Remote Sensing of the Diffuse Attenuation Coefficient and Related Parameters in Turbid Waters: State of the Art and Future Perspectives

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Underwater attenuation of light is of interest to a range of users including: ecosystem modellers, who require information on Photosynthetically Available Radiation for calculation of primary production, divers, who require information on horizontal visibility for underwater operations, water quality managers, for whom parameters such as euphotic depth can be important environmental indicators, and more generally marine biologists studying processes such as visual predation. Characterisation of these processes can be achieved by a range of parameters including diffuse attenuation coefficient of downwelling PAR, spectral diffuse attenuation coefficient for downwelling irradiance, horizontal visibility, euphotic depth, Secchi depth, etc. In this contribution algorithms for estimation of these parameters by remote sensing will be reviewed with a focus on applications and algorithms in turbid waters. Future perspectives will be discussed for both polar-orbiting and geostationary sensors.

INTRODUCTION

The main goal of the SeaWiFS ocean color mission was the assessment of the global climate change and its effects on the global carbon cycle (Hooker, Esaias et al. 1992). In this context, remote sensing of the marine chlorophyll concentration (CHL) and the diffuse attenuation of Photosynthetically Available Radiation (PAR), denoted hereafter by K_{PAR}, have been widely investigated for the remote sensing of primary production (Platt and Sathyendranath 1988; Sakshaug, Bricaud et al. 1997). Recently, it was demonstrated that coastal waters also play a key role in the global carbon budget (Chen 2004; Sabine, Heimann et al. 2004; Thomas, Bozec et al. 2005; Borges, Schiettecatte et al. 2006; Cai, Dai et al. 2006), however, characterization of CHL and light attenuation in these “case 2” waters is more complex. Appropriate remote sensing algorithms for turbid waters have emerged during the last decade and are still under development.

The feasibility of providing ocean color data from satellites that cover large areas and at much higher frequency than the field measurement has brought a continuously extending community of users and raised the need to develop suitable ocean color sensors and remote sensing algorithms (McClain 2009). A wide range of remote sensing users of underwater light attenuation products may be identified, a.o: oceanographers for estimation of the upper ocean radiant energy budget (Smith, Marra et al. 1989; Morel and Antoine 1994), marine biologists who study processes such as visual predation (Aksnes and Giske 1993; Lovvorn, Baduini et al. 2001), water quality managers who need information on environmental indicators such as the euphotic depth or water transparency (Heiskary and Wilson 1989; Kelble, Ortner et al. 2005), and divers for whom the horizontal visibility is an important information for underwater activities e.g. commercial diving (Leach and Morris 1993) and military operations (Bradley, Clark et al. 2000). Characterization of such processes can be achieved via remote sensing of a range of parameters including spectral diffuse attenuation coefficient for downwelling irradiance, horizontal visibility, euphotic depth, Secchi depth, etc. Remote sensing algorithms established to retrieve these parameters are reviewed with a focus on applications in turbid waters. Future perspectives are discussed for both polar-orbiting and geostationary sensors.

DEFINITIONS

An extensive terminology of marine ecological parameters related to PAR is presented in (Sakshaug, Bricaud et al. 1997). From the remote sensing side, it is important to discriminate the apparent from the inherent optical properties, (AOPs and IOPs) (Preisendorfer 1961; Kirk 1996), which generally orients the design of the ocean optics algorithms linking AOPs to IOPs (Zaneveld, Barnard et al. 2006). The IOPs are the absorption, *a*, the scattering, *b* and the volume scattering function *VSF*. Of special interest for remote sensing of turbid waters is the backscattering, b_b, which is a function of *b* and VSF. These parameters are *inherent* to the water body and its constituents. AOPs are determined by IOPs and by the incident light and sun position. Those related to underwater attenuation of light and considered in this paper are listed in Table 1.

Table 1: AOPs related to underwater attenuation of light.

