy: 1 m</td>
<td>% $E_0$</td>
<td>mol·photons·m$^{-2}$·day$^{-1}$</td>
<td>Depth (m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.46</td>
<td>0.13</td>
<td>26.0</td>
<td>1.15</td>
<td>0.33</td>
</tr>
<tr>
<td>South Bastia, depth DTM accuracy: 1 m</td>
<td>% $E_0$</td>
<td>mol·photons·m$^{-2}$·day$^{-1}$</td>
<td>Depth (m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.12</td>
<td>0.22</td>
<td>33.0</td>
<td>0.73</td>
<td>1.24</td>
</tr>
<tr>
<td>Calvi depth DTM accuracy: 5 m</td>
<td>% $E_0$</td>
<td>mol·photons·m$^{-2}$·day$^{-1}$</td>
<td>Depth (m)</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>0.44</td>
<td>0.13</td>
<td>28.0</td>
<td>0.96</td>
<td>2.04</td>
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### Table 3
Statistics of the fraction of surface light and the corresponding energy in mol·photons·m$^{-2}$·d$^{-1}$ observed at the lower limit of $L$. hyperborea in Brittany.

<table>
<thead>
<tr>
<th>Location</th>
<th>Min</th>
<th>Mean</th>
<th>Max</th>
<th>St. dev.</th>
<th>Nb points</th>
</tr>
</thead>
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<td>Abers</td>
<td>% $E_0$</td>
<td>mol·photons·m$^{-2}$·day$^{-1}$</td>
<td>Depth (m)</td>
<td></td>
<td></td>
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<td>0.42</td>
<td>21.1</td>
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<tr>
<td>Glénan</td>
<td>% $E_0$</td>
<td>mol·photons·m$^{-2}$·day$^{-1}$</td>
<td>Depth (m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.39</td>
<td>0.12</td>
<td>26.0</td>
<td>0.85</td>
<td>1.24</td>
</tr>
<tr>
<td>Groix Sud</td>
<td>% $E_0$</td>
<td>mol·photons·m$^{-2}$·day$^{-1}$</td>
<td>Depth (m)</td>
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</tr>
<tr>
<td></td>
<td>1.00</td>
<td>0.24</td>
<td>19.1</td>
<td>1.25</td>
<td>1.54</td>
</tr>
</tbody>
</table>

Fig. 12. Single-beam survey lines (thick lines) for the site Abers. Green dots denote the presence of kelp forest. Red dots are deepest occurrences of kelp forest.
References


