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Model of the attenuation coefficient of daily photosynthetically available radiation in the upper ocean

Jianwei Wei *, ZhongPing Lee

School for the Environment, University of Massachusetts Boston, 100 Morrissey Blvd., Boston, MA 02125, USA

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Penetration of the photosynthetically available radiation (PAR, over 400–700 nm) in the upper ocean is important for many processes such as water radiant heating and primary productivity. Because of this importance, daily PAR at sea surface ($\overline{\mathrm{PAR}}(0^+)$) is routinely generated from ocean-color images for global studies. To propagate this broadband solar radiation through the upper ocean, an attenuation coefficient of PAR (K_{PAR}) is also generated from the same ocean-color measurements. However, due to the empirical nature of the K_{PAR} algorithm, this K_{PAR} product corresponds to an instantaneous PAR at a fixed sun angle, with no diurnal variability. It is hence necessary to have an attenuation coefficient matching the temporal characteristics of daily PAR. This paper represents an effort to meet this need. Using ECOLIGHT, the subsurface light field for a wide range of water bodies was simulated, from which the attenuation coefficient ($K_{\overline{\mathrm{PAR}}}$) of daily PAR was calculated. We presented the diurnal and vertical variation of this attenuation coefficient, and found that it can be well predicted (within ~7%) as a function of the total absorption coefficient and backscattering coefficient at 490 nm and the noontime solar zenith angle. This new model offers an efficient and reasonably accurate approach for quantifying daily upper water column PAR within the global ocean from satellite measurements of water color.

* Corresponding author. Tel.: +1 617 287 7396; fax: +1 617 287 7474.
E-mail addresses: Jianwei.Wei@umb.edu (J. Wei), Zhongping.Lee@umb.edu (Z.P. Lee).

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1. Introduction

The visible light (400–700 nm) accounts for about half of the total radiant energy reaching the ocean surface. Penetration of this broadband solar radiation through the upper ocean is an essential driver determining many biological, chemical and physical processes (Dickey and Falkowski, 2002). For instance, thermal and dynamic evolution of the upper ocean is sensitive to the vertical distribution of available solar energy (Chang and Dickey, 2004; Dickey and Simpson, 1983; Lewis et al., 1990; Morel and Antoine, 1994; Murtugudde et al., 2002; Ohlmann and Siegel, 2000; Ohlmann et al., 2000; Siegel and Dickey, 1987a). The water radiant heating rate (RHR) can be defined by the one-dimensional heating equation (Ohlmann and Siegel, 2000)

$$\frac{dT}{dt} = -\frac{1}{\rho_w C_p}\frac{d\mathrm{PAR}}{dz}. \tag{1}$$

PAR represents the photosynthetically available radiation (in units of W m^{-2}) that is an integration of the irradiance over the spectral range 400–700 nm (a list of symbols and notations are given in Table 1), ρ_w is the sea water density, C_p is the specific heat capacity of sea water ($\sim$4100 J kg^{-1} °C^{-1}), T is the water temperature (unit: °C), and t is time (unit: s). When all the other properties are considered constant, the heating rate in Eq. (1) is determined by the vertical change of PAR with water depth.

Solar radiation is also the driving force of marine primary productivity. Its value at a depth can be described by a hyperbolic tangent model (Jassby and Platt, 1976; Platt and Gallegos, 1980)

$$P(z,t) = P_{\max}(z,t)\cdot\tanh\left(\frac{\mathrm{PAR}\,(z,t)}{E_k(z,t)}\right) \tag{2}$$

with PAR(z,t) here computed in quanta (units: mol photons m^{-2} s^{-1}), $P_{\max}$ (unit: mg C m^{-3} h^{-1}) the maximum photosynthetic rate, and E_k (unit: mol photons m^{-2} s^{-1}) the light saturation index. Accurate parameterization of the change of PAR along with water depth is critical for resolving the depth distribution of primary productivity in euphotic zone (Asanuma et al., 2003; Lohrenz et al., 1994; Marra et al., 2003; Morel and Berthon, 1989; Smith et al., 1987).

PAR (represented here by downwelling plane irradiance, E_d, in energy units of W m^{-2}) at depth z can be expressed as

$$\mathrm{PAR}\,(z) = \int_{400}^{700} E_d(z,\lambda)\,d\lambda \tag{3}$$

and the vertical propagation of E_d is

$$E_d(z,\lambda) = E_d(0^-,\lambda)\,e^{-K_d(\lambda)\,z} \tag{4}$$

with $K_d(\lambda)$ the diffuse attenuation coefficient of E_d at wavelength λ. Based on the radiative transfer theory, it has been found that K_d is a function of water's inherent optical properties (IOPs) and the solar zenith angle (Gordon, 1989; Kirk, 1984; Lee et al., 2005a; Loisel and Stramski, 2000; Morel and Gentili, 2004). For vertically homogeneous waters, K_d varies with depth, but generally within $\sim$10% for low solar zenith angle and low scattering waters. Following the scheme of Eq. (4), the vertical propagation of PAR is also commonly expressed as

$$\mathrm{PAR}\,(z) = \mathrm{PAR}\,(0^-)\,e^{-K_{\mathrm{PAR}} z} \tag{5}$$

with K_{PAR} the vertical attenuation coefficient for PAR. And like K_d, K_{PAR} varies with solar zenith angle (Lee et al., 2005b). However, unlike the mild vertical variation of K_d, due to the strong selective absorption by water constituents, K_{PAR} varies strongly with depth and can change by a factor of 3–4 between the surface and deeper depths (Lee, 2009; Paulson and Simpson, 1977; Siegel and Dickey, 1987a).

Many ocean circulation models use daily solar radiation as inputs (Brodeau et al., 2010; Large et al., 1997; Murtugudde et al., 2002), and the daily total solar radiation is

$$\overline{\mathrm{PAR}}\,(z) = \int_{\mathrm{sunrise}}^{\mathrm{sunset}}\int_{400}^{700} E_d(z,\lambda)\,d\lambda\,dt. \tag{6}$$