Parameter	Notation and definition
Radiance	$L[Wm^{-2}sr^{-1}nm^{-1}]$
Downwelling, upwelling and scalar irradiances	$E_d(z,\lambda),\ E_u(z,\lambda), E_o(z,\lambda)\ \ [Wm^{-2}nm^{-1}]$
Total irradiance over the *PAR* range	$E_o^{PAR}(z)=\int_{400nm}^{700nm} E_o(z,\lambda)\,d\lambda\ [Wm^{-2}nm^{-1},\ photons\ m^{-2}s^{-1}]$
Diffuse attenuation coefficient for downwelling irradiance	$K_d(z,\lambda)=-\frac{dE_d(z,\lambda)}{E_d(z,\lambda)\,dz}\ \ [m^{-1}]$
Diffuse attenuation coefficient for upwelling irradiance	$K_u(z,\lambda)=-\frac{dE_u(z,\lambda)}{E_u(z,\lambda)\,dz}\ \ [m^{-1}]$
Diffuse attenuation coefficient for scalar irradiance	$K_o(z,\lambda)=-\frac{dE_o(z,\lambda)}{E_o(z,\lambda)\,dz}\ \ [m^{-1}]$
Photosynthetically Available Radiation, *PAR* at depth z	$PAR(z)\ or\ E_o^{PAR}(z)=\int_{350nm}^{700nm} E_o(z,\lambda)\,d\lambda$ $[Wm^{-2}nm^{-1},\ mol\ photons\ m^{-2}s^{-1}]$
Diffuse attenuation coefficient for *PAR*	$K_{PAR}(z)=-\frac{dPAR(z)}{PAR(z)dz}\ \ [m^{-1}]$
Average cosine for total, downwelling and upwelling light field	$\bar{\mu}, \bar{\mu}_d, \bar{\mu}_u$
Euphotic zone depth	$Z_{eu}(1\%)=4.6\,/\,\bar{K}_{PAR}$

APPLICATIONS

K_{PAR}

Since the early 50s, eutrophication in lakes and coastal waters has shown to be a phenomenon of real concern for water quality managers and society in general (Nixon 1995). The community of limnologists was the first to undertake research establishing the eutrophication status in lakes and modeling the response of these waters to changes in nutrient inputs. (Cloern 1999) presents a review of such models that estimate the primary production from the hydraulic and morphometric fields and nutrient loads (*a.o. Dillon and Rigler 1975, Boyton et al 1982*). However, these models show diverging responses to a given nutrient loading on a seasonal scale (Le Pape, Del Amo et al. 1996), because they lack information on the optical conditions as pointed out by (Visser and Kamp-Nielsen 1996). A review by (Branco and Kremer 2005) on light attenuation parameterization in the ecological models published from 1976 to 2003, shows that these models are generally based on a formulation of K_{PAR} or K_d (this parameter was sometimes ambiguously defined) as function of CHL, and underestimate K_{PAR} in shallow waters. In a number of estuarine and coastal zones, it has been shown that K_d is almost entirely governed by suspended particulate matter (SPM) (Christian and Sheng 2003; Huret, Gohin et al. 2007; Devlin, Barry et al. 2008). In others coloured dissolved organic matter (CDOM) (Branco and Kremer 2005) may also be important in determining KPAR. In particular, the timing of algal blooms may be extremely sensitive to the light available underwater (Lacroix, Ruddick et al. 2007). A significant improvement in the prediction of algal bloom amplitudes and timing was obtained by integration of suspended matter loads in the modeling of K_{PAR} in coastal waters (Huret, Dadou et al. 2005; Tian, Merico et al. 2009).

SECCHI DEPTH, EUPHOTIC DEPTH AND UNDEWATER VISIBILITY

The *in situ* measurement of Secchi depth (*SD*) is the simplest and least expensive measure of water clarity, making it widely used in limnology (Carlson 1977; Hou, Lee et al. 2007). *SD*, total phosphorus and chlorophyll a concentrations were often used as proxies to lake trophic status (Carlson 1977). It has also been indicated to use SD as a proxy to water turbidity to assess the trophic status in estuaries (Bricker, Ferreira et al. 2003). (Heiskary and Wilson 1989) integrated *SD* information together with a set of water quality parameters to classify water types for water resource management. However, in waters where chlorophyll-a is decoupled from water clarity due to co-existing non-algal particles (e.g. in artificial lakes, turbid waters), *SD* is not appropriate to predict the primary production (Canfield and Bachmann 1981).

Since in situ *SD* may lack accuracy (Preisendorfer 1986) due to human reading and uncertainties in high current levels in rivers (Davies-Colley and Nagels 2008), estuarine or coastal waters, the use of remote sensed Secchi depth (Z_{SD}) or a suitably defined related parameter is beneficial. Underwater visibility was investigated by (Zaneveld and Pegau 2003; Doron, Babin et al. 2005) who give Z_{SD} as function of K_d and beam attenuation. Recently, an operational MERIS-Z_{SD} product has been developed, based on the work of (Kratzer, Brockmann et al. 2007) who retrieve Z_{SD} from the reflectance ratio at 490:620.

(Lee 2009) suggests the use of Z_{eu} instead of Z_{SD} as a more rigorous tracer of water clarity. (Lee, Weidemann et al. 2007) have set up a semi-analytical model for Z_{eu} retrieval from IOPs, which performed better than the CHL-based euphotic depth algorithm of (Morel and Berthon 1989).

REMOTE SENSING ALGORITHMS

In the present review the diffuse attenuation coefficient for downwelling irradiance, K_d is considered. The light received by phytoplankton may be better considered by use of the (omnidirectional) scalar irradiance, $E_{o,}$ and hence the diffuse attenuation coefficient for scalar irradiance, K_o, might be of more direct importance. However, the values of K_d instead of K_o and K_o are generally quite similar (Gordon and Clark 1980; Sakshaug, Bricaud et al. 1997) and most studies consider K_d because it is more easily measured.

From Hydrolight simulations in (Lee, Weidemann et al. 2007) covering a wide range of IOPs, E_u was found to be much smaller than E_d and the irradiance in [350nm-400nm] also remains small.

K_d is an AOP which may be computed from water IOPs and the angular dependence of the surface light field (and also the spectral dependence if KdPAR is required). Because of the lack of information on these IOPs, the first algorithms set up for remote sensing retrieval of K_d were empirical and designed as part of the inverse problem, thus giving K_d as a function of the blue-to-green ratio of water-leaving radiance or remote sensing reflectance (Austin and Petzold 1981; Gould and Arnone 1994; Mueller and Trees 1997; Mueller 2000; Loisel, Stramski et al. 2001) :

$$K_d(490) = f\left(\frac{L_{blue}}{L_{green}}\right) \tag{1}$$

This is described as the direct *one-step* scheme (see Figure 1 in (Lee, Darecki et al. 2005)). This formulation is most appropriate for "Case 1" waters where optical properties are determined entirely by algal particles and will therefore not perform well in Case 2 waters with significant non algal particles or CDOM not related to phytoplankton.

Algorithms relating K_d to water constituents have been first developed for the open ocean where strong correlations were found between CHL and K_d (Morel 1988; Morel, Antoine et al. 2007), CHL being the major component that controls light attenuation in these case 1 waters. Therefore, K_d –algorithms can be designed in a *two-step* scheme:

$$\text{a. } CHL = f\left(\frac{L_{blue}}{L_{green}}\right) \quad \text{b. } K_d = K_w + \chi\, CHL^{\gamma} \tag{2}$$

where χ and γ are determined empirically and CHL is retrieved as a spectral ratio of water reflectance (e.g. the OC3, OC4 algorithms).

A generalization of Eq 2.b expresses light attenuation as linear function of the concentrations of the main optically active components in case 2 waters, C_i (e.g. i being generally CHL, CDOM, total suspended matter (TSM)). Such equations follow the form (Smith and Baker 1978; Gohin, Loyer et al. 2005):

$$K_d = K_w + \sum_i \chi_i\, C_i^{\gamma_i} \tag{3}$$

where K_w is the diffuse attenuation coefficient due to water and χ_i, γ_i are empirically determined from field measurements of light attenuation and concentrations C_i. This is also a *two-steps* method which requires the estimates of C_i from satellite-derived IOPs or from satellite radiances or reflectances $C_i = f\left(R_{rs}\right)$. Linear, logarithmic or exponential functions of C_i were explored to predict K_d and showed equivalent performance in the study of (Devlin, Barry et al. 2008).

Equations like Eq. 3 find their origin in the relationships linking K_d to IOPs (Kirk 1994), which are established analytically based on the radiative transfer equation (RTE) (Gordon, Brown et al. 1975; Kirk 1981; Mobley 1994). (Dekker, Brando et al. 2001) presented a review of analytical algorithms a.o. (Gordon, Brown et al. 1975; Aas 1987; Sathyendranath, Platt et al. 1989; Kirk 1991) (some examples are provided in Table 2) and set up a generic model derived from (Aas 1987). However, the difficulty in such a "full" model is the need to characterize RTE parameters like the shape factors and the average cosines (see Table 2) which remain poorly documented in turbid waters. An alternative is to use model-generated lookup tables such as the model of (Lee, Du et al. 2005) (Table 2).

Table 2: K_d-IOPs relationships. G is a function of the VSF and $\bar{\mu}_d$ and $\bar{\mu}_u$ are respectively the downwelling and upwelling average cosines. of (Lee, Du et al. 2005). The factors r_d and r_u (Dekker, Brando et al. 2001) respectively refer to the shape factors for downwelling and upwelling scattering. R is the subsurface irradiance reflectance.

Reference	Model
(Gordon, Brown et al. 1975) (Sathyendranath, Platt et al. 1989)	$K_d = \frac{a+b_b}{\mu_0}$ $K_d = \frac{a+b_b}{\bar{\mu}_d}$
(Smith and Baker 1981)	$K_d = a + b_b$
(Aas 1987)	$K_d = \frac{a}{\bar{\mu}_d}\left[1+\frac{b_b}{a}\right]$, $K_d = \frac{a}{\bar{\mu}_d}\left[1+r_d\frac{b_b}{a}\right]$
(Kirk 1984; Kirk 1991)	$K_d = \frac{a}{\bar{\mu}_d}\left[1+G(\bar{\mu}_d, g)\frac{b}{a}\right]^{0.5}$
(Dekker, Brando et al. 2001)	$K_d = \frac{a}{\bar{\mu}_d}\left[1+r_d\frac{b_b}{a}\left(1-\frac{r_u\bar{\mu}_d}{\bar{\mu}_u+\bar{\mu}_d}\frac{b_b}{a+kb_b}\right)\right]$ $k = \frac{r_u\bar{\mu}_d + r_d\bar{\mu}_u}{\bar{\mu}_u+\bar{\mu}_d}$
(Lee, Du et al. 2005)	$K_d = \frac{1}{\bar{\mu}_d}a + \left(\frac{r_d}{\bar{\mu}_d} - \frac{r_u R}{\bar{\mu}_u}\right)b_b \qquad R = \frac{E_u}{E_d}$ $K_d(E_{10\%}) = (1+0.005\theta_0)a + 3.47\,b_b$

To achieve this, semi-analytical methods have emerged that parameterize the dependency of depth-averaged K_d on water IOPs and on the varying illumination conditions in a clear sky, using numerical simulations of the RTE such as (Lee, Du et al. 2005) who proposed the following equation:

$$K_{d(z,\theta_0)} = m_{0(z,\theta_0)}a + m_{1(z,\theta_0)}\left[1 - m_{2(z,\theta_0)}e^{-m_{3(z,\theta_0)}a}\right]b_b \tag{4}$$

where m_0, m_1, m_2 and m_3 were parameterized using Hydrolight simulations with a large set of artificial IOPs, K_d varying with the depth z and solar zenith angle Θ_0. A good approximation was found for K_d integrated from the surface to $Z_{10\%}$ where the downwelling irradiance reaches 10% of its value at the surface: $K_d\left(E_{10\%}\right) = \left(1+0.005\theta_0\right)a + 3.47\,b_b$.

Linking K_d to IOPs rather than to the concentrations of water components presents the advantage for such algorithms to be portable to all waters with similar ranges of IOPs, and alleviate the attempt to determine the individual contribution of components to light attenuation, depending on their composition, size, index of refraction…etc.

The performance and the limitations of the *one-step* and *two-steps* empirical algorithms have been addressed in (Lee, Du et al. 2005) and compared to the accuracy of the semi-analytical model (Eq. 4). (Lee, Du et al. 2005) pointed out the following sources of errors analyzed in these methods are: a) the reflectance blue:green ratio has a saturation limit at high concentrations which causes significant underestimation of K_d in turbid waters, (Wang, Son et al. 2009) found a factor of 2 to 3 between in situ and K_d(490) from MODIS data over the turbid waters of Chesapeake Bay, b) the band ratios are not sensitive to sun and viewing geometry, and c) they are more sensitive to variations in absorption and less to those in the scattering, which makes it less suitable for turbid water applications.

(Wang, Son et al. 2009) have recently set a semi-analytical model of K_d for turbid waters, based on the relationship between b_b at 490nm and R at a longer wavelength. But this model proved to be less adapted for clear waters. For that, use of a combination of the clear and turbid models is proposed. A set of K_d -models were also proposed for 3 water types being clear, turbid and “transitional” in (Devlin, Barry et al. 2009), which further needs objective criteria to be set for discrimination of water types.

FUTURE PERSPECTIVES

Polar orbiting satellites make acquisition of images over a given scene each 1 to 4 days. Cloud cover also may hugely decrease the number of data available on a given area. While long trends and climatologic information may be obtained from long time series of ocean colour data archive, the smaller time scale variations are missed. For that, the geostationary satellites may provide valuable information bridging the gaps in the polar orbiting retrieved data, and enabling studies of high frequency patterns. (Neukermans, Ruddick et al. 2009) demonstrated the feasibility of SPM retrieval in turbid waters at a temporal resolution of 15 minutes from the geostationary SEVIRI weather satellite and demonstrated high fluctuations of SPM during the day. In these turbid North Sea waters, K_{PAR} is mainly governed by SPM concentration (Devlin, Barry et al. 2009; Lacroix, Sirjacobs et al. 2010) and high frequency variability of SPM may dramatically affect the daily K_{PAR} budget. Geostationary K_{PAR} products may help to improve the estimation of algal blooms, particularly their timing.

During the last decade, efforts have been made in ocean optics research to develop algorithms for remote sensing of underwater light attenuation, responding to a large community of users. At the crossroad of these algorithms, K_d is the key parameter that has been modeled with empirical, analytical and semi-analytical techniques based on the RTE. The semi-analytical relationships for K_d allow their easy implementation and quick processing from the remote sensing data, and present good tools for a better understanding of light interactions in an aquatic medium.

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